CLHCP 2025

Constraining HHVV Couplings via VBS VVH Processes

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Documentation & Current status

- **VBS Same-Sign WWH: CMS-PAS-HIG-24-001**
  - **Completely finished by PKU**
  - **PAS has been released and reported on ICHEP 2024**
- **Full combination of VBS VVH: CMS-PAS-HIG-24-003**
  - **UCSD, Notre Dame, Florida, …**
  - **PAS has been released and Reported on EPS 2025**

Available on the CERN CDS information server **CMS PAS HIG-24-001**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-higgs@cern.ch 2024/07/24

Search for HHWW couplings in the VBS production of $W^{\pm}W^{\pm}H$, with $H \to b\bar{b}$ decays

The CMS Collaboration

Abstract

A search is performed for anomalous HHWW couplings based on the process $pp \to W^{\pm}W^{\pm}H + jj$, using proton-proton collision data collected by the CMS experiment at a center-of-mass energy of $\sqrt{s} = 13$ TeV in the LHC Run 2, corresponding to a total integrated luminosity of 138 fb^{-1}. The search is performed in final states that contain a forward-backward jet pair, two W bosons that decay to same-sign leptons, and a Higgs boson that decays into two bottom quarks. Boosted decision trees are trained to separate the signal from the background. The HHWW coupling modifier κ_{WW} is constrained at 95% confidence level to be in the interval [-3.3, 5.3], consistent with the expected interval of [-2.4, 4.4].

Available on the CERN CDS information server **CMS PAS HIG-24-003**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-higgs@cern.ch 2025/07/07

Search for associated production of a Higgs boson and of two vector bosons via vector boson scattering

The CMS Collaboration

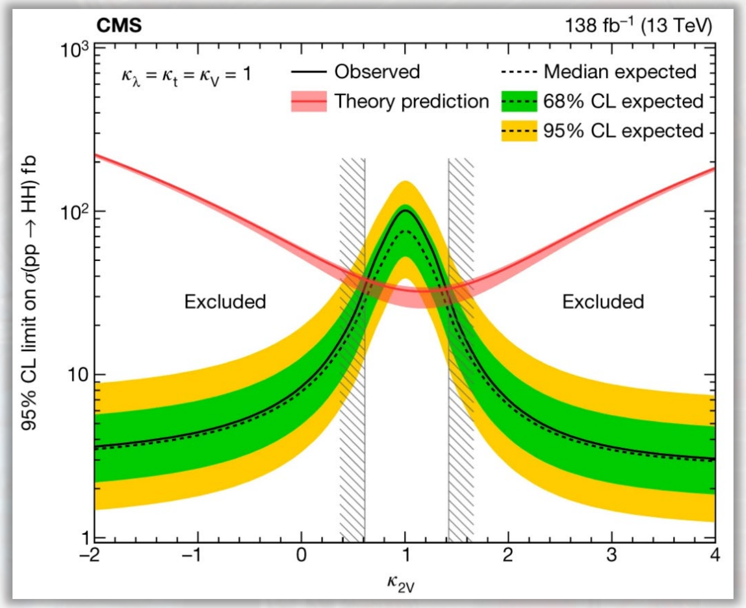
Abstract

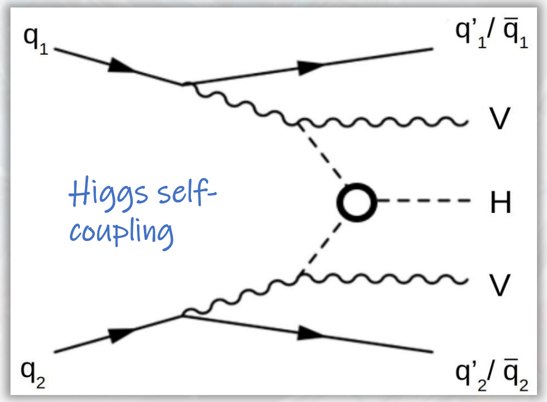
A search for the production of a Higgs boson in association with two vector bosons via vector boson scattering is presented. The search uses CMS data from proton-proton collisions at $\sqrt{s} = 13$ TeV collected from 2016 to 2018, corresponding to an integrated luminosity of 138 fb^{-1}. Selected events are consistent with the presence of two jets originating from vector boson scattering and a Higgs boson decaying into a pair of b quarks, reconstructed as a single large-cone jet, while final states with 0, 1 or 2 charged leptons coming from the decays of the two vector bosons are studied. The study constrains the quartic VVHH coupling strength relative to the standard model, κ_{2V}, in the observed (expected) range [0.40, 1.60] ([0.34, 1.66]) at 95% confidence level when the other Higgs boson couplings are fixed to their SM values. The process is also sensitive to the WWHH and ZZHH quartic couplings independently, whose strengths relative to the standard model are constrained in the observed (expected) ranges [0.17, 1.84] ([0.11, 1.89]) and [−0.37, 2.38] ([−0.54, 2.54]), for κ_{2W} and κ_{2Z} respectively. A two-dimensional scan is performed to determine exclusion regions in the κ_{2W}-κ_{2Z} plane.

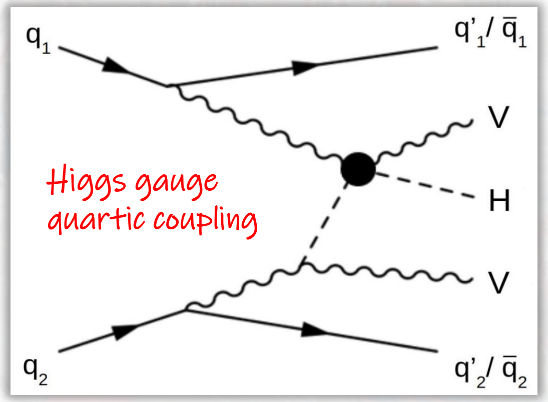
Introduction

Nature 607, 60–68 (2022)

- In 2022, $\boldsymbol{\kappa_{VV}} = \mathbf{0}$ is excluded for the first time by **HH->4b production in CMS**
  - 6.3σ deviation when $\kappa_t = \kappa_V = \kappa_\lambda = 1$
- Despite well-constraint results for $\boldsymbol{\kappa_{VV}}$, separate constraints for $\boldsymbol{\kappa_{WW}}/\boldsymbol{\kappa_{ZZ}}$ are not satisfactory enough
  - **Observed(expected) results: [−14.0, 15.4] ([-10.2, 11.6]) for $\boldsymbol{\kappa_{WW}}$** in CMS VHH analysis
- VBS VVH processes serve as an ideal channel to constrain HHVV and separate HHWW/HHZZ couplings
  - Datasets: Full Run II data with a luminosity of 138 fb^{-1}
  - In HIG-24-001: $\boldsymbol{pp \rightarrow W^\pm W^\pm H + jj}$, $\boldsymbol{W^\pm \rightarrow \ell\nu(\ell = e, \mu, \tau)}$, $\boldsymbol{H \rightarrow bb}$
  - In HIG-24-003: VBS **WWH, WZH, ZZH**
    - **Orthogonal final states -> can be combined**
    - **Details in the following pages**
- **Main target:**
  - **Competitive with HH in the $\boldsymbol{\kappa_{VV}}$ scan**
  - **Give similar sensitivity to $\boldsymbol{\kappa_{WW}}$ and $\boldsymbol{\kappa_{ZZ}}$**



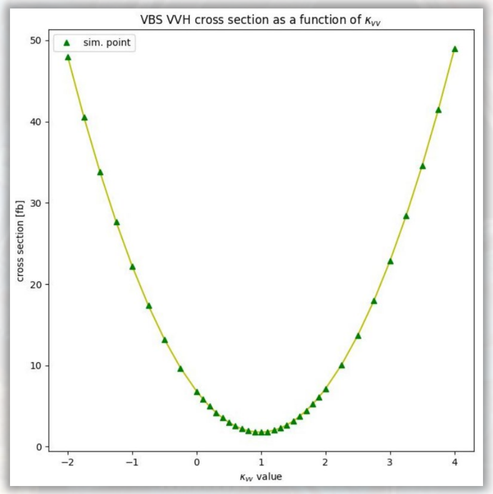


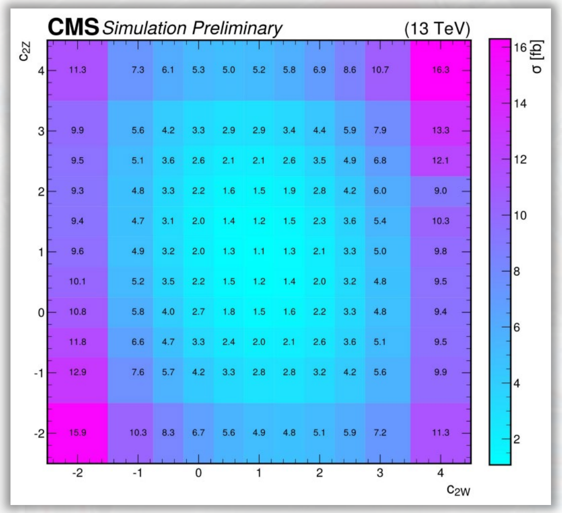


Studies of $\boldsymbol{\kappa_\lambda}$ are left to future work, realistically with HL-LHC data

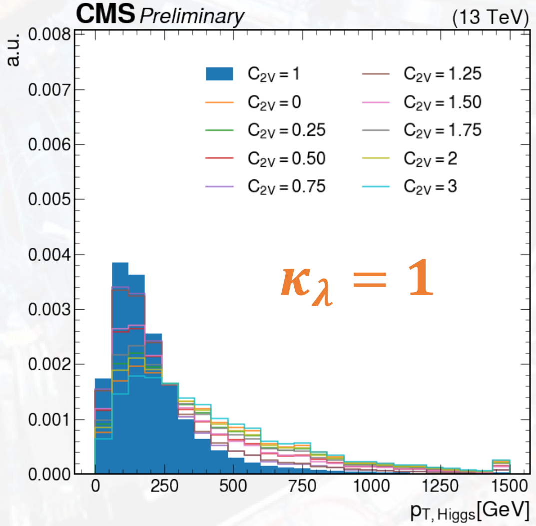
LHE-level check on the signal processes

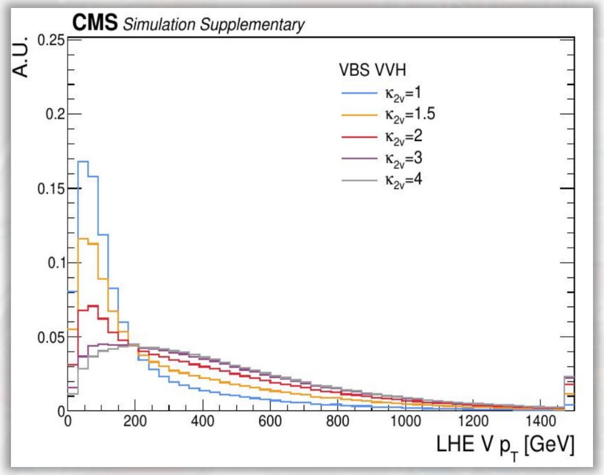
- Low **SM** cross-sections
  - 1.77/fb -> **~244 events in Run2**, most of which are in **hadronic** final states
  - Hard to achieve high significance for SM measurement
- Cross-sections increases rapidly as a function of κ_{VV}
  - Quadratic dependence on the coupling for each process
  - Similarly as a function of κ_{WW} and κ_{ZZ}
- The final state bosons receive a significant **Lorentz boost** as the parameter κ_{VV} deviates from its SM value
  - For both Higgs and W/Z bosons
  - Evidence for performing the analysis based on the **boosted-jets decayed from bosons**





➢ VVH Cross-sections as a function of κ_{VV} & $(\kappa_{WW}, \kappa_{ZZ})$





➢ $\mathbf{p_{T,Higgs}}$ and $\mathbf{p_{T,V}}$ distributions for different κ_{VV} values

Categorization

- **6 channels in total**
  - HIG-24-001: same-sign dileptonic channel, based on $W^{\pm}W^{\pm}H$ process (SS channel)
    - Based on lepton flavors: $\ell\ell$ channel, $\ell\tau$ channel, $\ell = e, \mu$
  - HIG-24-003: 5 channels with similar strategies
    - Hadronic channels:
      - Fully boosted channel with 3 AK8 jets (VVH)
      - Semi-boosted channel with 2 AK8 jets (VH) + 2 AK4 jets (V)
    - Semileptonic channel with 2 AK8 jets (VH) + 1 lepton (W)
    - Dilepton channels:
      - OS ZV channel with 2 AK8 jets (VH) + 2 leptons from onshell Z
      - OS WW channel with 1 AK8 jet (H) + 2 leptons from WW (exclude events with $m_{\ell\ell}$ close to Z)
- In all final states the **Higgs is reconstructed as an AK8 jet**
- Additional **2 VBS AK4 jets** are required

SS channel: Strategies & selections

◆ **Pre-selection criteria:**

Leptons

- 2 leptons passing tight selections, with overlaps dropped by $\Delta R = 0.4$
- Events with a third lepton passing veto selections are dropped
- $p_{T\ell} > 30$ GeV, $|\eta_{e/\mu/\tau}|$ < 2.5/2.4/2.3

AK4 jets

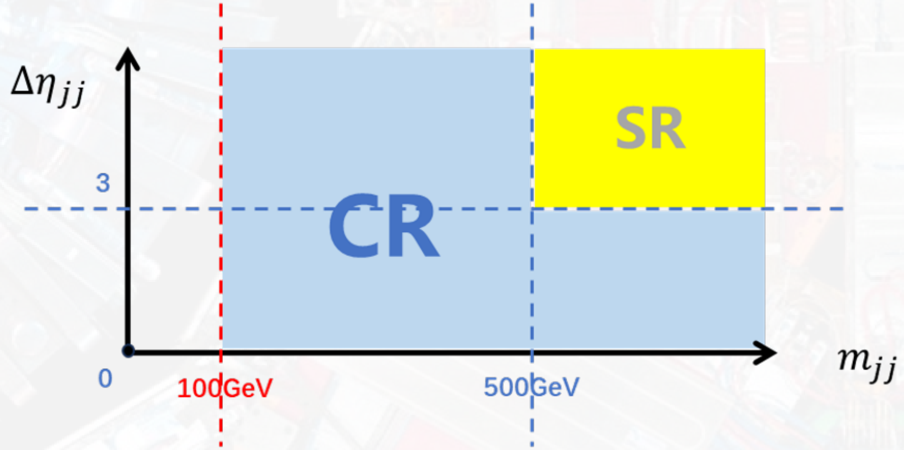
- 2 VBS jets passing tight selections & failing b-tagging WPs, with overlaps dropped by $\Delta R = 0.4$
- $p_{Tj} > 30$ GeV, $|\eta_j| < 4.7$

AK8 jets

- 1 AK8 fat jet passing tight selection, with overlaps dropped by $\Delta R = 0.8$
- $p_{TJ} > 300\text{GeV},\ M_J > 50\text{GeV},\ M_{softdrop} > 40\text{GeV}$
- Pass ParticleNet ID: $\frac{\text{particleNetMD(Xbb)}}{\text{particleNetMD(Xbb)+particleNetMD(QCD)}}$ > 0.9

◆ **Based on the pre-selection criteria:**

- **Signal region**
  - $m_{jj} > 500\ \mathbf{GeV}, |\Delta\eta_{jj}| > 3$, PNet-Xbb score > 0.9
- **Control region**
  - $m_{jj} > 100\ \mathbf{GeV}$, fail SR m_{jj} & $|\Delta\eta_{jj}|$ cut, PNet-Xbb score > 0.3
- Backgrounds from **tt_1l, tt_2l, ttW, ttZ** are merged together as **a floating rate parameter**



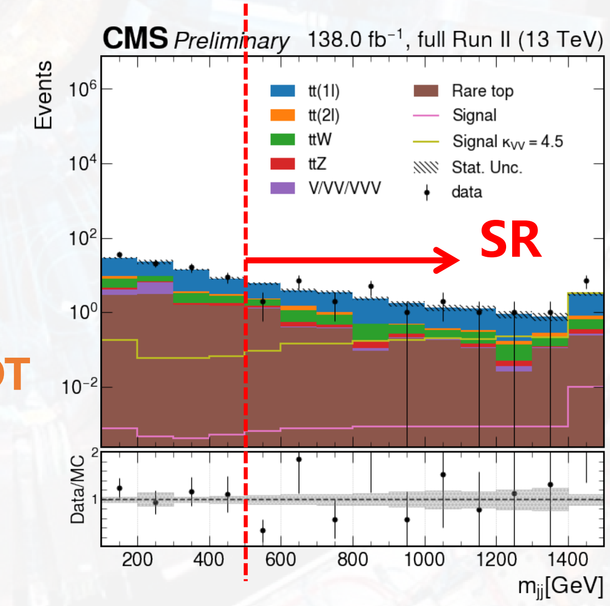
SS channel: Events extraction & BDT training

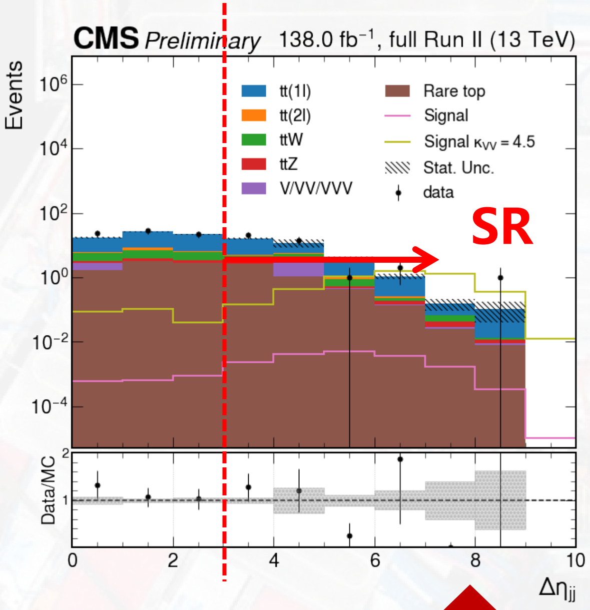
- **1 BDT model**, with both the SR and the CR distributed into the training
  - $\boldsymbol{m_{jj}}$ & $|\boldsymbol{\Delta\eta_{jj}}|$ are excluded from BDT input variables
- Training weight:
  - Backgrounds: $\boldsymbol{n_L = \sigma_X L / N_{G_X}}$ for process X, $L =$ Luminosity, $N_{G_X} =$ Sum of enerator weight
  - Signal: Use reweighting weights with $\boldsymbol{\kappa_{VV} = 4.5}$
  - $\sum_{\text{signal}} \mathbf{w}^{\mathbf{i}} = \sum_{\text{background}} \mathbf{w}^{\mathbf{i}}$
- Avoid over-training by setting **gamma=0.05** in BDT parameters
- Divide each region into **2 lepton channels ($\ell\ell, \ell\tau$)** with **BDT score shapes**
  - **SR: [0, 0.1, 0.25, 1]; CR: [0, 1]**

Shorthand	Description
η_J	η of the leading merged jet
$p_{T,J}$	p_T of the leading merged jet
$p_{T,jj}$	p_T of the VBS-jet system
P_{j_0}	magnitude of the three-momentum of the leading VBS jet
P_{j_1}	magnitude of the three-momentum of the subleading VBS jet
$M_{\ell\ell}$	invariant mass of the SS dilepton system
p_{T,ℓ_0}	p_T of the leading lepton
p_{T,ℓ_1}	p_T of the subleading lepton
E_T^{miss}	missing transverse energy
L_T	scalar sum of $p_{T,\ell_0}, p_{T,\ell_1}$, and E_T^{miss}
S_T	scalar sum of $p_{T,J}$ and L_T

Table 1: All BDT input variables used for AK8 channel.

- **BDT input variables, with m_{jj} & $|\Delta\eta_{jj}|$ excluded**





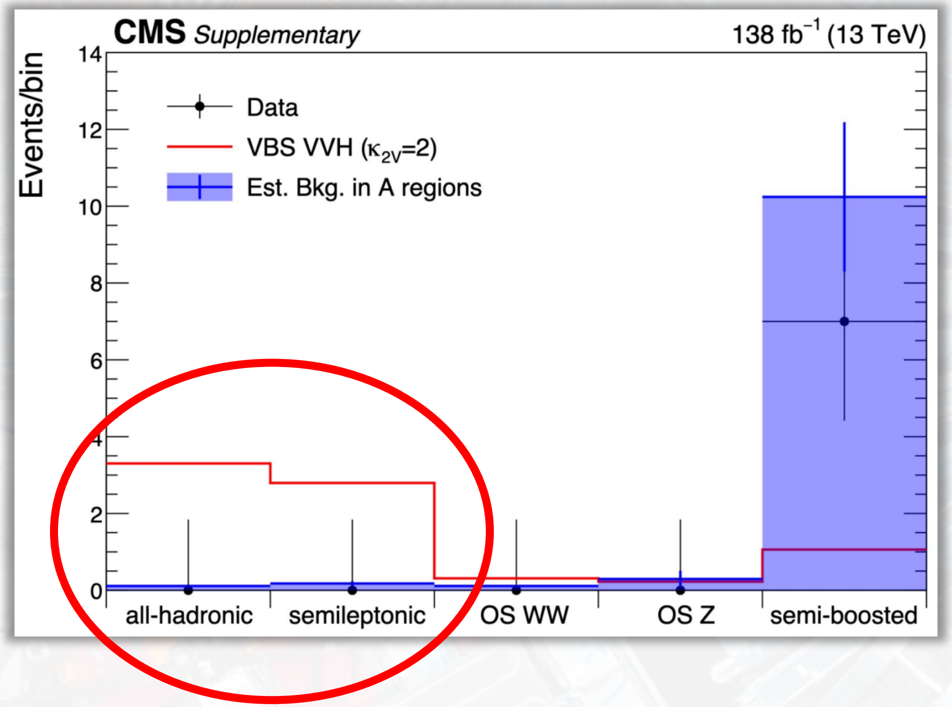
Other channels: Strategies & selections

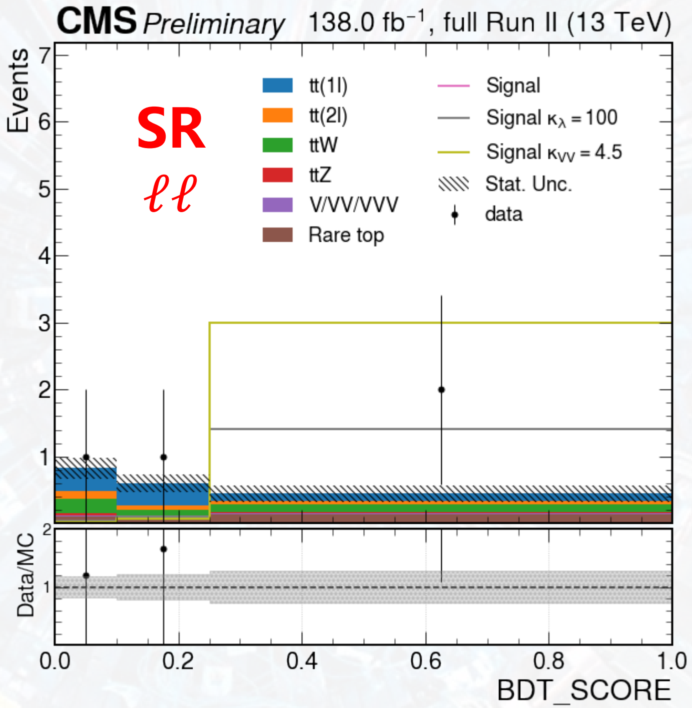
- **A common baseline strategy** is applied to all the channels in HIG-24-003
  - **Lepton** selections based on **ttH ID ->** excludes events with additional veto leptons
  - **AK8 jet** selections based on **ParticleNet Xbb & Xqq scores** -> for Higgs & W/Z
  - Similar selections & tagging for **VBS jets**
- **Backgrounds estimation**
  - **DNN models** are trained separately for **Full Hadronic channels** and **Semileptonic channel**
  - **BDTs** are trained separately for **Semileptonic channel** and **Dileptonic channels**
  - **ABCD method** is applied to all the channels to control **total backgrounds**
    - Fully boosted channel: Defined with **DNN and** $|\Delta\eta_{jj}|$ for VBS jets
    - Semi boosted channel: Defined with **DNN and** $(m_{jj}, |\Delta\eta_{jj}|)$ for VBS jets
    - Semileptonic channel: Defined with **DNN and BDT outputs**
    - Dileptonic OS WW channel: Defined with **BDT and** $(m_{jj}, |\Delta\eta_{jj}|)$ for VBS jets
    - Dileptonic OS Z channel Defined with **BDT and** $(m_{jj}, |\Delta\eta_{jj}|)$
  - **Decorrelation cross-checks of all the ABCD arms are performed**

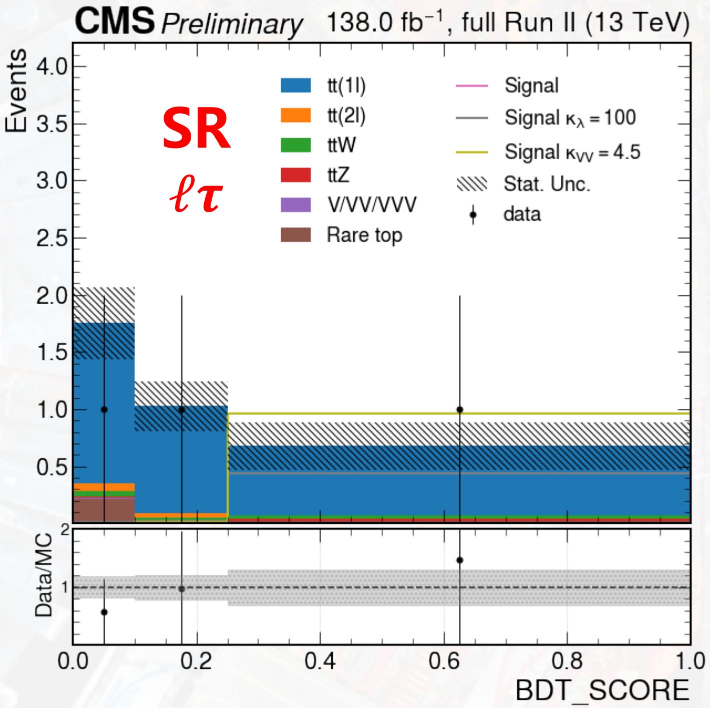
- **More details in backup**

Results

◆SR yields in each region



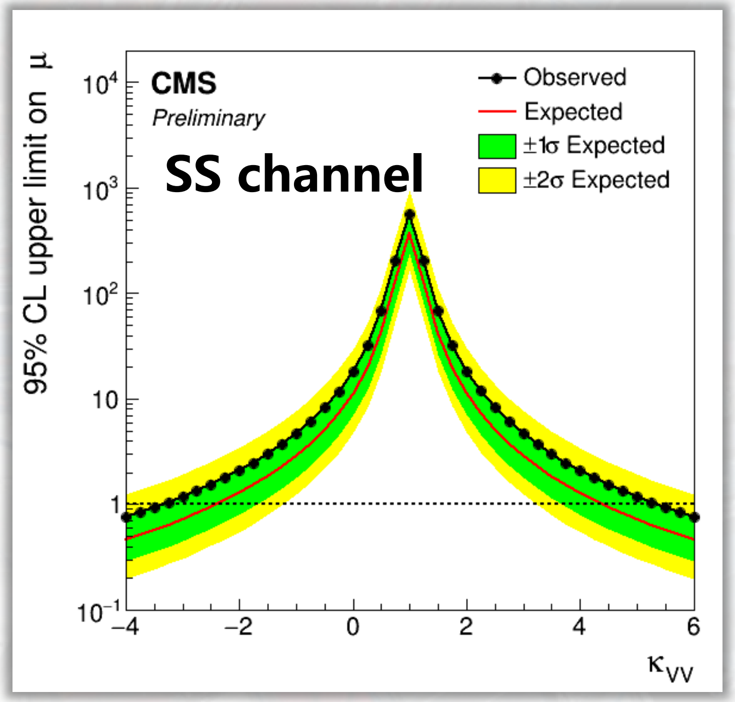


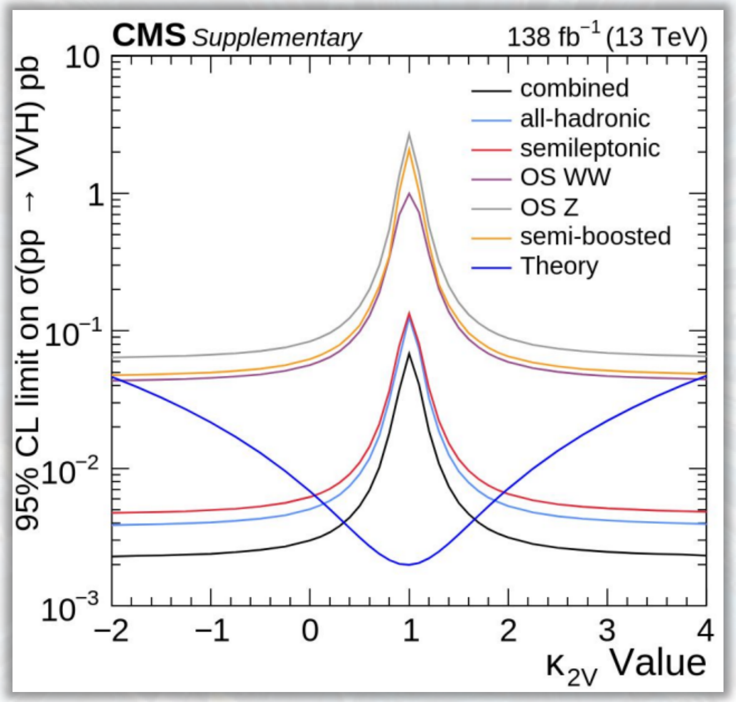


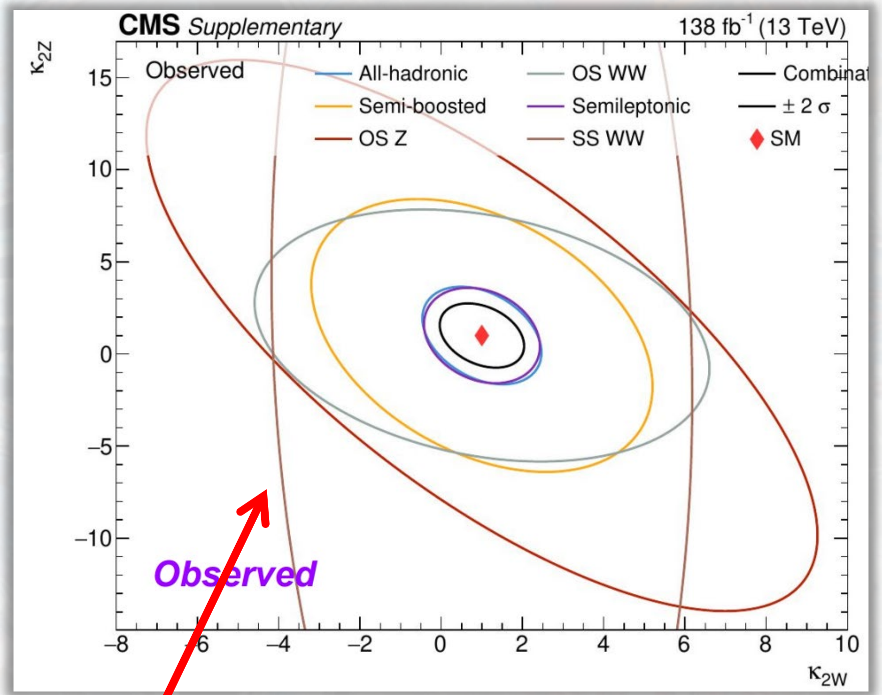
□ Sensitivities are mainly dominated by all-hadronic full boosted channel & semileptonic channel

Split Results for κ_{VV}

◆ κ_{VV} limits for each channel



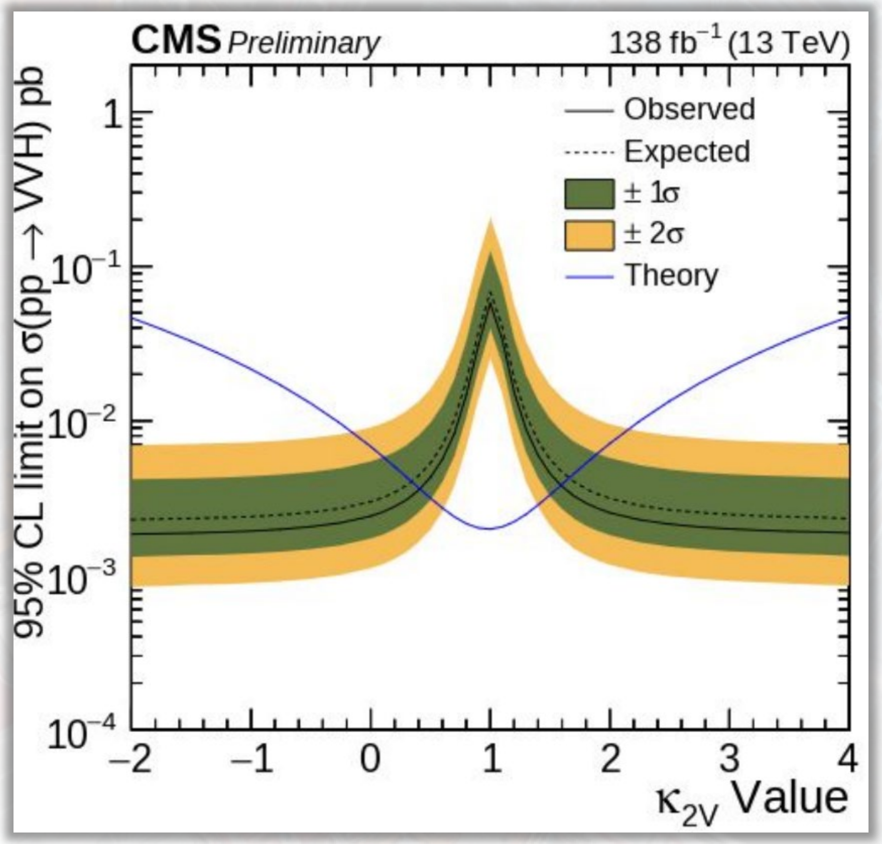


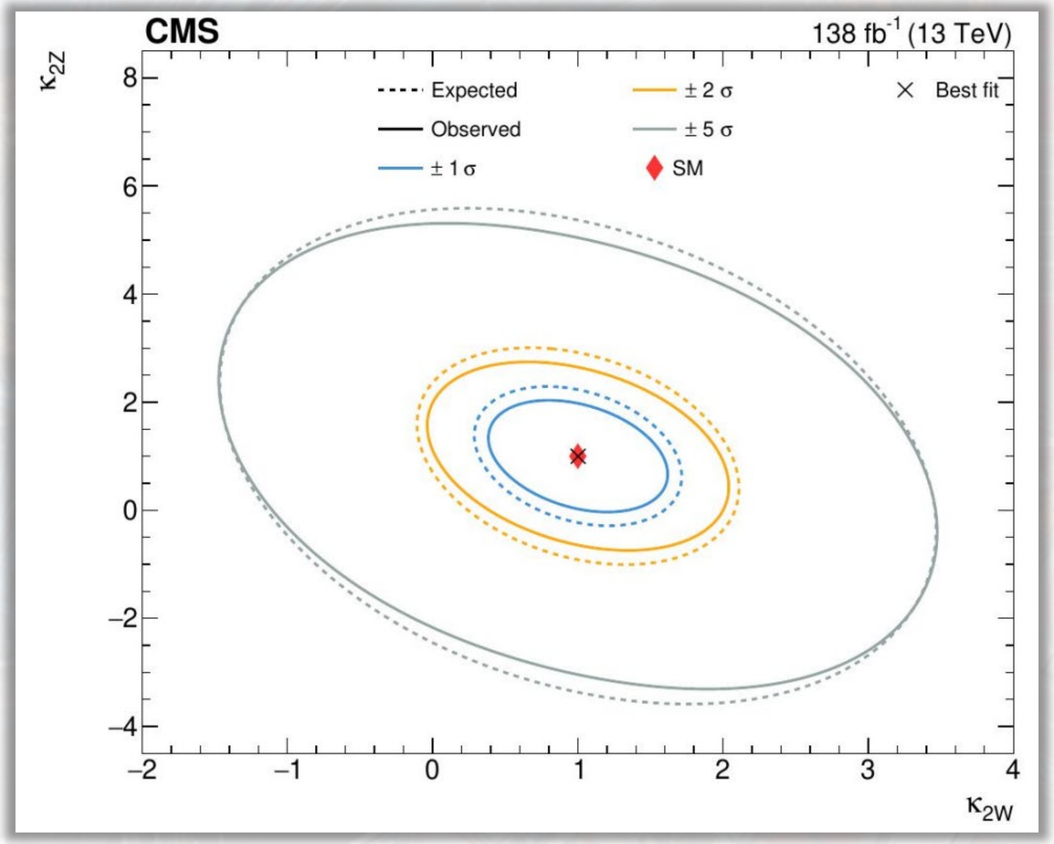


- ◻ SS channel shows high sensitivity to κ_{WW} but low to κ_{ZZ} -> in consistent with intuition

Combination Results for κ_{VV}

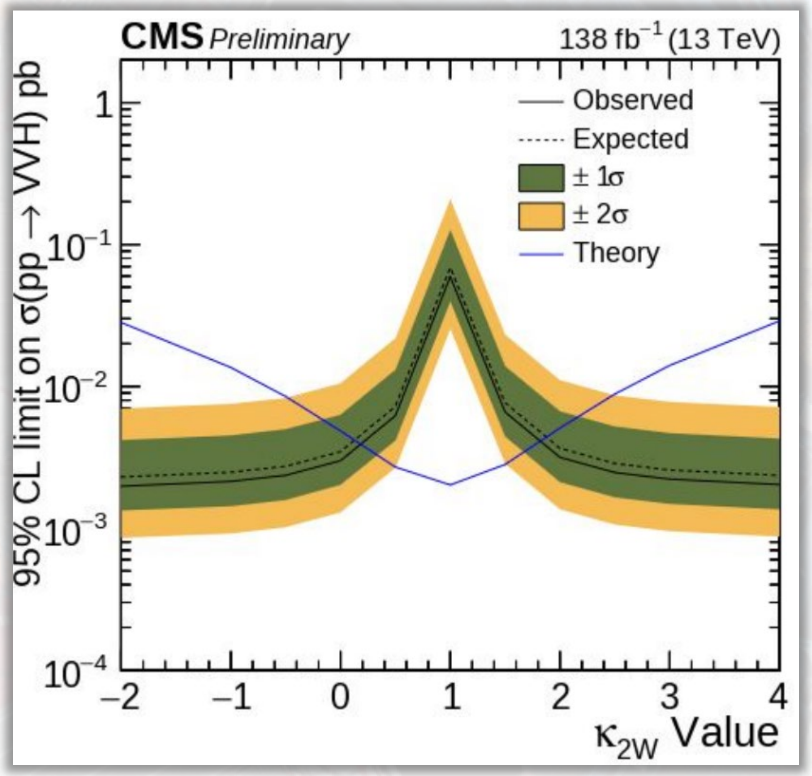
- κ_{VV} expected constrain [0.34,1.66] - observed [0.41,1.59]
  - Low sensitivity for HIG-24-001 -> results almost unchanged after the combination

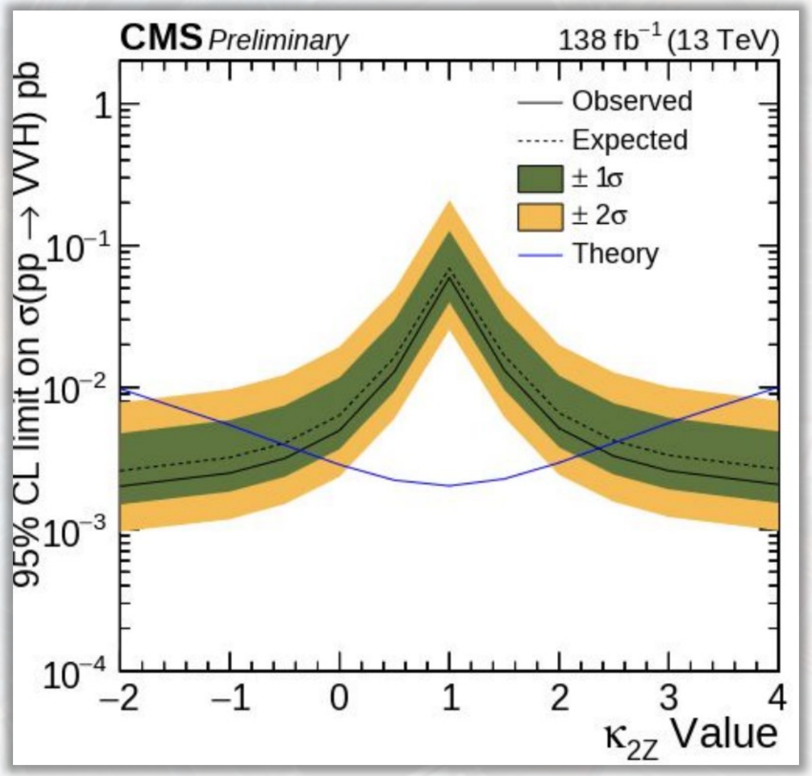




Results for κ_{WW} & κ_{ZZ}

- κ_{WW}: expected constrain [0.12, 1.89] - observed [0.17, 1.83]
- κ_{ZZ}: expected constrain [-0.53, 2.53] - observed [-0.37, 2.37]





□ Exclude $\kappa_{WW} = 0$ at a 95% CL -> First time in CMS!

Summary & Future Prospects

- Constraint on HHVV couplings was measured based on VBS VVH channels
- Set limit on κ_{VV} - approaching current constraints from di-Higgs
  - $\boldsymbol{\kappa_{VV}} \in$ **[0.41, 1.59]** ([0.34, 1.66]) - observed (expected)
  - **CMS HH->4b boosted regime: [0.67, 1.38] observed**
- **Produced current tightest limits on $\boldsymbol{\kappa_{WW}}$ and $\boldsymbol{\kappa_{ZZ}}$**
  - **$\boldsymbol{\kappa_{WW}} \in$ [0.17, 1.80] ([0.12, 1.89])**
  - **$\boldsymbol{\kappa_{ZZ}} \in$ [-0.37, 2.37] ([-0.53, 2.53])**

- [ ] **Target Journal: PRL**

Thanks for your attention!

BACKUP

Table 2: The post-fit yields of the CR, for $\ell\ell$ and $\ell\tau$ categories separately. The errors for total background include the statistical and systematic uncertainties.

Process	$\ell\ell$ category	$\ell\tau$ category
Signal	0.25	0.06
$t\bar{t} \to 1\ell$	18.02	36.69
$t\bar{t} \to 2\ell$	1.51	1.33
$t\bar{t}W$	11.41	1.79
$t\bar{t}Z$	1.50	0.58
Rare top	4.54	4.79
V/VV/VVV	1.57	3.09
Total background	38.56 ± 5.14	48.26 ± 8.52
Data	39	49

Table 2: Data yields in the B, C, D regions, used to estimate the background in region A, together with data, predicted background and expected signal in region A. For signal, the $\kappa_{2V} = 2$ benchmark and the SM expected yields are reported.

	All-hadronic		Semileptonic	2 Leptons	
	fully boosted	semi-boosted		OS WW	Z
Region B data	1	410	3	2	1
Region C data	73	399	61	10	5
Region D data	654	15 974	1039	179	17
Region A data	0	7	0	0	0
Region A pred.	$0.11^{+0.26}_{-0.09}$ (stat.) ± 0.03 (syst.)	$10.24^{+0.78}_{-0.72}$ (stat.) ± 1.95 (syst.)	$0.18^{+0.18}_{-0.10}$ (stat.) ± 0.06 (syst.)	$0.11^{+0.18}_{-0.08}$ (stat.) ± 0.02 (syst.)	$0.29^{+0.91}_{-0.25}$ (stat.) ± 0.21 (syst.)
Region A signal ($\kappa_{VV} = 2$)	3.30 ± 0.02 (stat.) ± 1.01 (syst.)	1.06 ± 0.01 (stat.) ± 0.36 (syst.)	2.79 ± 0.02 (stat.) ± 0.84 (syst.)	0.31 ± 0.01 (stat.) ± 0.10 (syst.)	$0.22 \pm (< 0.01)$ (stat.) ± 0.07 (syst.)
Region A signal (SM)	0.04 ± 0.01	$0.01 \pm (< 0.01)$	0.04 ± 0.02	$0.01 \pm (< 0.01)$	$(< 0.01) \pm (< 0.01)$

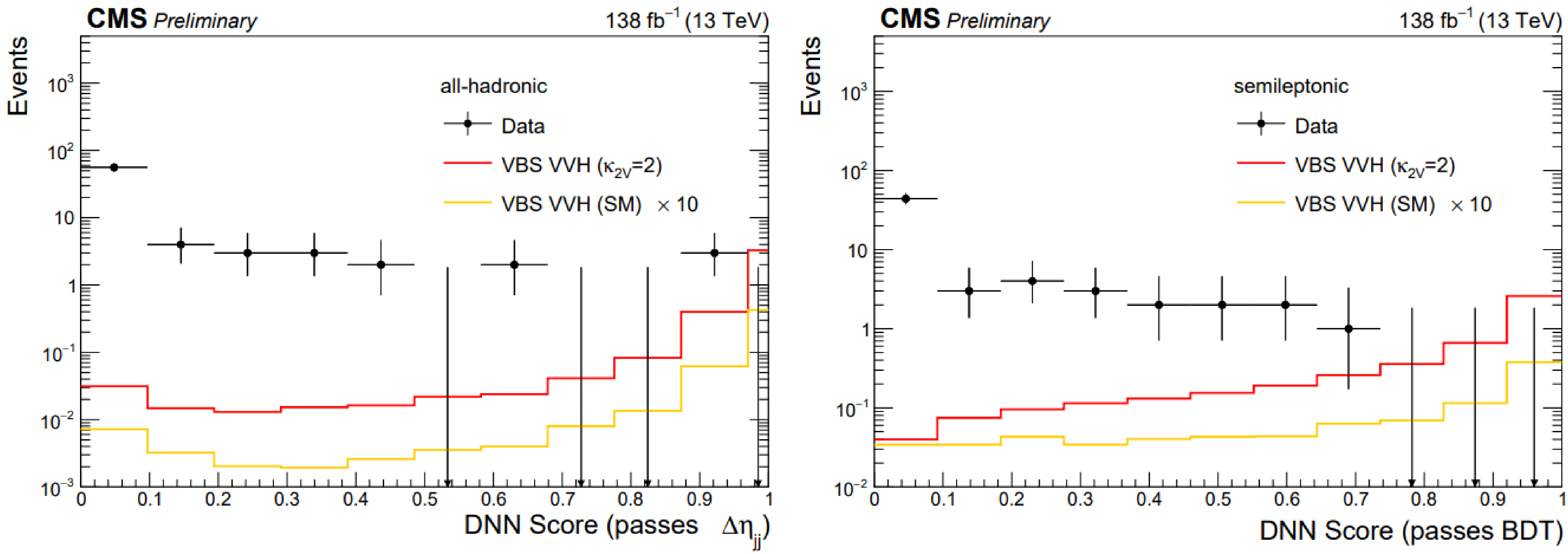
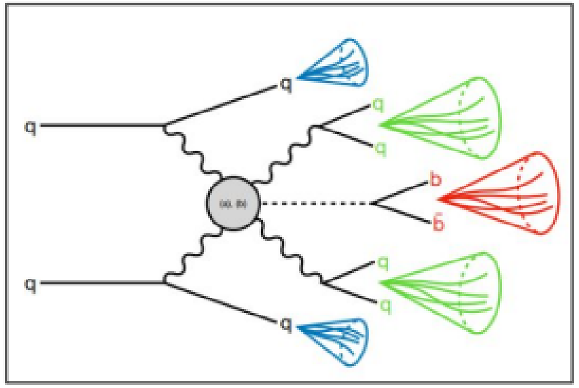


Figure 2: DNN discriminator distribution for the all-hadronic fully boosted channel (left) and semileptonic channel (right) in the regions A and C. The expected signal for the SM scenario (orange line) and for $\kappa_{2V} = 2$ (red line) is superimposed to the data (black dots).

All-hadronic channel - fully boosted



- HLT PFHT800/900/1050 on JetHT datasets
- 0 loose leptons (we use the ttH ID), >=3 AK8 jets, with p_T>300 GeV, central and with m_{SD} > 40 GeV for the VVH system, >=2 AK4 jets (for the VBS jets)
  - The leading AK8 p_T > 550 GeV to remove trigger turn-on effects
- The tagging of the H and V bosons is done using the Xbb and Xqq particleNet mass decorrelated discriminators
  - For the 3 AK8 jets we resample the QCD background distributions of the scores from data in an independent region -> improved agreement for the optimization of the analysis, even though the background estimate is data-driven
  - The **H(bb) candidate** is taken as the leading Xbb AK8, with Xbb score > 0.5
  - The **V candidates** are taken as the leading and subleading AK8 left, with Xqq score > 0.3
- The **VBS jet pair** is taken as the one with the largest $\Delta\eta_{jj}$

All-hadronic channel - fully boosted

- After the preselection, we train a **DNN** which is designed to be orthogonal to $|\Delta\eta_{jj}|$ (automated ABCD PhysRevD.103.035021) via a decorrelation term used at training time
  - The decorrelation is checked after training in simulation
- A **multidimensional scan** is run to optimize the signal region and define consistent ABCD regions
  - Optimal SR with tighter cuts also on Xbb and Xqq scores
  - B,C,D regions defined by inverting DNN and $|\Delta\eta_{jj}|$ selections
- A region background predicted as **A = B*C/D** in data
  - Several closure tests in MC and data sidebands
  - Statistical uncertainty of **inferred by the fit from windows on the B,C,D data yields**
  - Systematic uncertainty of **30% from closure tests**
    - Determined from the average closure bias over a data scan in the ABCD sideband

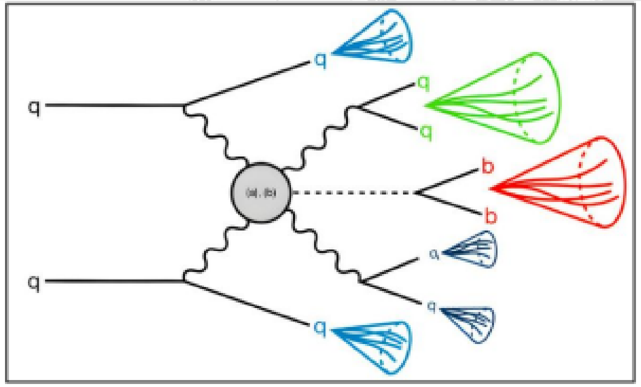
DNN inputs

- $H \to b\bar{b}$ candidate $p_T, \eta, \phi, M_{PNet}$
- Leading $V \to qq$ candidate $p_T, \eta, \phi, M_{PNet}$
- Trailing $V \to qq$ candidate $p_T, \eta, \phi, M_{PNet}$
- m_{jj}

SR definition

- ABCDNet > 0.97
- $|\Delta\eta_{jj}| > 5$
- $\text{Xbb}(H \to b\bar{b}) > 0.8$
- $\text{XWqq}(\text{leading } V \to qq) > 0.8$
- $\text{XWqq}(\text{trailing } V \to qq) > 0.7$

Region	Data Yield	Prediction
Region A	–	0.11
Region B	1	
Region C	73	
Region D	654	



All-hadronic channel - semi-boosted

- HLT PFHT800/900/1050 on JetHT datasets
- 0 loose leptons (we use the ttH ID), exactly 2 AK8 jets as defined in the fully boosted 0 lepton channel, >=4 AK4 jets, 2 of which central for the resolved Vqq and 2 within $|\eta| < 4.7$ for the VBS tagging
  - leading AK8 pT > 550 GeV to remove trigger and AK8 HT > 1100 GeV cuts are also applied turn-on effects
- The tagging of the H boson is done using the Xbb particleNet mass decorrelated discriminator
  - The **H(bb) candidate** is taken as the leading Xbb AK8, with Xbb score > 0.8
  - The **boosted V candidate** is taken as the remaining AK8 jet, with Xqq score > 0.637/0.579/0.59 (centrally defined working points) depending on the year
  - The **resolved V candidate** is defined using the dijet pair with minimum ΔR
- The **VBS jet pair** is taken as the one with the largest $\Delta\eta_{jj}$

All-hadronic channel - semi-boosted

- As in the fully boosted case, we train a **DNN which is by construction orthogonal to $|\Delta\eta_{jj}|$** (automated ABCD PhysRevD.103.035021) via a decorrelation term used at training time
- After training we check the decorrelation between DNN output and $|\Delta\eta_{jj}|$ / M_{jj}
- We run **a scan including $|\Delta\eta_{jj}|$, M_{jj} and the DNN score** to define the signal region
- A region background predicted as **A = B*C/D** in data
  - Several closure tests in MC and data sidebands
  - Statistical uncertainty of **inferred by the fit from windows on the B,C,D data yields (~7% from error propagation)**
  - Systematic uncertainty of **19% from a closure test** (MC closure)

DNN inputs

- $H \to b\bar{b}$ candidate p_T, η, ϕ, msoftdrop
- $V \to qq$ candidate (AK8 fat jet) p_T, η, ϕ, msoftdrop
- Leading $V \to qq$ candidate (AK4 jet) p_T, η, ϕ, mass
- Trailing $V \to qq$ candidate (AK4 jet) p_T, η, ϕ, mass
- S_T
- vqqjets_Mjj: Invariant mass of the $V \to qq$ candidate reconstructed from 2 AK4 jets
- H_T

SR definition

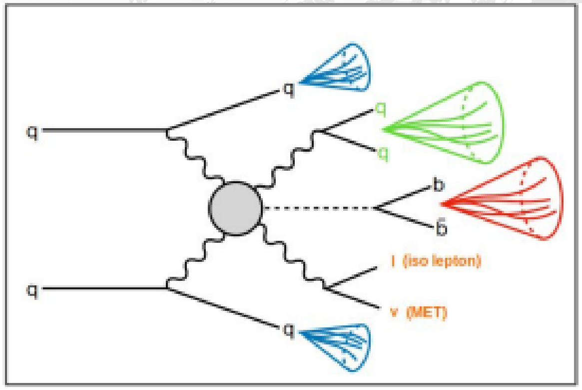
- ABCDNet > 0.8
- $|\Delta\eta_{jj}| > 6$
- $M_{jj} > 1300$

NB: For ABCD regions definitions we invert the DNN or $|\Delta\eta_{jj}|$ and M_{jj} selections, where $|\Delta\eta_{jj}|$ and M_{jj} are inverted together

Region	Data Yields	Final Prediction
A	Blinded	10.24 ± 0.72 (stat) ± 1.95 (syst)
B	410 ± 20.25	
C	399 ± 19.97	
D	15974 ± 126.39	

Signal
1.06 ± 0.01

Semileptonic channel



- Single Muon/Electron triggers (IsoMu24/27 - Ele27/32) using single Muon and single Electron datasets
- 1 lepton passing the ttH tight ID, pT>40 GeV -> **leptonic W candidate** / 0 extra leptons passing the ttH veto ID
- >=2 AK8 jets, pT>250 GeV, central, m_SD > 40 GeV (H(bb) and W hadronic candidates)
- Leading ParticleNet Xbb MD picked first as the **H(bb) candidate** - Leading ParticleNet W MD picked as the **V hadronic candidate** among others
- **VBS jets** selected from the AK4 collection - Take pair with max p (energy) in each hemisphere, in case there are no jets with positive and negative η -> take max |Δηjj|
- Veto events with a tight b-tagged AK4 - if there is an AK4 loose b-tagged jet -> compute m(lb)
- ST>1000 GeV

$$S_{\mathrm{T}} = p_{T,\ell} + p_{T,\mathrm{H(b\bar{b})}} + p_{T,\mathrm{V(qq)}} + p_{T,miss}$$

Semileptonic channel

- As in the all-hadronic channel, we train a **DNN which is by construction orthogonal to the second ABCD arm**
- The ABCD arm is a **BDT trained using VBS jets inputs** (“VBS BDT”)
  - Decorrelation checked in background simulation after training
- As in the all-hadronic channel **multidimensional scan** is run to optimize the signal region and define consistent ABCD regions
  - Optimal SR with tighter cuts also on Xbb and Xqq scores
  - B,C,D regions defined by inverting DNN and BDT selections
- A region background predicted as **A = B*C/D** in data
  - Closure tests in MC and data sidebands
  - Statistical uncertainty of **inferred by the fit from windows on the B,C,D data yields**
  - Systematic uncertainty of **35% from closure** (average closure bias)

Region	data yield	prediction
region A	-	0.18
region B	61	
region C	3	
region D	1039	

DNN inputs

- $H(b\bar{b})$ candidate particleNet regressed mass
- $H(b\bar{b})$ candidate p_T
- $V(qq)$ candidate particleNet regressed mass
- $V(qq)$ candidate p_T
- Lepton p_T
- $m_{\ell,b}$
- MET (or $p_{T,miss}$).

VBS BDT inputs

- $\Delta\eta_{jj}$
- m_{jj}
- p_T for the first VBS jet
- η for the first VBS jet
- p_T for the second VBS jet
- η for the second VBS jet

SR definition

- $H(b\bar{b})$ score > 0.5
- $V(qq)$ score > 0.7
- DNN > 0.9
- VBS BDT > 0.82.

Dileptonic channel - OS WW

- Single lepton datasets/triggers
- Event pre-selection in table
- **BDT is trained** as the main event discriminator, using “central” event features (without VBF characteristics)
- BDT output score used with VBF M_{jj} and $|\Delta\eta|_{jj}$ to define signal and control regions

OS WW Event Selection	
Preselection	HLT & Flag filters Exactly 2 leptons that pass **tight** ttH id No extra leptons that pass **veto** ttH id ≥ 1 AK8 Jet ≥ 2 AK4 Jets
Lepton Pair	Opposite charge dR > 0.5 Z Veto on $M_{\ell\ell}$ (for same flavor pairs) P_T Cuts all above HLT thresholds
Higgs AK8 Jet	p_T > 250 GeV Leading ParticleNet Xbb MD Score ParticleNet regressed mass 70 < Mass < 160
b Jet Veto	Veto event with AK4 jets that pass medium deepJet B-Tagging WP Jets must not overlap with Higgs AK8
VBF AK4 Jets	AK4 Jet pair with highest |dη|
MET	MET > 100 GeV
S_T	S_T > 500 GeV

Dileptonic channel - OS WW

- Profiles of M_{jj} vs BDT and $|\Delta\eta|_{jj}$ vs BDT show no signs of correlation
- **A multi-dimensional scan** is run to optimize the SR in M_{jj} $|\Delta\eta|_{jj}$ and BDT score, alongside Higgs AK8 ParticleNet Xbb Score
  - Optimized asymptotic significance considering only MC
- Check closure in data by further cutting in control region (D)
- M_{jj} and $|\Delta\eta_{jj}|$ inverted separately
  - Take more conservative option as systematic
  - Systematic uncertainty of 17%

BDT inputs

Higgs AK8	pT, eta, softdrop mass
Lepton	pT, eta
Lepton Pair	Flavor, |dEta|, dR, mll
	MET, ST

SR definition

Variable	Cut Value
M_{jj}	760 GeV
$\|\Delta\eta\|_{jj}$	4.9
BDT Score	0.85
Higgs AK8 Hbb Score	0.7

Region	Bkg MC	Sig MC	Data
A	0.125 ± 0.011	0.309 ± 0.008	-
B	12.39 ± 0.221	0.16 ± 0.006	$10^{+4.27}_{-3.11}$
C	1.98 ± 0.073	0.098 ± 0.005	$2^{+2.64}_{-1.29}$
D	178.4 ± 4.89	0.073 ± 0.004	$179^{+14.4}_{-13.4}$
A Predicted	0.137 ± 0.0067	-	0.112 ± 0.087

Dileptonic channel - OS Z

- Single lepton and Double lepton datasets/triggers
- Event pre-selection in table
- **BDT** with central features is used as main event discriminator as in OS WW (without VBF characteristics)
- Again, BDT output score core is used with VBF M_{jj} and $|\Delta\eta_{jj}|$ to define signal and control regions

OS Z Event Selection	
Preselection	Single and double e/mu HLT and flag filters Leptons passing tight ttH id = 2 No extra leptons that pass the veto ttH id ≥ 1 AK8 jet ≥ 2 AK4 Jets
Leptonically Decaying Z Selection	Two oppositely charged lepton candidates: Lead $p_T \geq$ 25GeV (19GeV for muons) Sublead $p_T \geq$ 18GeV (12GeV) $\|M_{ll} - M_Z\| <$ 5GeV
Higgs AK8 Selection	$p_T >$ 250GeV PN Regressed Mass 70 < Mass < 160 Highest ParticleNet score in event (>0.2)
Z/W AK8 Selection	$p_T >$ 200GeV Highest ParticleNet score in event (>0.6)
B Jet Veto	Veto events with AK4 jets that both pass the medium deepJet B-Tagging WP and don't overlap with Higgs AK8 Jet
VBF AK4 Selection	$\|\Delta\eta\| >$ 2.0 (and highest $\|\Delta\eta\|$ pair chosen) $M_{jj} >$ 200GeV
H and Z Object Cuts	$S_T >$ 500GeV Invariant mass of reconstructed H and Z objects > 500GeV

Dileptonic channel - OS Z

- Profiles of M_{jj} vs BDT and $|\Delta\eta|_{jj}$ vs BDT show no signs of correlation
- **A 3 variable scan is run to optimize the SR in M_{jj} $|\Delta\eta|_{jj}$ and BDT score**
  - Optimized SR: M_{jj}> 750GeV && $|\Delta\eta|$>4.0 and BDT > 0.9
  -
- Check closure in data by further cutting in control region (D)
- M_{jj} and $|\Delta\eta_{jj}|$ inverted separately
  - Take more conservative option as systematic
  - Systematic uncertainty of 72%

BDT inputs

- p_T and η of Higgs and Z candidate jets'
- p_T, η, and SIP3D of leading and sub-leading leptons
- Invariant mass of lepton pair
- Sum of relative isolations of lepton pair
- Vector invariant mass of all reconstructed Z and Higgs Objects
- S_T

ABCD Results

Region	Data	MC Signal	MC Background
D	$17^{+5.2}_{-4.1}$	0.018 ± 0.0015	21.3 ± 10.9
C	$5^{+3.4}_{-2.2}$	0.131 ± 0.0039	-0.49 ± 3.55
B	$1^{+2.3}_{-0.83}$	0.020 ± 0.0016	0.22 ± 0.013
A	-	0.224 ± 0.0051	0.050 ± 0.0063
A Predicted	$0.29^{+0.71}_{-0.28}$	-	-0.005 ± 0.037