Understanding Quark Yukawa Interactions
Latest results and prospects

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On behalf of ATLAS and CMS Collaborations

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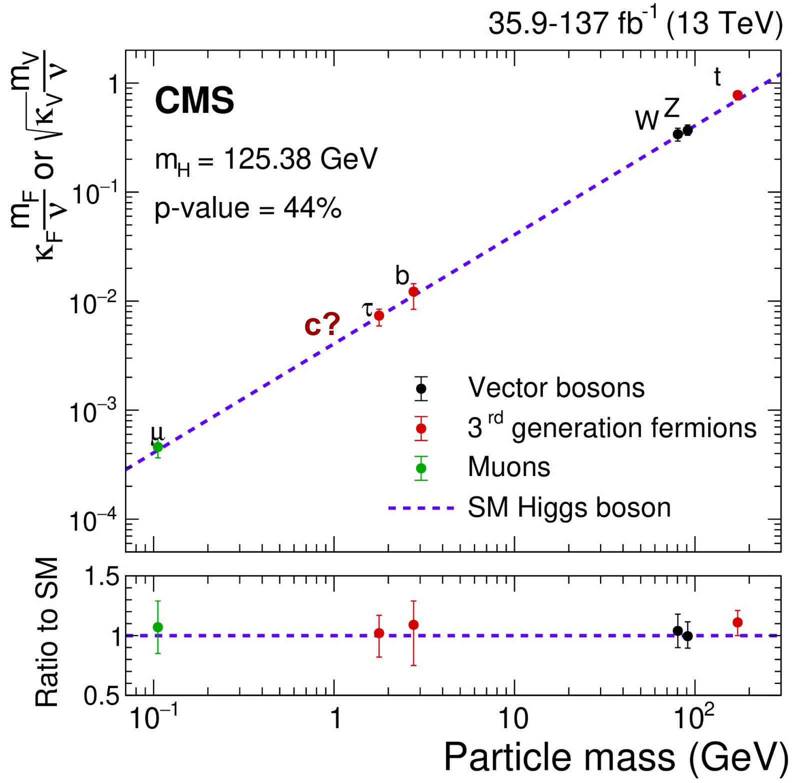
Introduction

- Higgs (H) physics continues to play the central role in LHC scientific programme.
- Numerous measurements and theoretical developments
  ⇒ H is standard model (SM)-like
  → lot more needed for pinning it down more precisely.
- Unfinished mandates include understanding in detail the interaction between H and the fermion sector; described by the *Yukawa* coupling in SM.

  Hff coupling: $y_f = \sqrt{2}\, m_f/v$

- Analyses of ATLAS and CMS data have already established that H directly couples to top and bottom quarks as well as to taus and muons in the lepton sector with strengths as envisaged in SM, within uncertainties.

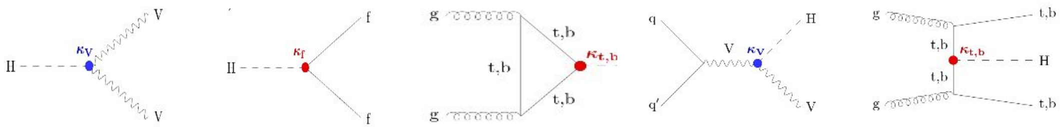
- Very good sensitivity achieved recently for probing H coupling with the 2nd generation quark, charm.



- Extract from data the coupling strength modifiers (κ_i) wrt SM:
- κ_i =1 → SM
- κ_i ≠1 → BSM

Interplay of 2 types of couplings: κ_V & κ_f

ATLAS-CONF-2021-053

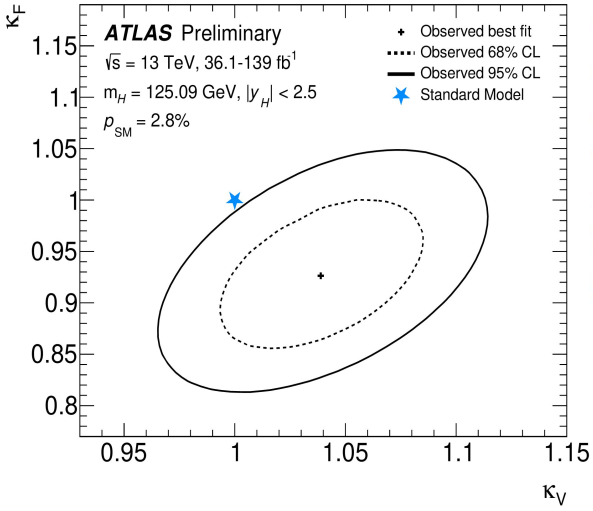


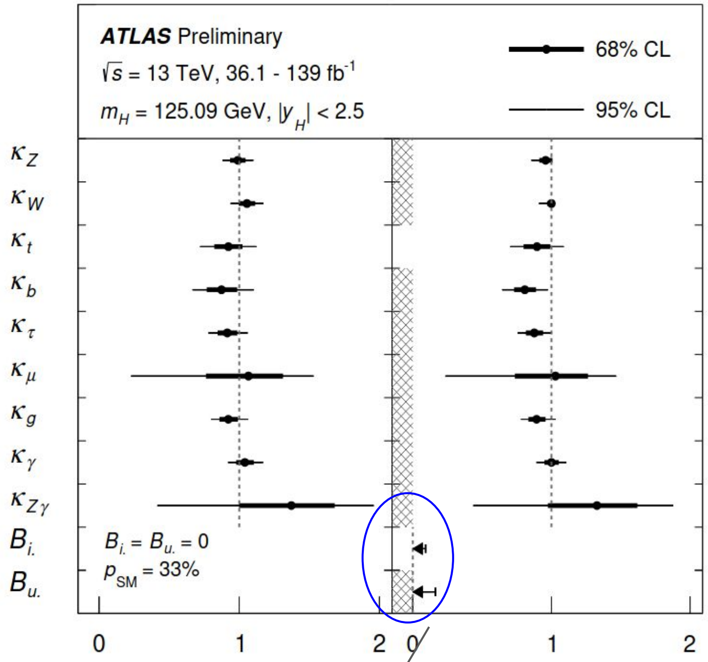
- Signal strengths for individual production and decay channels compared wrt SM for $i \to H \to f$

$$\mu_{if} = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{B_f}{B_f^{SM}}$$

- BSM effects expected to modify production and decays in similar ways
  → interaction vertices modified
  → define coupling modifiers κ_i

$$\kappa_i^2 = \sigma_i^{obs} / \sigma_i^{SM}$$





$B_i = \mathcal{B}(H \to BSM)$
$B_u = \mathcal{B}(H \to undet.)$

Upper limits on B_i, B_u, when considered as free parameters in the fit, with $\kappa_{W,Z} \leq 1$

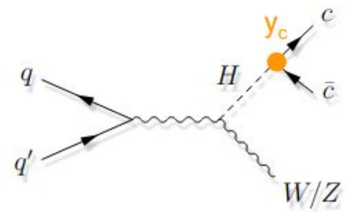
Direct constraint on Higgs-charm coupling

- Most recent measurements by ATLAS and CMS: upper limit on the signal strength for Hcc coupling.
- Extremely challenging:

  i) Br (H→ cc) ~ 3% ⇒ small signal rate, large background due to QCD production

  ii) Identification of charm jets in hadronic environment of the LHC is more difficult than b jet

  iii) H→bb is an irreducible background (it has higher rate as well)
- New tools developed for jet reconstruction, merged jets, ML-based charm-tagging.



Strategy:

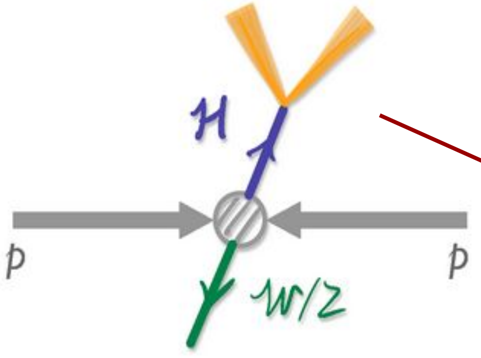
- Exploit associated production: VH (V=W, Z), with leptonic decays of V ⇒ 0, 1, 2 leptons in the final state
- Use boosted H to reduce other backgrounds (inclusive production of V+jets, single and pair of top quarks, multi-bosons)
- Veto events with additional jets and leptons.

ATLAS: targets for best constraint on κ_c , κ_b and κ_c / κ_b by combining VH(H→bb) and VH(H→cc) analyses.

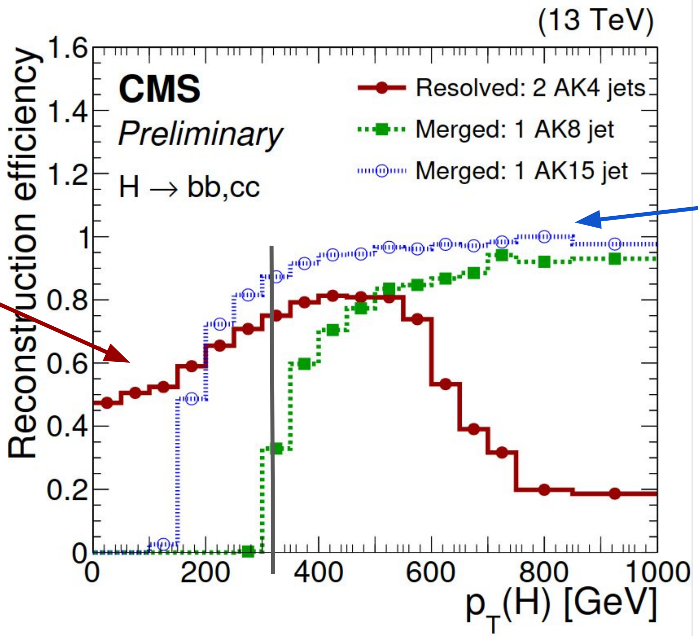
CMS: use of ParticleNet algorithm to identify and measure charm jets efficiently to achieve better sensitivity.
Observed VZ, Z →cc.

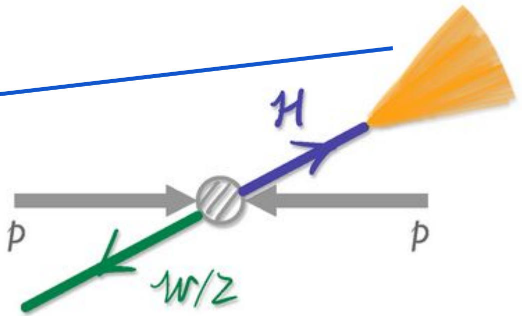
VH, H→cc analysis overview in CMS

[CMS HIG-21-008]



2 resolved AK4 jets





1 merged AK15 jet

$\Delta R(c,c) = 2m_{cc} / p_T^{H}$

- *Analysis validated by studying VZ(Z→cc)*

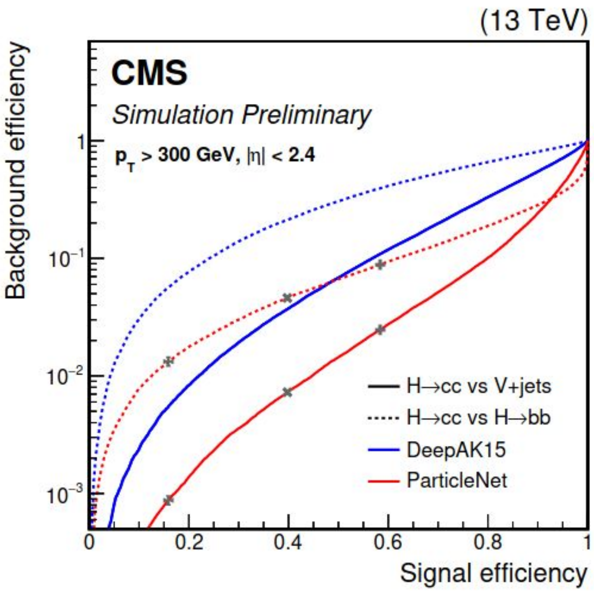
Merged jets:

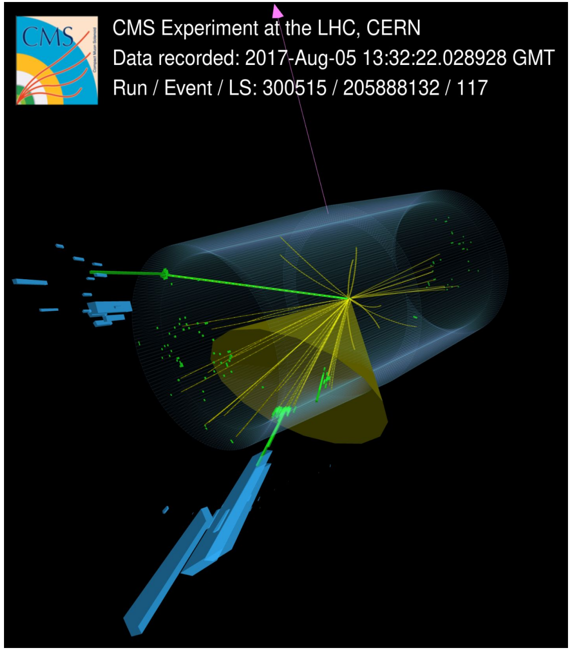
- Small signal acceptance but high purity
- Better exploits the correlation between 2 charm quarks

⇒ require good identification capability

CMS identification of wide jets from boosted H(→cc)

CMS HIG-21-008 CMS-DP-2020-002





Highlights:

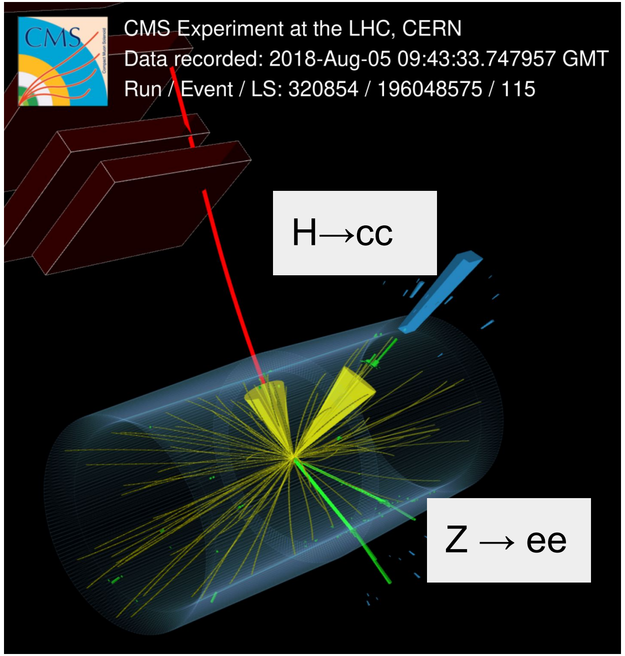
- *Charm-tagger* using ParticleNet → concept of graph NN (considers a jet as an unordered set of particles in η-φ space).
- Mass decorrelation to avoid sculpting jet mass shape in background after selection with tagger.
- Charm tagging efficiency derived from data.
- ParticleNet-based regression algorithm to improve the large-R jet mass reconstruction.

- Analysis proceeds in a factorized fashion with independent steps: Kinematic BDT, ParticleNet charm-tagger and Regressed jet mass → unbiased and robust method for background estimation and signal extraction.

CMS: charm-tagging in the resolved-jet topology

CMS-BTV-20-001

- DeepJet algorithm for 2 efficient charm taggers, to discriminate c jets from i) b jets and ii) light quark jets *separately.*
- Use different physics processes for calibration of c jet discriminators.
- Dedicated c jet regression to improve c jet energy scale and resolution



Extraction of results:

i) Merged-jet topology: distribution of the Higgs boson candidate mass.

ii) Resolved-jet topology: ordering of the events by BDT score.

In the combined statistical analysis, *merged-jet topology* class drives the sensitivity.

VH(H→cc) result from CMS

CMS HIG-21-008

- Observed (expected)
  σ(VH) $\mathcal{B}$(H→cc) < 0.94 ($0.50^{+0.22}_{-0.15}$) pb

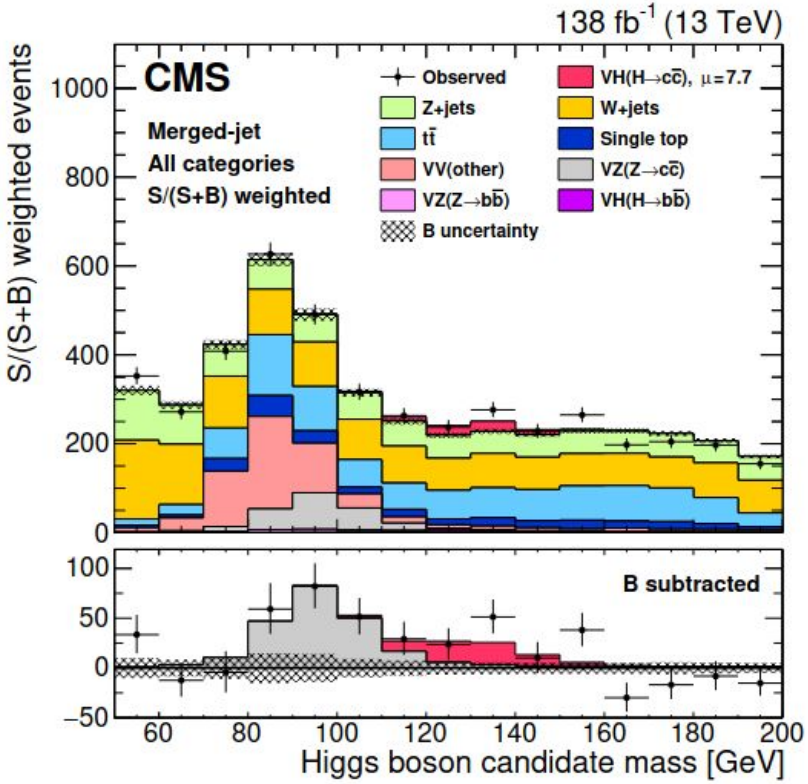
- Upper limit (UL) on signal strength at 95% CL:
  μ < 14 ($7.6^{+3.4}_{-2.3}$)

⇒ Strongest limits on VH(H→cc) process to date!

- Best fit signal strength: μ = $7.7^{+3.8}_{-3.5}$
  ⇒ Consistent with the SM prediction within 2 s.d.

- Obs. (exp.) UL from each topology:
  i) Resolved-jet topology: 14 (19) × SM
  ii) Merged-jet topology: 17 (8.8) × SM

- **Observation of Z→cc with significance 5.7 s.d. (exp.: 5.9s.d.)**
  → first in a hadron collider!
- Signal strength obsd.: 1.01 ± 0.22 (exp.: 1 ± 0.21)



$$\mu_{\mathrm{VH(H\to c\bar{c})}} = \frac{\kappa_c^2}{1 + \mathcal{B}_{\mathrm{SM}}(\mathrm{H \to c\bar{c}}) \times (\kappa_c^2 - 1)}$$

⇒ **1.1 < |κ_c| < 5.5 obs. (|κ_c|<3.4 exp.)** *assuming all other κ_i =1*
→ most stringent (better than indirect estimate)

VH(H→cc) result from ATLAS

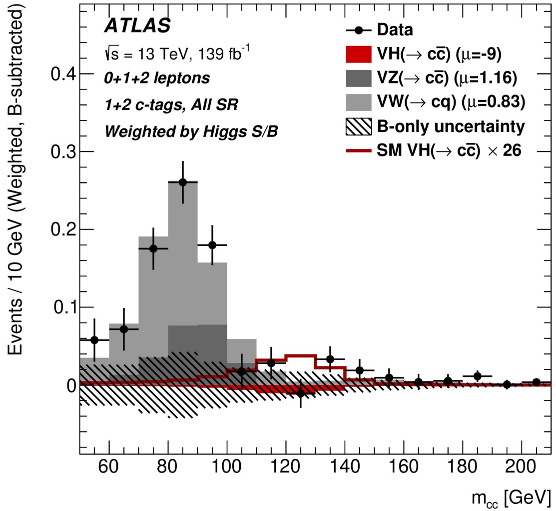
ATLAS-HIGG-2021-12

- **Obsd. (exp.) σ(VH) 𝓑(H→cc) < 26 (31) X SM   @95% CL**
  ⇒ $|\kappa_c|$ < 8.5   obs. ($|\kappa_c|$ < 12.4 exp.)
- Constraint on Yukawa coupling modifier: $|\kappa_c|$< 8.5 (12.4) obs (exp.)

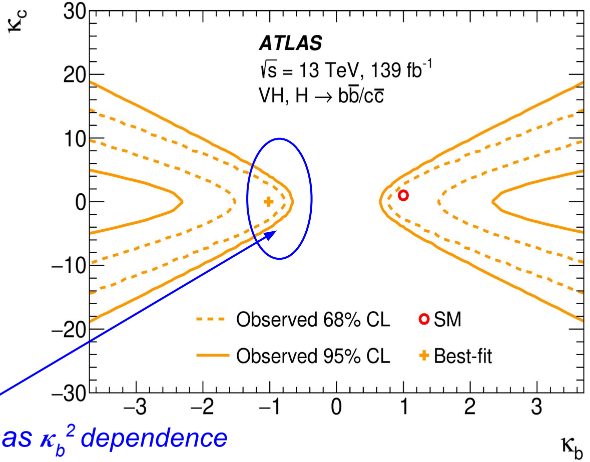
$$\boxed{\kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}} \qquad \boxed{\sigma_i \times B_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H}}$$

- Combine with σ(VH) 𝓑(H→bb) to constrain κ_c / κ_b independent of H width

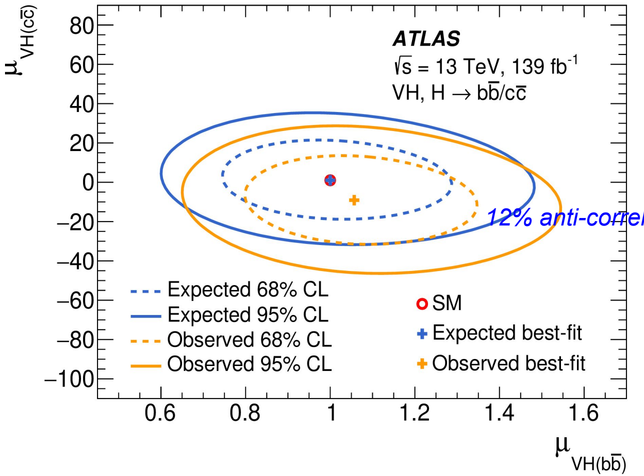
  → at 95% CL $| \kappa_c / \kappa_b |$ < 4.5 , smaller than ratio of the b & c quark masses!
  ⇒ **Higgs-charm coupling weaker than the Higgs-bottom coupling.**



- *Analysis validated by VZ(Z→cc), VW (W→cq) processes.*
- *Observed (exp.) significance for VZ(Z→cc): 2.6 (2.2) s.d.*
- *Observed (exp.) significance for VW(W→cq): 3.8 (4.6) s.d.*



[-1.02, 0]: *gg→ZH parametrization has κ_b^2 dependence*

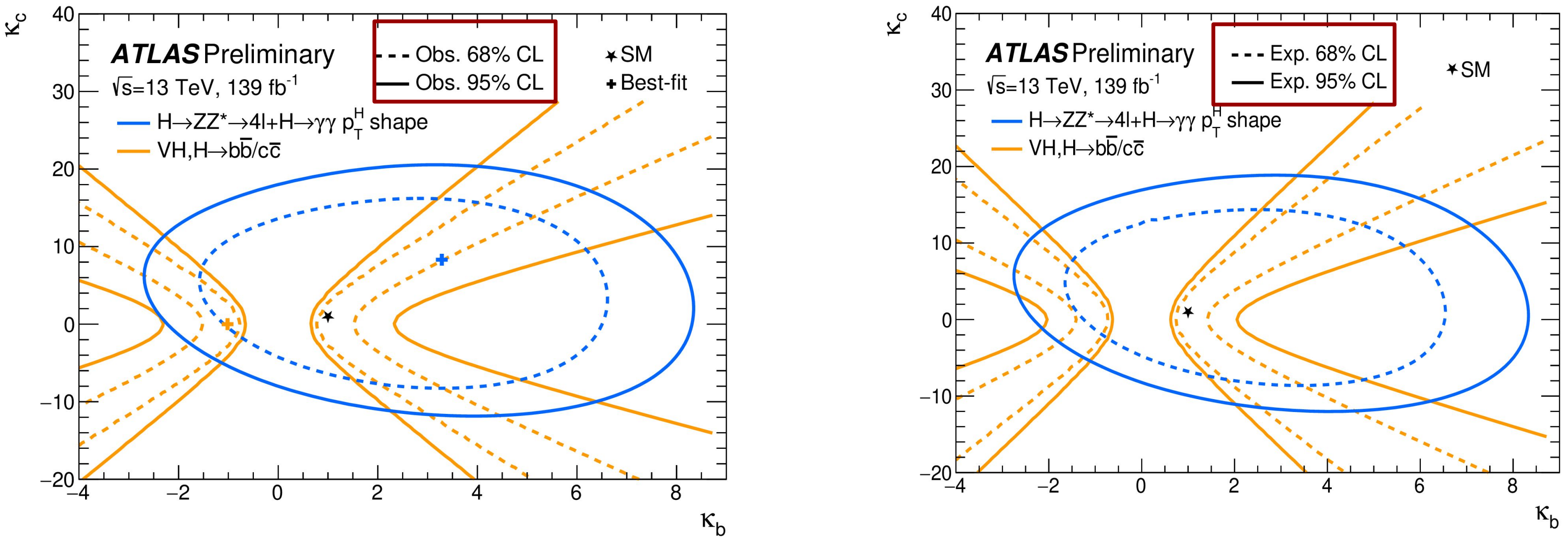


Further constraint on κ_c vs. κ_b from ATLAS

ATLAS-PHYS-PUB-2022-002

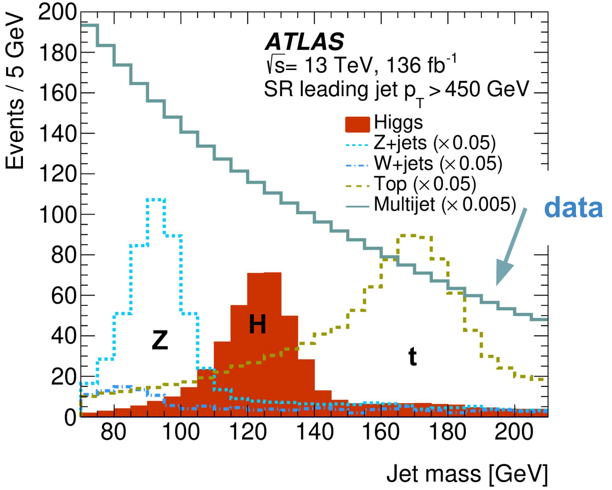
Combination of the κ_c / κ_b constraint contour from the interpretation of the search for VH,H→bb/cc and from the combination of the $H\to\gamma\gamma$ and $H\to ZZ^*\to 4\ell$ differential cross-sections as a function of p_T^H

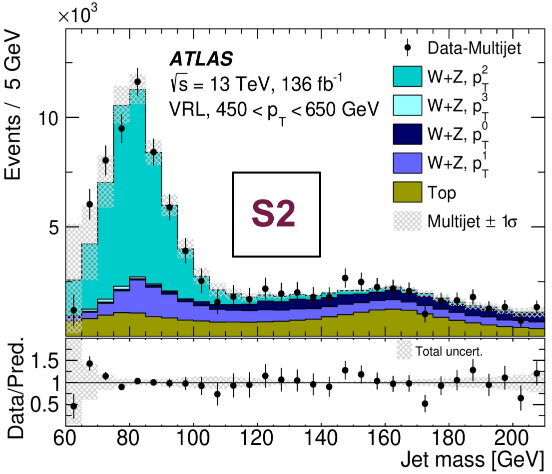
- VH analyses: predictions for σ(VH) and $\mathcal{B}$(H→cc/bb) parameterised as a function of κ_c & κ_b assuming no other anomalous contributions to the Higgs boson width.
- Interpretation of the p_T^H distributions only considers the effect of κ_c & κ_b but ignores any modification on H decays .

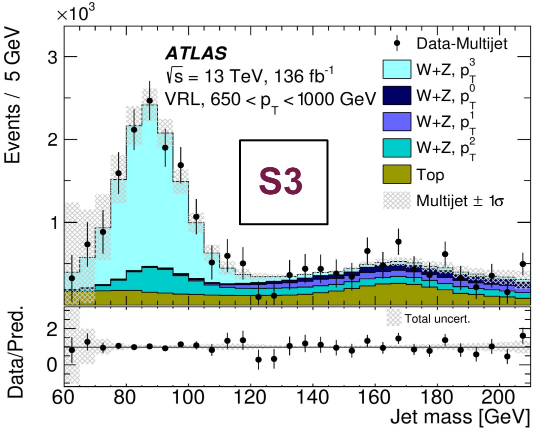


Boosted Higgs (H→bb) in STXS analysis: ATLAS

ATLAS HIGG-2021-08







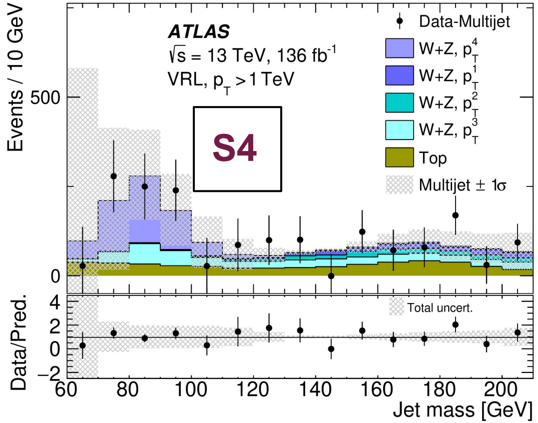
- H→bb reconstructed as single large-radius (R=1) jet recoiling against a high p_T hadronic system.

- Binned maximum-likelihood fit to measure μ.

- *Analysis validated in the same kinematic region using Z→ bb.*

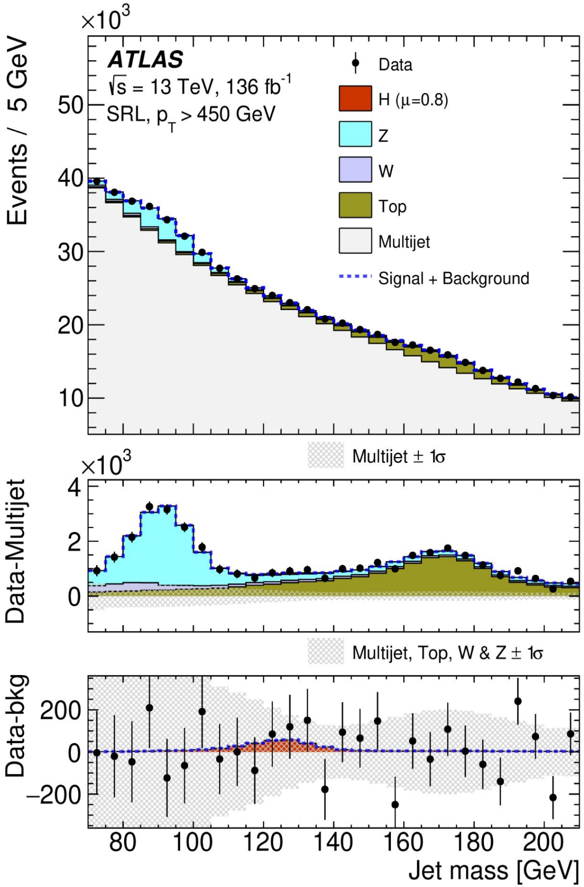
Volume		p_T^H [GeV]	$\|y_H\|$
Fiducial		>450	S/B < 2
STXS	S1 S2 S3 S4	300–450, 450–650, 650–1000, >1000	< 2

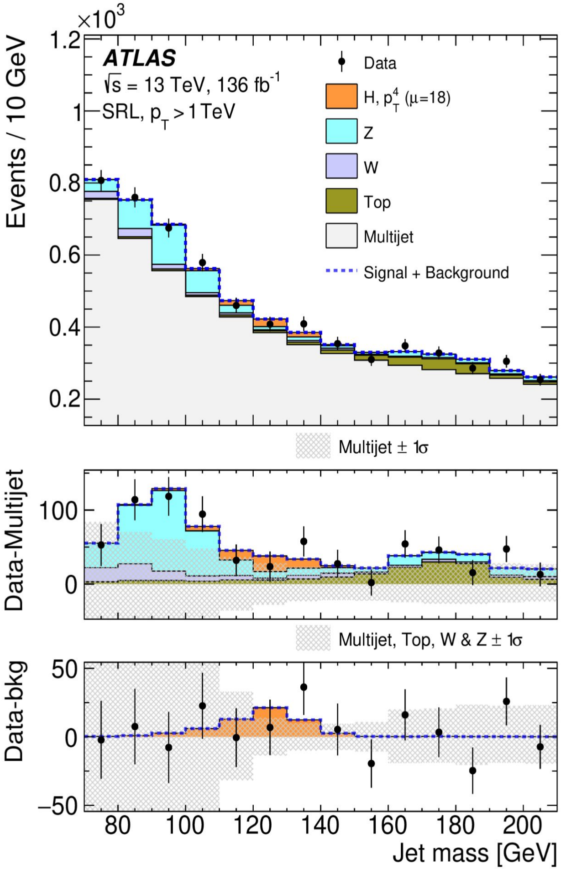
Simplified template cross section



Boosted Higgs (H→bb) STXS analysis: ATLAS results

[ATLAS HIGG-2021-08]





Signal strengths in inclusive fits:

Result	μ_H	μ_Z	$\mu_{t\bar{t}}$
Expected	1.0 ± 3.2	1.00 ± 0.17	1.00 ± 0.07
Observed	0.8 ± 3.2	1.29 ± 0.22	0.80 ± 0.06

95% CL upper limit on σ(H+X) $\mathcal{B}$(H→bb) for

p_T^H > 450 GeV : 115 fb (exp.: 128 fb)
SM: 18.4 fb

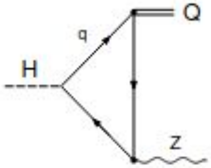
p_T^H > 1 TeV : 9.6 fb (exp.: 7.4 fb)
SM: 0.13 fb

$$\sigma_H(p_T^H > 1\ \text{TeV}) = 2.3 \pm 3.9\ (\text{stat.}) \pm 1.3\ (\text{syst.}) \pm 0.5\ (\text{theory})\ \text{fb}$$

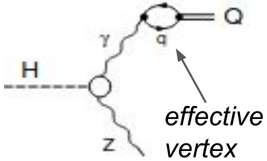
Higgs to quarkonia decays: CMS

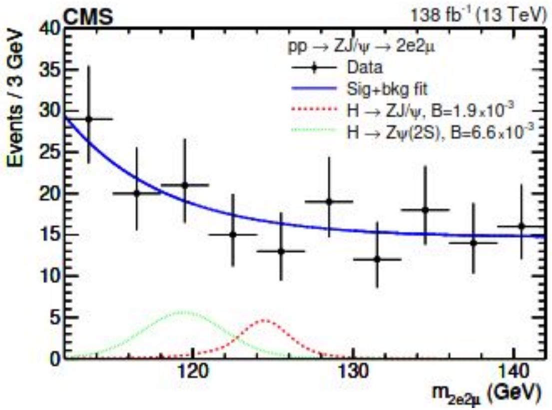
CMS-PAS-HIG-20-008

- Marked by low BRs but promising probes for BSM scenarios
- Current UL on $\mathcal{B}(H \to \gamma\mathcal{V})$ larger by factors 2 to 5 , $\mathcal{V}$ = vector meson
- $\mathcal{B}(H \to ZJ/\psi \,/\, ZJ/\psi(2S))_{SM} \sim 10^{-6}$ (sizeable bkg.)
- $\mathcal{B}(H \to \Upsilon\Upsilon)_{SM} \sim 10^{-5} \sim 10^{-10}$ (negligible bkg.)
- Search using $Z \to e^+e^- \,/\, \mu^+\mu^-$; $J/\psi, \Upsilon \to \mu^+\mu^-$; eff. ~ 30%

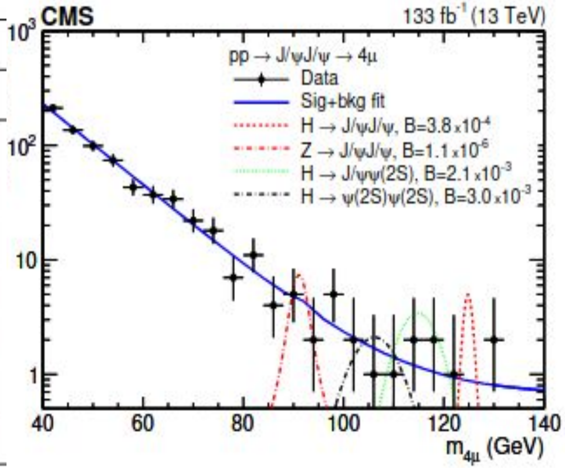


Direct diagram





Process	Observed	Expected
	Longitudinal	Longitudinal
$\mathcal{B}(H \to ZJ/\psi)$	1.9×10^{-3}	$(2.6^{+1.1}_{-0.7}) \times 10^{-3}$
$\mathcal{B}(H \to Z\psi(2S))$	6.6×10^{-3}	$(7.1^{+2.8}_{-2.0}) \times 10^{-3}$
$\mathcal{B}(H \to J/\psi J/\psi)$	3.8×10^{-4}	$(4.6^{+2.0}_{-0.6}) \times 10^{-4}$
$\mathcal{B}(H \to \psi(2S)J/\psi)$	2.1×10^{-3}	$(1.4^{+0.6}_{-0.4}) \times 10^{-3}$
$\mathcal{B}(H \to \psi(2S)\psi(2S))$	3.0×10^{-3}	$(3.3^{+1.5}_{-0.9}) \times 10^{-3}$
$\mathcal{B}(H \to \Upsilon(nS)\Upsilon(mS))$	3.5×10^{-4}	$(3.6^{+0.2}_{-0.3}) \times 10^{-4}$
$\mathcal{B}(H \to \Upsilon(1S)\Upsilon(1S))$	1.7×10^{-3}	$(1.7^{+0.1}_{-0.1}) \times 10^{-3}$



@95% CL

$\mathcal{B}(H \to ZJ/\psi) < 1.9 \times 10^{-3}$

826 X SM

Good prospect to check phenomenological predictions at the HL-LHC.

the simulated signals are equivalent to observed yield in each channel

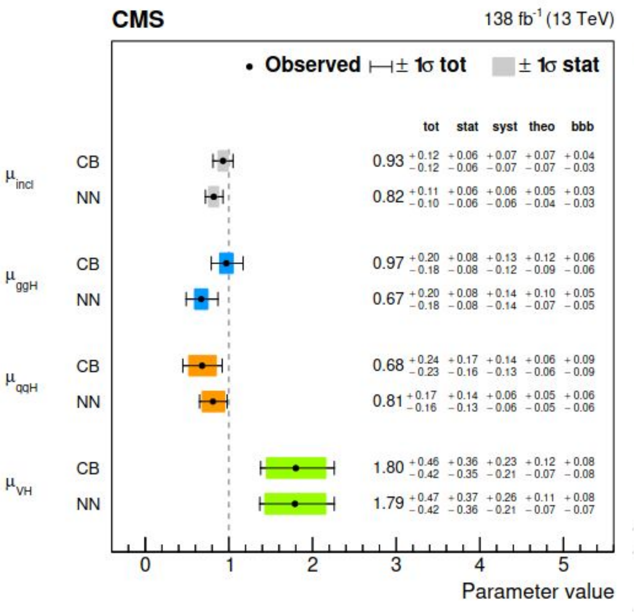
CMS measurement of cross section for H $\rightarrow\tau\tau$

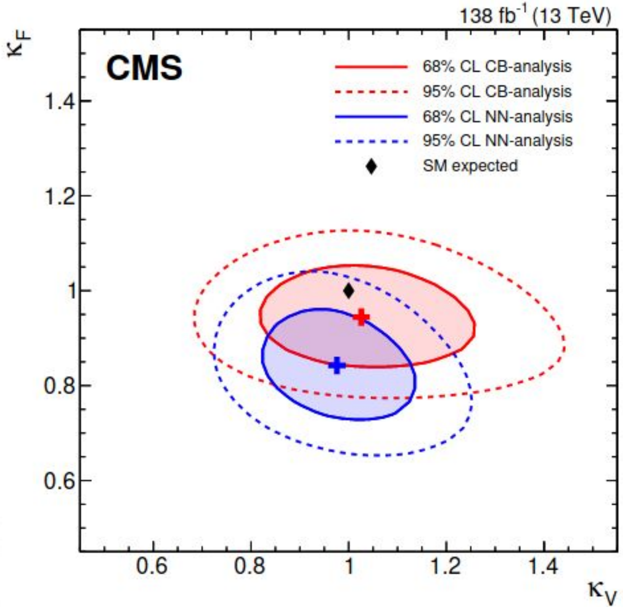
CMS-HIG-19-010
to be submitted soon

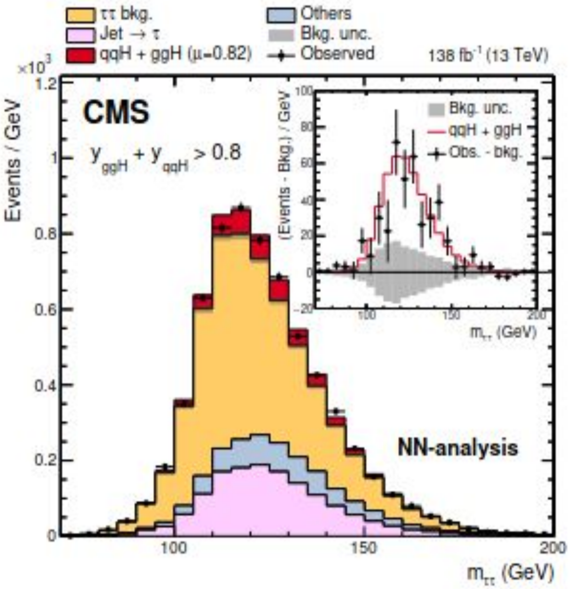
NEW!

CMS-TAU-20-001

- Several BSM scenarios envisage modification in down-type *Hff* couplings.
- **H** $\rightarrow\tau\tau$ allows to measure direct coupling of the H to down-type lepton of 3rd generation (τ).
- Significant improvement for τ performance of CMS in Run 2.
- Both cut-based and NN-based analyses.







σ(pp $\rightarrow$H +X) $\mathcal{B}$(H$\rightarrow\tau\tau$)

$= 0.85^{+0.12}_{-0.11}$ * SM

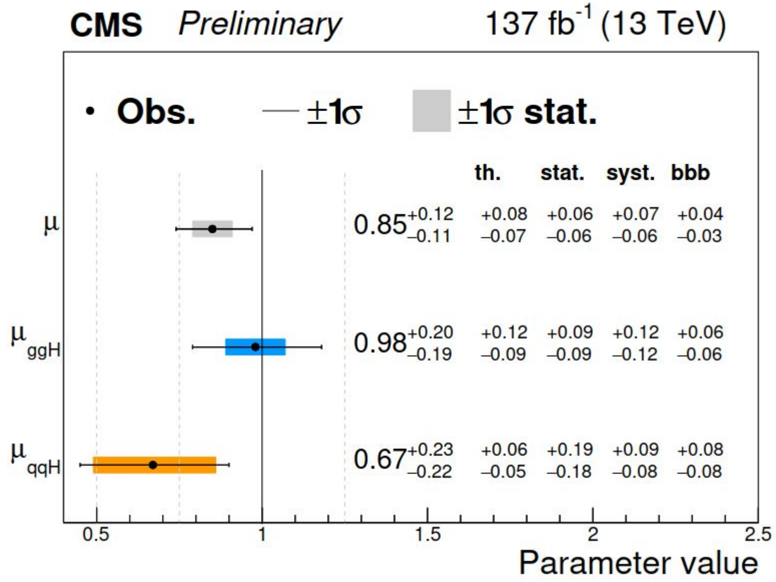
CMS result for inclusive σ(H →ττ)

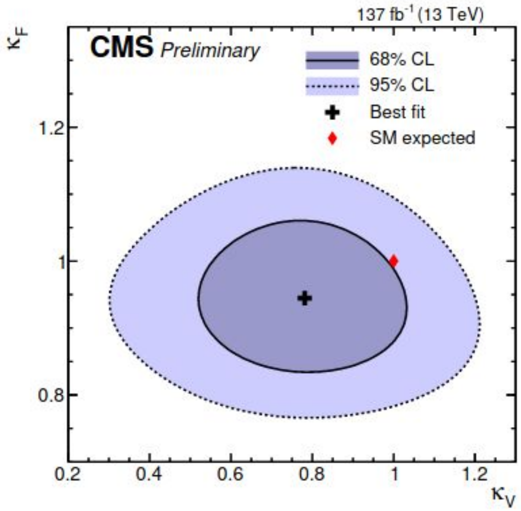
CMS-HIG-19-010
to be submitted soon

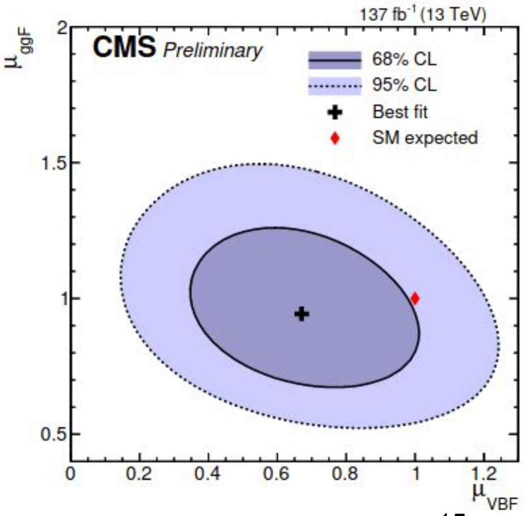
CMS-TAU-20-001

	$\sigma\mathcal{B}(\mathrm{H}\to\tau\tau)$ (fb)	
Process	Measured	SM Prediction
Inclusive	2960^{+394}_{-370}	3422^{+172}_{-172}
ggH	3060^{+592}_{-552}	3051^{+160}_{-160}
qqH	$221^{+75.3}_{-73.3}$	$329^{+9.67}_{-9.67}$

Watch out!

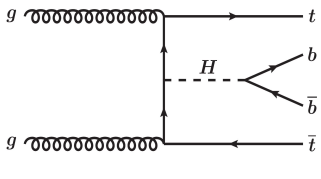




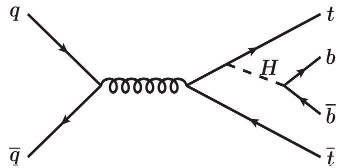


ttH(H→bb) production in ATLAS

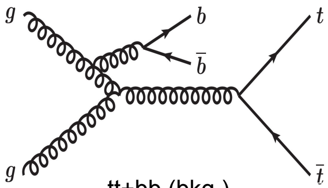
ATLAS-HIGG-2020-23



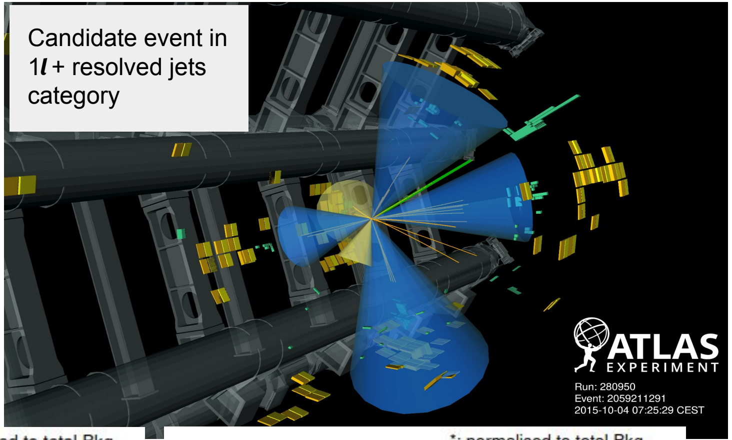
ttH(H→bb) t-channel



s-channel



tt+bb (bkg.)



- SM: σ(ttH) = 507^{+35}_{-50} fb with accuracy of NLO QCD + EW.
- State-of-the-art generators put to task for modeling tt+ ≥ 1b bkg.(biggest source of syst. uncertainty).
- Ample use of machine learning for H candidate identification & classification of ttH signal categories.
- Single lepton (resolved & boosted H using BDT and DNN resp.ly) and dilepton final states.

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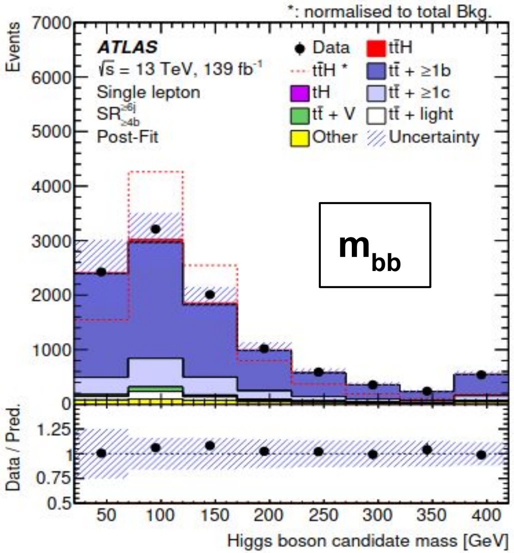
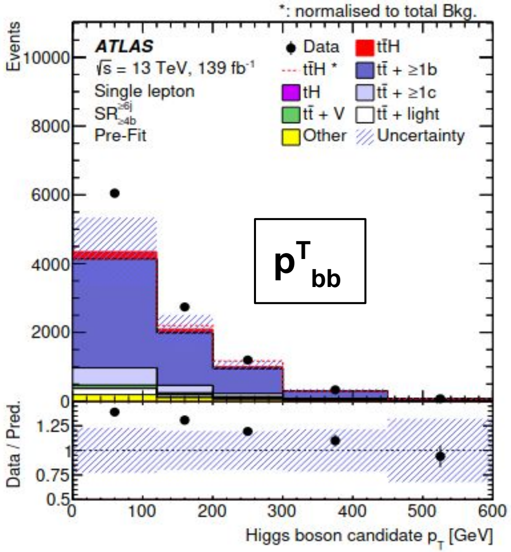
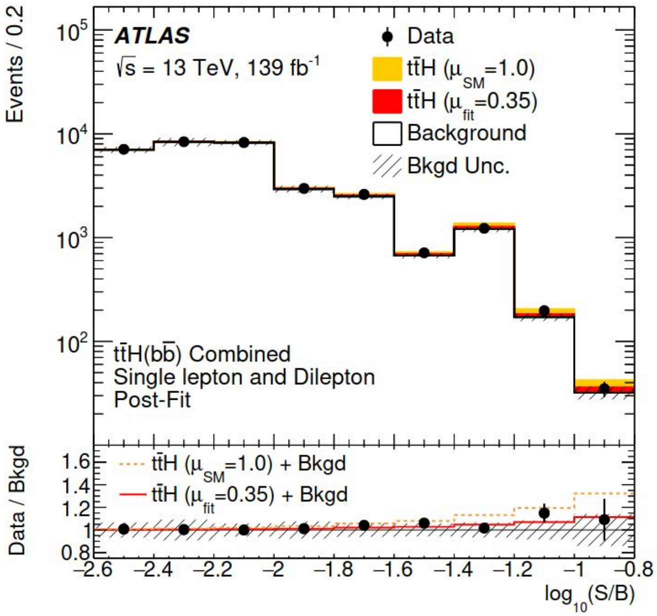
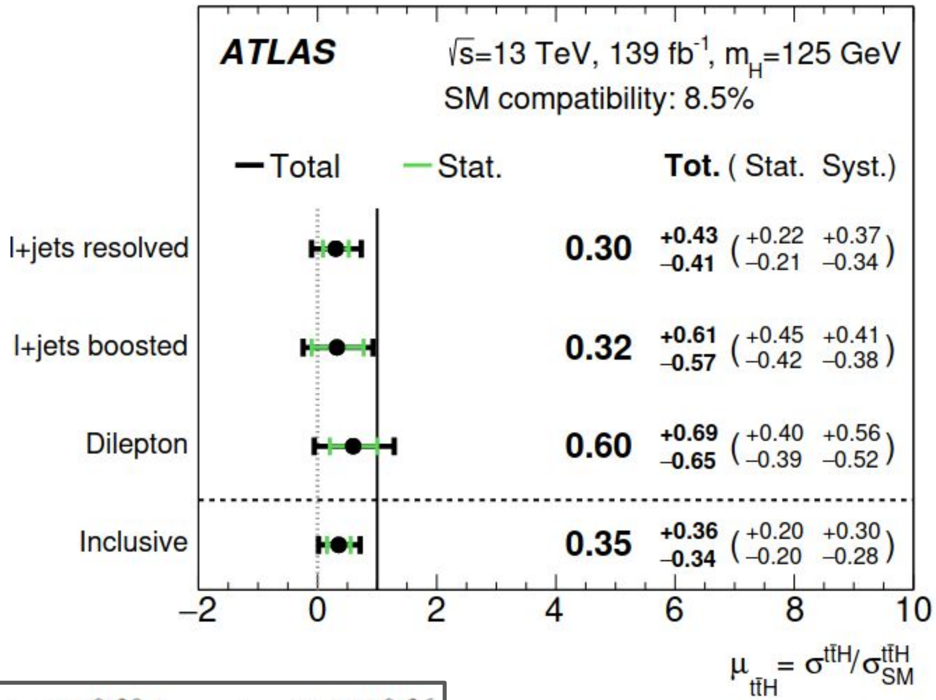




ATLAS results for ttH(H→bb) production

ATLAS-HIGG-2020-23



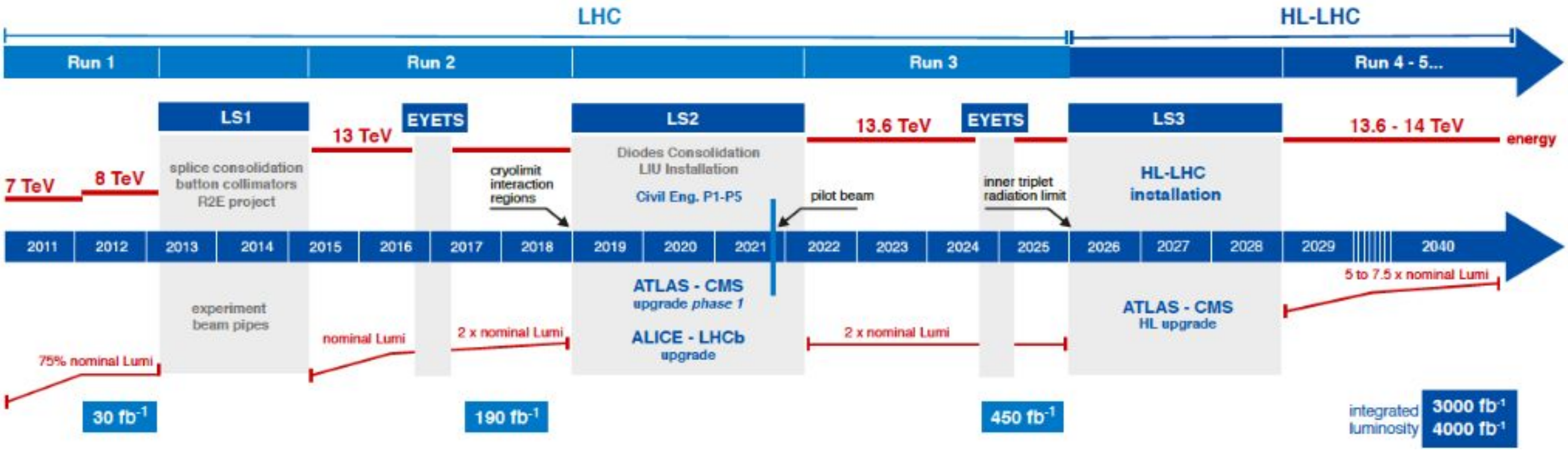


Final result based on discriminator output

- Signal strength wrt SM: $\mu = 0.35 \pm 0.20\,(\text{stat.})\,^{+0.30}_{-0.28}\,(\text{syst.}) = 0.35^{+0.36}_{-0.34}$
- Compatibility with SM: ~ 8.5%
- **Observed (exp.) signal significance wrt bkg.-only hypothesis: 1.0 (2.0)**

Watch out!

Future of probing Yukawa interactions at the LHC



LHC schedule as of January, 2022

Prospects for immediate future: Run 3

CMS -PAS-FTR-18-011

- Increased $\sqrt{s}$ = 13.6 TeV → some of the signal rates will increase, but not much effect on trigger
- Pileup 50-60 →higher than in Run 2, but now with luminosity/pileup levelling
- Expected integrated luminosity $\mathcal{L}$ = 300/fb

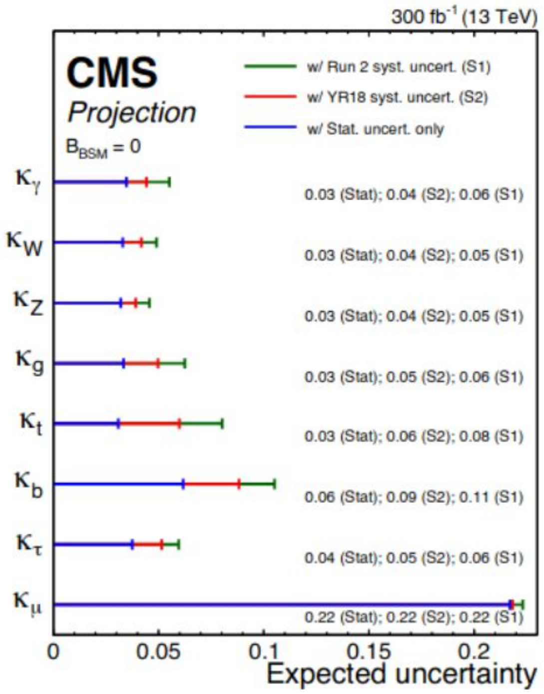
  - Main factors for improvement of overall precision:

    i) better detectors, improved acceptance in some cases, better computing.

    ii) larger dataset ⇒ better statistical precision ⇒ improved treatment of theory systematics and background modelling, object performance and calibration ....

    iii) better estimates of data-driven background, scale factors

    iv) several improvements on theoretical aspects: eg., PDF, full usage of higher order simulations, etc.



- **Phenomenology: eventual combination of data from Run1, Run2, Run 3 will provide powerful interpretation.**

Recent projections for HL-LHC with Phase-2 upgraded detectors

HL-LHC: $\sqrt{s}$ =14 TeV, $\mathcal{L}$ = 3000 - 4000 /fb → significant upgrades for experiments.

- Opens up opportunity for several processes not easily accessible with the current data.
- Also gain from enhanced performance of detectors and fiducial coverage.
  Studies mostly considered Run 2 systematics, will improve substantially in future.

CMS estimates:

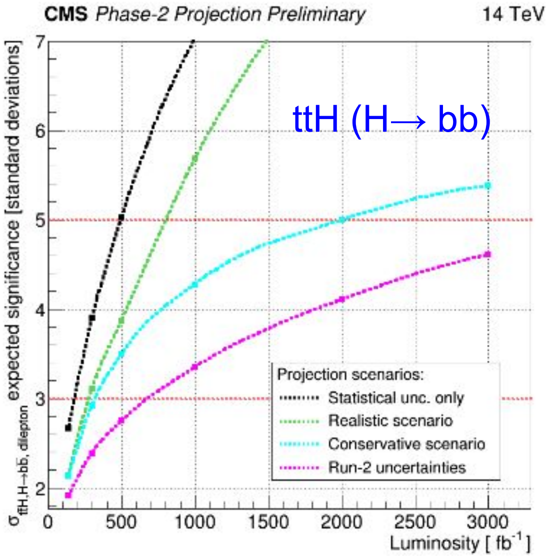
- Simultaneous measurement of VH production for H→cc and H→ bb using merg jets (assume mis-id rate of H→ bb as H→ cc to be ~ 20%)
  ⇒ **expect about 14% precision in $\mu_{VH(H \to bb)}$ with $\mathcal{L}$ = 400 /fb**

  $\mu_{VH(H \to bb)}$: 1.00 ± 0.03(stat) ± 0.04(sys)

  HIG-21-008 suppl.

  $\mu_{VH(H \to cc)}$: 1.00 ± 0.6(stat) ± 0.5(sys)

- **5 sigma discovery of ttH (H→ bb) anticipated with $\mathcal{L}$ = 500 /fb**
- Total uncertainty on cross section in opposite sign dilepton channel: ~12%



FTR-21-002

Summary

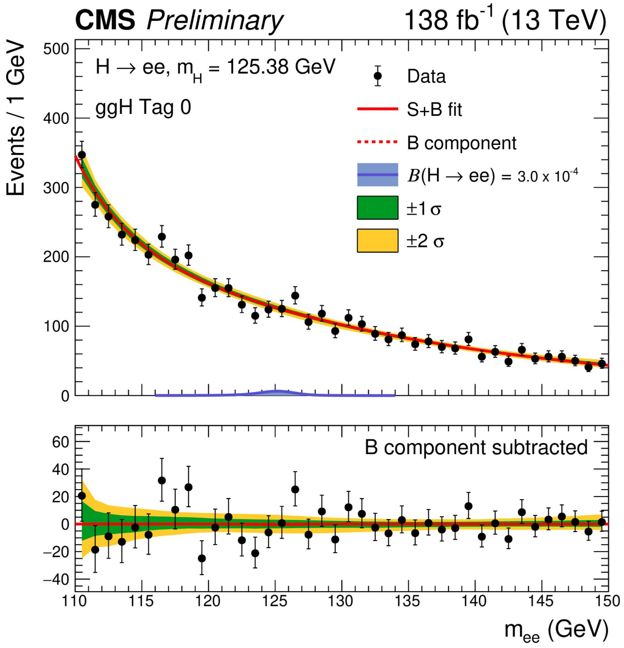
- ATLAS and CMS have made various measurements to probe Higgs Yukawa interaction Run 2 data and corresponding to $\mathcal{L}$ ~ 140 /fb with improved precision.
- With commendable techniques and efforts some of the difficult and rarer decay modes, like H→ cc, have started to show up.
- This has paved the way to study the Higgs-quark Yukawa coupling structures in production and decay.
- **Till now all measurements seem compatible with standard model.**
- Several more results from Run 2 data analysis are on the way.
- With imminent LHC restart, there is huge anticipation to close in on the as-yet elusive couplings as well as to constrain the allowed ranges of the couplings already measured.

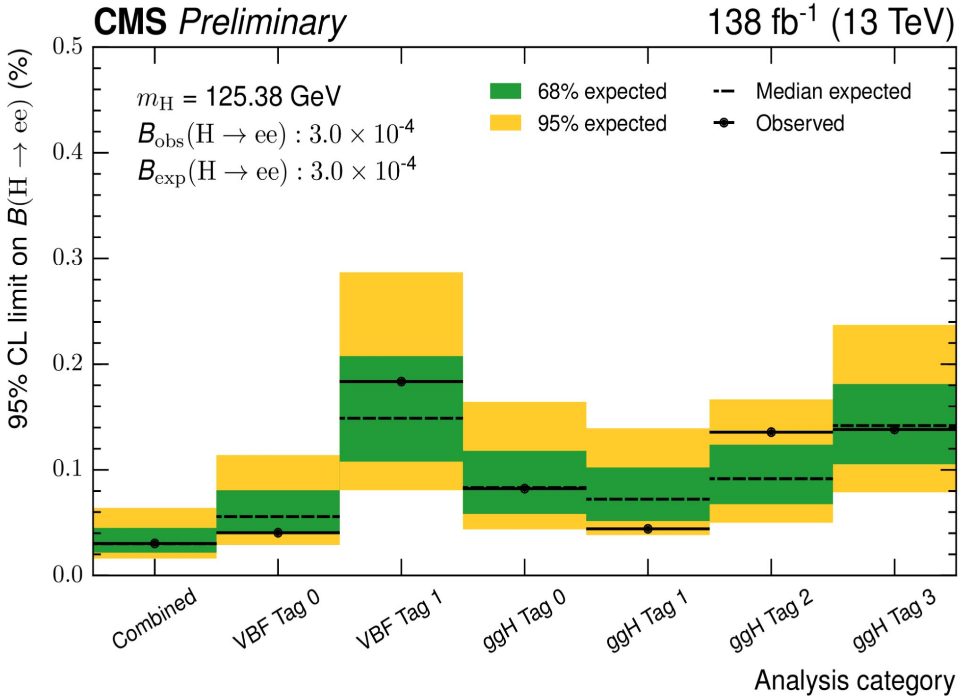
→ **Grand time ahead for probing Higgs-fermion Yukawa interactions → Stay tuned!**

Backup

H → e⁺e⁻

CMS-PAS-HIG-21-015





SM:B(H→ e^+e^-): 5.0 X 10^{-9}

ATLAS 95% CL on B(H→e^+e^-): 3.6 X 10^{-4} (exp.3.5 X 10^{-4})

CMS 95% CL on B(H→e^+e^-): 3.0 X 10^{-4} (exp.3.0 X 10^{-4}) → ***Best to date !***

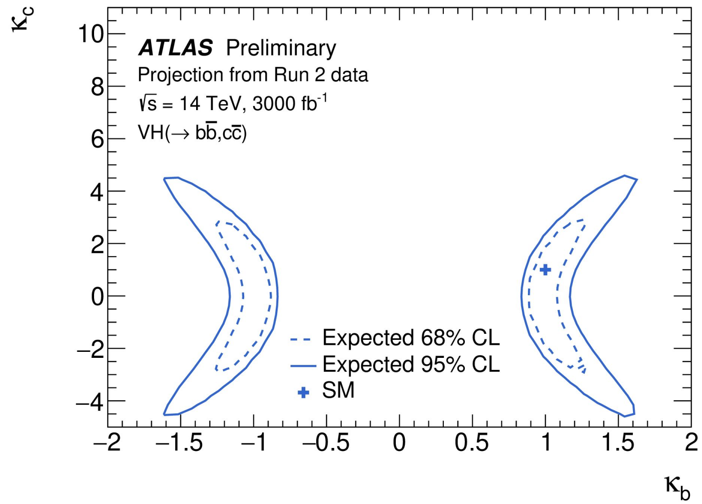
Uncertainty break up for ttH(H→bb)

Uncertainty source	$\Delta\mu$	
Process modelling		
$t\bar{t}H$ modelling	+0.13	−0.05
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ NLO matching	+0.21	−0.20
$t\bar{t}+\geq 1b$ fractions	+0.12	−0.12
$t\bar{t}+\geq 1b$ FSR	+0.10	−0.11
$t\bar{t}+\geq 1b$ PS & hadronisation	+0.09	−0.08
$t\bar{t}+\geq 1b$ p_{T}^{bb} shape	+0.04	−0.04
$t\bar{t}+\geq 1b$ ISR	+0.04	−0.04
$t\bar{t}+\geq 1c$ modelling	+0.03	−0.04
$t\bar{t}+$ light modelling	+0.03	−0.03
tW modelling	+0.08	−0.07
Background-model statistical uncertainty	+0.04	−0.05
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+0.03	−0.02
c-mis-tag rates	+0.03	−0.03
l-mis-tag rates	+0.02	−0.02
Jet energy scale and resolution		
b-jet energy scale	+0.00	−0.01
Jet energy scale (flavour)	+0.01	−0.01
Jet energy scale (pile-up)	+0.00	−0.01
Jet energy scale (remaining)	+0.01	−0.01
Jet energy resolution	+0.02	−0.02
Luminosity	+0.01	−0.00
Other sources	+0.03	−0.03
Total systematic uncertainty	+0.30	−0.28
$t\bar{t}+\geq 1b$ normalisation	+0.04	−0.07
Total statistical uncertainty	+0.20	−0.20
Total uncertainty	+0.36	−0.34

Uncertainty components in VHcc signal strength: CMS

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

ATLAS projection for κ_c vs. κ_b at HL-LHC



Constraint from combination of the measurements of the *VH,H→bb* and *VH,H→cc*

⇒ $|\kappa_c / \kappa_b|$ <2.7 at 95 % confidence level for $\mathcal{L}$ = 3000 /fb

Source of uncertainty		$\Delta\mu_{VH}^{c\bar{c}}$
Total		3.21
Statistical		1.97
Systematics		2.53
Statistical uncertainties		
Data statistics only		1.59
Floating normalisations		0.95
Theoretical and modelling uncertainties		
$VH, H \to c\bar{c}$		0.27
Z+jets		1.77
Top-quark		0.96
W+jets		0.84
Diboson		0.34
$VH, H \to b\bar{b}$		0.29
Multi-Jet		0.09
Experimental uncertainties		
Jets		0.59
Leptons		0.20
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.18
Pile-up and luminosity		0.19
Flavour tagging	c-jets	0.61
	b-jets	0.16
	light-jets	0.51
	τ-jets	0.19