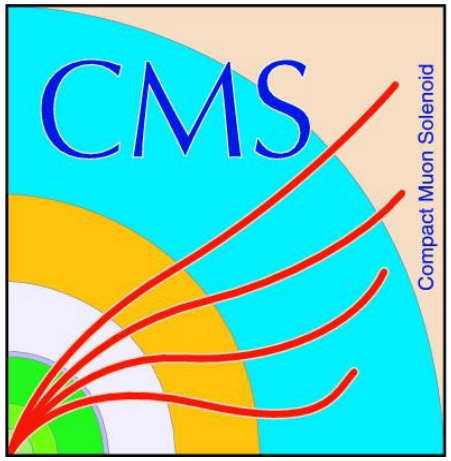


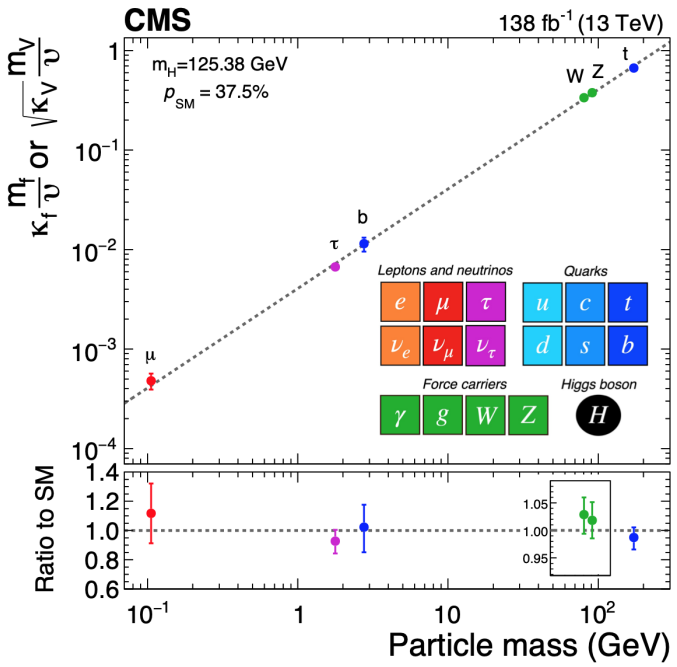
Rare Higgs Decay and Production Modes at LHC

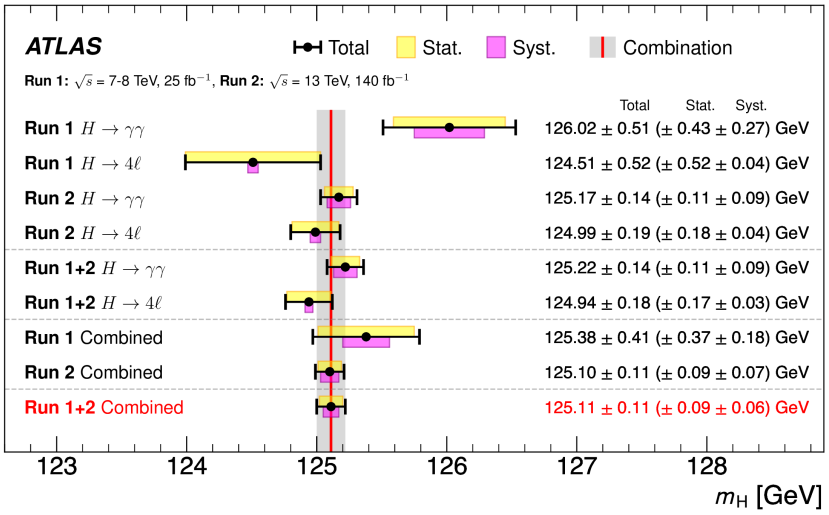
Alexei Raspereza

on behalf of the ATLAS and CMS Collaborations

QCD at LHC, Freiburg - 7/10/2024

Introduction



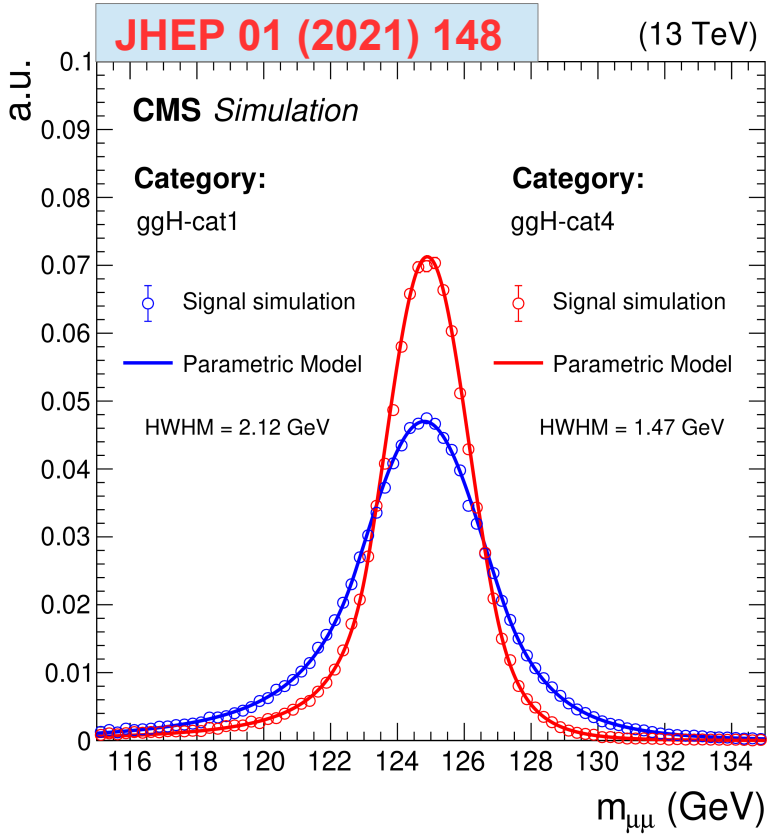


- In 12 years Higgs boson properties have been studied in great detail
  - so far good agreement with SM predictions
- Most of information is inferred from well established production and decay modes
- Many open questions remain
  - Does mass-coupling relation hold for earlier generations of fermions?
  - Can we probe sign of couplings?
  - Does Higgs couple to BSM particles?
  - …
- Study of rare Higgs decays and production mechanisms is crucial for addressing these questions

Rare Higgs Decay Modes

Search for H→μμ decay

- Probe of Yukawa coupling to 2nd generation of fermions
- Small branching ratio in the SM ($2 \cdot 10^{-4}$) can be modified by BSM physics
- Clean signature and excellent mass resolution
- Major production mechanism targeted : ggH, VBF, VH, ttH
- Main backgrounds : Drell-Yan, top pairs and diboson events



Search for H→μμ (Run 2 results)

- Signatures of exploited production modes are targeted by dedicated multivariate (BDT) event categorization
- Signal extracted from parametric fit of $m_{\mu\mu}$ spectrum in all categories

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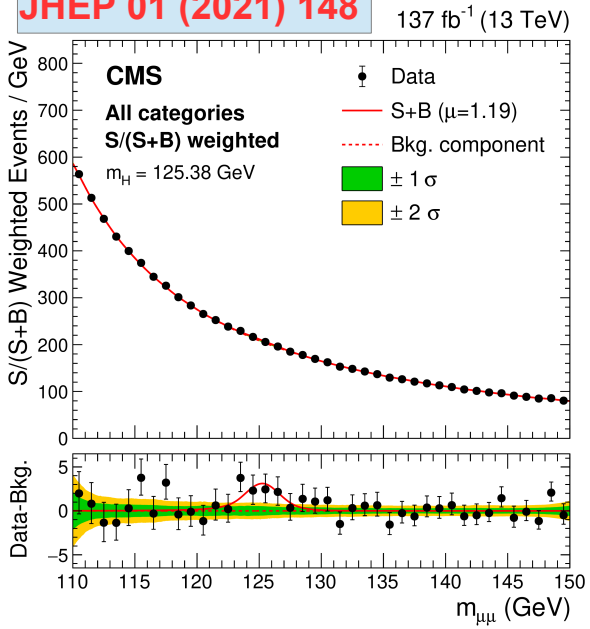

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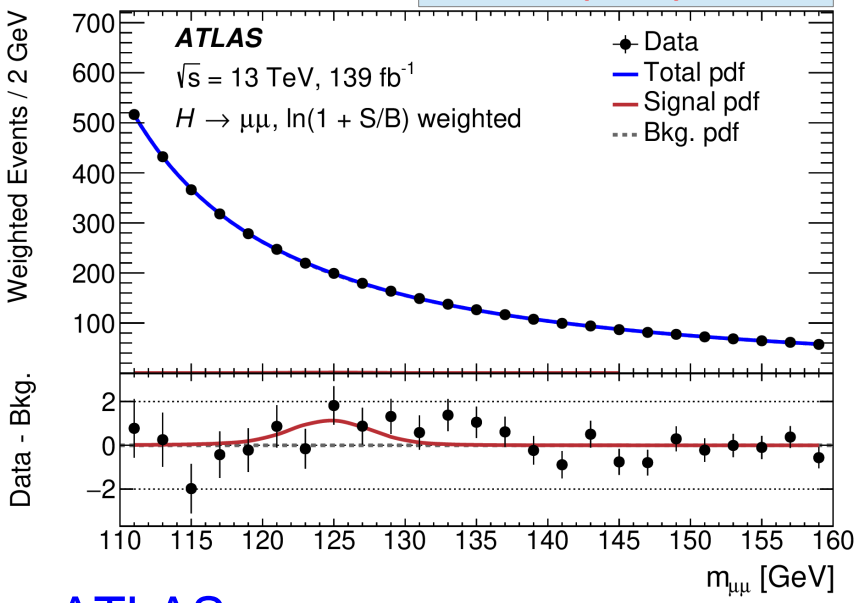


CMS:

- obs. (exp.) significance : 3.0σ (2.5σ) evidence for H→μμ decay!
- measured μ = 1.19±0.43

ATLAS :

- obs. (exp.) significance : 2.0σ (1.7σ)
- measured μ = 1.2±0.6

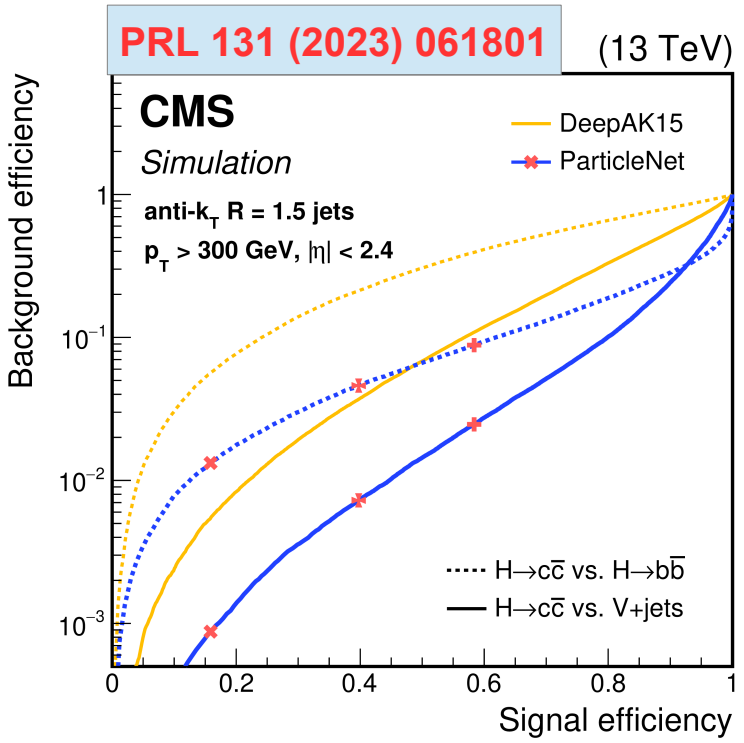
Goal for Run2+Run3 combination : >5σ observation

Search for H→cc decay

- H→cc decay probes Higgs coupling to charm quarks
- BR(H→cc) = 2.8%
  can be modified by BSM physics
- Charm-jet tagging is essential
- Inclusive search is impractical:
  signal is overwhelmed by QCD multijet background
- Most promising production mode:
  W(Z)H with W→lν, Z→ll,νν decays
- Major backgrounds:
  V+jets, VV, Top, V+H→bb

PartcleNet : advanced charm-jet tagger based on graph DNN (used in CMS to identify boosted H->cc decay)

dramatic improvement in performance w.r.t. previously used tagger

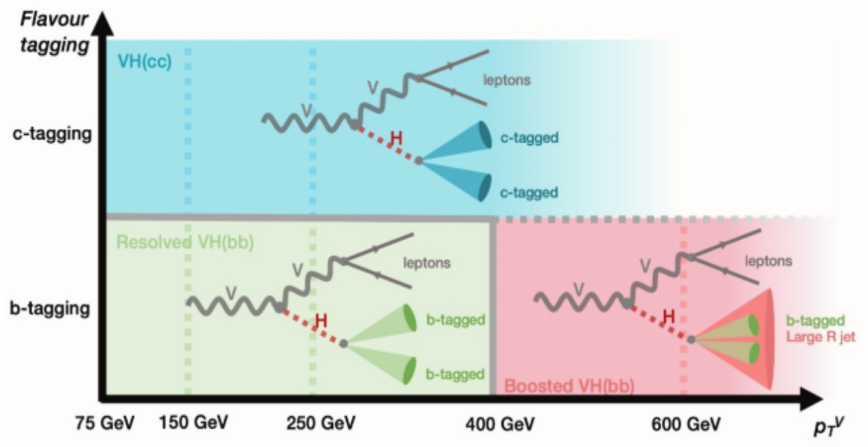


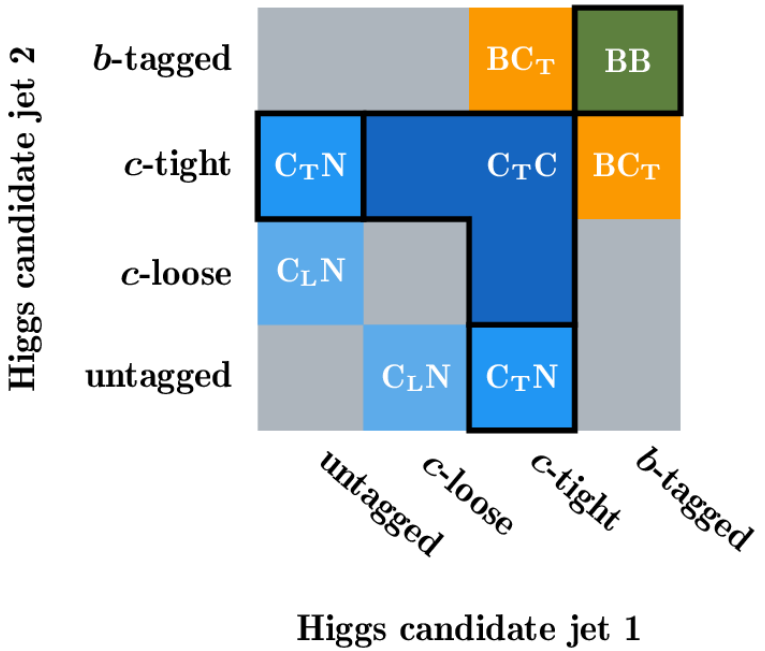
V(lep)H→bb/cc with ATLAS

ATLAS-CONF-2024-010

Simultaneous re-analysis of VH(bb) and VH(cc) channels

- event categorization based on lepton multiplicity and flavour, event kinematics
  – covers resolved and merged topologies
- orthogonal selection based on b/c-tagging
  – form Higgs candidate
  – define multiple SRs (Hbb, Hcc) and CRs
- complex statistical model
  – 97 CRs and 59 SRs (27 Hbb and 32 Hcc)
- main backgrounds: Top, V+jets, multijets, VV
  – suppressed with BDT in SRs
  – shapes modeled with simulation
  – normalizations constrained in CRs
- simultaneous fit in all regions
  – SRs : BDT score for VH(→cc)/VH(→bb) signals
  – CRs : m(bb/cc), pT(V) or total yield

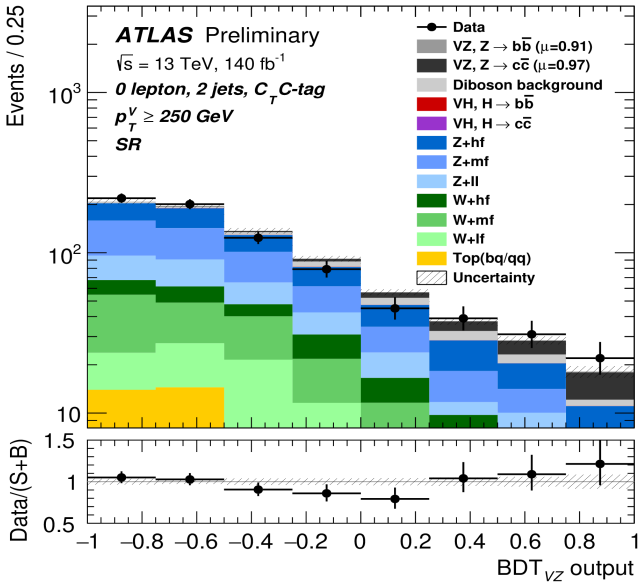




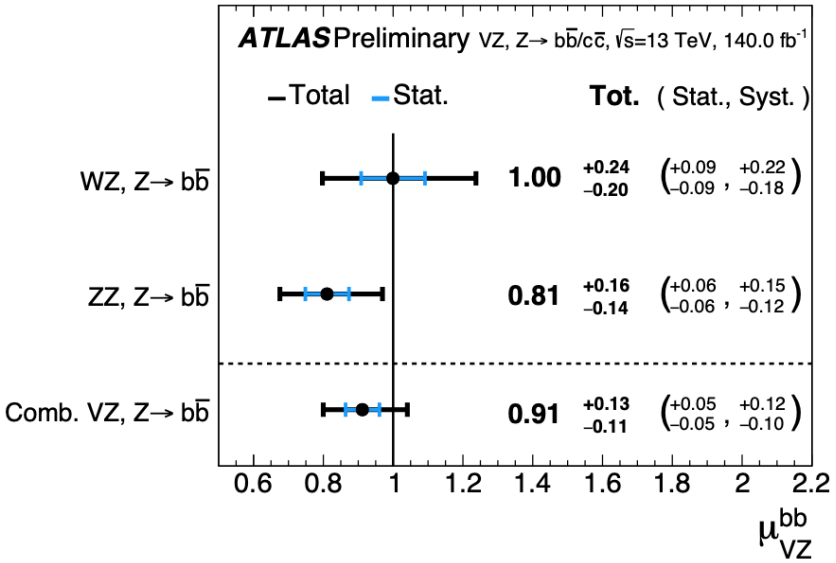
V(lep)H→bb/cc with ATLAS

ATLAS-CONF-2024-010

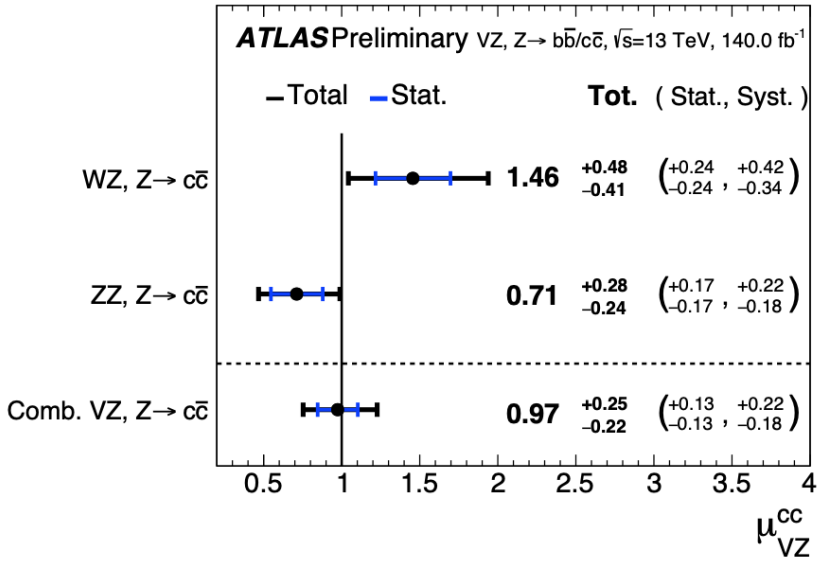
- Analysis validated with standard candles: VZ(cc) and VZ(bb)
- Dedicated BDT is trained with VZ as signal (BDT score is used for signal extraction in SRs)
- Simultaneous extraction of VZ(cc) and VZ(bb) : measurement compatible with SM predictions



significance > 10σ



obs. (exp.) significance = 5.2σ (5.3σ)



V(lep)H→bb/cc with ATLAS

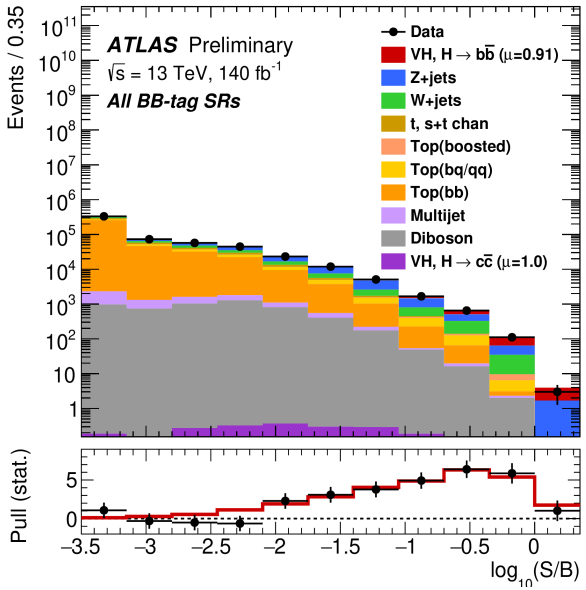
ATLAS-CONF-2024-010

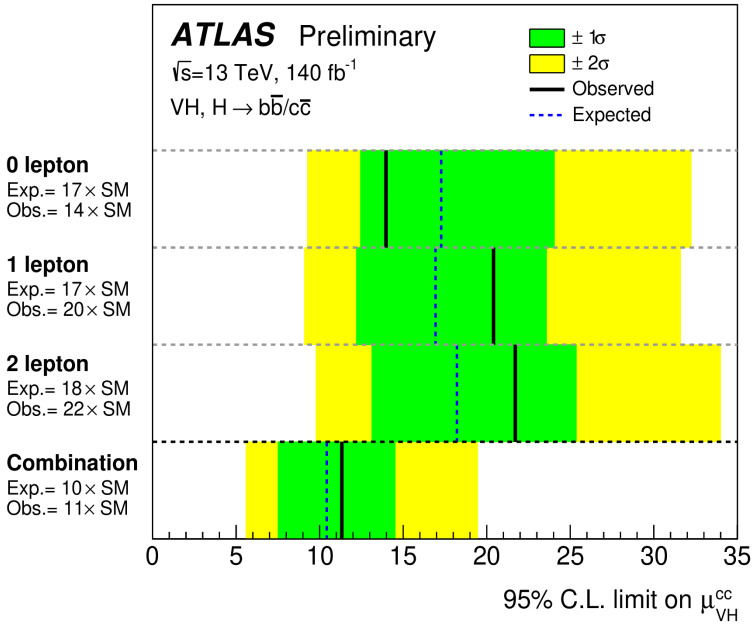
- Simultaneous measurement of VH(bb) and VH(cc)

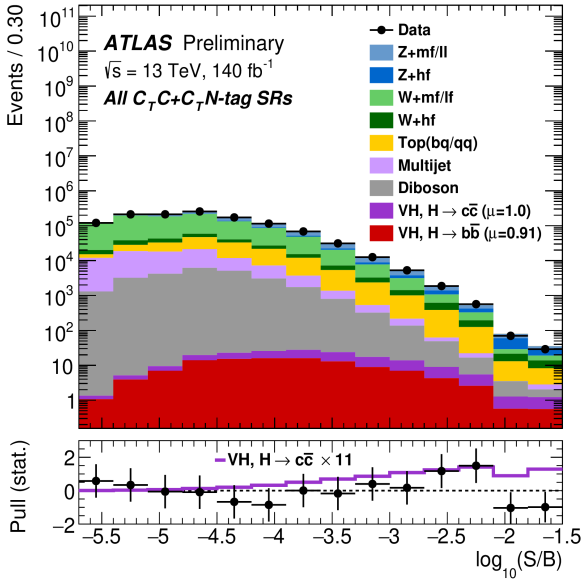
$$\mu_{VH}^{bb} = 0.91^{+0.16}_{-0.14} = 0.91 \pm 0.10\,(\text{stat.})^{+0.12}_{-0.11}\,(\text{syst.})$$

$$\mu_{VH}^{cc} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}\,(\text{stat.})^{+3.6}_{-3.5}\,(\text{syst.}).$$

- VH(cc) signal strength < 11.2 (10.4) at 95% CL
  strongest limit to date!







V(lep)H→bb/cc with ATLAS

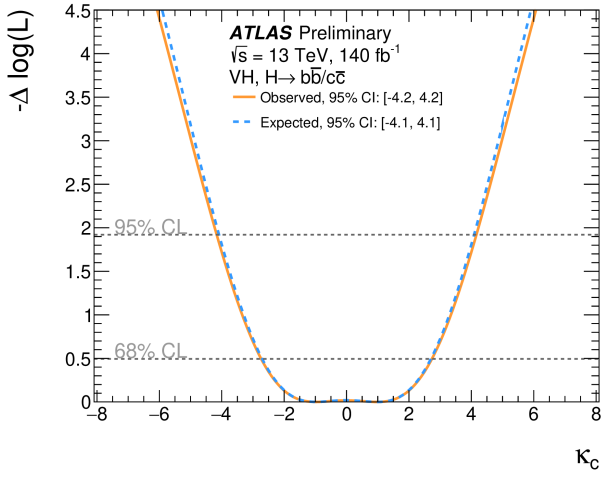
ATLAS-CONF-2024-010

- Signal strength modifiers parameterized via κ_b and κ_c, which alter BRs of H→bb and H→cc decays

$$\mu_{VH}^{cc} = \frac{\kappa_c^2}{1 + B_{hbb}^{SM}(\kappa_b^2 - 1) + B_{hcc}^{SM}(\kappa_c^2 - 1)} \qquad \mu_{VH}^{bb} = \frac{\kappa_b^2}{1 + B_{hbb}^{SM}(\kappa_b^2 - 1) + B_{hcc}^{SM}(\kappa_c^2 - 1)}$$

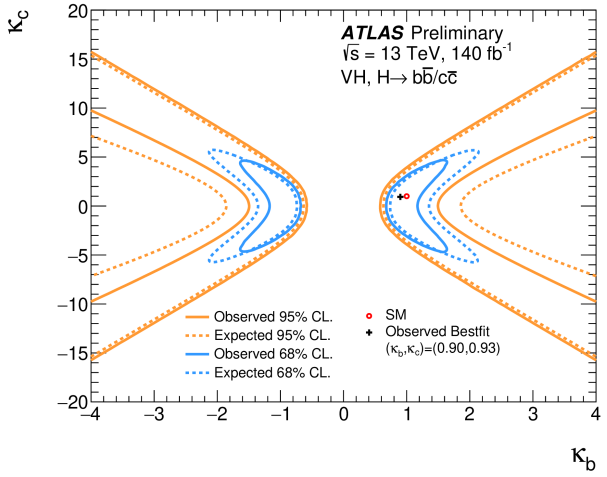
- all other Higgs couplings are set to SM predictions

1D scan of κ_c , $\kappa_b = 1$

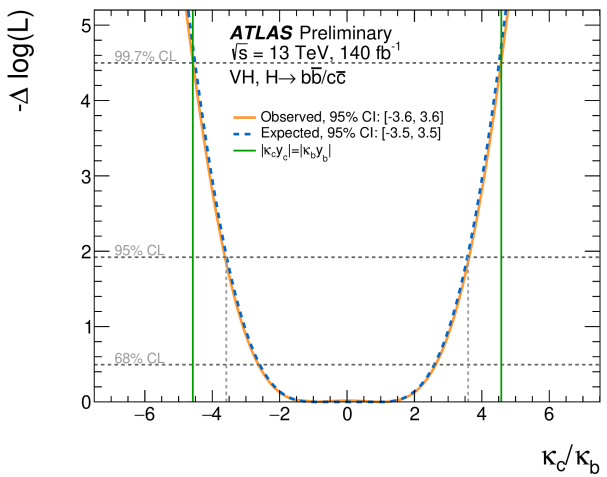


$|\kappa_c| < 4.2$ at 95% CL

2D scan of (κ_c , κ_b)



1D scan of κ_c/κ_b (VH(bb)) profiled



$|\kappa_c/\kappa_b| < 3.6$ at 95% CL

VH(→cc) in CMS

PRL 131 (2023) 061801

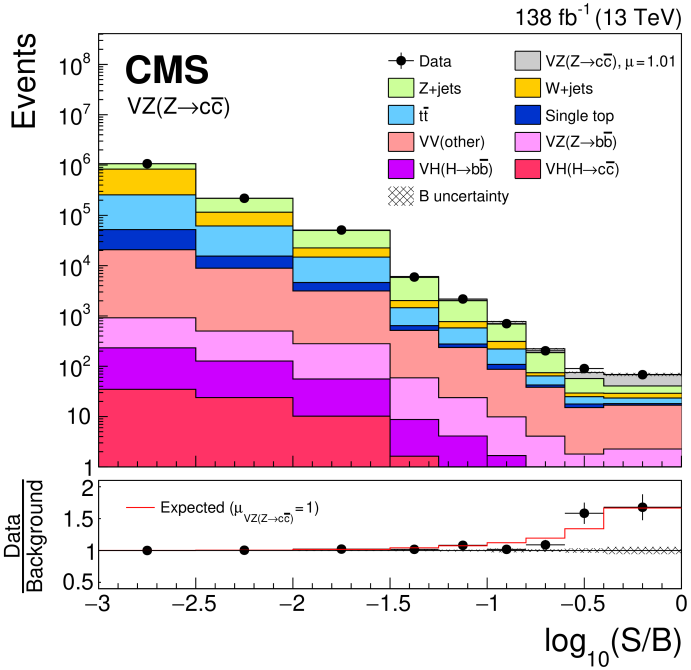
- Event selection and categorization based on
  - number and flavour of leptons : target specific W/Z decays
  - pT(V) and event topology : resolved vs. boosted
  - cc-purity : score of dedicated cc-tagger (ParticleNet) in boosted category

- Major backgrounds
  - V+Jets and multijets : constrained in dedicated CRs
  - Top, VV and VH(bb) : constrained to SM predictions within uncertainties

- Dedicated BDT to establish VZ(cc) standard candle

$$\mu_{\mathrm{VZ(cc)}} = 1.01^{+0.23}_{-0.21}$$

Significance : 5.7σ



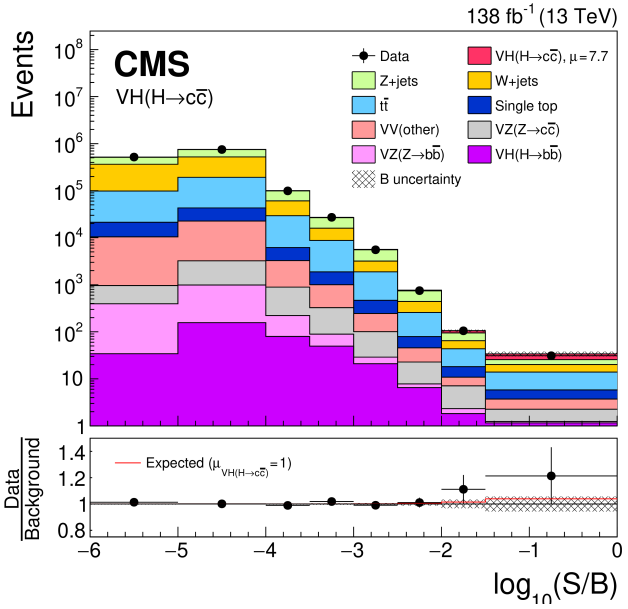
VH(→cc) in CMS

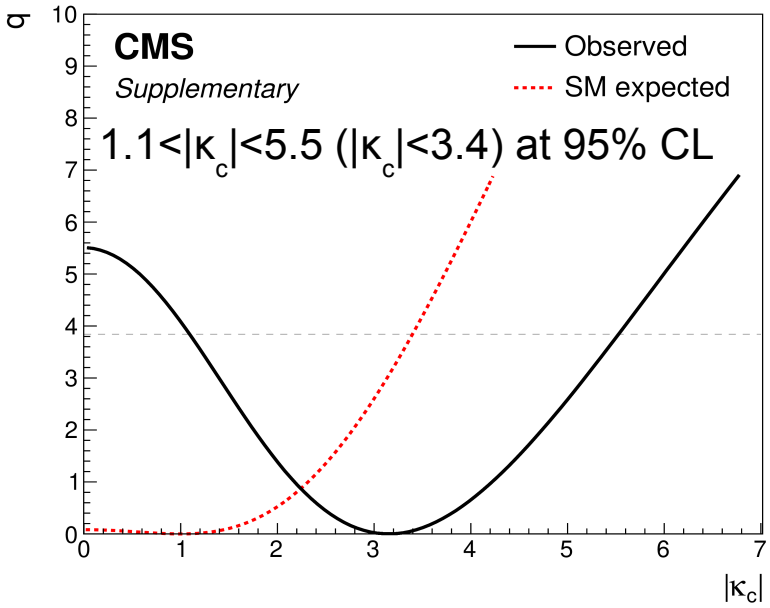
PRL 131 (2023) 061801

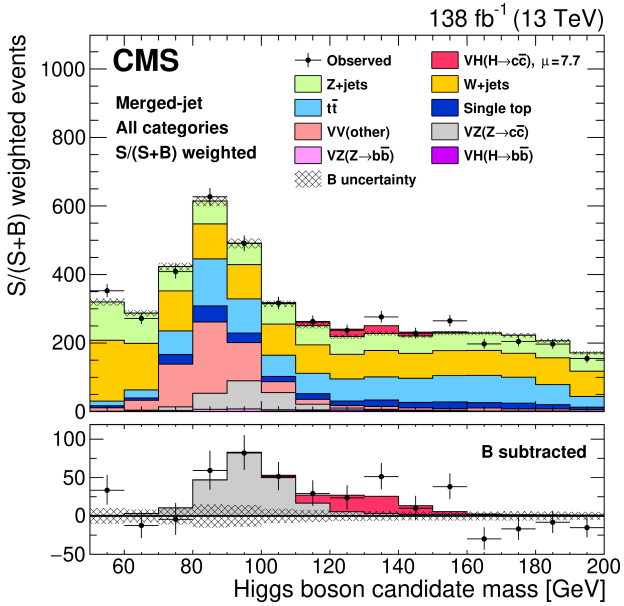
- Separate BDT with VH(cc) as signal
- Signal extracted from distributions of
  - BDT score in resolved categories
  - m(cc) in boosted categories
- Measured signal strength

$$\mu_{\mathrm{VZ(cc)}} = 7.7^{+3.8}_{-3.5}$$

translated into constraints on $|\kappa_c|$



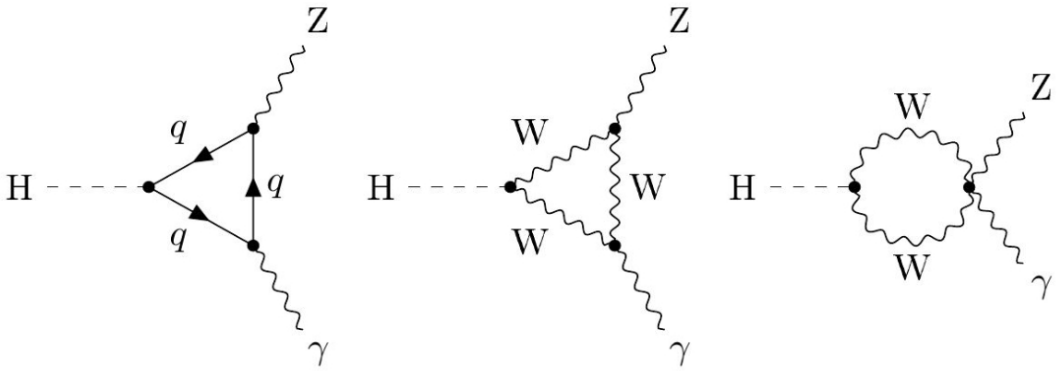




Search for H→Zγ

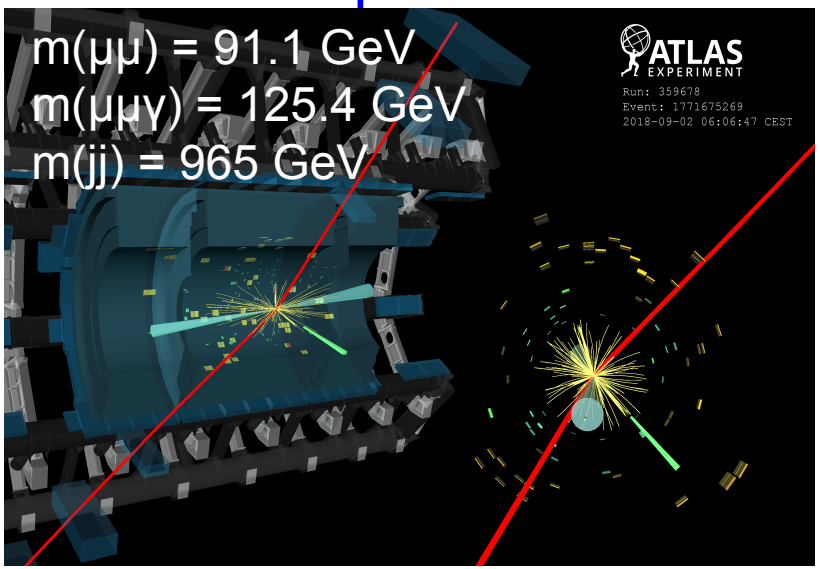
- Loop induced decay
  probe BSM physics in loops

- $B(H\to Z\gamma) = (1.6\pm0.1)\cdot 10^{-3}$
  $B(Z\to ee+\mu\mu) = 6.8\cdot 10^{-2}$



- Signature: Z→ee,μμ + γ with resonant m(ℓℓγ) peak around H mass
  Major backgrounds : Drell-Yan with FSR γ or jets

VBF H→Zγ candidate



Both ATLAS and CMS performed search with full Run 2 dataset

- Event categories targeting major production modes: ggH, VBF, VH

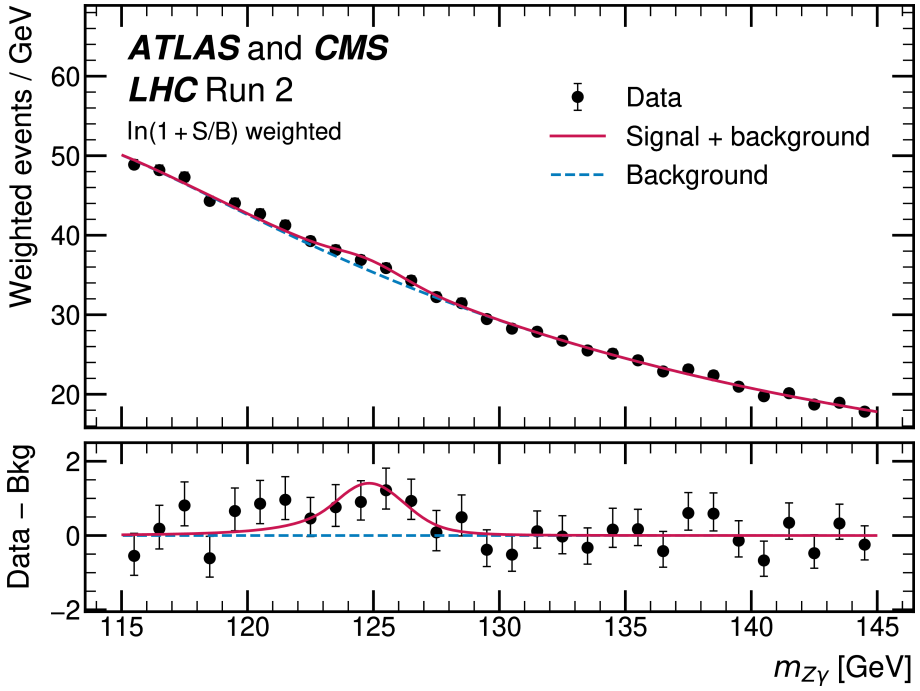
- Signal extracted from parametric fit of m(ℓℓγ) spectrum in all categories

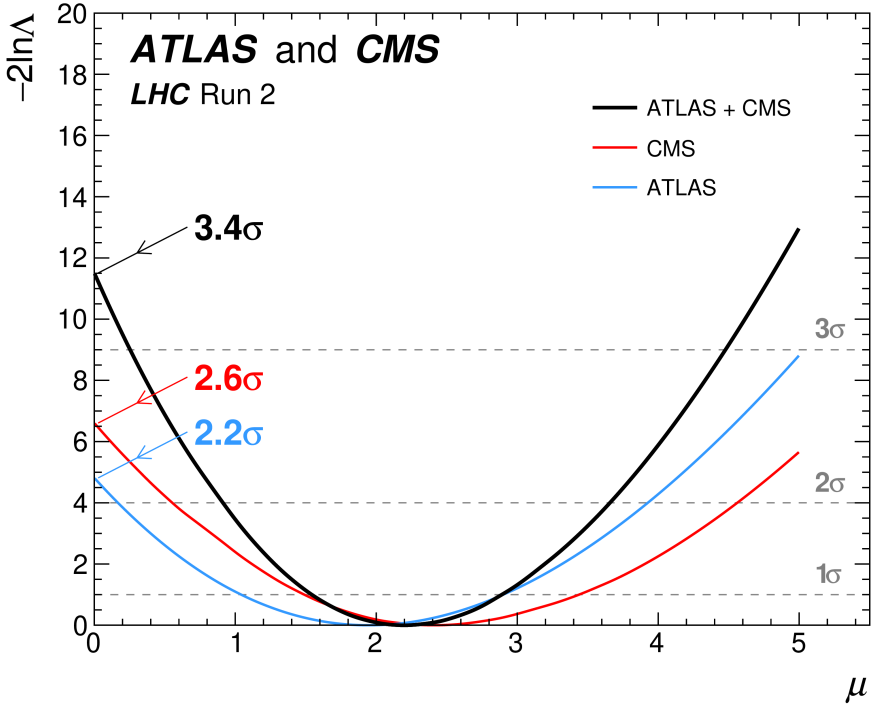
H→Zγ : ATLAS+CMS Combination

- Evidence of signal with significance of 3.4σ (1.6σ exp.) from ATLAS+CMS combination

PRL 132 (2024) 021803

  - Measured μ = 2.2±0.7 x SM prediction
    measured B(H→Zγ) = (3.4±1.1)·10^{-3} (1.9σ within SM prediction)





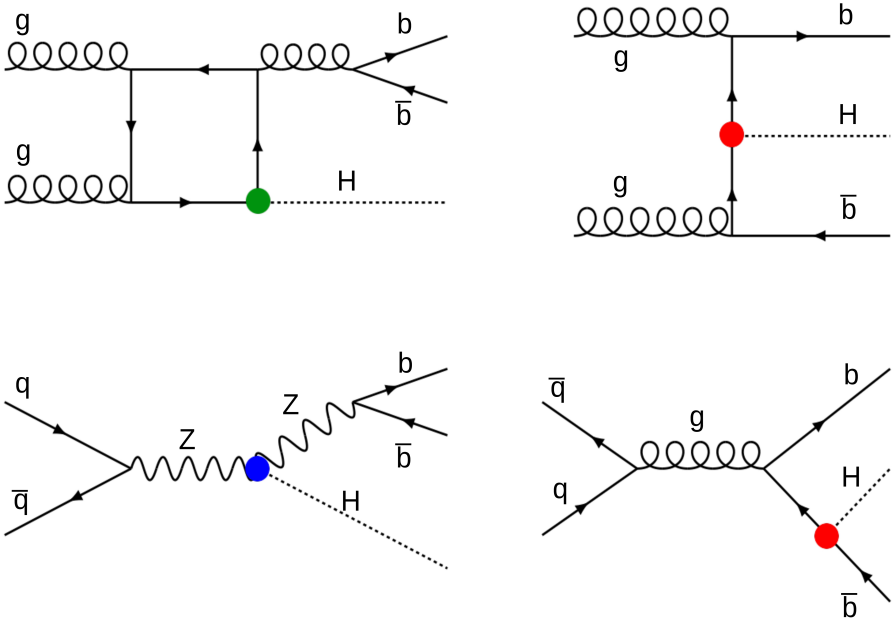
  - Precision is statistics limited → clear prospect of scrutinizing excess using Run 3 data

Rare Higgs Production Modes

b(b)H production with CMS arXiv:2408.01344

- Yukawa coupling to b-quarks was established in H→bb decay. Can we probe this coupling in production?

- Contributions to inclusive b-quark associated Higgs production
  - ggH with g→bb splitting ~ y_t^2
  - via direct bbH coupling ~ y_b^2
  - interference ~ $y_t \cdot y_b$
  - ZH, Z→bb (considered as bkgd)



- Analysis goals
  - measure cross section of b-quark associated production involving y_t and y_b couplings:
  - set constraints on y_b

term	σ (pb)
y_t^2	$1.04^{+0.47}_{-0.49}$
y_b^2	$0.48^{+0.05}_{-0.07}$
$y_t \cdot y_b$	$0.03^{+0.01}_{-0.01}$

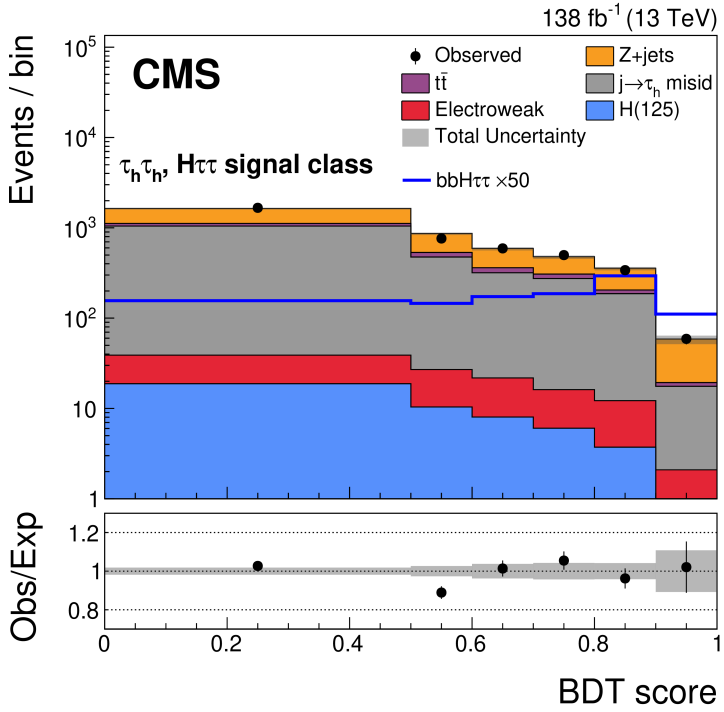
JHEP 11 (2020) 036
JHEP 07 (2019) 054

b(b)H production with CMS

arXiv:2408.01344

- Targeted final states:
  - $H\to\tau\tau$ ($e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$) and $H\to WW$ ($e\mu$)
  - selection requires at least one b-tagged jet

- Estimation of major backgrounds:
  - DY+b-jets : simulation calibrated with the $Z\to\mu\mu$+b-jets standard candle
  - misidentified leptons: extrapolated from sidebands with inverted lepton id
  - TT, VV and Higgs bkgds: simulation



- BDT multi-classifier
  - b-tag information
  - kinematics of jets
  - kinematics of leptons
  - missing ET

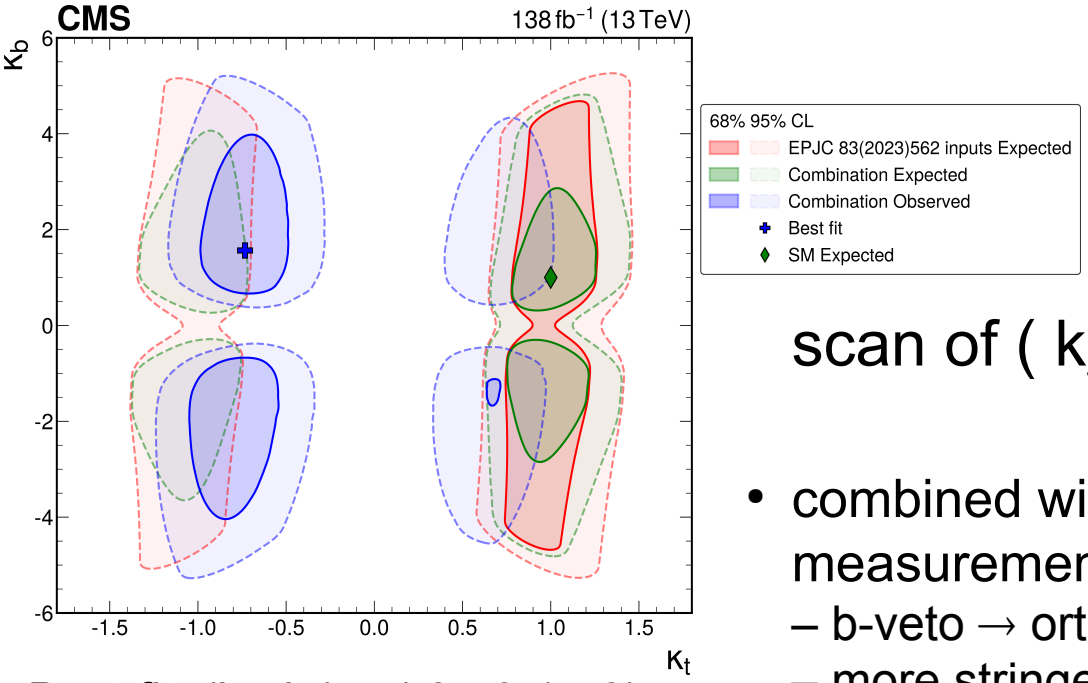
Channel	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
BDT Categories	DY, TT, $b\bar{b}H(\to WW)$, $b\bar{b}H(\to\tau\tau)$	DY, TT, $b\bar{b}H(\to\tau\tau)$	DY, TT, $b\bar{b}H(\to\tau\tau)$	DY+Higgs, TT, j$\to\tau_h$ misid., $b\bar{b}H(\to\tau\tau)$

- Combined fit to BDT score distributions in all background and signal classes → constrain backgrounds and extract signal

b(b)H production with CMS arXiv:2408.01344

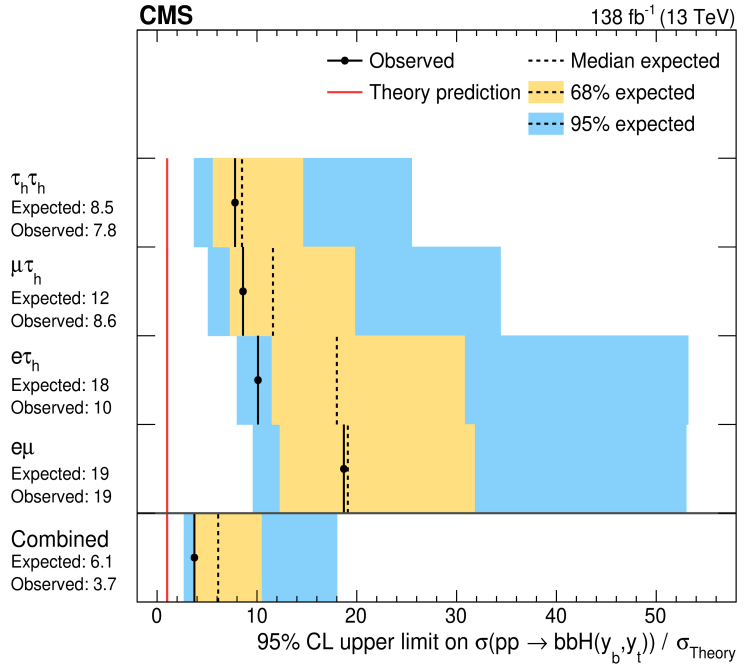
- Measurement of σ(pp→bbH(y_b, y_t))
  templates associated with y_t^2, y_b^2 and $y_t \cdot y_b$
  are all scaled with common rate modifier

- obs. (exp.) UL at 95% CL = 3.7 (6.1) x SM



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

$0.3 < |\kappa_b| < 5.5$ at 95% CL



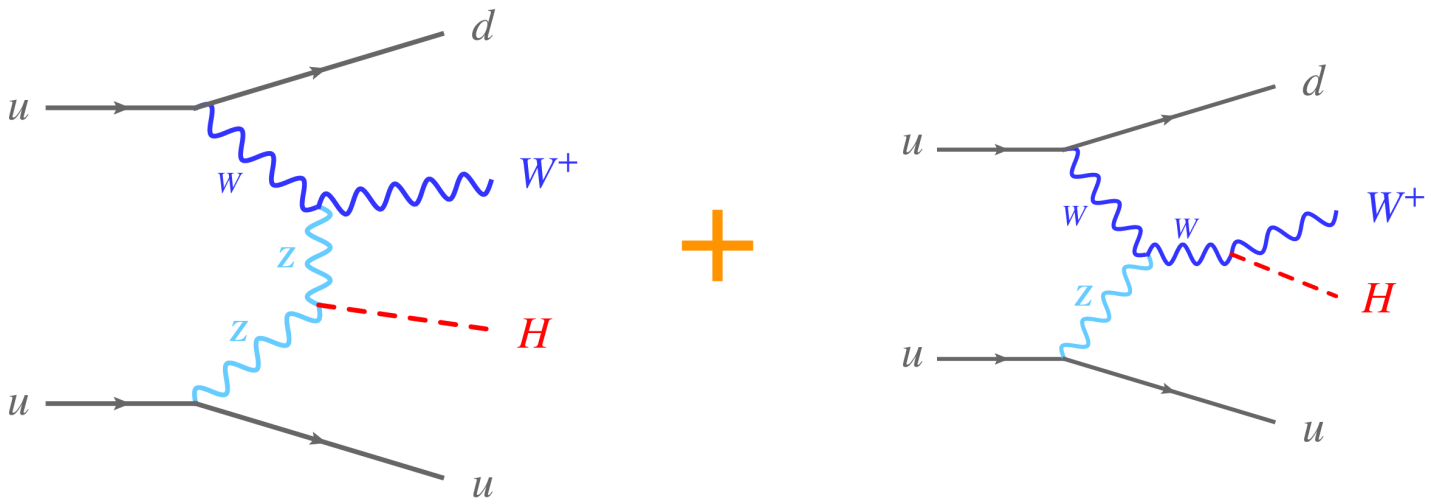
scan of (k_t, k_b) with k_T freely floating

- combined with previous CMS analysis: STXS measurement in H→ττ (EPJC 83 (2023) 562)
  – b-veto → orthogonality to this analysis
  – more stringent constraint on k_t
- constraints consistent with the SM at 95% CL

VBF WH with ATLAS

arXiv:2402.00426

VBF WH production



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

$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\kappa_Z \kappa_W \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$
$$= \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\kappa_Z^2 \lambda_{WZ} \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$

- $\lambda_{WZ} > 0 \rightarrow$ destructive interference : process rate is extremely low
- $\lambda_{WZ} < 0 \rightarrow$ constructive interference : process rate is enhanced, considerable change in event kinematics

VBF WH with ATLAS

arXiv:2402.00426

- Studied final state : W→lν, H→bb decays + two VBF jets

- Two separate analyses targeting:
  – signal with $\lambda_{WZ} = +1$ (probe SM-like scenario)
  – signal with $\lambda_{WZ} = -1$ (probe BMS scenario)

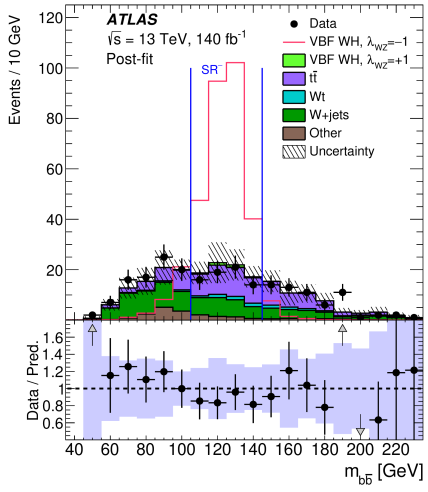
  both analyses exploit distinct signatures of VBF WH process

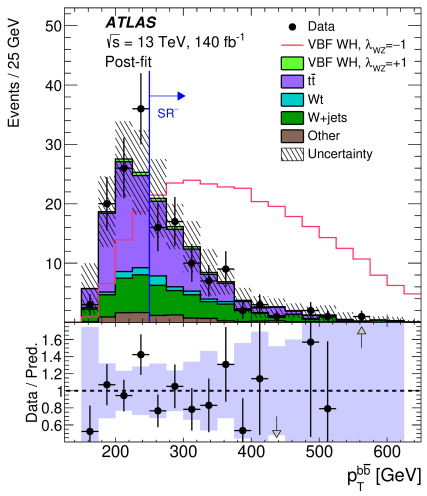
- Simple and robust cut-and-count approach : simultaneous fit of yields in multiple analysis regions
  – single signal region for $\lambda_{WZ} = -1$: SR^{-}
  – two orthogonal regions for $\lambda_{WZ} = +1$: SR^{+}(loose), SR^{+}(tight)
  – multiple control regions to constrain normalization of major backgrounds: TTbar, W+top, W+Jets

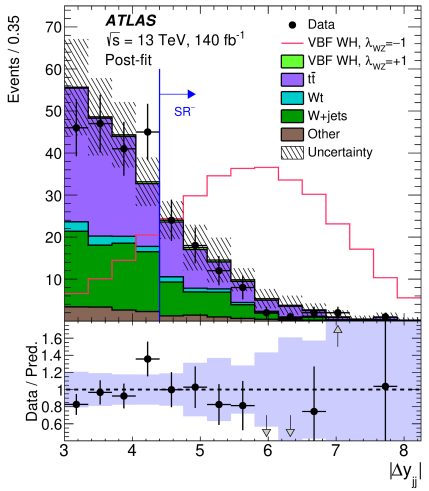
VBF WH with ATLAS

arXiv:2402.00426

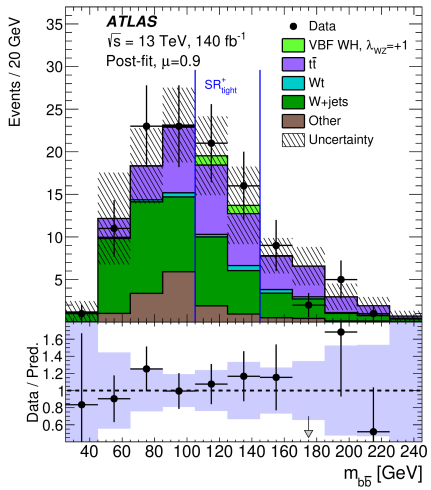
- High rate negative λ_{WZ} signal is well separable from background

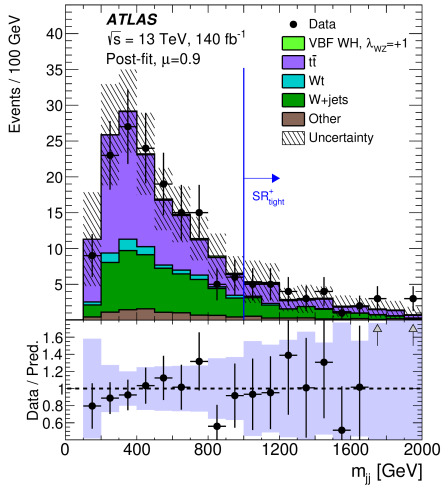


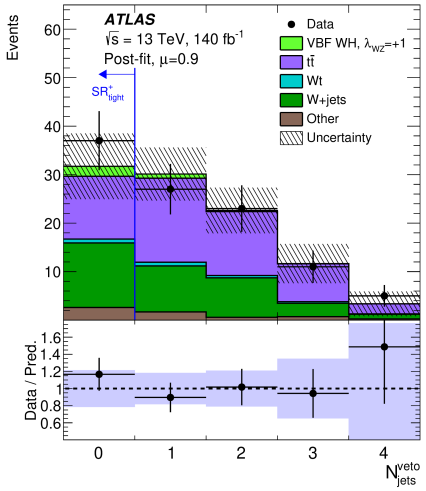




- Positive λ_{WZ} signal is more difficult to separate given its low rate





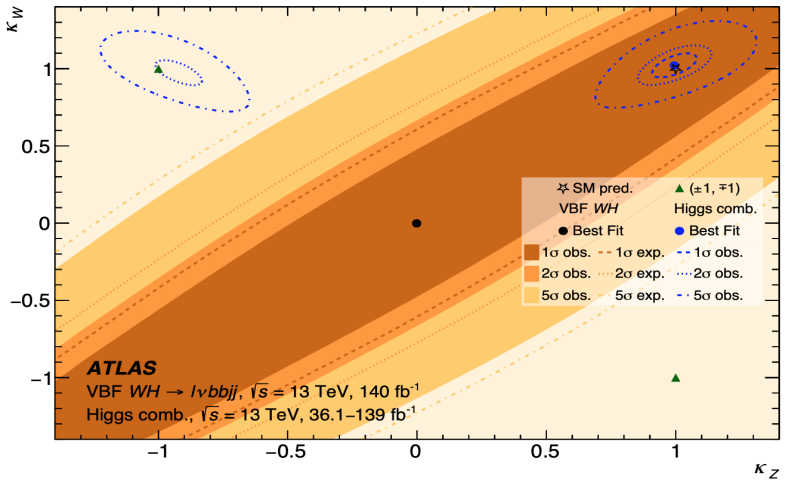


VBF WH with ATLAS

arXiv:2402.00426

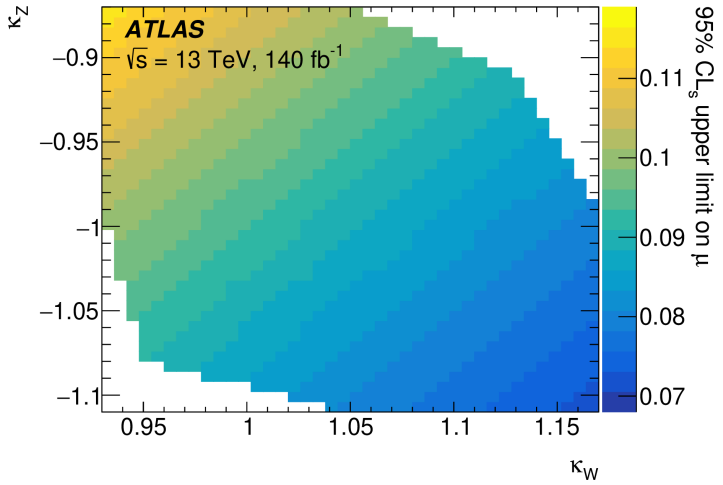
- No excess above background expectation
- Negative λ_{WZ} analysis

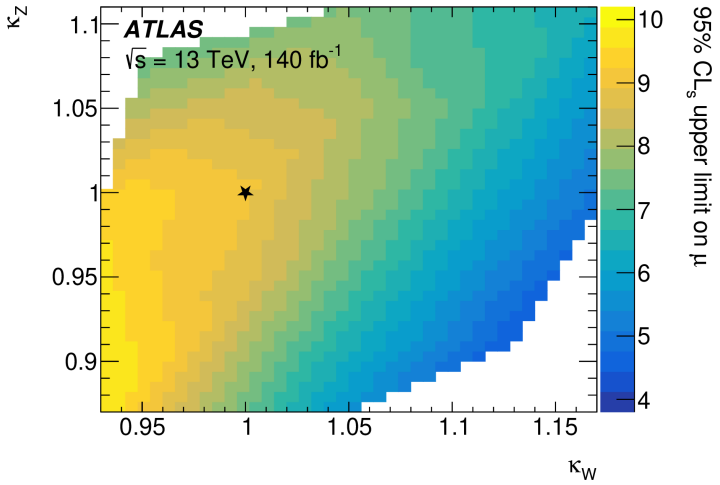
  rules out opposite sign scenario (>5σ) for experimentally allowed values of κ_W and κ_Z
- Couplings of Higgs to W and Z bosons have same sign!



- Positive λ_{WZ} analysis

  sets upper limit on $\sigma(\text{VBF WH})/\sigma_{SM}$ of 9.0 at 95 %CL (8.7 exp.)





Summary

- Rare Higgs decays and productions play crucial role in exploration of Electroweak Symmetry Breaking and searches for BSM physics

- Highlights from LHC Run 2 presented in this talk
  - 3σ evidence of H→μμ decay by CMS, 2σ observation by ATLAS
  - 3.4σ evidence of H→Zγ decay from combination of ATLAS and CMS searches
  - Constraints on charm Yukawa coupling derived from V(lep)H(cc) analyses [1] :
    $1.1 < |\kappa_c| < 5.5$ at 95% CL by CMS , $|\kappa_c| < 4.2$ at 95% CL by ATLAS
  - First probe of bottom Yukawa coupling in production by CMS :
    $0.3 < |\kappa_b| < 5.5$ at 95% CL
  - Scenario of opposite sign Higgs couplings to W and Z bosons is excluded with significance exceeding 5σ in the study of VBF HW production by ATLAS

- Most of these analyses are statistics limited → bright prospect for further exploration of these channels with Run 3 data

[1] Both ATLAS and CMS performed also searches for c+H(→γγ) process with lower sensitivity to κ_c (arXiv:2407.15550, CMS-PAS-HIG-23-010)