CMS VHH Search

Search for HH with smaller production modes

Dec-21st, 2024

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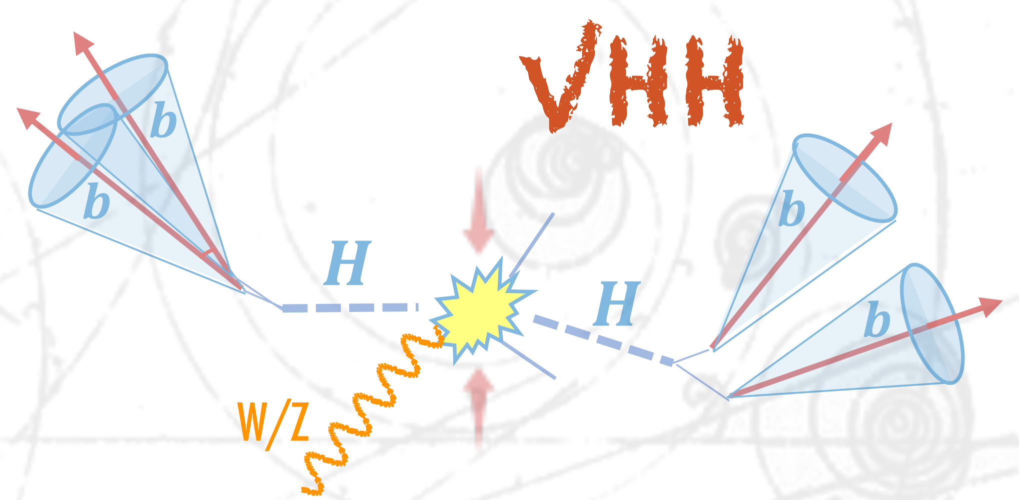
On behalf of the CMS VHH analysis team



Higgs Potential 2024 workshop
For Higgs potential and BSM opportunities
University of Science and Technology of China (USTC),
Dec-19～23, 2024, Hefei.

- > 10 years after the discovery of the Higgs Boson on the LHC
  - Higgs couplings to fermions and vector bosons compatible with SM <10%
  - Exceptions are HH related couplings such as K_λ and K_{VV}
- HH productions is the direct prob to the Higgs self-coupling(Higgs potential) on the LHC
- HH searches have explored a big variety of decay modes and also started to expand beyond the gluon-gluon fusion production, looking into smaller productions
  - VBF, VHH, ttHH etc.
  - Low stats, but **unique** final states or/and **advantages** in featured phase space

ggF HH

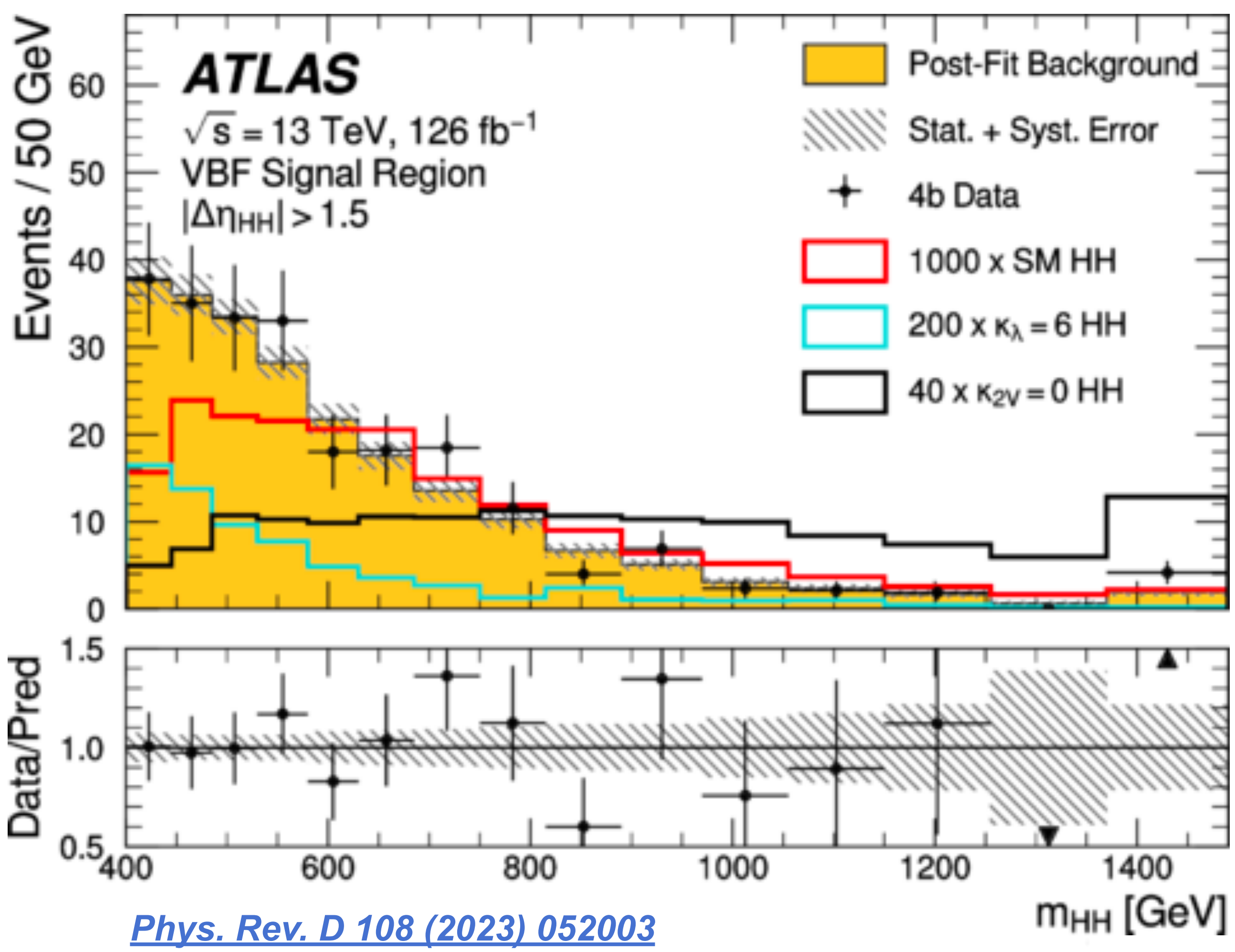
VBF HH

ttHH

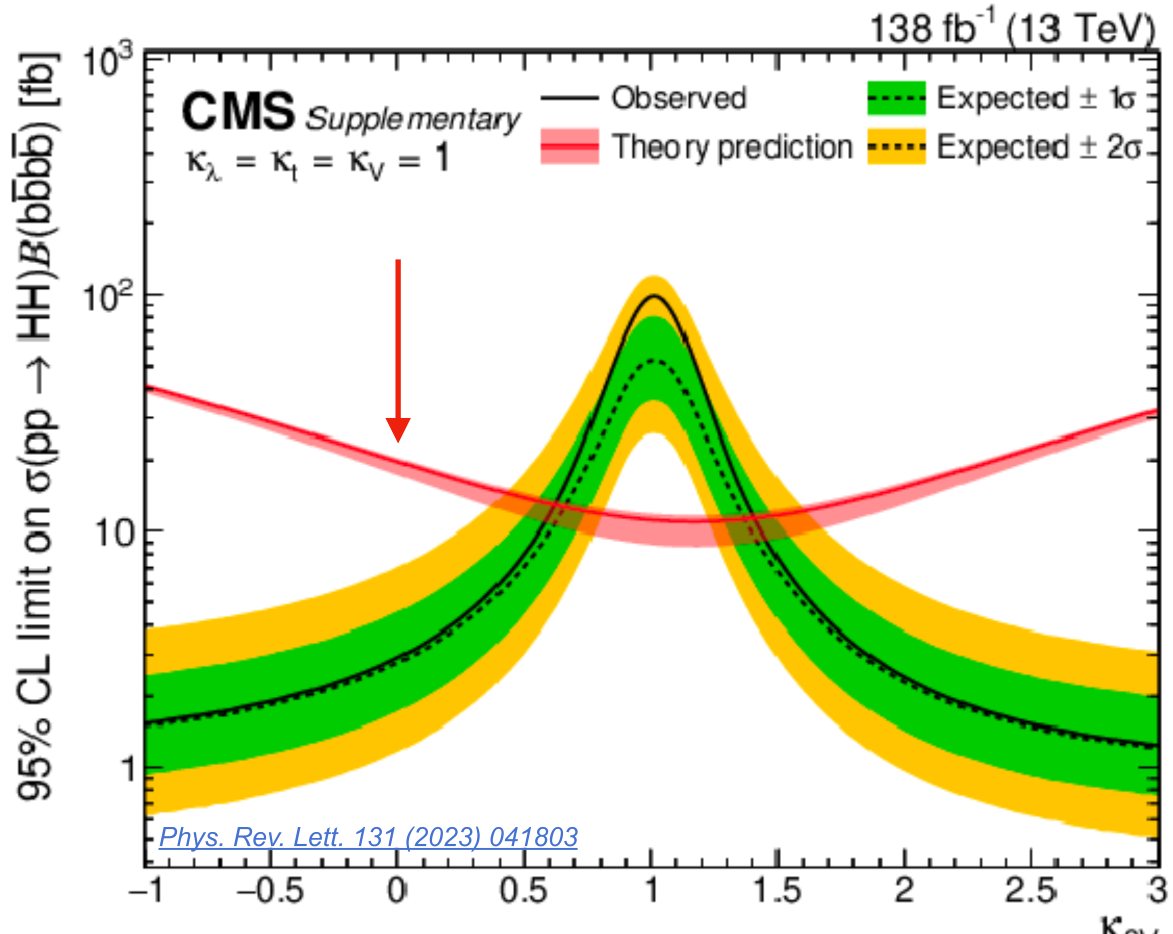
VHH

	$\sqrt{s}=13\text{TeV}$ (LO)	NLO
HH (EFT loop-improv.)	$(19.1^{+33\%}_{-23\%})$	$29.3^{+15+2.1\%}_{-14-2.5\%}$
$HHjj$ (VBF)	$(1.543^{+9.4\%}_{-8.0\%})$	$1.684^{+1.4+2.6\%}_{-0.9-1.9\%}$
$t\bar{t}HH$	$(1.027^{+37\%}_{-25\%})$	$0.792^{+2.8+2.4\%}_{-10-2.9\%}$
W^+HH	$(0.252^{+1.4\%}_{-1.7\%})$	$0.326^{+1.7+2.1\%}_{-1.2-1.6\%}$
W^-HH	$(0.133^{+1.5\%}_{-1.7\%})$	$0.176^{+1.6+2.2\%}_{-1.2-2.0\%}$
ZHH	$(0.240^{+1.4\%}_{-1.7\%})$	$0.315^{+1.7+2.0\%}_{-1.1-1.6\%}$
$tjHH(\cdot 10^{-3})$	$(23.20^{+0.0\%}_{-0.8\%})$	$29.77^{+4.8+2.8\%}_{-2.8-3.2\%}$

- VBF HH analysis is usually included in ggF HH publication
  - Treated as a separate signal region
  - Fitted simultaneously with ggF, as ggF contamination is not negligible in the VBF phase space
- Kinematics gets harder when K_{VV} increases → strong constraints for high K_{VV} couplings



Phys. Rev. D 108 (2023) 052003

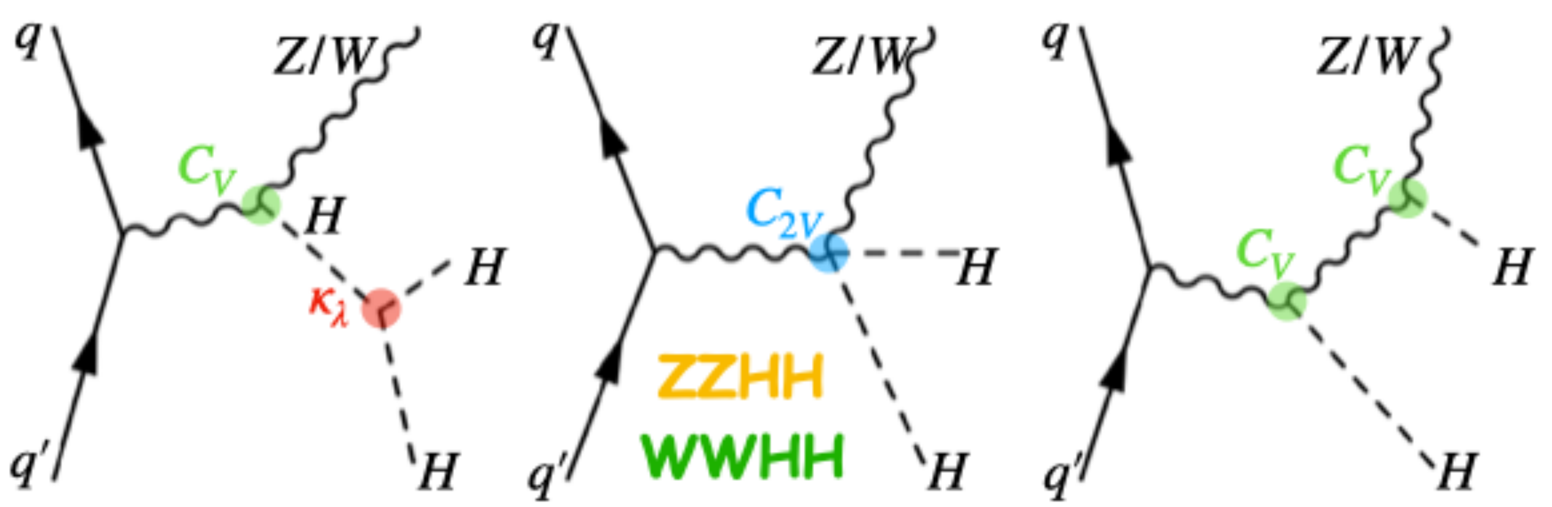


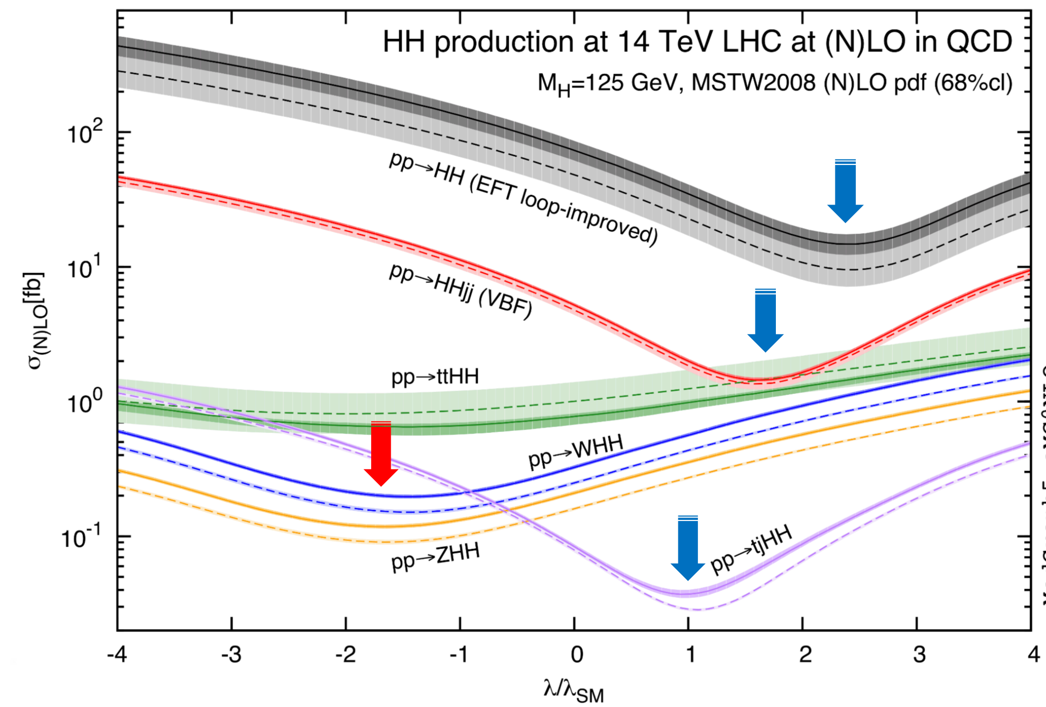
C2V constrained [0.62, 1.41] ([0.66, 1.37]) at 95% CL

Excluding C2V=0 for the first time

Introduction VHH

- Search for HH production mode associated with one vector boson (Z/WHH)
  - Focus on HH decay to 4b final states and leptonic decay and hadronic decay for V-bosons.
  - Complementary to ggF and VBF analyses with cleaner signal with V-leptonic selection
- Cross-sections are enhanced by the constructive interference.
  - Contribution on sensitivities over κ_λ at positive branch is expected.





- VHH channel has the unique feature to disentangle *ZZHH/WWHH* vertices according to the V-leptonic decay.
- Four orthogonal search channels depending on lepton multiplicity: *MET, SL, DL, FH.**

* MET, Single-Lepton, Double-Lepton, Full-Hadronic

Data/MC Samples

- **Analysis uses full run2 samples/dataset(138fb^{-1}) with UL nano v9**
  - 2016,2017: SingleMuon, DoubleMuon, SingleElectron, DoubleElectron, MET, BTagCSV
  - 2018: SingleMuon, DoubleMuon, EGamma, MET, JetHT
- **Signals:**
  - **ZHH** signal re-weighted and scaled to NNLO
    - ★ Re-weighting and Scaling, residual differences after basic selections are covered by syst. Uncertainties.
  - **WHH** signal scaled to NLO
  - Linearly interpolate/extrapolate existing samples to get more couplings for limit scan
    - According to the talk, implemented in HHModel that used by all HH analysis
  - Use Moore-Penrose inverse to accommodate 8 signal samples

LO

κ_V	κ_{2V}	κ_λ
0.5	1.0	1.0
1.0	0.0	1.0
1.0	1.0	0.0
1.0	1.0	1.0
1.0	1.0	2.0
1.0	2.0	1.0
1.5	1.0	1.0
1.0	1.0	20.0

$$\sigma(\kappa_\lambda, \kappa_V, \kappa_{2V}) = c^T(\kappa_\lambda, \kappa_V, \kappa_{2V})C^{-1}\sigma$$

- **Backgrounds:**
  - **DY+Jets**: Re-weighted to NLO and scaled to NNLO with K-fac
  - **TT**: Replace TT+B events in tt(5FS) with ttbb(4FS)(TT stitching)
    - ★ Validated to have smaller uncertainty and better kinematics modeling.
  - **Others**: SingleTop, TTV, TTH, Zto$\nu\nu$+Jets using MC

Full Run-2 Ultra Legacy MC samples are used for sig/bkg studies

All 3 years triggers have been studied

Leptonic Triggers

Muon

1L / 2L

Channel	Year	HLT paths	
$W(\mu\nu)H$	2016	HLT_IsoMu24 OR HLT_IsoTkMu24	
	2017	HLT_IsoMu27	
	2018	HLT_IsoMu24	
$Z(\mu\mu)H$	2016	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL	OR
		HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ	OR
		HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL	OR
		HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ	
	2017	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8	OR
		HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass8	
	2018	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8	

Electron

1L / 2L

Channel	Year	HLT paths
$W(e\nu)H$	2016	HLT_Ele27_WPTight_Gsf
	2017	HLT_Ele32_WPTight_Gsf (emulation)
	2018	HLT_Ele32_WPTight_Gsf
$Z(ee)H$	2016	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ
	2017	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL
	2018	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL

MET

Year	HLT path for analysis	
2016	HLT_PFMET110_PFMHT110_IDTight	OR
	HLT_PFMET120_PFMHT120_IDTight	
	OR HLT_PFMET170_NoiseCleaned	OR
	HLT_PFMET170_BeamHaloCleaned	OR
	HLT_PFMET170_HBHECleaned	
2017	HLT_PFMET120_PFMHT120_IDTight	OR
	HLT_PFMET120_PFMHT120_IDTight_PFHT60	
2018	HLT_PFMET120_PFMHT120_IDTight	

Hadronic Triggers

Jet

- 2016:
  HLT_QuadJet45_TripleBTagCSV_p087 ||
  HLT_DoubleJet90_Double30_TripleBTagCSV_p087 ||
  HLT_DoubleJetsC100_DoubleBTagCSV_p014_DoublePFJetsC100MaxDeta1p6
- 2017:
  HLT_PFHT300PT3_QuadPFJet_75_60_45_40_TriplePFBTagCSV_3p0 ||
  HLT_DoublePFJets100MaxDeta1p6_DoubleCaloBTagCSV_p33
- 2018:
  HLT_PFHT330PT30_QuadPFJet_75_60_45_40_TriplePFBTagDeepCSV_4p5 ||
  HLT_DoublePFJets116MaxDeta1p6_DoubleCaloBTagDeepCSV_p71

Dedicated efficiencies measurement for leptons approved by POGs

Electron SF: Reco X ID_ISO X Trigger
Muon SF: ID X ISO X Trigger
MET Trigger SF: Start from 150GeV

V-leptonic SFs are good for VHbb/VHcc on UL analyses (documented in AN-21-209)

* More details about trigger scale factors can be found in the backup slides

Lepton Selection

- **MET**
  - Met Filters
  - MET_pt > 150GeV
  - No jet (pt >30GeV and eta <10) with dPhi(Jet,MET) < 0.3 (suppress QCD)

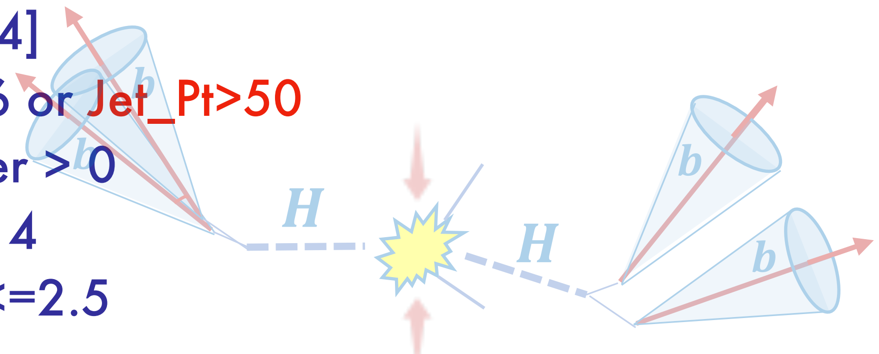
- **Single-Lepton**
- GoodMuon: (1 Muon for W)
  - |Muon_eta| < 2.4
  - Muon_pt > 25GeV
  - Muon_pfRelIso04_all < max_rel_iso [0.06]
- GoodElectron: (1 Electron for W)
  - |Electron_eta| < 2.5
  - Electron_pt > 32(17/18); Electron_pt > 28(16)
  - Electron_pfRelIso03_all < max_rel_iso [0.06]
  - Electon_mvaFall17V2Iso_WP90>0

- **Double-Lepton**
- GoodMuons: (2 Muons for Z)
  - |Muon_eta| < 2.4
  - Muon_pt > 20GeV
  - Muon_pfRelIso04_all < max_rel_iso [0.25]
- GoodElectrons: (2 Electrons for Z)
  - |Electron_eta| < 2.5
  - Electron1_pt > 23GeV; Electron2_pt > 14GeV
  - Electron_pfRelIso03_all < max_rel_iso [0.15]
  - Electon_mvaFall17V2Iso_WP90>0
- Z mass window [80,100] GeV in DL channel
  - [80,100] GeV: Z mass region (research region)
  - Outside: TT Control region

Electron selections optimized in all 3 V-Leptonic channels

Jets Selection

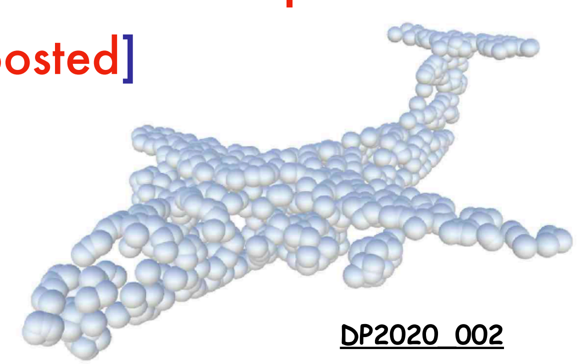
V-Leptonic channels



- GoodJets: [AK4]
  - Jet_puId>6 or Jet_Pt>50
  - Jet_lepFilter > 0
  - Jet_jetId > 4
  - |Jet_eta|<=2.5
- 4 leading DeepJet GoodJets [Resolved]
  - Using DeepJet b-tag [WP = Medium]
  - ptCut for all 4 jets
    - MET: pT>35GeV
    - SL: pT>25GeV(j1-j3), pT>15GeV(j4)
    - DL: pT>20GeV

DeepJet for AK4 jets and ParticleNet for AK8 jets

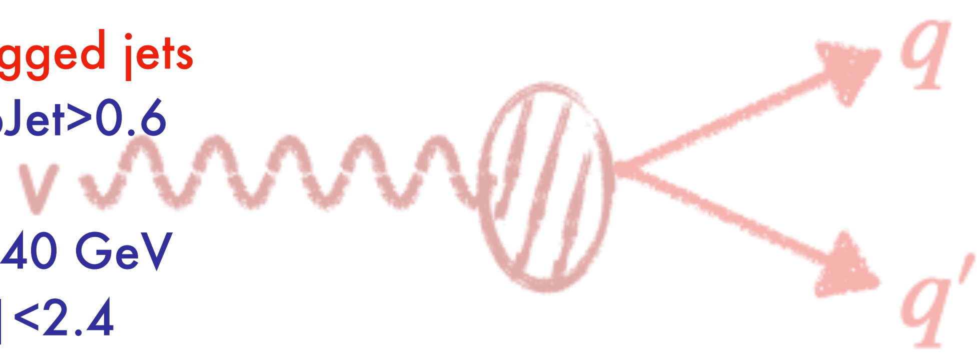
- 2 leading Dbb AK8 jets [Boosted]
  - |Jet_eta|<=2.5
  - Jet_Pt > 200GeV
  - Softdrop mass>50GeV
  - dR(Jet,V)>0.8



DP2020_002

$$D_{bb} = \frac{ParticleNetMD\_score(X \to b\bar{b})}{ParticleNetMD\_score(X \to b\bar{b}) + ParticleNetMD\_score(QCD)}$$

V-Hadronic channel



- >= 4 b-tagged jets
  - DeepJet>0.6
- >= 6 jets
  - pT > 40 GeV
  - |eta|<2.4
  - PUID medium WP

DeepJet for AK4 jets

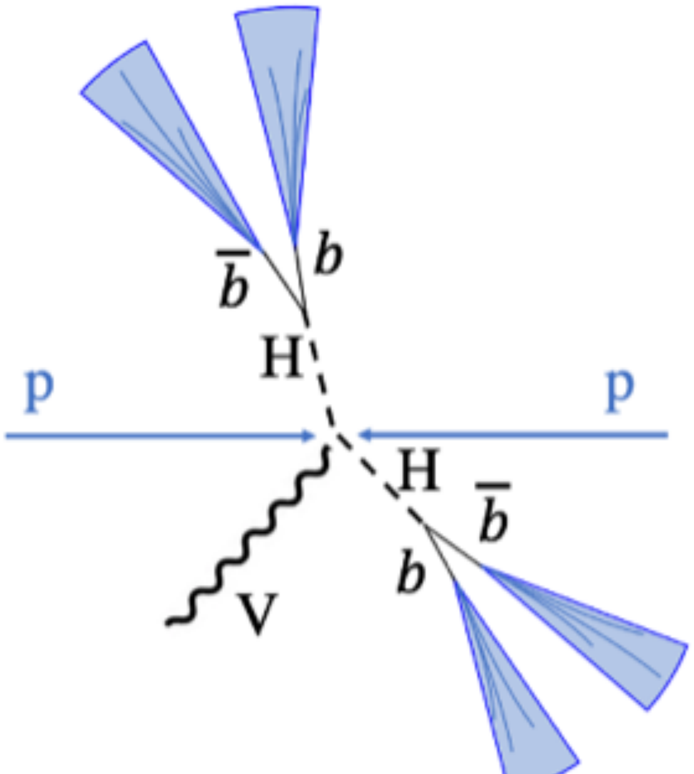
- Higgs Candidate Jets: (4 leading DeepJet score jets)
  - Form 2 di-jets satisfying 45GeV < m_jj < 190GeV

$$360/m_{4j} - 0.5 < \Delta R(Leading\ S_T\ dijets) < max(1.5, 650/m_{4j} + 0.5)$$
$$235/m_{4j} < \Delta R(Sub\ leading\ S_T\ dijets) < max(1.5, 650/m_{4j} + 0.7)$$

- Vector Boson Candidate Jets:
  - Pairing all candidates and find 65GeV < m_{jj} < 105GeV
- SvB NN-based Classifier is trained
  - SvB score > 0.8

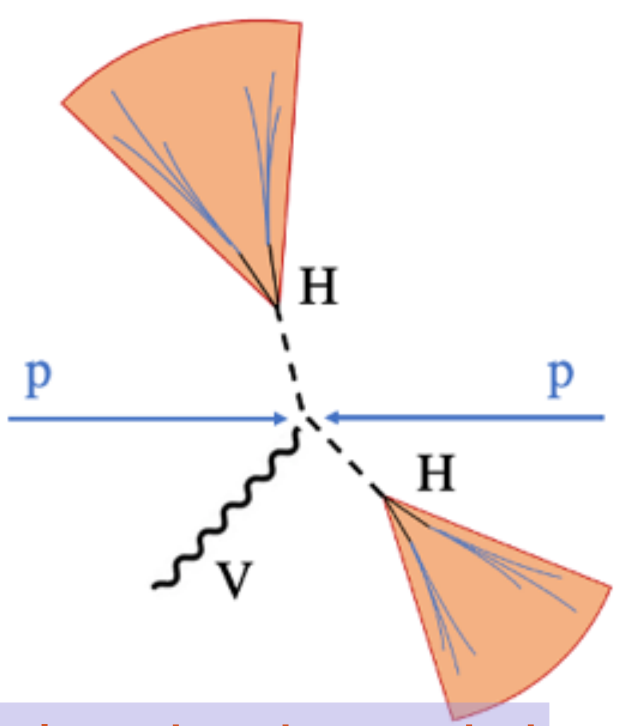
Jet selections are optimized in all 4 channels

Analysis Channels & Topologies



Resolved Topology

Boosted Topology

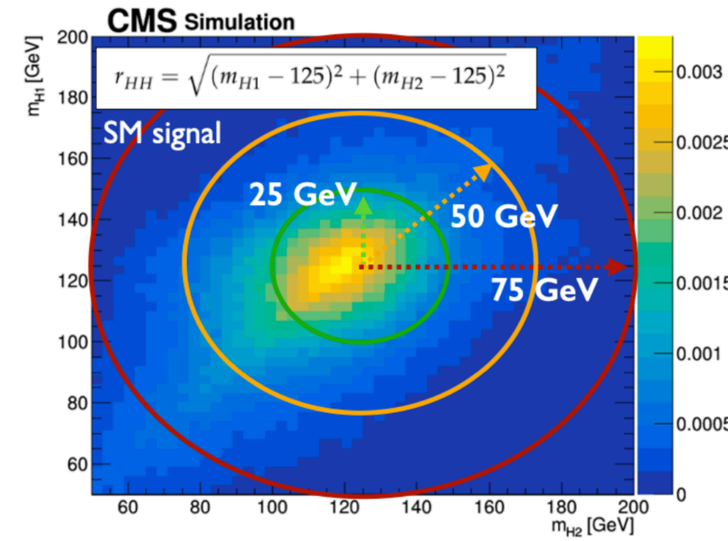


Both topologies have been studied

Leptonic Channels

$$R_{HH} = \sqrt{(M(H_1) - 125)^2 + (M(H_2) - 125)^2}$$

- Signal Region(**SR**) : rHH < 25GeV
- Control Region(**CR**) : 25GeV<rHH<50GeV
- SideBand(**SB**) : 50GeV < rHH

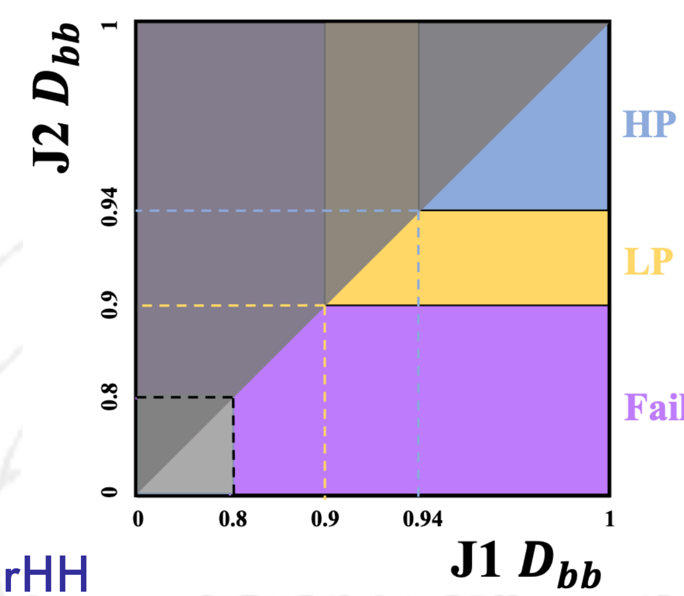


Hadronic Channels

- Signal Region(**SR**) $\sqrt{\left(\frac{m_{2j,H}^{Lead\ S_T} - 125.0GeV \times 1.02}{0.1 m_{2j,H}^{Lead\ S_T}}\right)^2 + \left(\frac{m_{2j,H}^{Subl\ S_T} - 125.0 \times 0.98}{0.1 m_{2j,H}^{Subl\ S_T}}\right)^2} < 1.9$
- SideBand(**SB**) $m^{H1} \in$ (52,180) GeV and $m^{H2} \in$(50,173) GeV

MET+SL

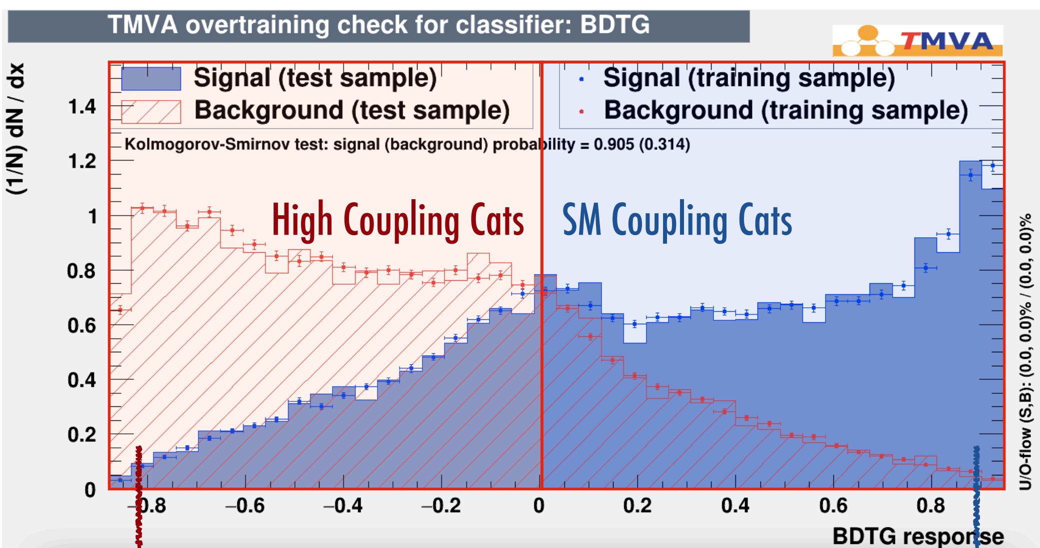
- High Purity (**HP**) : Dbb > 0.94
- Low Purity(**LP**) : 0.90<Dbb<0.94
- Failed Region(**FR**) : 0.80<Dbb<0.90
- ParticleNet score is used to calculate Dbb
- ParticleNet regression mass is used to calculate rHH



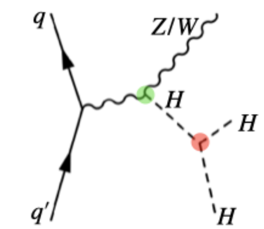
$$D_{bb} = \frac{score(X \to b\bar{b})}{score(X \to b\bar{b}) + score(QCD)}$$

HLT/Object/Event Selections

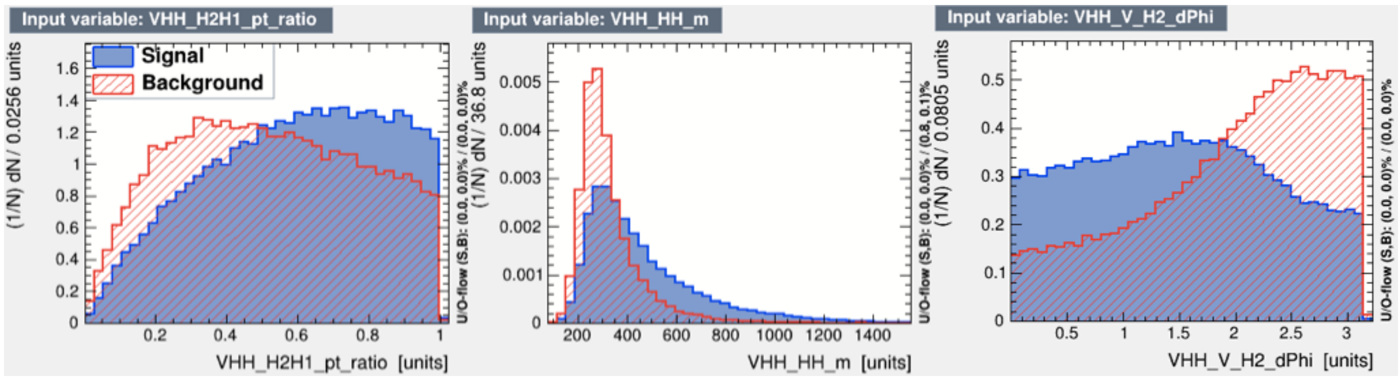
Kl Categorization



Kl Categorization

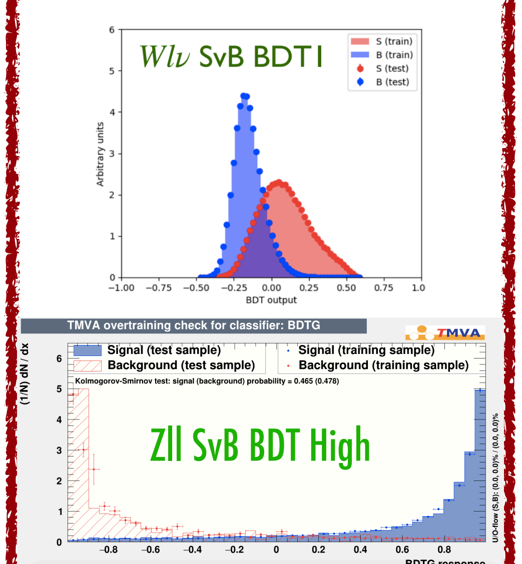


Bring extra sensitivity over Kl

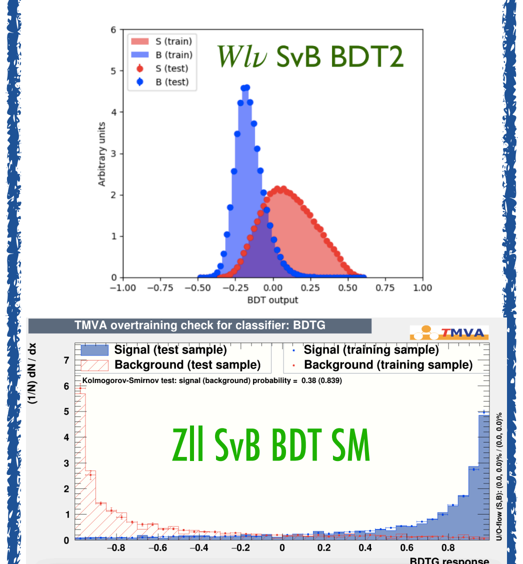


- Samples used for training is Kl = 20 vs Kl = 0
- 3 year MC are combined for training
- Variables and BDT models are optimized in all channels

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.

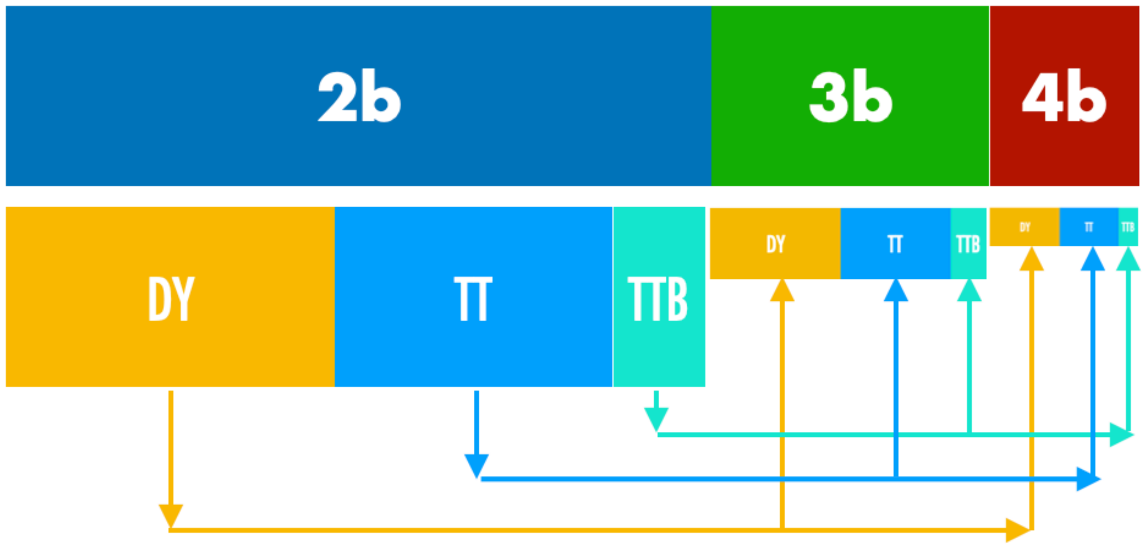
SvB Classifier scores will be used as the observables for template fit

Background Modeling

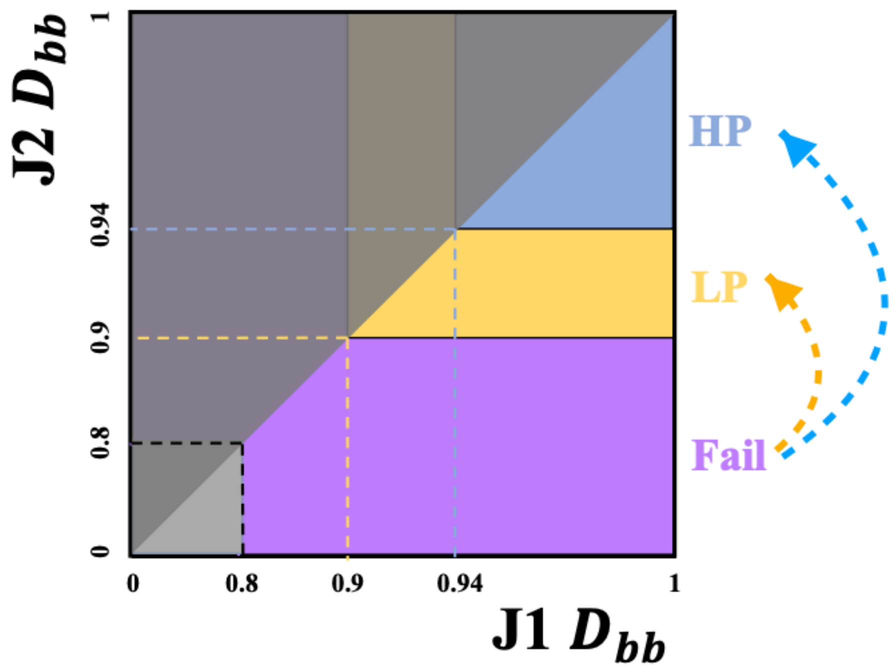
- **V-Leptonic**: All backgrounds modeled from MC and SRs are simultaneously fit with SB to control the systematics uncertainty from normalization.
- In 2L channel and Boosted topology, we use BDT based re-weighting technique to model the backgrounds in SRs.

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

- 2L channel:



- Boosted topology:



- Re-weight BDTs are trained to include the information about the differences between 2b-tagged events and 3/4 b-tagged events
- 3 main BKGs and 2 b-jet multiplicities introduce 6 RwT. BDTs to realize the re-weighting.
- SB events are used for training, CR for validation and finally apply on SR events.

- Input variables are same as the SvB BDTs for constructive reason.
- Similar method adapted in boosted topology using Failed region to model the backgrounds in HP/LP SR.

  - 2 types of uncertainty can cover the difference properly.

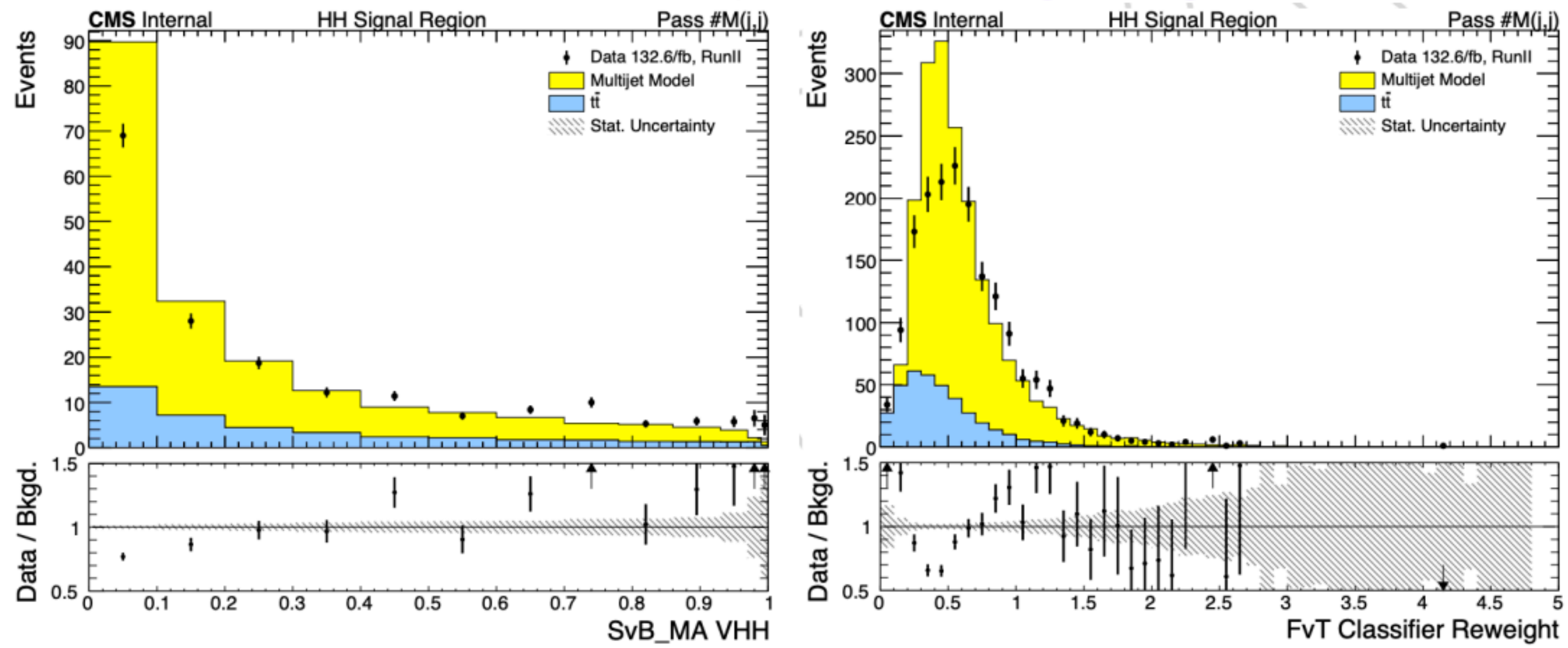
VHH@CMS Background Modeling

- **V-Hadronic**: Dominant background from Multi-Jets are modeled by 2 steps ResNet based Data-Driven method.
- The 4-tagged-jets background is modeled by 3-tagged-jets data.

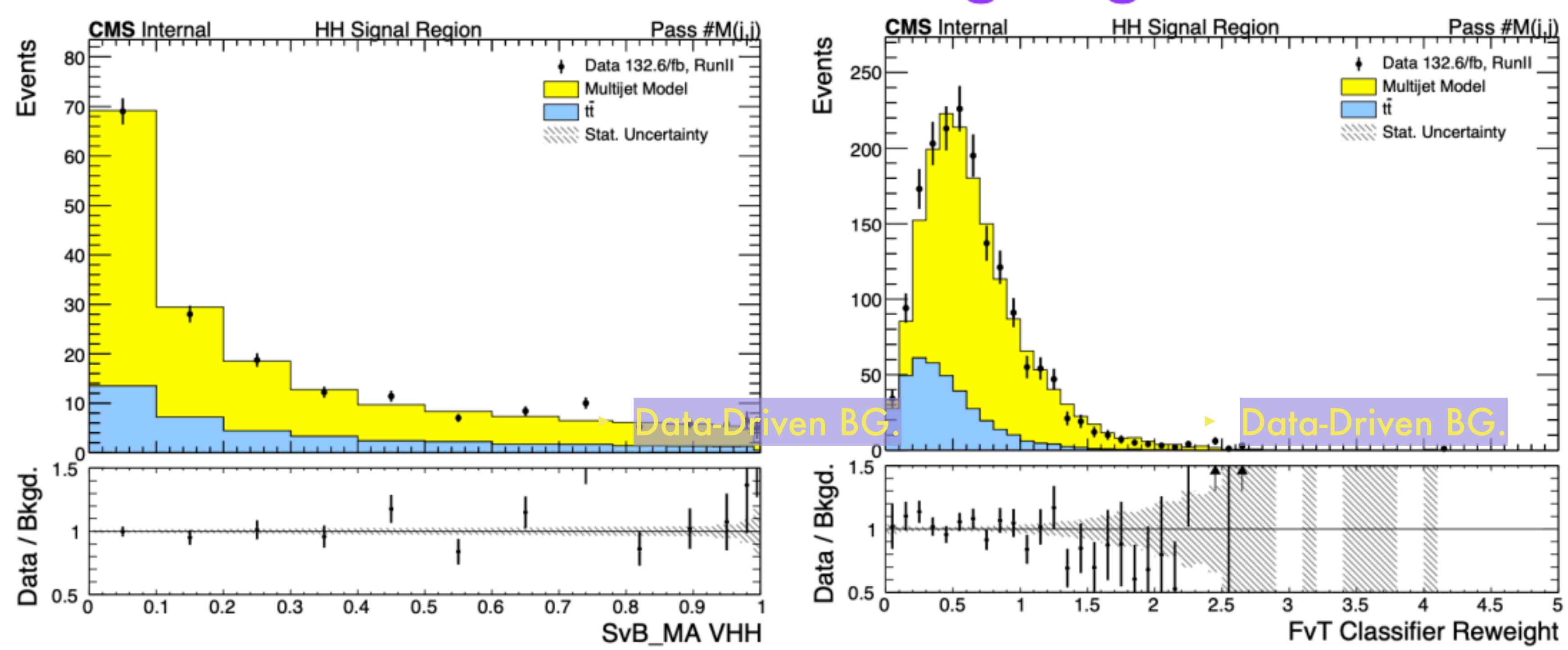
①Jet Combinatoric Model(JCM): A weight only based on jet multiplicity (pseudo-tag rate fitted in the data minus TT)

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

Before FvT reweighting



After FvT reweighting



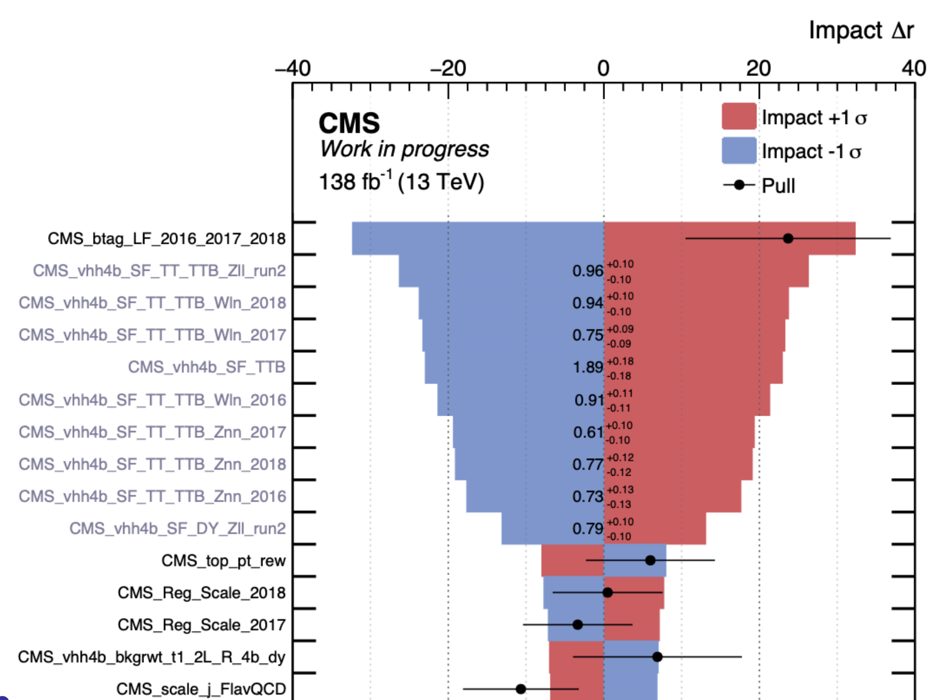
- Introduce the new uncertainty to cover the difference properly.

Uncertainties

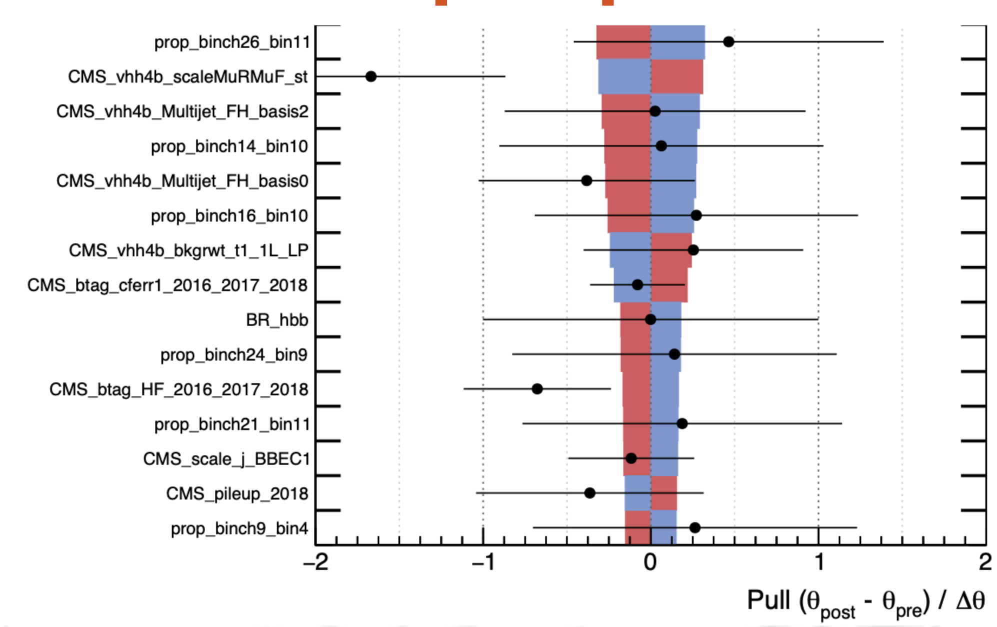
- The largest uncertainty comes from **statistical uncertainty**
- **B-tagging, background normalization, JES/JER** are the leading contributors for systematic uncertainties

Uncertainty sources (abs.)	2L	1L	MET	FH	inclusive
Systematic uncertainties					
Lepton uncertainties	+1.2% -0.4%	+3.7% -0	+0 -0	+0 -0	+5.4% -4.5%
MET uncertainties	+0 -0	+0 -0	+1.6% -0	+0 -0	+4.3% -0
Jet uncertainties	+17.2% -5.2%	+19.7% -16.0%	+26.5% -23.5%	+19.9% -2.0%	+26.3% -15.0%
Fat jet uncertainties	+0 -0	+3.3% -9.1%	+3.3% -2.2%	+0 -0	+6.2% -3.0%
btagging uncertainties	+40.5% -4.1%	+35.0% -3.2%	+56.1% -29.3%	+36.4% -0.9%	+61.7% -34.1%
Normalization uncertainties	+40.2% -11.7%	+33.9% -4.2%	+52.0% -25.3%	+35.2% -0	+58.6% -31.4%
Re-Weight uncertainties	+13.5% -12.0%	+13.2% -17.2%	+22.0% -12.8%	+0 -0	+21.8% -11.5%
Other modelling uncertainties	+10.4% -10.5%	+16.6% -2.9%	+13.2% -3.2%	+24.5% -24.2%	+19.9% -13.7%
Luminosity uncertainty	+5.3% 0	+5.0% -1.0%	+8.3% -1.6%	+4.2% -0	+7.6% -3.6%
Theoretical uncertainties	+15.1% -3.0%	+2.5% -11.0%	+23.1% -10.0%	+15.5% -2.3%	+17.6% -7.0%
Others	+2.9% -5.6%	+4.4% -2.6%	+9.1% -7.3%	+7.0% -1.3%	+8.8% -8.6%
Total systematic uncertainty	+46.8% -21.3%	+46.0% -32.6%	+62.7% -40.7%	+46.7% -24.4%	+66.8% -43.5%
Statistical uncertainties					
Statistical uncertainty	+88.2% -97.8%	+89.0% -94.6%	+77.6% -91.1%	+70.0% -97.0%	+74.4% -90.1%
Total uncertainty					
Total uncertainty	+136 -98.6	+111 -82.6	+161 -123	+163 -132	+81.1 -62.7
Center value					
Center value	101	12.5	283	190	145

- The freely-floating normalizations for tt(ttb) and DY are among the largest impact parameters
- B-tagging SFs, Top Pt re-weighting and b-jets energy regression uncertainty are also important nuisances

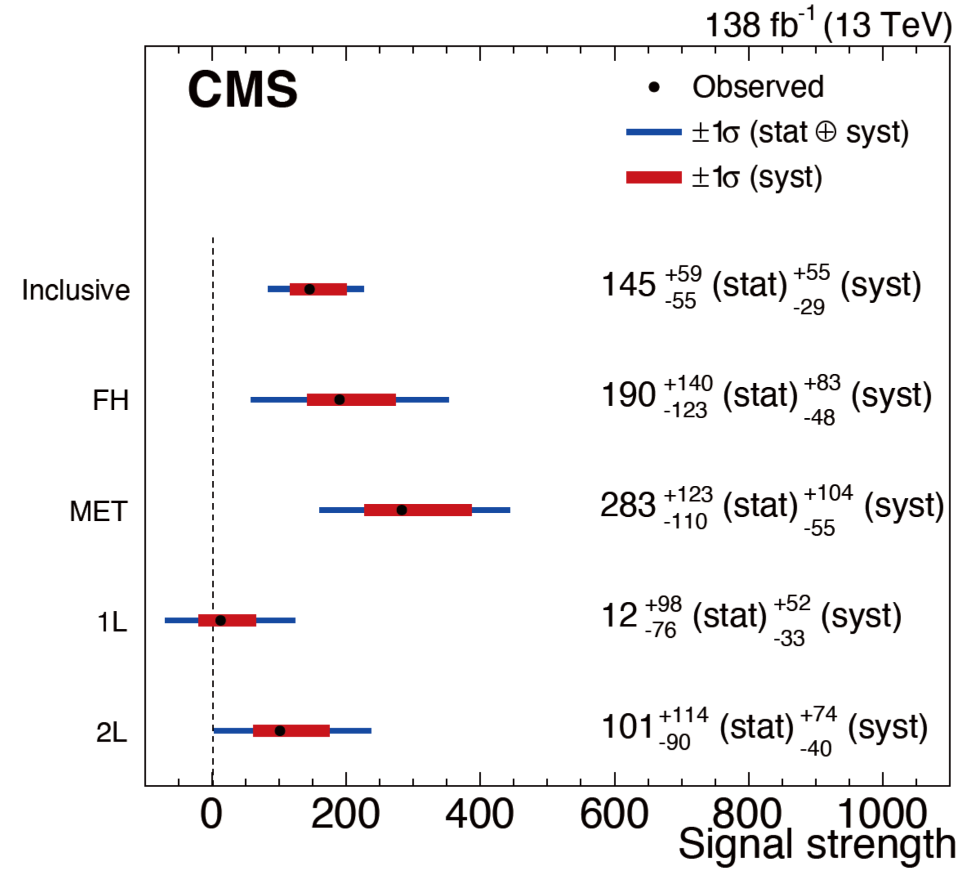


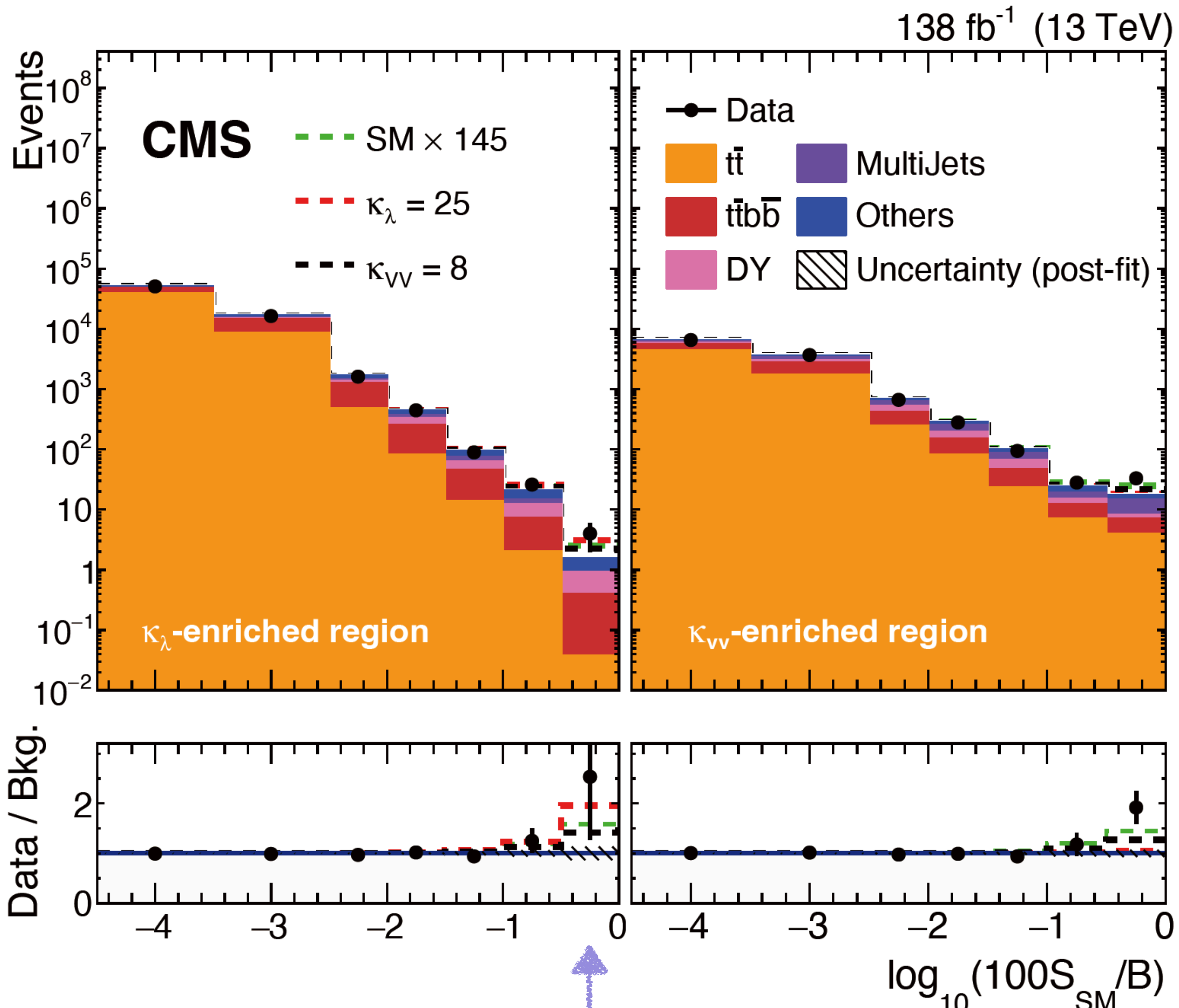
Impact plots

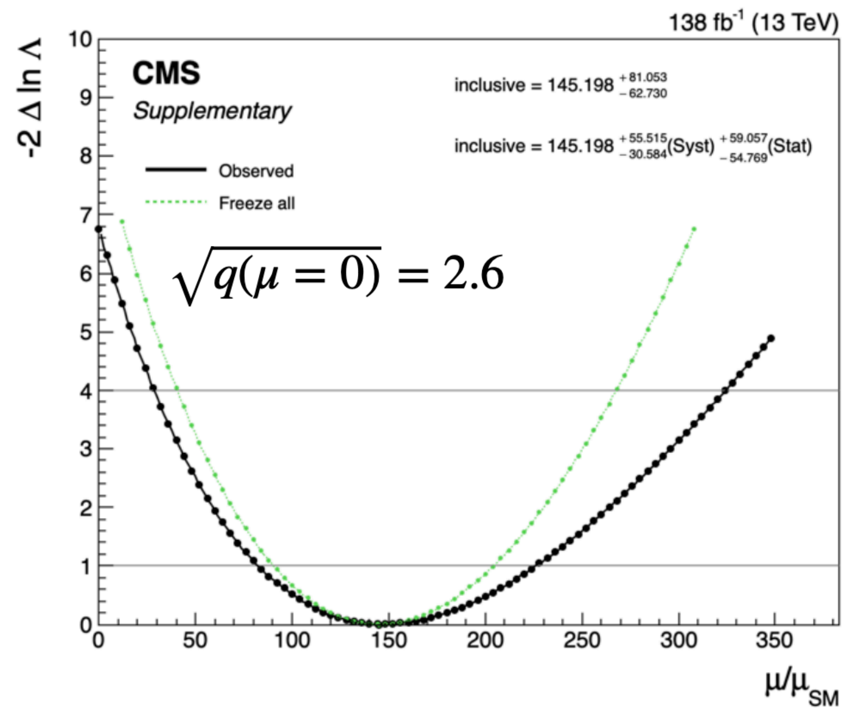


Post-Fit Plots in the backup slides

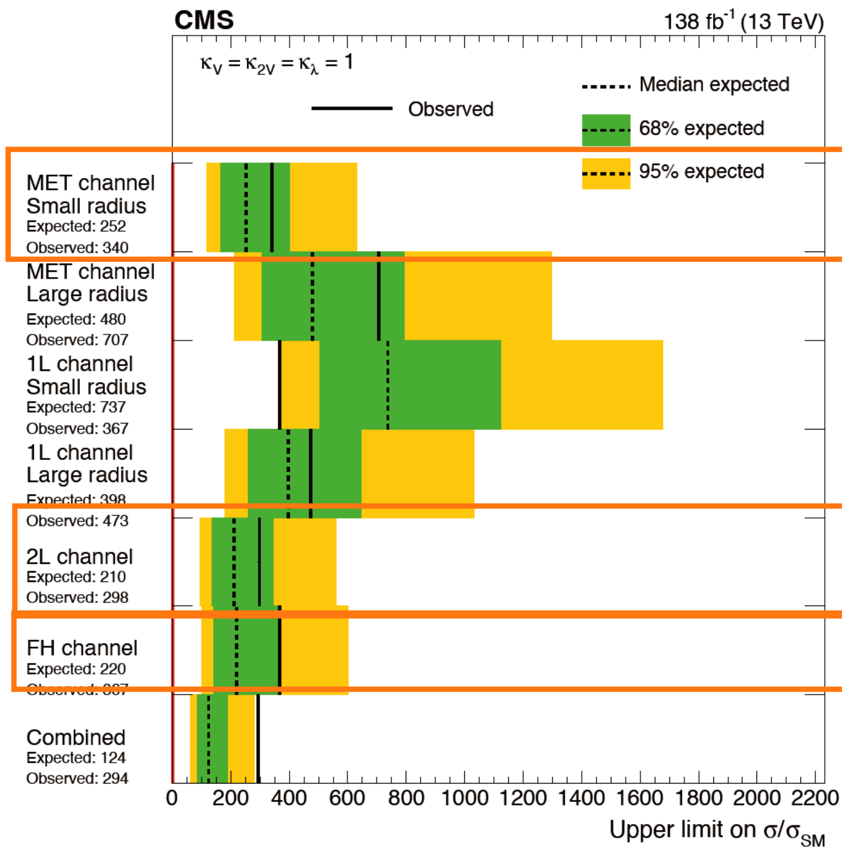
- The best fit signal strength is 145^{+81}_{-63}
- Observed **excess is 2.6σ** with SM signal

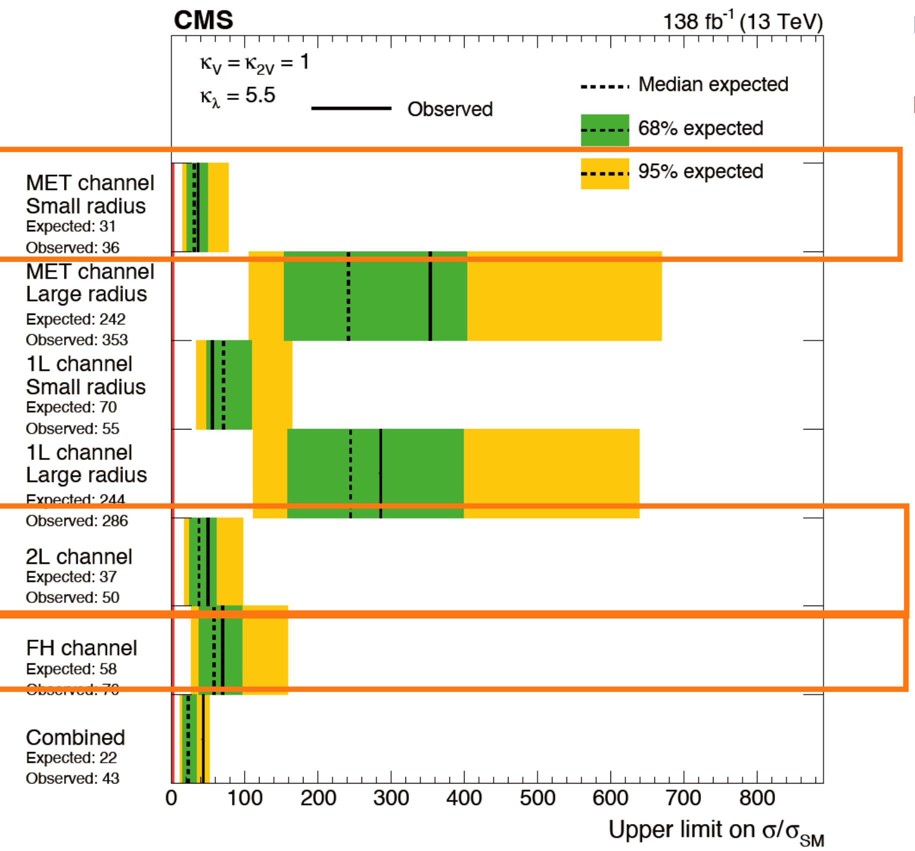






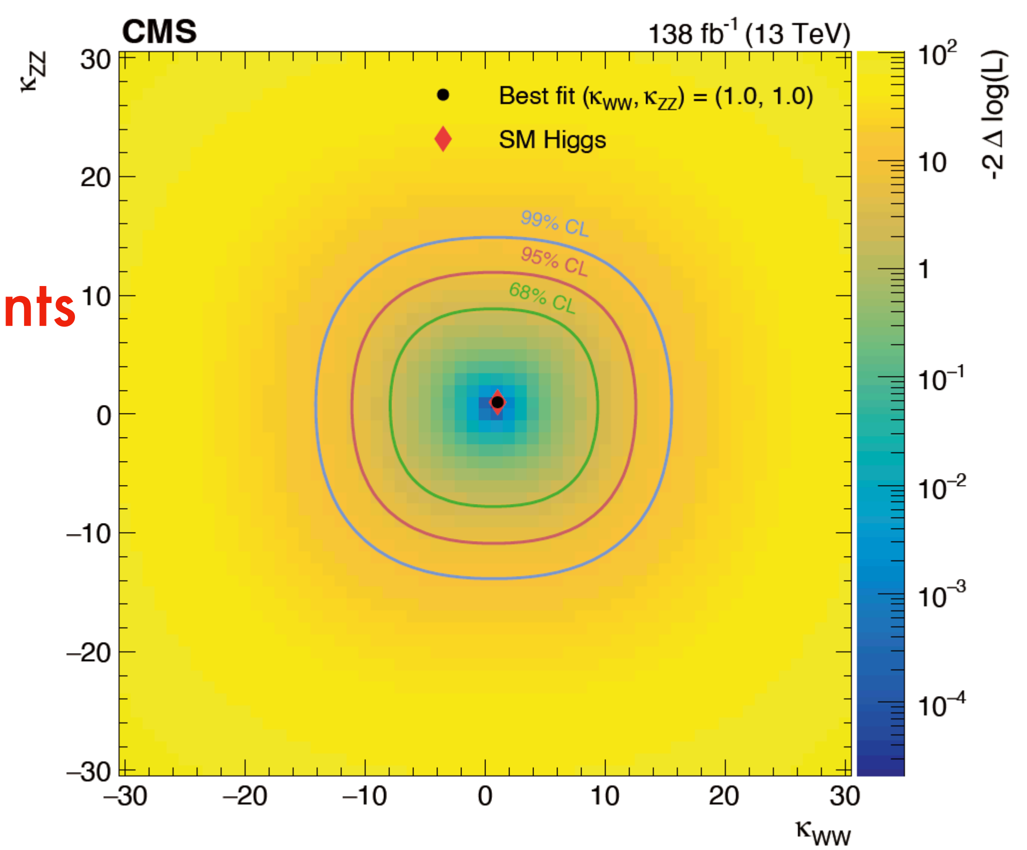
- Machine learning output distributions are transformed to Log(100 x S_{SM}/B) and summed for κ_λ-enriched and κ_{VV}-enriched SR samples separately.

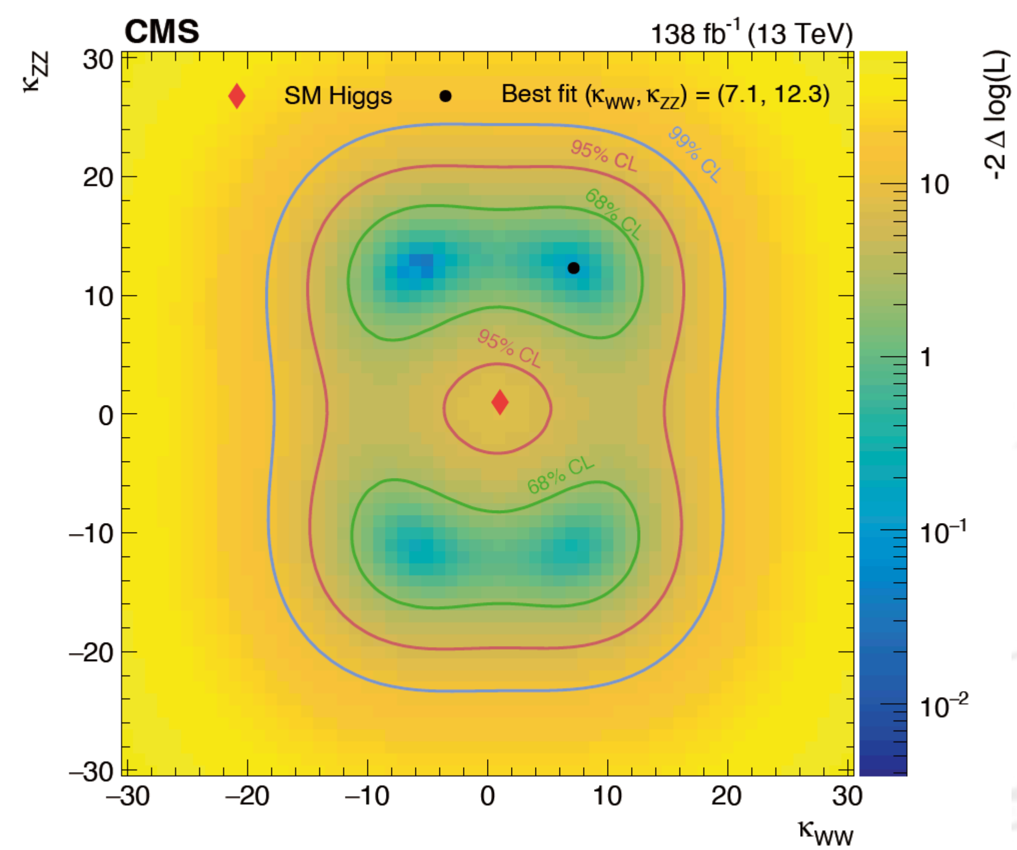




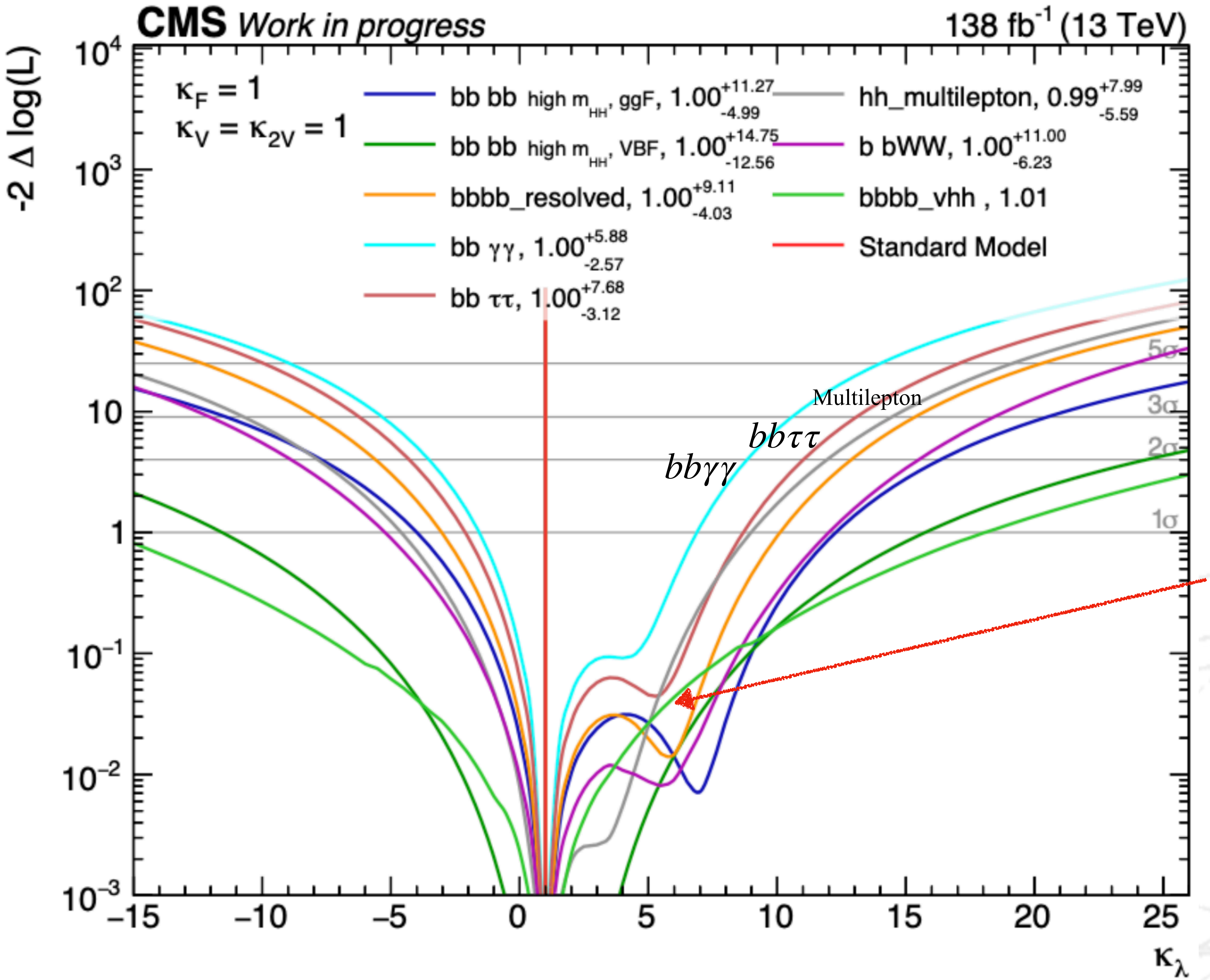
- Upper limit @ SM is 294(124)
- Upper limit @ K_λ=5.5 is 43(22)
  - MET channel has large BR
  - DL channel has clean SR
  - ML boosted the FH sensitivity

- Separate measurements on K_{zz} and K_{ww}
- Left is expected
- Right is observed





Results

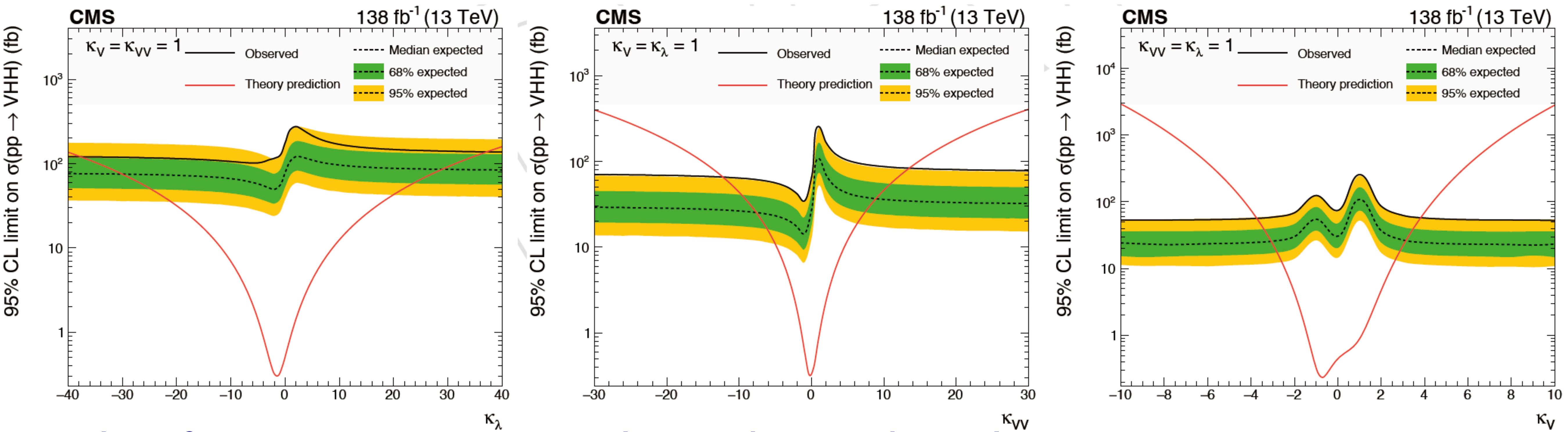


VHH has competitive sensitivity at κ_λ at around 5, where most of ggF HH are weak

VHH@CMS Conclusion & Outlook

- First search for VHH production in CMS, published on Moriond 2023
  - Complementary to ggF and VBF HH analyses, strong sensitivity at κ_λ around 5
- 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)



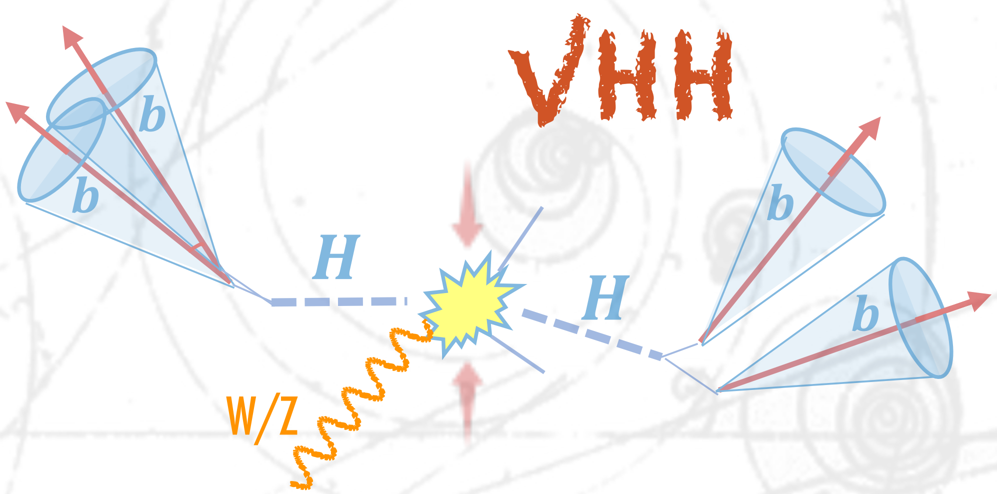
- Seeking for more opportunities in this production channel in Run3
  - Double the statistics to optimize the background modeling
  - Strategies and (ML) algorithms can be dedicated adapted for better sensitivity
  - Potentials can also come from the multi-leptonic decaying channel

Thank You!

Dec-21st, 2024

Chris Palmer, Xiaohu Sun(孙小虎), Licheng Zhang(章立诚)
On behalf of the CMS VHH analysis team

backup

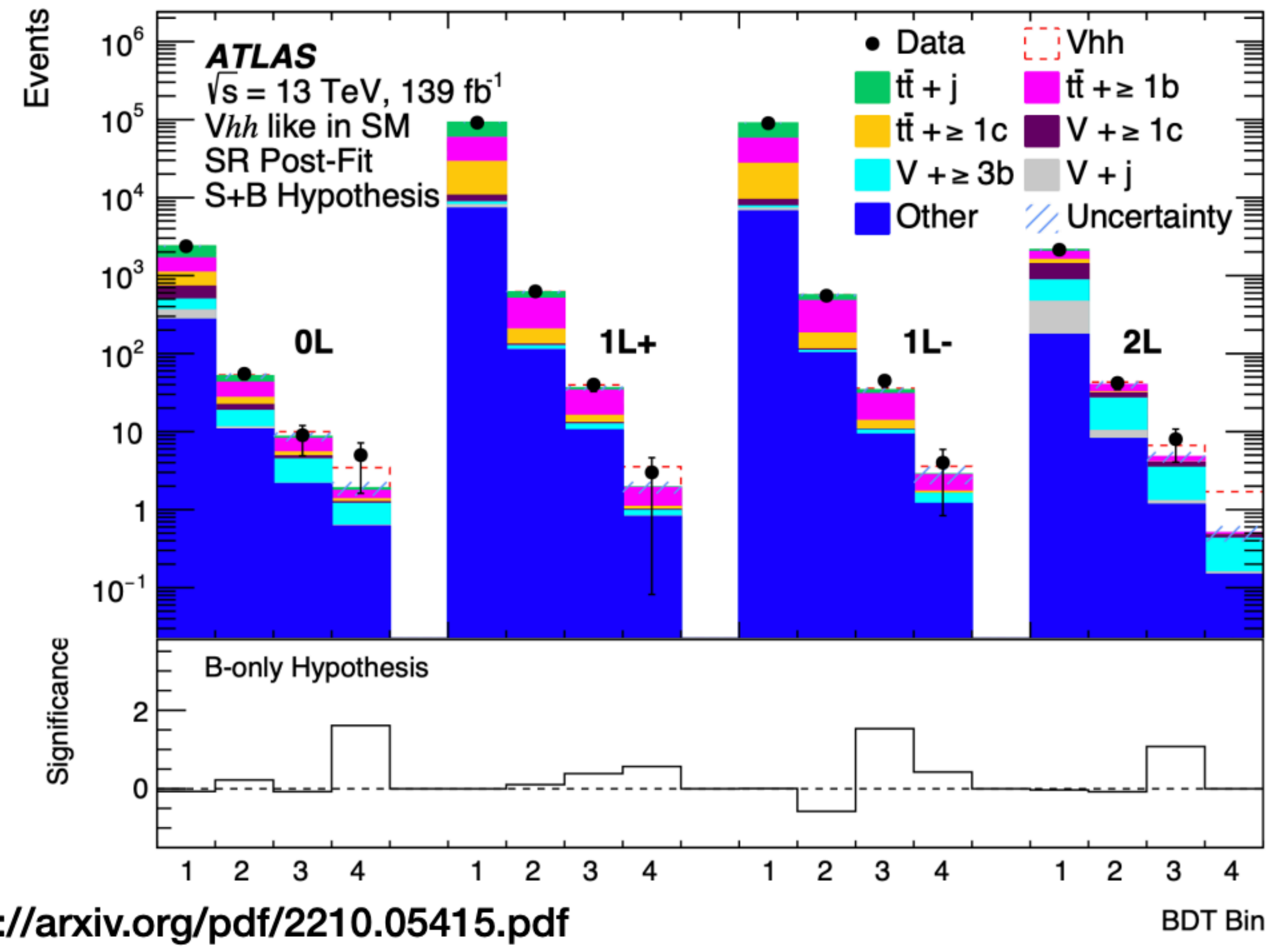


Higgs Potential 2024 workshop
For Higgs potential and BSM opportunities
University of Science and Technology of China (USTC),
Dec-19～23, 2024, Hefei.

ATLAS VHH results

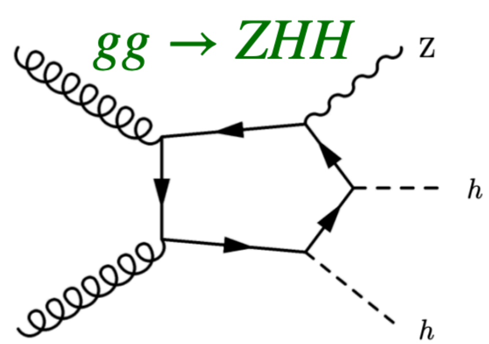
- For SM VHH production, a 95% confidence-level (CL) upper limit of 183 on μ is observed compared with 87^{+41}_{-24} expected

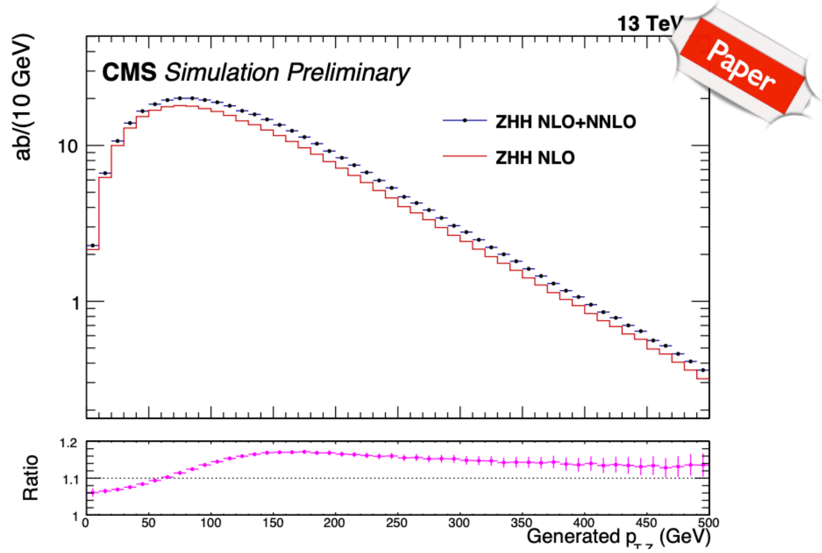
	κ_λ	κ_{VV}	κ_{ZZ}	κ_{WW}
Observed	(-34.4, 33.3)	(-8.6, 10.0)	(-9.9, 11.3)	(-12.3, 13.5)
Expected	(-24.1, 22.9)	(-5.7, 7.1)	(-7.1, 8.5)	(-8.6, 9.8)



https://arxiv.org/pdf/2210.05415.pdf

Signal Modeling



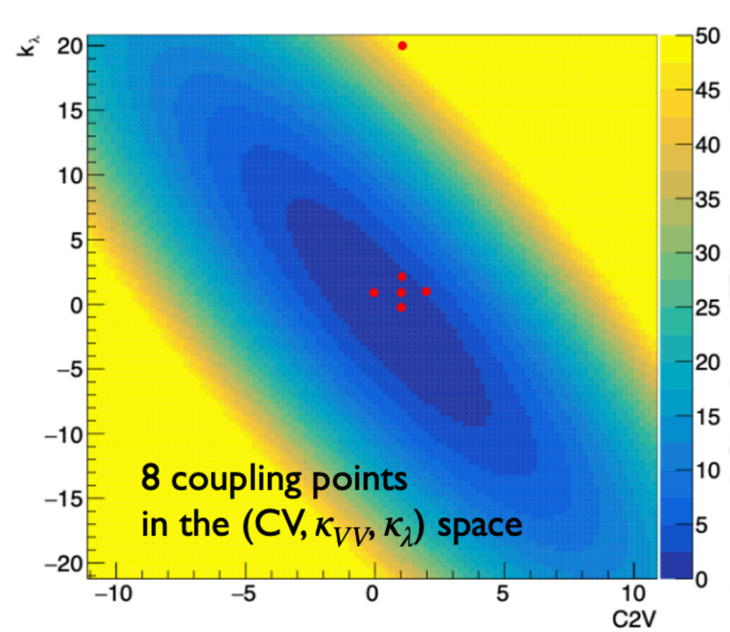


- Linearly interpolate/extrapolate existing samples to get more couplings for limit scan
  - According to the talk, implemented in HHModel that used by all HH analysis
- Use Moore-Penrose inverse to accommodate 8 signal samples

$$\sigma(\kappa_\lambda, C_V, C_{2V}) = \mathbf{c}^T(\kappa_\lambda, C_V, C_{2V})\mathbf{C}^{-1}\boldsymbol{\sigma}$$

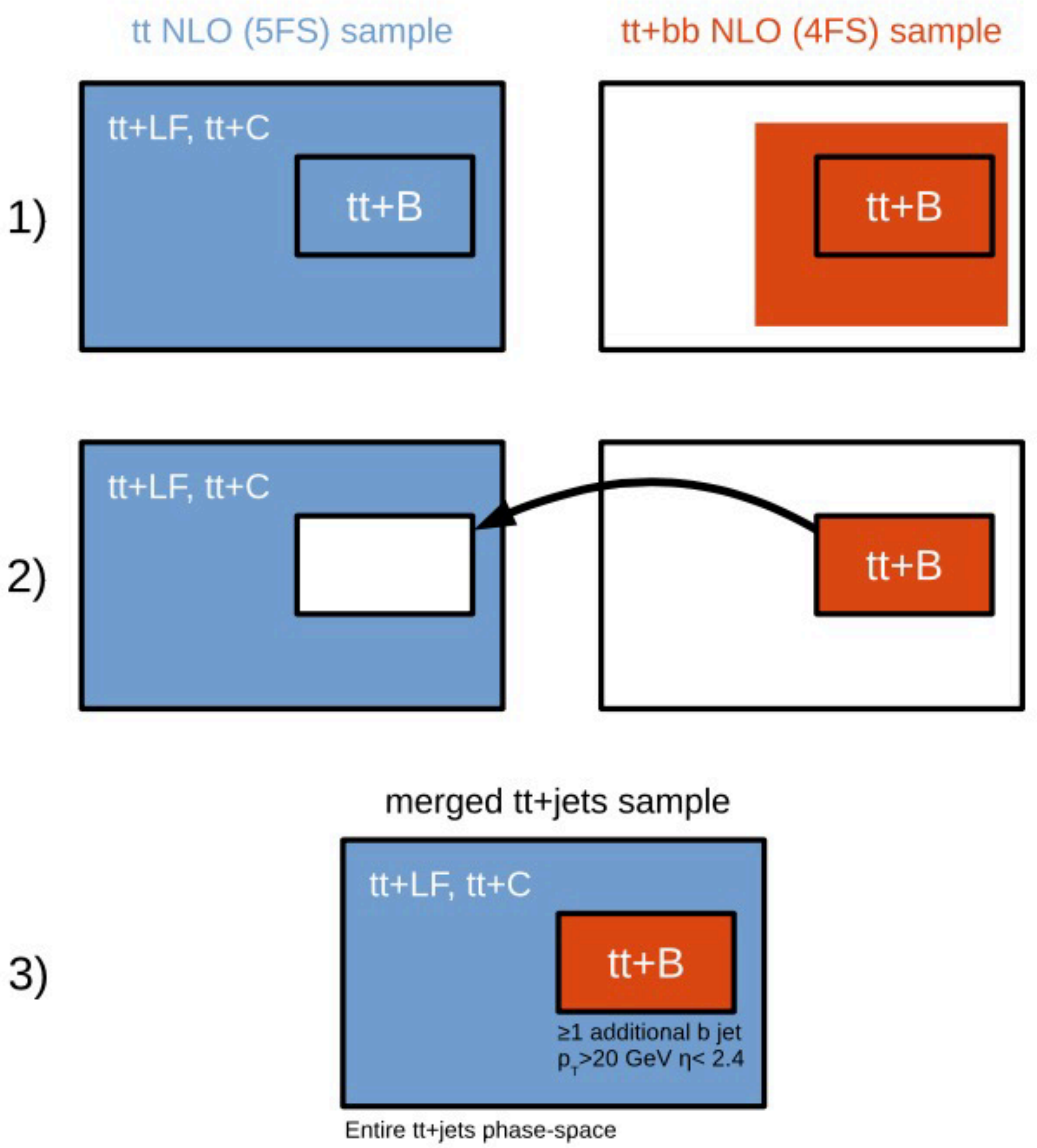
LO

κ_V	κ_{VV}	κ_λ
0.5	1.0	1.0
1.0	0.0	1.0
1.0	1.0	0.0
1.0	1.0	1.0
1.0	1.0	2.0
1.0	2.0	1.0
1.5	1.0	1.0
1.0	1.0	20.0



Background Modeling

- Following the strategies in tH/ttH(bb) Analysis:
  - $t\bar{t}b\bar{b}$ in Powheg NLO $t\bar{t}$ 5FS sample is from parton shower which will bring large uncertainties.
  - Powheg NLO 4FS sample has better performance in modeling $t\bar{t}+b\bar{b}$ kinematics.
- We need to stitch together these two samples for better background modeling.
  - In each $t\bar{t}$ event, define 'additional b-jet' as a particle level b jet with pT>20GeV and |eta|<2.4 and not from top decay.
  - Replace $tt+B$ events in tt(5FS) with ttbb(4FS)

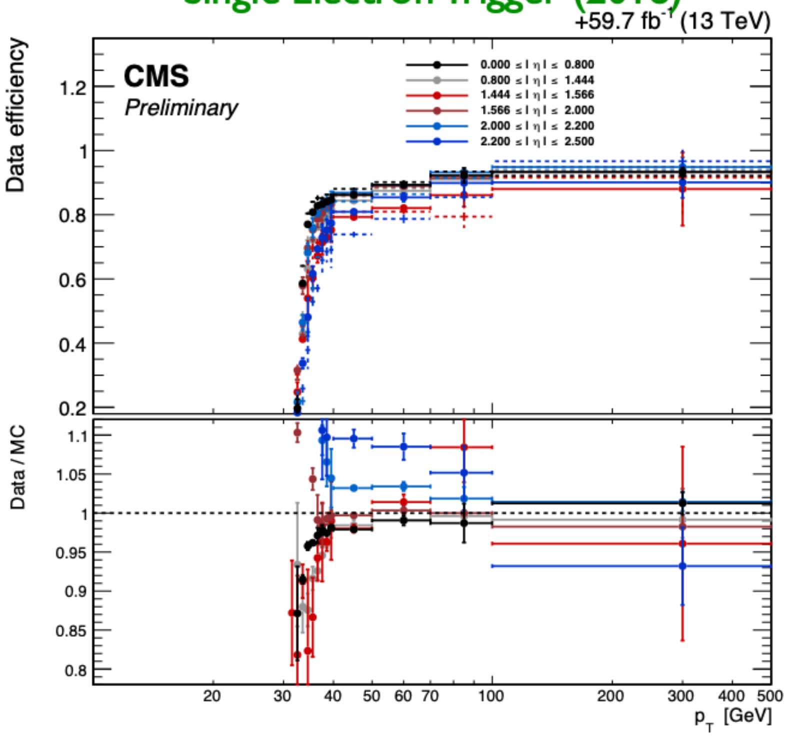


https://indico.cern.ch/event/943919/contributions/3987268/attachments/2099755/3530092/slides_20_09_09_Hbb_ttBModel.pdf

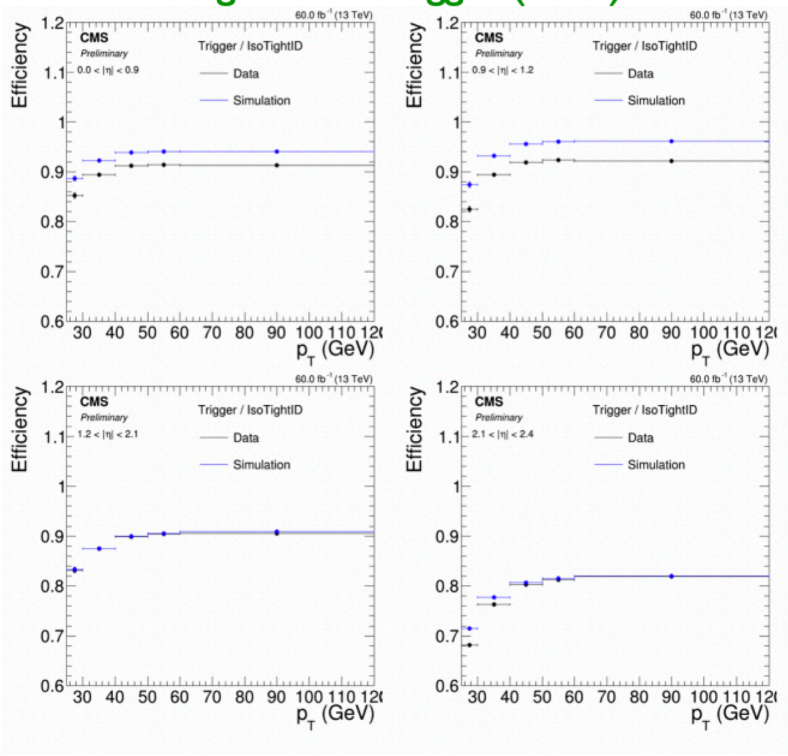
Scale Factors

- Electron SF: Reco X ID_ISO X Trigger
- Muon SF: ID X ISO X Trigger
- MET Trigger SF: Start from 150GeV

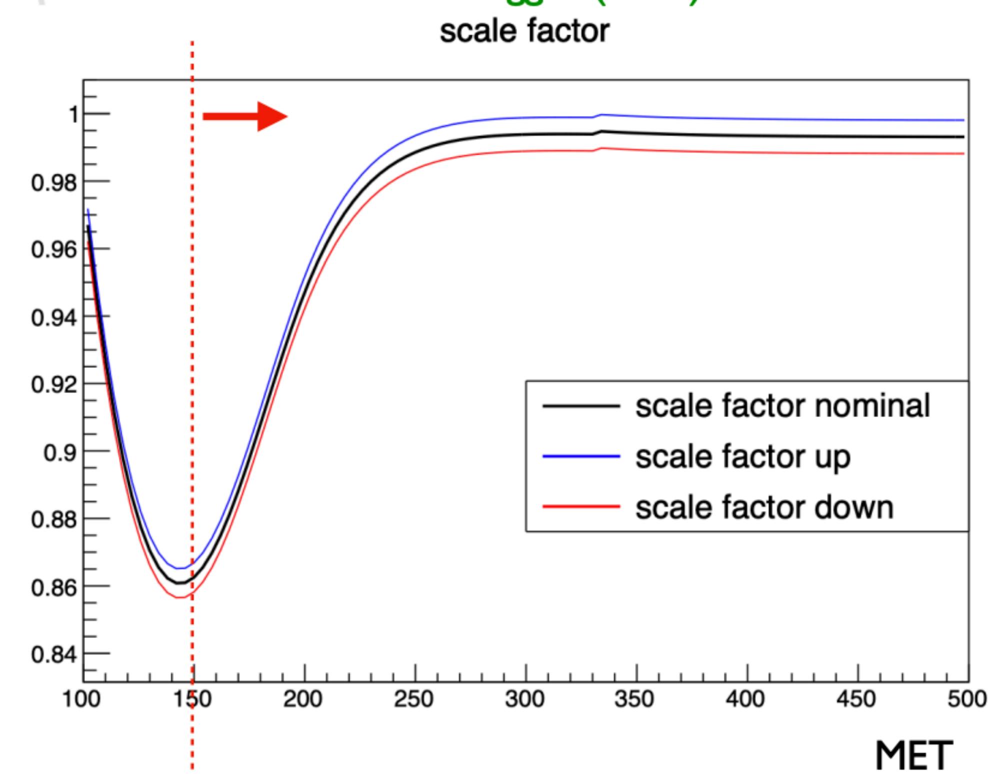
Single Electron Trigger (2018)



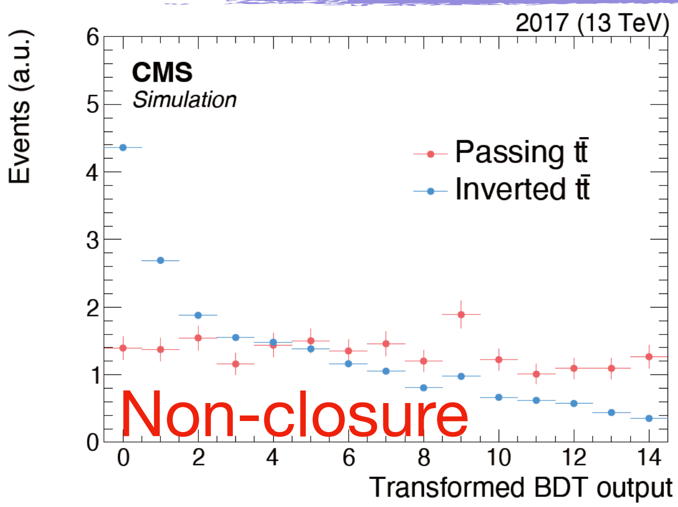
Single Muon Trigger (2018)

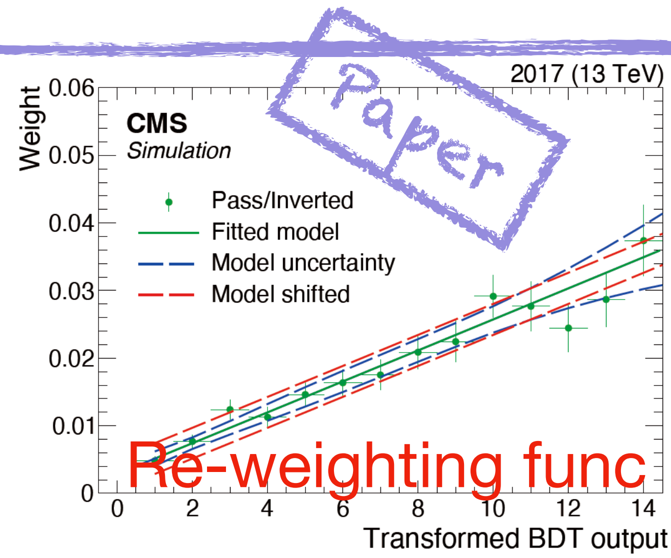


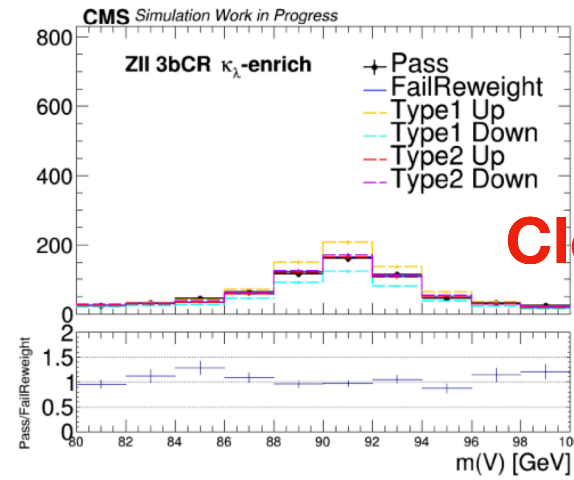
MET Trigger (2018)

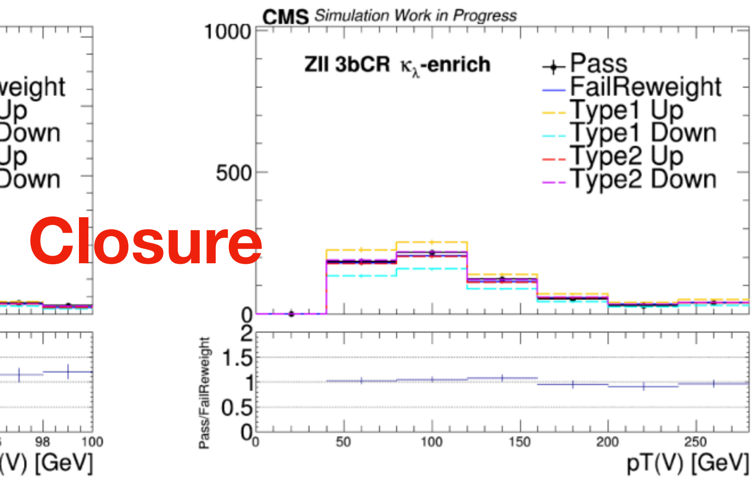


Background Modeling









- An example, **2 types of uncertainties** are introduced to cover the uncertainty brought by the method.
- An example, comparison between original MC and re-weighted fail-selection MC and how the 2 types of uncertainty can cover the difference properly.

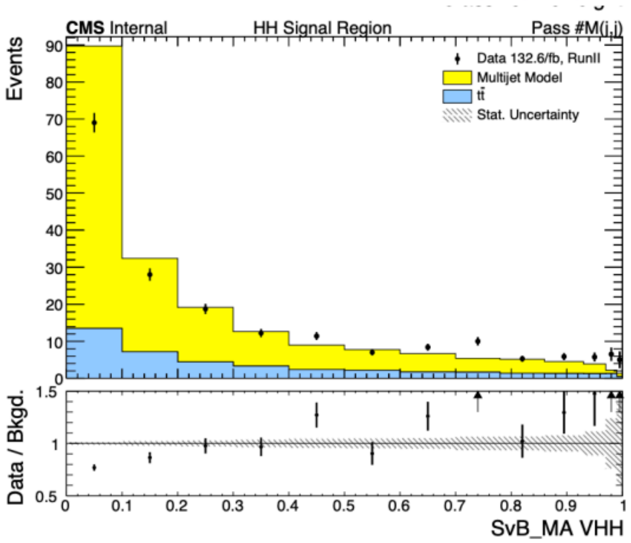
● **V-Leptonic**

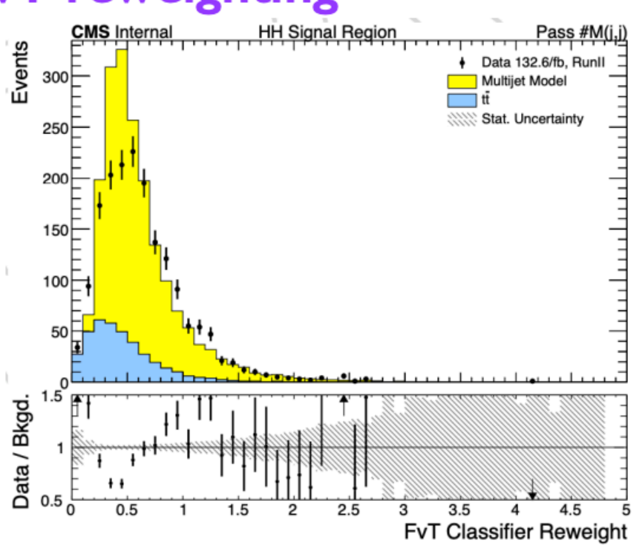
- **V-Hadronic**: Dominant background from Multi-Jets are modeled by 2 steps ResNet based Data-Driven method.
- The 4-tagged-jets background is modeled by 3-tagged-jets data.

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

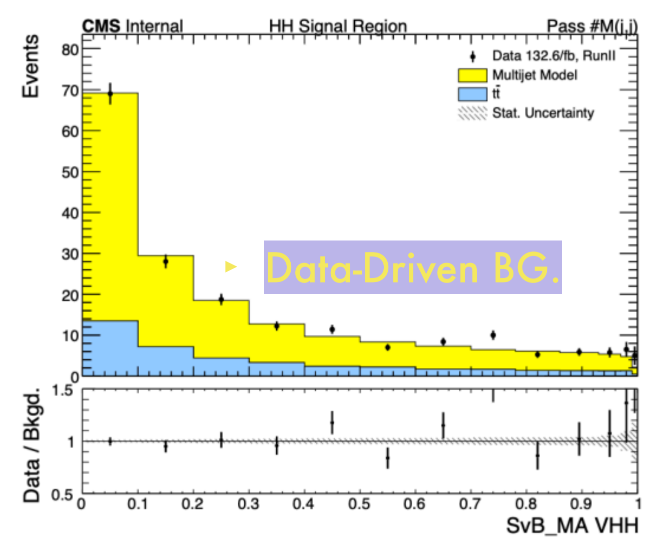
② FvT Classifier: A weight mostly based on kinematic, derived by a ResNet which has the same architecture as the SvB Classifier.

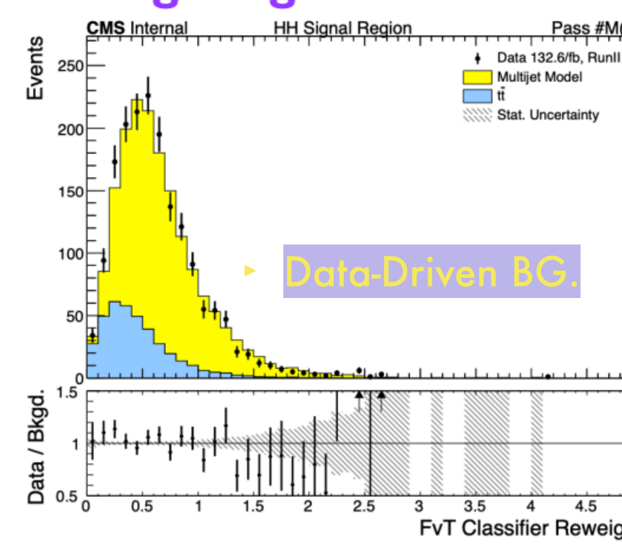
Before FvT reweighting





After FvT reweighting





Parameters Used

Variables used in the Kl BDTs

mass(HH)	dR(H1,H2)	pT(H1)
dPhi(L1,L2)	pT(V)	dEta(L1,L2)
dR(H2b1,H2b2)	dR(H1b1,H1b2)	pT(L1)/mass(V)
dPhi(V, H2)	pT(H2)/pT(H1)	pT(L2)/pT(L1)
pT(L1)	Variables for Kl BDT in DL channel	

pT(V)	pT(H1)	pT(H2)
mass(H1)	mass(H2)	mass(HH)
E(H2)	E(HH)	dPhi(H1, H2)
deta(H1, H2)	dR(H1, H2)	dPhi(V, H2)
pT(HH)	E(H1)	eta(HH)
pT(H2)/pT(H1)	Year	
	Variables for Kl BDT in SL/MET/FH channels	

Variables used in the SvB Classifiers

B-tag(H1j1)	B-tag(H1j2)	B-tag(H2j1)
pT(V)	pT(H1)	pT(H2)
mass(H1)	mass(H2)	mass(HH)
Phi(H1)	Phi(H2)	Year
B-tag(H2j2)	pT(HH)	Phi(V)
	Variables for SvB BDT in SL/MET channel	

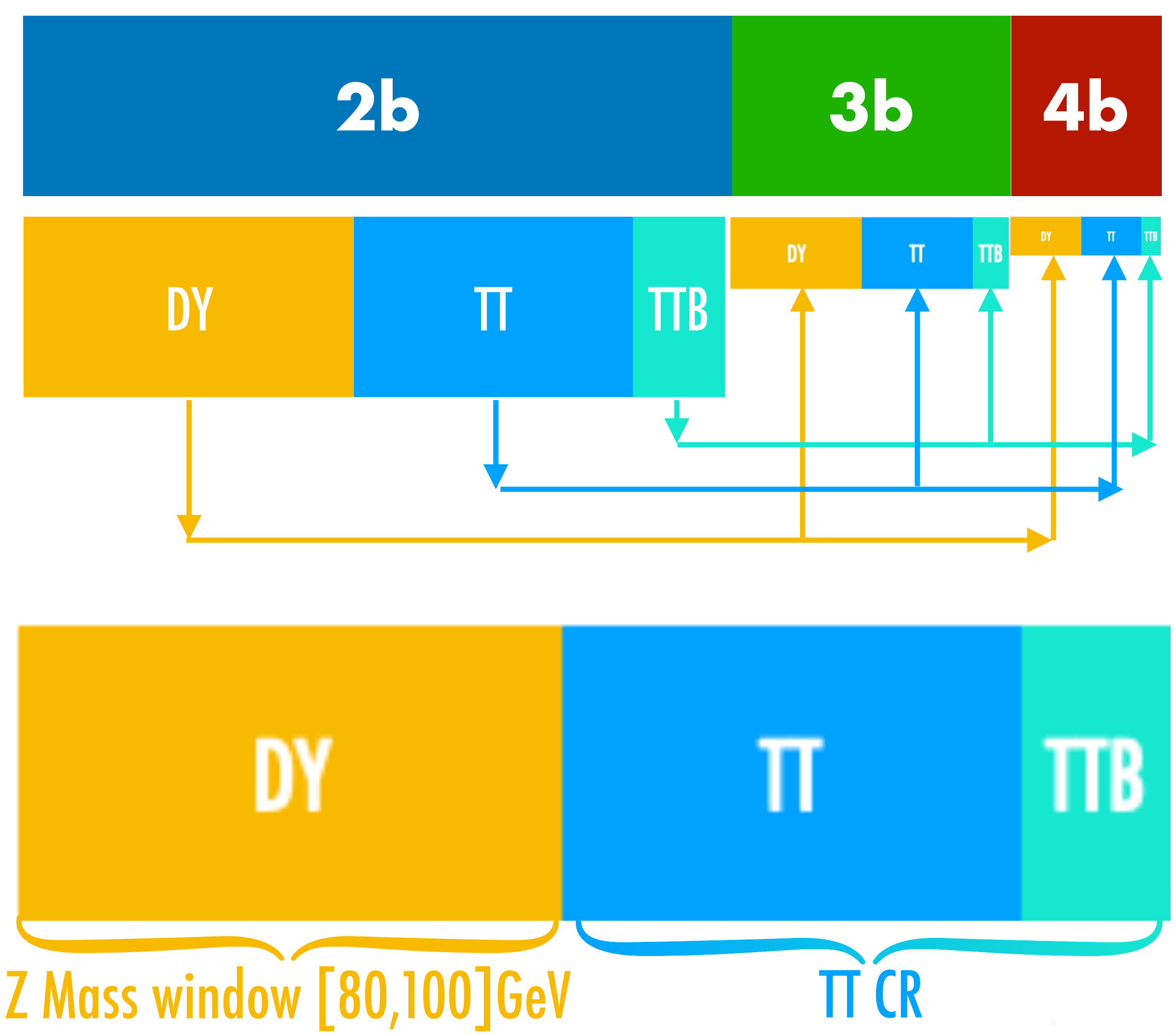
mass(V)	mass(H1)	HT(llijjj)
dPhi(V, H1)	dEta(L1,L2)	dPhi(V, HH)
dR(H1,H2)	mass(HH)	pT(H1)
pT(j No.4 btag)	E(H1)	pT(V)
deta(H1, H2)	pT(j No.3 btag)	pT(HH)
pT(V)/pT(HH)	pT(L1)/mass(V)	
	Variables for SvB BDT in DL channel	

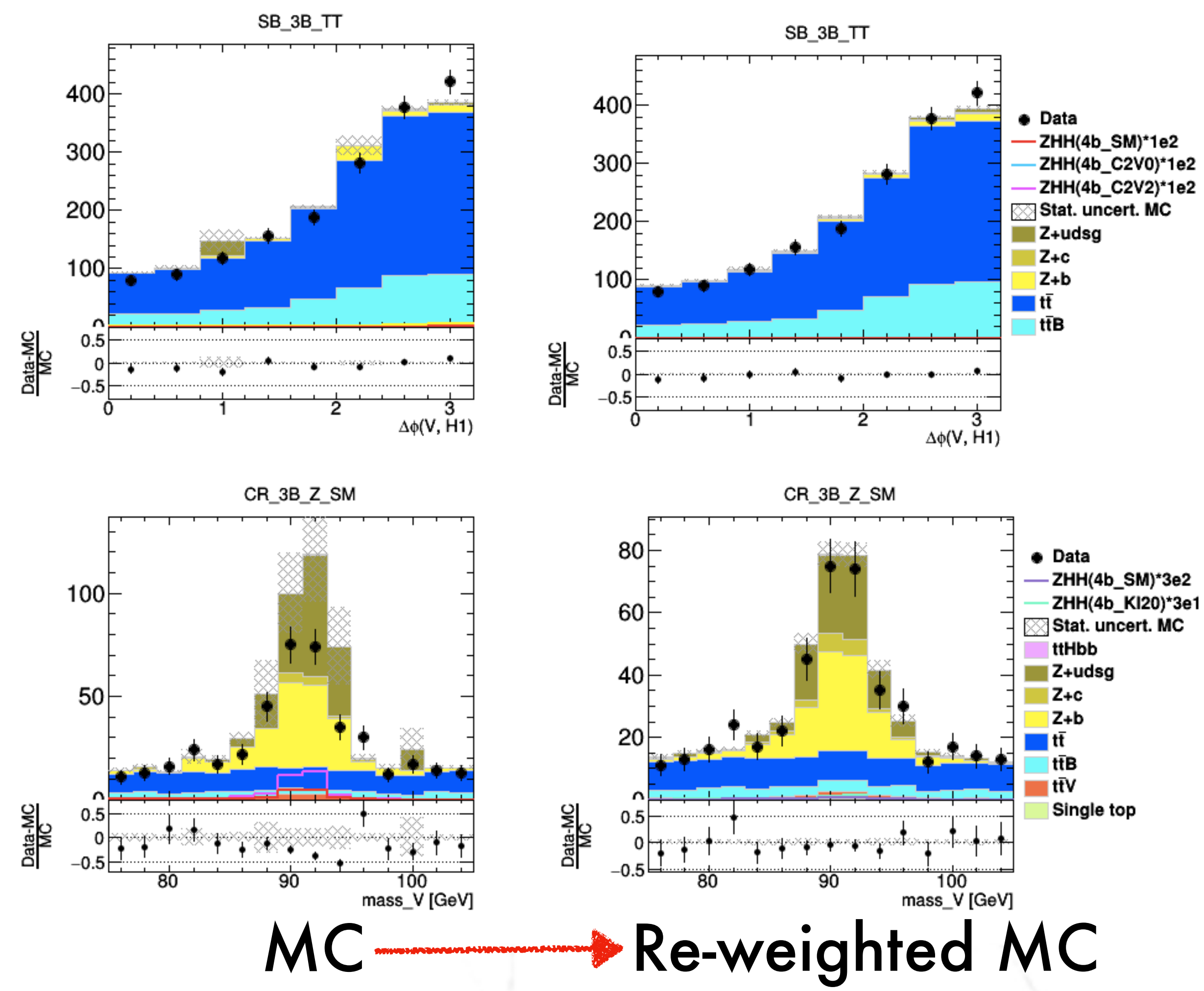
pT(V)	pT(H1)	eta(HH)
E(HH)	mass(HH)	eta(H1)
eta(H2)	deta(H1, H2)	dPhi(H1, H2)
dR(H1, H2)	dPhi(V, H2)	pT(H2)/pT(H1)
	Variables for SvB Classifier in FH channel	

Coupling Cats BDT and SvB Classifiers are optimized in all channels

Double-Lepton Channel

- Main background are TT(TTBB), DY+Jets
  - Re-weight BDTs are trained to include the information about the differences between 2b-tagged events and 3/4 b-tagged events.
  - 3 main BKGs and 2 b-jet multiplicities introduce 6 RwT. BDTs to realize the re-weighting.
  - SB events are used for training, CR for validation and finally apply on SR events.
  - Input variables are same as the SvB BDTs.



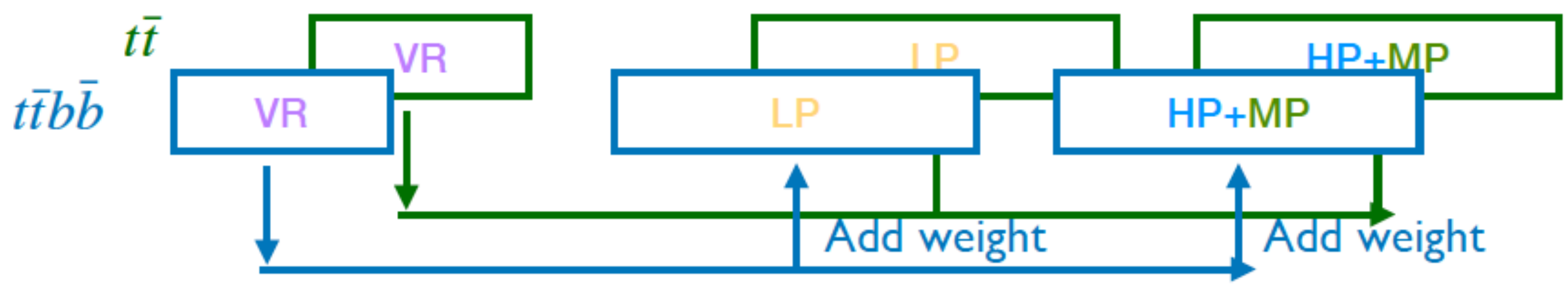


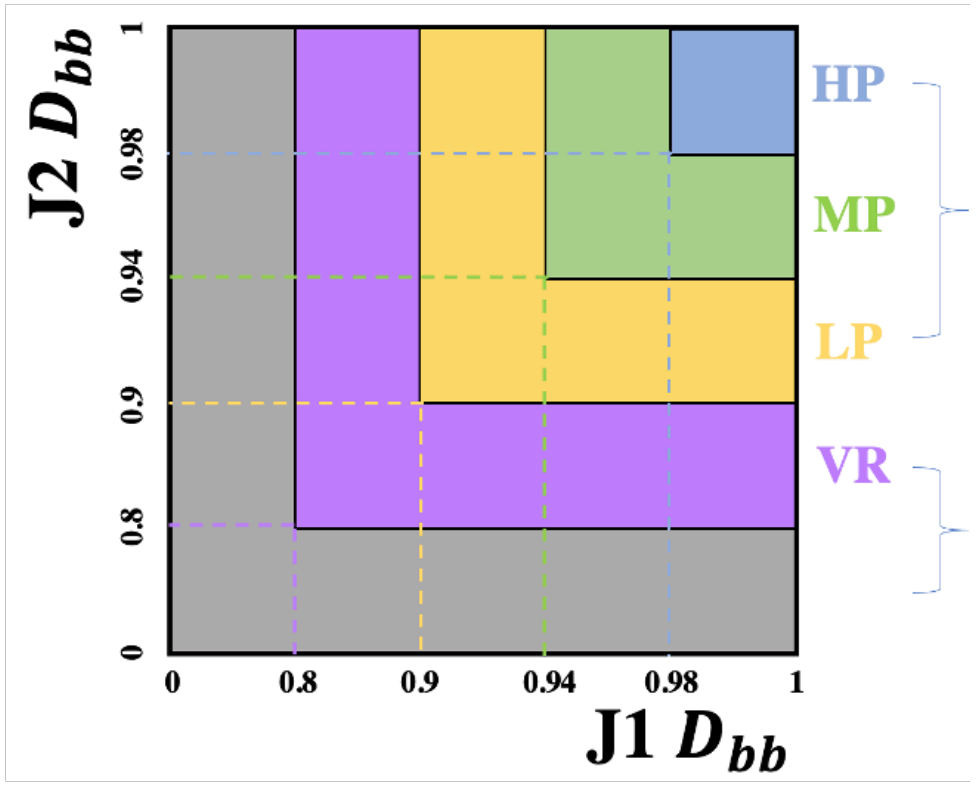
Smaller Stat. Uncertainties ; Reliable background model;

- Inside Z mass window, a fraction fit is applied in every regions to achieve better Data/MC agreement.
- DY/TT/TTBB process are free float in the final fit.

Background Modeling

- Main background are TT(TTBB)
- Same strategy from previous slides about DL channel
- Re-weight events in **VR** to mimic **LP**, **HP+MP**
  - 2 sets of weights





pT(V)	pT(H1)	pT(H2)
pT(HH)	mass(HH)	mass(H1)
mass(H2)	Phi(V)	Phi(H1)
Phi(H2)	Year	

Variables for RwT BDTs and SvB Classifier in Boosted channel

- Topology priority
  - By comparing the limit scan results
- Conclusion
  - prioritize the Boosted topology

Boosted topology has been studied in SL, MET channels

Systematic uncertainties

- **Theoretical Uncertainties**

  log-normal uncertainty
  - Signal cross section (NNLO accuracy)
  - H → bb Branching ratio

  Shape uncertainty
  - LO ZHH reweight to NNLO
  - LO Drell-Yan reweight to NLO
  - Factorization and renormalization scales
  - Proton PDFs
  - Parton shower initial-state and final-state radiation showers

- **Freely-floating normalizations**
  - CMS_vhh4b_SF_TT_TTB_ch_year → $t\bar{t}$ and $t\bar{t}b\bar{b}$
  - CMS_vhh4b_SF_TTB → $t\bar{t}b\bar{b}$
  - CMS_vhh4b_SF_DY_Zll_run2 → DY

- **Experimental Uncertainties**

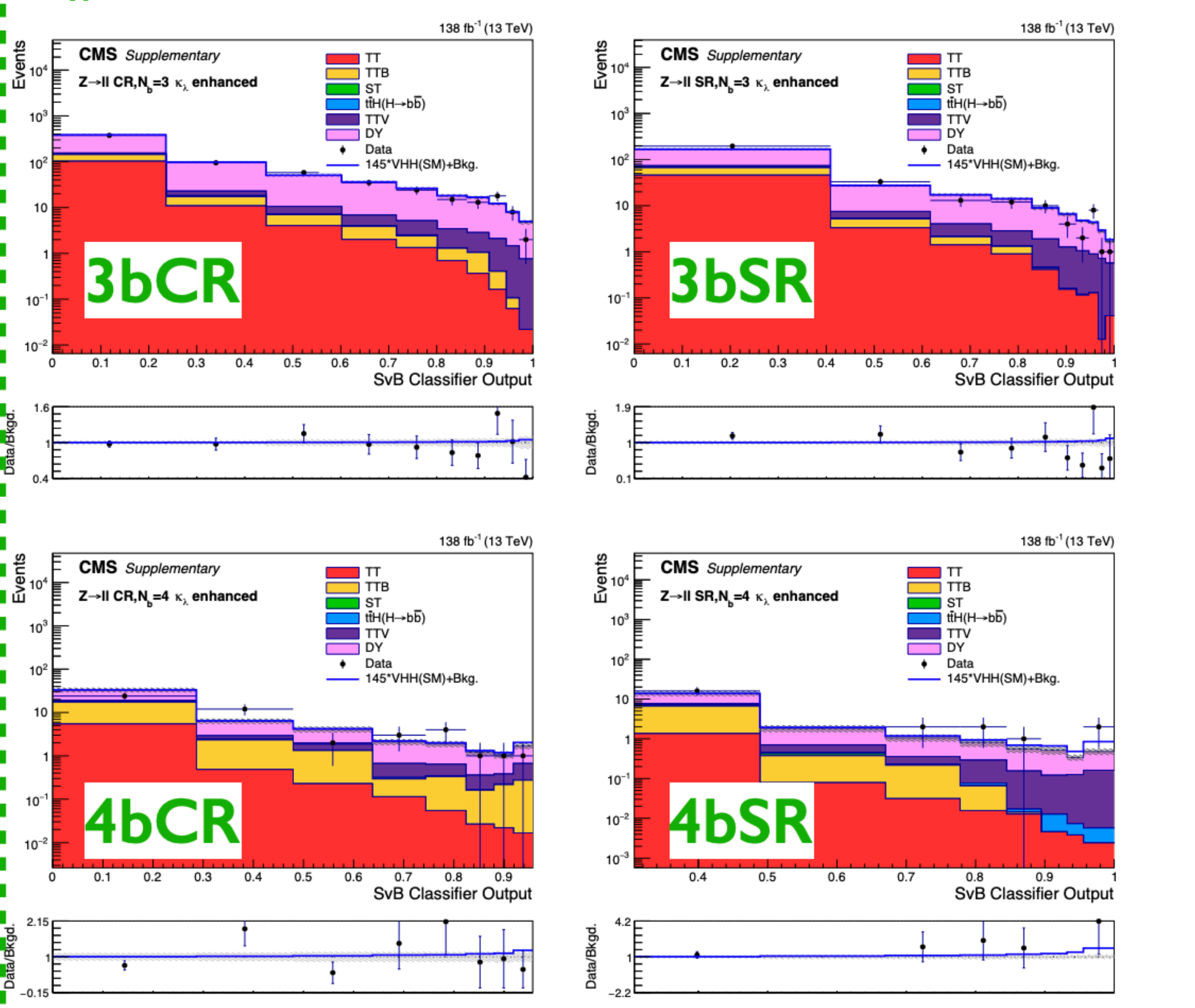
  log-normal uncertainty
  - Luminosity uncertainty

  Shape uncertainty
  - PileUP uncertainty
  - L1 prefiring uncertainty
  - Lepton identification and reconstruction SF
  - JES, JER uncertainty
  - b jet energy regression uncertainty
  - ParticleNet mass regression uncertainty
  - DeepJet b-tagging efficiency uncertainty
  - ParticleNet tagging uncertainty
  - Background reweighting uncertainties
  - Top pT reweighting uncertainties
  - FH: background systematic uncertainty, extracted from mix models

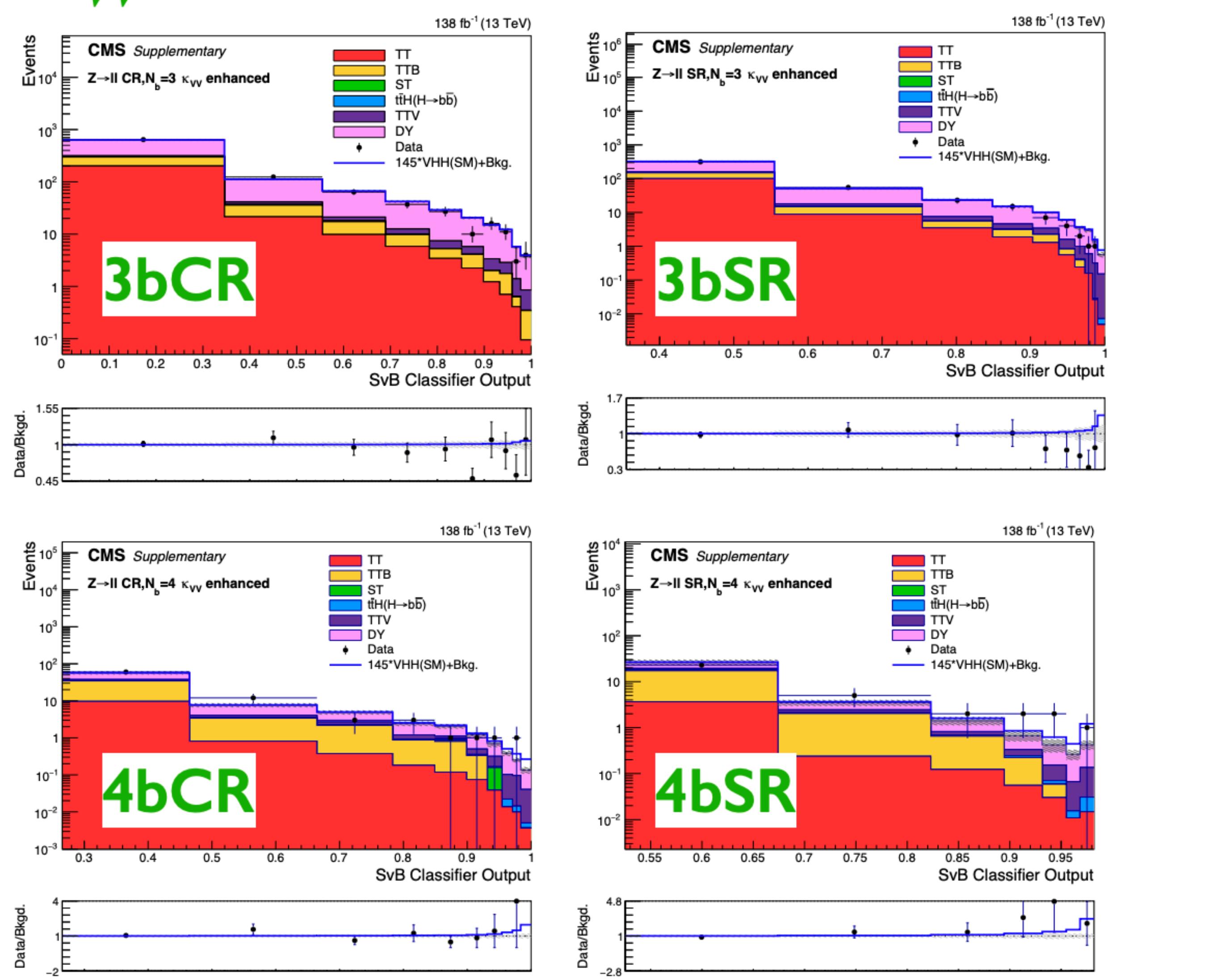
Post-Fit

2L

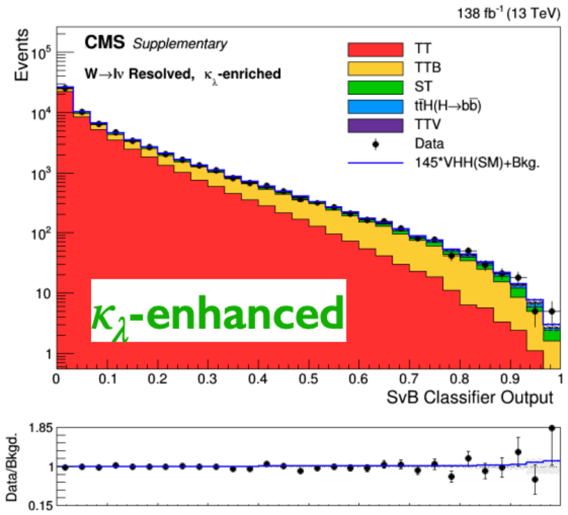
κ_λ-enhanced



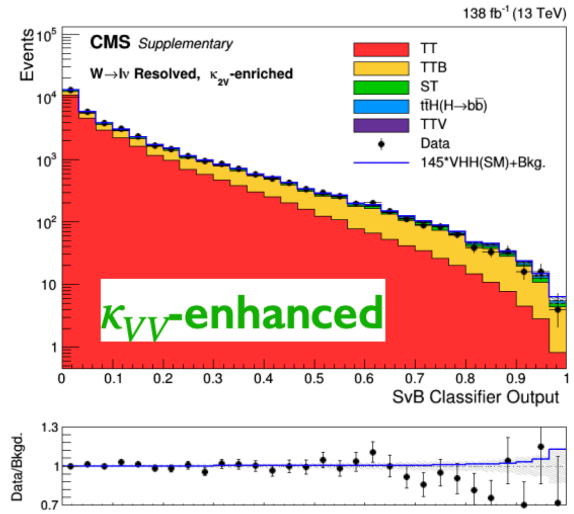
κ_{VV}-enhanced



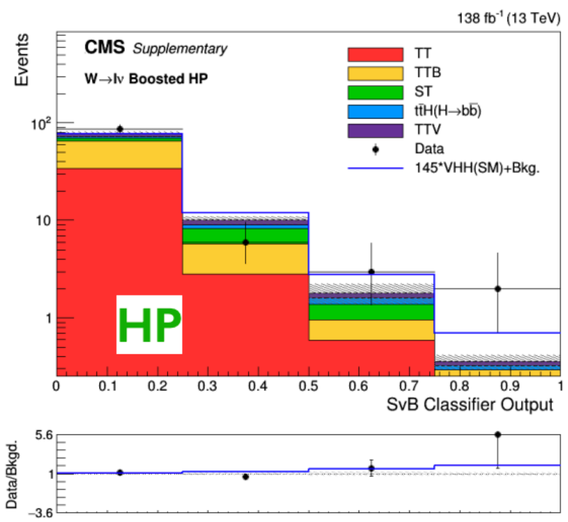
1L



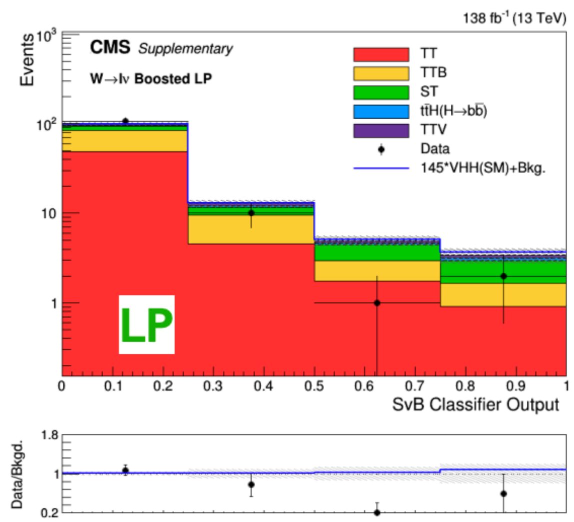
138 fb-1 (13 TeV)
CMS Supplementary
W→lν Resolved, κλ-enriched
TT
TTB
ST
ttH(H→bb)
TTV
Data
145*VHH(SM)+Bkg.
κλ-enhanced
Events
SvB Classifier Output
Data/Bkgd.



138 fb-1 (13 TeV)
CMS Supplementary
W→lν Resolved, κ2V-enriched
TT
TTB
ST
ttH(H→bb)
TTV
Data
145*VHH(SM)+Bkg.
κVV-enhanced
Events
SvB Classifier Output
Data/Bkgd.

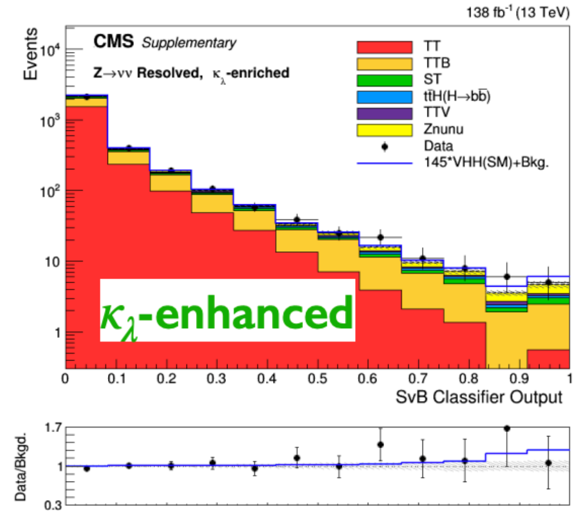


138 fb-1 (13 TeV)
CMS Supplementary
W→lν Boosted HP
TT
TTB
ST
ttH(H→bb)
TTV
Data
145*VHH(SM)+Bkg.
HP
Events
SvB Classifier Output
Data/Bkgd.

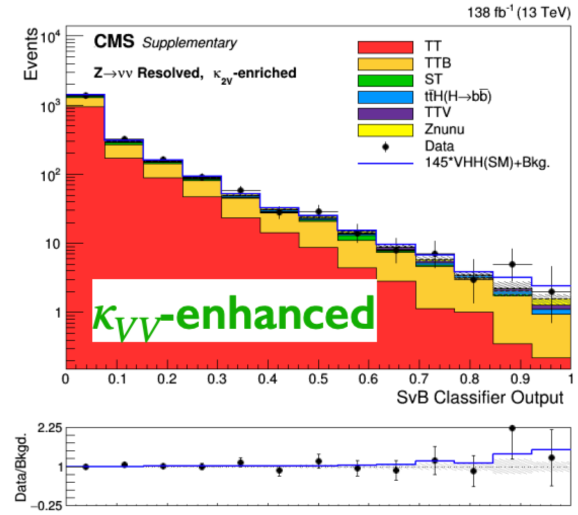


138 fb-1 (13 TeV)
CMS Supplementary
W→lν Boosted LP
TT
TTB
ST
ttH(H→bb)
TTV
Data
145*VHH(SM)+Bkg.
LP
Events
SvB Classifier Output
Data/Bkgd.

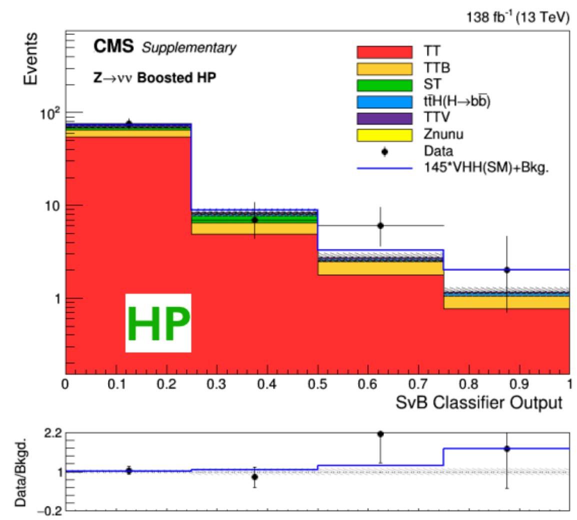
MET



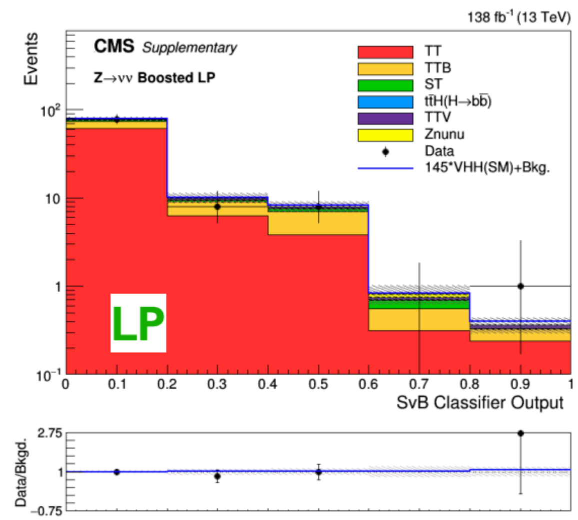
138 fb-1 (13 TeV)
CMS Supplementary
Z→νν Resolved, κλ-enriched
TT
TTB
ST
ttH(H→bb)
TTV
Znunu
Data
145*VHH(SM)+Bkg.
κλ-enhanced
Events
SvB Classifier Output
Data/Bkgd.



138 fb-1 (13 TeV)
CMS Supplementary
Z→νν Resolved, κ2V-enriched
TT
TTB
ST
ttH(H→bb)
TTV
Znunu
Data
145*VHH(SM)+Bkg.
κVV-enhanced
Events
SvB Classifier Output
Data/Bkgd.

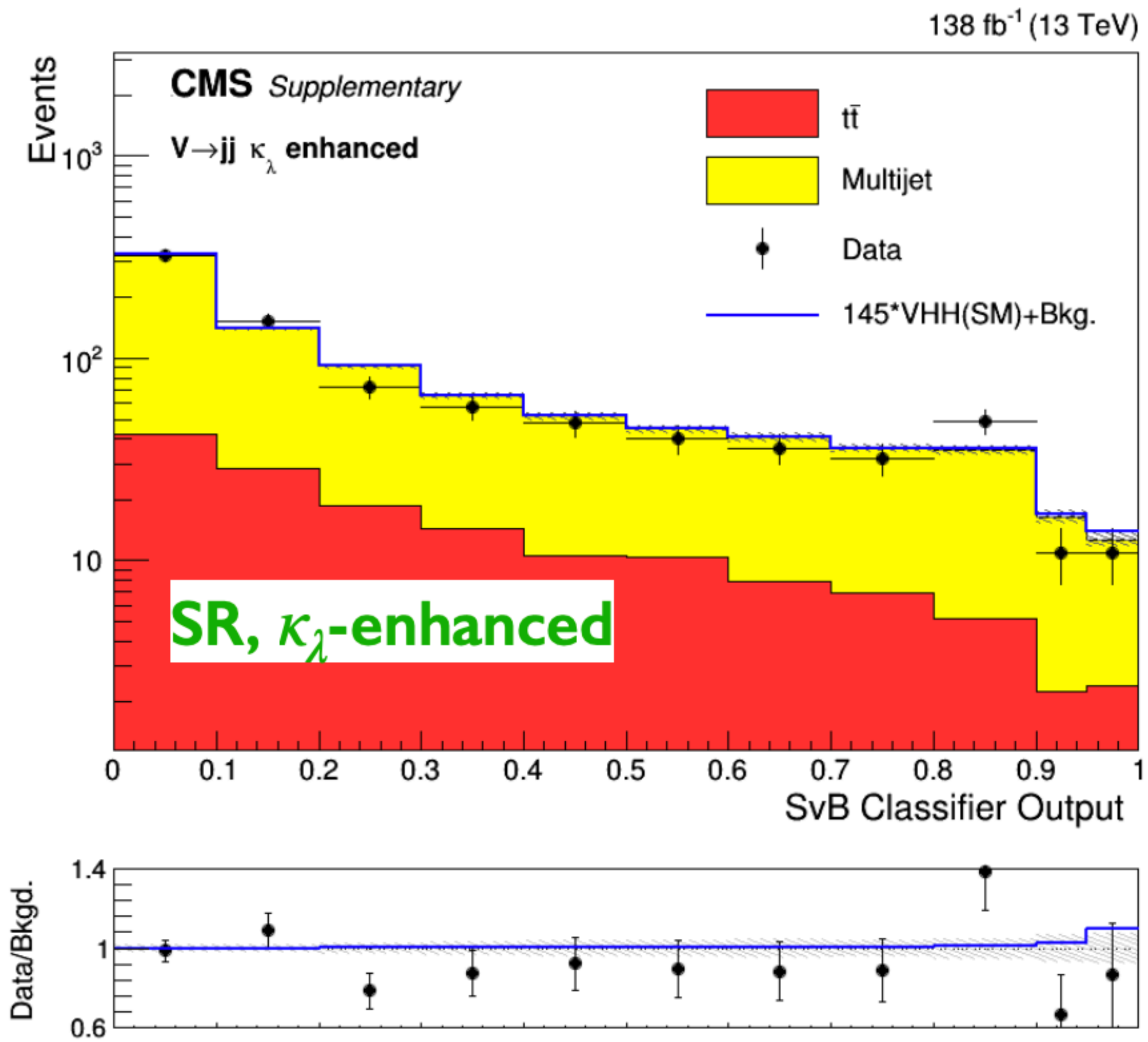


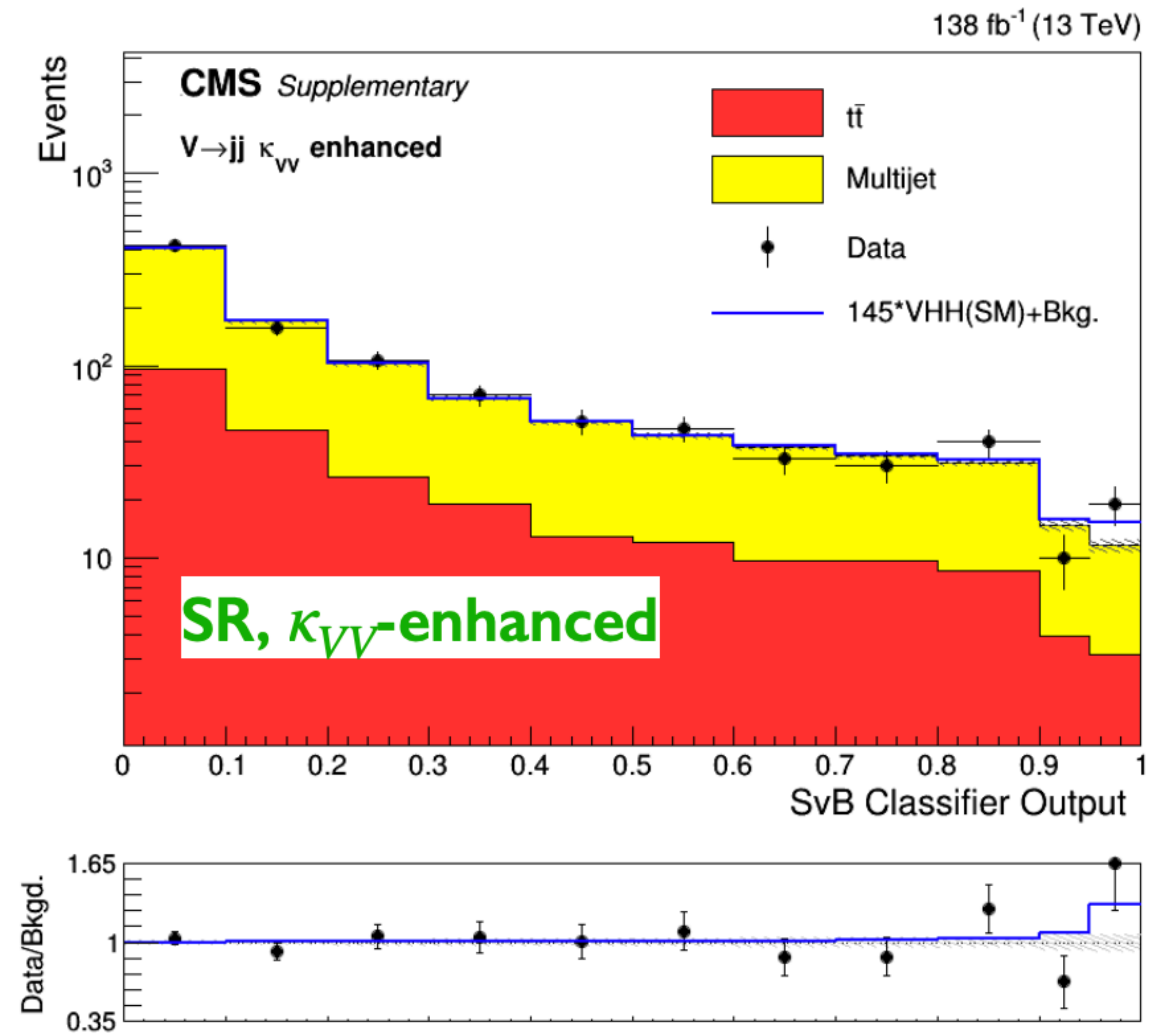
138 fb-1 (13 TeV)
CMS Supplementary
Z→νν Boosted HP
TT
TTB
ST
ttH(H→bb)
TTV
Znunu
Data
145*VHH(SM)+Bkg.
HP
Events
SvB Classifier Output
Data/Bkgd.

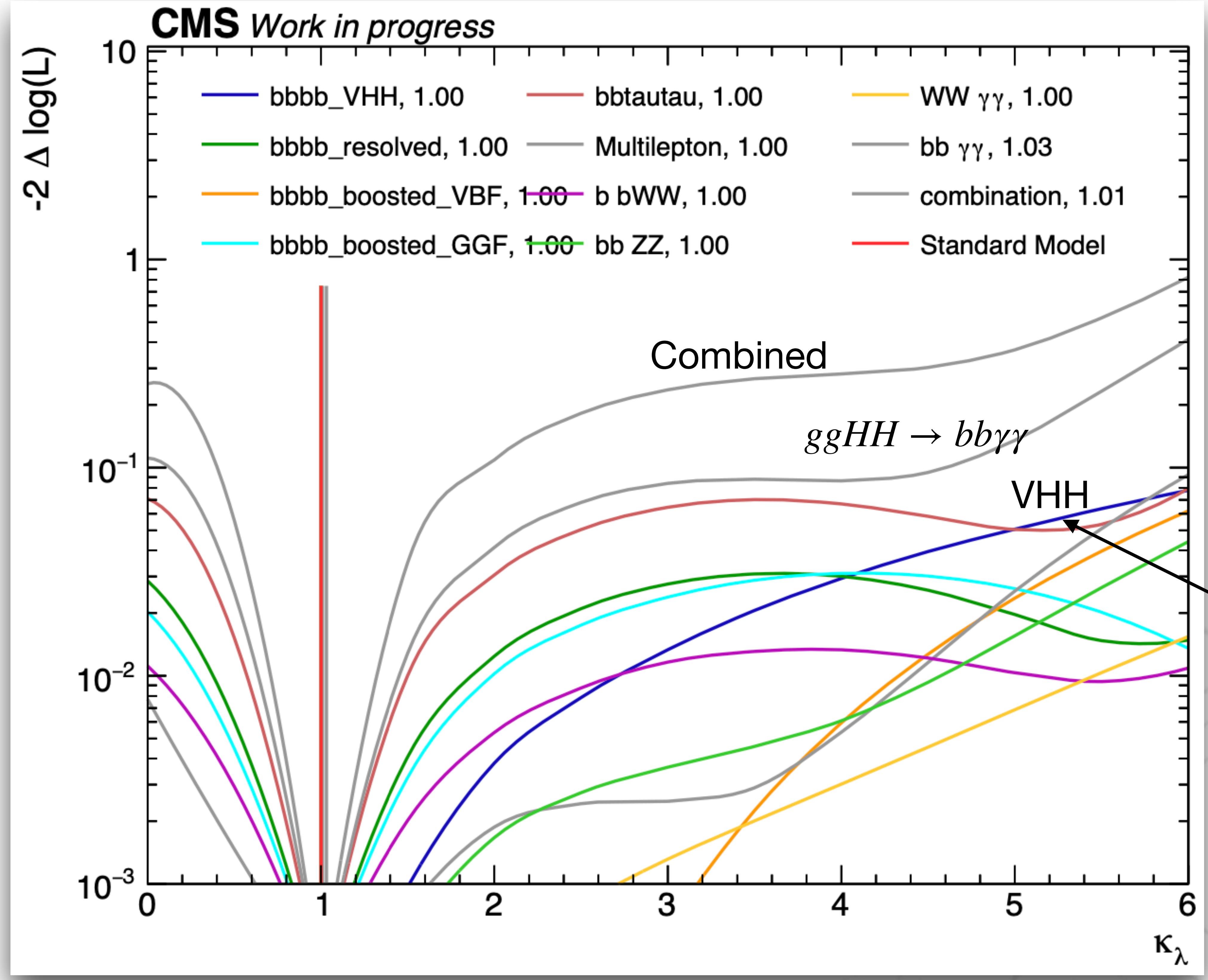


138 fb-1 (13 TeV)
CMS Supplementary
Z→νν Boosted LP
TT
TTB
ST
ttH(H→bb)
TTV
Znunu
Data
145*VHH(SM)+Bkg.
LP
Events
SvB Classifier Output
Data/Bkgd.

FH

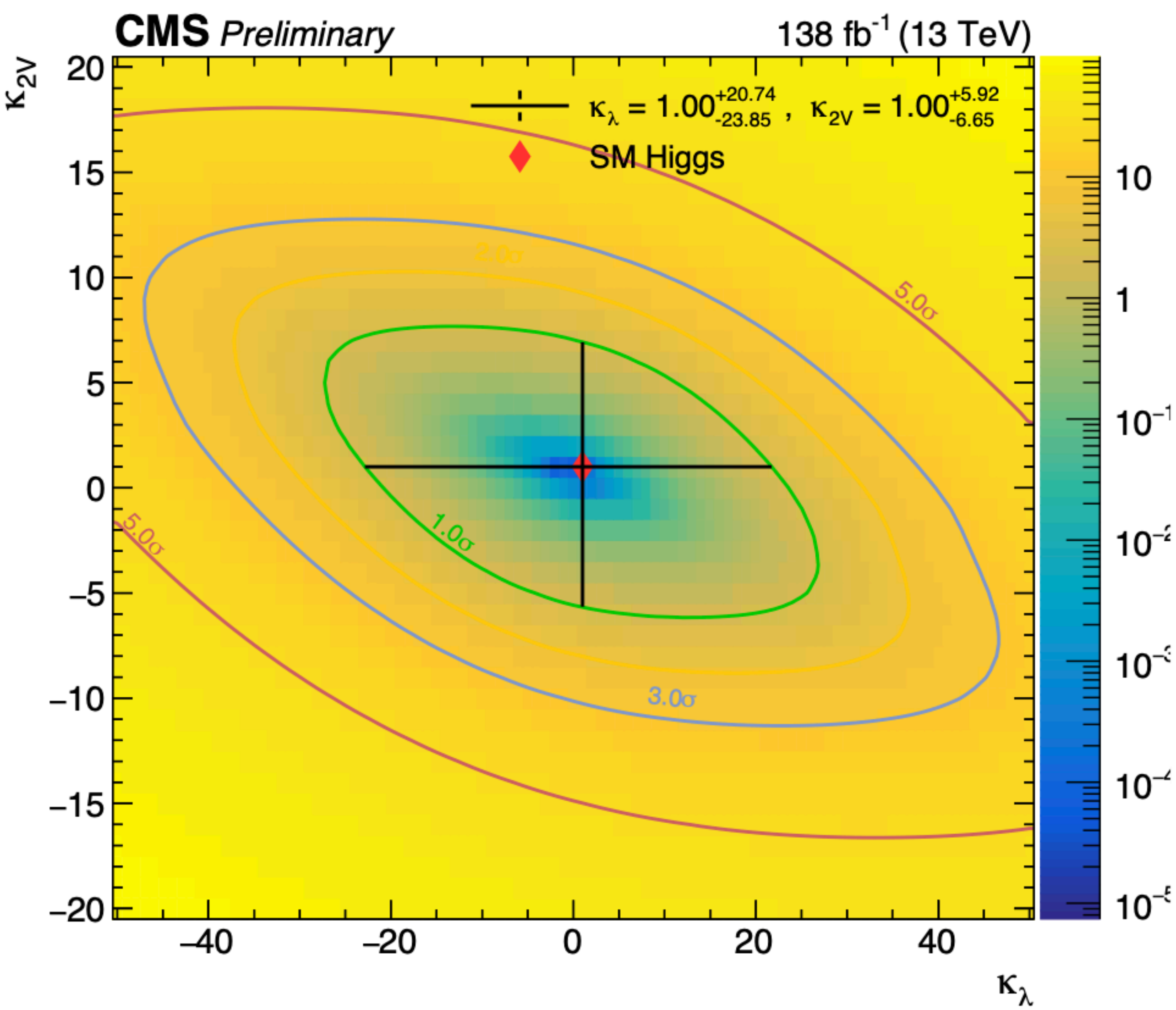

138 fb^{-1} (13 TeV)
CMS Supplementary
V→jj κ$_λ$ enhanced
tt̄
Multijet
Data
145*VHH(SM)+Bkg.
SR, κ_λ-enhanced
Events
SvB Classifier Output
Data/Bkgd.

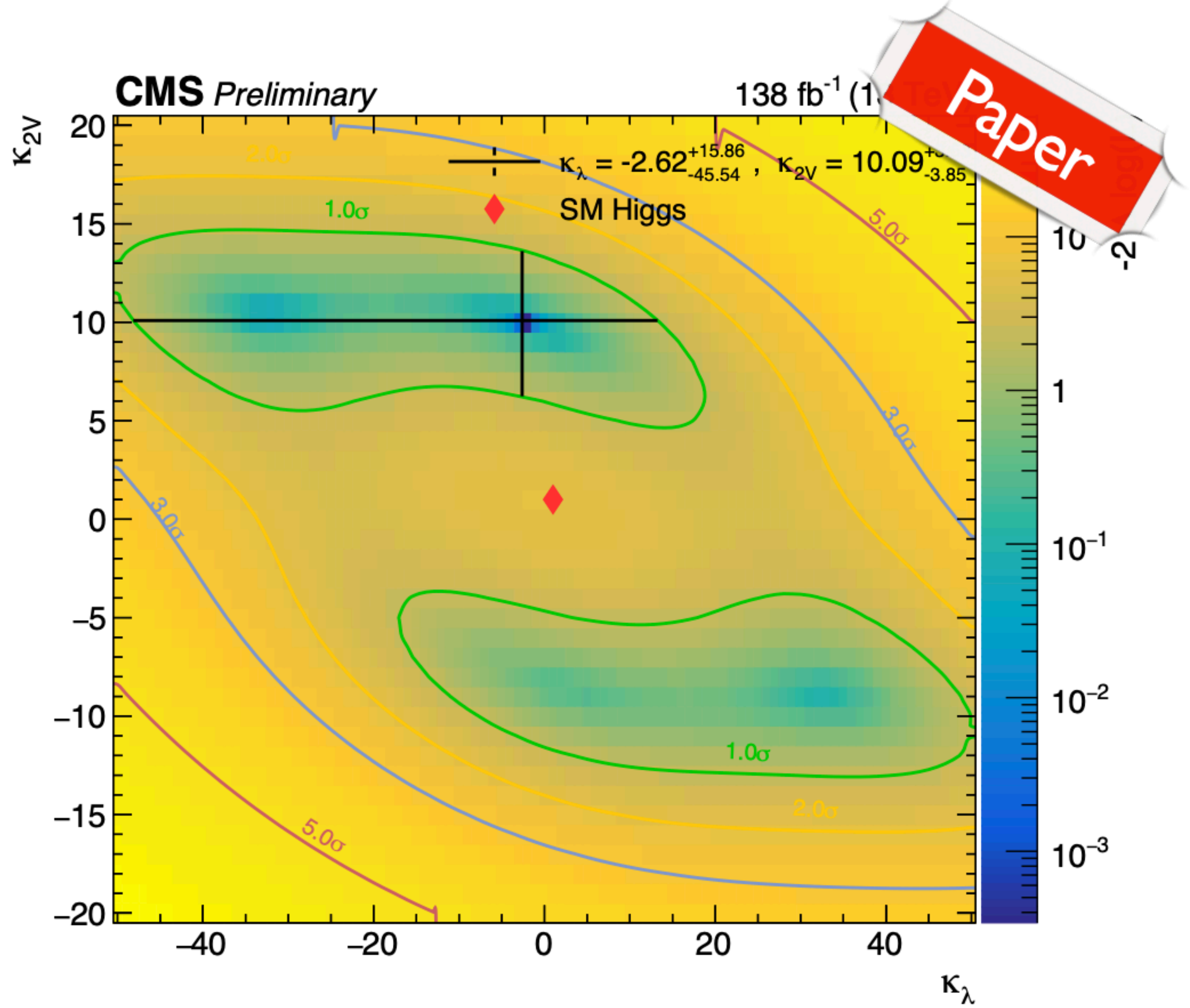

138 fb^{-1} (13 TeV)
CMS Supplementary
V→jj κ$_{VV}$ enhanced
tt̄
Multijet
Data
145*VHH(SM)+Bkg.
SR, κ_{VV}-enhanced
Events
SvB Classifier Output
Data/Bkgd.



VHH has competitive sensitivity at κ_λ at around 5, where most of ggF HH are weak

- 2D likelihood scan, left is expected, right is observed





- Decompose κ_{VV} to κ_{ZZ} and κ_{WW} (left is expected, right is observed)
- MET, 2L channels mainly affect κ_{ZZ} coupling, but not κ_{WW}. We have excess mainly from MET channel, so we also see enhancement in κ_{ZZ}