Higgs couplings to fermions at CMS

Elisabetta Gallo
(DESY and University of Hamburg, on behalf of the CMS Collaboration)

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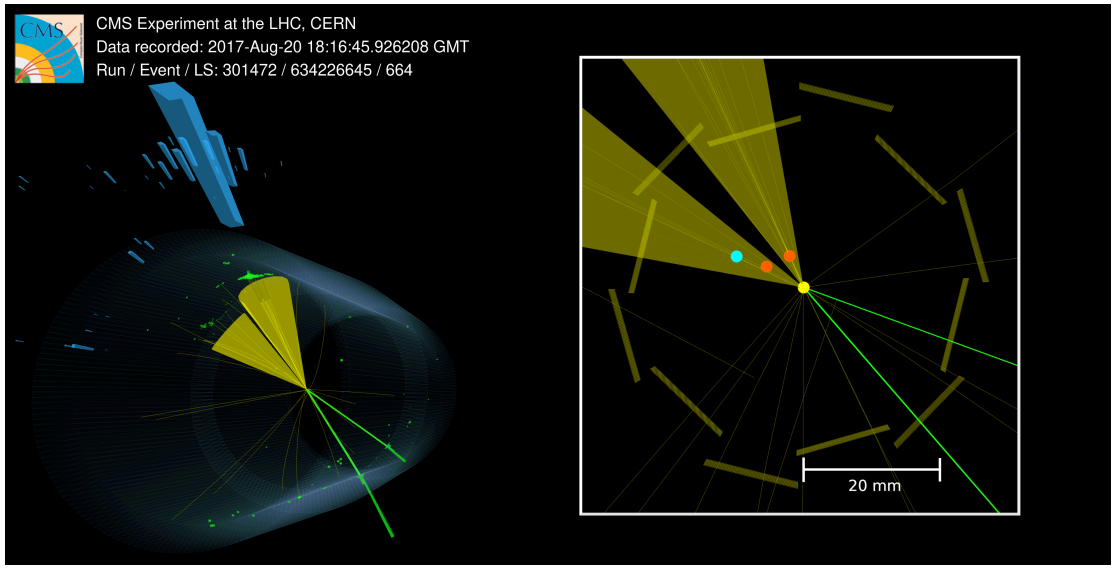


A candidate $H \to b\bar{b}$ event in CMS produced in association with a Z

DIS23 MICHIGAN STATE UNIVERSITY

East Lansing,
28th March 2023

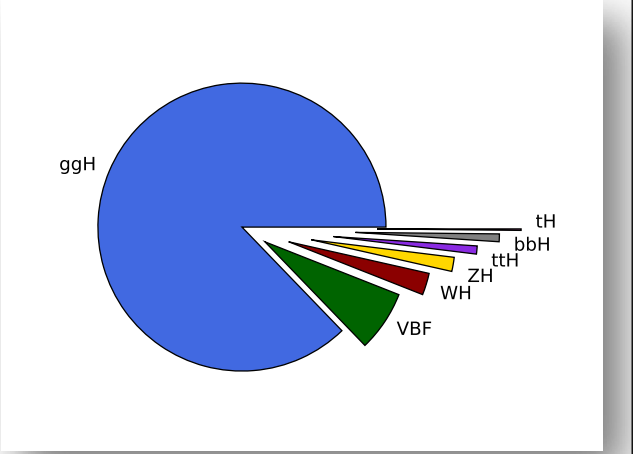
Higgs couplings

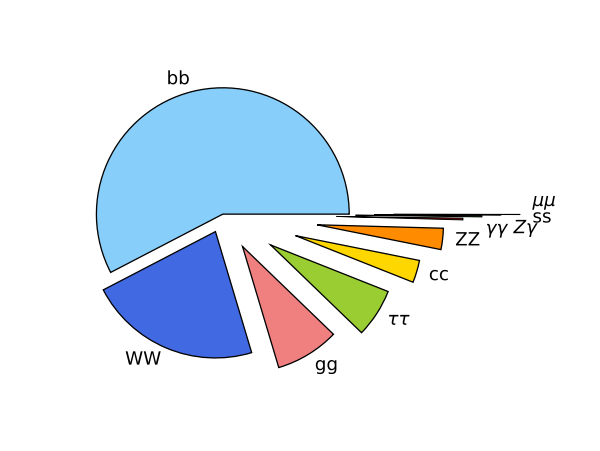
Theoretical cross sections at a mass of 125.38 GeV

The Higgs Yukawa coupling is best measured:

- For top in direct ttH production and/or in combination with ggH production
- For tau leptons and b-, c-quarks in decays
  - b-quark largest branching ratio, but large V+jets or QCD background
  - tau leptons, smaller branching ratio but less background
  - c-jets low BR and challenging background

Production mode	Cross section (pb)	Decay channel	Branching fraction (%)
ggH	48.31 ± 2.44	bb	57.63 ± 0.70
VBF	3.771 ± 0.807	WW	22.00 ± 0.33
WH	1.359 ± 0.028	gg	8.15 ± 0.42
ZH	0.877 ± 0.036	$\tau\tau$	6.21 ± 0.09
ttH	0.503 ± 0.035	cc	2.86 ± 0.09
bbH	0.482 ± 0.097	ZZ	2.71 ± 0.04
tH	0.092 ± 0.008	$\gamma\gamma$	0.227 ± 0.005
		$Z\gamma$	0.157 ± 0.009
		ss	0.025 ± 0.001
		$\mu\mu$	0.0216 ± 0.0004

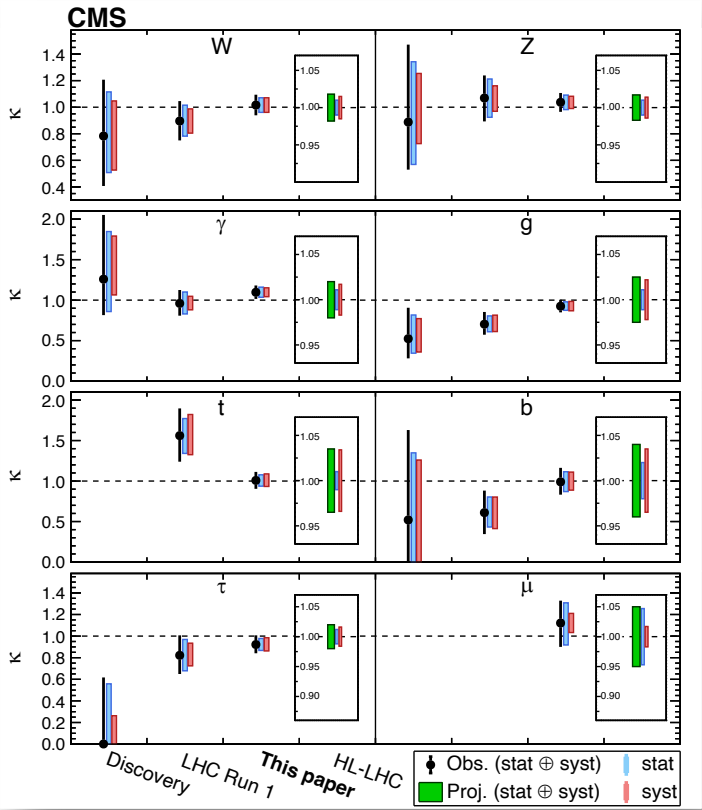


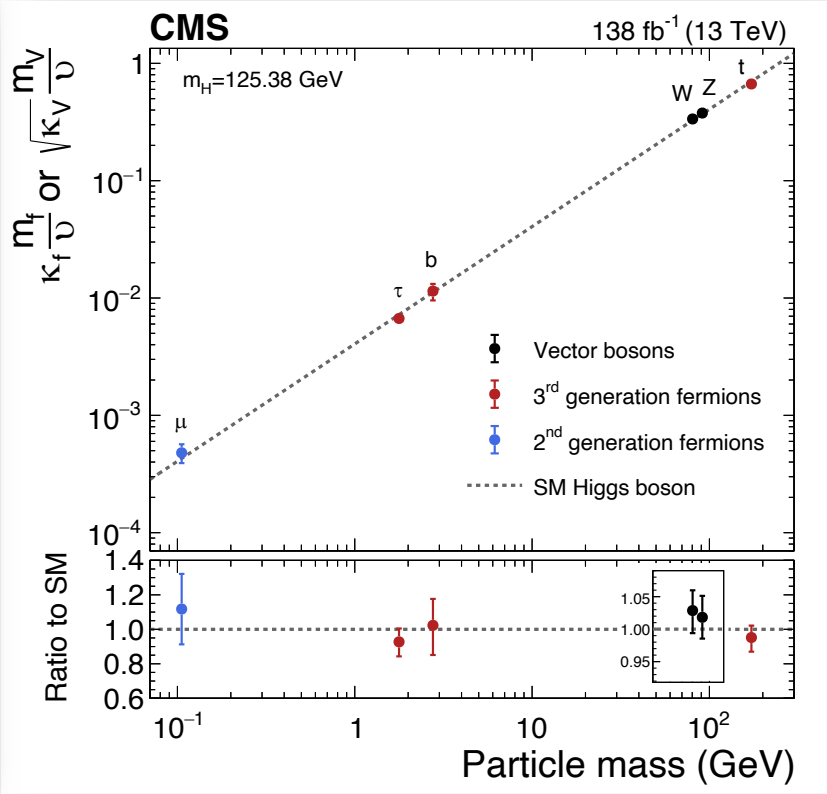


Higgs to fermion Yukawa coupling

- Third generation coupling established at 5 σ in CMS alone in $b\bar{b}$ (2018) and $\tau^+\tau^-$ (2017) in decay and in top (2018) in production
- Recent combined extraction of couplings: precision of 10% for the tau coupling, >~15% for the top and b-couplings in the k-framework
- Now moving also to Simplified Template Cross Section (STXS) and more differential distributions
- Also CP constraints in τ decays (paper)
- A selection of latest results shown here in τ, b and c decays

A portrait of the Higgs boson by the CMS experiment ten years after the discovery Nature 607 (2022) 60-68



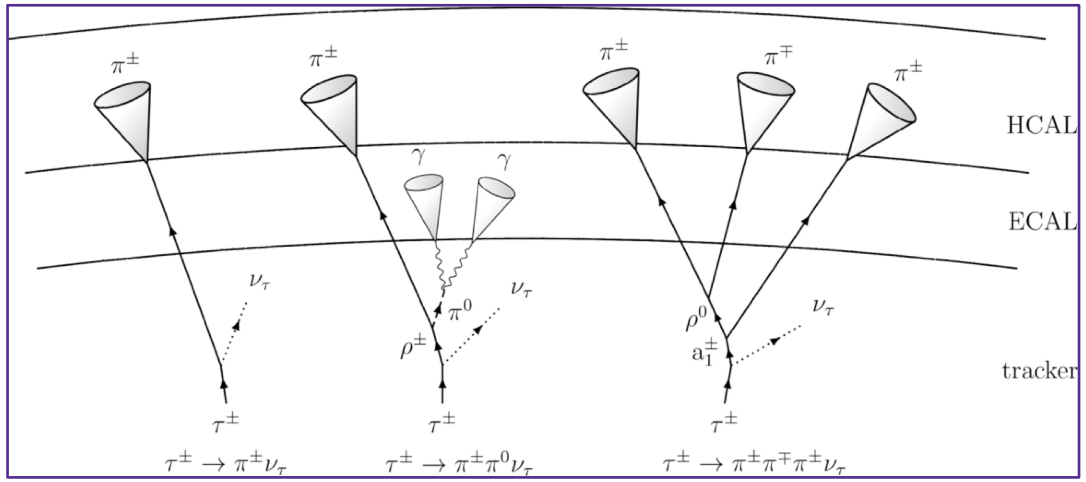


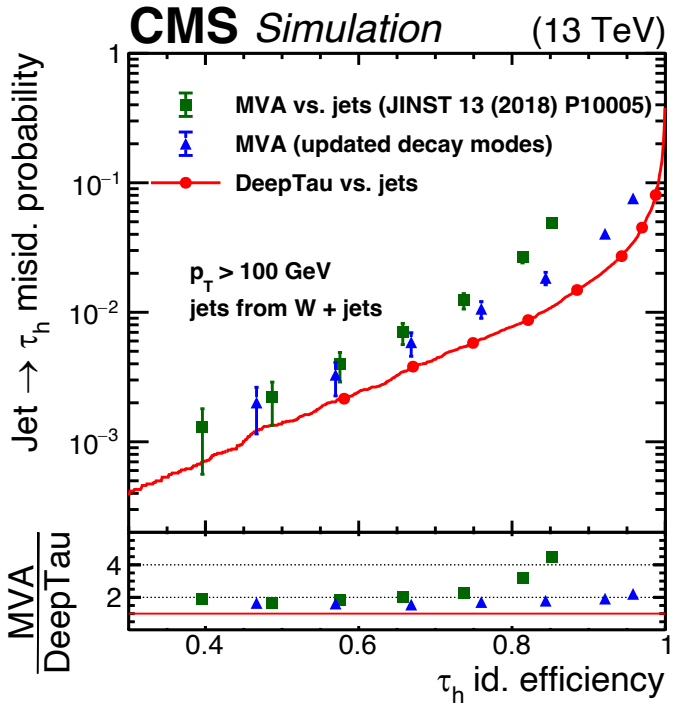
τ lepton reconstruction in CMS

- For $H \to \tau\tau$, decay channels included: $e\mu, e\tau_h, \mu\tau_h, \tau_h\, \tau_h,$

- CMS has an algorithm for hadronic tau decays, HadronPlusStrip (HPS) and a Deep neural network for further discrimination from electrons, muons, and QCD jets (DeepTau)

Decay mode	Resonance	$\mathcal{B}$ (%)	
Leptonic decays		35.2	
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$			17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$			17.4
Hadronic decays		64.8	
$\tau^- \to h^- \nu_\tau$			11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$		25.9
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$		9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$		9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$			4.8
Other			3.3





JINST 17 (2022) P07023

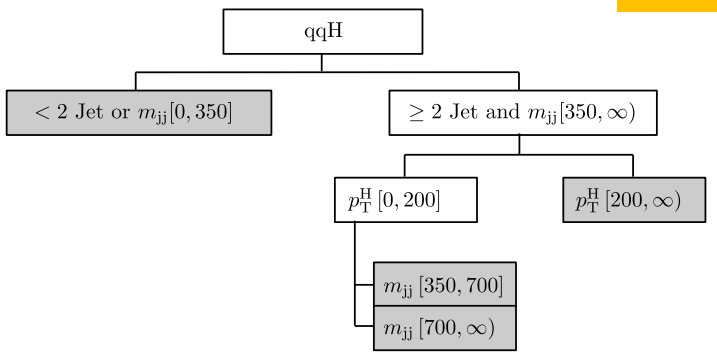
$H \rightarrow \tau\tau$

arXiv:2204.12957

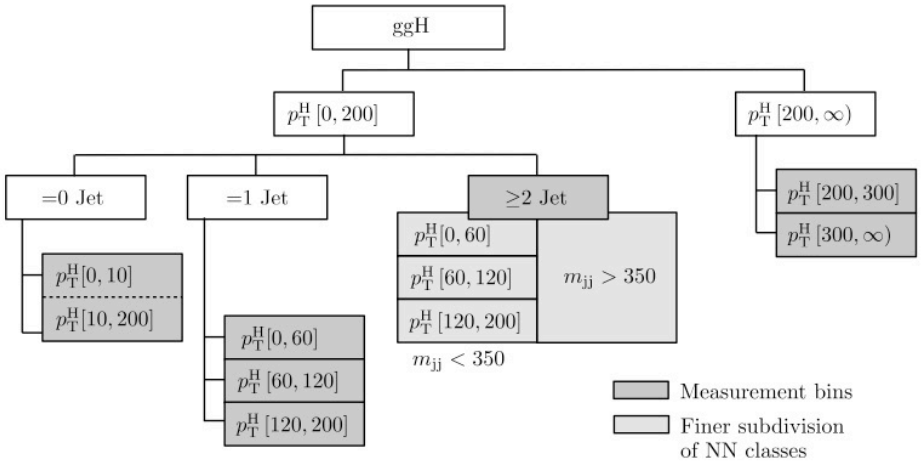
- Based on all Run 2 CMS data (138 fb^{-1})
- Goal and analysis strategy: measure the STXS stage 0 and 1.2 in the ggH, qqH and VH channels

- Two analyses strategies for ggH+qqH: one Cut Based (CB), one based on a Neural Network (NN)
- One analysis targeting VH production

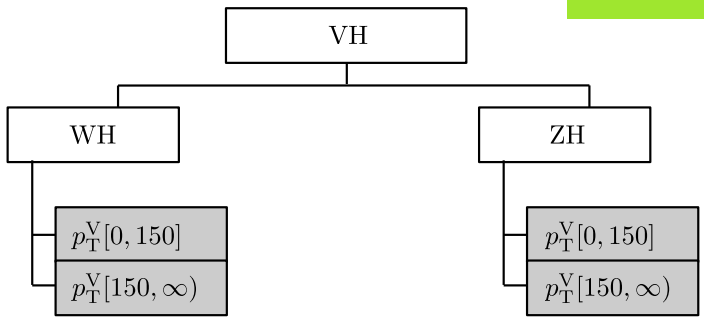
qqH



ggH

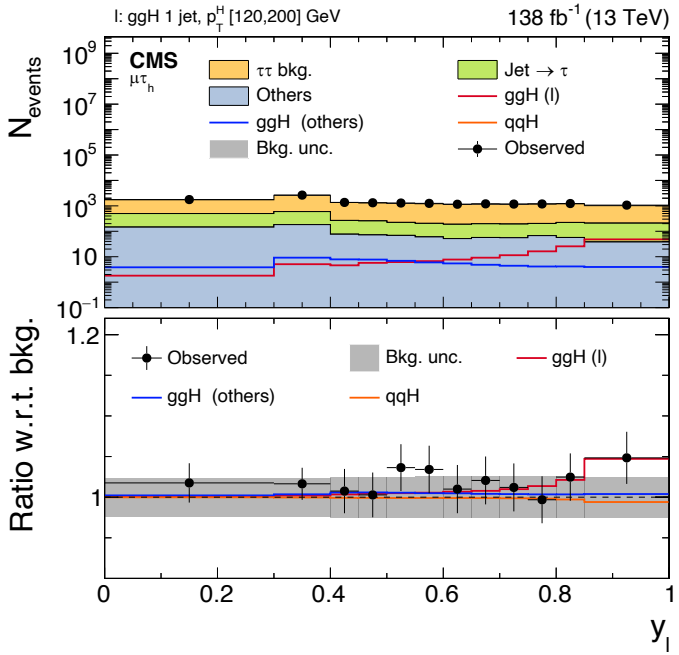


VH



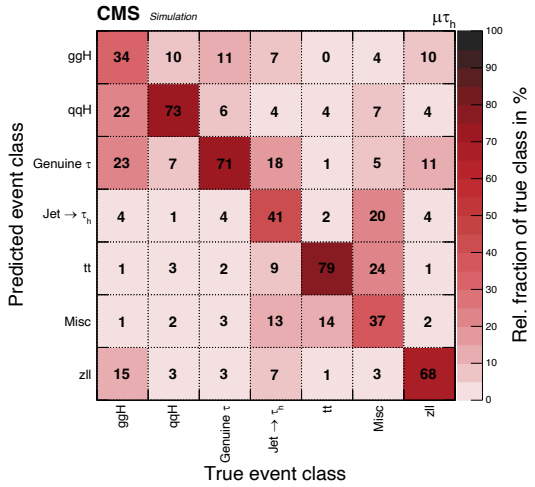
Neural Network classes

- Multiclass neural networks trained on signal and backgrounds:
  - For Stage 0 two signal classes (ggH and qqH) and 5 background classes
  - For Stage 1.2 20 classes (15 signal STXS bins)

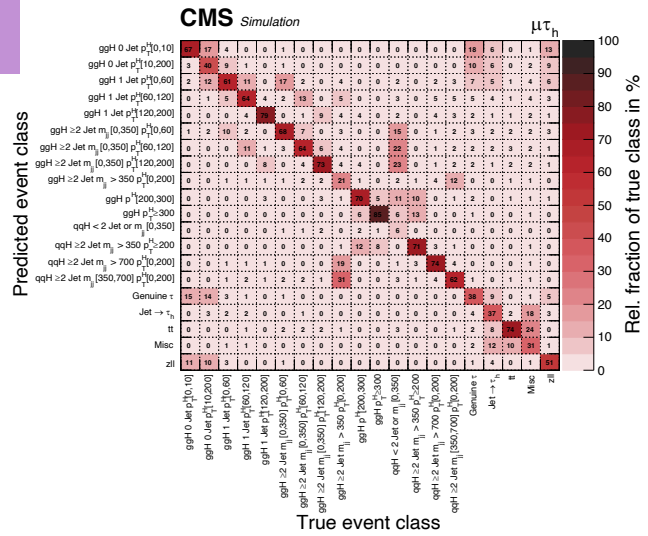


Example of output discriminant in one of the NN classes

Stage 0



Stage 1.2

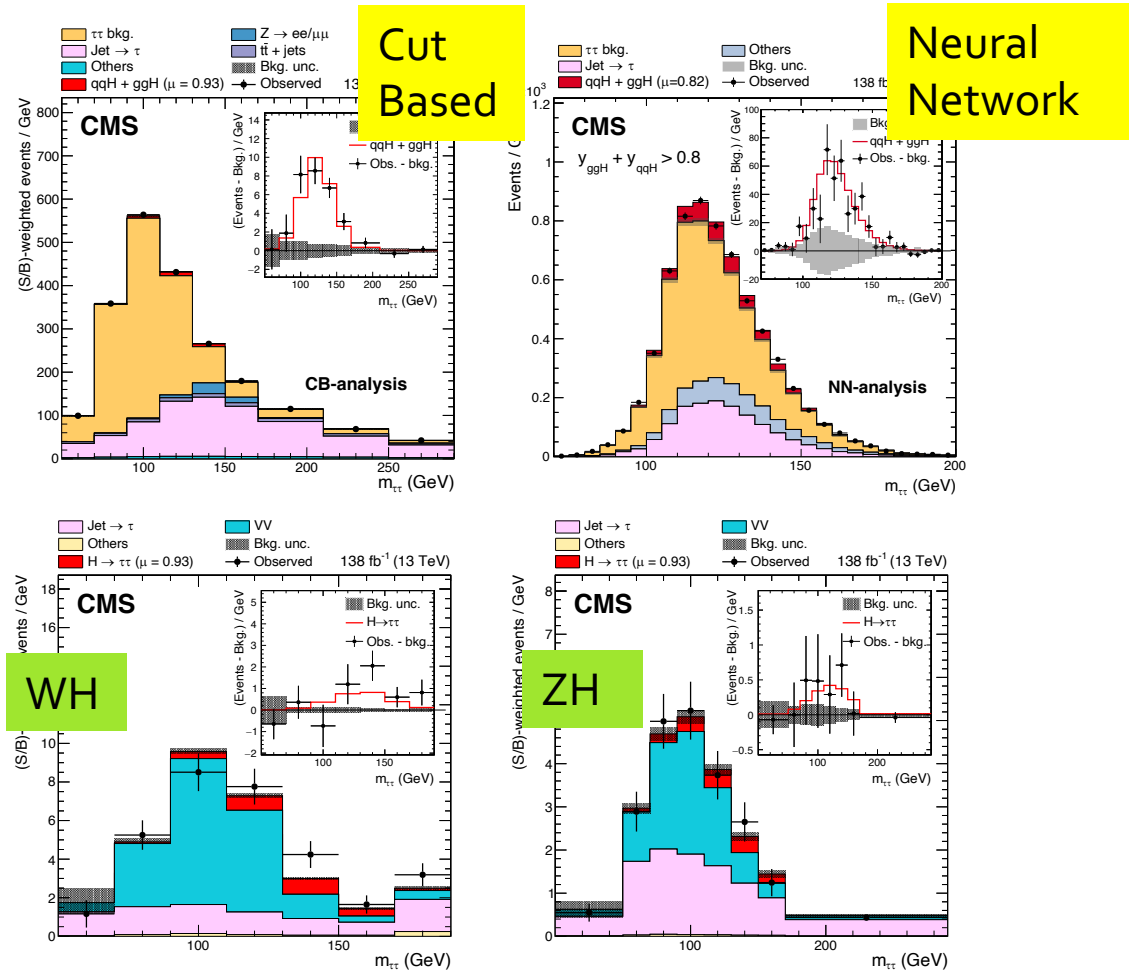


Confusion matrix in the $\mu\tau_h$ channel

Output distributions

- ~ 90% of background is estimated from data:
  - Z→ ττ with an embedding technique starting from Z → μμ data, assuming LFU and substituting the muons with simulated $\tau's$
  - Jets in fake tau candidates with a fake factor method, where the factors are evaluated in an orthogonal application region

- The CB analysis (ggH+qqH) is based on event categorization optimized to signal versus background in 1-D or 2-D distributions
- The NN analysis (ggH+qqH) uses the 2D(ggH-qqH) or 1D (STXS bins) distributions of the discriminants as fitting variable
- The VH analysis fits the 2D distribution in reconstructed Higgs mass and p_T

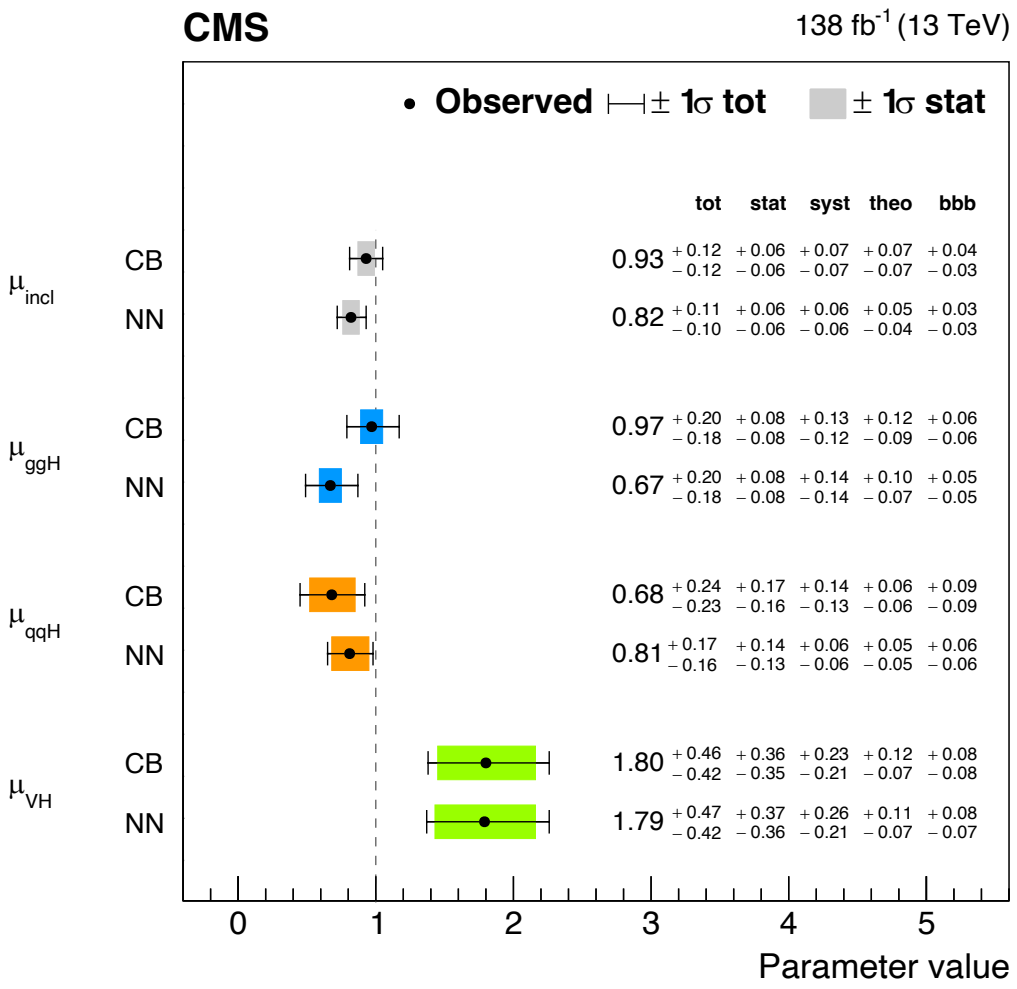


Results in STXS stage 0

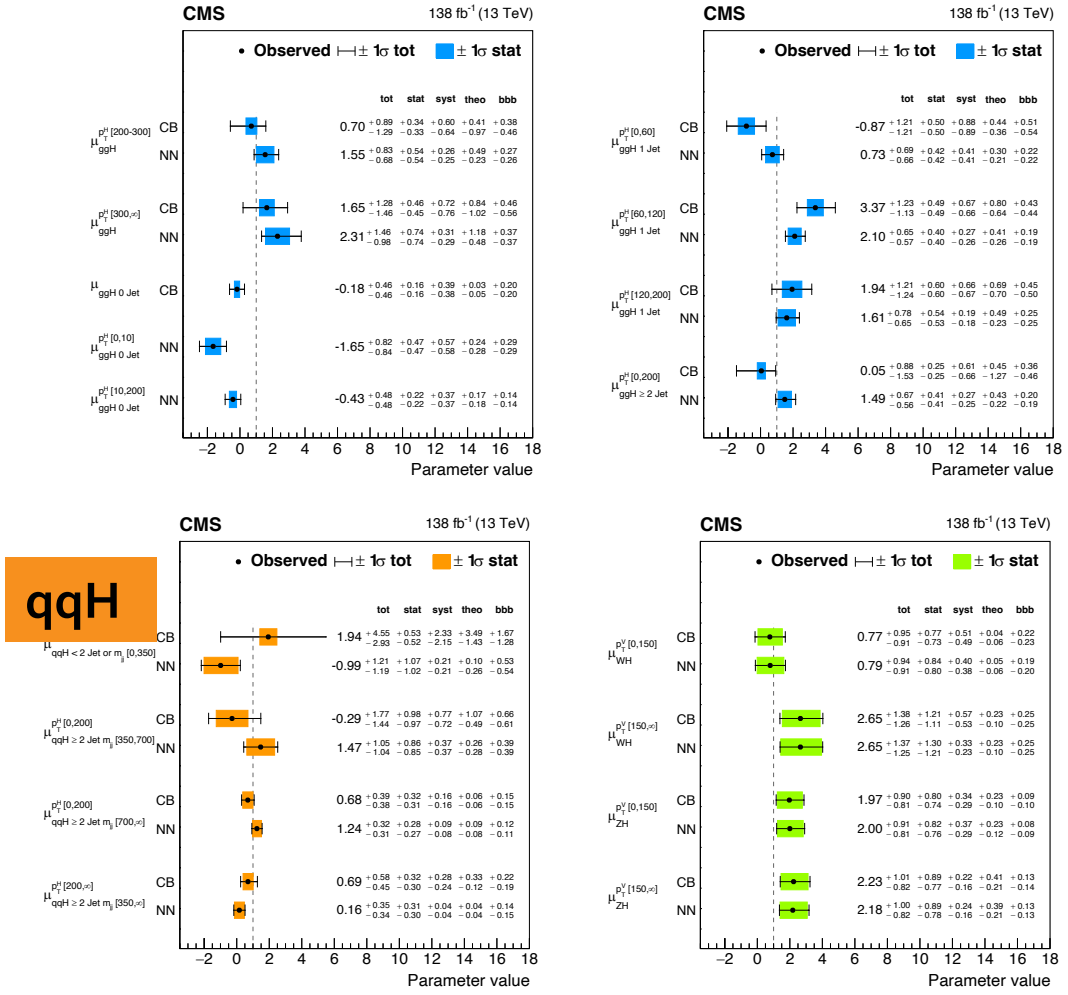
- Stage 0 cross sections/signal strengths are in agreement with the SM
- Experimental systematics uncertainties (”syst”) are of the same order of statistical uncertainties
- Theoretical uncertainties are of similar order
- The bin-by-bin uncertainties are due to the limited MC statistics
- The NN analysis is more performant compared to the CB in the VBF channel

- Inclusive signal strength:

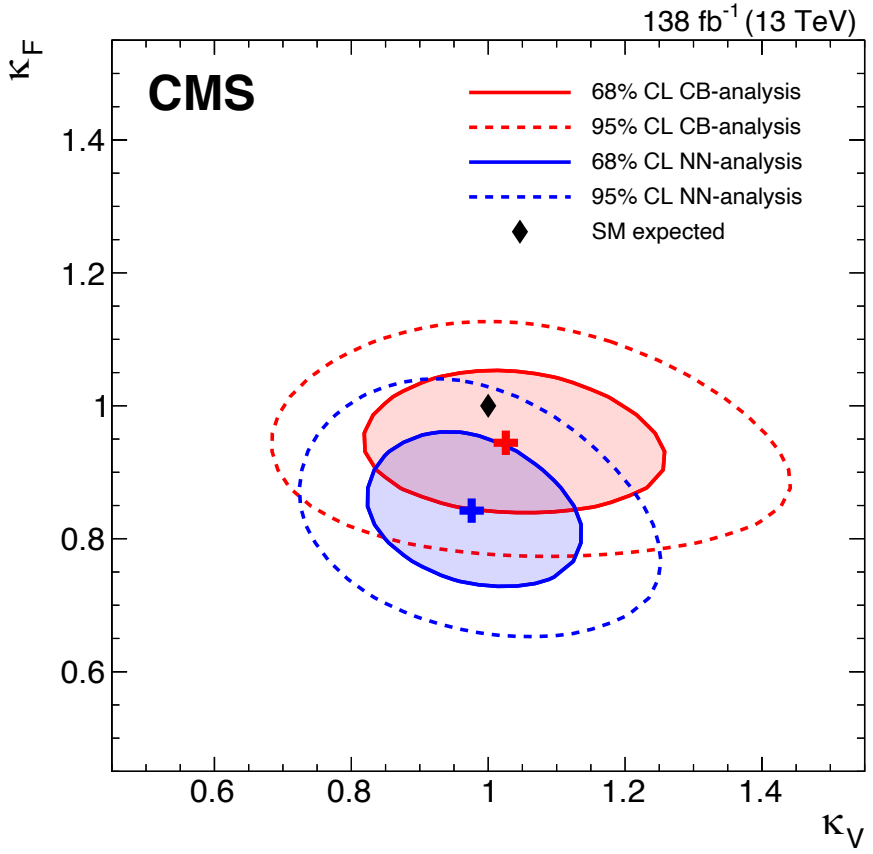
$$\mu = 0.82 \pm 0.11$$



Results in STXS stage 1.2



Also fermion and vector couplings from a fit in the k-framework



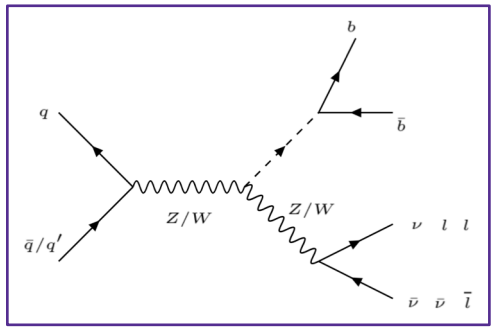
VH, $H \rightarrow bb$ channel

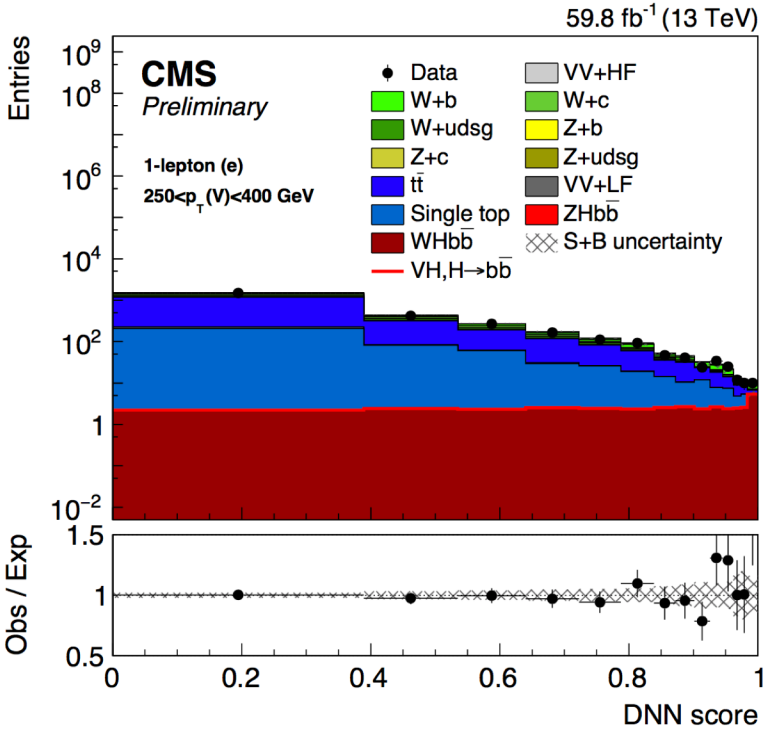
- b-Yukawa coupling best measured in associated WH (1-lepton) or ZH production (0-leptons, 2 leptons)

- Analysis strategies:
  - Resolved and merged jet (for high Higgs p_T) categories
  - FSR recovery, b-jet energy regression and kinematic fit for the 2 lepton channel
  - Main backgrounds (V+light jets, V+ HF jets, top pair) constrained in control regions
  - BDTs or DNN output as discriminating variable to extract the signal

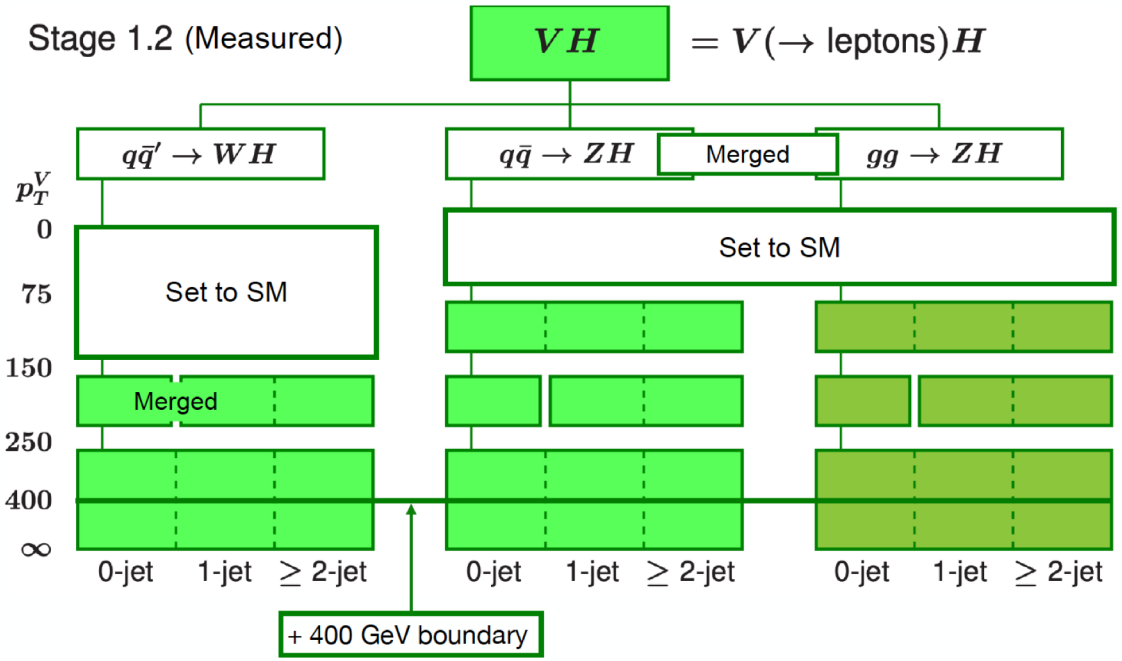
- Cross checks: VZ, $Z \rightarrow bb$; m_{jj} independent analysis

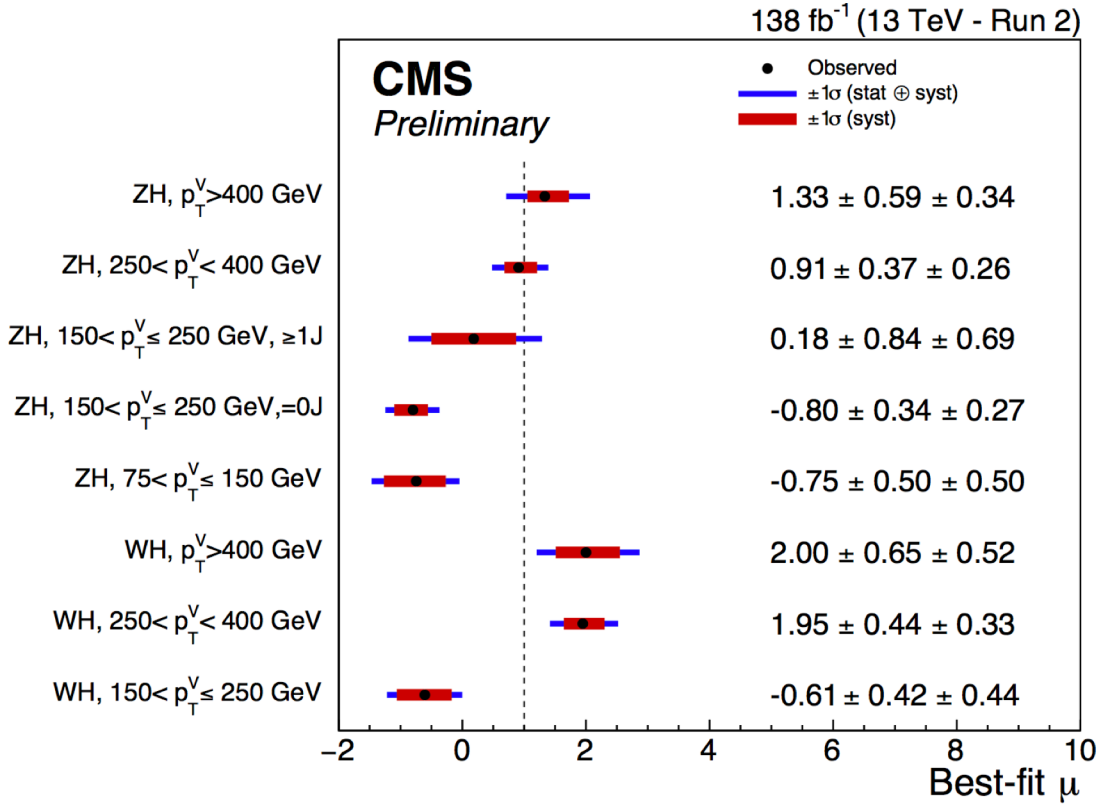
CMS-PAS-HIG-20-001





STXS in the $H \to bb$ channel





- Analysis categories are designed to match the STXS bins
- The splitting in the highest p_T bins will give sensitivity to anomalous couplings and EFT effects.

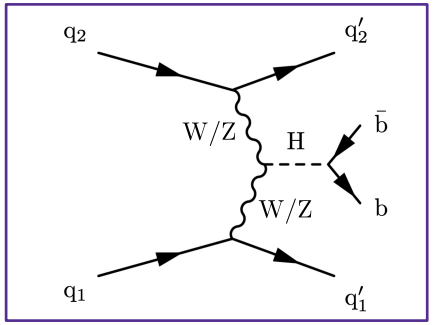
In general good agreement with the SM STXS predictions

$H \rightarrow bb$ in the VBF channel

CMS-PAS-HIG-22-009

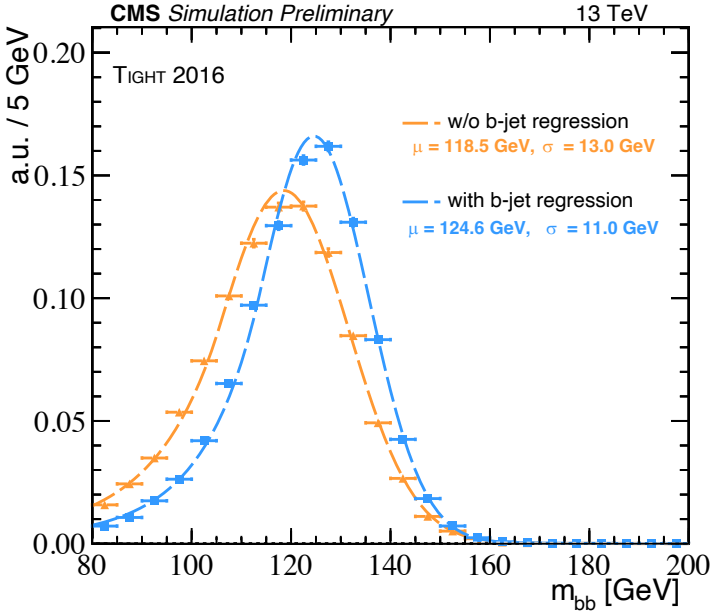
- Dedicated analysis based on 91 fb^{-1} at 13 TeV, adding sensitivity on the b-Yukawa on top of the traditional VH channel

- Signature: two b-jets from the Higgs decay, two additional jets with large m_{jj}, $\Delta\eta_{jj}$



- Two VBF triggers in 2016, 2018 data with Loose and Tight VBF criteria on the VBF topology. Analysis strategy:
  - For the Tight: a BDT binary classifier VBF vs QCD
  - For the Loose: a BDT multiclass, VBF, ggH, Z->bb

- b jets identified by the DeepJet algorithm based on a DNN and energy regression algorithm applied, based on a DNN trained in top-pairs events



$H \to bb$ in the VBF channel

The signal is extracted from the fit of a parametric function to the m_{bb} distribution as sum of:

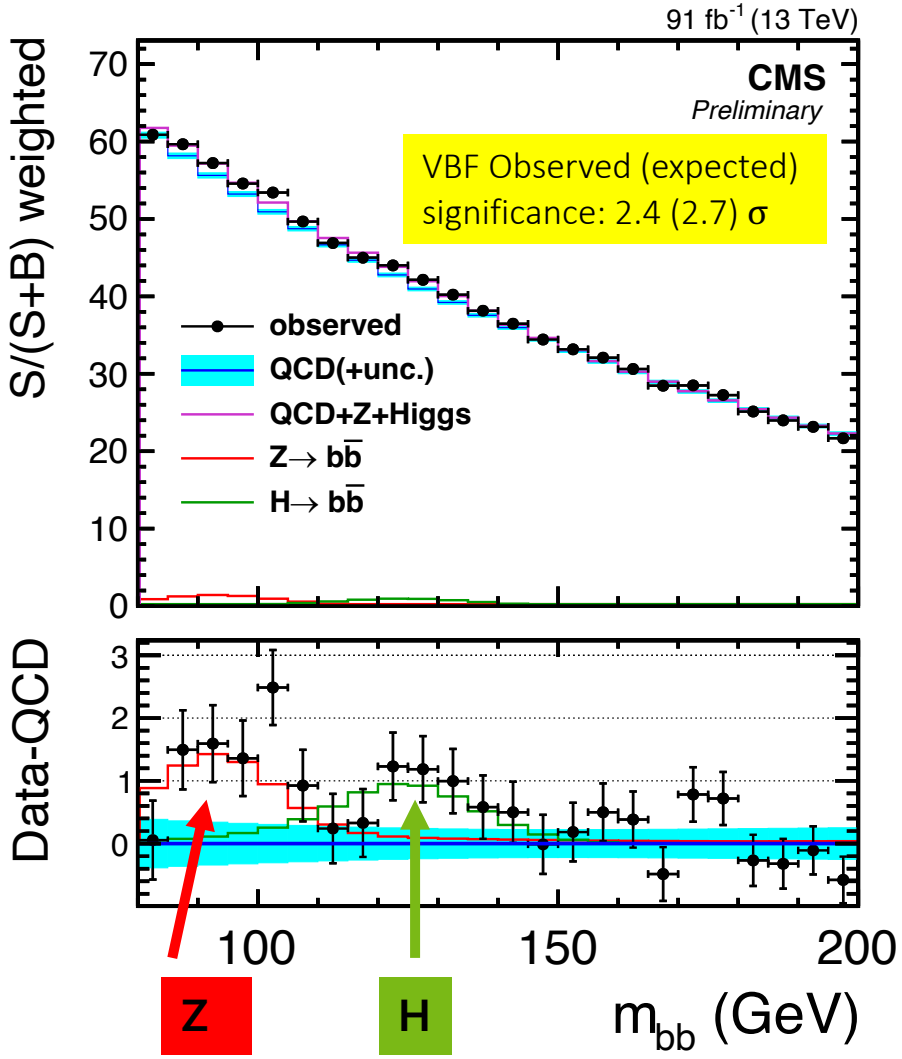
- a smooth function (polynomial*exp) for the continuum (dominated by QCD jets)
- the resonant Z+jets background
- the Higgs signal

- The normalizations of signal and of the Z+jets standard candle are free parameters

- Largest uncertainty: choice of Parton Shower model for the VBF signal (Pythia8 versus Herwig7)

- Exclusive VBF signal strength (ggH considered as background and constraint to SM value):

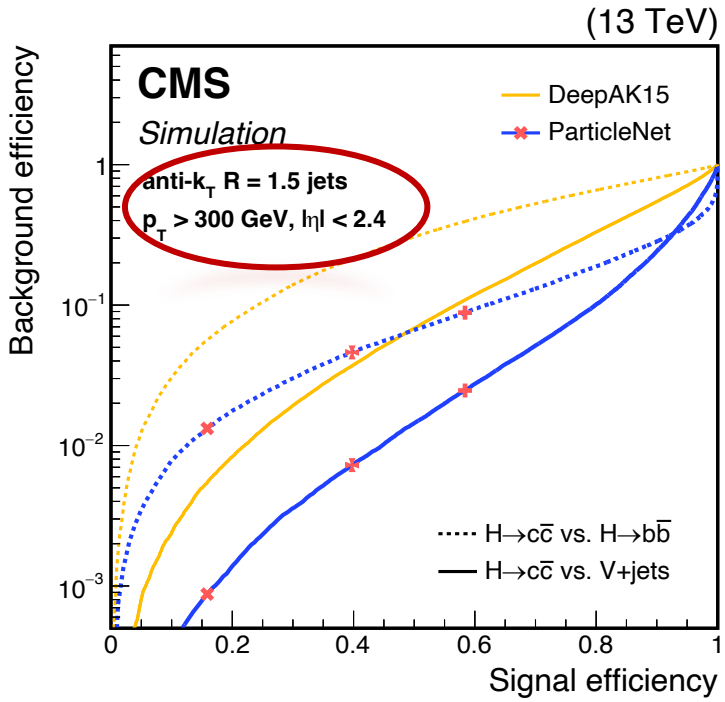
$$\mu = 0.97 \pm 0.35^{+0.39}_{-0.28}$$

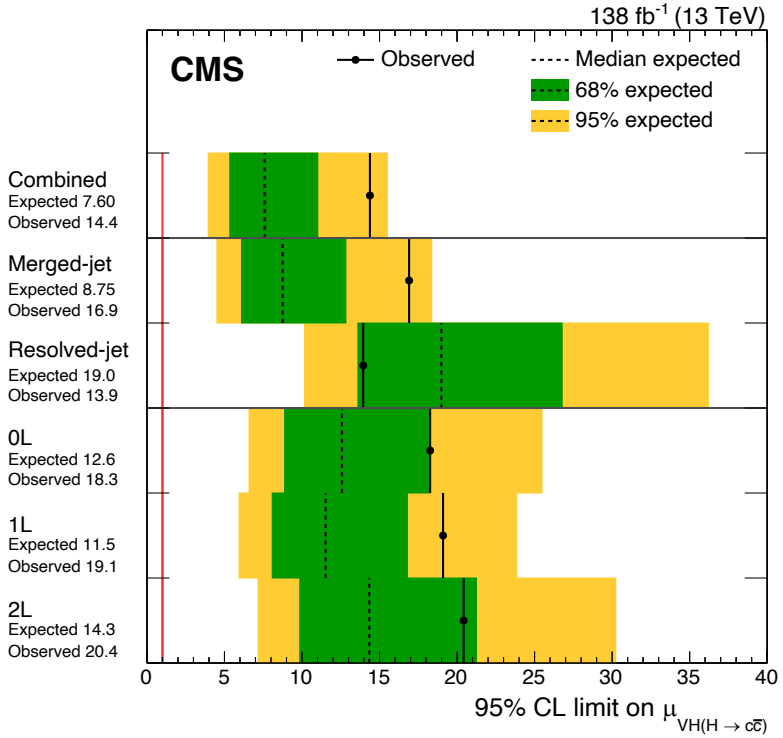


VH, H→ cc

- Enormous progress also in 2nd generation couplings, i.e. in c-Yukawa:
  - Two topologies, "merged" and "resolved"
  - new c-tagger based on ParticleNet graph NN in the merged regime (p_T (Higgs) > 300 GeV)
  - c-jet energy regression, refined analysis based on NN

arXiv:2205.05550, accepted in PRL





- Cross-check measurement of VZ, Z-> cc, first observation at hadron colliders:

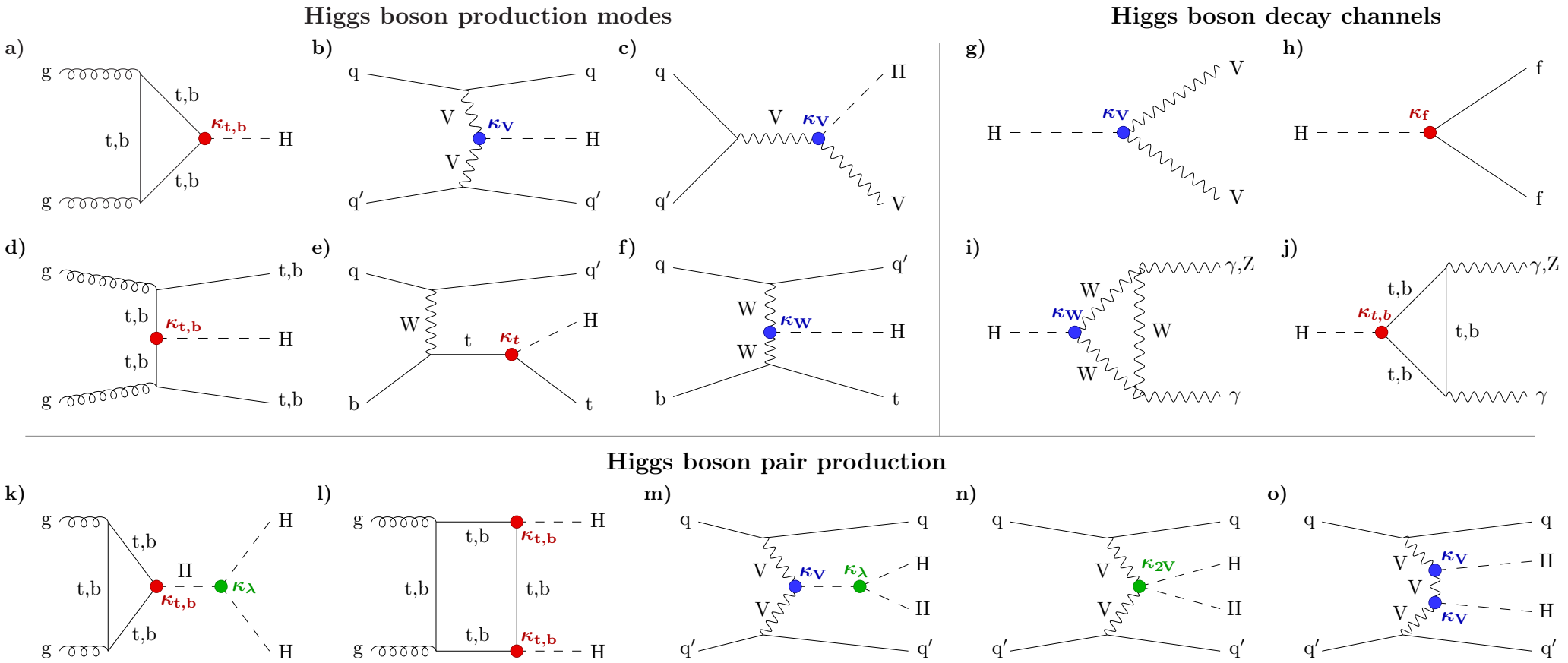
$$\mu = 1.01 \pm 0.22$$

Observed (expected) limit on the signal strength:
$\mu = 14$ (7.6)
$1.1 < |k_c| < 5.5 (|k_c| < 3.4)$

Summary

- After the discovery of the Higgs Yukawa coupling, CMS has measured cross sections in the STXS framework and more differentially in the τ and/or b channels
- STXS 0 and 1.2 measured in the τ channel, overall signal strength $\mu = 0.82 \pm 0.11$
- STXS measured in the VH, $H \rightarrow bb$ channel for the first time in CMS
- CMS has a new dedicated analysis in VBF $H \rightarrow bb$, reaching a very good sensitivity
- Sensitivity in $H \rightarrow cc$ significantly improved thanks to sophisticated c-taggers and c-jet energy regression. $Z \rightarrow cc$ observed for the first time at a hadron collider
- We are continuing on all fronts in refining analysis techniques for all these decays in Run 3

Backup


Higgs boson production modes
Higgs boson decay channels
Higgs boson pair production
a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
k)
l)
m)
n)
o)
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q′
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