

HIGGS SELF-COUPLING AT CMS

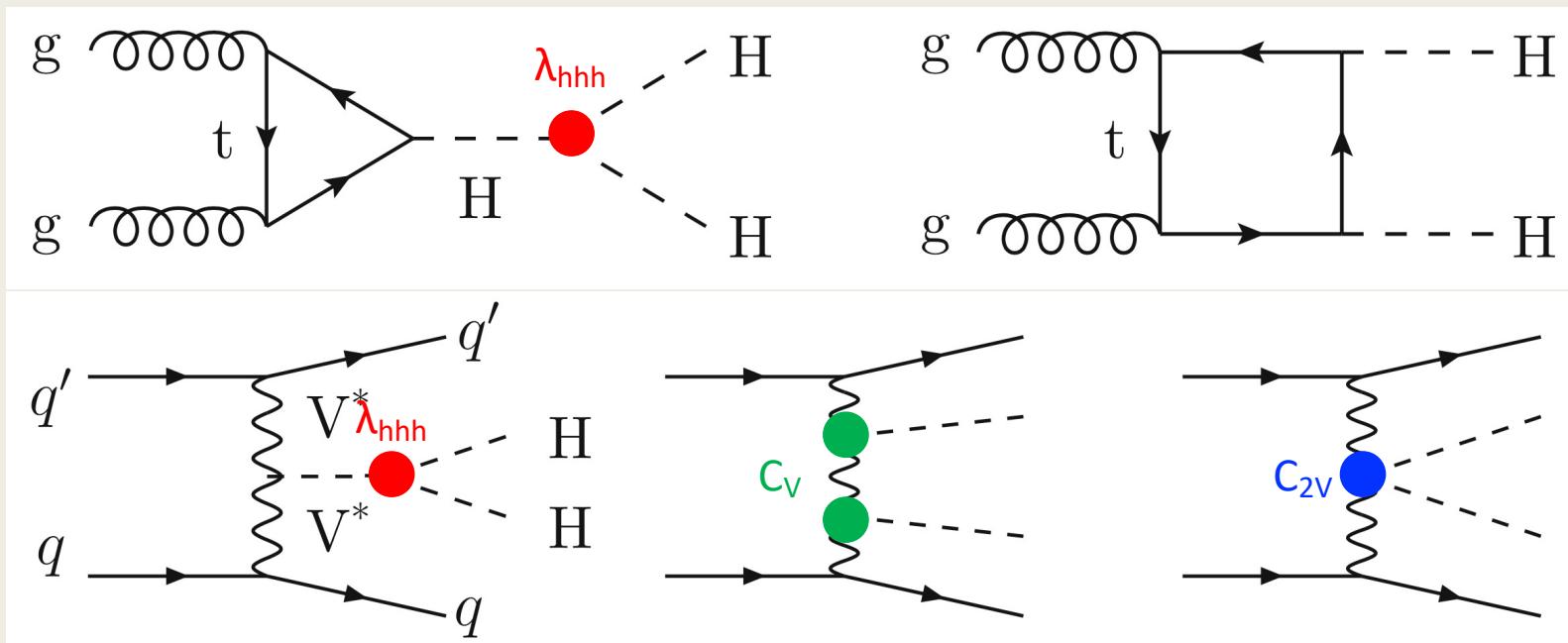
Davide Zuolo

INFN Milano - Bicocca

On behalf of the CMS collaboration

Introduction

- The measurement of $\sigma(HH)$ is the best way to extract the Higgs self-coupling λ_{HHH}
- The production cross section of the single Higgs processes also depends on λ_{HHH} , as a result of [NLO electroweak corrections](#)
- Shape of the Higgs potential defined by m_H ([measured with high precision](#)) and the vacuum expectation value (v , [calculated with high precision](#)) → need experimental measurement of λ_{HHH} to test model prediction: $\lambda_{HHH} = \frac{m_H^2}{2v^2}$

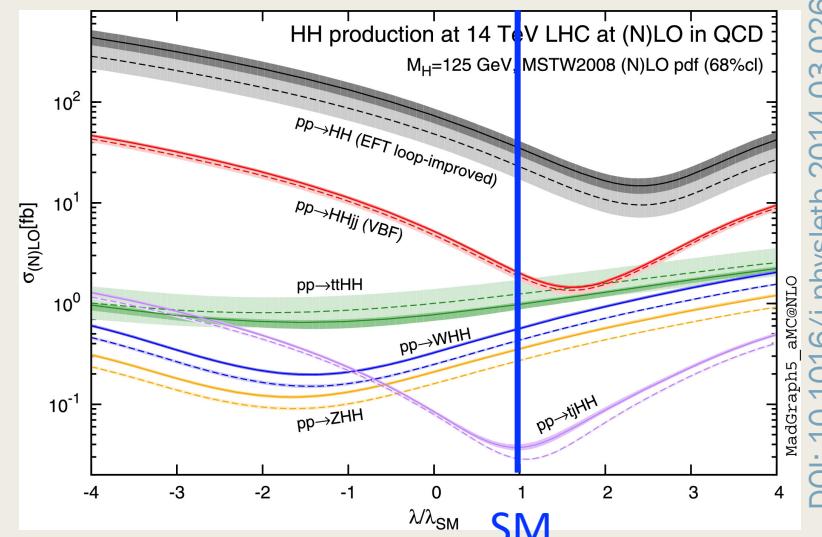


Gluon-Gluon Fusion (GGF):
Destructive interference
between the two diagrams
leads to a **small cross
section (31.05 fb)**

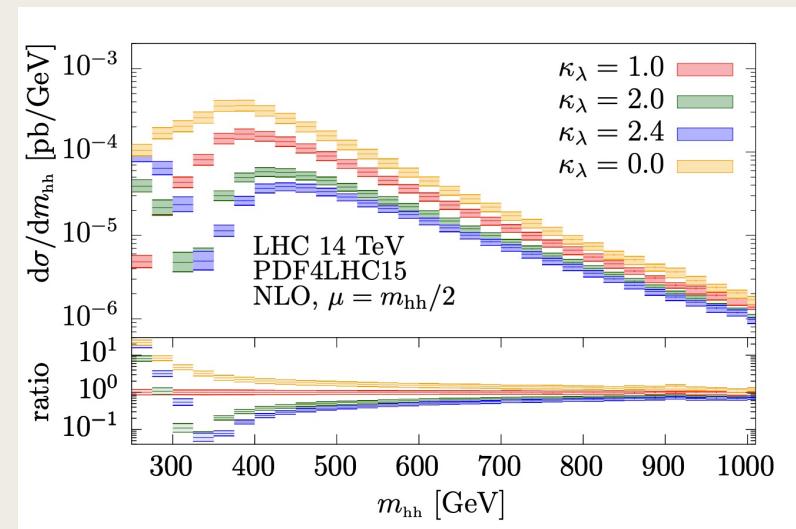
Vector Boson Fusion (VBF):
Cross section: 1.726 fb
**Unique handle to probe
VVHH coupling (C_{2V})**

SM coupling modifiers

- Anomalous values of the SM couplings affect both the cross section and the kinematics of HH production.
- They are modelled through coupling modifiers
 - $k_\lambda = \lambda_{\text{HHH}}/\lambda_{\text{HHH,SM}}$
 - $k_{2V} = C_{2V}/C_{2V,\text{SM}}$
 - $k_V = C_V/C_{V,\text{SM}}$



DOI: 10.1016/j.physletb.2014.03.026



DOI: 10.1007/JHEP06(2019)066

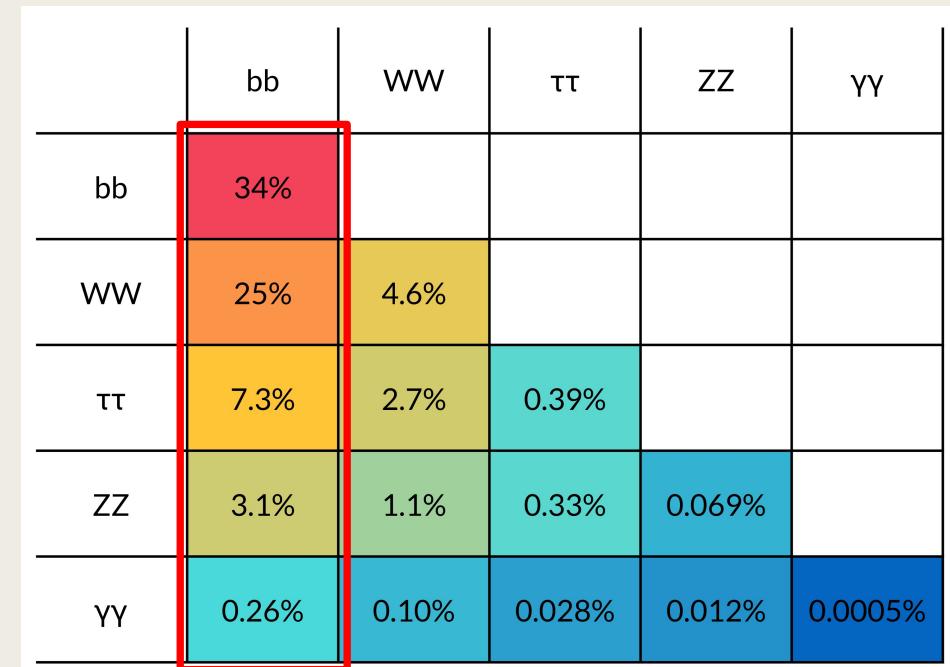
Outline

This talk: analyses made public in 2021 and 2022 using
2016+2017+2018 LHC Run II dataset (138 fb^{-1})

- GGF + VBF $\text{HH} \rightarrow \text{bbbb}$ resolved ([CMS-PAS-HIG-20-005](#))
- GGF + VBF $\text{HH} \rightarrow \text{bbbb}$ boosted ([CMS-PAS-B2G-22-003](#))
- $\text{HH} \rightarrow \text{MultiLepton}$ ([CMS-PAS-HIG-21-002](#))
- $\text{HH} \rightarrow \text{bb}\tau\tau$ ([CMS-PAS-HIG-20-010](#))

Older Analysis

- $\text{HH} \rightarrow \text{bb}\gamma\gamma$ ([10.1007/JHEP03\(2021\)257](#))
- $\text{HH} \rightarrow \text{bbZZ}$ ([HIG-20-004](#))



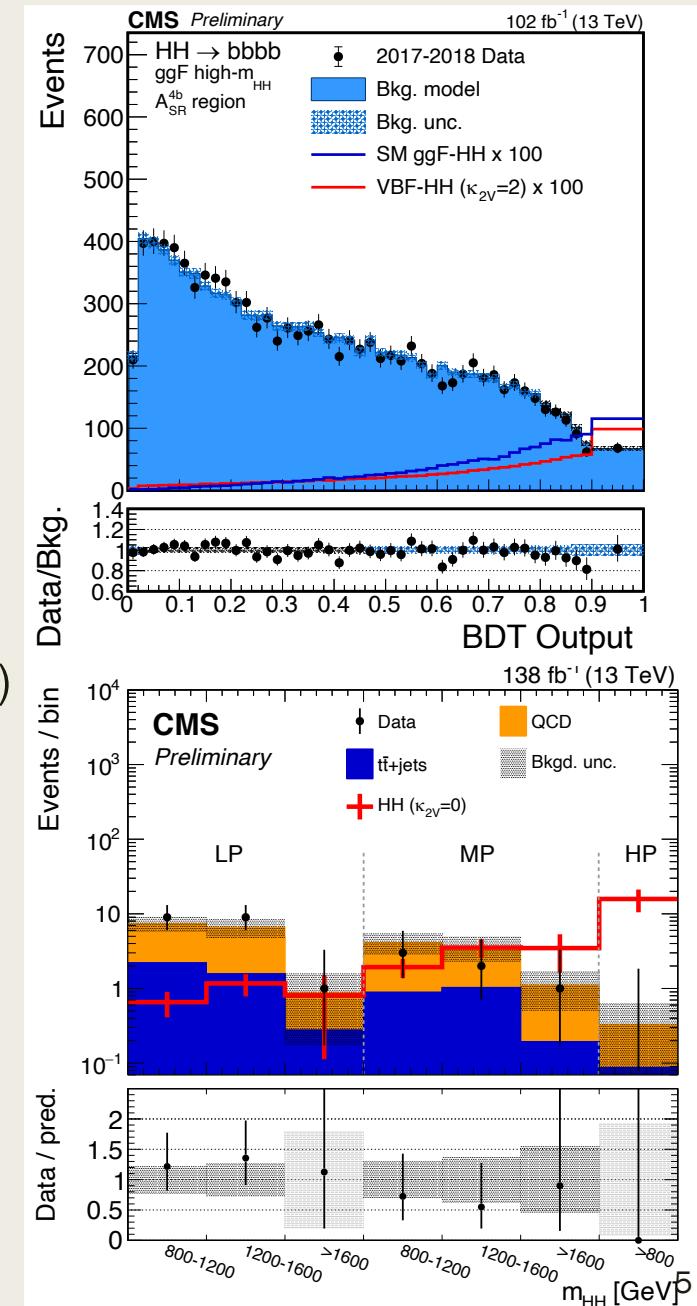
bbbb final state

Resolved

- Reconstruct $H \rightarrow bb$ decays from **AK4 (small radius) jets**
- b-jets tagged using DNN-based [deepJet](#) algorithm
- 4 b-jets \rightarrow three possible pairings \rightarrow large combinatorial
- “GGF killer” BDT to separate GGF and VBF events

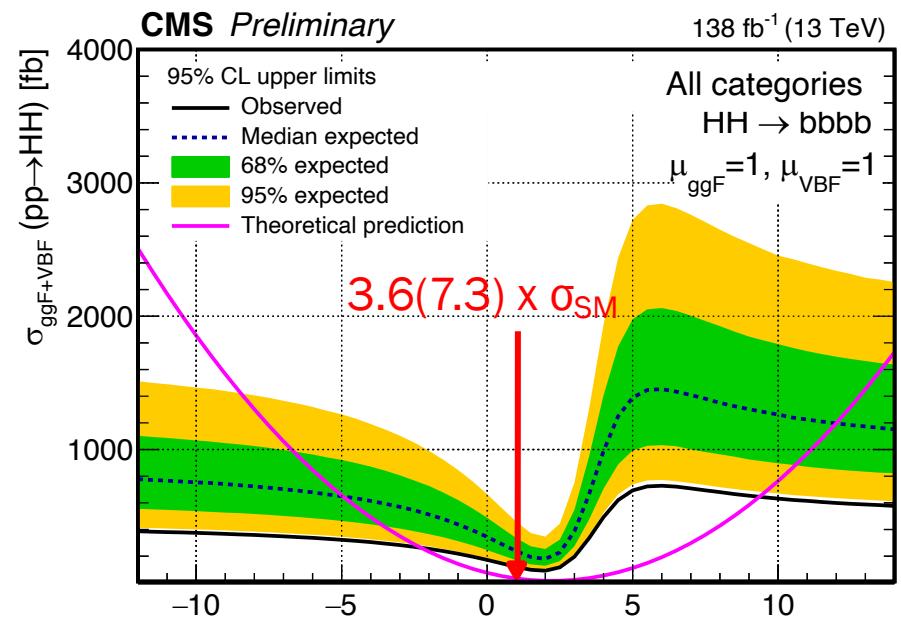
Boosted (see [talk](#) on boosted algorithms for searches by C. Li)

- Reconstruct $H \rightarrow bb$ decays as **AK8 (large radius) jets**
- Use AK8 jet substructure to identify $H \rightarrow bb$ decays with [ParticleNet](#) algorithm [Graph Neural Network - [1](#),[2](#)]
- MD = “Mass Decorrelated” \rightarrow No sign of sculpting of jet mass (crucial for background estimate!)
- Take the two highest p_T AK8 jets as H_1 and H_2

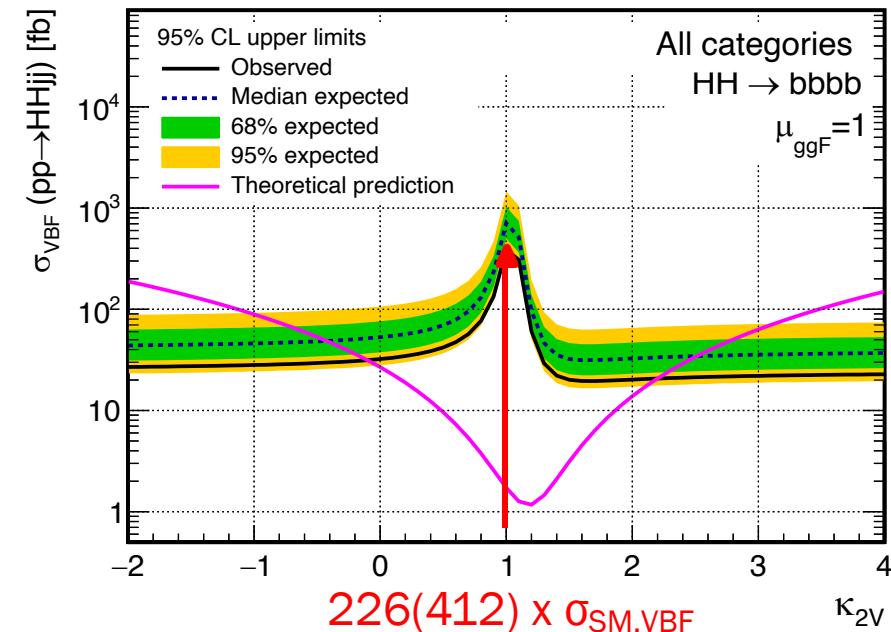


GGF + VBF $\text{HH} \rightarrow \text{bbbb}$ resolved

- b-jet pairs ordered according to $D = \frac{|m_{H_1} - km_{H_2}|}{1+k^2}$
 \rightarrow correct jet pairing ranging between 82 – 96%
(91 – 98%) for the different couplings in ggF
(VBF) signal events
- VBF production mode signature: 2 small radius jets with high m_{jj} and large $\Delta\eta$
- events categorized according to GGF-killer BDT score \rightarrow GGF, VBF-SM and VBF-BSM enriched categories
- large contamination from QCD multijet production and $t\bar{t} + \text{jets}$ \rightarrow Fully data driven background estimation



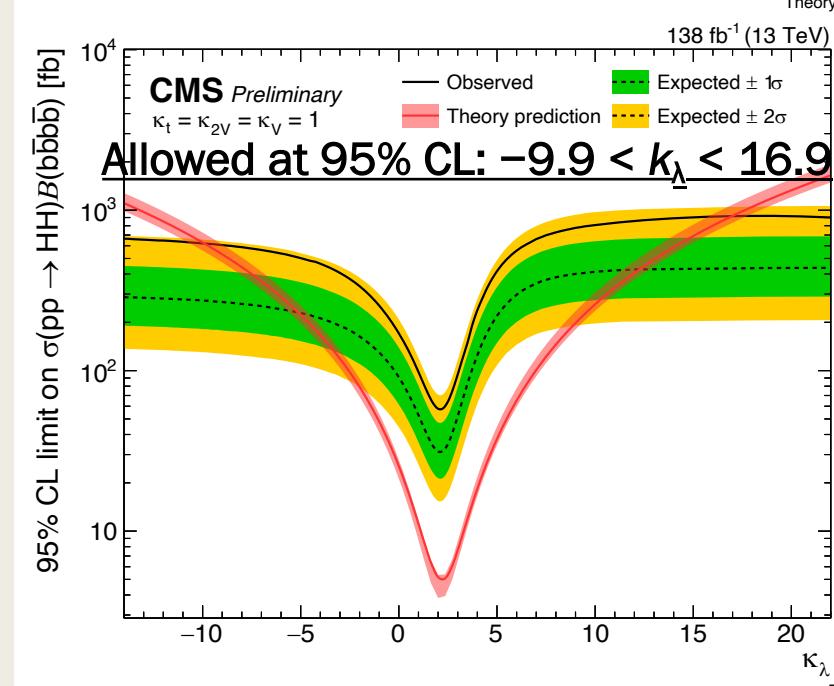
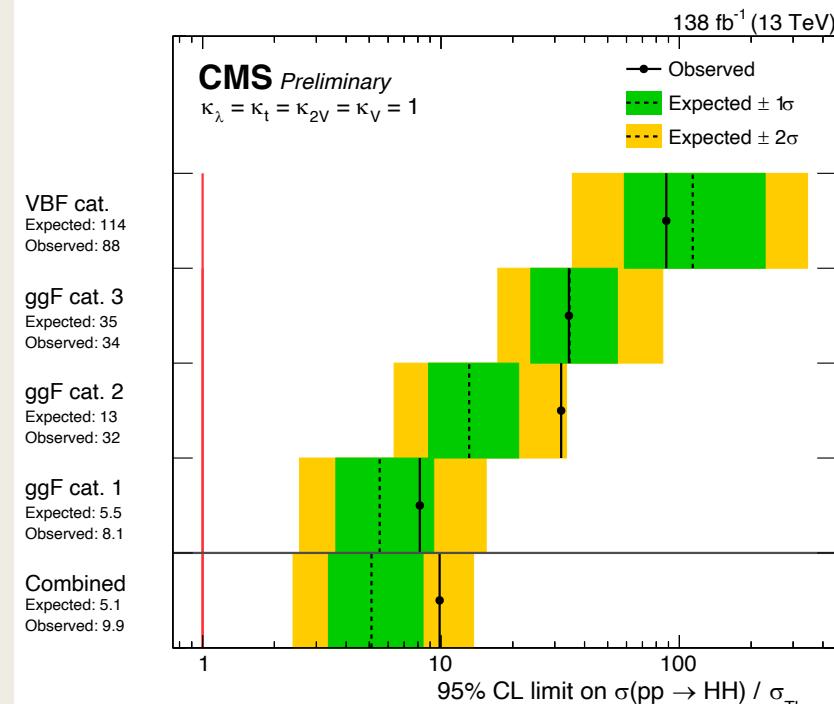
Allowed at 95% CL: $-2.3 < \kappa_\lambda < 9.4$



Allowed at 95% CL: $-0.1 < \kappa_{2V} < 2.2$

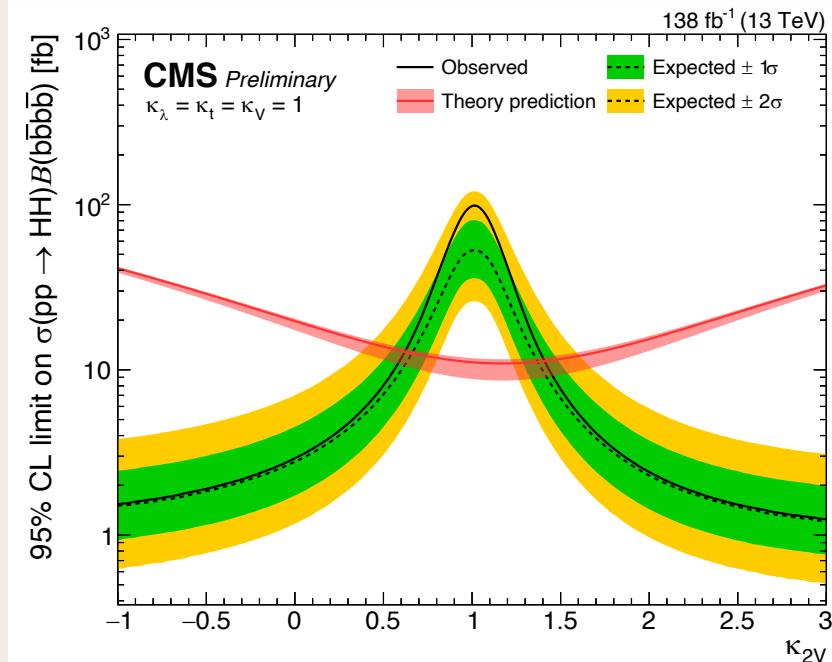
GGF + VBF $\text{HH} \rightarrow \text{bbbb}$ boosted

- Reconstruct Higgs candidate mass with [ParticleNet-based regression algorithm](#)
- VBF signal
 - *three purity categories based on ParticleNet large radius jets score*
- GGF signal
 - *pick events not passing VBF selections*
 - *BDT trained to discriminate between the HH signal and QCD multijet or tt background processes*
 - *three purity categories based on BDT score*

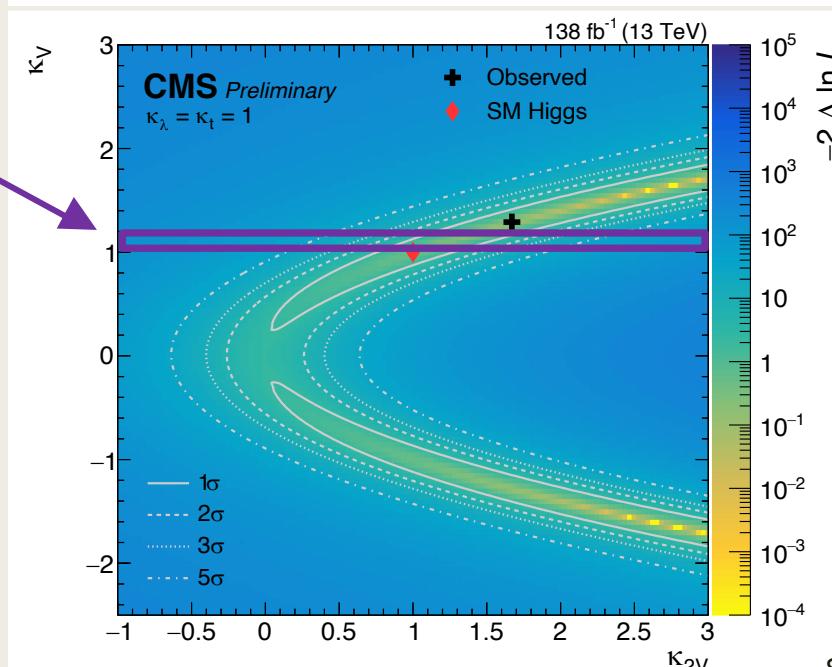


GGF + VBF $\text{HH} \rightarrow \text{bbbb}$ boosted

- the search excludes $\kappa_{2V} = 0$ for the first time with a significance of 6.3 standard deviations when $\kappa_\lambda = \kappa_t = \kappa_V = 1$
- When considering the κ_V [measured value](#) and its uncertainty, coming mainly VH measurements, the $\kappa_{2V} = 0$ hypothesis remains strongly disfavoured

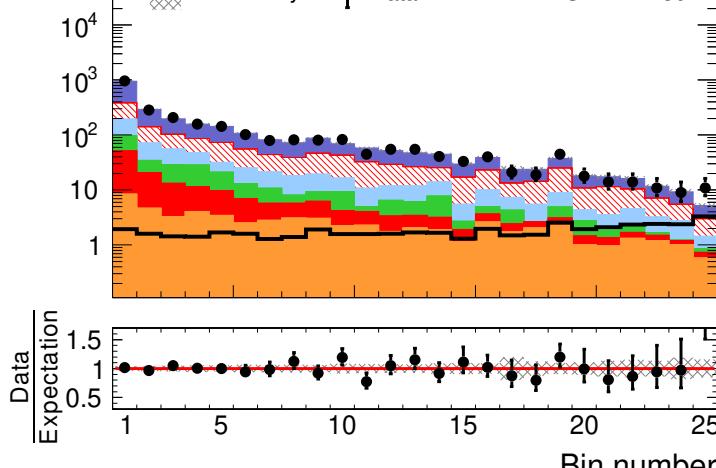
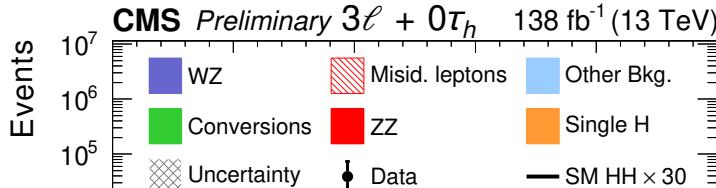
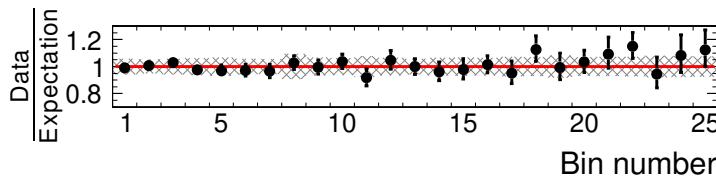
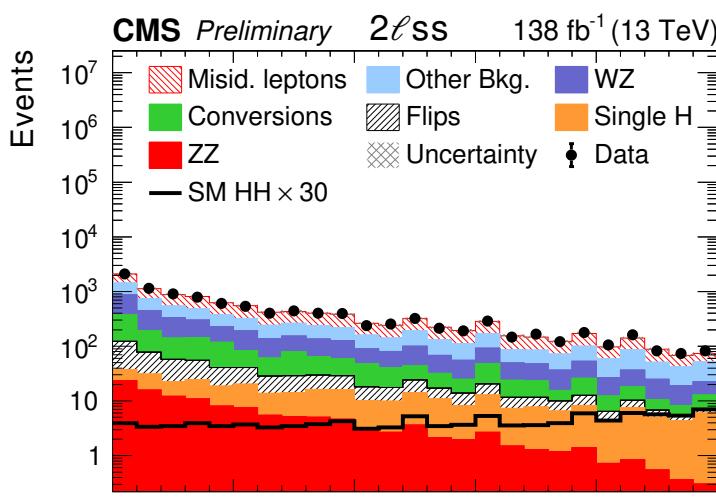


Allowed at 95% CL: $0.62 < \kappa_{2V} < 1.41$



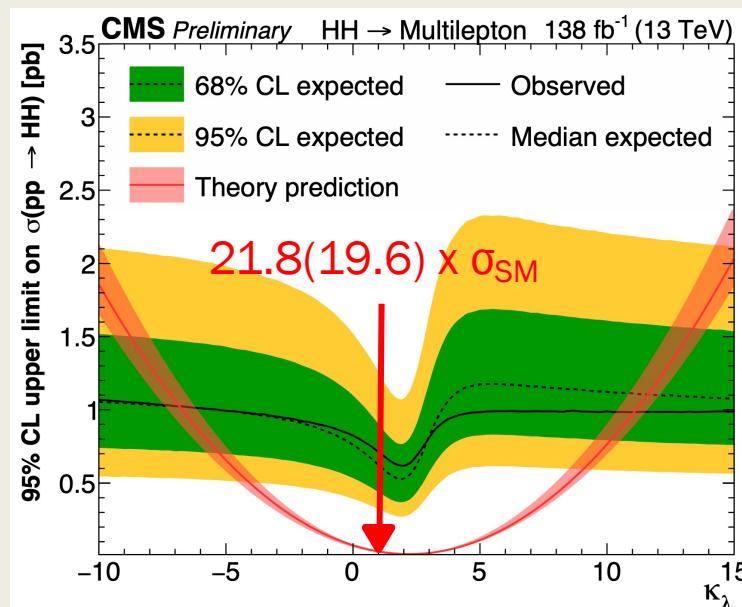
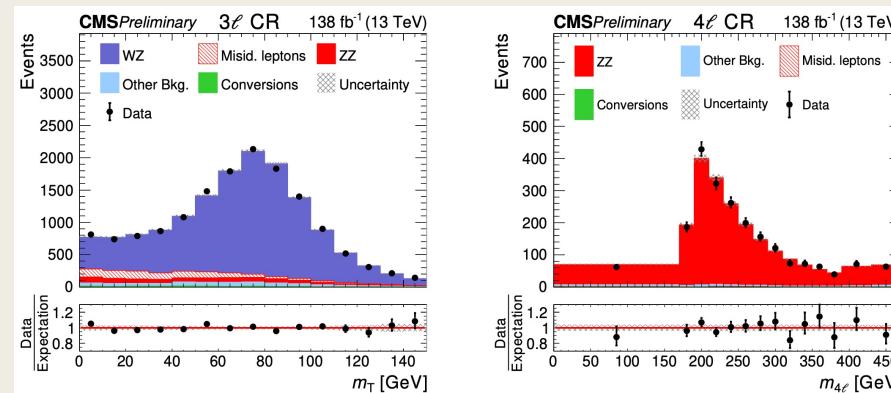
HH → MultiLepton - 1

- Target decay modes: $\text{HH} \rightarrow \text{WWWW} / \text{WW}\tau\tau / \tau\tau\tau\tau$, covering $\sim 7.7\%$ of the HH decays
- 7 search categories, distinguished by the number of reconstructed electrons or muons (l) and tau decaying to hadrons (τ_h)
 - $4l$, $3l+0\tau_h$, $2lss+0/1\tau_h$,
 - $3l+1\tau_h$, $1l+3\tau_h$, $2l+2\tau_h$, $0l+4\tau_h$.
- Main background sources:
 - *misidentified leptons or τ_h* → data driven
 - *WZ and ZZ* → from MC
- BDT classifiers trained for each of the seven search categories → Higgs couplings as inputs

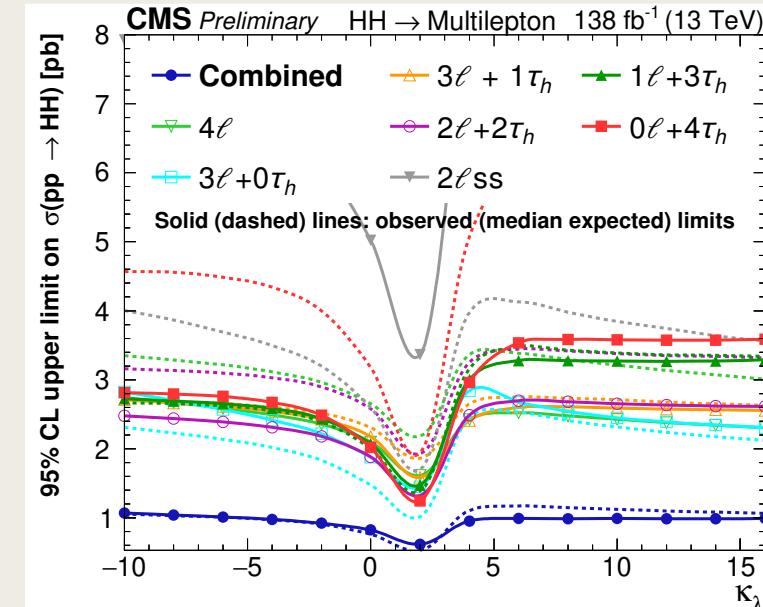


HH → MultiLepton - 2

3I WZ and 4I ZZ control regions included in the fit for irreducible bkg estimation

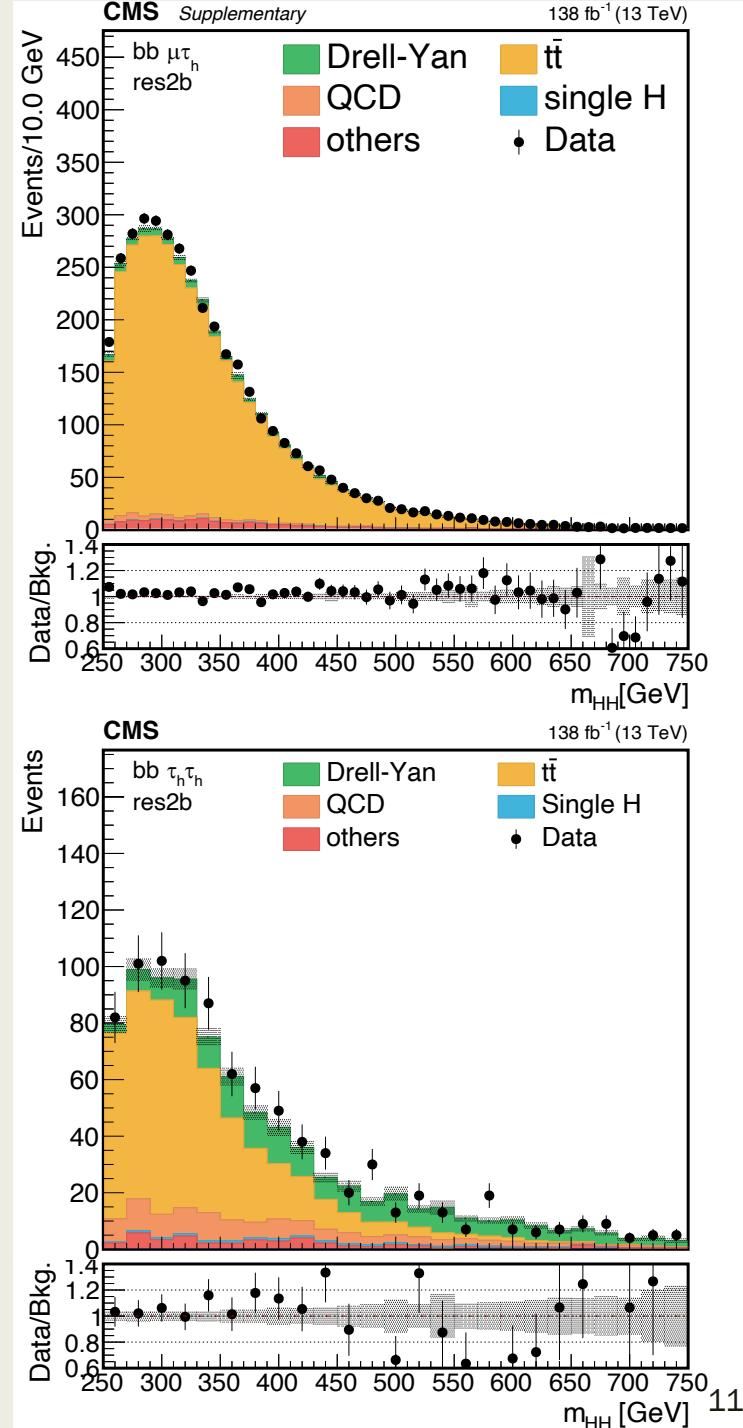


Allowed at 95% CL: $-7.0 < \kappa_\lambda < 11.2$

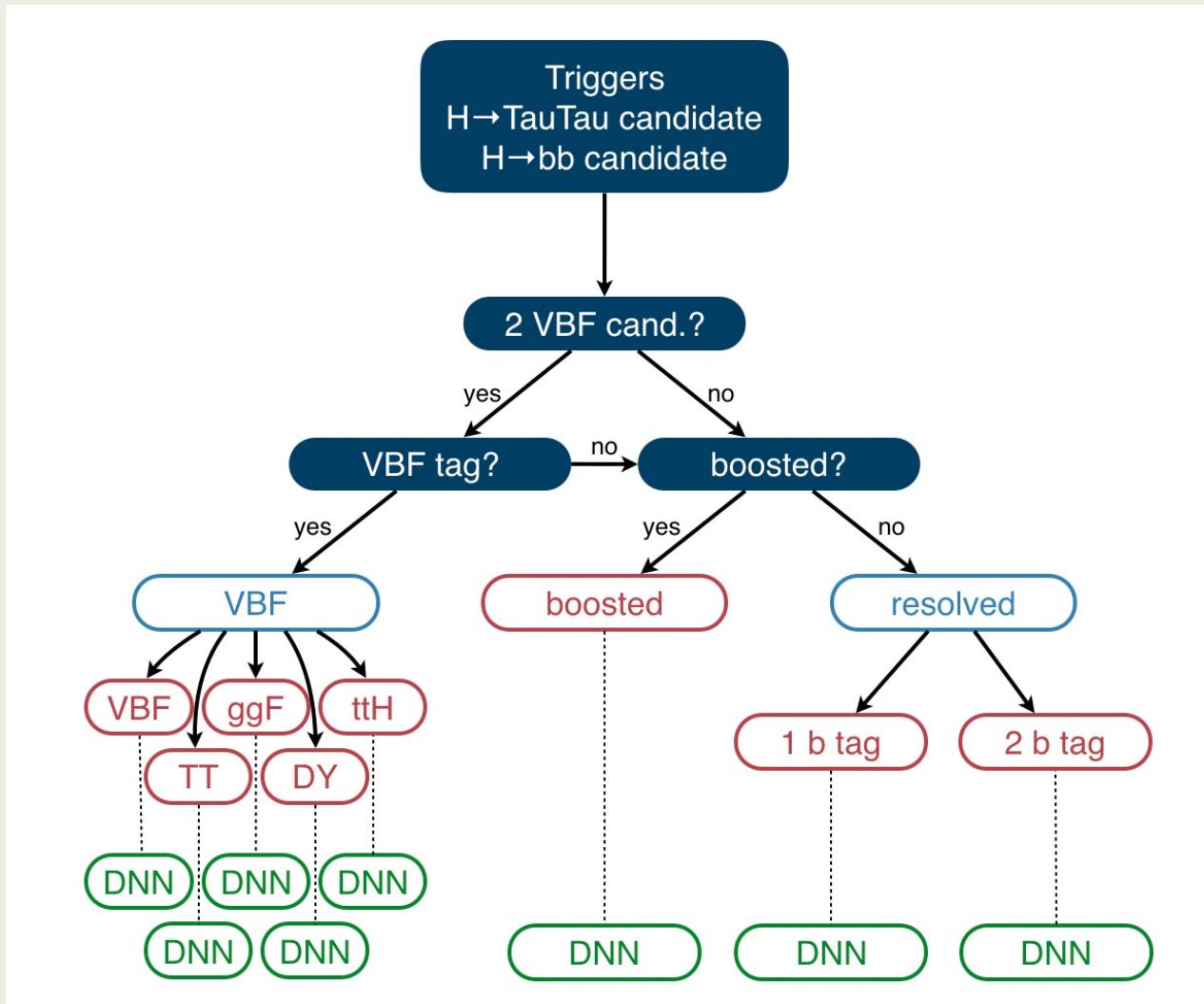


$\text{HH} \rightarrow \text{bb}\tau\tau - 1$

- Three final states of the tau lepton pair decay considered: $\tau_e\tau_h$, $\tau_\mu\tau_h$ (semi-leptonic) $\tau_h\tau_h$ (hadronic)
 - *fully leptonic decays hard to discriminate from DY background*
- Main backgrounds:
 - *$t\bar{t}$ in semi-leptonic channels*
 - *DY and QCD multi-jet in hadronic channel*
 - *QCD estimation fully data-driven*
 - *DY and $t\bar{t}$ normalization corrected from CRs*
- Several DNNs employed:
 - *to identify b-jets from $\text{HH} \rightarrow \text{bb}\tau\tau$ events (HHBTAG)*
 - *to improve sig-bkg separation in the VBF category and constrain bkg unc (Multi-classification)*
 - *as final sig-bkg discriminant*



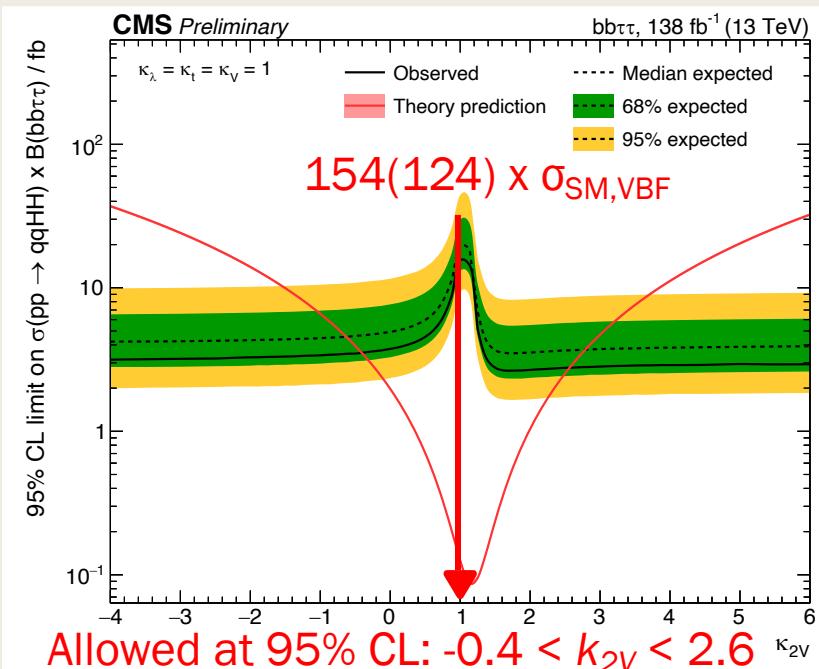
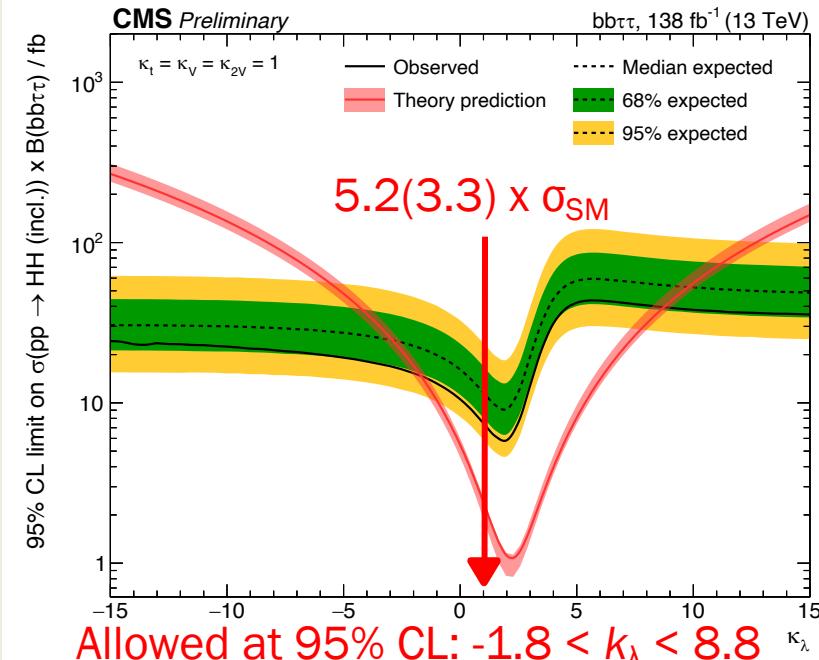
$\text{HH} \rightarrow \text{bb}\tau\tau - 2$



- require one τ_h in each event
- form $\tau_e\tau_h$, $\tau_\mu\tau_h$ or $\tau_h\tau_h$ pairs
- veto additional isolated muons or electrons
- require 2 jets within tracker acceptance (b-jets candidates)
- priority given to **VBF topology**
- **boosted** (1 large-radius jet with two small-radius sub-jets) and **resolved** (2 small radius -jets) regimes explored

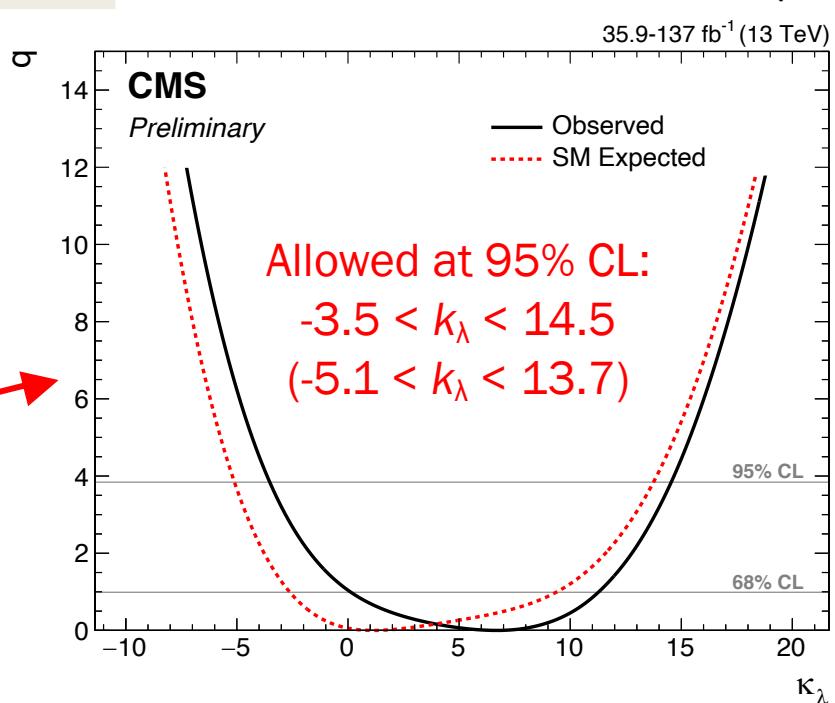
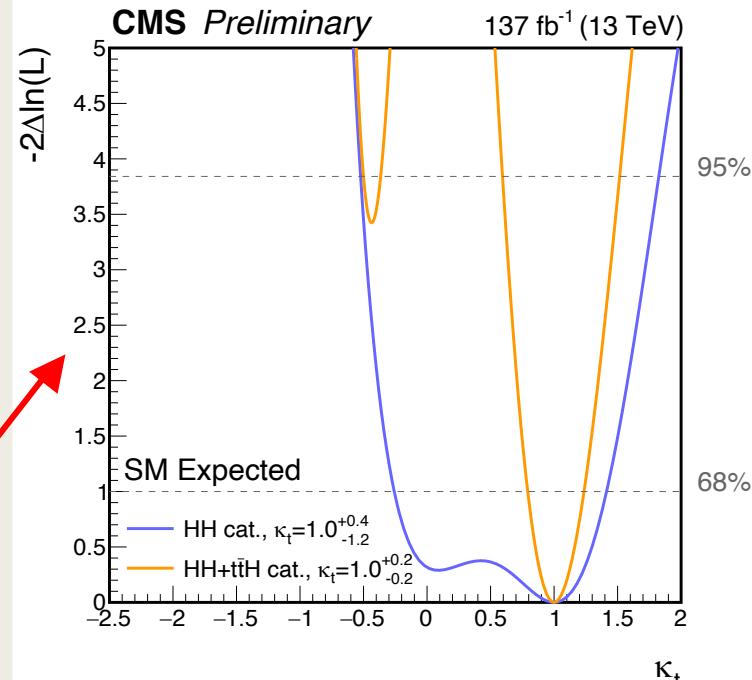
$\text{HH} \rightarrow \text{bb}\tau\tau$ - 3

- An elliptical mass cut on $m_{\tau\tau}$ and m_{bb} is applied to remove outlying background events in regions where no signal is expected prior to DNN prediction
 - *optimized requiring minimal background acceptance for 90% signal efficiency*
- Kinematic fit for HH mass reconstruction
 - *kinFit mass and chi2 amongst the most important features for DNN training*
- Strongest constraint on $\text{pp} \rightarrow \text{VBF-HH}$ cross section measured so far



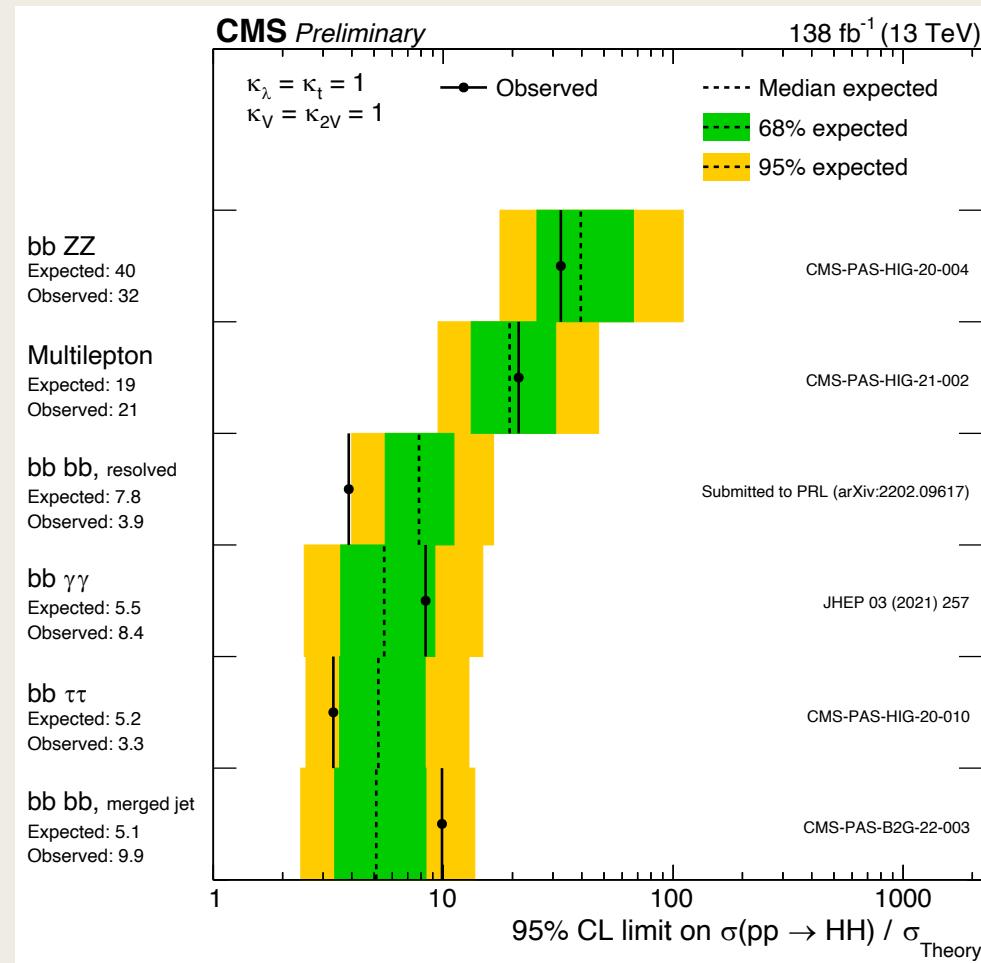
Constraints from single Higgs

- The production cross section of the single Higgs processes also depends on k_λ , as a result of [NLO electroweak corrections](#)
- In the case of anomalous values of k_λ , the process with the largest modification of the cross section is ttH
- Additional orthogonal categories targeting the ttH process are included in the bb $\gamma\gamma$ analysis
- Sensitivity to H-t yukawa coupling strongly enhanced
- A different approach, based on production and decay modes scaling, has been used in the [partial Run-2 single H combination](#)



Conclusions

- Searches for HH production using the LHC Run 2 dataset have run at full swing in CMS during 2020 and 2021
- The three most sensitive analyses (bbbb, $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$) have been made public → each of them sees **factor 2 improvement compared to 2016 combination**
- Many interesting results from the investigation of boosted final states
- First studies of Higgs self-coupling from single-Higgs processes performed
- Many BSM scenarios conceivable for interpreting results
 - *additional BSM couplings (EFT contact interactions/couplings: c_2 , c_g , c_{2g})*
 - *resonant production*
 - *more details in the talks of this session*



The bbbb resolved and bbbb boosted results are derived using a phase space with a minor overlap of signal events.

Additional material

Previous H \rightarrow bb ID algorithms ([PAS](#))

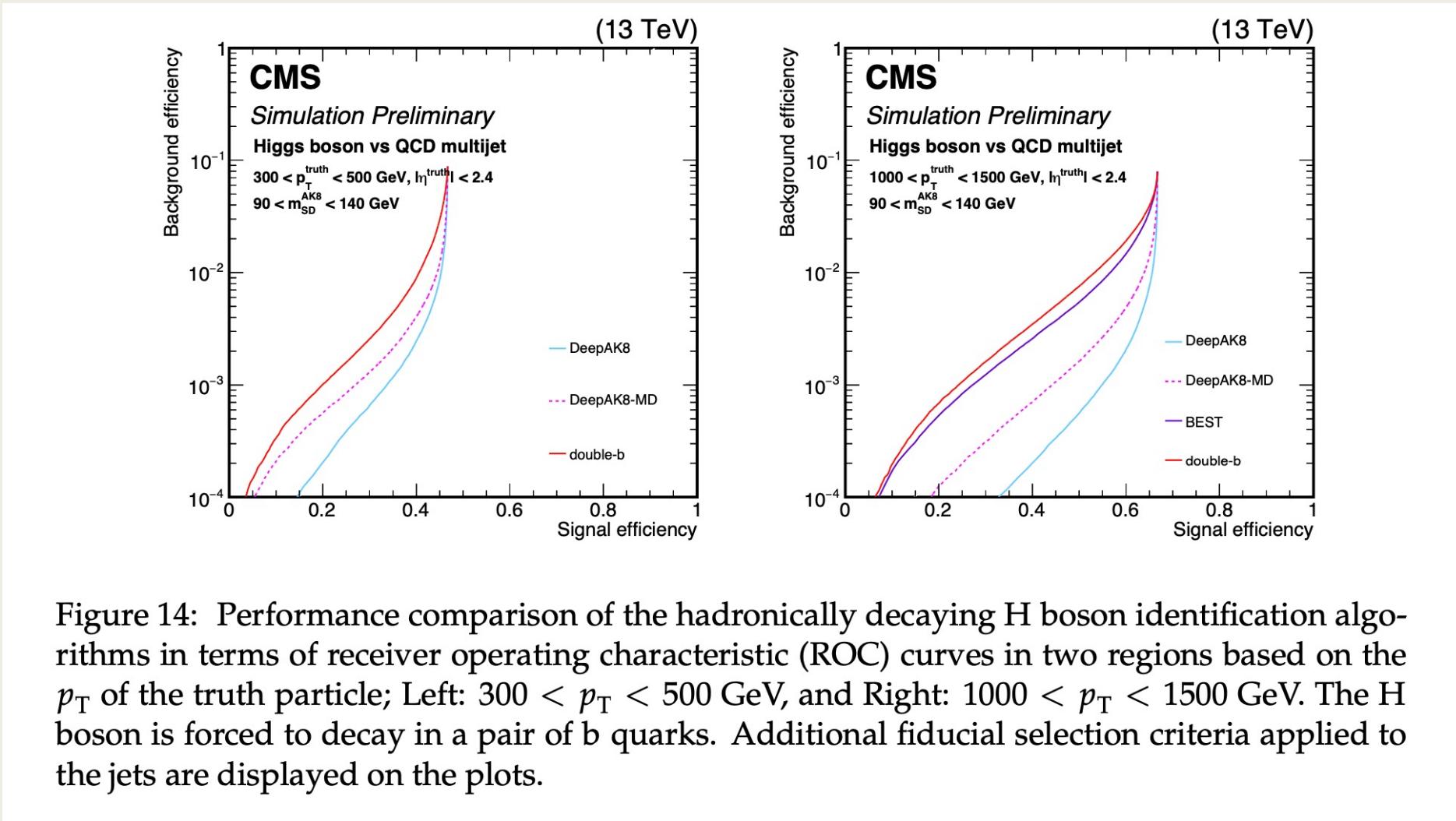


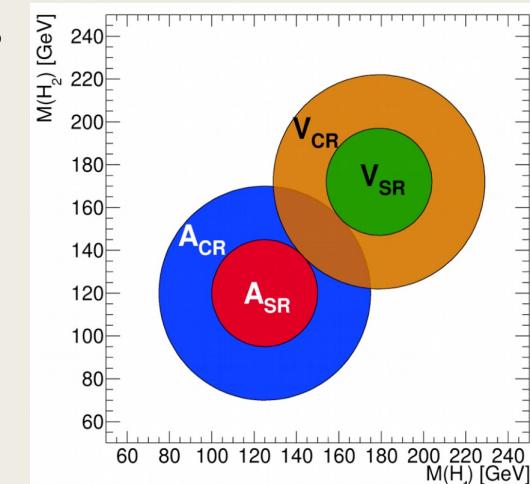
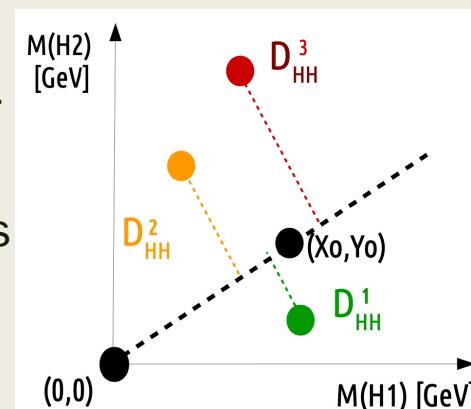
Figure 14: Performance comparison of the hadronically decaying H boson identification algorithms in terms of receiver operating characteristic (ROC) curves in two regions based on the p_T of the truth particle; Left: $300 < p_T < 500 \text{ GeV}$, and Right: $1000 < p_T < 1500 \text{ GeV}$. The H boson is forced to decay in a pair of b quarks. Additional fiducial selection criteria applied to the jets are displayed on the plots.

GGF + VBF HH → bbbb resolved - 1

- Trigger selections require the presence of at least four jets, three b-tagged jets, and a minimal jet momentum scalar sum (H_T)
- b-jet candidates: $P_T > 30\text{-}40$ GeV, central, deepJet medium WP, PUJetID, PFJetID
- pairings ordered according to $D = \frac{|m_{H_1} - km_{H_2}|}{1+k^2}$ → correct jet pairing ranging between 82 – 96% (91 – 98%) for the different couplings in ggF (VBF) signal events
- Reject events with one reconstructed muon or electron
- VBF-jet candidates (excluding b-jets) $P_T > 25$ GeV, $|\eta| < 4.7$, PUJetID, PFJetID
- VBF-jet pair selection: Two highest P_T jets with $\eta(j_1) \times \eta(j_2) < 0$

Background estimation is fully data-driven

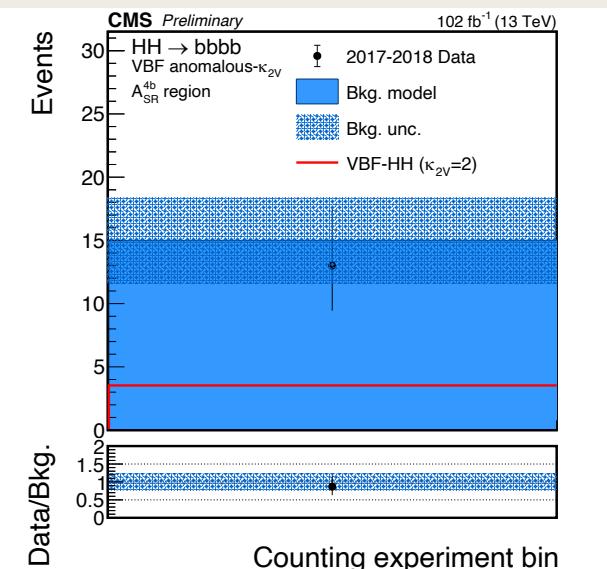
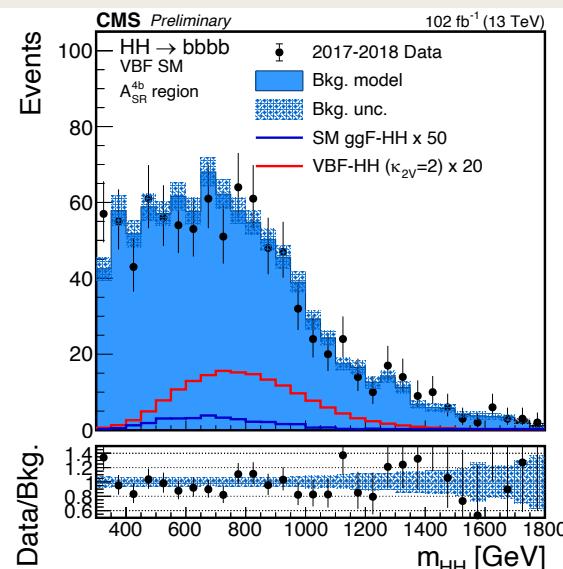
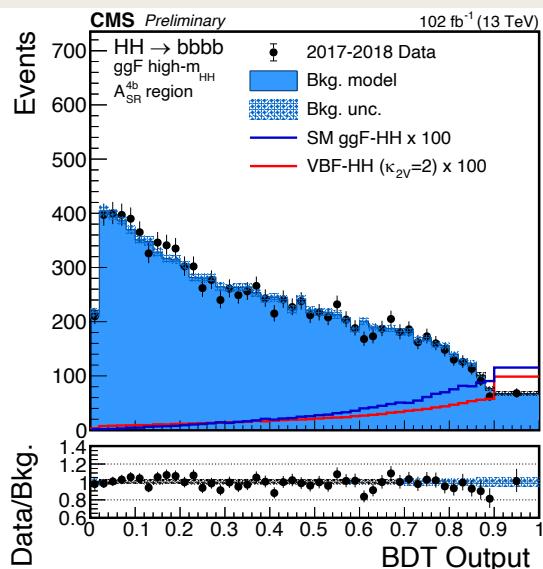
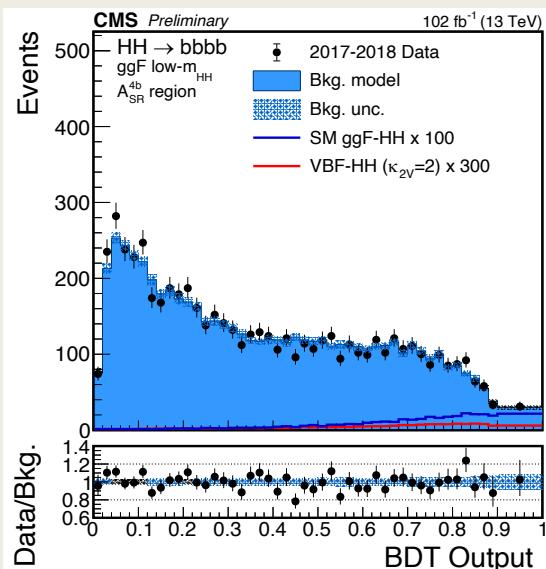
- Analysis (A) and Validation (V) regions
- ‘4b’ and ‘3b’ region (4^{th} jet btag score fails medium WP)
- BDT-based reweighting to correct for differences between the 3b and the 4b regions



GGF + VBF $\text{HH} \rightarrow \text{bbbb}$ resolved - 2

Gluon fusion categorization

- ggF cat1 or Low- m_{HH} : $m_{\text{HH}} < 450 \text{ GeV}$
- ggF cat2 or High- m_{HH} : $m_{\text{HH}} \geq 450 \text{ GeV}$
- Observable: BDT output distribution
 - SM ggF vs data-driven bkg model
 - Trained by category



Vector Boson Fusion categorization

- VBF cat1 or VBF-SM:
 - $0.5 \leq \text{ggfKiller} < 0.97$
 - Observable: m_{HH} distribution
- VBF cat2 or VBF-anomalous- κ_{2V} :
 - $0.97 \leq \text{ggfKiller} \leq 1.0$
 - Observable: Counting experiment

VBF HH → bbbb boosted - 1

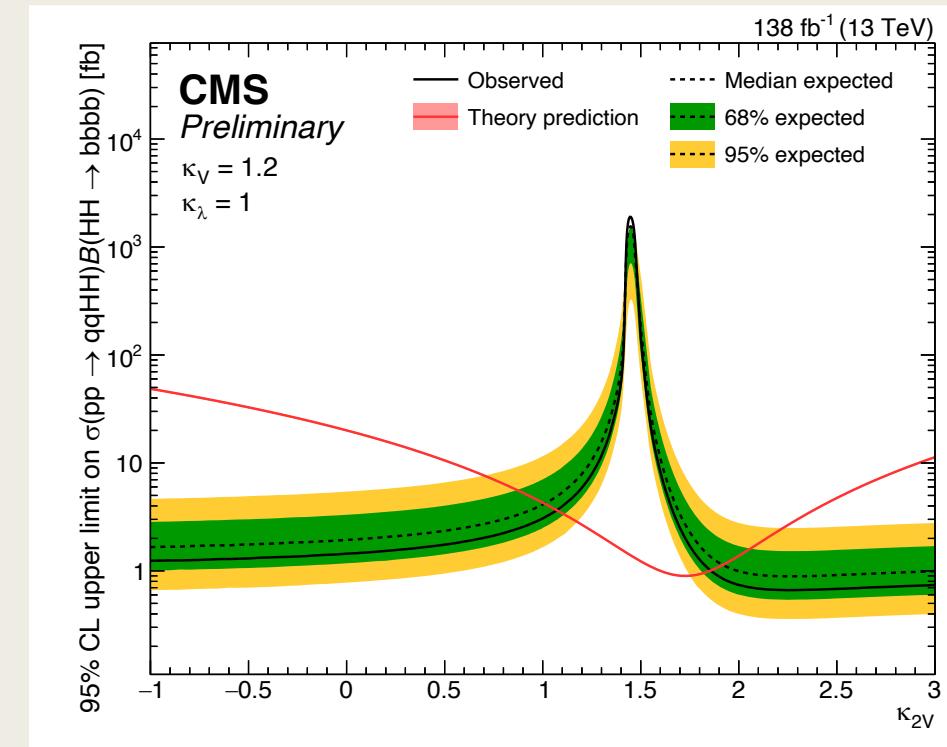
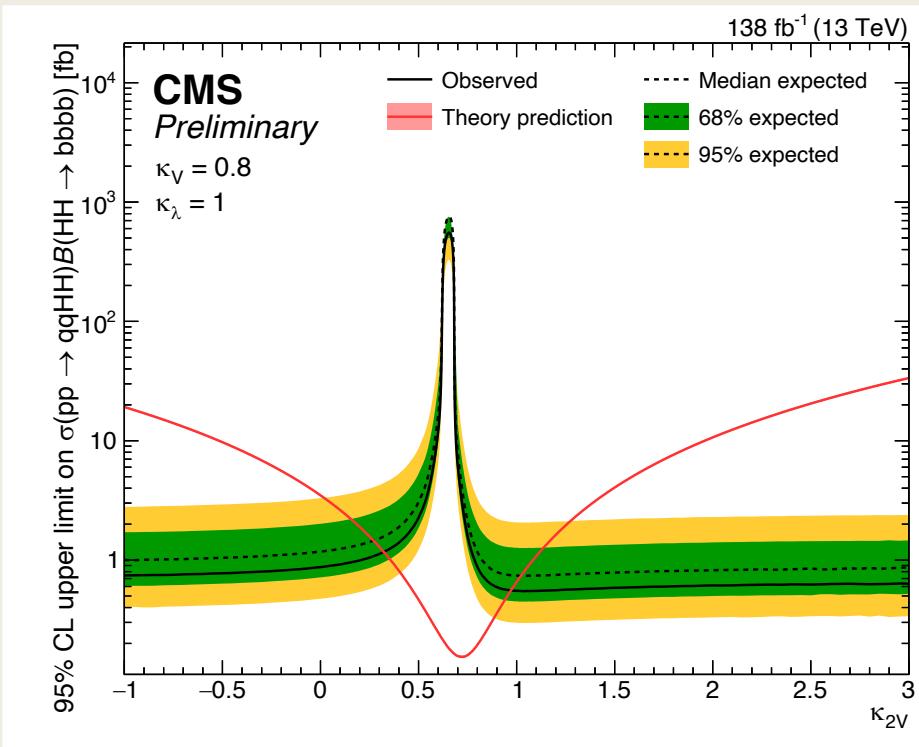
Trigger	Combination of H_T and single-jet triggers
Higgs boson candidates	≥ 2 large-radius jets with $ \eta < 2.4$ $p_T^{\text{lead}} > 500 \text{ GeV}$, $p_T^{\text{subl}} > 400 \text{ GeV}$ $\Delta\phi > 2.6$, $\Delta\eta < 2.0$
Lepton veto	$N_e = 0$, $N_\mu = 0$
$H \rightarrow bb$ identification with ParticleNet	Three exclusive search categories based on D_{bb} working points: high purity (HP), medium purity (MP) and low purity (LP)
VBF selections	≥ 2 small-radius jets with $p_T > 25 \text{ GeV}$, $ \eta < 4.7$ $m_{jj} > 500 \text{ GeV}$, $\Delta\eta_{jj} > 4.0$
Signal mass range	$110 < m^{\text{lead}} < 150 \text{ GeV}$, $100 < m^{\text{subl}} < 145 \text{ GeV}$

$$D_{bb} = \frac{P(X \rightarrow bb)}{P(X \rightarrow bb) + P(QCD)}$$

Background contamination very limited, tail of SM processes

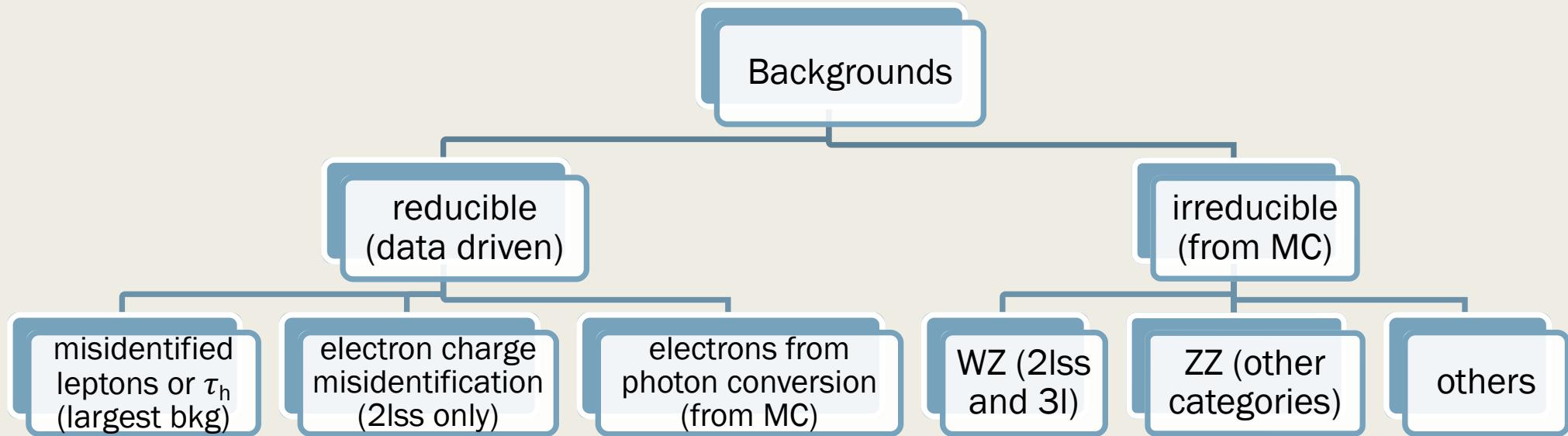
- **TTbar** background from simulation, with corrections from a top-enriched region
- **QCD multijet** background estimated with a data-driven method (ABCD)

VBF HH → bbbb boosted - 2

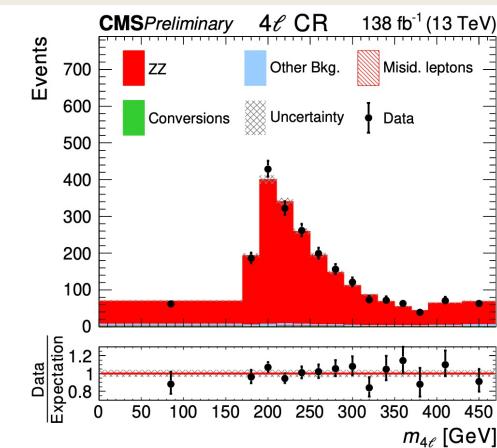
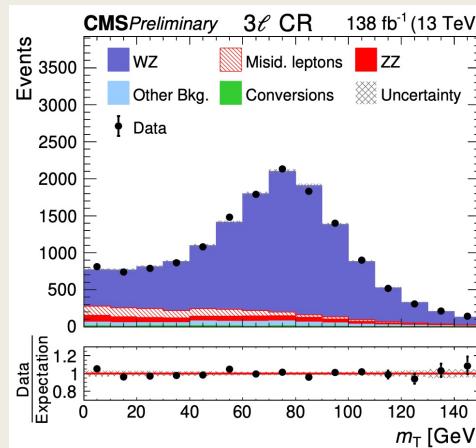


While the excluded k_{2V} range changes depending on the value of k_V , the $k_{2V} = 0$ hypothesis remains excluded also in these scenarios with varied k_V values.

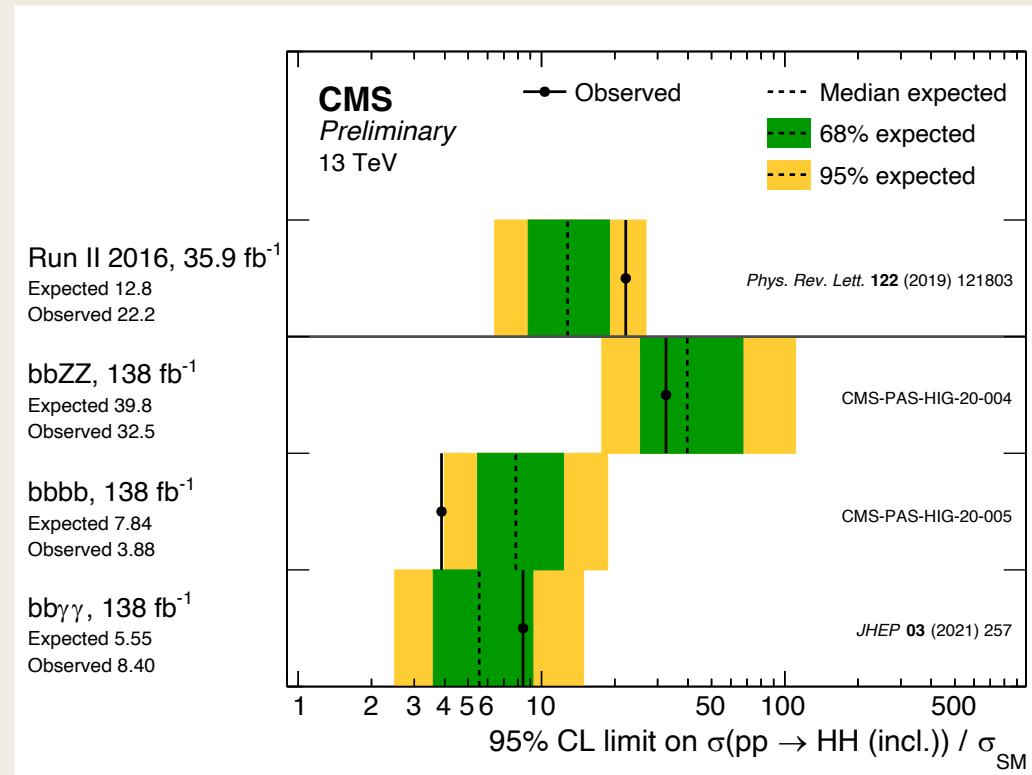
HH → MultiLepton



Dedicated BDT trained to separate prompt leptons (from W, Z and τ decay) from nonprompt (from hadron decay) or misidentified leptons.



HH searches summary



Each of the expected limits of 4b and $\text{bb}\gamma\gamma$ with run 2 statistics are 2 times more stringent than the 2016 combination!

