Higgs Couplings Measurements

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CMS Compact Muon Solenoid

Introduction

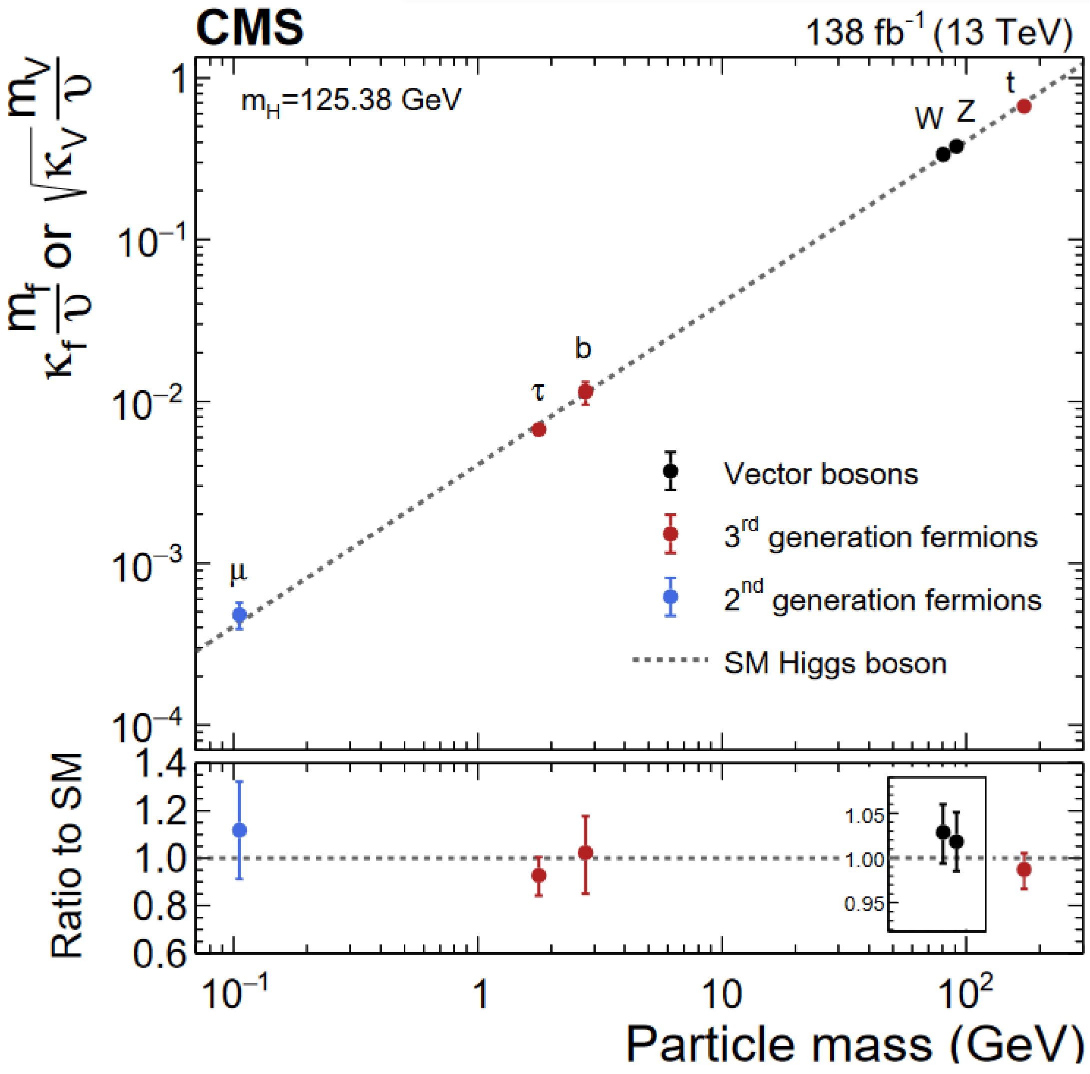
Higgs Boson couples to gauge bosons $\propto \frac{m_V^2}{v}$

and fermions (Yukawa coupling) $\propto \frac{m_f}{v}$

Status with full run 2 dataset:

- Good precision on coupling to vector bosons
- Observation of Higgs couplings to all third-generation charged fermions!
- Evidence of H coupling to μ
- Significant improvements in Hcc coupling search
- Access to probe the CP-structure of some couplings → see talk by L. Kang

Nature 607, 60–68 (2022)



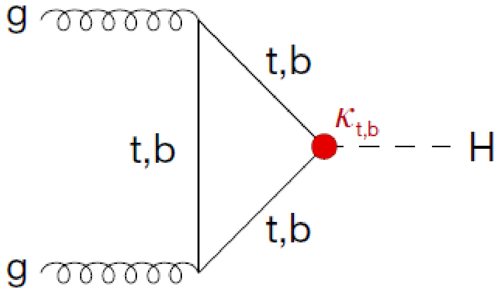
How to study the couplings?

Via its production mode or decay

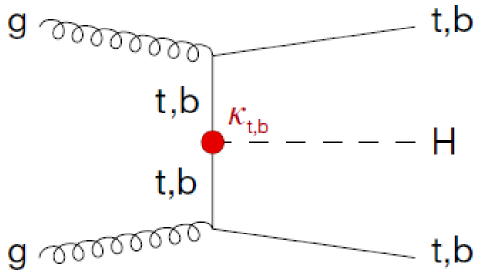
Can define the coupling modifiers κ:

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}}$$

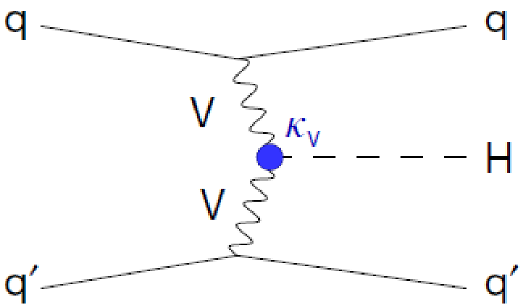
$$\kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$$



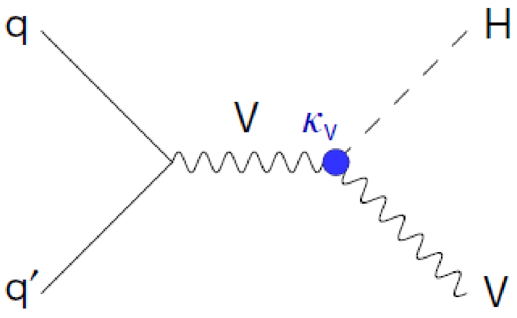
$\sigma \sim 49$ pb



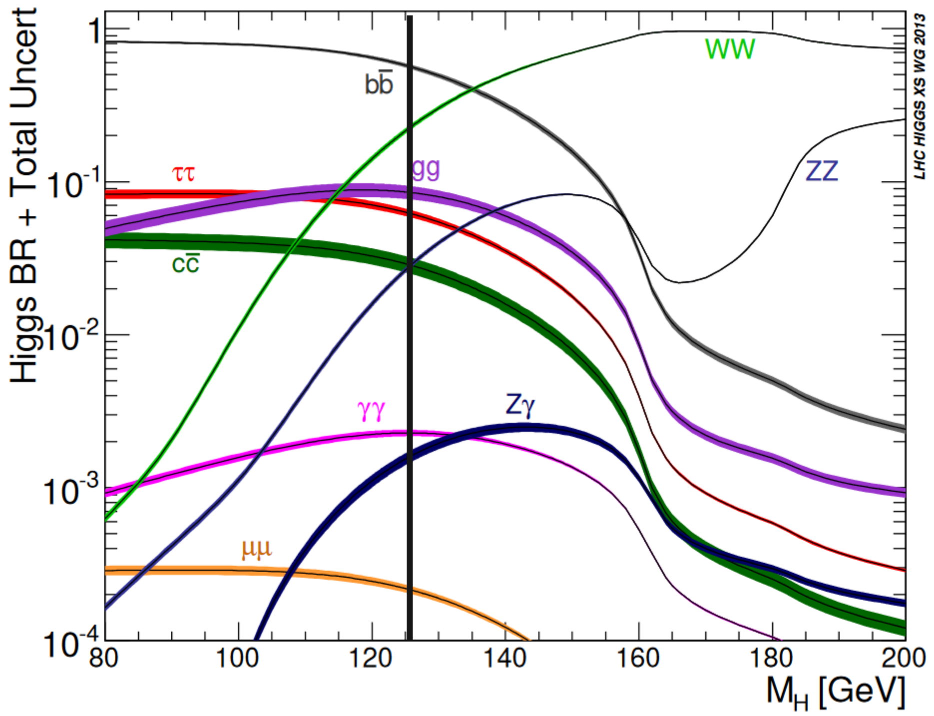
$\sigma \sim 0.5$ pb



$\sigma \sim 3.8$ pb



$\sigma \sim 2.3$ pb



Coupling to W,Z and γ

Nature 607, 60–68 (2022)

- **Coupling to γ**

Decay (via loops) to photons also allows to measure it with high precision

- **Coupling to W and Z:**

Already with high precision using the decay and production

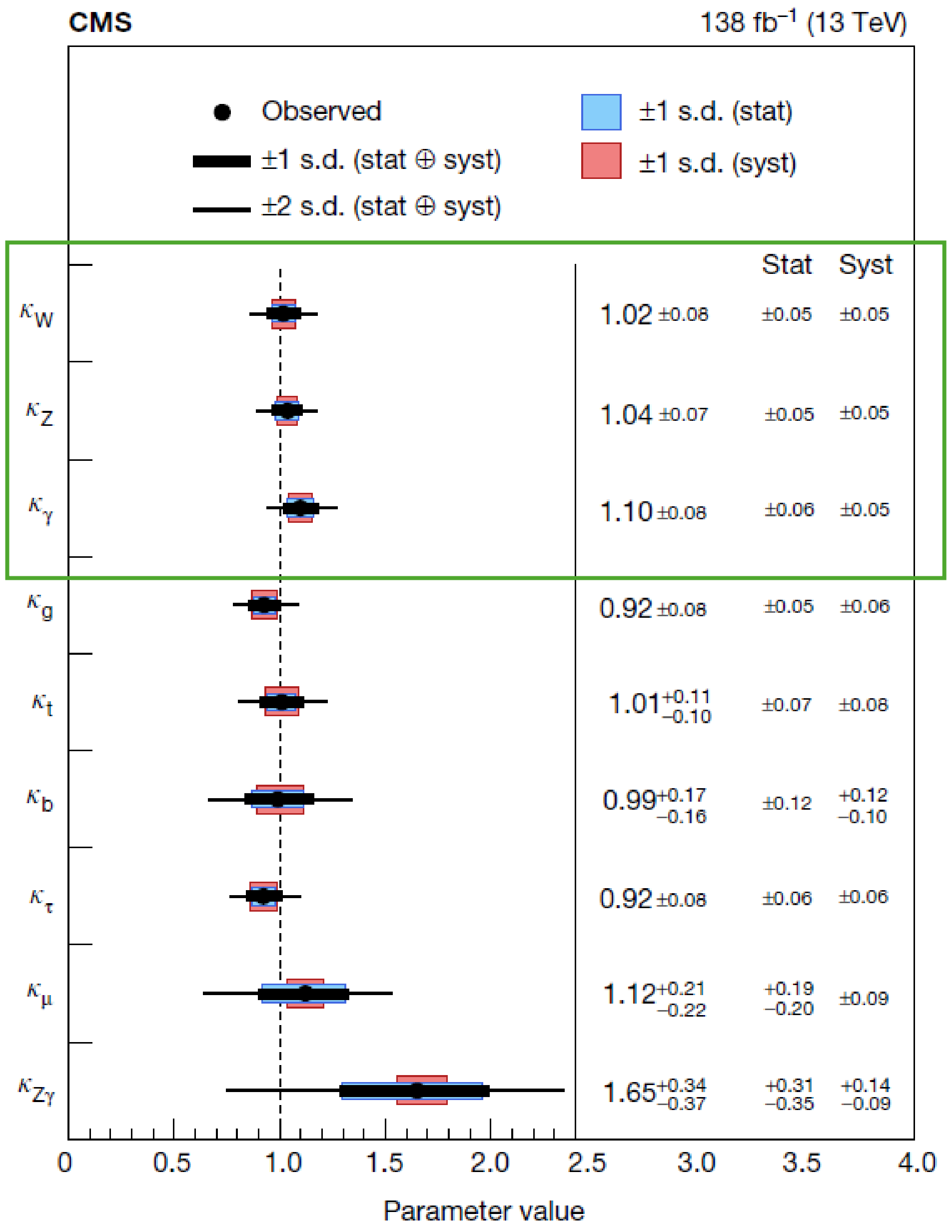
precision ~7%

- Relative sign of the k_W and k_Z constrained using VH via VBS → Arxiv:2405.16566

Submitted to PLB

in this talk

Using production



Coupling to top

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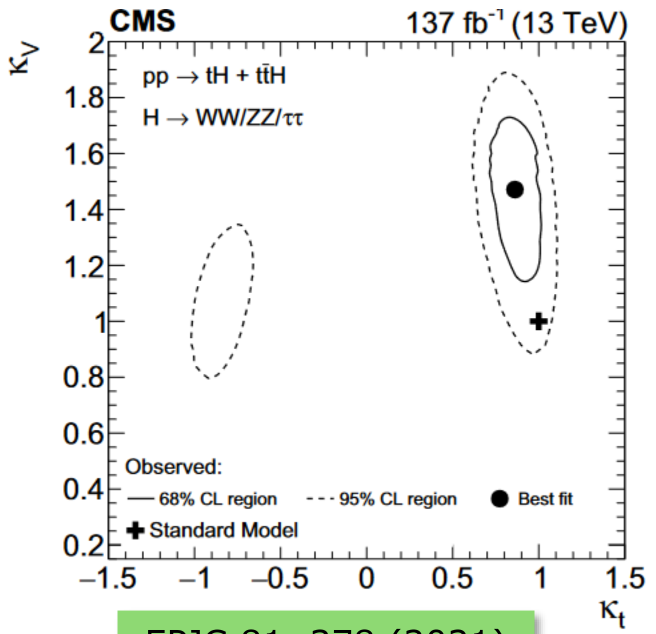
Using production

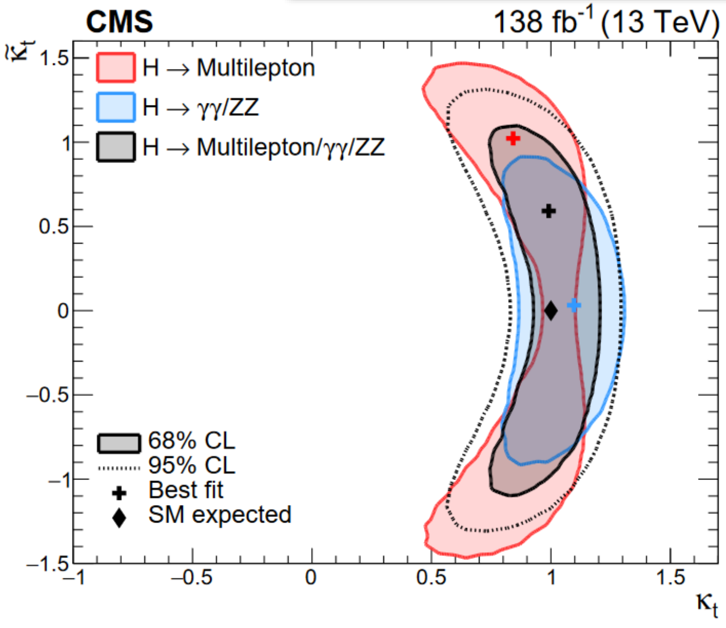
Coupling to top:

Mainly constrained using ttH and tH (see talk by M. Marchegiani)

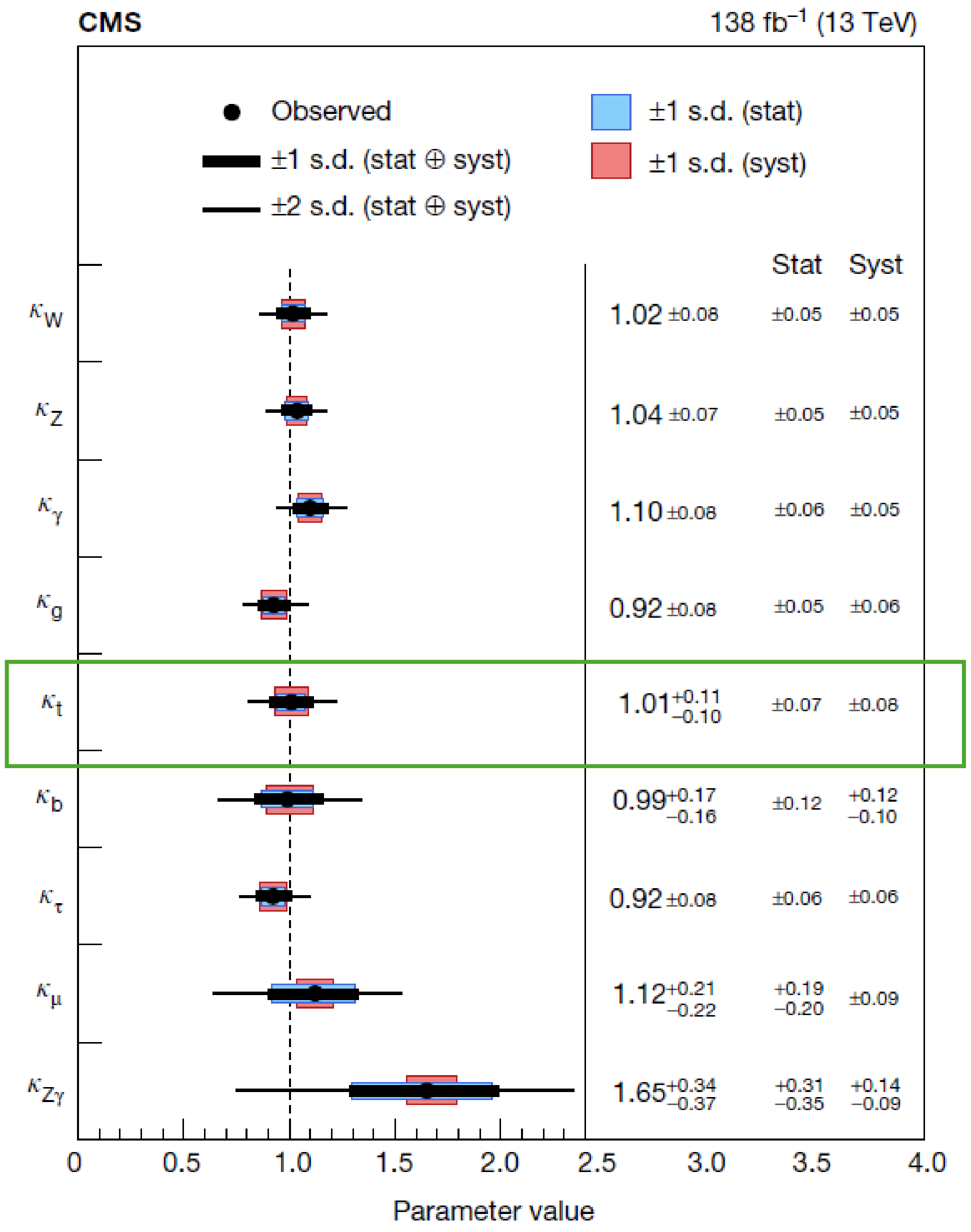
- Sensitive to k_t and k_V
- Beyond the combination: constraints on the CP structure available

JHEP 07 (2023) 092





EPJC 81, 378 (2021)



Coupling to τ and b

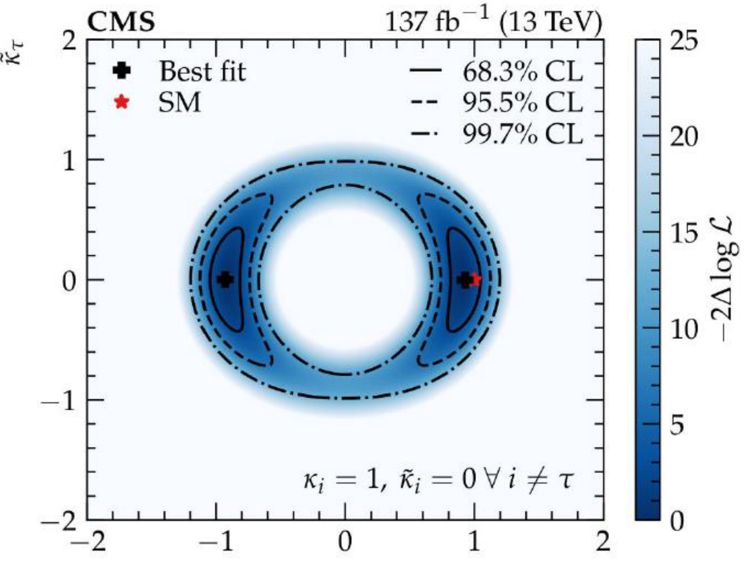
Nature 607, 60–68 (2022)

Coupling to tau:

Using decay

- k_τ measured with ~8% precision
- Beyond the combination: using the angle between the τ decay plane to constrain the CP structure

JHEP06(2022)012

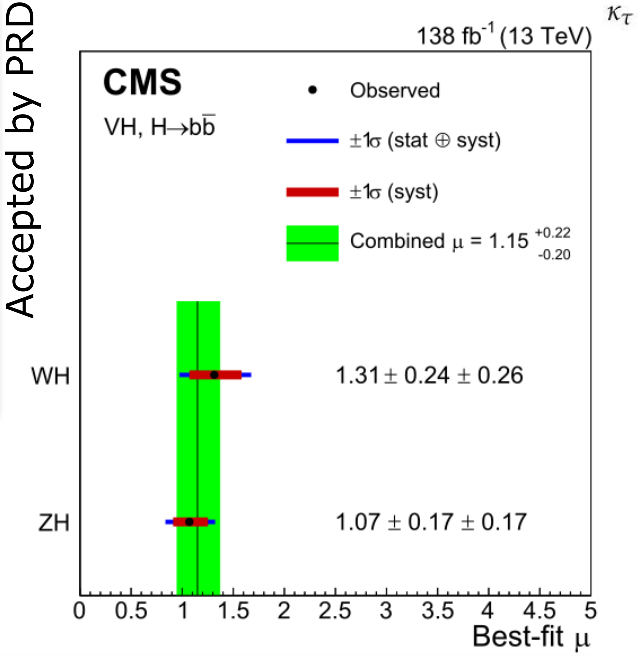


Coupling to bottom:

Using decay

- Most suitable production mode is VH (allows to control backgrounds)

arXiv:2312.07562 Accepted by PRD



Using production
Using decay

- **In this talk: bbH and ttH→ bb**

CMS-PAS-HIG-23-003

CMS-PAS-HIG-19-011

Coupling to second generation fermions

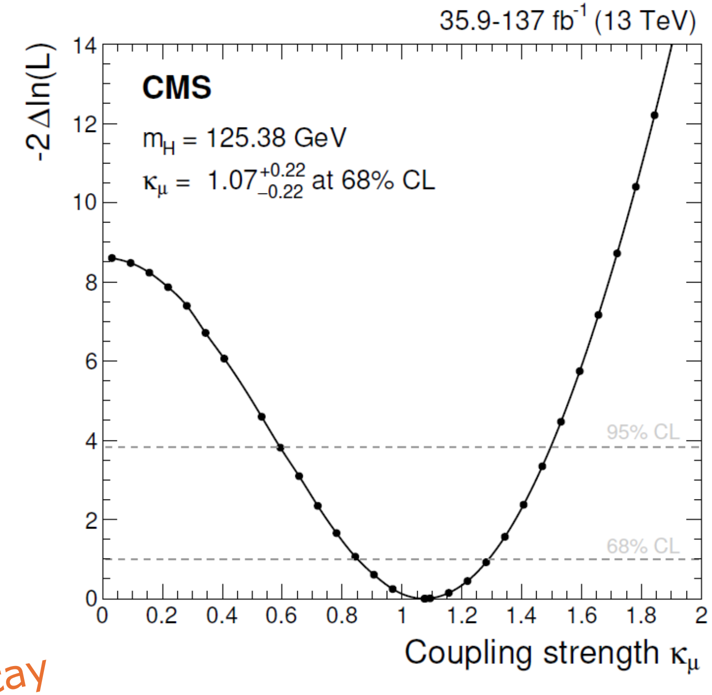
[Nature 607, 60–68 (2022)]

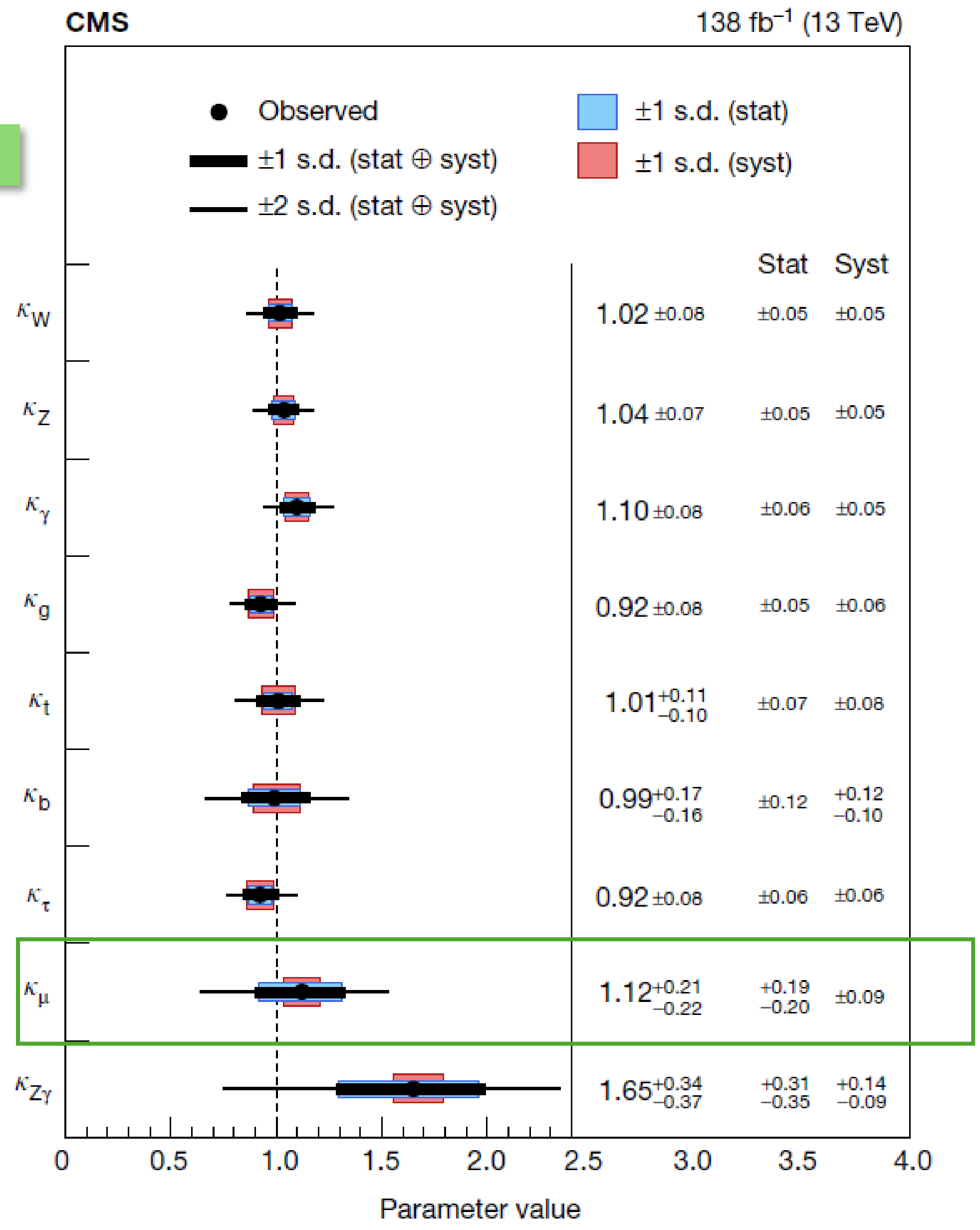
Using decay

First evidence of the **coupling to μ**

[JHEP01 (2021) 148]

Including ggF, VBF, WH, ZH, and ttH production modes





coupling to charm:

Using decay

Studied using:

- **ggH** [PRL 131 (2023) 041801]
- **VH** **[PRL 131 (2023) 061801]** **In this talk**

$H \to cc$

PRL 131 (2023) 061801

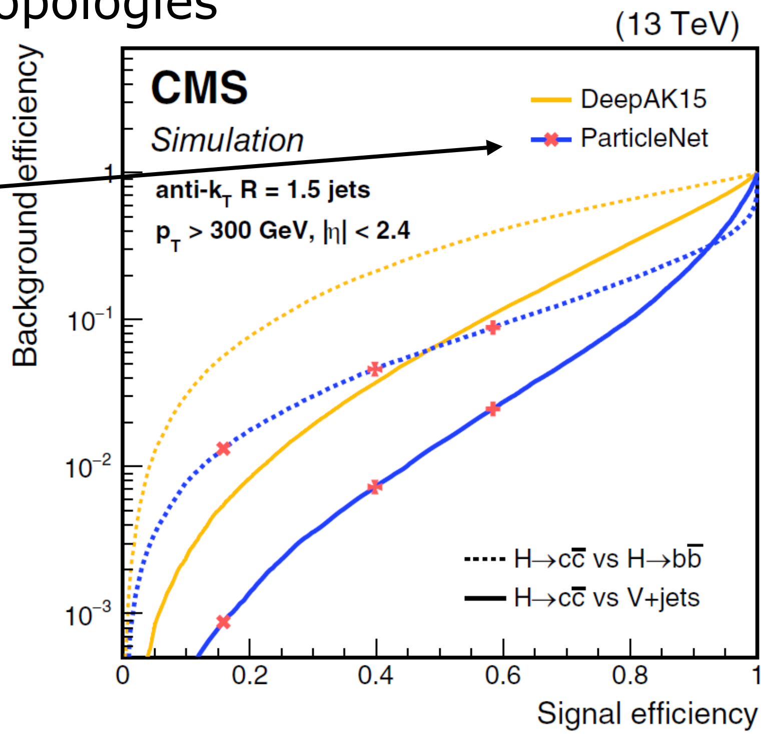
VH production: trigger on leptonic final states and reduce backgrounds
Final states with 0, 1 or 2 leptons:

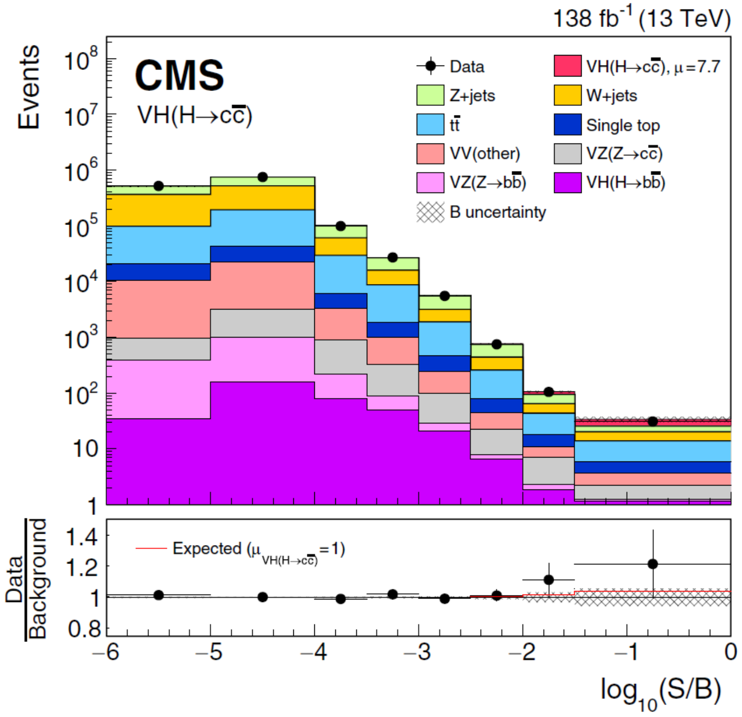
- $Z \to \nu\nu$ $W \to \ell\nu$ $Z \to \ell\ell$

Two (orthogonal) categories on $p_T(H_{cand})$ to further exploit H decay topologies

- Resolved: two fully resolved c-jets (tagging based on a DNN [1])
  - Regression to improve m_H resolution
- Merged: one jet with p_T (H_{cand}) > 300 GeV.

Graph NN for cc-tagging





- Each region: BDTs to discriminate signal vs background

[1]Comput. Software Big Sci. 4, 10 (2020)

H → cc (results)

PRL 131 (2023) 061801

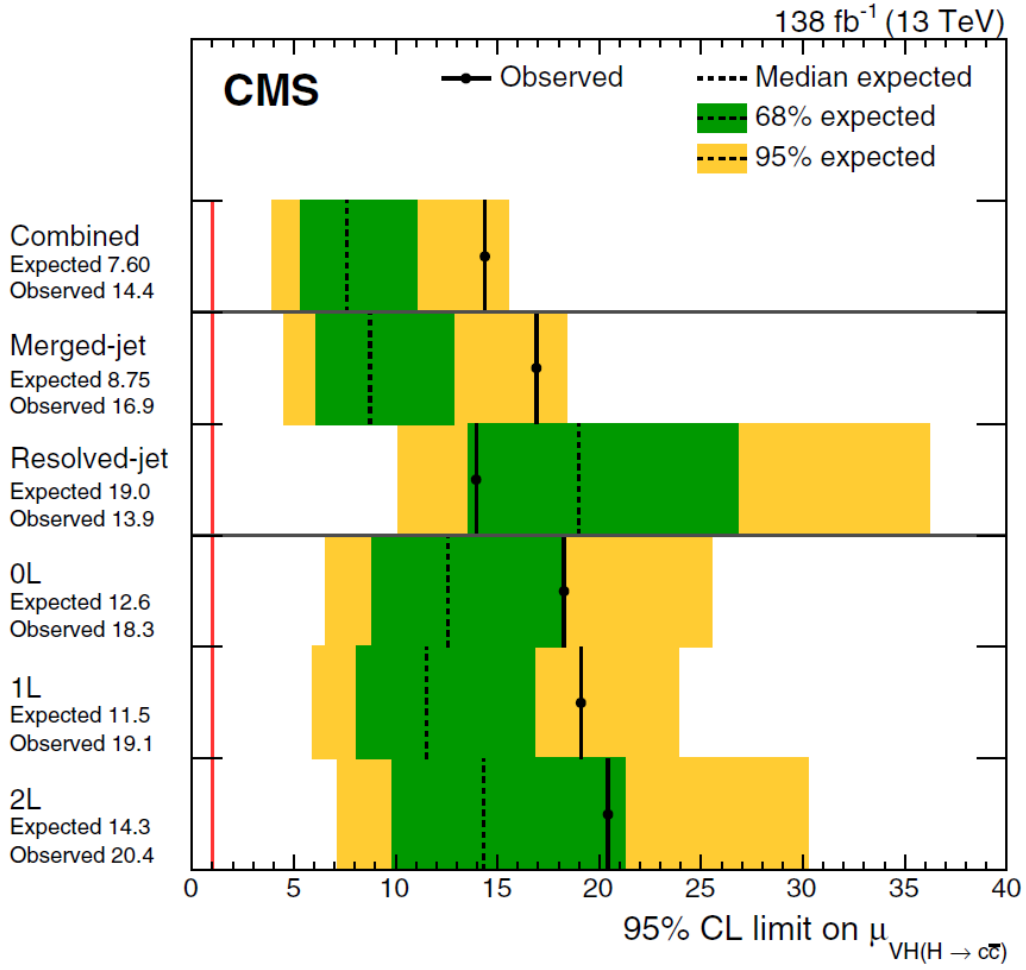
Maximum likelihood fit to extract $\sigma(\mathrm{VH})\,\mathrm{BR}(\mathrm{H}\rightarrow \mathrm{c}\bar{c})$

SM VZ (Z→cc) measured to validate methodology:

- $\mu(\mathrm{VZ}\; \mathrm{Z}\rightarrow \mathrm{cc}) = 1.01^{+0.23}_{-0.21}$
- First observation of Z → cc at a hadron collider
- Observed (expected) significance of 5.7 (5.9) s.d.

Observed (expected) $\boldsymbol{\sigma(\mathrm{VH})\,\mathrm{BR}(\mathrm{H}\rightarrow \mathrm{c}\bar{c})}$ < 14 $(7.6^{+3.4}_{-2.3})$ times the SM at 95% CL

- Results interpreted on terms of the **coupling**:
  1.1 < $|\kappa_c|$ < **5.5** (expected: $|\kappa_c|$ < 3.4) at 95% CL



ttH+tH (H→ bb)

CMS-PAS-HIG-19-011

ttH+ tH production allows to access k_t, k_b and k_V

- Low signal production cross-section
- Irreducible tt+jets background especially difficult to model

Selection & Event Categorization

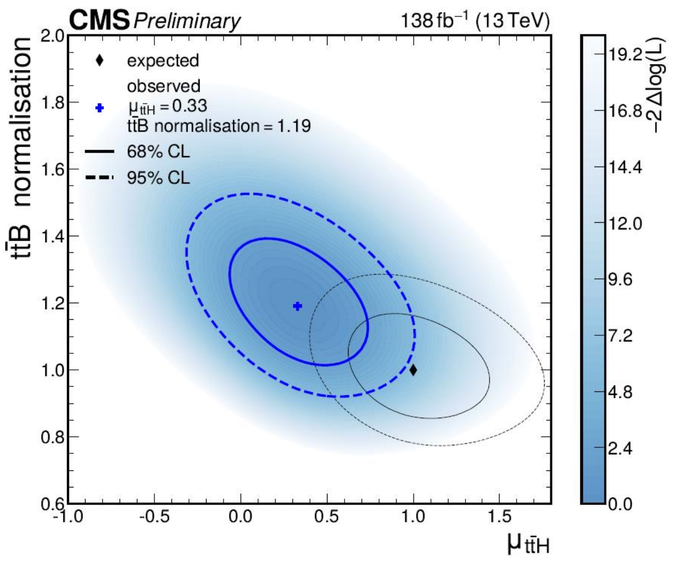
- Three channels: Fully hadronic, 1l, 2l
- Further classification based on jet and b-tag multiplicity
- NN to separate signal from background

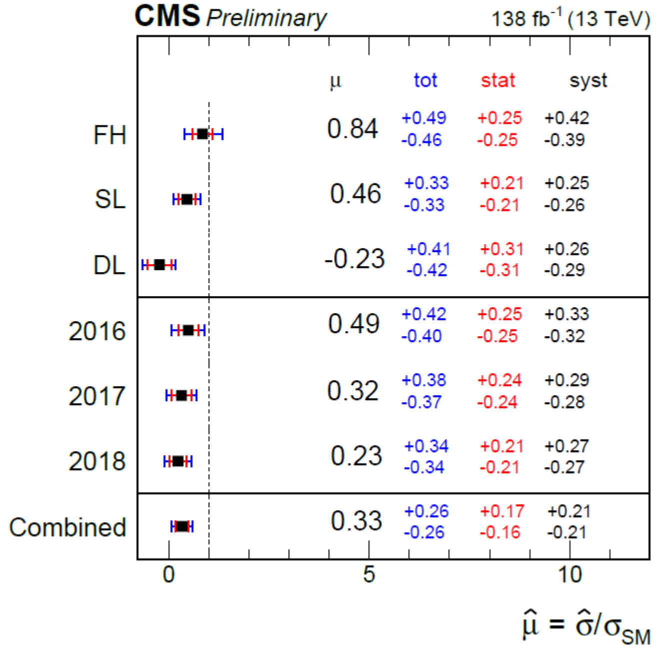
Results:

tt+bb modelling: normalization extracted from the fit simultaneously to the signal

ML fit is performed to all signal and control regions
Signal strength below prediction

$$\mu = 0.33^{+0.26}_{-0.26}$$

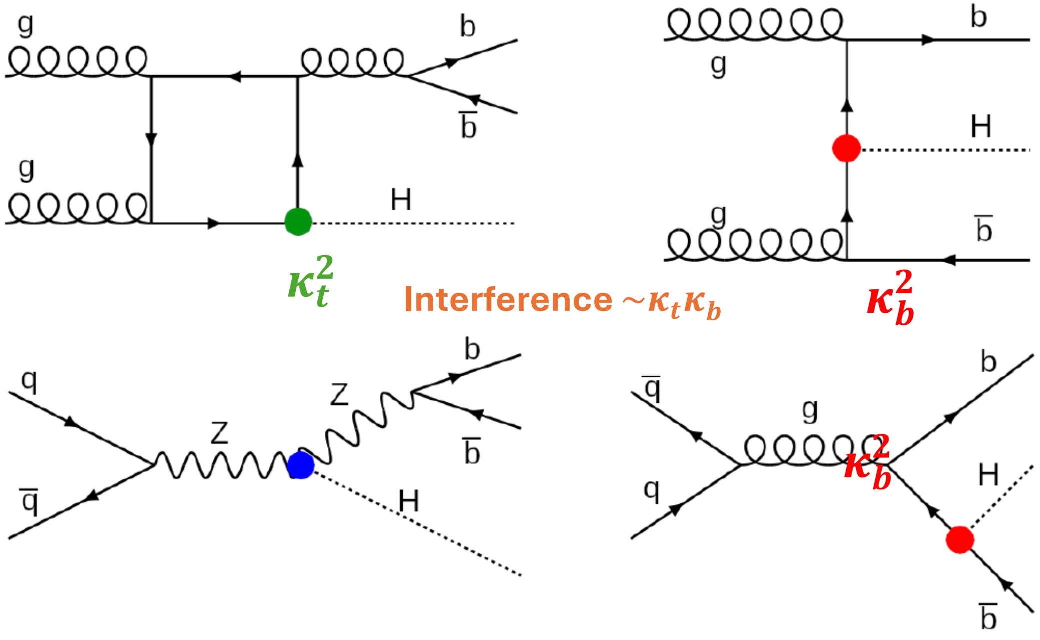


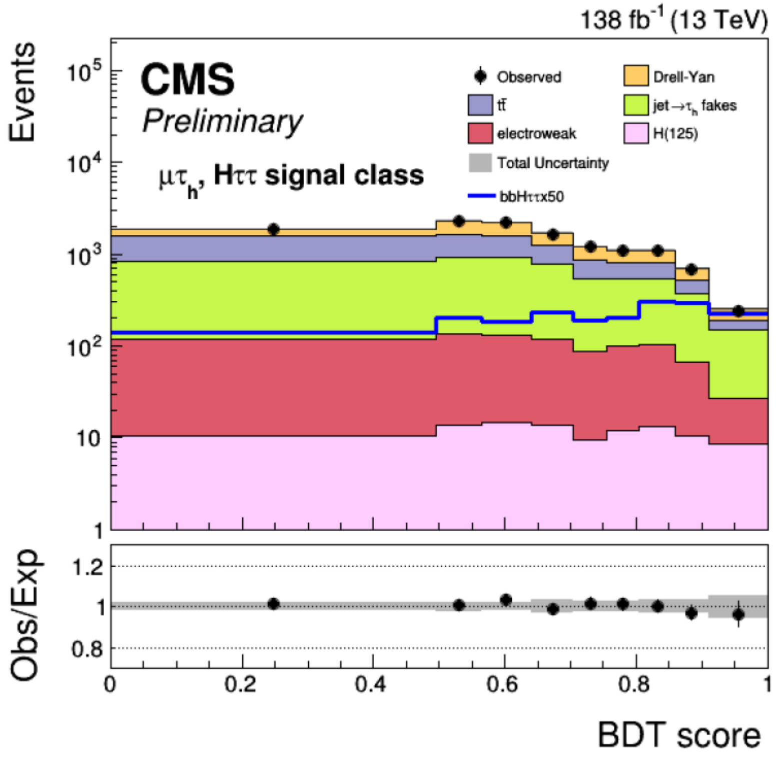


bbH

CMS-PAS-HIG-23-003

- Using the **production** mode to constrain b coupling
- Also sensitive to y_t
- Contribution from several diagrams:
  - Bottom quark fusion
  - gg fusion with gluon splitting
  - ZH: treated as background





Strategy:

- Targeting the $\mathrm{H} \to \tau\,\tau,\ \mathrm{H} \to W^+W^-$
- 4 signal categories: $\tau_h\tau_h, e\tau_h, \mu\tau_h, e\mu$

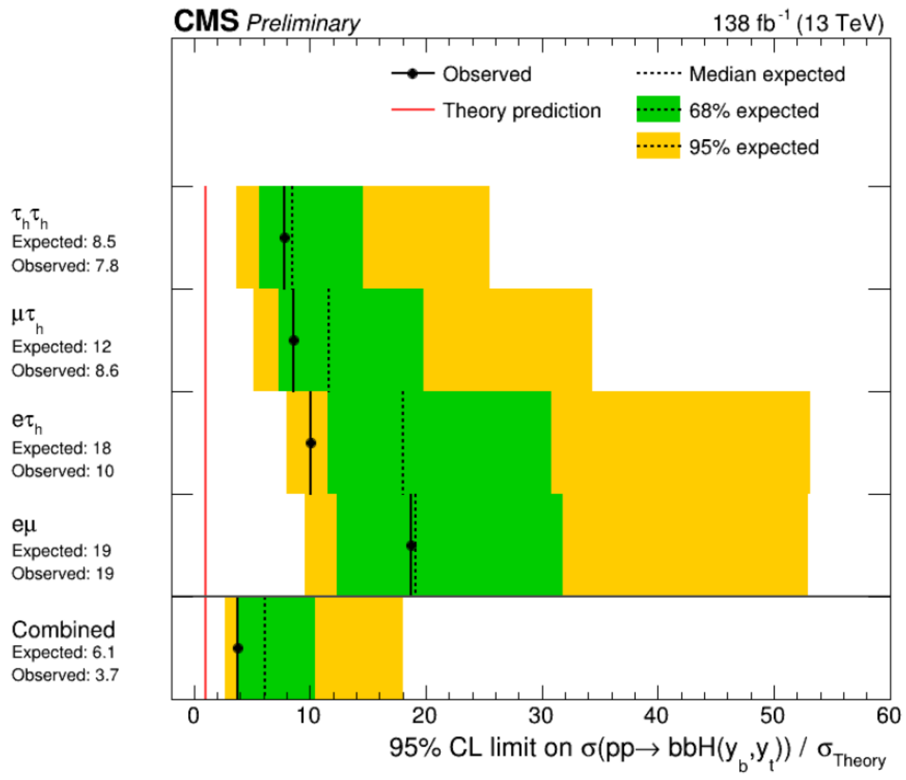
- BDT in each category to discriminate signal vs background

bbH (results)

CMS-PAS-HIG-23-003

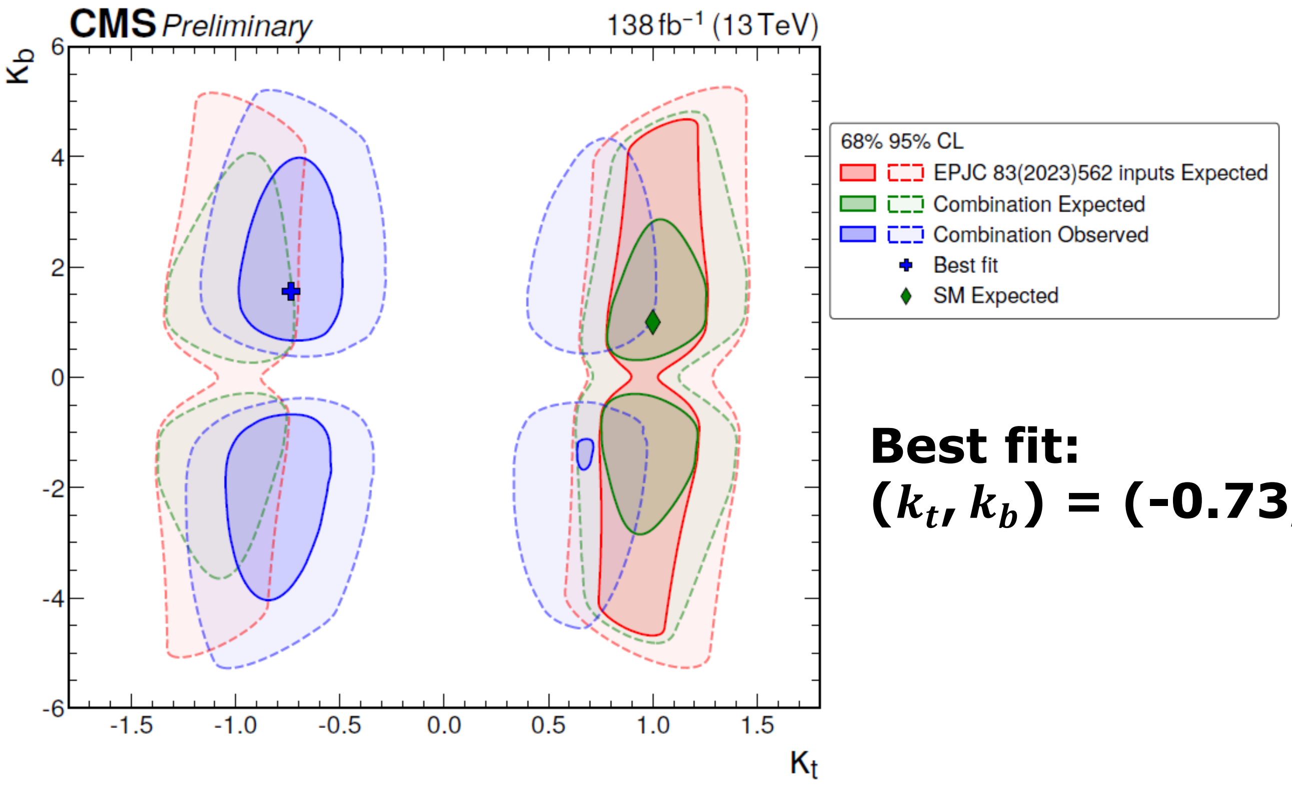
Simultaneous ML fit to all signal regions

Observed (expected) upper limits on the **signal strength: 3.7 (6.1)** times the SM



Coupling interpretation:

- k_t and k_b extracted from the fit. k_τ is profiled
- Results combined with $H \to \tau\tau$ to constrain k_t [EPJC 83 (2023) 56]
- Compatible with SM within 2 s.d.



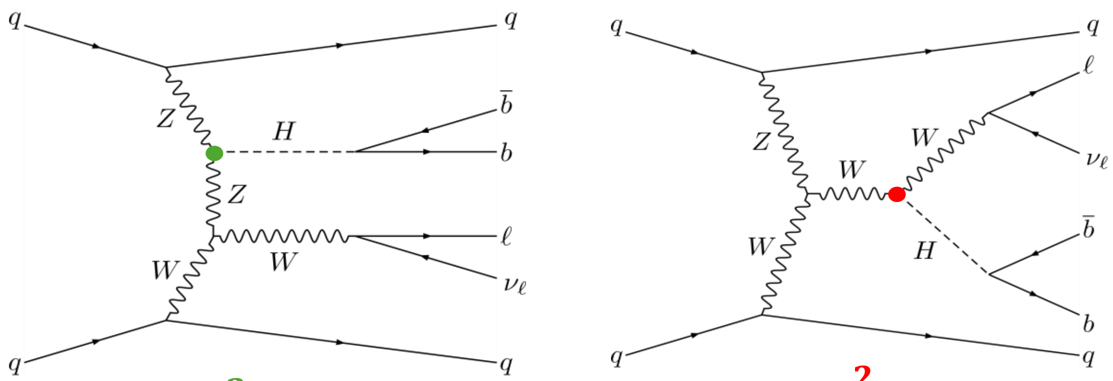
Best fit:
(k_t, k_b) = (-0.73,1.58)

HW and HZ coupling

Arxiv:2405.16566

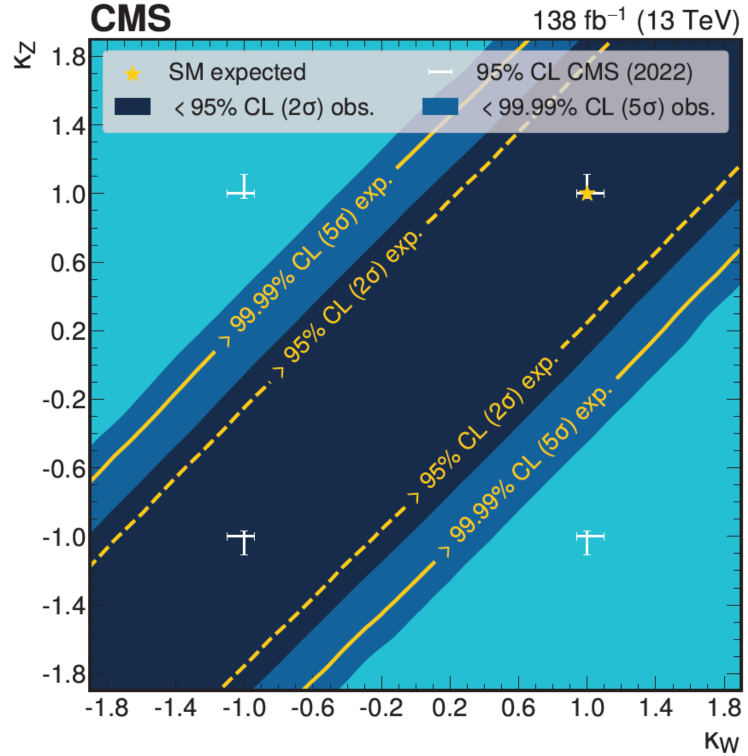
Submitted to PLB

WH production via vector boson scattering:
- Sensitive to **relative sign of k_W and k_Z**
- SM very low cross section
- BSM model with k_W/ k_Z = -1
  - Different topology: Boosted H and W
  - Change in cross section



κ_Z^2 Interference $\sim\kappa_W\kappa_Z$ κ_W^2

Analysis strategy:
- H → bb (boosted) tagged using Graph NN + mass requirements
- Single isolated lepton with high p_T from the W
- +2 jets (from the VBS) with requirements on $|\Delta\eta_{jj}|$



Results:
- Observed (expected) upper limit on the rate to the SM at 95% CL of **14.3 (9.0)** New!
- BSM scenario k_W/ k_Z = -1, **excluded at a CL > 99%** (beyond 5 s.d. sensitivity)
- Two dimensional limits also plotted

Best limits $|k_W| = 1.02 \pm 0.08$ and $|k_z| = 1.04 \pm 0.07$ in white

Summary

We are able to perform precision measurements of the Higgs boson properties

- **Coupling to W/Z well established**
  - Precision < 8%

- Coupling to massive **fermions: t, b and τ** also known with high precision
  - ~10-17%
  - Searches for CP violation in the Yukawa coupling

- **Second generation**:
  - 3-sigma evidence for H→μμ
  - Competitive limits on coupling to c quark

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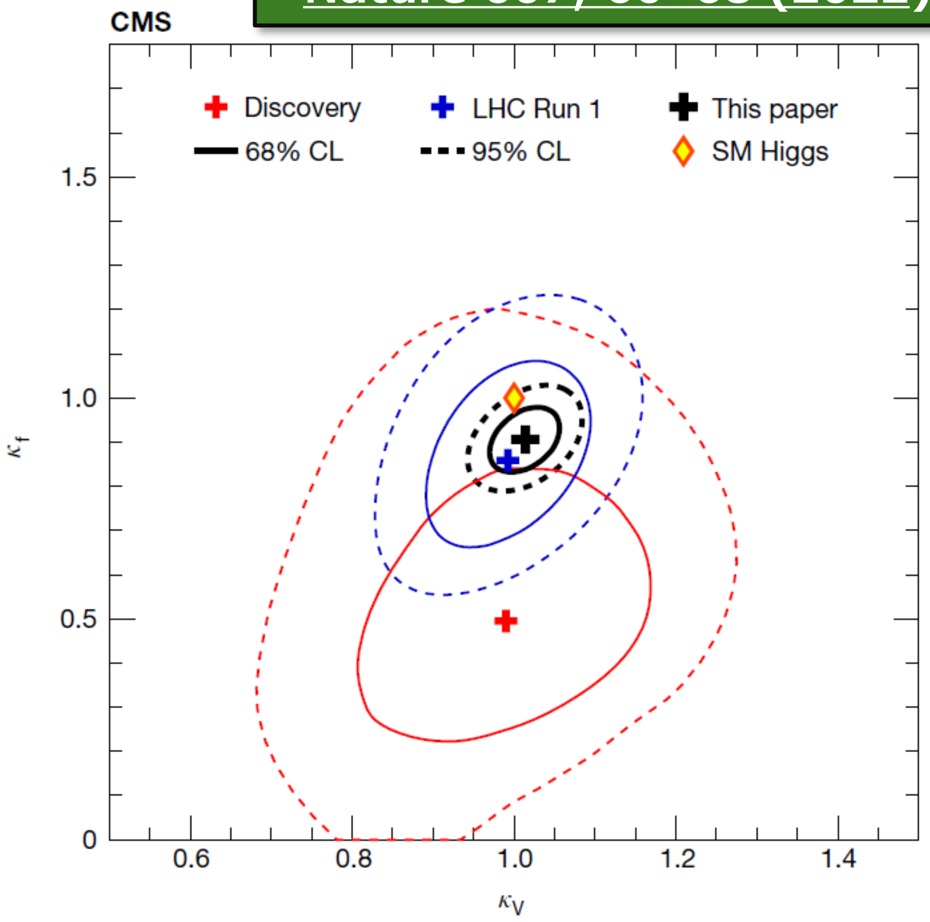
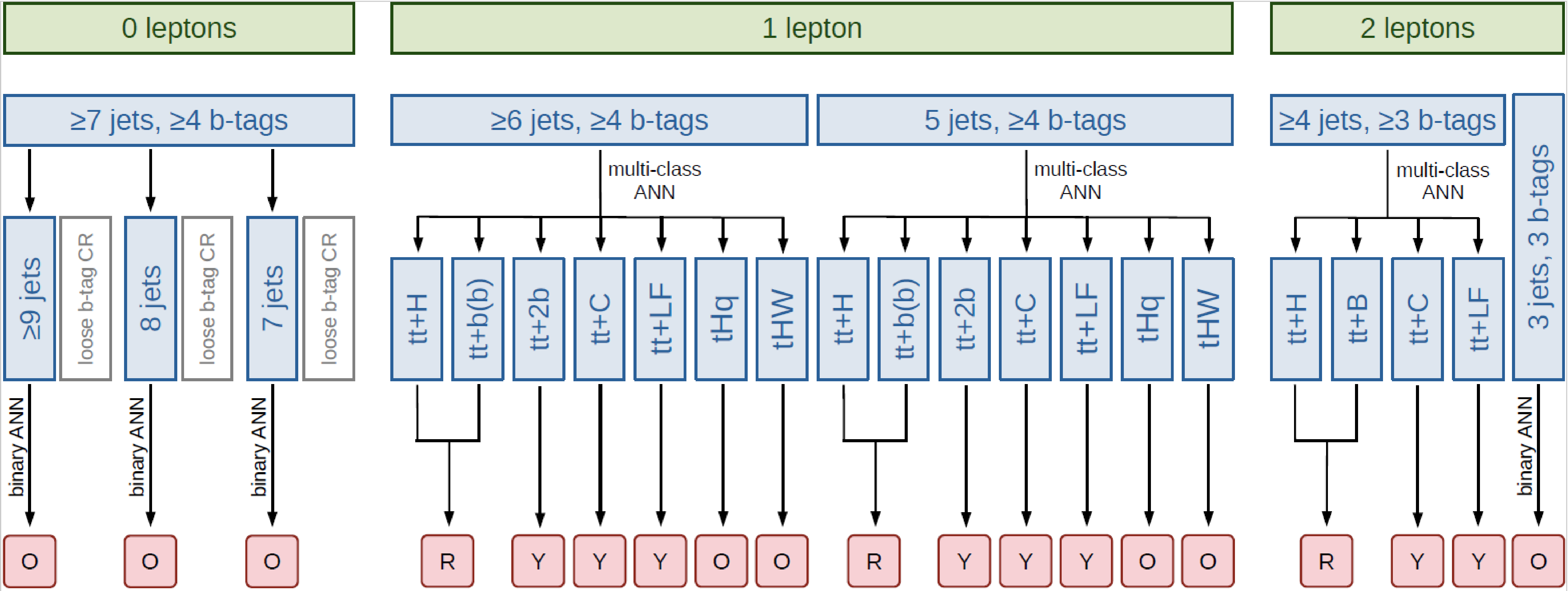


Back-up

H -> bb



Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

bbH input variables for the BDT

Variable	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$m_{\tau\tau}$	×	✓	✓	✓
m_{vis}	✓	✓	✓	✓
Collinear mass	×	✓	✓	×
D_ζ	✓	✓	✓	×
$\Delta\eta$ between lepton and τ_h	×	✓	✓	×
Total transverse mass	✓	×	×	×
Di-τ p_T	✓	✓	✓	✓
Electron p_T	✓	×	×	×
Muon p_T	✓	×	×	×
p_T of leading τ_h	×	×	×	✓
p_T of trailing τ_h	×	×	×	✓
Transverse mass	×	✓	✓	×
Number of b-jets	✓	×	×	✓
p_T of leading b-jet	✓	✓	✓	✓
p_T of trailing b-jet	×	✓	✓	×
B-tag score for leading b-jet	×	✓	✓	✓
$\Delta\eta$ between di-τ p_T and leading b-jet	×	✓	✓	×
B-tag score for trailing b-jet	×	✓	✓	✓
Number of jets	✓	×	×	✓
p_T of leading jet	✓	×	×	✓
p_T of trailing jet	✓	×	×	✓
Di-jet invariant mass	×	×	×	✓
Di-jet $\Delta\eta$	✓	×	×	✓
p_T^{miss}	×	×	×	✓

tt+bb simulation

	$t\bar{t}$ sample NLO	$t\bar{t}b\bar{b}$ sample NLO
POWHEG version	`Powheg v2`	`Powheg-Box-Res`
PYTHIA version	8.230	8.230
Flavour scheme	5	4
PDF set	NNPDF3.1	NNPDF3.1
m_t	172.5 GeV	172.5 GeV
m_b	0	4.75 GeV
μ_R	$\sqrt{\frac{1}{2}\left(m_{T,t}^2 + m_{T,\bar{t}}^2\right)}$	$\frac{1}{2}\sqrt[4]{m_{T,t} \cdot m_{T,\bar{t}} \cdot m_{T,b} \cdot m_{T,\bar{b}}}$
μ_F	μ_R	$\frac{1}{4}\left[m_{T,t} + m_{T,\bar{t}} + m_{T,b} + m_{T,\bar{b}} + m_{T,g}\right]$
h_{damp}	$1.379 \cdot m_t$	$1.379 \cdot m_t$
Tune	CP5	CP5

Additional b quarks computed from ME

CP measurements by CMS

HVV/Hgg coupling:

- Anomalous H couplings $(H \to \tau\,\tau)$ Phys. Rev. D 108, 032013
- Anomalous H couplings $(H \to 4l)$ Phys. Rev. D 104 (2021) 052004
- Anomalous H couplings (H → WW) HIG-PAS-22-008

Hff coupling:

- H$\tau\tau$ coupling JHEP 06 (2022) 012
- Htt coupling (ttH, H→ $\gamma\gamma$) Phys. Rev. Lett. 125, 061801
- Htt coupling (ttH, H→ $4l$) Phys. Rev. D 104 (2021) 052004
- Htt coupling (ttH, H→ multileptons)