Higgs boson – fermionic decays

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on behalf of the CMS collaboration

Higgs Hunting, September 12th 2022

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Introduction

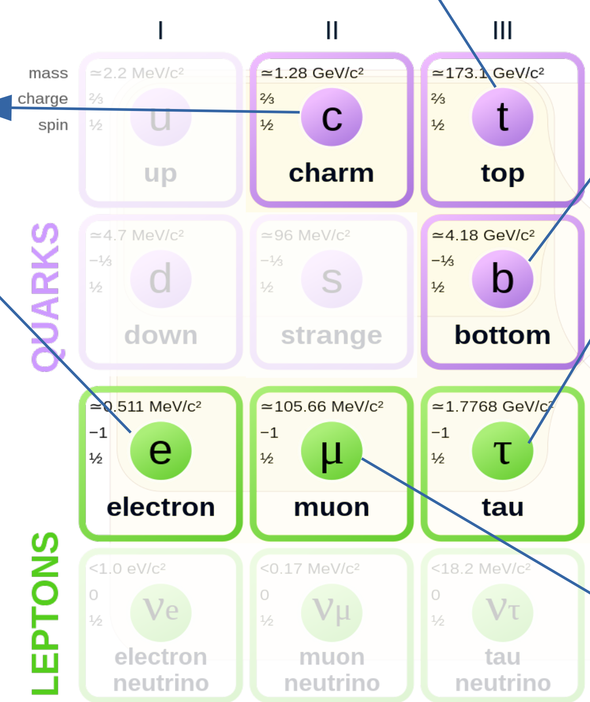
- Higgs boson coupling to fermions proportional to fermion's mass in the Standard Model (Yukawa coupling)
- unresolved questions, e.g. CP properties of Yukawa interactions

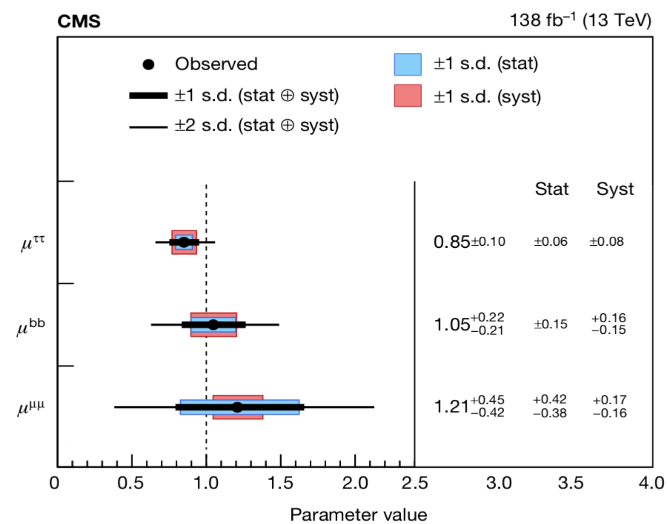
Yukawa coupling measured via production process

observation with 5σ significance with partial Run II datasets

→ updated analysis with full Run II datasets and new interpretations (STXS, effective couplings, CP)

improved limits on branching fractions with full Run II



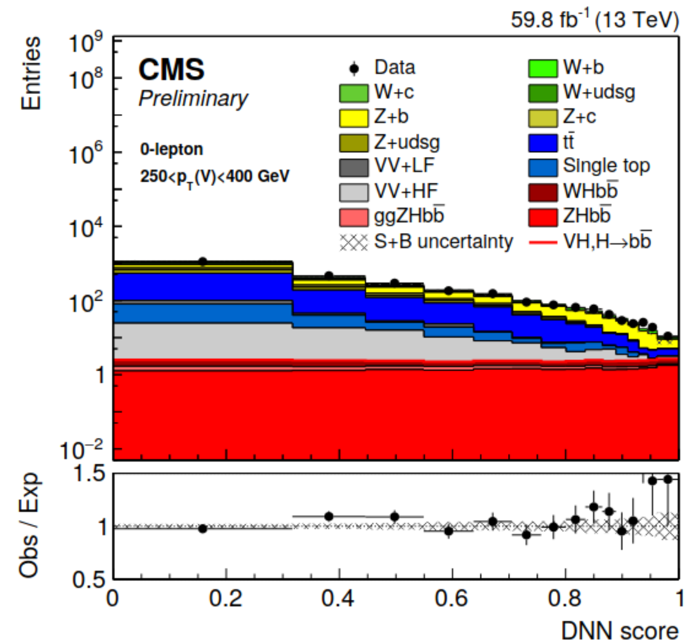


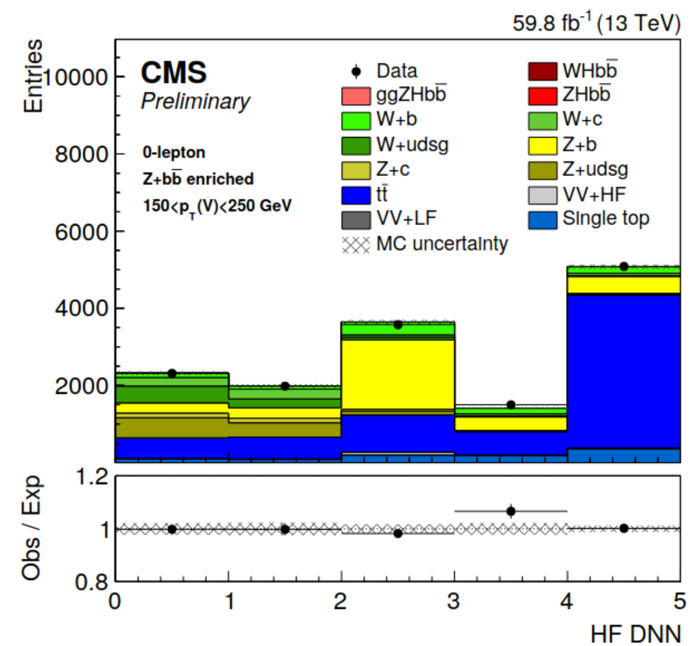
Nature 607, 60–68 (2022)

evidence with 3σ significance with full Run II dataset

UPDATE VH → $b\bar{b}$

- **most sensitive Higgs production channel for H → $b\bar{b}$** (suppression of multi-jet background)
- **event selection** targets 3 control regions enriched in the **main backgrounds**
  V+light flavour jets (LF), V+heavy flavour jets (HF), $t\bar{t}$
- **improvements**:
  - categories for Higgs boson decays reconstructed as a single merged jet (boosted topology)
  - optimization of overlap between boosted and resolved topology
  - V+jets modelling (NLO, flavour treatment)
  - interpretation of results in STXS framework
- simultaneous template fit using **MVA output scores** in the signal regions and V+HF dominated control regions
- V+HF control region: multiclassifier for main backgrounds (V+$b\bar{b}$, V+c, V+LF, single top, $t\bar{t}$)



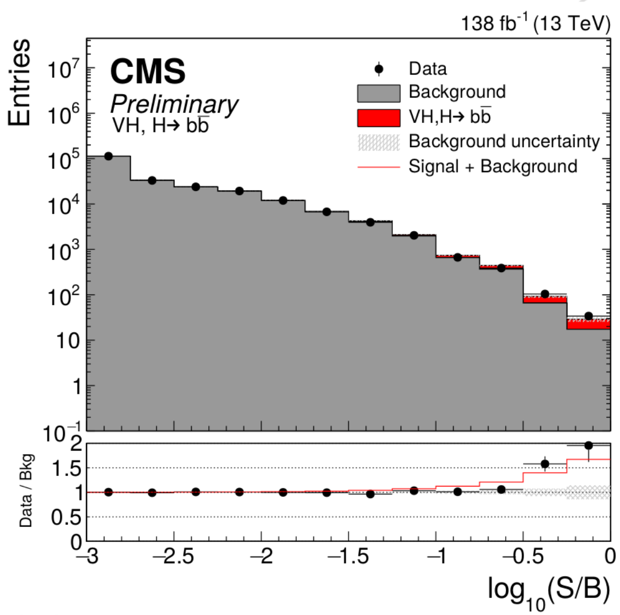


UPDATE

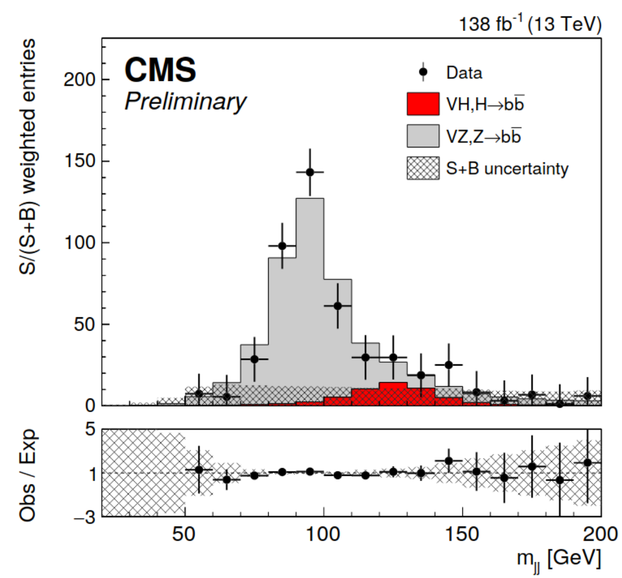
VH → $b\bar{b}$

CMS-HIG-20-001

- **inclusive signal strength**:
  $\mu = 0.58^{+0.19}_{-0.18}$ with observed (expected) significance of 3.3σ (5.2σ)
- background scale factors extracted insitu from simultaneous fit of signal and control regions
- **dominant uncertainties**: MC statistics and signal modelling theory uncertainties
- **cross check analysis**:
  - direct visualization of excess using dijet invariant mass: μ = 0.34±0.34 (mass-decorrelated DNN for event categorization)
  - VZ analysis: μ = 1.16±0.13



	$\Delta\mu$
Background (theory)	+0.067 -0.064
Signal (theory)	+0.082 -0.060
MC stats.	+0.092 -0.093
Sim. modelling	+0.070 -0.066
b-tagging	+0.059 -0.041
JER	+0.045 -0.057
Luminosity	+0.041 -0.034
Jet energy scale	+0.029 -0.036
LeptonID	+0.016 -0.002
Trigger(MET)	+0.001 -0.001

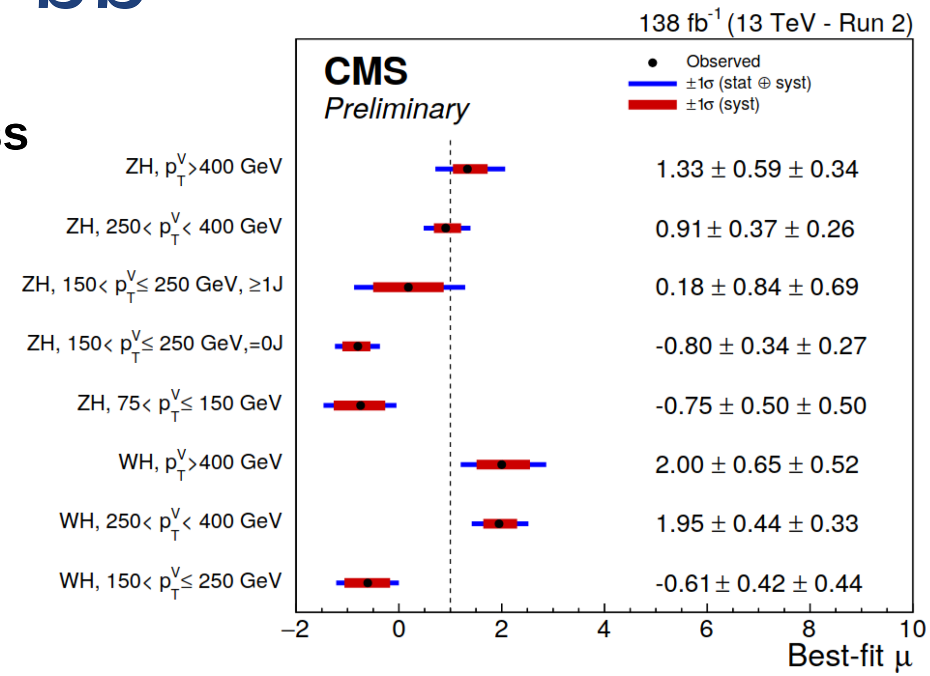


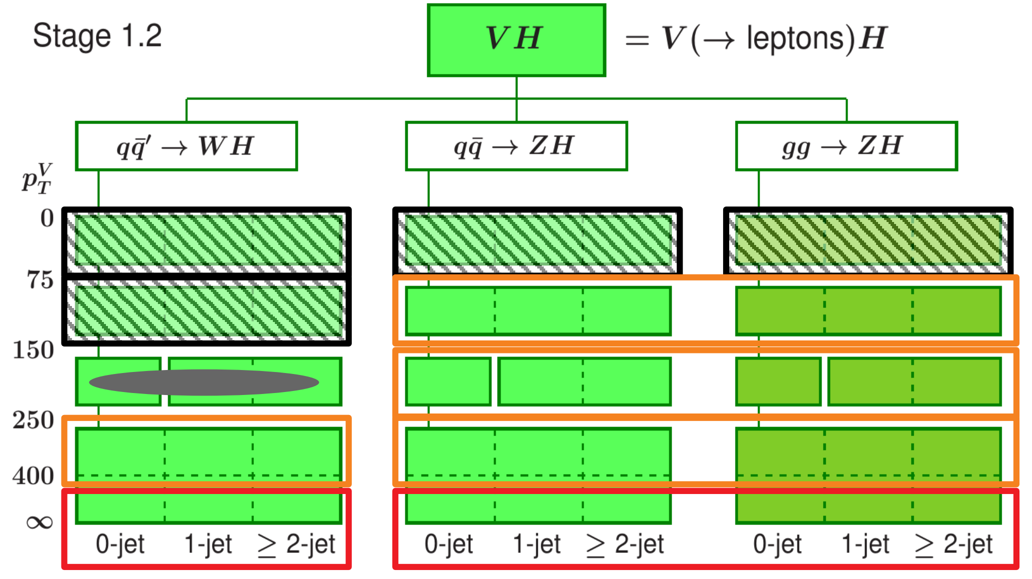
(background subtracted)

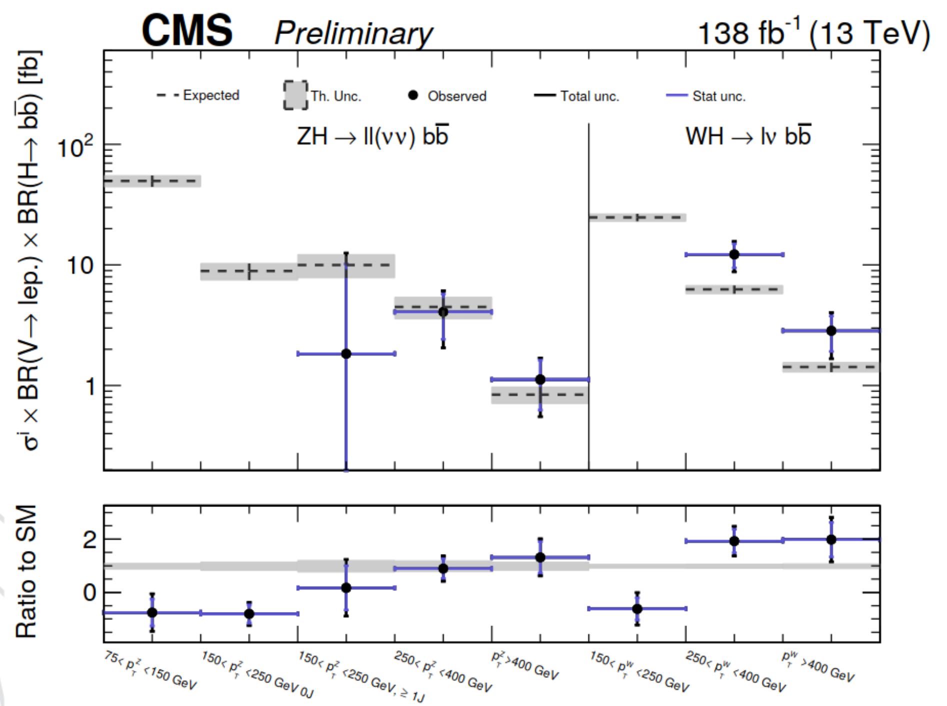
UPDATE VH → $b\bar{b}$

CMS-HIG-20-001

- STXS is a **combination of fully fiducial cross sections and direct fits**
- reduction of impact of theoretical uncertainties on Higgs boson measurements



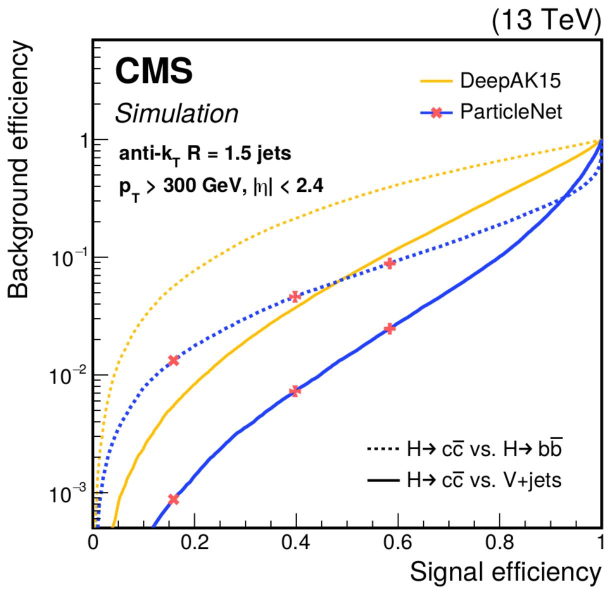


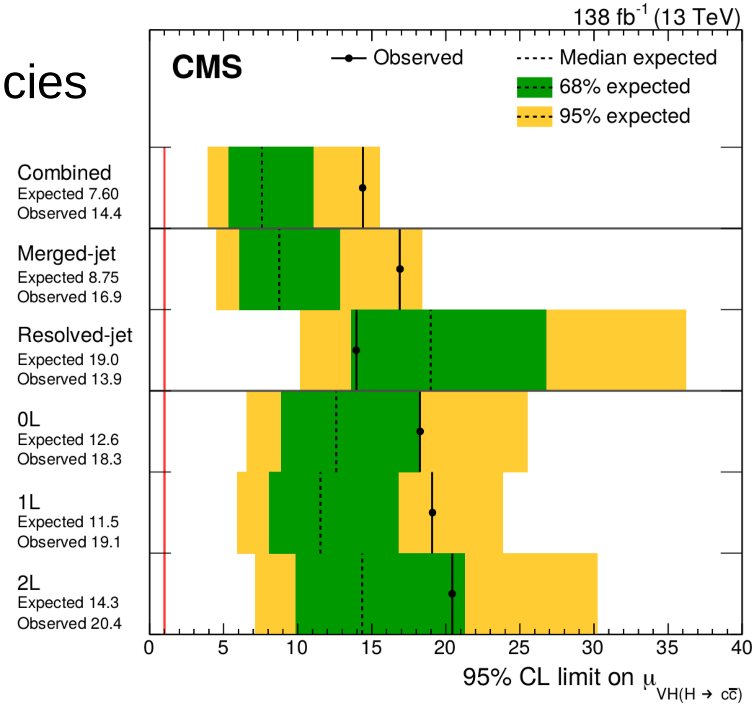


- normalization fixed to SM expectation
- merge of Njets
- qqZH and ggZH categories merged
- splitting of categories with 250 GeV < Vp_T < 400 GeV and Vp_T > 400 GeV

VH → $c\bar{c}$

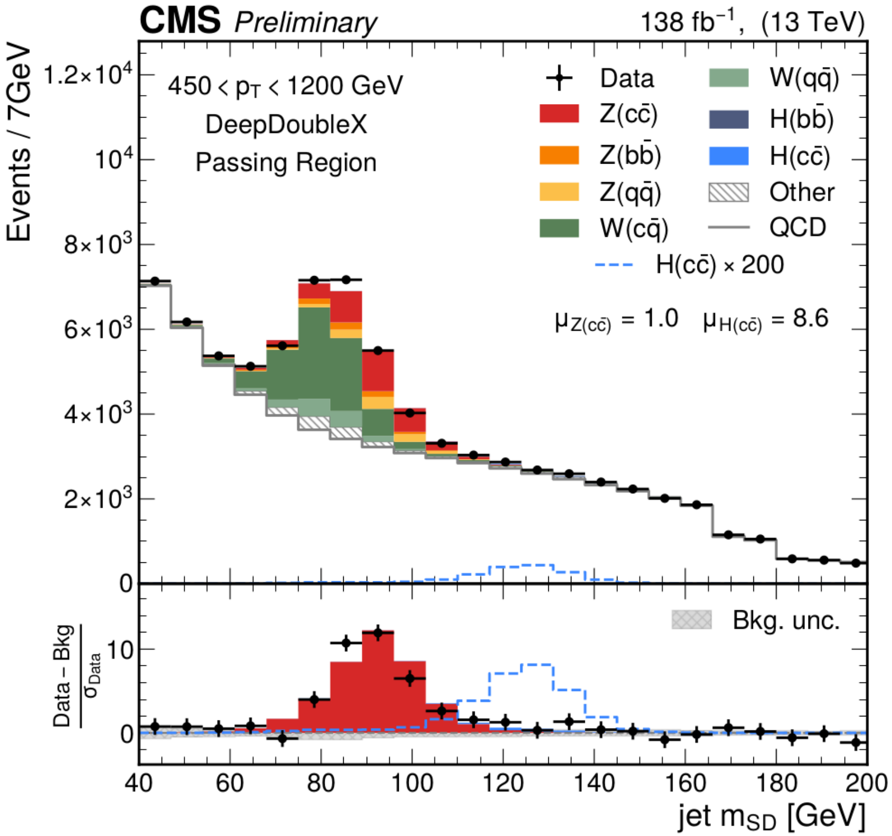
- difficulty of **charm jet identification** in high jet environment at LHC JINST 17 P03014
- **event categorization**:
  exploration of merged-jet (p_T > 300 GeV)
  and resolved-jet topologies
- **discriminant**:
  mass of the Higgs boson candidate (merged-jet topology) and BDT output score (resolved-jet topology)
- dominant **uncertainties**:
  statistical, limited MC statistics, c jet identification efficiencies
- cross check: VZ→ $c\bar{c}$ leading to **first observation at a hadron collider**
- observed (expected) **upper limit** on σ(VH)xBR(H→$c\bar{c}$) 0.94 ($0.50^{+0.22}_{-0.15}$) pb at 95% CL corresponding to 14 ($7.6^{+3.4}_{-2.3}$)xSM
- most stringent constraint on Higgs-charm Yukawa coupling modifier





ggH → $c\bar{c}$

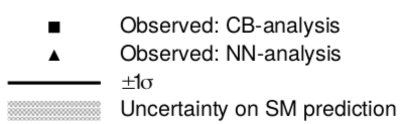
- Higgs production with p_T(Higgs) > 450 GeV in inclusive Higgs production mode
- similar analysis strategy to ggF H → $b\bar{b}$ analysis JHEP12 (2020) 085
- orthogonal constraint on the charm coupling w.r.t. VH → $c\bar{c}$ analysis
- exploration of single large radius jets tagged by the **DeepDoubleX tagger** CMS-DP-2018-046
- DDCvL used to define signal and control regions **event categorisation**: p_T, DDCvL pass/fail
- dominant **uncertainties**: QCD pass-fail ratio, statistical
- **first observation** of Z → $c\bar{c}$ at a hadron collider in Z+jets production mode and boosted topology
- **upper limit** 45(38)xSM at 95% CL

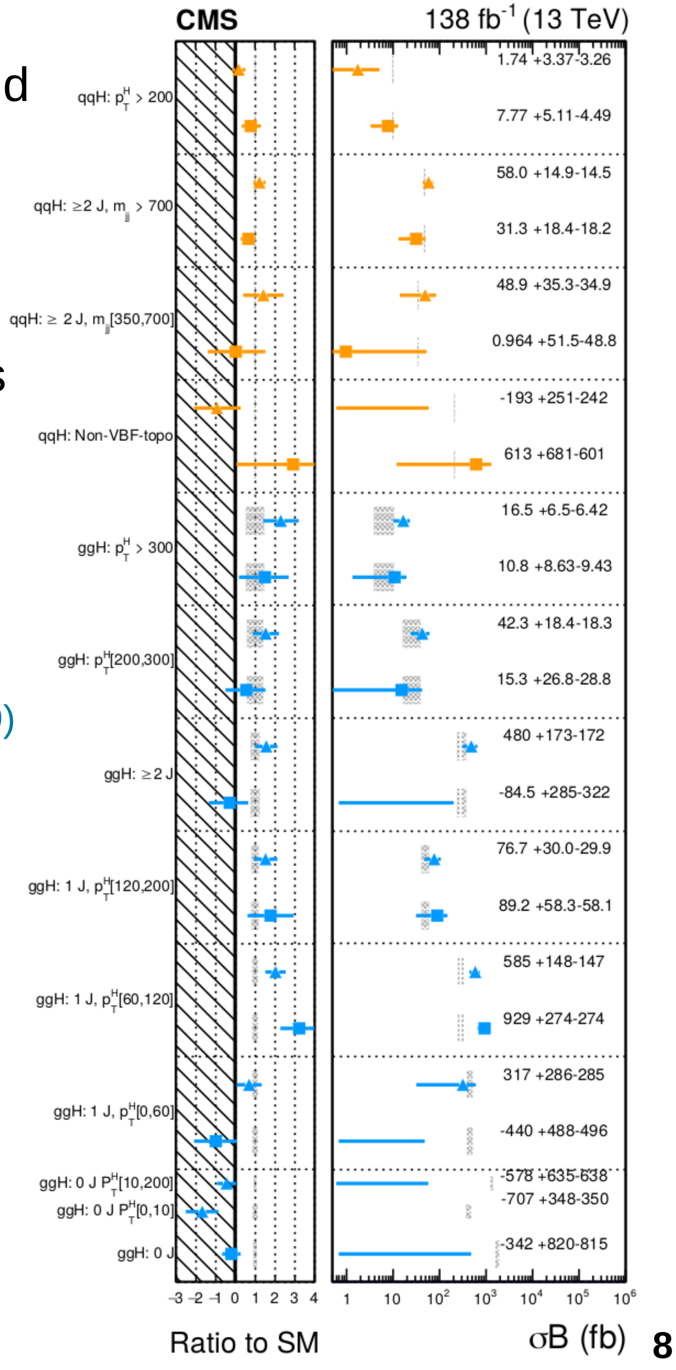


$H \rightarrow \tau\bar{\tau}$

arXiv:2204.12957

- relative large branching ratio (~6%) and reduced background compared to $H \rightarrow b\bar{b}$
- two analysis focussing on ggF and VBF production: cut based (CB) and neural network based (NN)
- **event selection** based on number of e, μ and τ_h candidates
- **event categorization**: five classes (CB) and multiclassification output (NN)
- major **backgrounds**:
  - $Z \rightarrow \tau\bar{\tau}$ (estimated with embedding technique) JINST 14 (2019)
  - jets misidentified as τ_h,e,μ (estimated with fake factor technique)
- **discriminant**:
  CB: $m_{\tau\tau}$ vs. $p_T(\tau)$ / m_{jj} / $p_T(H)$
  NN: classifier output in each node
- 30 – 40% stronger constraints with NN based analysis

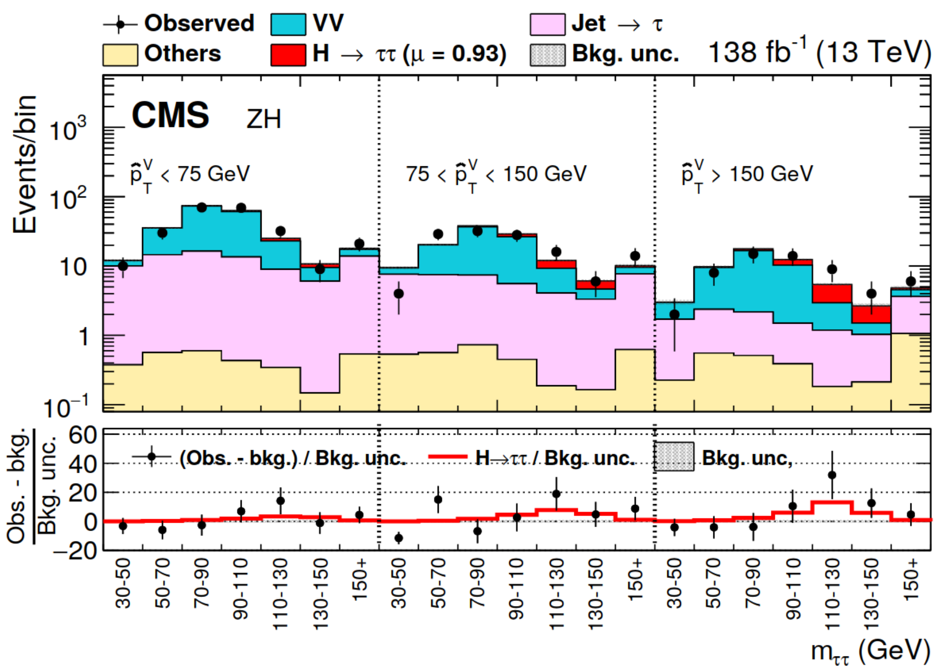


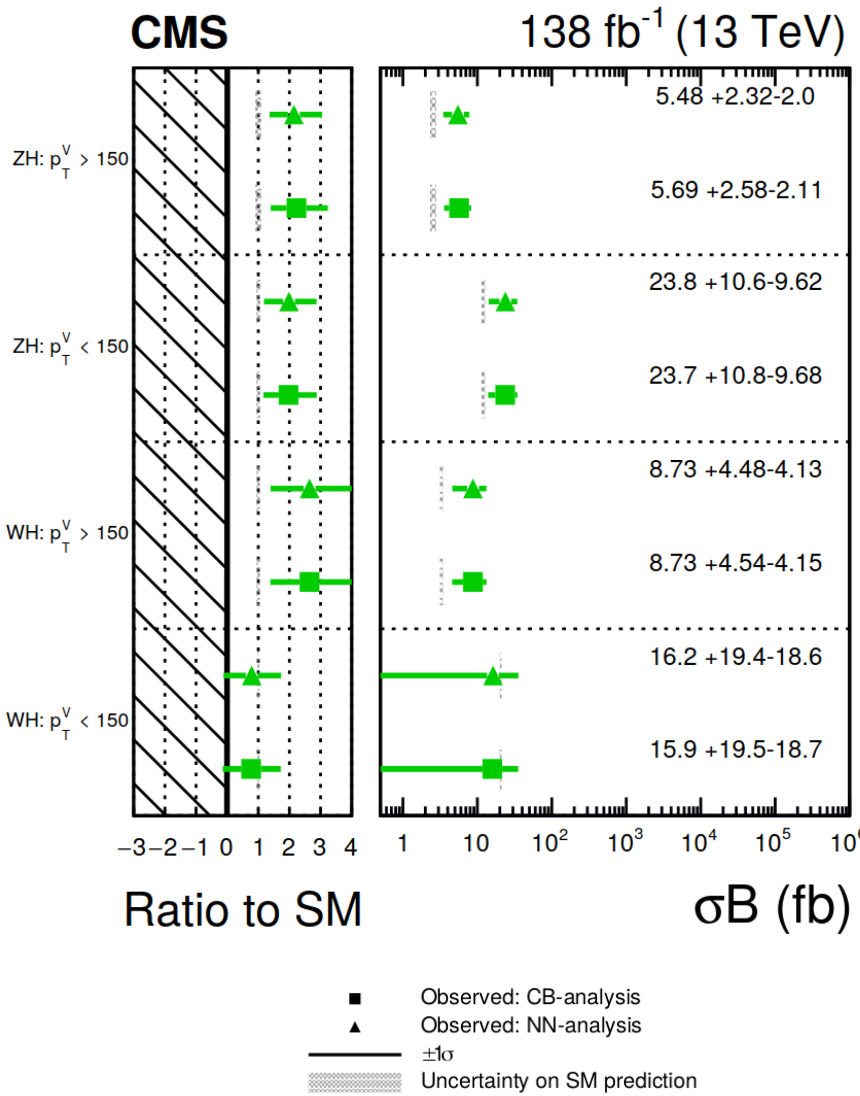


$H \rightarrow \tau\bar{\tau}$

arXiv:2204.12957

- combination with analysis focusing on **Higgs production in association with W/Z**
- purely leptonic τ pair decays not considered (small branching fraction, overlap with H→WW)
- **2D discriminant**: $m_{\tau\tau}$ vs. $p_T(V)$
- together with VBF and ggH analysis: 16 kinematic regions tested (**STXS stage 1.2**)

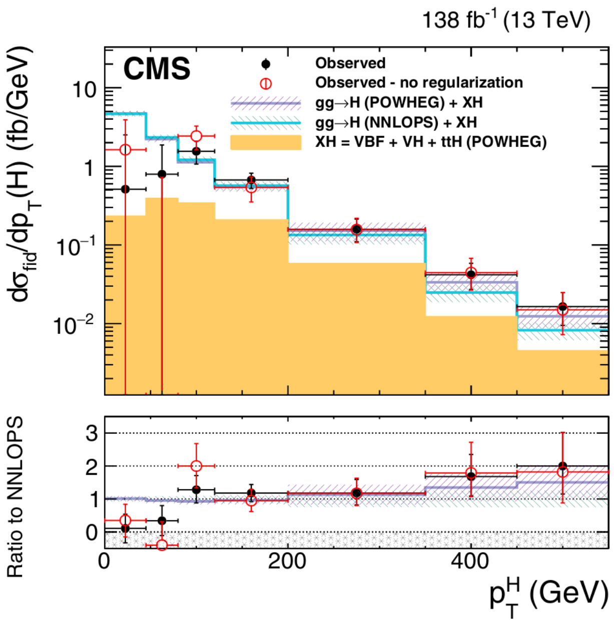


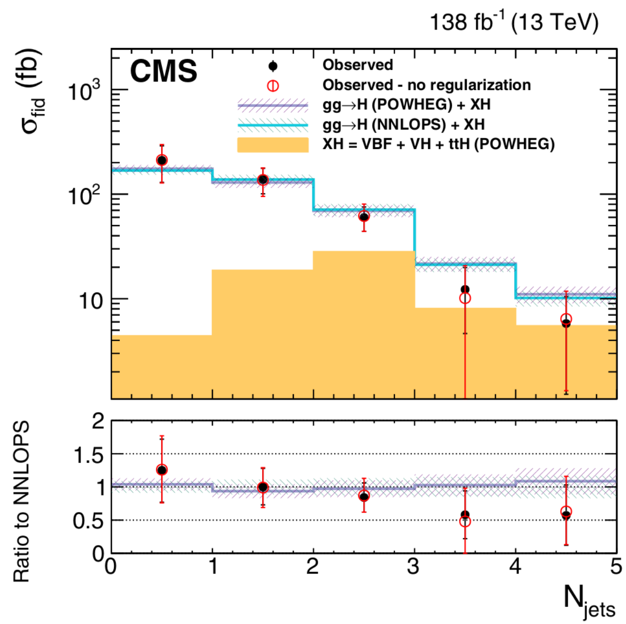


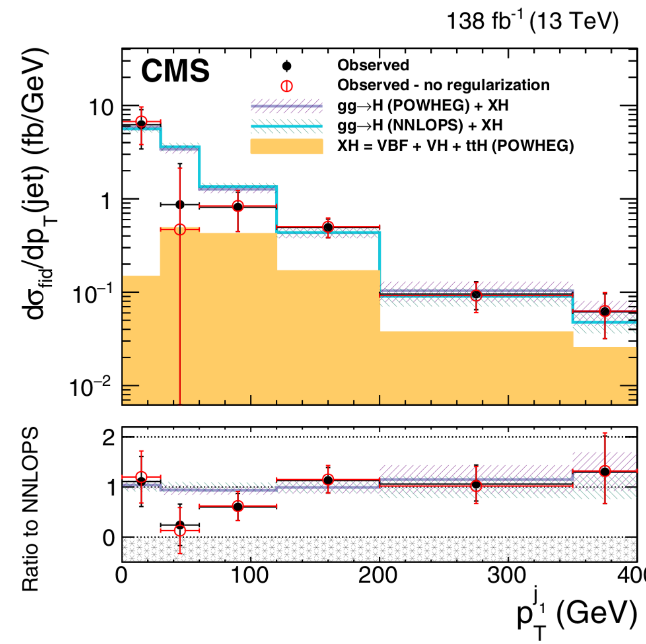
$H \to \tau\bar{\tau}$ (differential)

Phys. Rev. Lett. 128, 081805

- extension of the $H \to \tau\bar{\tau}$ analysis to a differential cross section measurement in terms of p_T(Higgs), jet multiplicity and p_T(leading jet)
- **first fiducial differential measurements** in final states with τ's
- significant improvement over other final states in phase space with large jet multiplicity or high p_T(Higgs)
- signal extracted using **2D-distributions** of $m_{\tau\tau}$ vs. differential variable







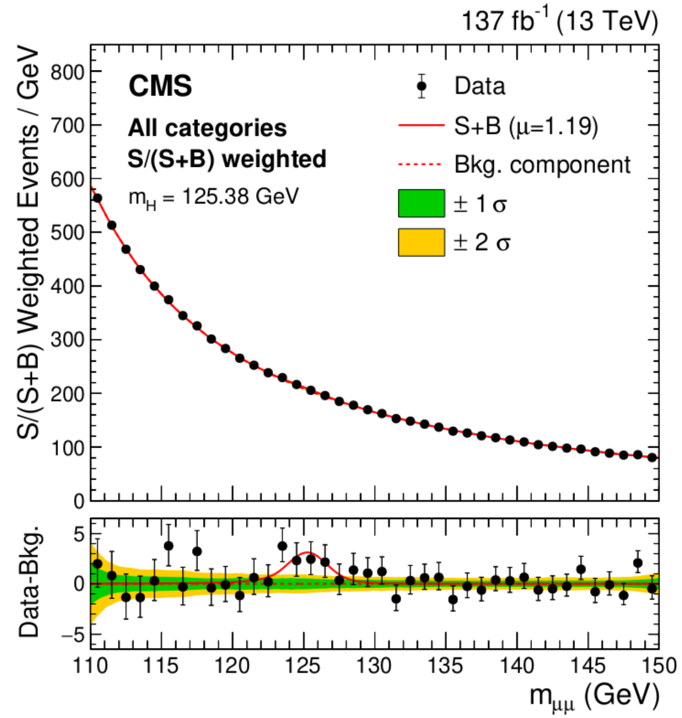
$H \rightarrow \mu\bar{\mu}$

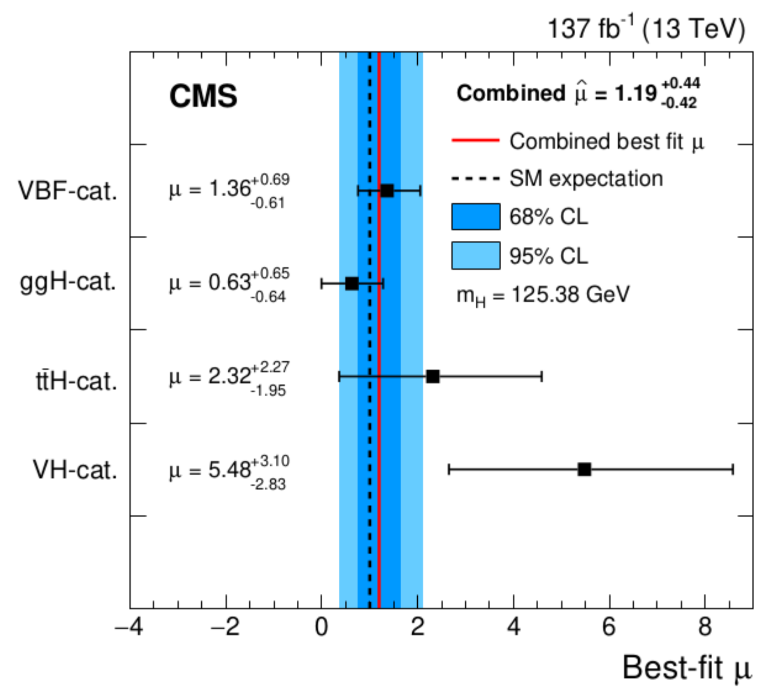
JHEP01 (2021) 148

- **first evidence** for decays of the Higgs boson to 2nd gen fermions with observed significance of 3.0σ
- most precise measurement of the Higgs boson couplings to μ's reported to date
- **four exclusive categories** targeting the different production channels of the Higgs boson
- **backgrounds:** estimated from data with discrete profiling method JINST 10 (2015)

category	**event categorization**	**discriminant**
VBF	$m(\mu\bar{\mu})$	DNN output score
ggH, $t\bar{t}$H and VH	BDTs	$m(\mu\bar{\mu})$

- measurement **statistically dominated**

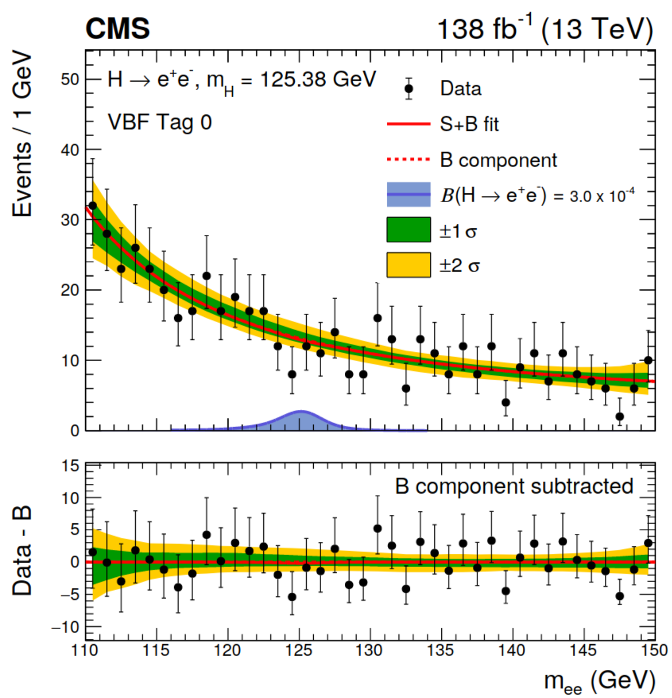


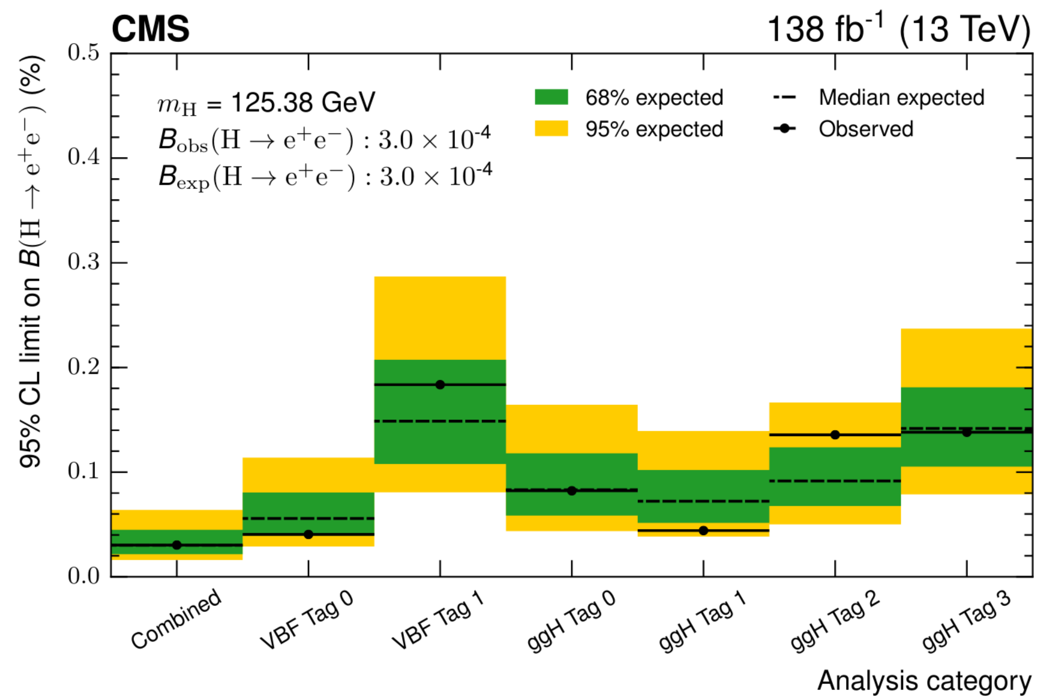


$H \rightarrow e^+e^-$

arXiv:2208.00265

- SM branching ratio **out of reach for LHC** (~5 x 10^{-9}) 😔
  BUT: modifications possible e.g. 2-Higgs doublet modell
- analysis targets Higgs boson production via ggF and VBF
- **BDT classifier** used to define analysis categories
- simultaneous fit to **m(e^+e^-)** distribution
  → backgrounds modelled using discrete profiling method JINST 10 (2015)
- **most stringent upper limit up to date:** 3.0x10^{-4} (3.0x10^{-4}) at 95 % CL



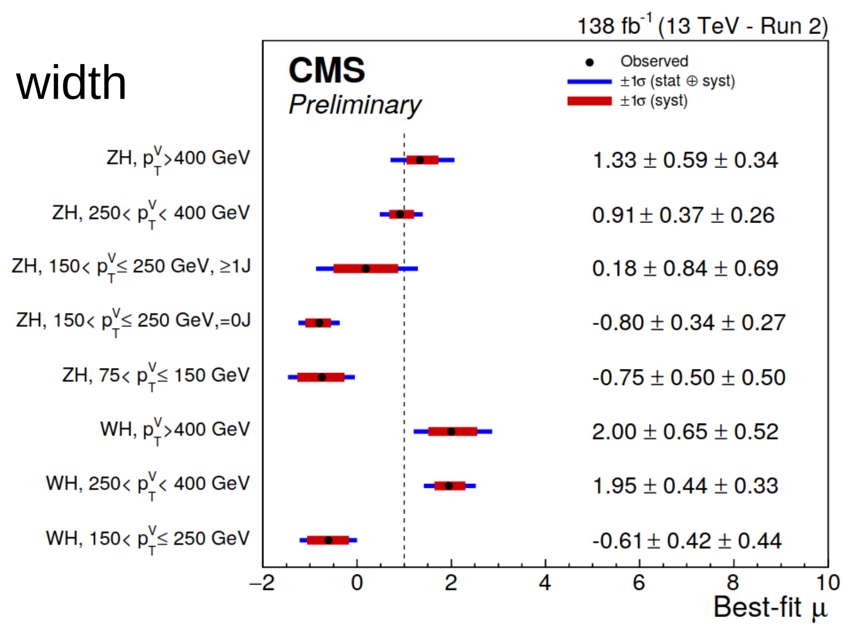


Summary & Outlook

- measurements of the Higgs-fermion coupling **crucial tests** of the SM
- approaching the era of precision measurements for $H \to b\bar{b}$ and $H \to \tau\bar{\tau}$
- major updates with **full Run II datasets**
  - improvements due to **larger statistics** and **improved analysis strategies**
  - **new interpretations** (STXS, effective couplings)
- fermions used in **BSM searches,** searches for **double-Higgs production** and for **anomalous coupling measurements** in the Higgs boson production

UPDATE **new result: $VH \to b\bar{b}$**

- $H \to b\bar{b}$ drives uncertainty of the total Higgs boson width
- update in the most sensitive channel for measuring $H \to b\bar{b}$ decays!



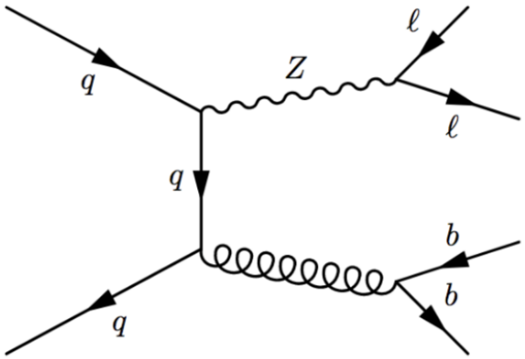
- stay tuned! still outstanding Run II results & improvements with larger Run III dataset
- possible thanks to the fantastic performance of LHC and CMS

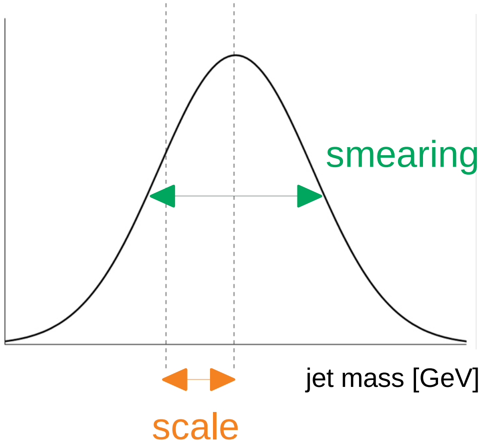
Backup

VH → $b\bar{b}$

b jet energy regression Comput Softw Big Sci 4, 10 (2020)

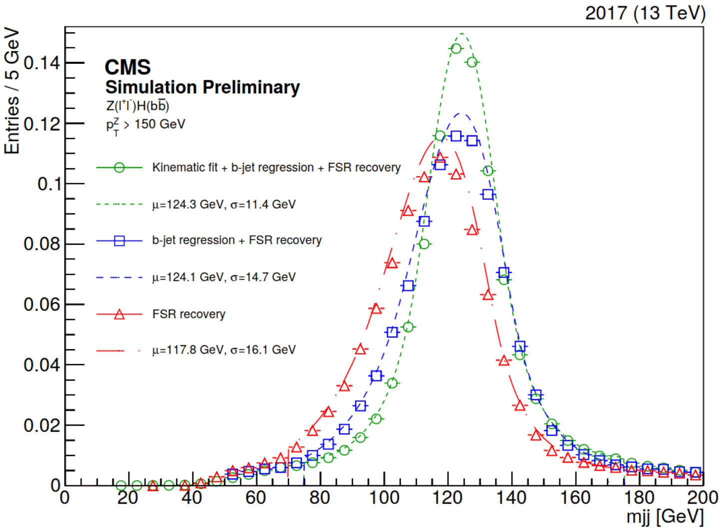
- DNN regression on b jet specific kinematic properties for jet momentum reconstruction
- **dedicated smearing and scaling** correction to account for different jet resolution in data and MC
  - fit uses 2-jet event topology in which the jet resolution can be measured by the jet system balance against the Z in the transverse plane



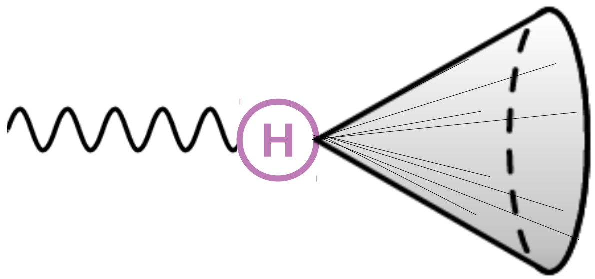


Kinematic fit (2 lepton channel)

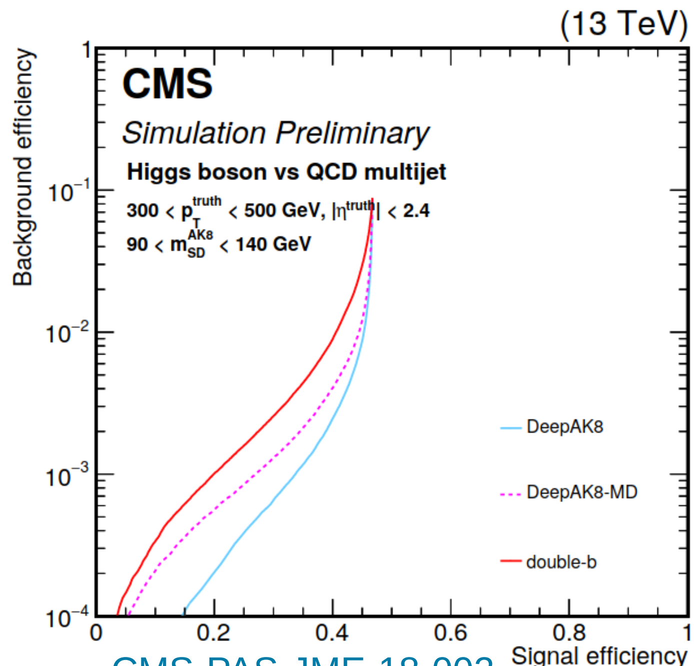
- Use information about Z mass to constrain mass of Higgs boson reconstructed from jets and final state radiation
- possible due to better momentum resolution of leptons than jets and absence of intrinsic MET in 2 lepton channel
- fit of lepton and jet kinematics takes into account uncertainties



$VH \rightarrow b\bar{b}$



- boosted measurement employs a single fat jet (reconstructed with anti-k_t and $\Delta R = 0.8$)
- soft-drop corrections applied to jet mass
- double b-tagger algorithm for selection and variable in multivariate discriminant used for signal extraction



CMS-PAS-JME-18-002

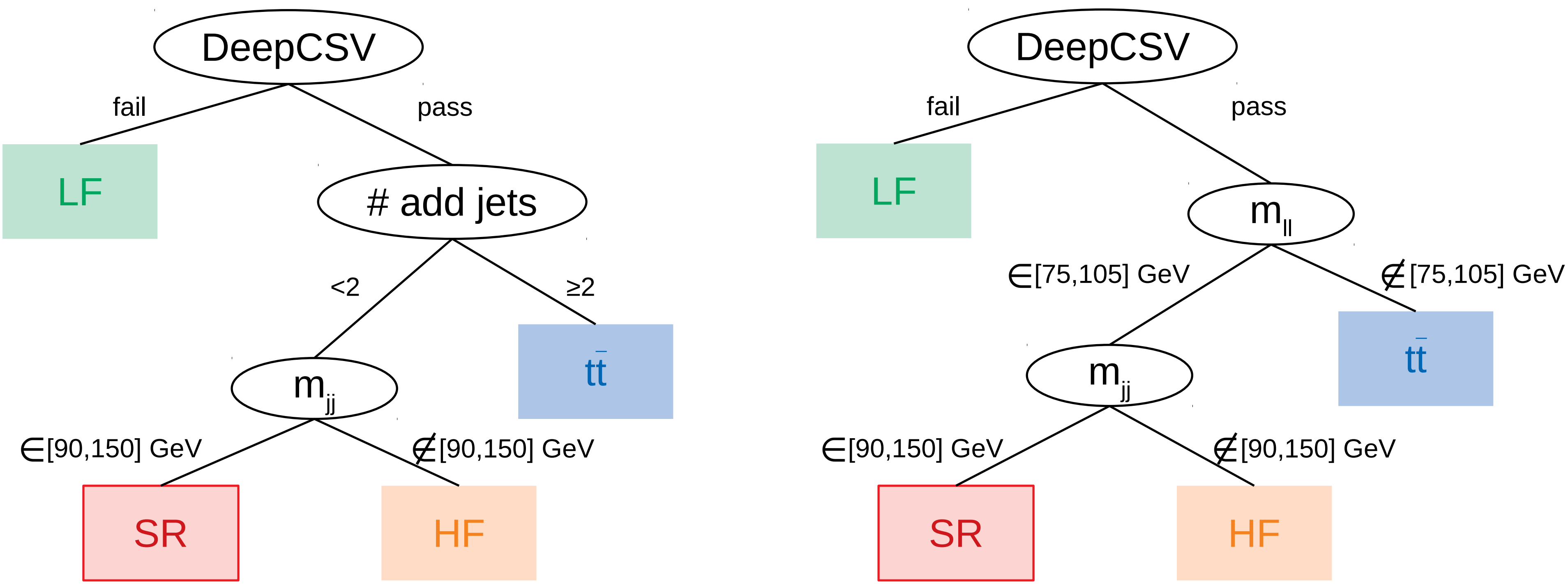
- double b-tagger: **DeepAK8**
  - significant improvement with respect to double-B algorithm (usage of a DNN and low-level information)
  - output decorrelated from the soft-drop mass
  - multiple output classes: analysis uses bb vs. light output node
  - DeepAK8 SF's extracted from $g \rightarrow b\bar{b}$ topology (extrapolated to $H \rightarrow b\bar{b}$ phase-space) on the signal and freely-floating in-situ rate parameters for background DeepAK8 SF's

$VH \rightarrow b\bar{b}$

Event Selection (resolved topology)

<u>0/1 lepton</u>

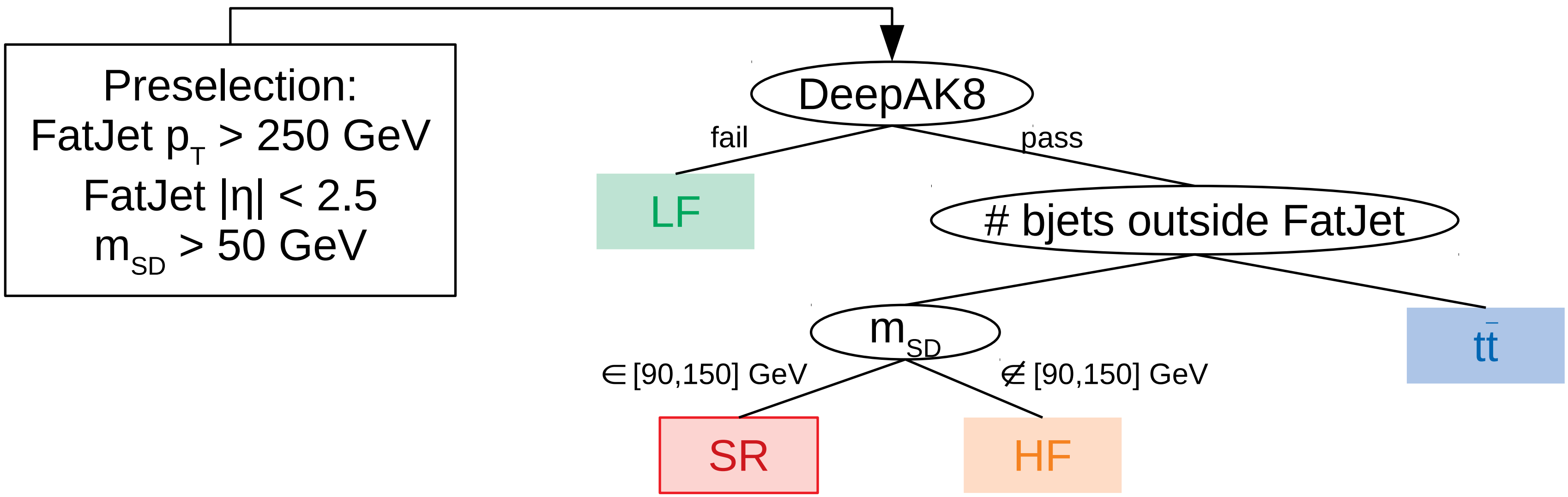
<u>2 lepton</u>



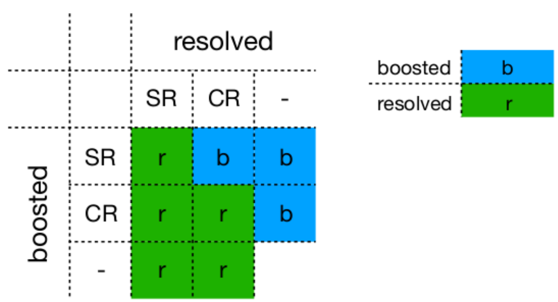
$VH \rightarrow b\bar{b}$

CMS-HIG-20-001

Event Selection (boosted topology)



- overlap treatment with resolved analysis optimized by maximizing Asimov sensitivity
- all events assigned to resolved analysis, unless event categorized as resolved CR and boosted SR

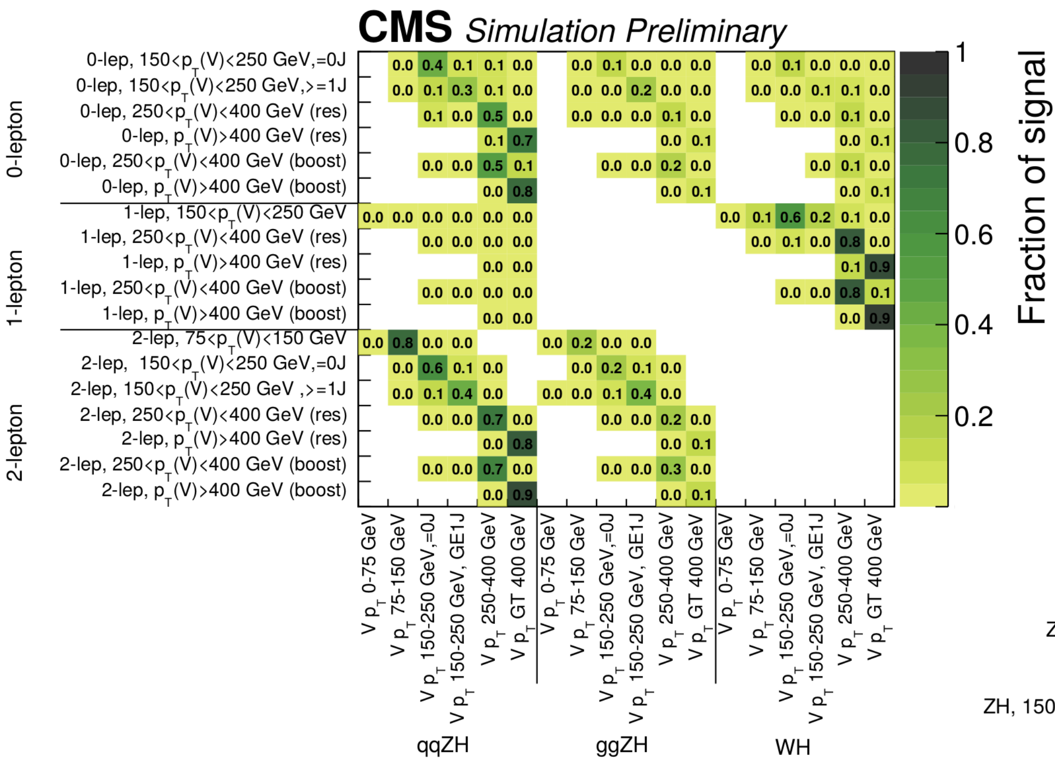


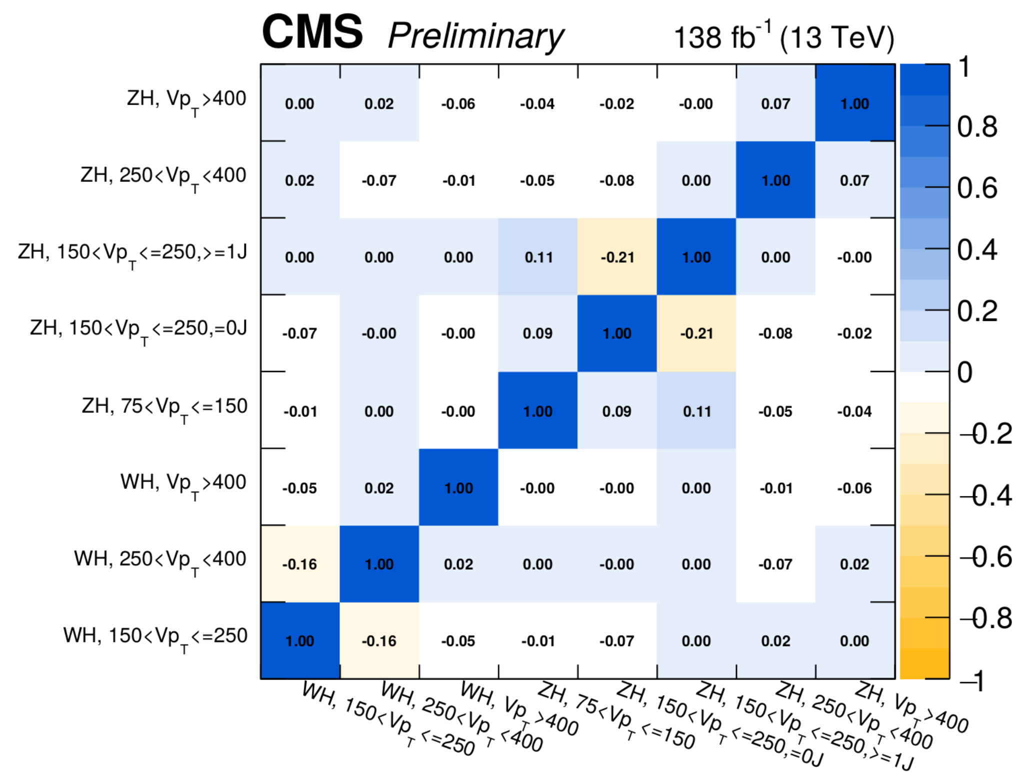
overlap to resolved, unless
boosted SR+resolved CR

VH → $b\bar{b}$

	SR	$t\bar{t}$ CR	V+LF CR	V+HF CR
0-lepton, resolved	DNN	$p_T(V)$	$p_T(V)$	HFDNN
0-lepton, boosted	BDT	DeepAK8bbVsLight	DeepAK8bbVsLight	DeepAK8bbVsLight
1-lepton, resolved	DNN	$p_T(V)$	$p_T(V)$	HFDNN
1-lepton, boosted	BDT	DeepAK8bbVsLight	DeepAK8bbVsLight	DeepAK8bbVsLight
2-lepton, resolved	DNN	$p_T(V)$	$p_T(V)$	DeepCSV scores
2-lepton, boosted	BDT	DeepAK8bbVsLight	DeepAK8bbVsLight	DeepAK8bbVsLight

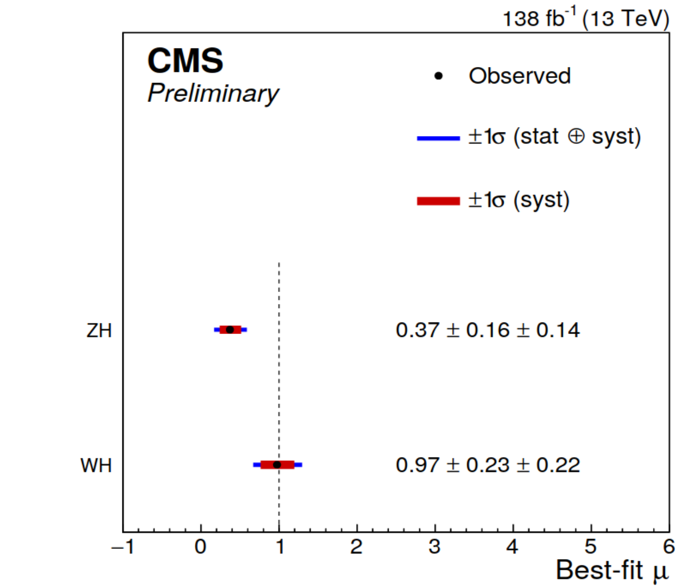
VH → $b\bar{b}$

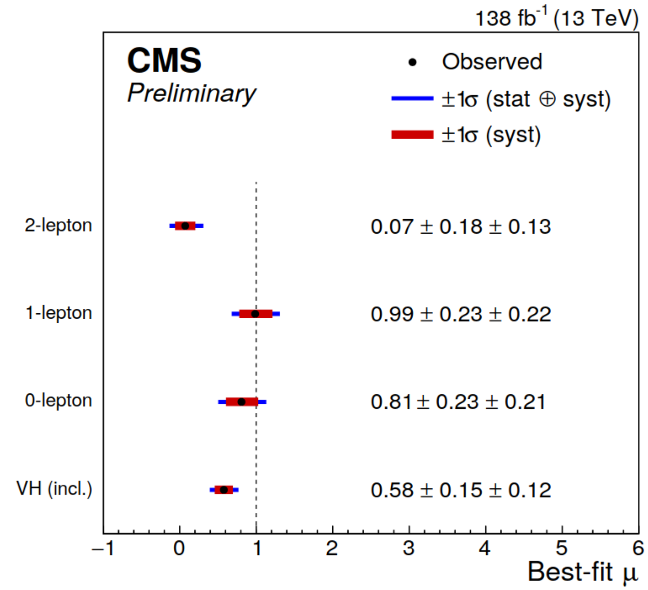

CMS Simulation Preliminary
0-lep, 150<p_T(V)<250 GeV,=0J
0-lep, 150<p_T(V)<250 GeV,>=1J
0-lep, 250<p_T(V)<400 GeV (res)
0-lep, p_T(V)>400 GeV (res)
0-lep, 250<p_T(V)<400 GeV (boost)
0-lep, p_T(V)>400 GeV (boost)
1-lep, 150<p_T(V)<250 GeV
1-lep, 250<p_T(V)<400 GeV (res)
1-lep, p_T(V)>400 GeV (res)
1-lep, 250<p_T(V)<400 GeV (boost)
1-lep, p_T(V)>400 GeV (boost)
2-lep, 75<p_T(V)<150 GeV
2-lep, 150<p_T(V)<250 GeV,=0J
2-lep, 150<p_T(V)<250 GeV ,>=1J
2-lep, 250<p_T(V)<400 GeV (res)
2-lep, p_T(V)>400 GeV (res)
2-lep, 250<p_T(V)<400 GeV (boost)
2-lep, p_T(V)>400 GeV (boost)
0-lepton
1-lepton
2-lepton
V p_T 0-75 GeV
V p_T 75-150 GeV
V p_T 150-250 GeV,=0J
V p_T 150-250 GeV, GE1J
V p_T 250-400 GeV
V p_T GT 400 GeV
qqZH
ggZH
WH
Fraction of signal
1
0.8
0.6
0.4
0.2

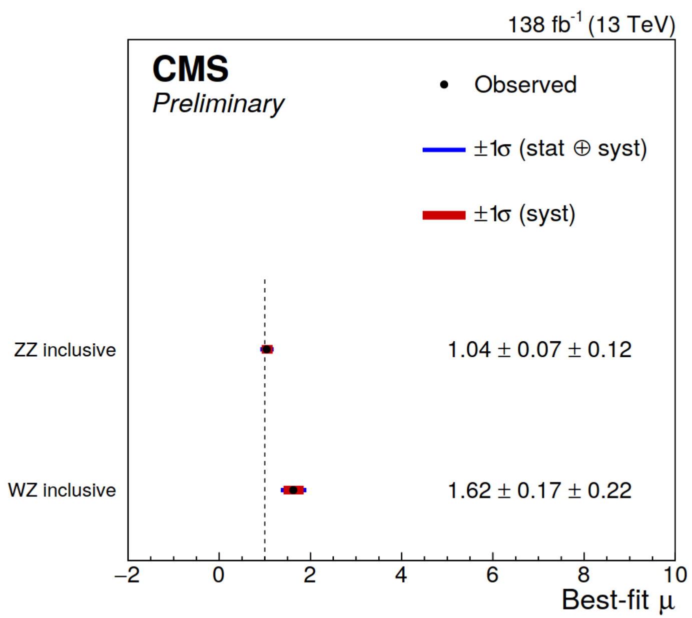

CMS Preliminary
138 fb^-1 (13 TeV)
ZH, Vp_T>400 0.00 0.02 -0.06 -0.04 -0.02 -0.00 0.07 1.00
ZH, 250<Vp_T<400 0.02 -0.07 -0.01 -0.05 -0.08 0.00 1.00 0.07
ZH, 150<Vp_T<=250,>=1J 0.00 0.00 0.00 0.11 -0.21 1.00 0.00 -0.00
ZH, 150<Vp_T<=250,=0J -0.07 -0.00 -0.00 0.09 1.00 -0.21 -0.08 -0.02
ZH, 75<Vp_T<=150 -0.01 0.00 -0.00 1.00 0.09 0.11 -0.05 -0.04
WH, Vp_T>400 -0.05 0.02 1.00 -0.00 -0.00 0.00 -0.01 -0.06
WH, 250<Vp_T<400 -0.16 1.00 0.02 0.00 -0.00 0.00 -0.07 0.02
WH, 150<Vp_T<=250 1.00 -0.16 -0.05 -0.01 -0.07 0.00 0.02 0.00
WH, 150<Vp_T<=250
WH, 250<Vp_T<400
WH, Vp_T>400
ZH, 75<Vp_T<=150
ZH, 150<Vp_T<=250,=0J
ZH, 150<Vp_T<=250,>=1J
ZH, 250<Vp_T<400
ZH, Vp_T>400
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1

$VH \rightarrow b\bar{b}$

CMS-HIG-20-001







previous result (partial Run II result):

- expected sensitivity 4.2σ
- $\mu = 1.06 \pm 0.26$ (2016+2017)
- $\mu = 1.08 \pm 0.34$ (2017)

CMS-PAS-HIG-18-016

$VH \rightarrow b\bar{b}$

- Jackknife resampling is a **non-parametric method of estimating uncertainty on a parameter by removing partitions from total event dataset**.
- we divide the **2017 dataset** combined from 2 analyses into g equal-sized orthogonal partitions
- for each partition *i*:
  - Remove that set of events from each analyses datacards
  - Redo both the fits to get μ_i
- jackknife estimate of the variance on $\Delta\mu$ is calculated from the variance of $\Delta\mu_i$:

$$var_I(\Delta\mu) = \frac{g-1}{g}\sum(\Delta\mu_{(i)} - \overline{\Delta\mu_d})^2 = \frac{(g-1)^2}{g} var(\Delta\mu_{(i)})$$

- Compute disagreement on $\Delta\mu$ ($\sigma_{\Delta\mu}$)

$$\sigma_{\Delta\mu} = \frac{\overline{\Delta\mu}}{\sqrt{var(\Delta\mu)}} = \frac{\overline{\Delta\mu}}{\frac{(g-1)}{\sqrt{g}} \times std.dev_{\Delta\mu}}$$

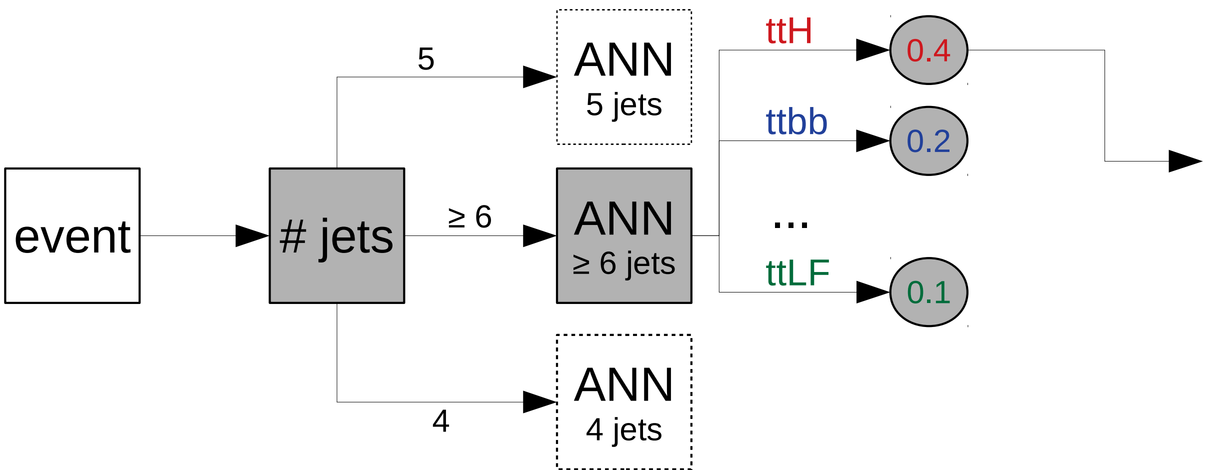
$\sigma_{\Delta\mu}$ = 2σ
correlation ρ ~ 0.5

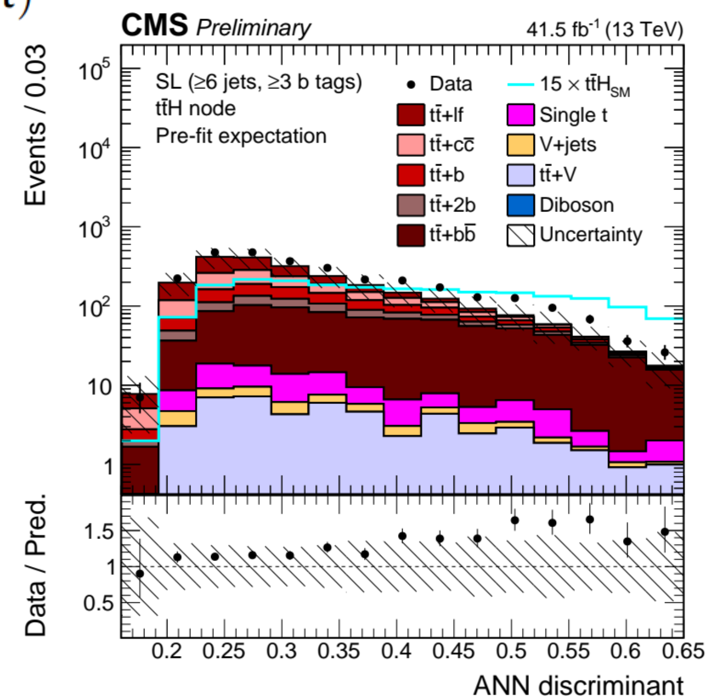
- for our purpose we are using 1000 equal sized partitions

$t\bar{t}H \rightarrow b\bar{b}$ (partial Run II)

CMS-PAS-18-030

- events are classified according to number of jets, number of b tagged jets and output node of ANN (artificial neural network)
- inputs to ANN: kinematics of leptons, jets and missing transverse energy, but also high-level variables (e.g. event shape or Matrix-Element Method discriminant)
- ANN discriminant output used also as final discriminant in fit
- evidence for $t\bar{t}H(b\bar{b})$ found with observed (expected) significance of 3.9σ (3.5σ) using data collected in 2016/2017
- signal strength found to be $\hat{\mu} = 1.15 \, ^{+0.15}_{-0.15}(\mathrm{stat}) \, ^{+0.28}_{-0.25}(\mathrm{syst})$

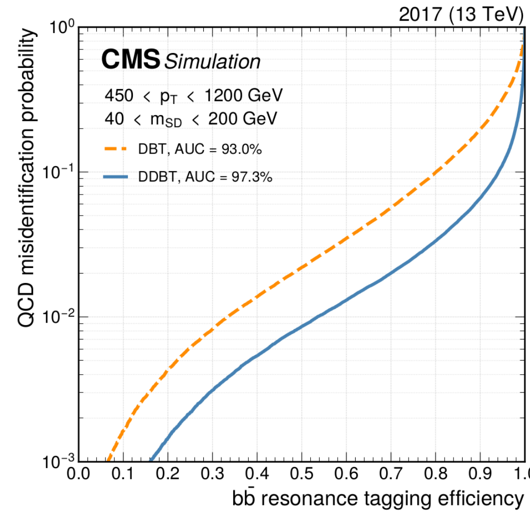




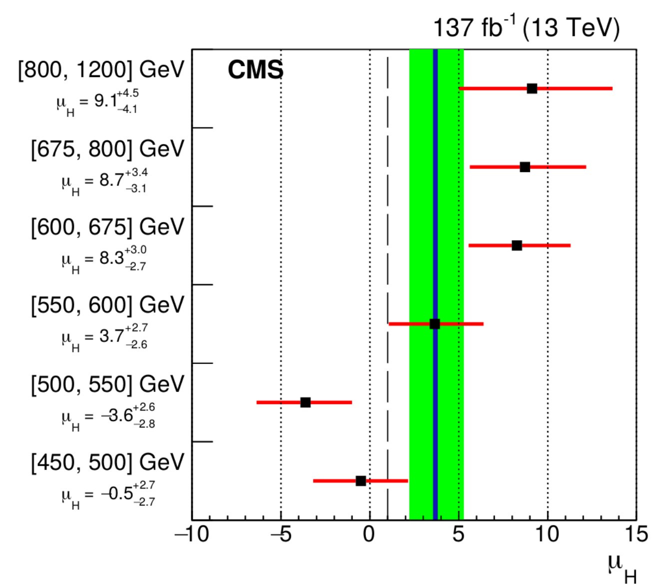
ggF $H \to b\bar{b}$ (boosted)

JHEP12 (2020) 085

- inclusive Higgs production with p_T(Higgs) > 450 GeV
- Higgs bosons reconstructed as single large-R jet with two prong structure
- application of dedicated b-tagging algorithms to target boosted topologies (DDBT) CMS-DP-2018-046

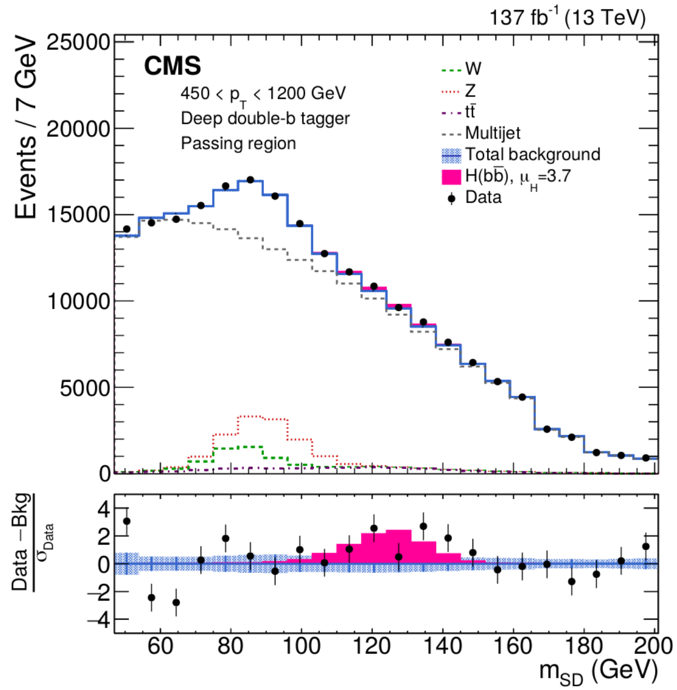


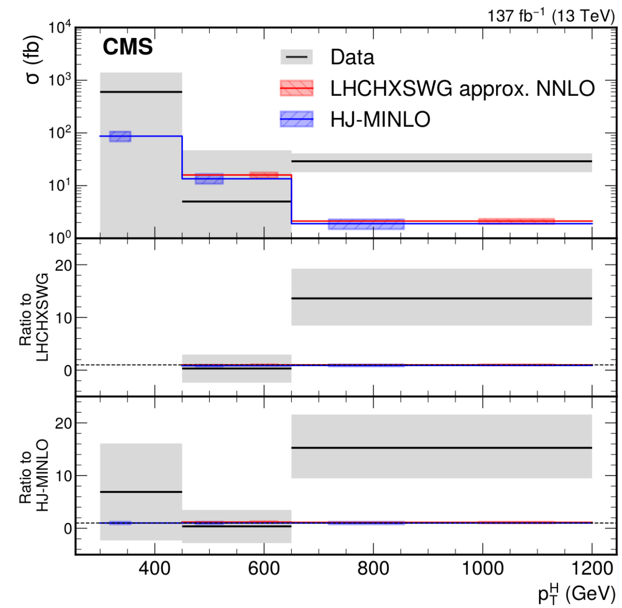
- major **backgrounds**:
  QCD/$t\bar{t}$ (estimated in control regions)
  W/Z+jets resonance (used to constrain uncertainties)
- **event categorisation**: p_T, DDBT pass/fail
- **improvements**: ggF p_T(Higgs) modelling, improved b tagging algorithm for large-R jets
- dominant **uncertainties**: statistical, QCD pass-fail ratio
- observed (expected) significance: 2.5σ (0.7σ) with 1.9σ above SM expectation
- differential measurement interpretation in terms of p_T(Higgs) in the boosted $H \to b\bar{b}$ region

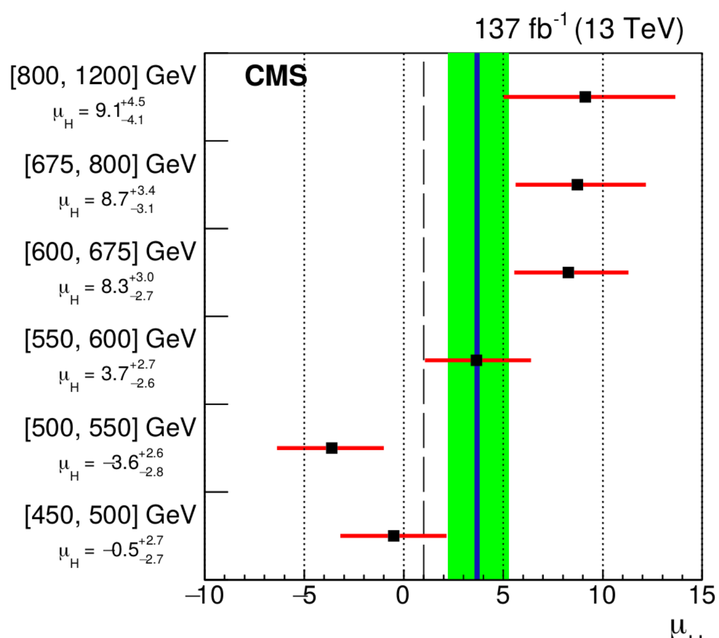


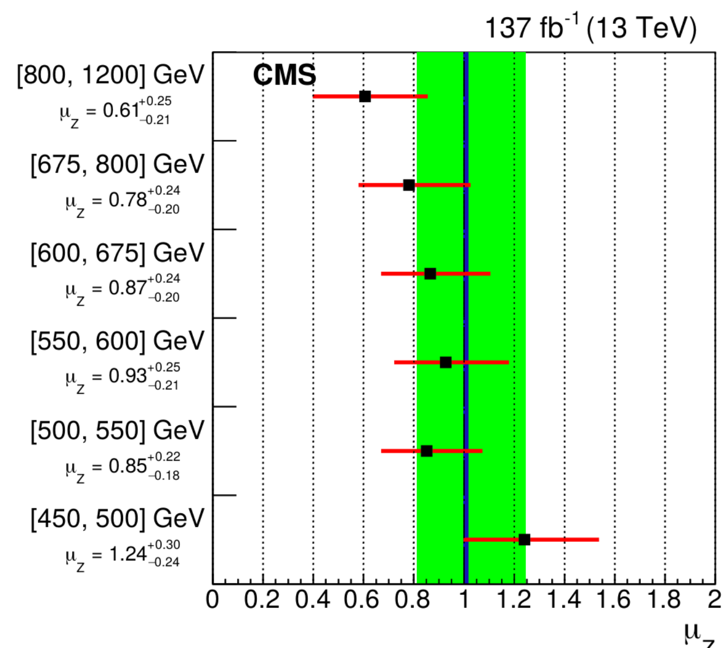
ggF H → $b\bar{b}$ (boosted)

JHEP 2012 (2020) 085



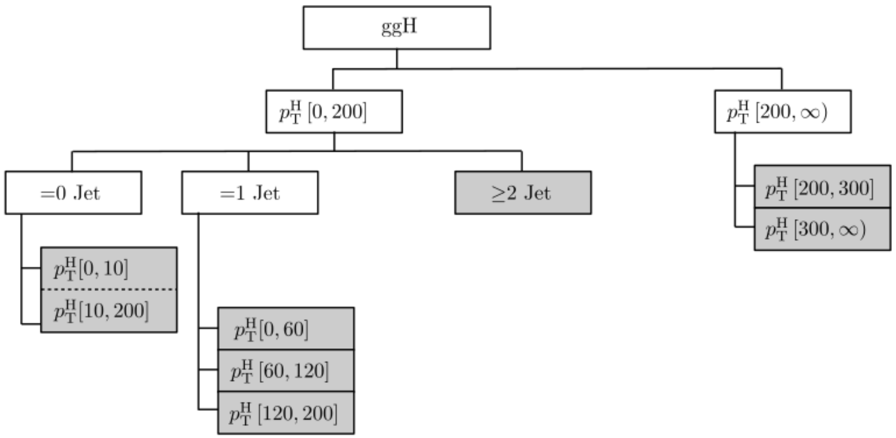


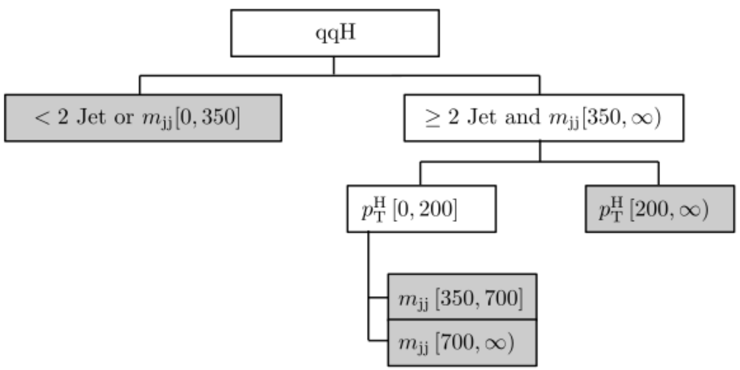


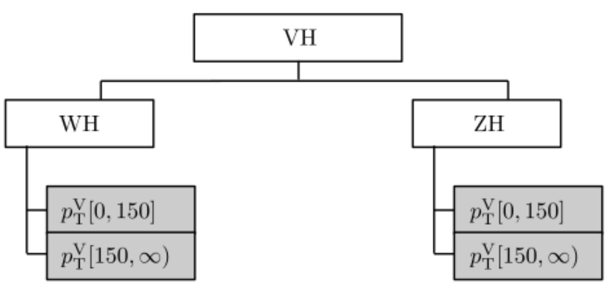


$H \to \tau\bar{\tau}$

arXiv:2204.12957





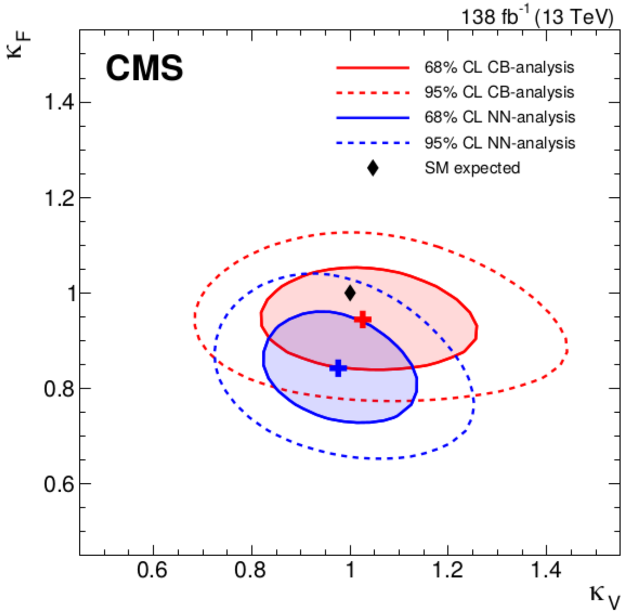


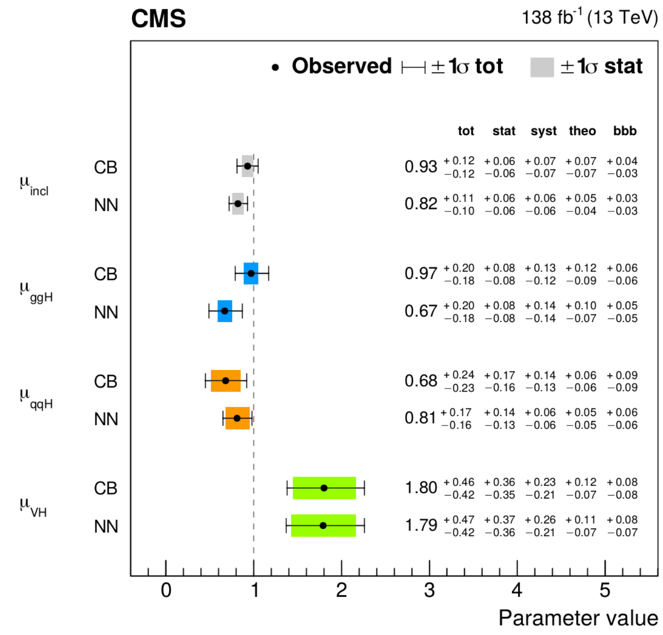
	Classes per final state			
Process	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
τ-embedding	genuine τ	genuine τ	genuine τ	genuine τ
QCD/F_F-method	jet $\to \ell$	jet $\to \tau_h$	jet $\to \tau_h$	jet $\to \tau_h$
$t\bar{t}(e/\mu + X)$	tt	tt	tt	misc
$Z \to \ell\ell$	misc	zll	zll	misc
Diboson/single t	db	misc	misc	misc

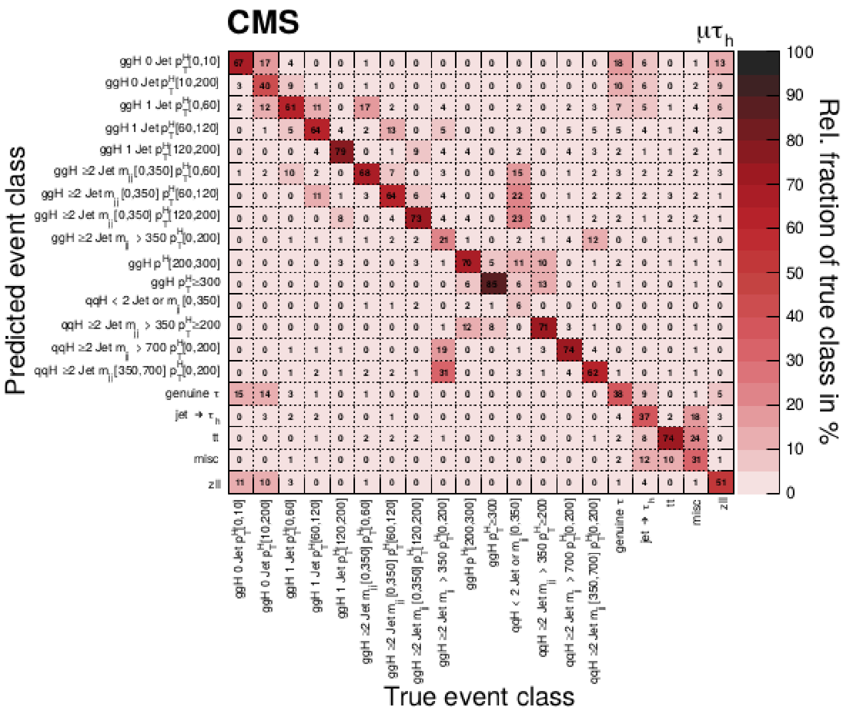
Final state	Category	Selection	Observables
$\ell\tau_h$, $e\mu$	0-jet	0 jet	$m_{\tau\tau}$, $p_T^{\tau_h}$ ($\ell\tau_h$) $m_{\tau\tau}$ ($e\mu$)
	VBF low p_T^H	≥2 jets, $m_{jj} > 350$ GeV, $\hat{p}_T^H < 200$ GeV	$m_{\tau\tau}$, m_{jj}
	VBF high p_T^H	≥2 jets, $m_{jj} > 350$ GeV, $\hat{p}_T^H > 200$ GeV	$m_{\tau\tau}$, m_{jj}
	Boosted 1 jet	1 jet	$m_{\tau\tau}$, $\hat{p}_T^H$
	Boosted ≥2 jets	Not in VBF, ≥2 jets	$m_{\tau\tau}$, $\hat{p}_T^H$
$\tau_h\tau_h$	0-jet	0 jet	$m_{\tau\tau}$
	VBF low p_T^H	≥2 jets, $\Delta\eta_{jj} > 2.5$ (2.0 for 2016), $100 < \hat{p}_T^H < 200$ GeV	$m_{\tau\tau}$, m_{jj}
	VBF high p_T^H	≥2 jets, $\Delta\eta_{jj} > 2.5$ (2.0 for 2016), $\hat{p}_T^H > 200$ GeV	$m_{\tau\tau}$, m_{jj}
	Boosted 1 jet	1 jet	$m_{\tau\tau}$, $\hat{p}_T^H$
	Boosted ≥2 jets	Not in VBF, ≥2 jets	$m_{\tau\tau}$, $\hat{p}_T^H$

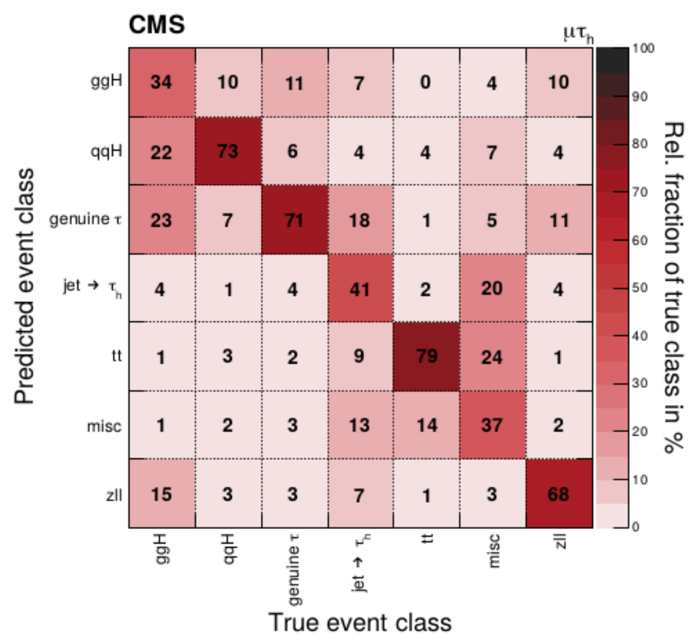
$H \to \tau\bar{\tau}$

arXiv:2204.12957









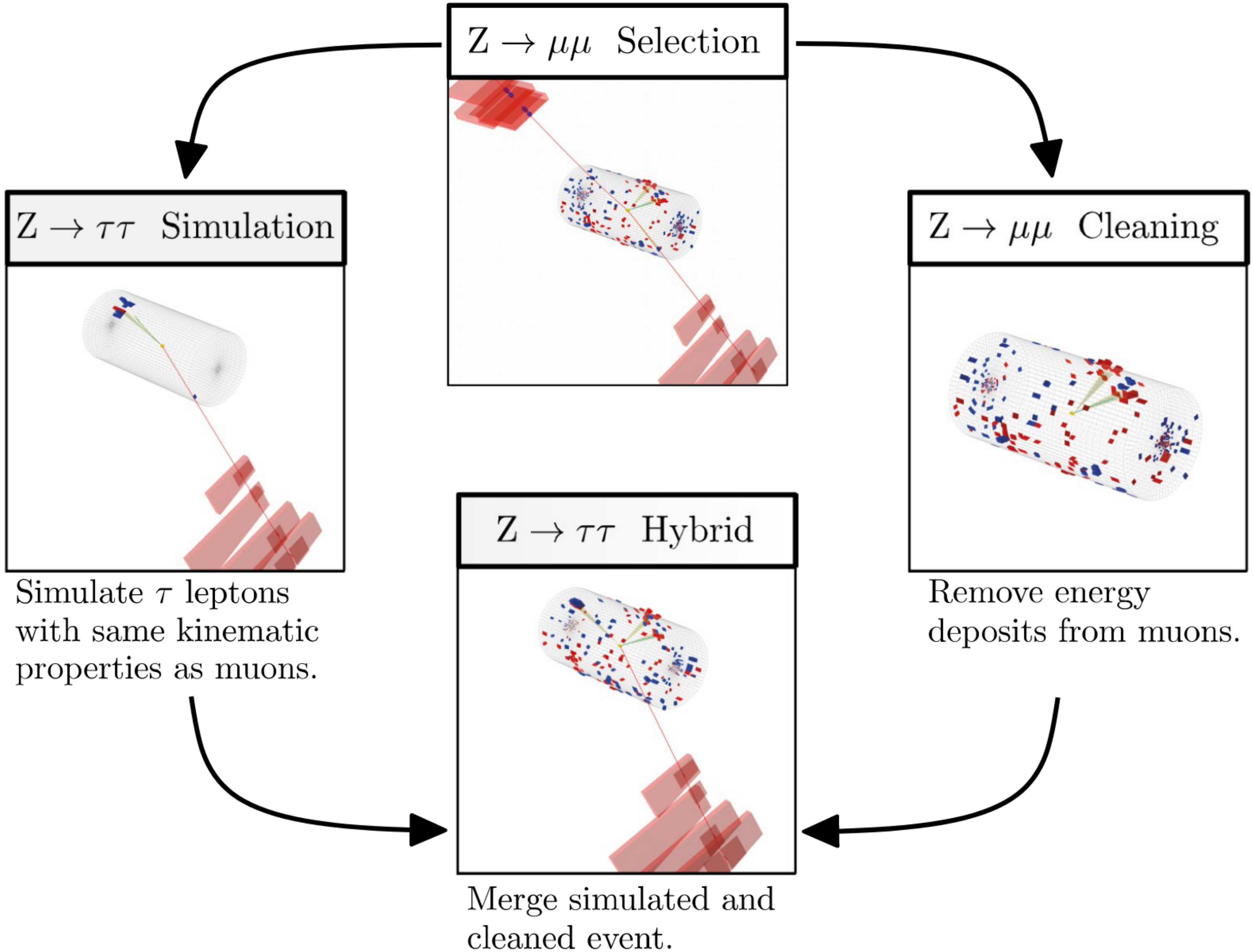
$H \rightarrow \tau\bar{\tau}$

arXiv:2204.12957

- comparison CB and NN based analysis for stage-0 STXS:
  - compatible constrains on μ_{incl} and μ_{ggH}:
    - inclusive result driven by μ_{ggH} which is dominated by systematic uncertainties
      → not taken into account during the training process of the NN
    - separation very difficult between ggH vs. qqH/$Z \rightarrow \tau\bar{\tau}$
- comparison CB and NN based analysis for stage-1.2 STXS:
  - systematic variations smaller in NN-based approach
    → NN uses 14D input space, so systematic variations of single features impact result less
  - NN includes discriminating distributions for background
    → high purity control regions help to constrain nuisance parameters
  - larger samples used for training of NN approach
  - STXS bins in CB approach based on event selection, NN targets best possible separation with multiclassification approach

Embedding technique: $Z \rightarrow \tau\bar{\tau}$

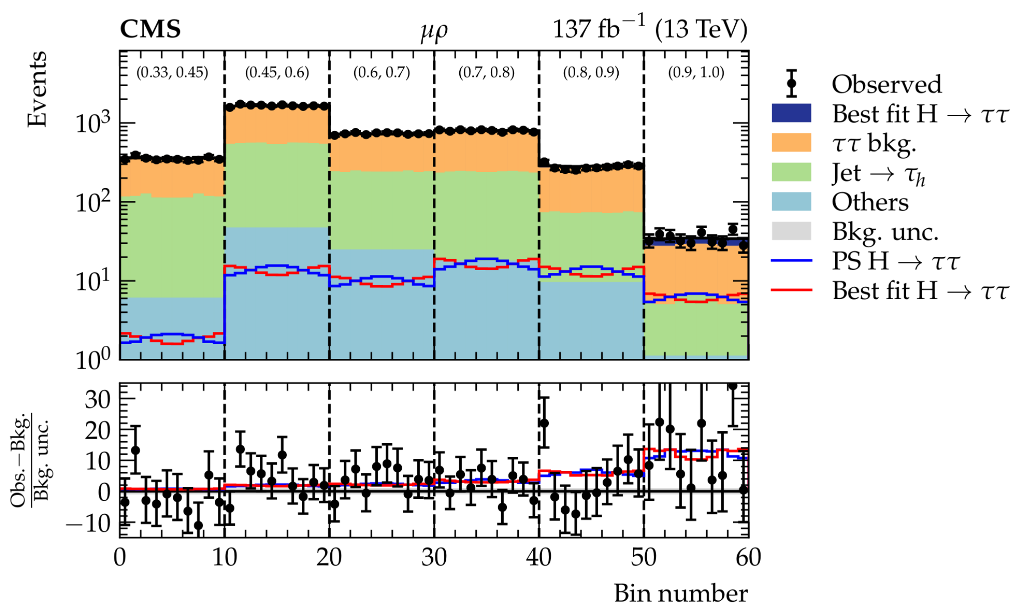
JINST 14 (2019)

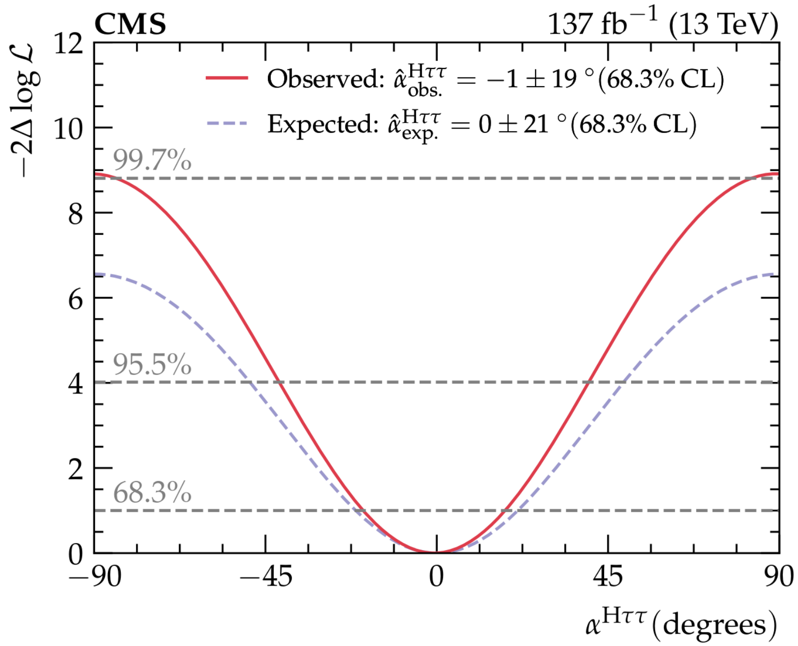


$H \to \tau\bar{\tau}$ (CP)

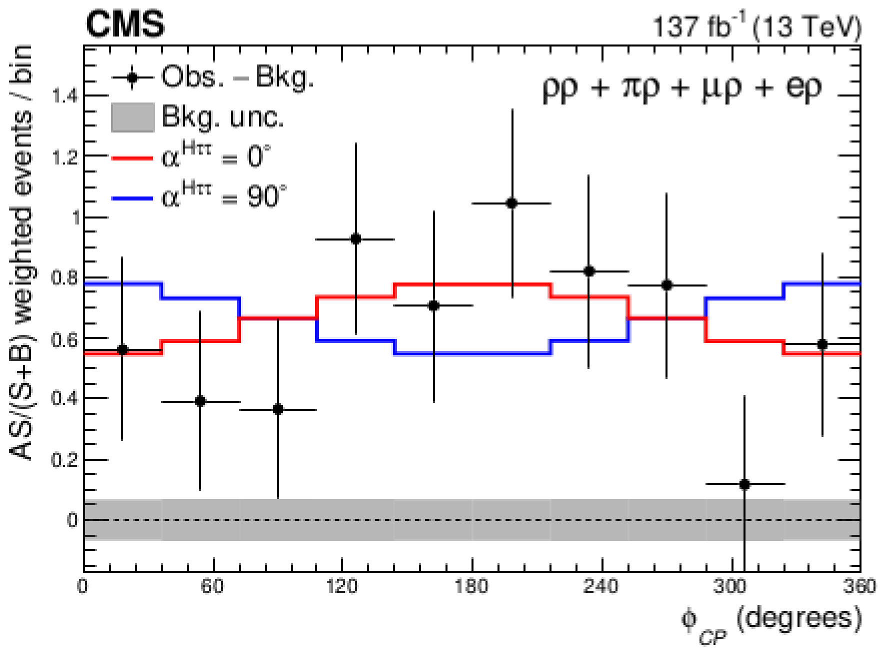
JHEP06 (2022) 012

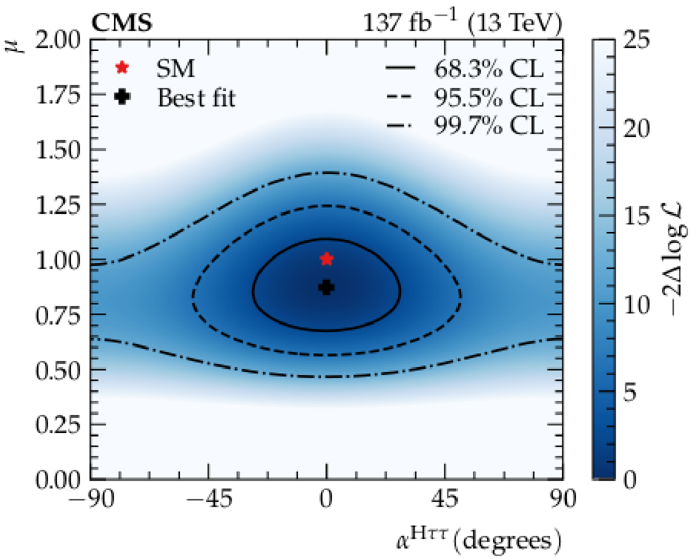
- **first measurement of the CP structure** of the Higgs boson coupling to τ leptons
- **multi-class DNN/BDT discriminant**
  (categories: Higgs, two genuine τ leptons, hadronic jet misidentified as τ_h)
- extraction of results with **2D fit** to maximum multiclass output score and angular correlation between decay planes of τ's
- measurement dominanted by **statistical uncertainty**
- disfavour pure CP-odd scenario at 3σ → **compatible with SM Higgs boson**

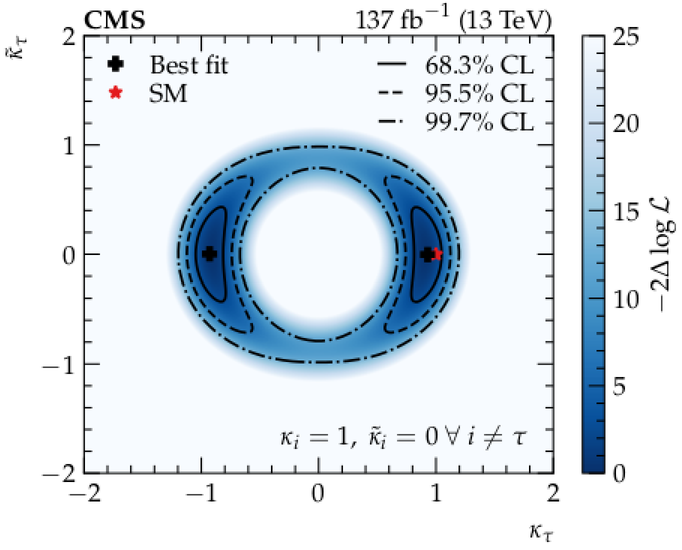




$H \rightarrow \tau\bar{\tau}$ (CP)





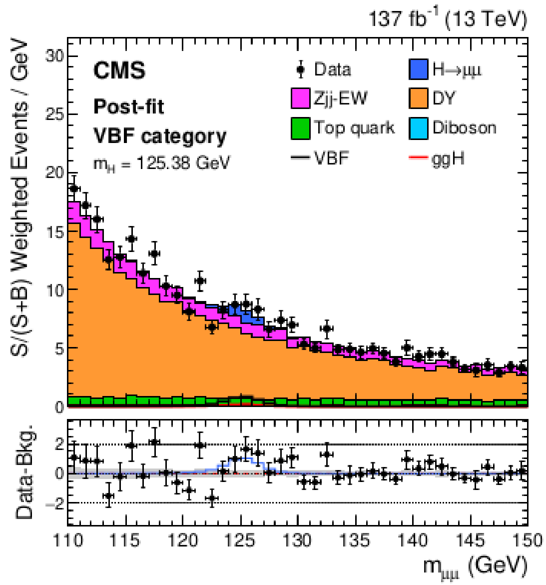


Reconstruction of CP-sensitive observables:

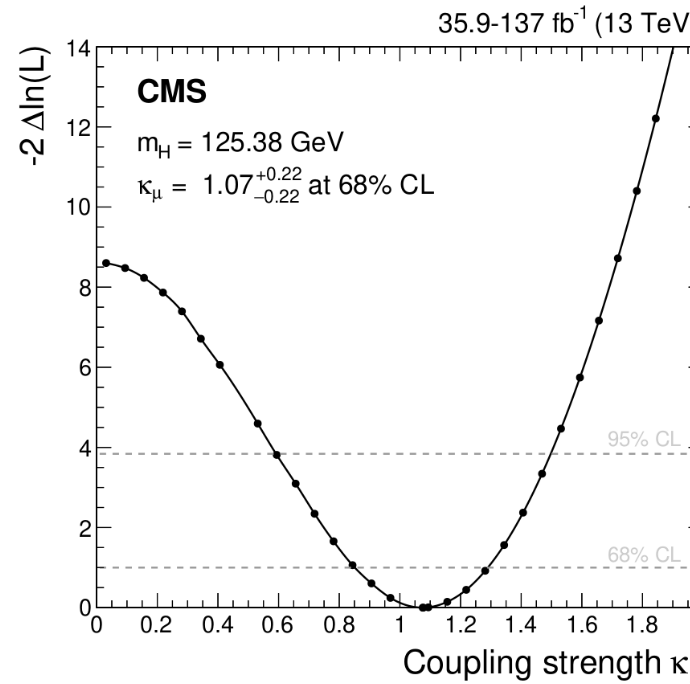
- impact parameter method
- neutral-pion method
- combined method
- polarimetric vector method

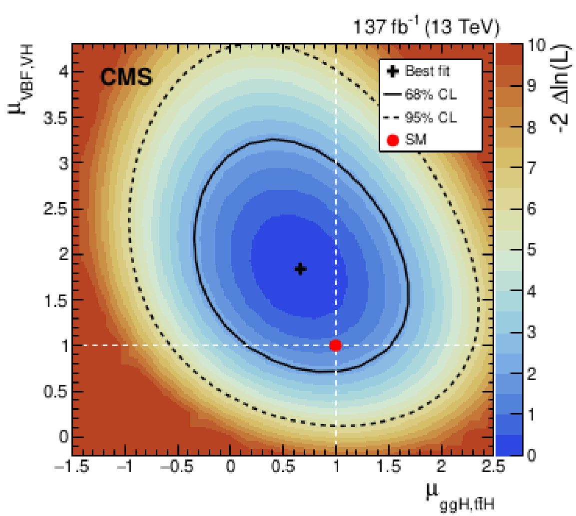
$H \rightarrow \mu\bar{\mu}$

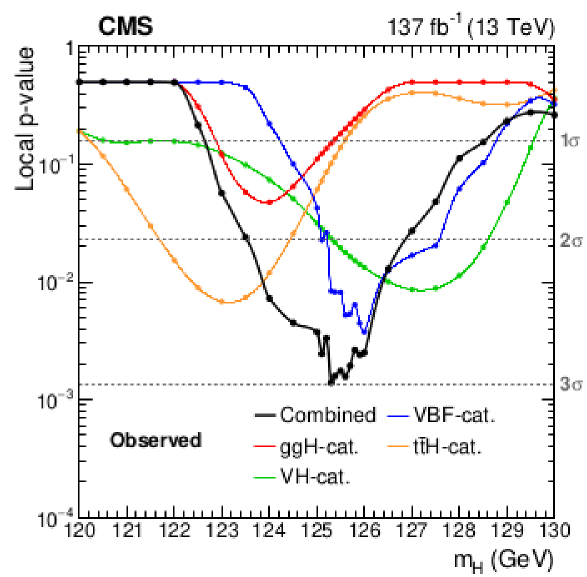
JHEP01 (2021) 148

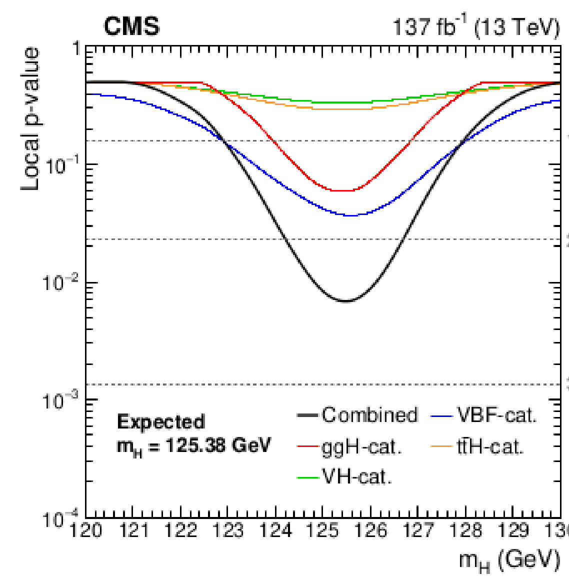


Uncertainty source	$\Delta\mu$	
Post-fit uncertainty	+0.44	−0.42
Statistical uncertainty	+0.41	−0.40
Systematic uncertainty	+0.17	−0.16
Experimental uncertainty	+0.12	−0.11
Theoretical uncertainty	+0.10	−0.11
Size of simulated samples	+0.07	−0.06



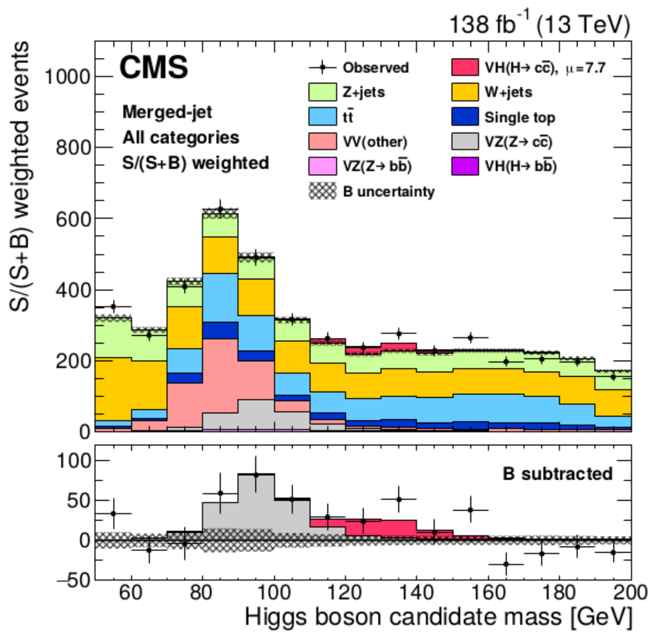


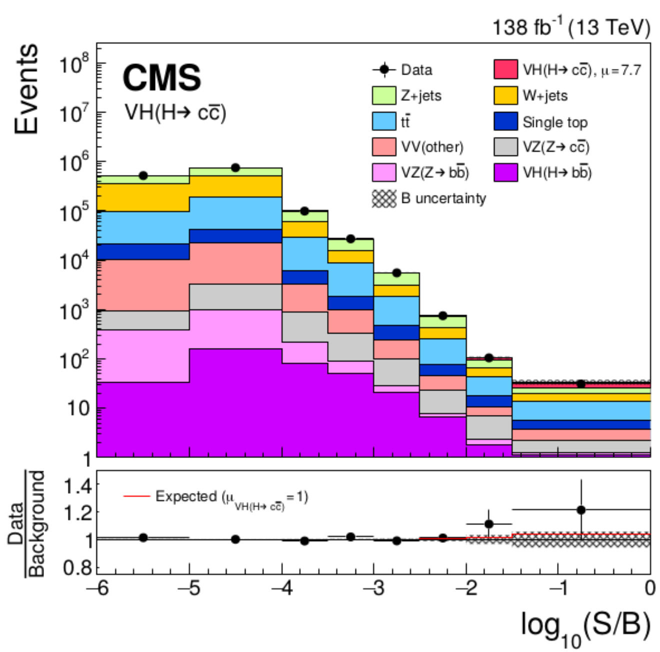




$VH \rightarrow c\bar{c}$

CMS-HIG-21-008



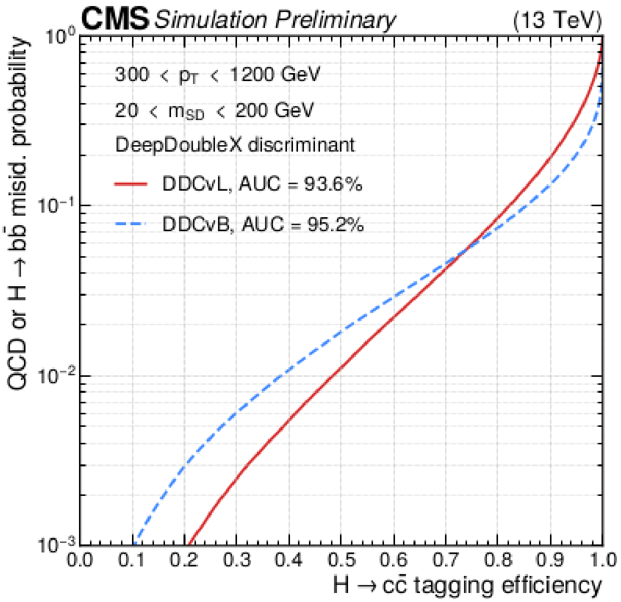


Uncertainty source	$\Delta\mu / (\Delta\mu)_{tot}$
Statistical	85%
Background normalizations	37%
Experimental	48%
Sizes of the simulated samples	37%
c jet identification efficiencies	23%
Jet energy scale and resolution	15%
Simulation modeling	11%
Integrated luminosity	6%
Lepton identification efficiencies	4%
Theory	22%
Backgrounds	17%
Signal	15%

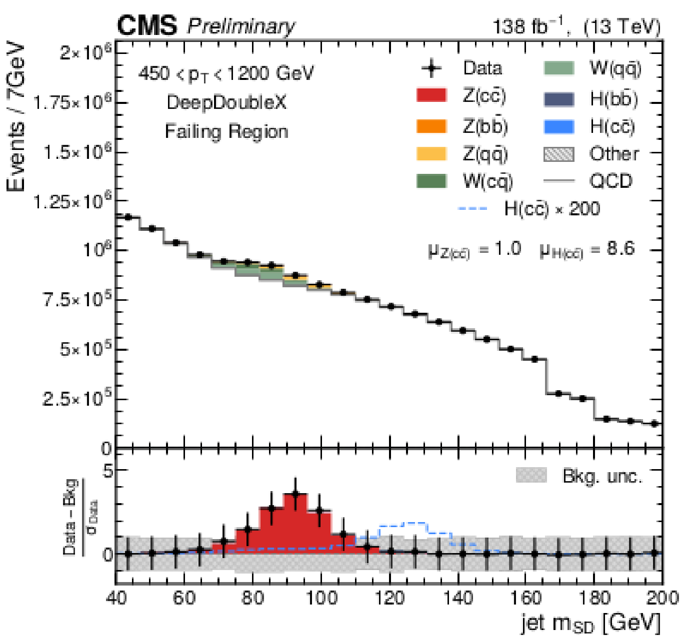
$$1.1 < |\kappa_c| < 5.5 \; (|\kappa_c| < 3.4)$$

ggH → $c\bar{c}$

CMS-HIG-21-012

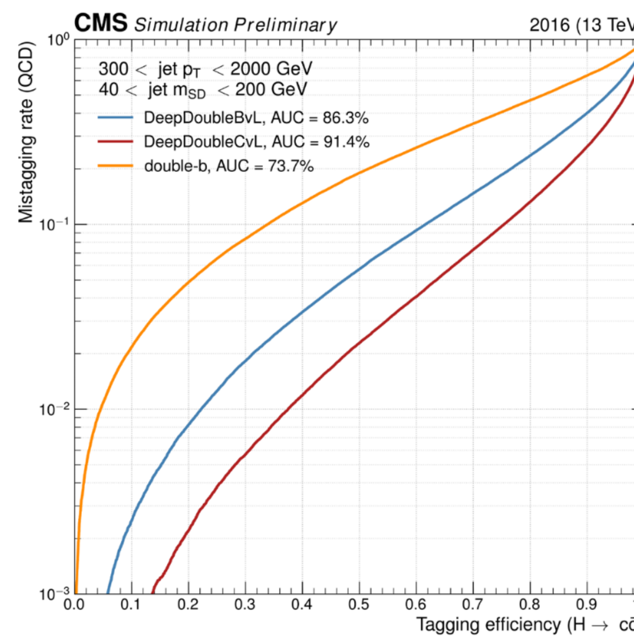


Uncertainty source	$\Delta\mu_H$	
Statistical	+9.2	−9.1
Signal extraction	+6.5	−6.2
QCD pass-fail ratio (data correction)	+7.2	−7.2
$t\bar{t}$ normalisation and misidentification	+0.9	−0.0
Systematic	+10.4	−10.1
QCD pass-fail ratio (simulation)	+9.8	−9.7
Flavour (mis-)tagging efficiency	+2.3	−1.2
Simulated sample size	+3.8	−3.5
Other experimental uncertainties	+0.9	−0.0
Theoretical	+3.5	−1.4
V+jets modelling	+0.9	−1.0
H boson modelling	+3.3	−1.0
Total	+19.9	−19.4



$$\rho(m_{SD}, p_T) = 2\ln(m_{SD}/p_T)$$

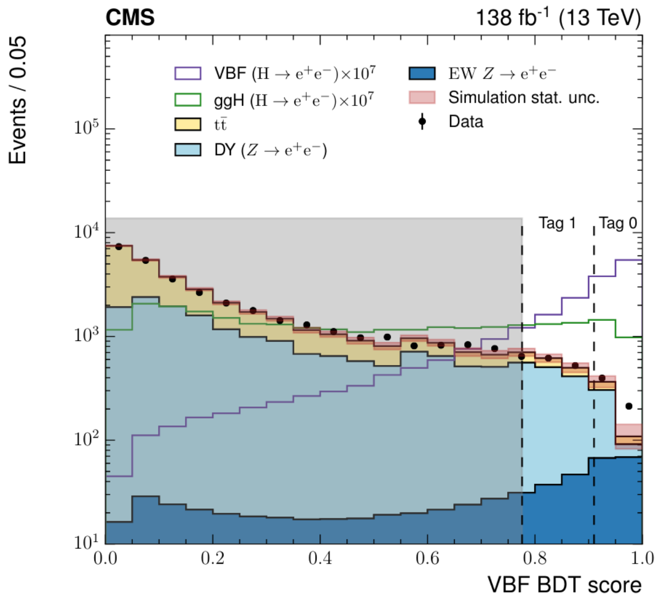
$$-6 < \rho < -2.1$$

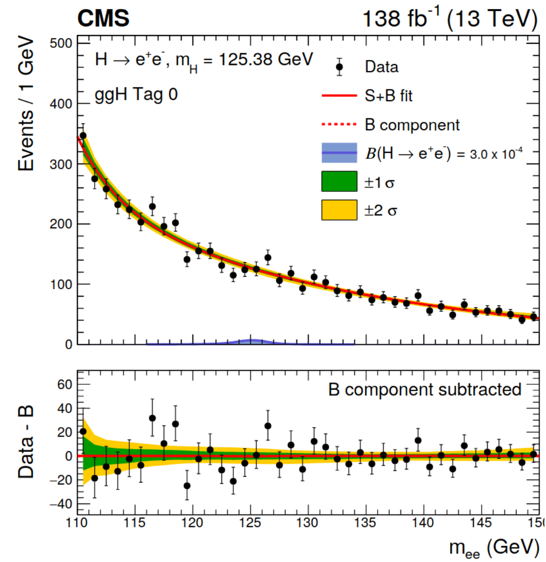


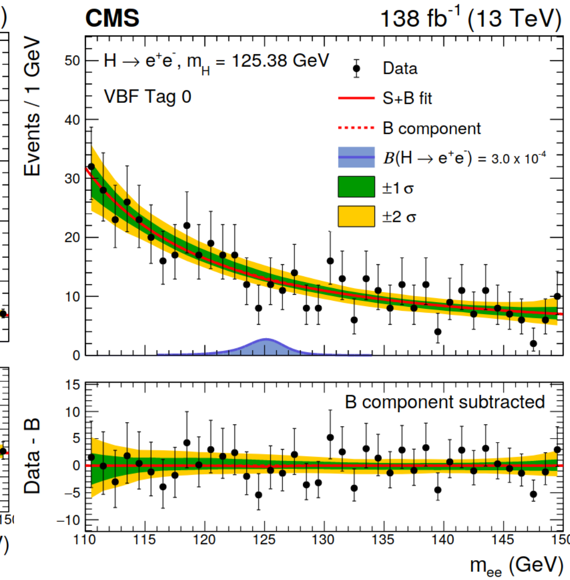
CMS-DP-2018-046

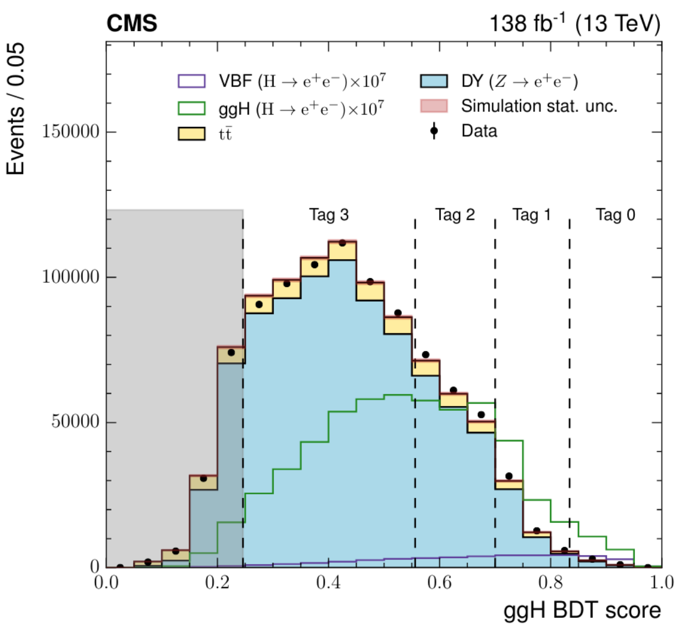
$H \to e^+e^-$

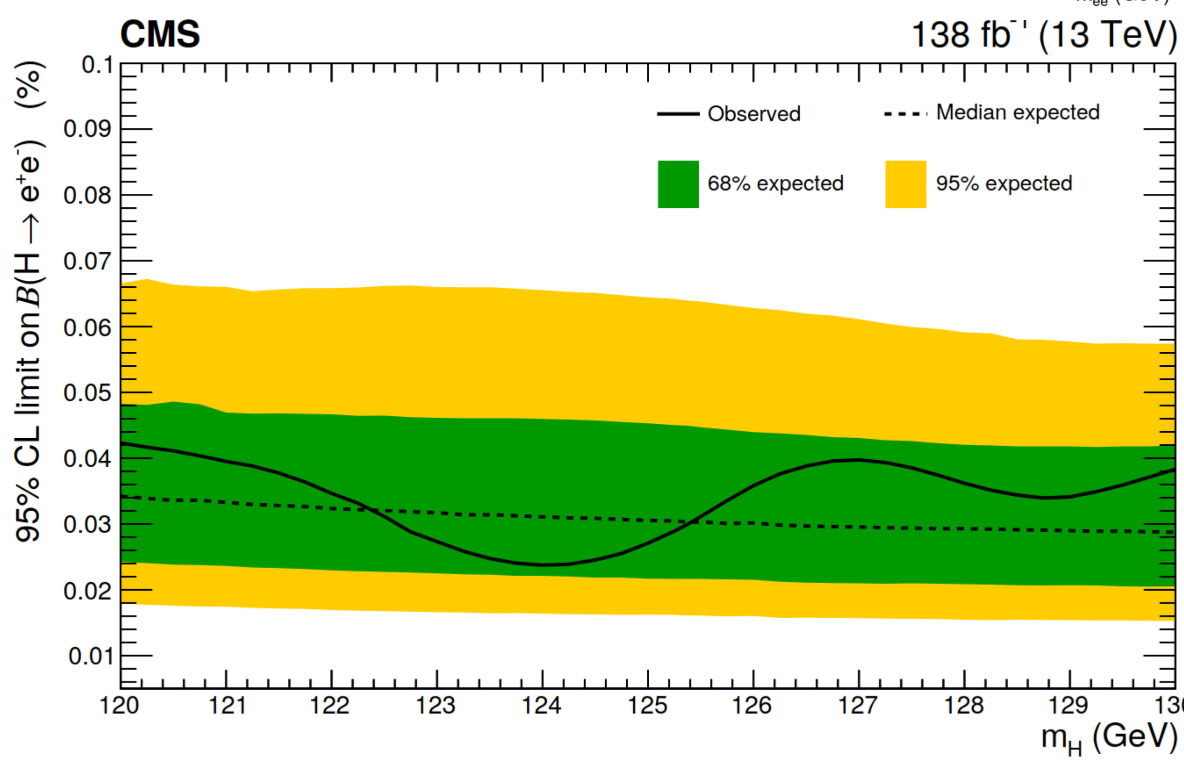
arXiv:2208.00265





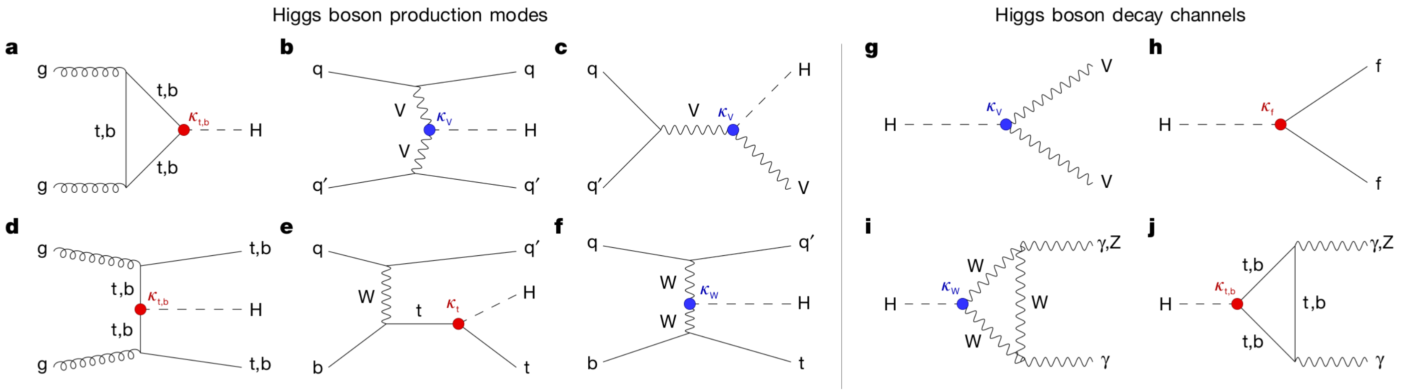




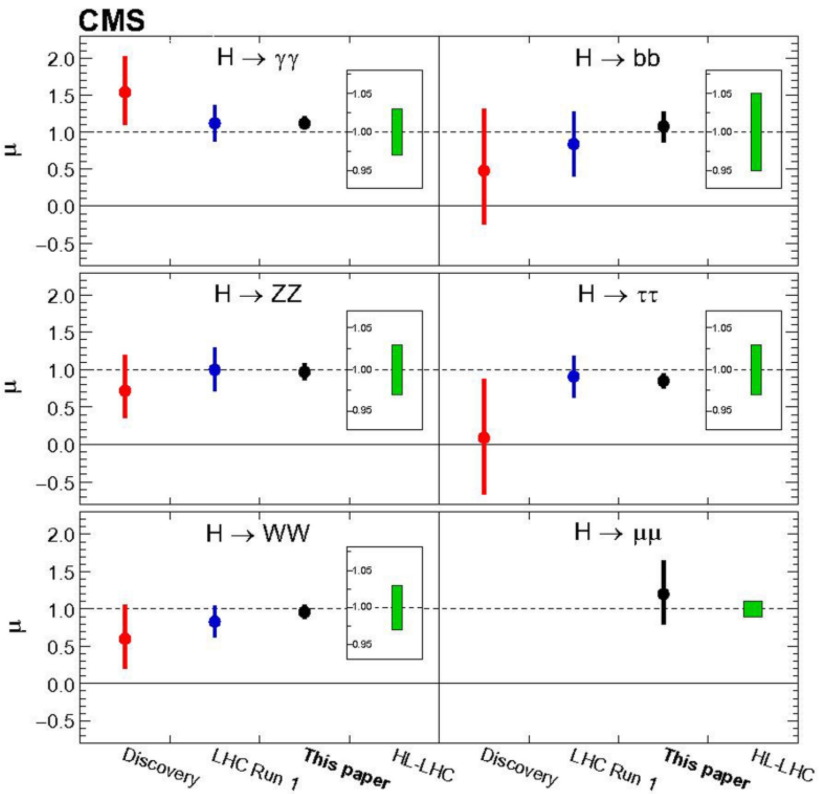


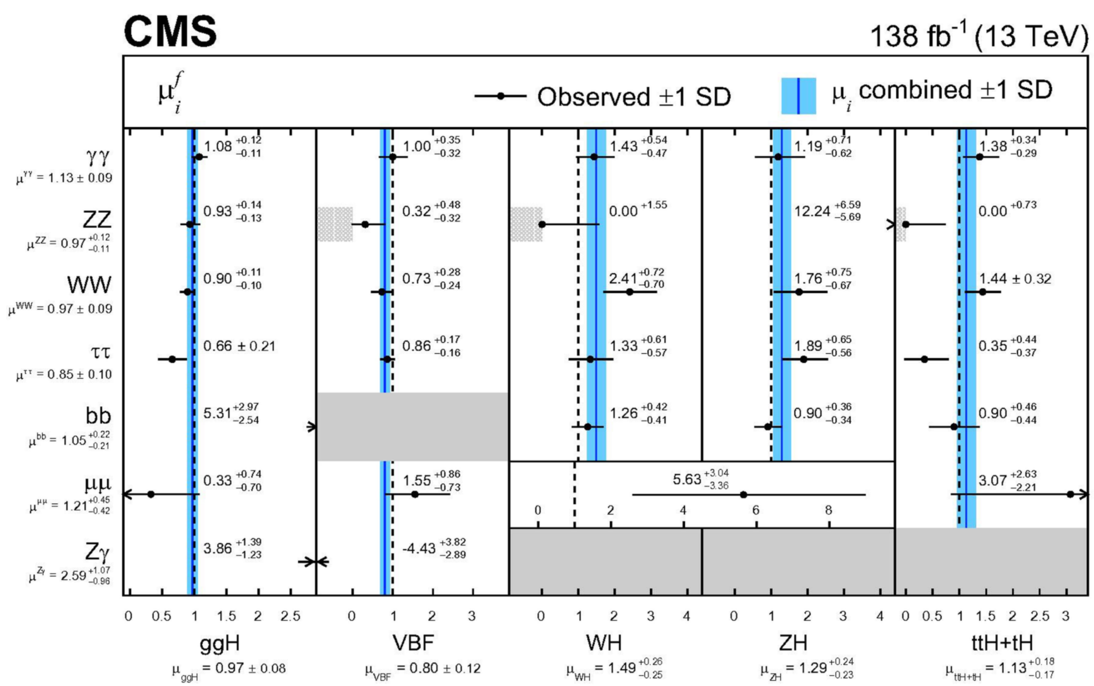
Combination plots

Nature 607, 60–68 (2022)



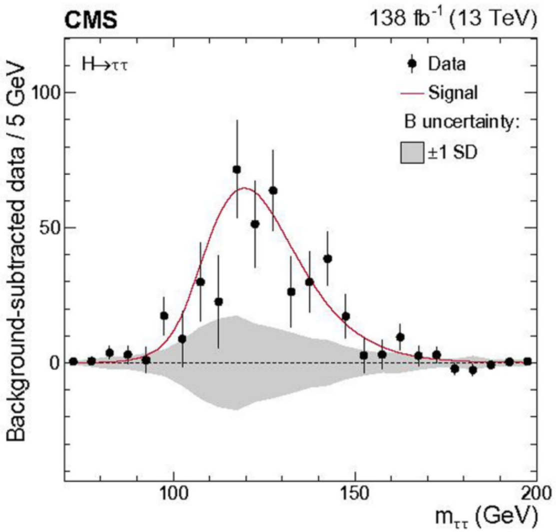
Decay channel	Branching fraction (%)
bb	57.63 ± 0.70
WW	22.00 ± 0.33
gg	8.15 ± 0.42
ττ	6.21 ± 0.09
cc	2.86 ± 0.09
ZZ	2.71 ± 0.04
γγ	0.227 ± 0.005
Zγ	0.157 ± 0.009
ss	0.025 ± 0.001
μμ	0.0216 ± 0.0004

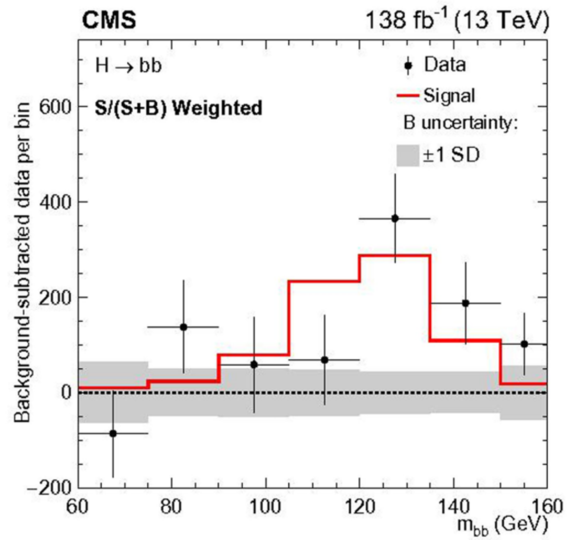


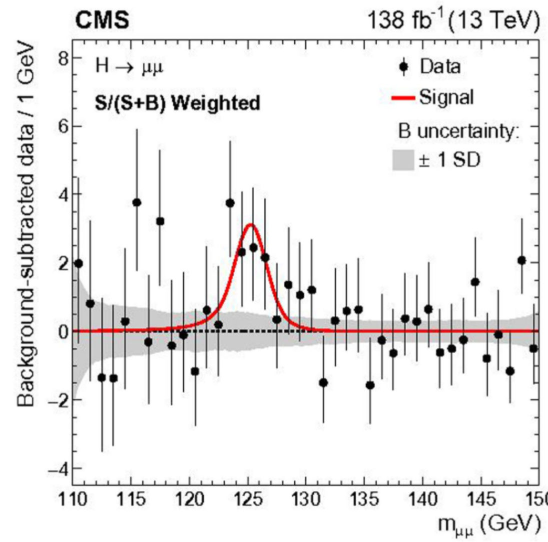


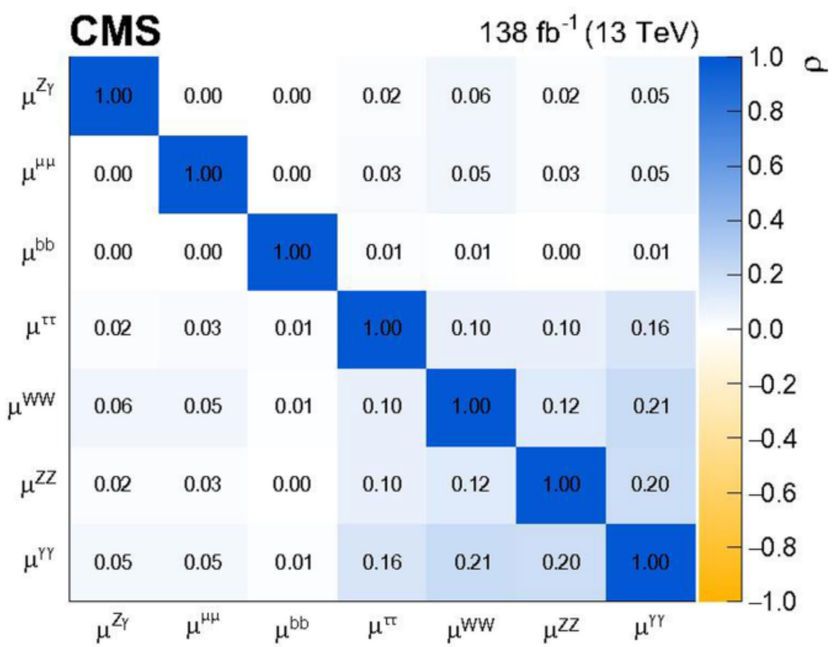
Combination plots

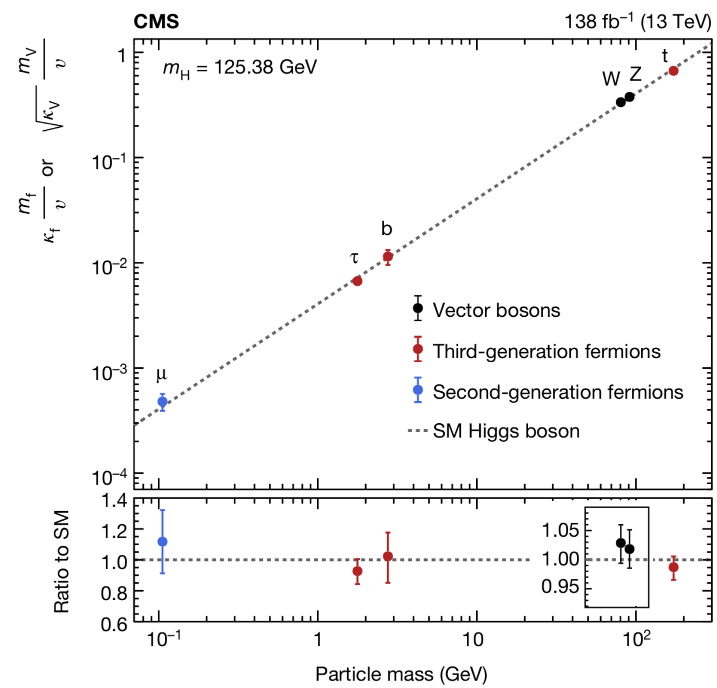
Nature 607, 60–68 (2022)











Combination plots

Nature 607, 60–68 (2022)