Higgs fermion couplings and CP measurements

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on behalf of the ATLAS and CMS collaborations

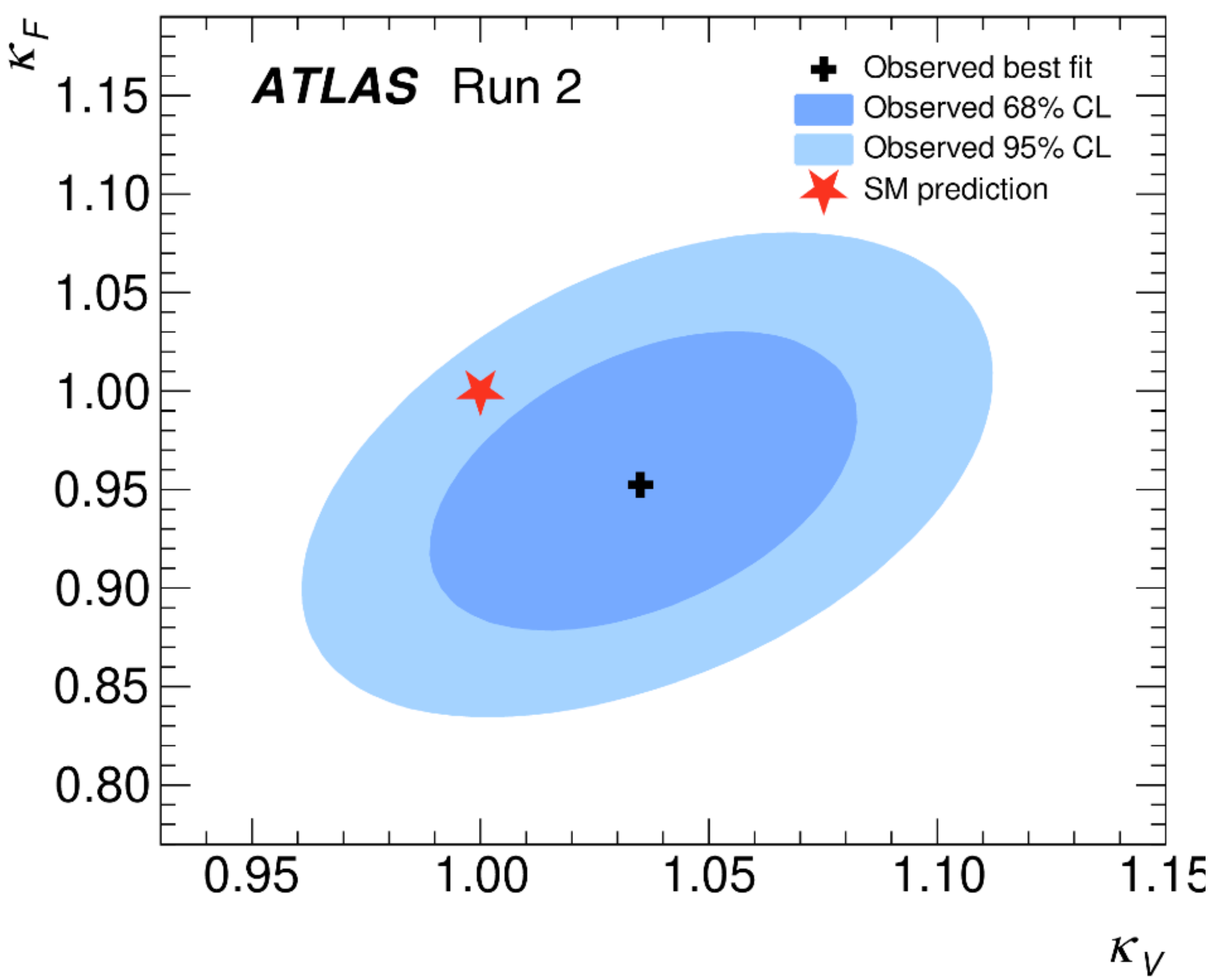
List of publications

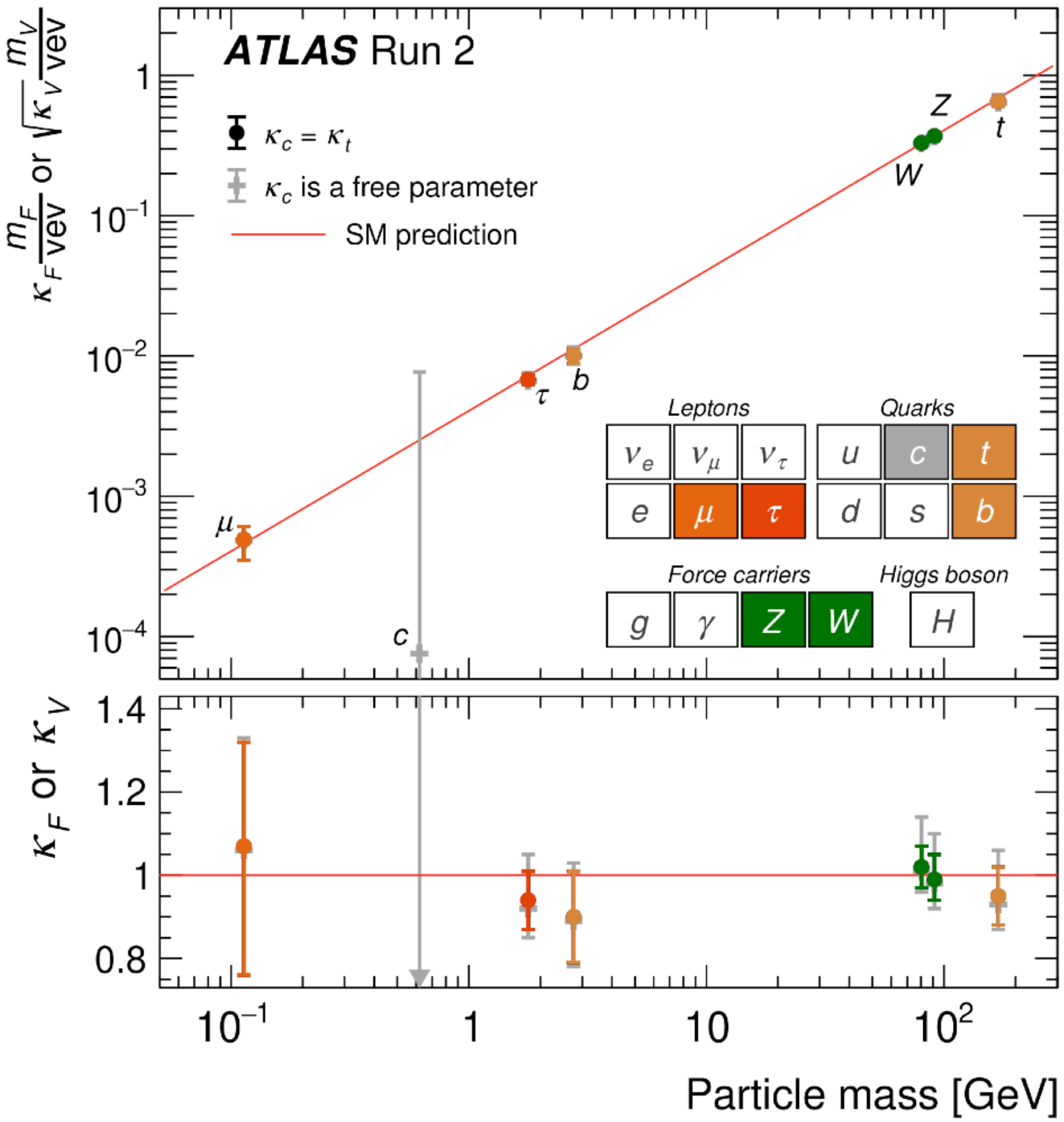
Only a limited subset of results presented here, much more available at:

- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

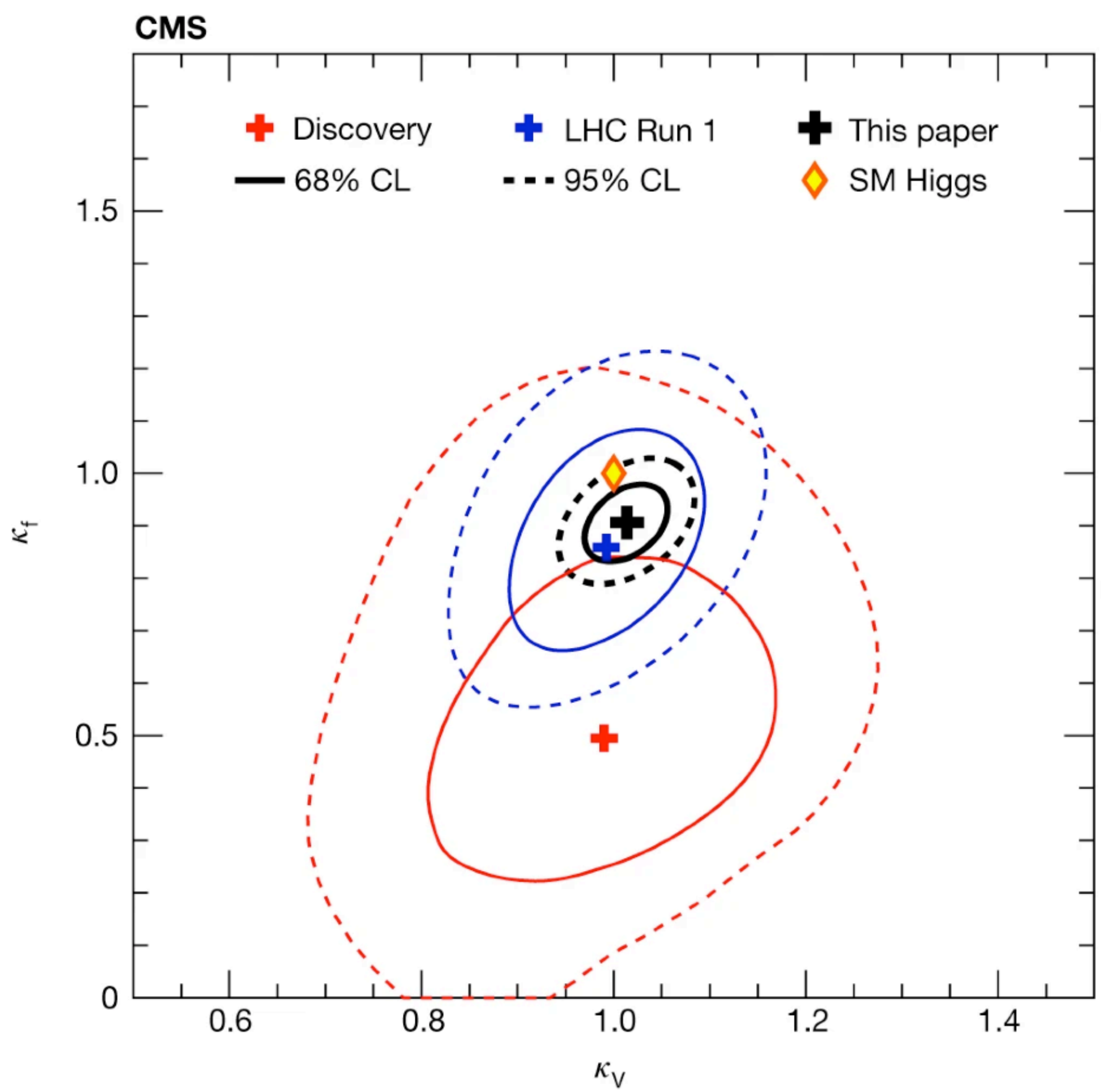
Accepted for publication in Phys. Rev. Lett. (arXiv:2211.14181)	Search for boosted Higgs boson decay to a charm quark-antiquark pair in proton-proton collisions at $\sqrt{s}$ = 13 TeV	138 fb^{-1}
Accepted for publication in J. High Energy Phys. (arXiv:2208.02686)	Search for CP violation in ttH and tH production in multilepton channels in proton-proton collisions at $\sqrt{s}$ = 13 TeV	138 fb^{-1}
Nature 607 (2022) 60-68 (arXiv:2208.02686)	A portrait of the Higgs boson by the CMS experiment ten years after the discovery.	
CMS-PAS-HIG-20-001	Simplified template cross section measurements of Higgs boson produced in association with vector bosons in the H→bb decay channel in proton-proton collisions at $\sqrt{s}$ = 13 TeV	138 fb^{-1}
Accepted for publication in EPJC (arXiv:2212.05833)	Measurement of the CP properties of Higgs boson interactions with τ -leptons with the ATLAS detector	139 fb^{-1}
Submitted to JHEP (arXiv:2302.05225)	Searches for lepton-flavour-violating decays of the Higgs boson into eτ and μτ in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector	139 fb^{-1}
HIGG-2018-30	Test of CP-invariance of the Higgs boson in Vector Boson Production and its decay to Four Leptons	139 fb^{-1}
Submitted to PLB (arXiv:2303.05974)	Probing the CP nature of the top-Higgs Yukawa coupling in $t\bar{t}H$ and tH events with $H\to b\bar{b}$ decays using the ATLAS detector at the LHC	139 fb^{-1}
Nature 607, pages 52-59 (2022) (arXiv:2207.00092)	A detailed map of Higgs boson interactions ten years after the discovery	

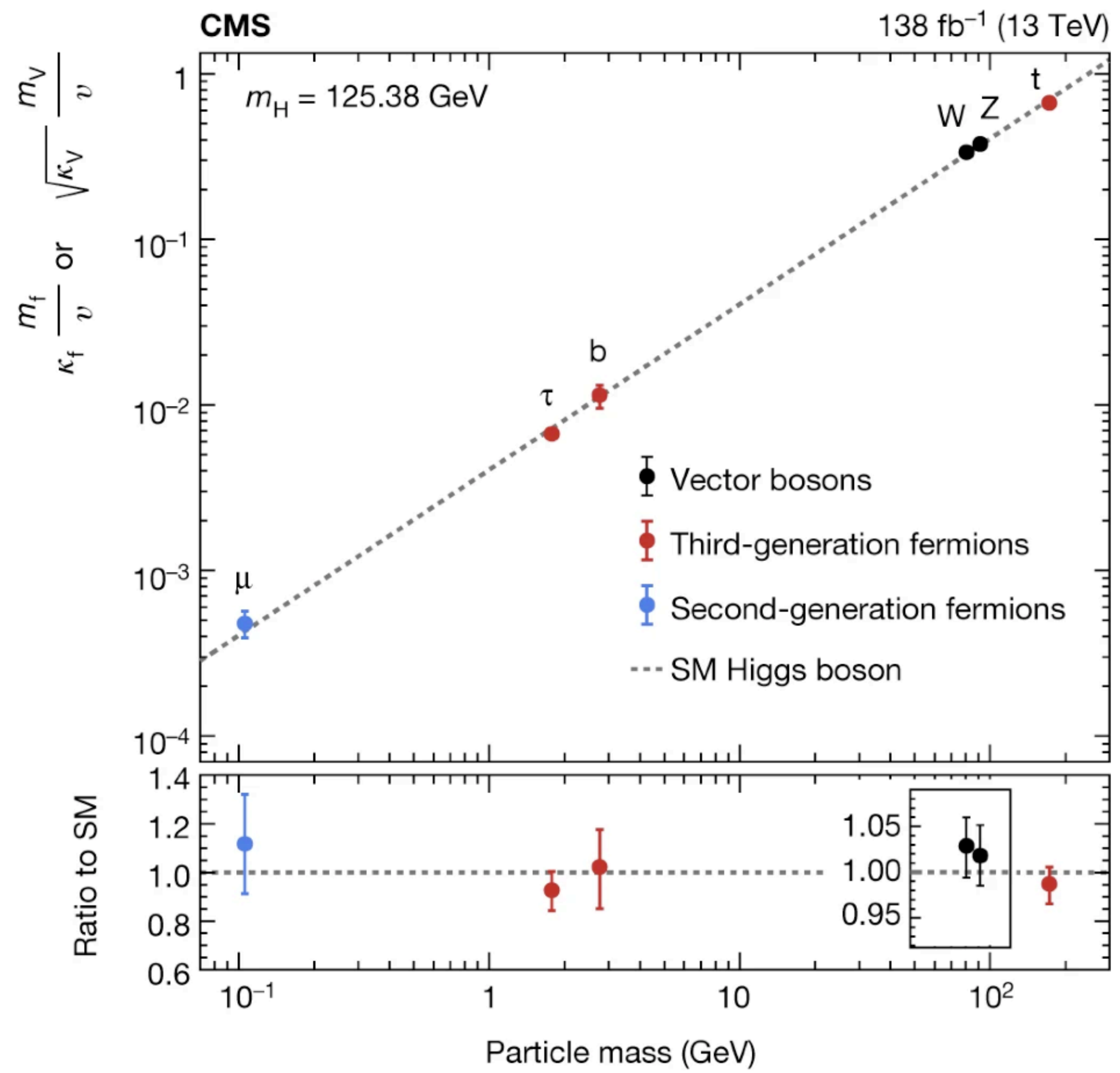
State of the Art





State of the Art

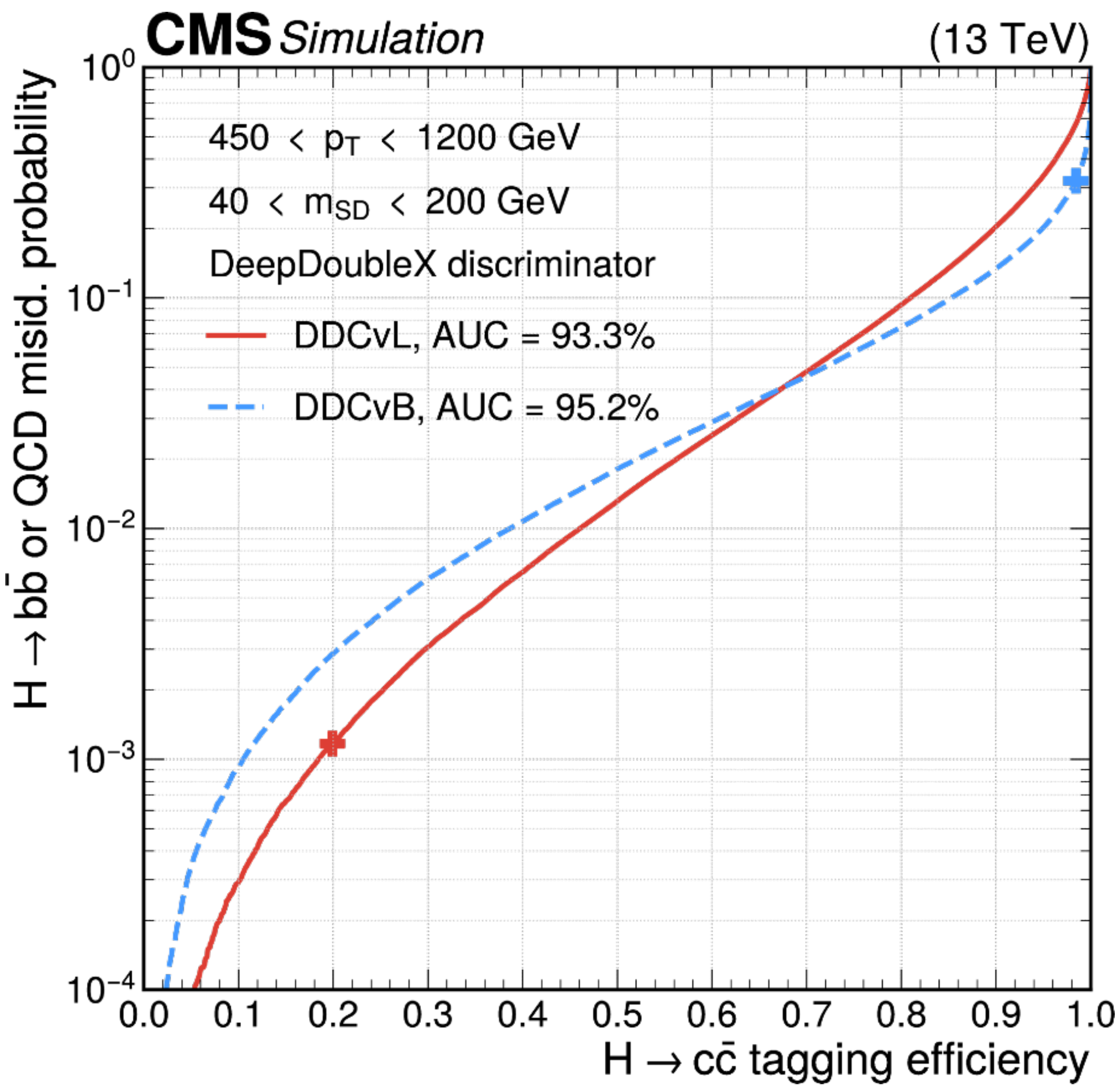


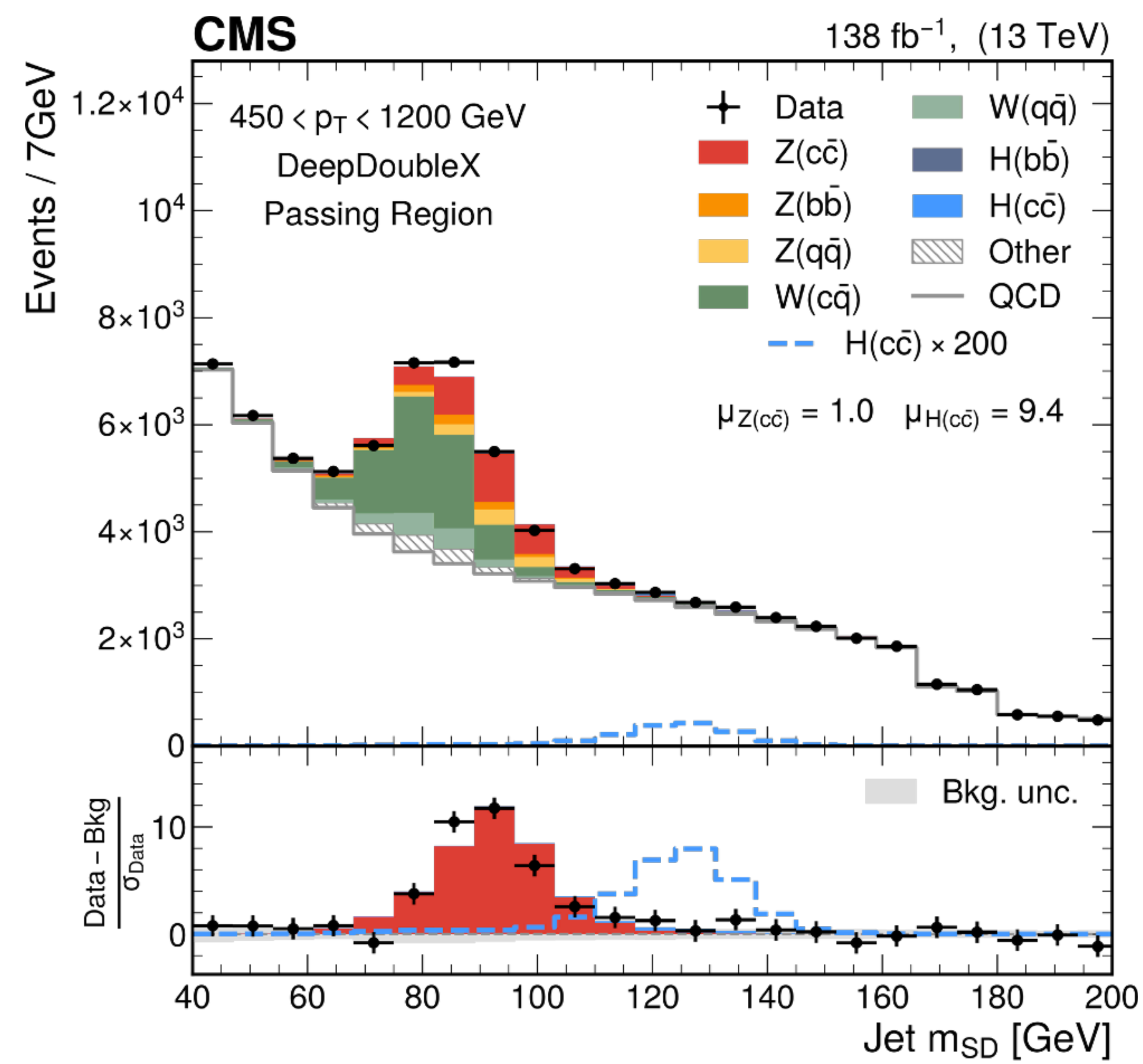


p-value with respect to the SM prediction 37.5%.

Search for boosted Higgs boson decay to a charm quark-antiquark pair

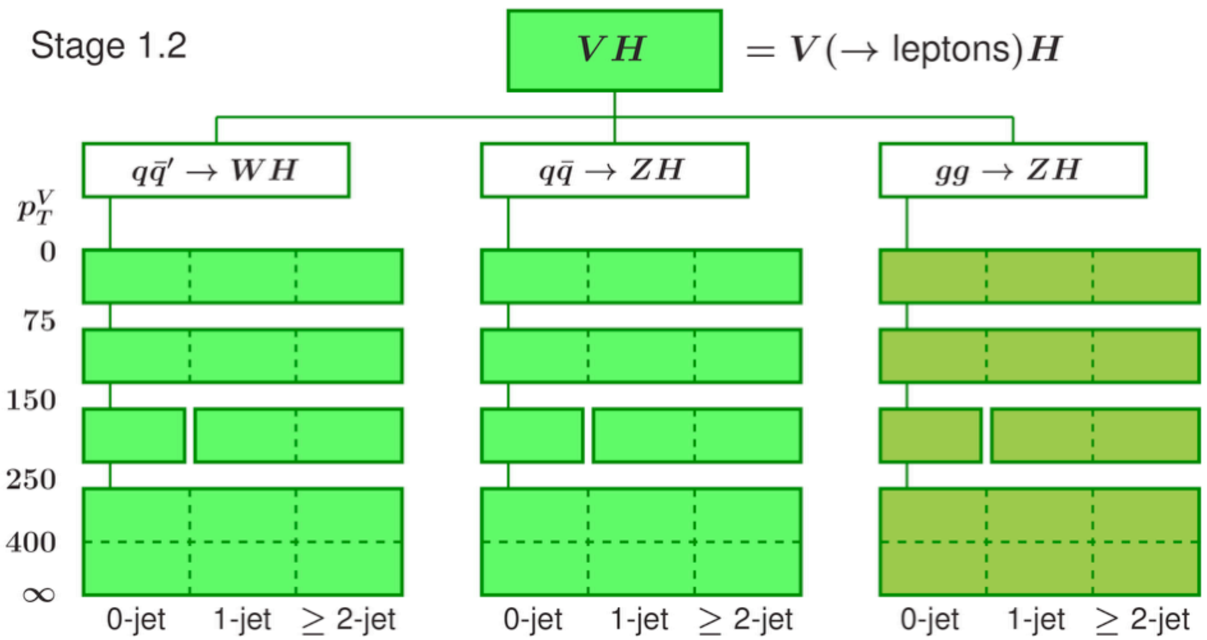
First search for the H → cc decay at the LHC Higgs Pt > 450 GeV, enriched in ggF
Deep neural network discriminators to separate the signal from QCD-induced multijet events.

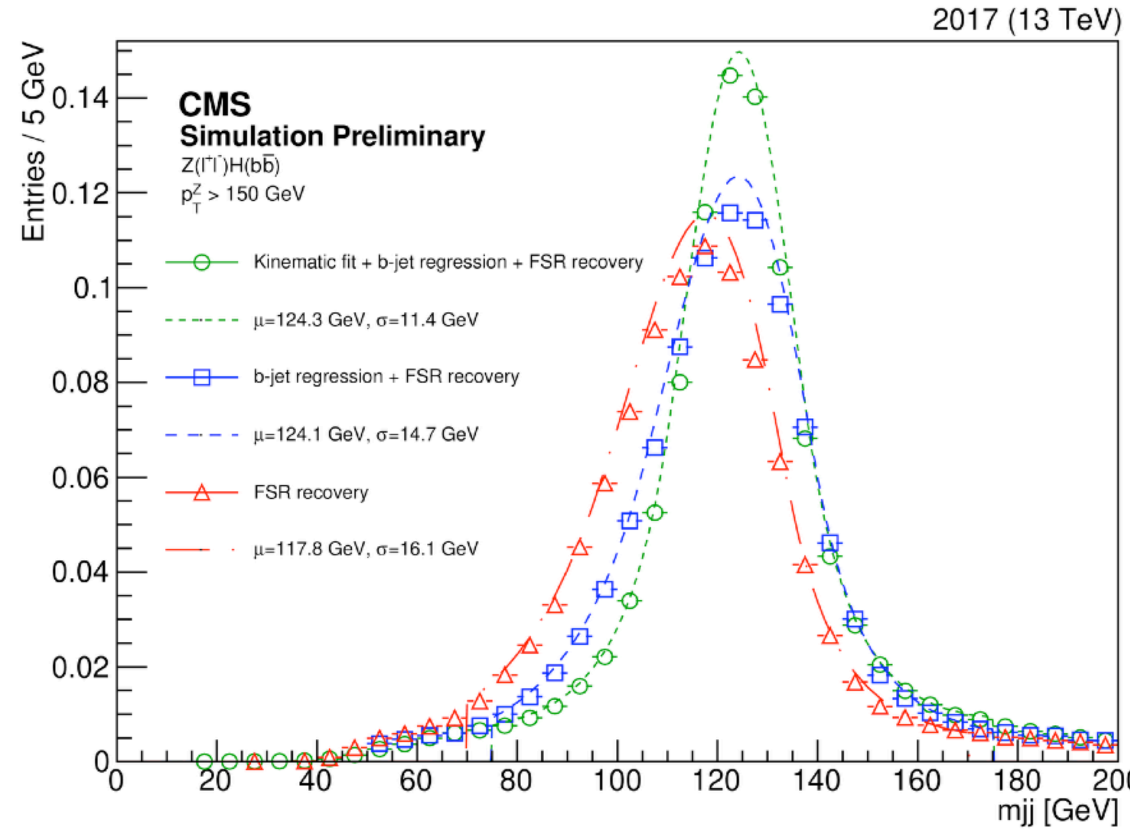


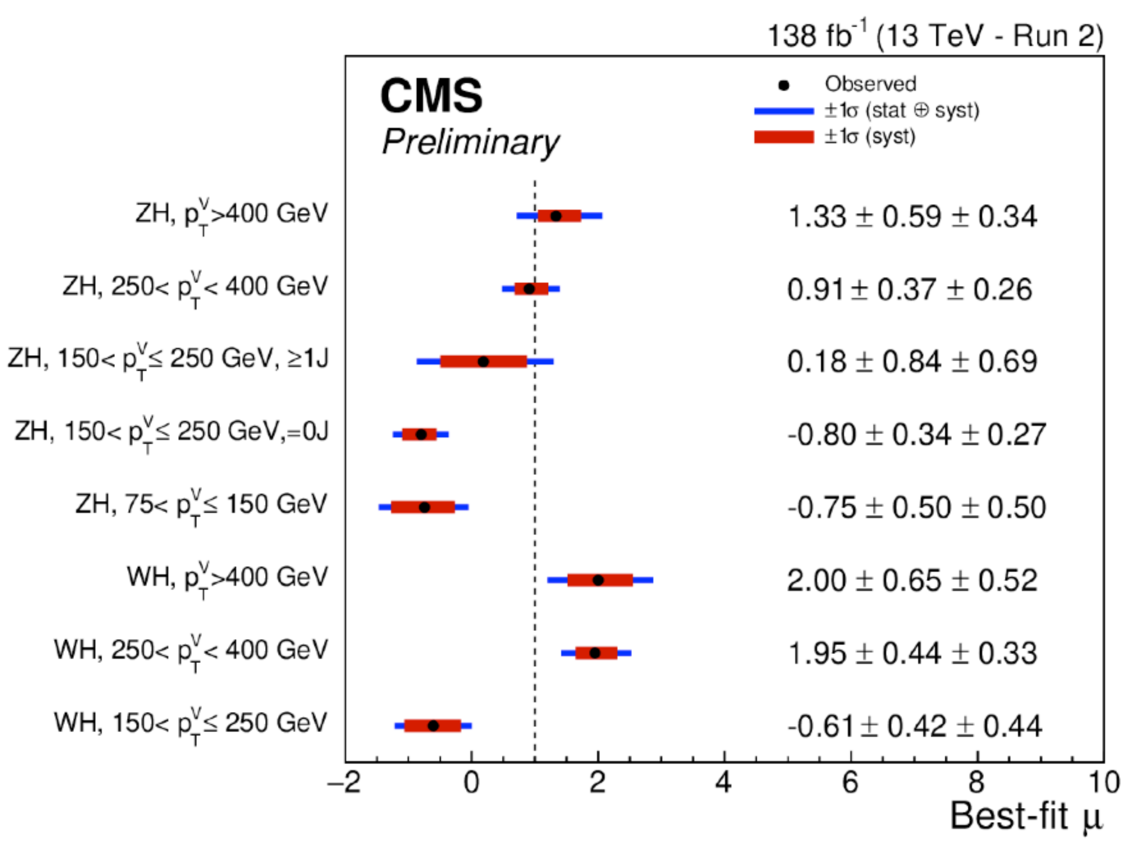


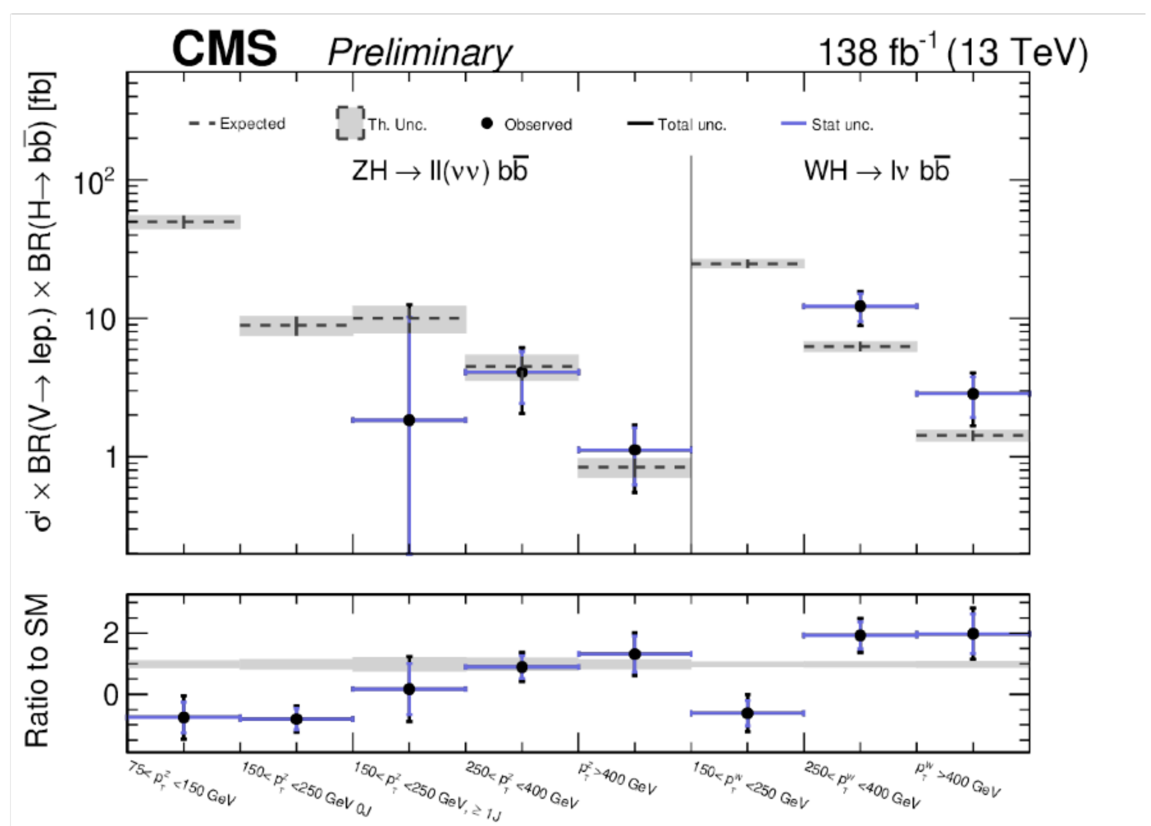
Z→cc observed in association with jets with a signal strength of 1.00 +0.19 −0.17
Observed (expected) upper limit on H—> cc of 47 (39) times the SM expectation at 95% confidence level.

Simplified template cross section measurements of Higgs boson produced in association with vector bosons in the H→bb









Higgs and CP violation

CP violation occurs in the Standard model

- Complex phase of CKM-matrix
- QCD instanton effects

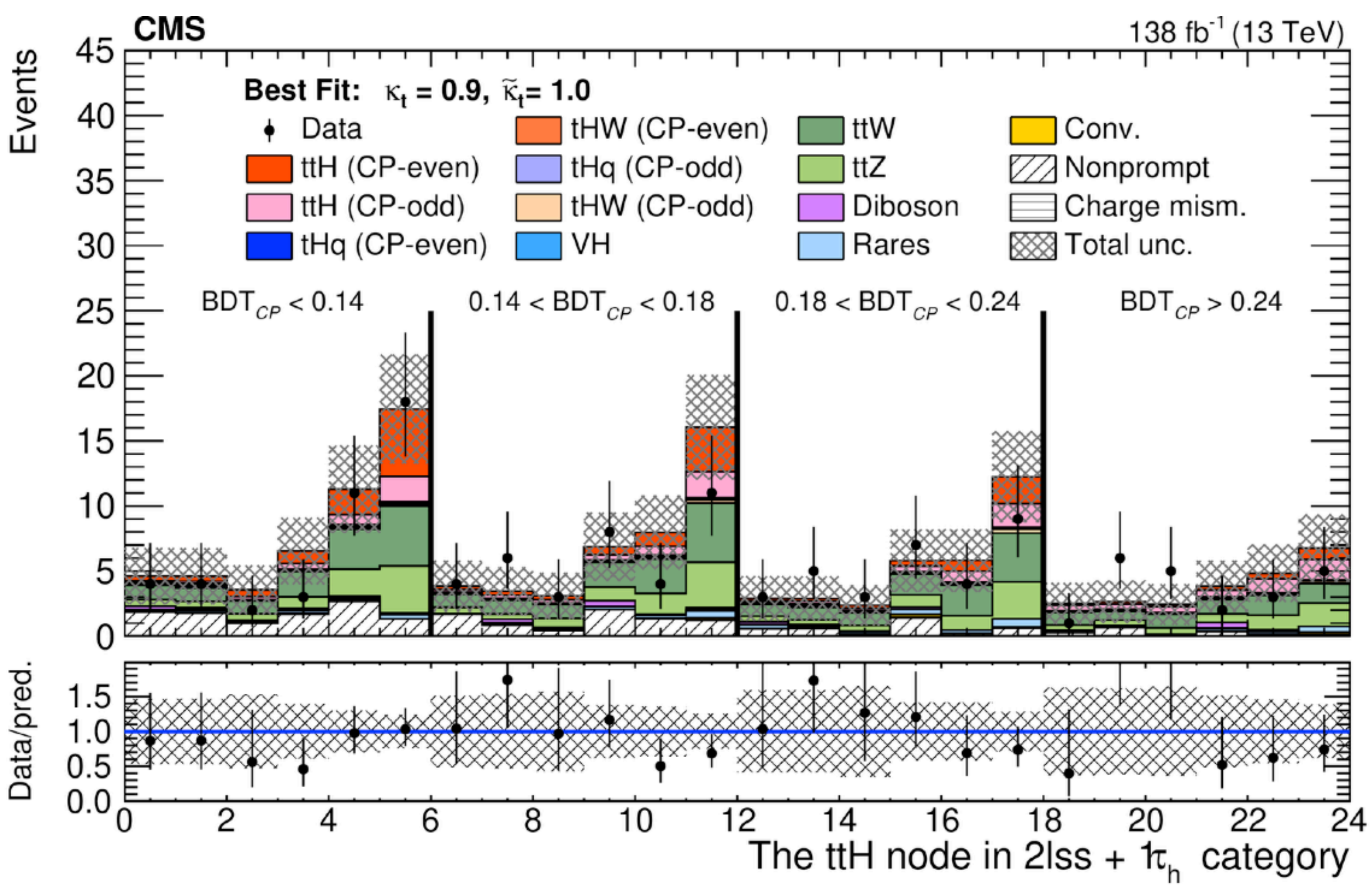
- All too small to explain baryogenesis: There need to be BSM sources of CP-Violation to explain Matter/Anti-matter Asymmetry in the universe

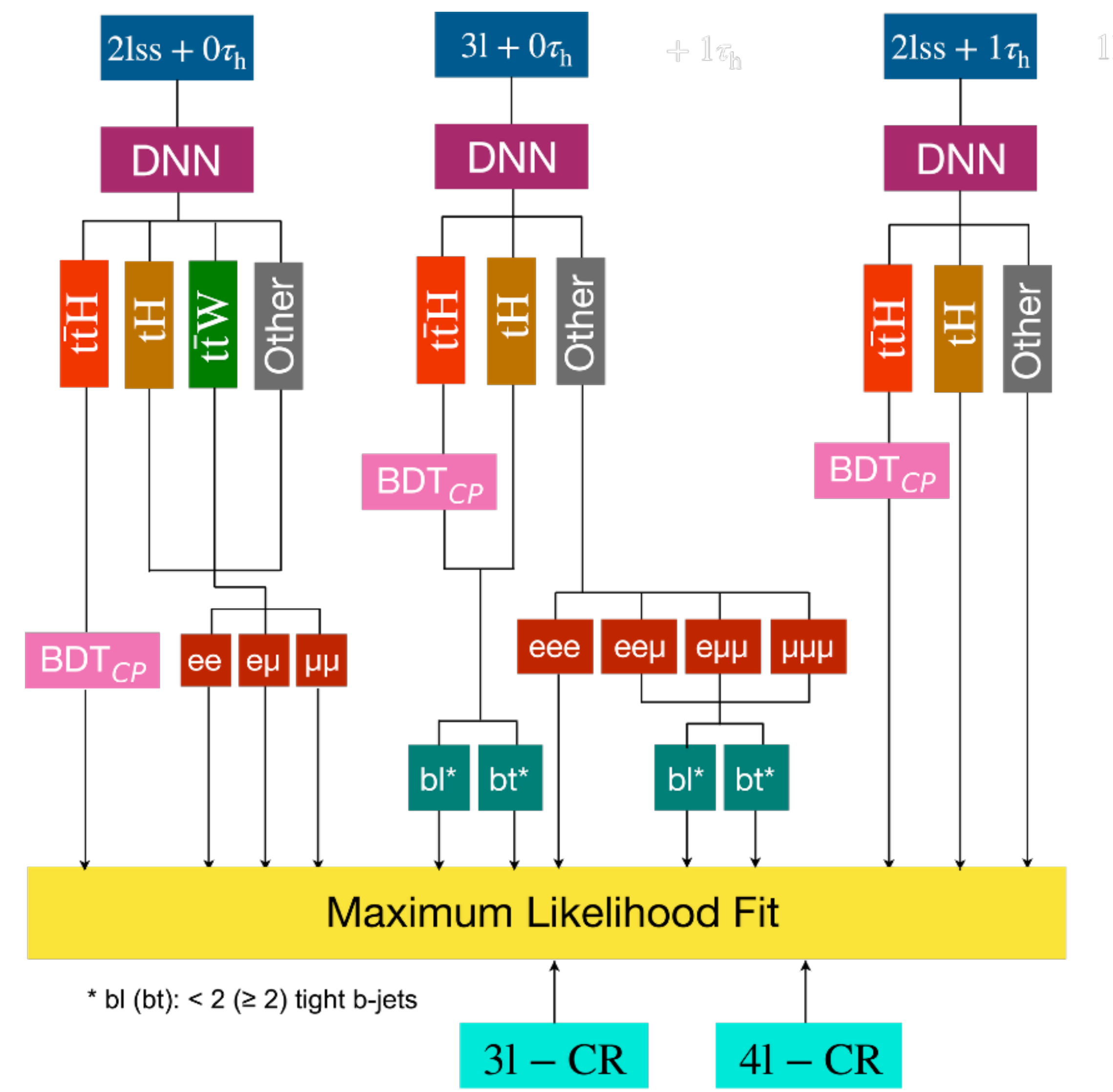
Searching for new sources of CP-Violation

- Direct searches in particle decays
- Based on minimal extensions of the SM / Effective Field Theories
- In SM Higgs boson is predicted to have scalar (CP-even) couplings to SM particles
- 2HDM or SUSY predict multiple Higgs bosons and can produce CP-violating couplings

Search for CP violation in ttH and tH production in multilepton channels

H→ WW or H → ττ and the top quarks decay via t → Wb. W decays either leptonically or hadronically.
Final states characterised by the presence of at least two leptons.





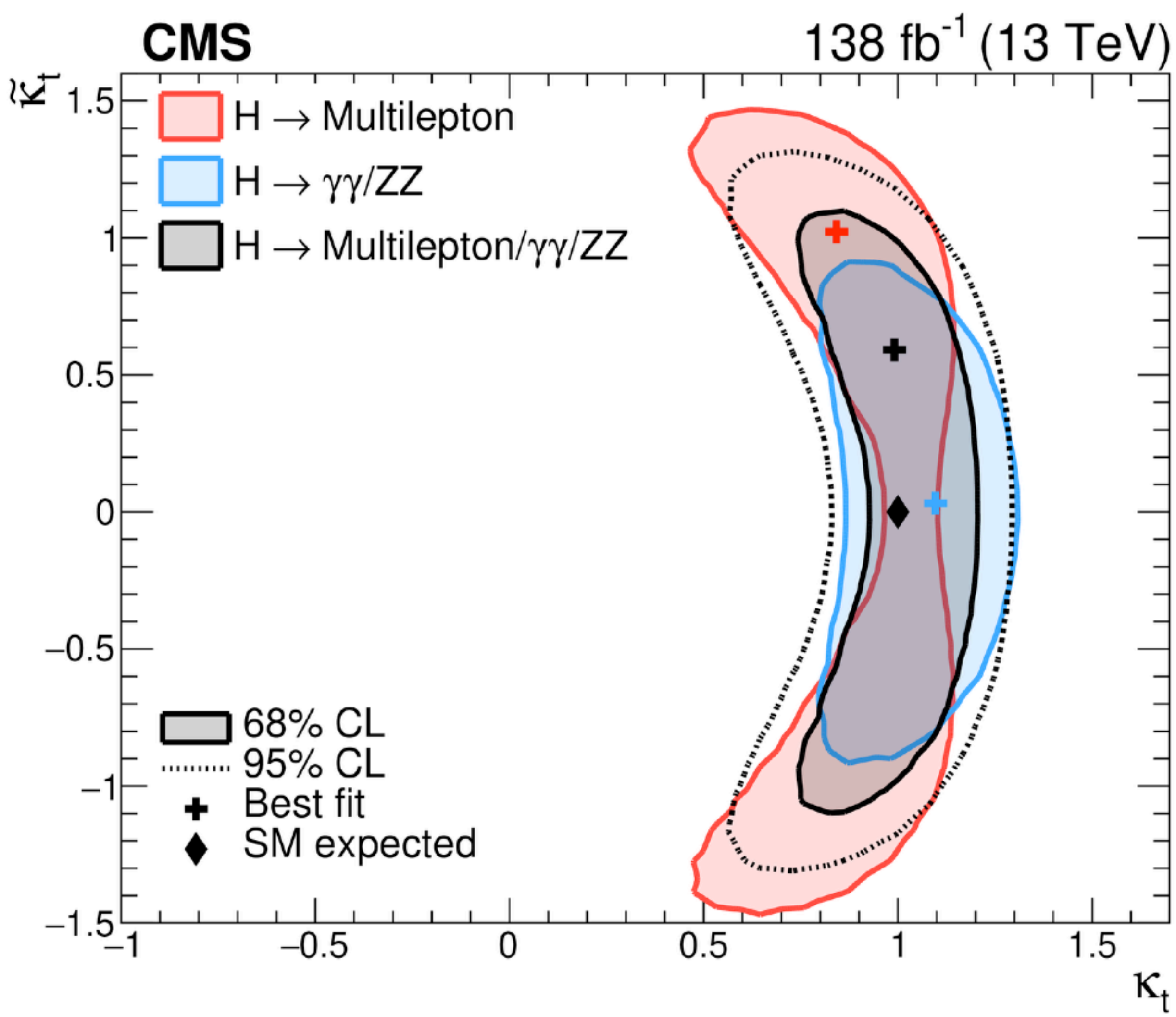
BDT classifier trained to efficiently select prompt leptons
DeepJet discriminator to discriminate jets produced by heavy-flavour quarks vs jets from light-flavour quarks and gluons
BDT classifiers to separate CP-even and CP-odd scenarios for each of the channels

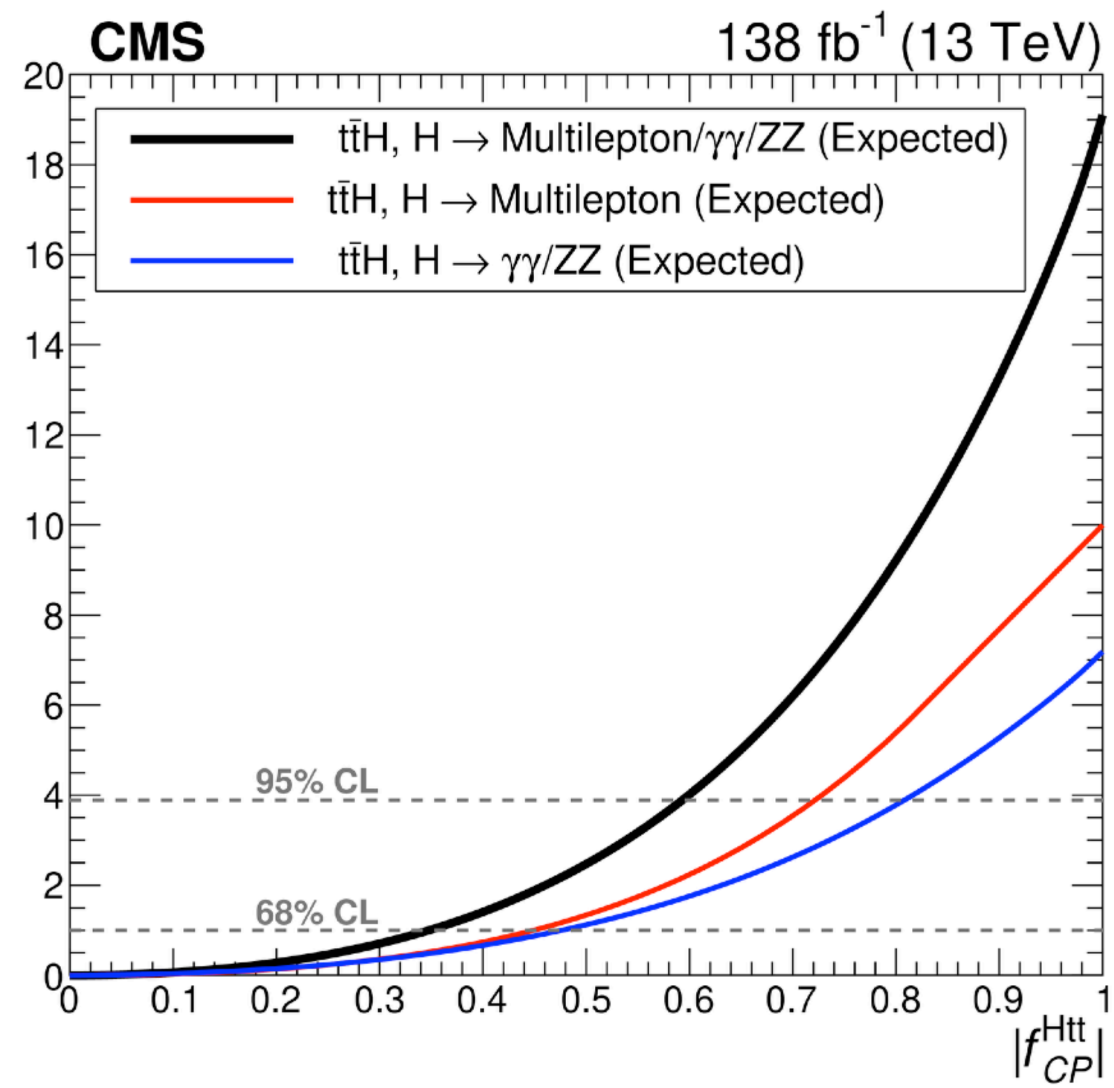
Search for CP violation in ttH and tH production in multilepton channels

H→ WW or H → ττ and the top quarks decay via t → Wb: the W bosons decay either leptonically or hadronically. Final states with at least two leptons.

$$\mathcal{L}_{t\bar{t}H} = \frac{m_t}{v}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H$$

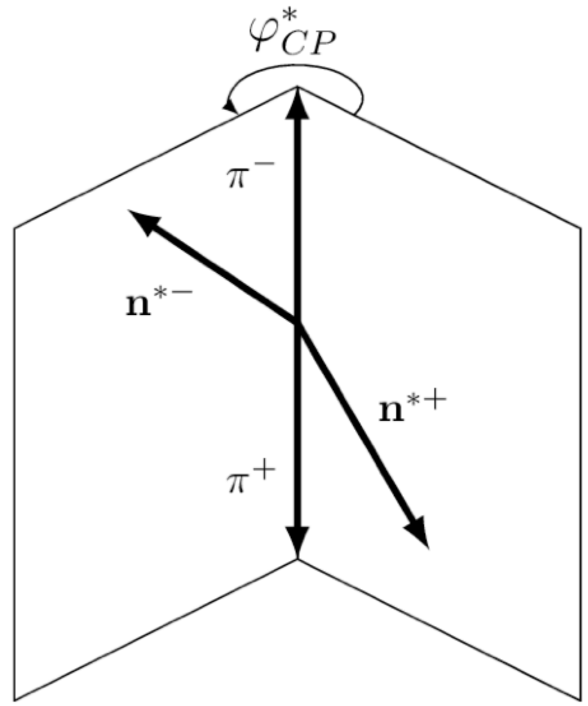
$$|f_{CP}^{Htt}| = \frac{|\tilde{\kappa}_t^2|}{(|\tilde{\kappa}_t|^2+|\kappa_t|^2)}$$

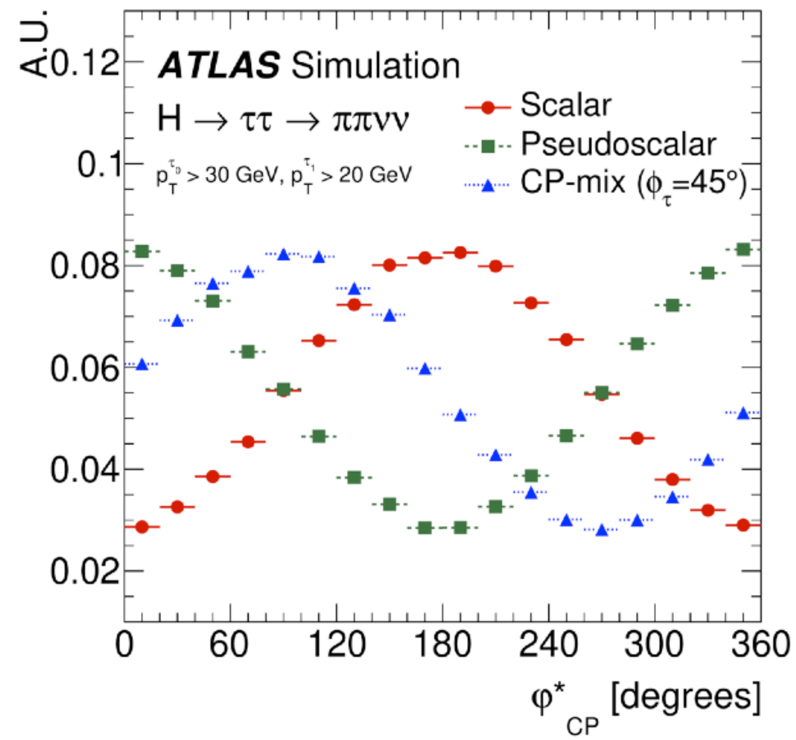


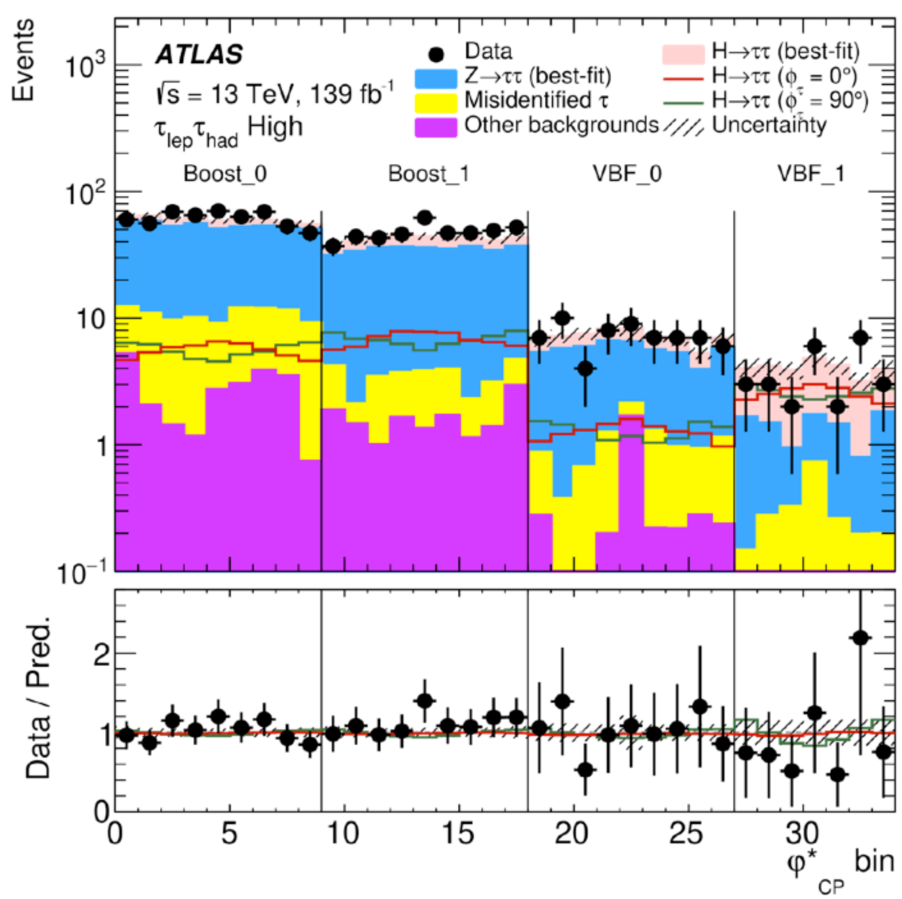


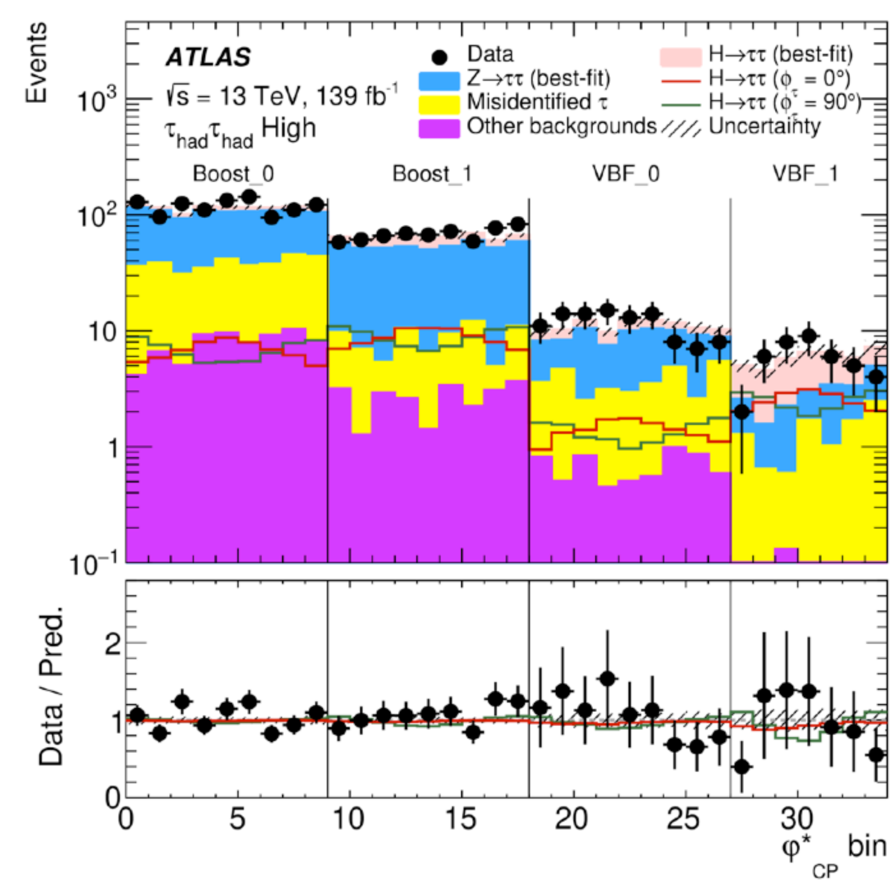
Measurement of the CP properties of Higgs boson interactions with τ - leptons

φ^*_{CP} (signed acoplanarity angle between the τ-lepton decay planes) observable built depending on the τ-lepton decay modes. A φ^*_{CP} phase shift correlates directly with a phase shift in ϕ_τ



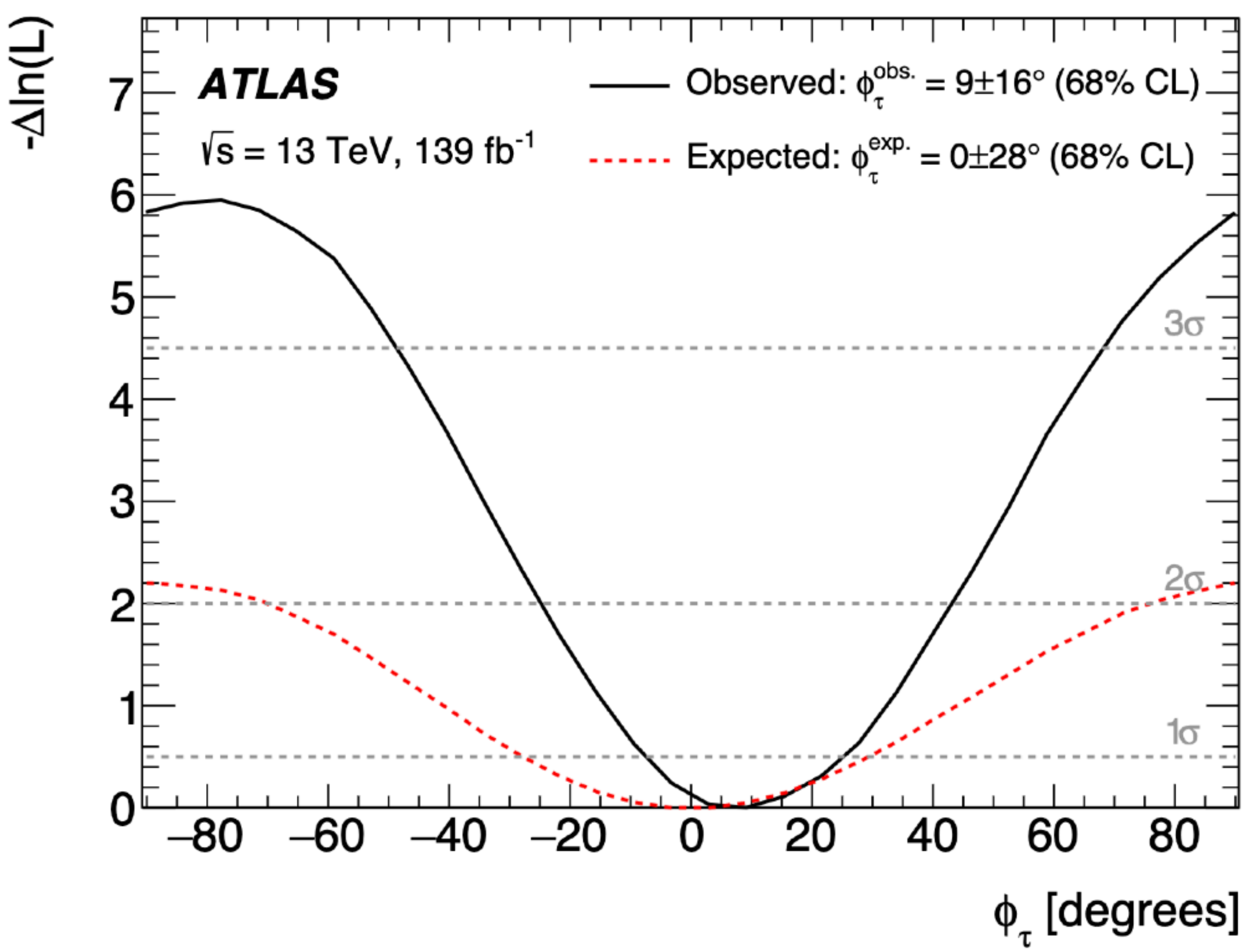


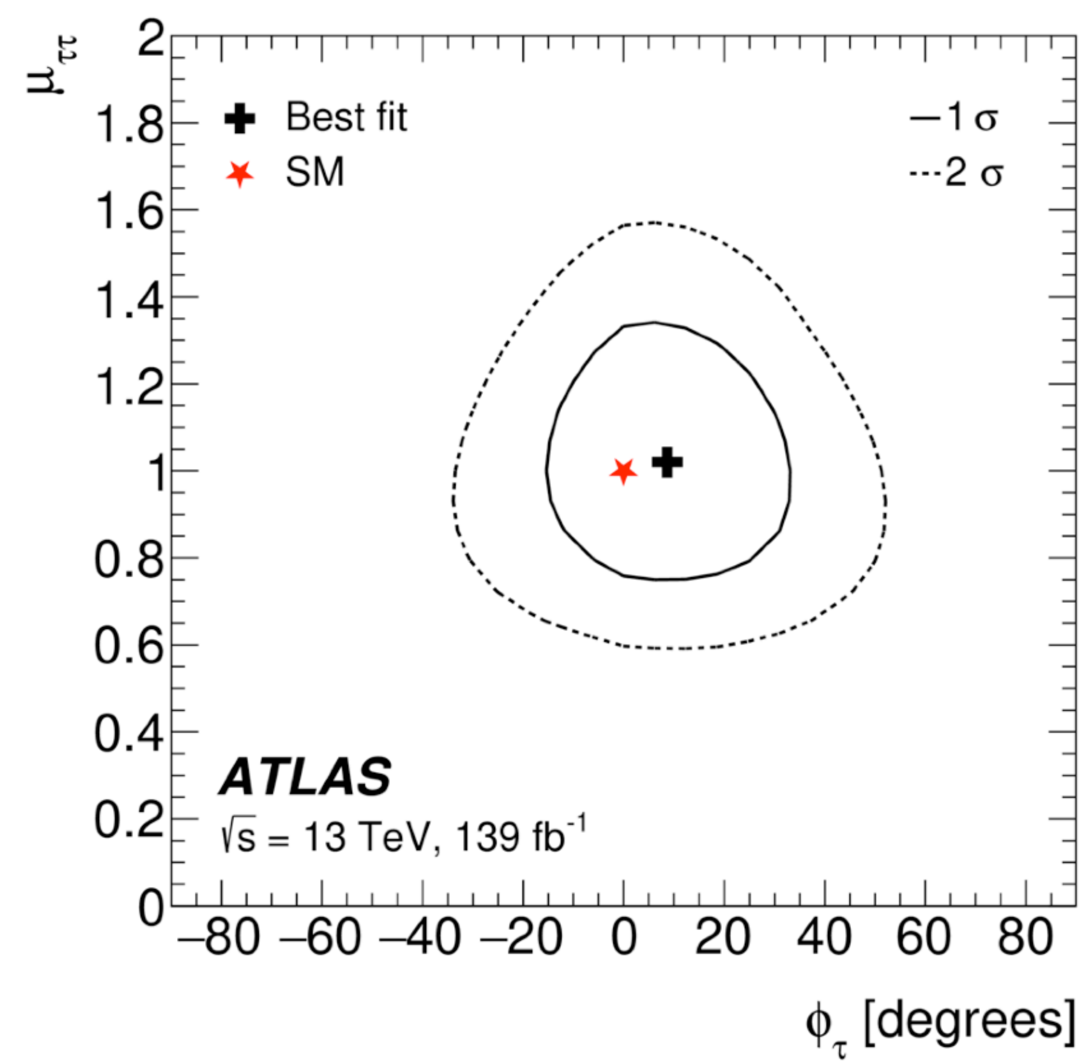




Measurement of the CP properties of Higgs boson interactions with τ - leptons

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

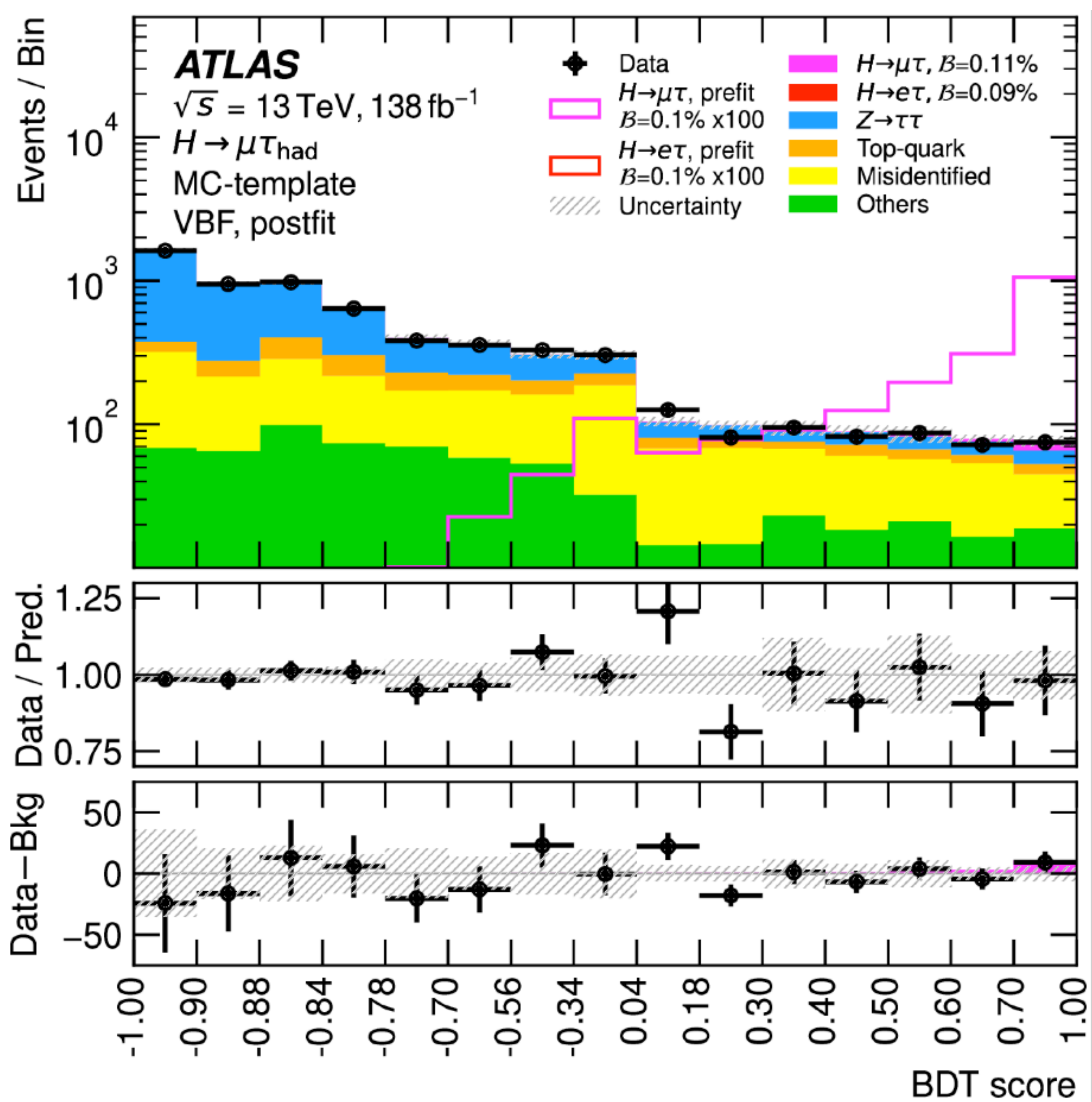


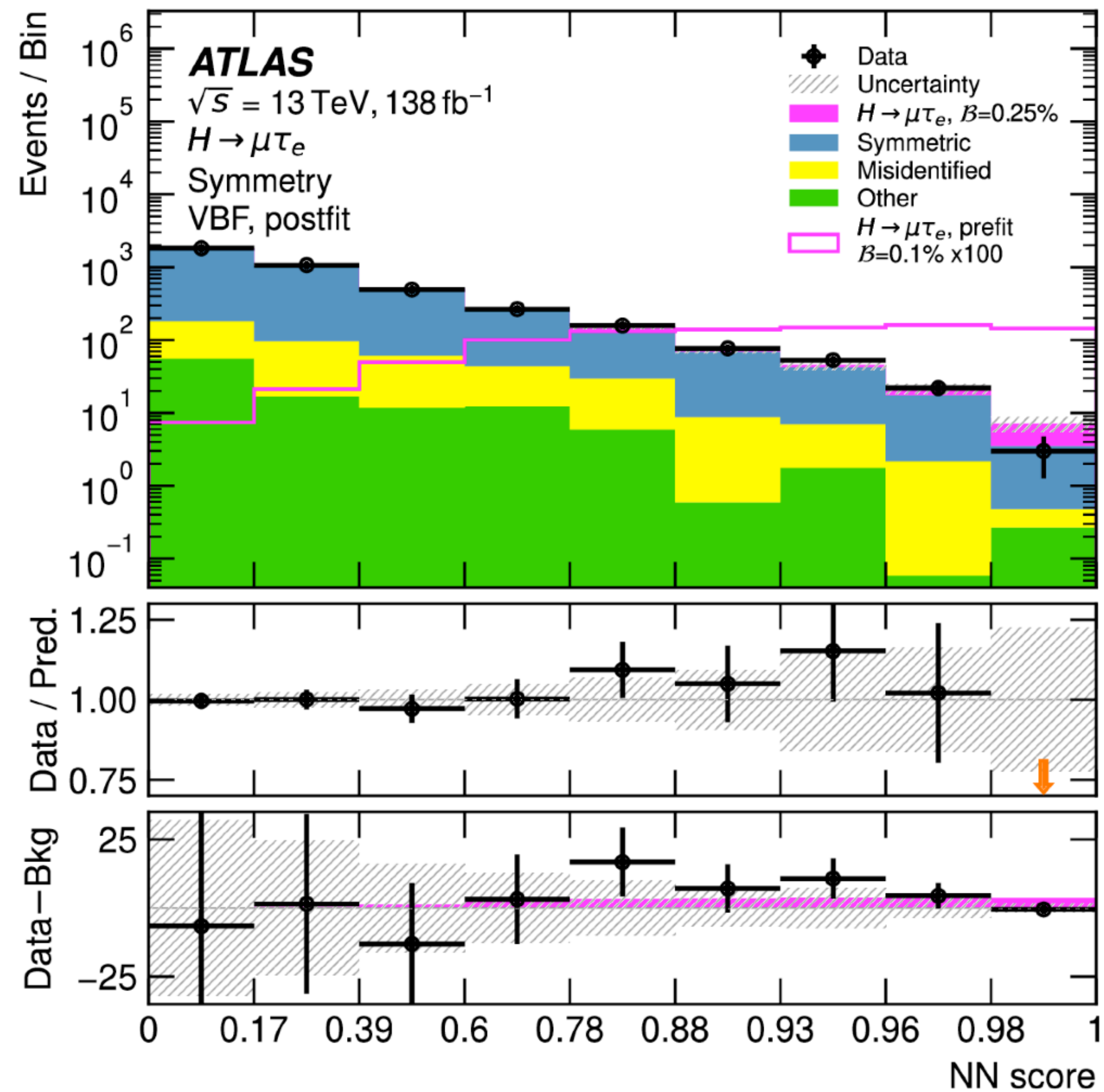


The ϕ_τ is measured to be 9 ± 16 degrees, with an expected value of 0 ± 28 at the 68% confidence level. The pure CP-odd hypothesis is disfavoured at a level of 3.4 standard deviations.

Two complementary background estimation techniques are exploited.

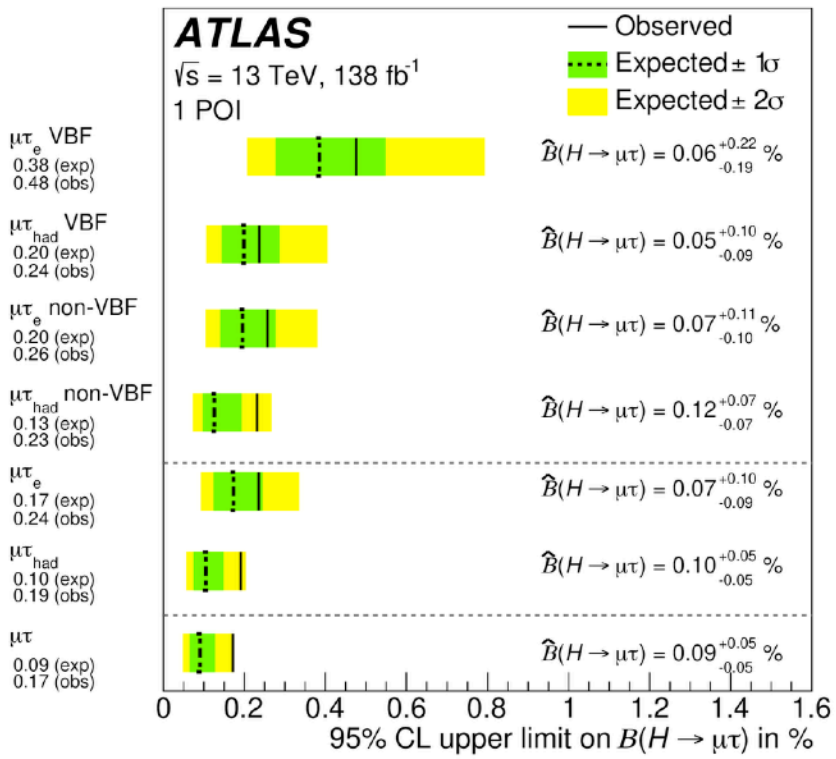
- Simulation/template ($\ell\tau_\ell$,$\ell\tau_{\rm had}$) BDT
- Symmetry method (τ_ℓ) NNs

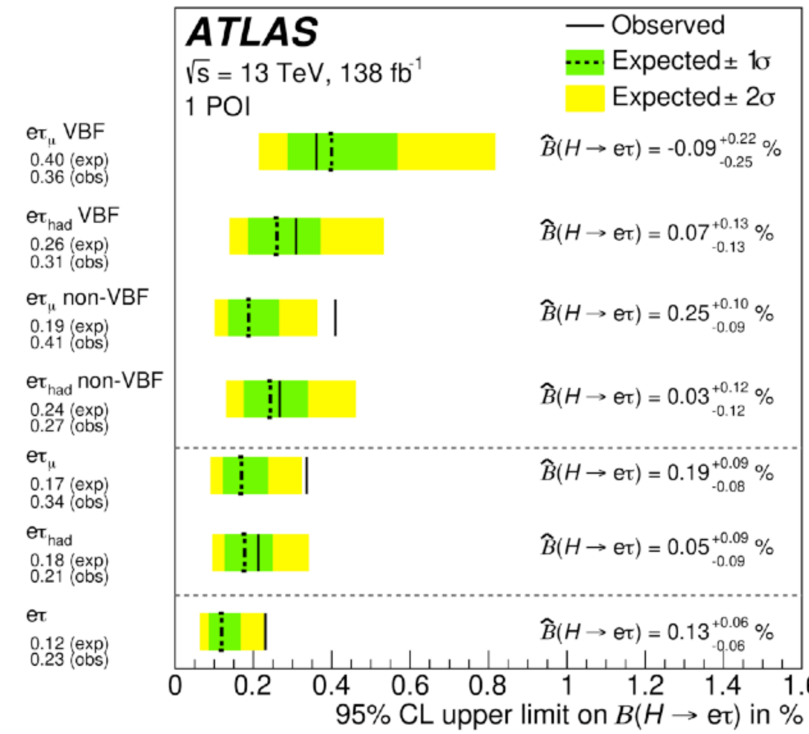




Searches for lepton-flavour-violating decays of the Higgs boson into eτ and μτ

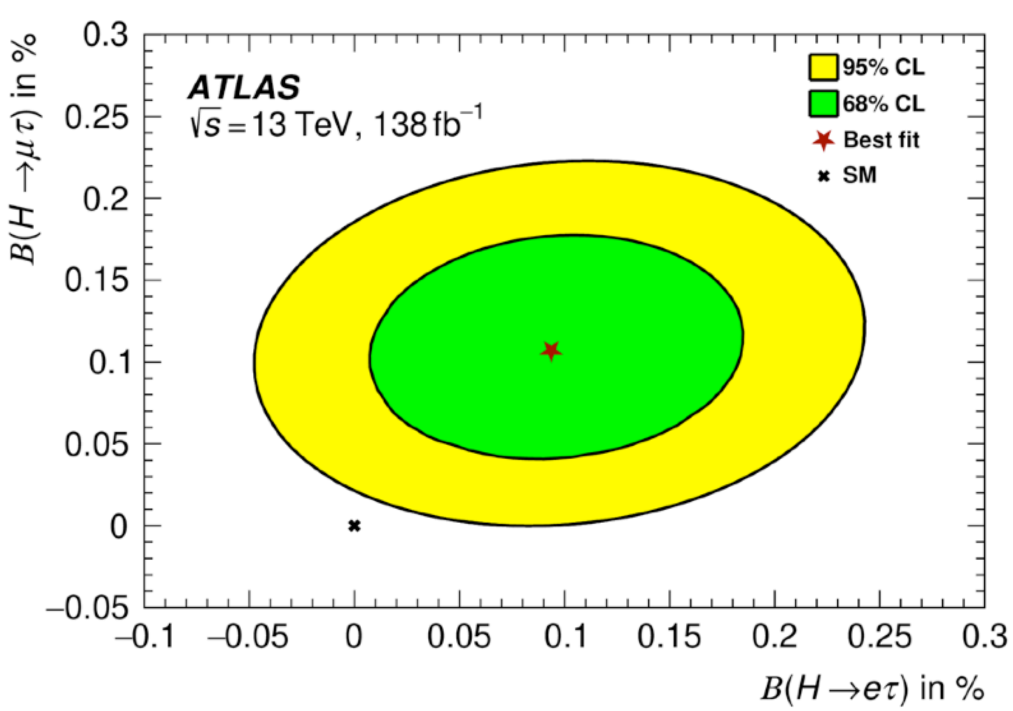
B(H→ eτ)=0 **B(H→ μτ)=0**

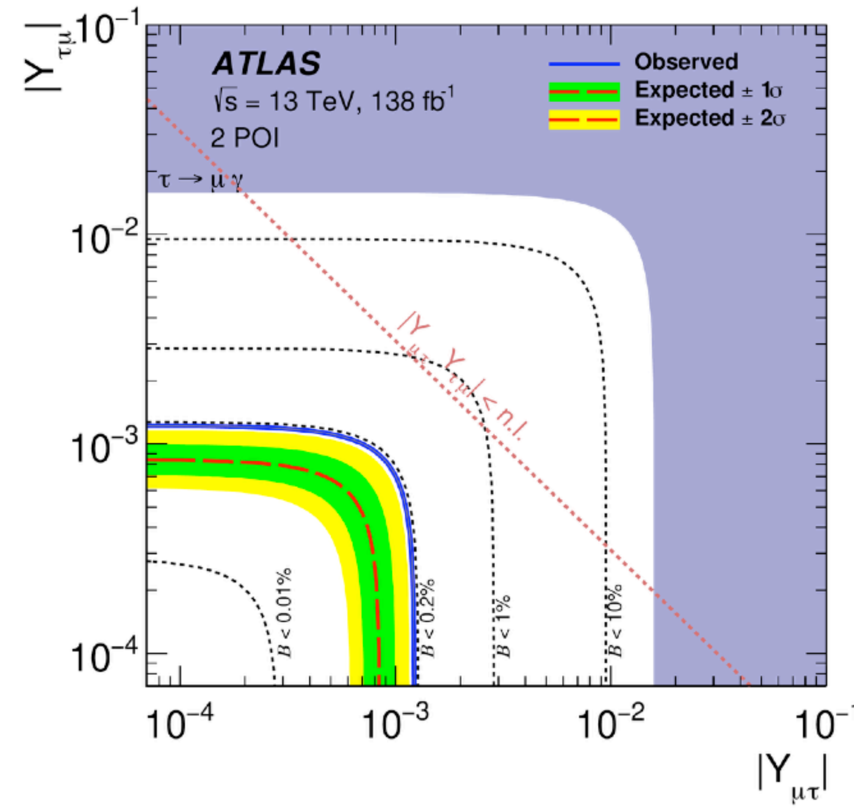




$$|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2 = \frac{8\pi}{m_H}\,\frac{\mathcal{B}(H\to\ell\tau)}{1-\mathcal{B}(H\to\ell\tau)}\,\Gamma_H(\mathrm{SM}).$$

2 POI fit: Simultaneous search for H→eτ and H→μτ



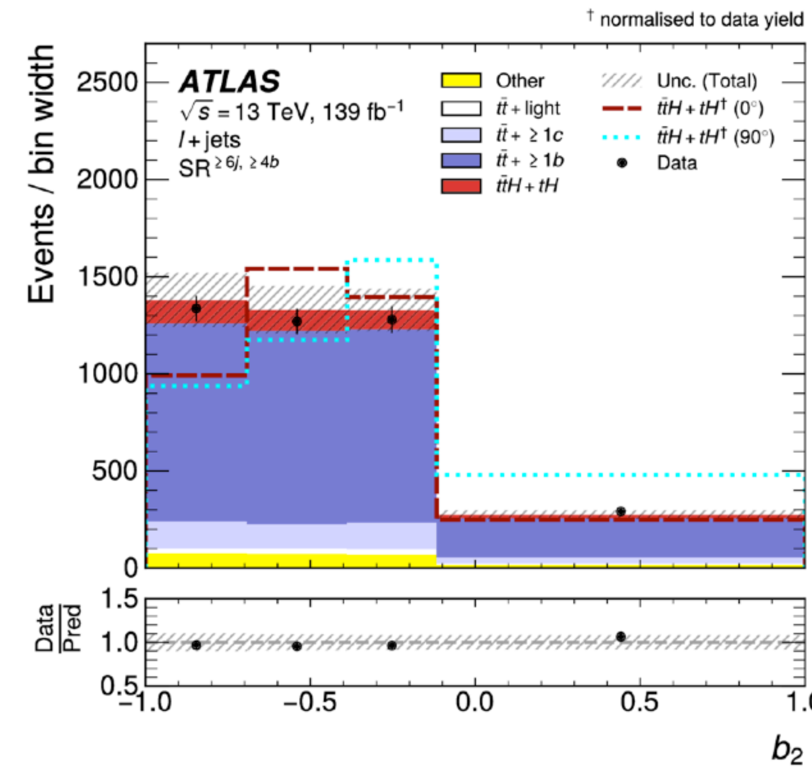


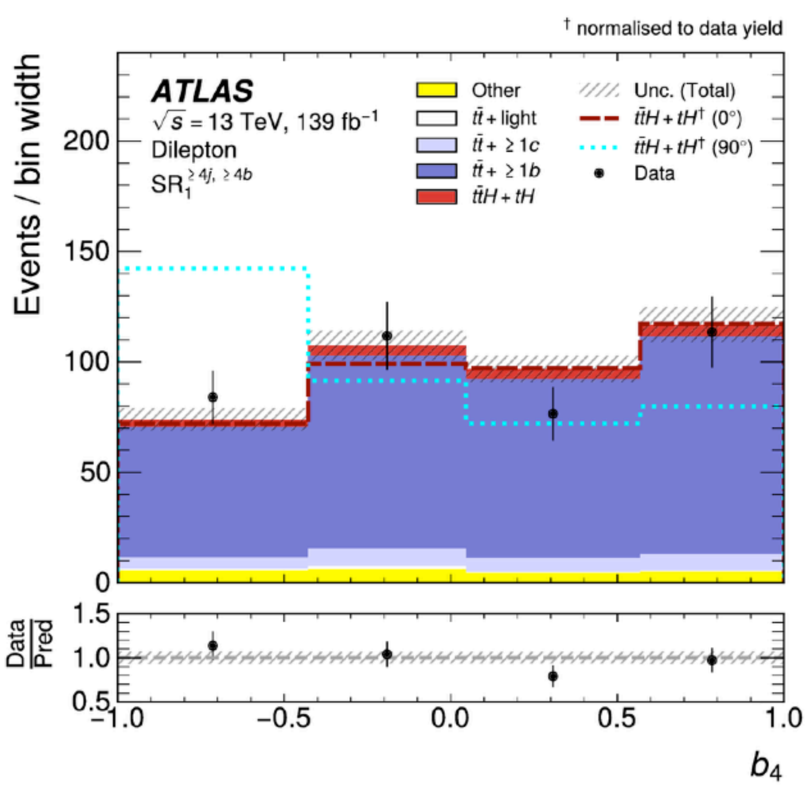
Probing the CP nature of the top-Higgs Yukawa coupling in tt-H and tH events with H→bb- decays

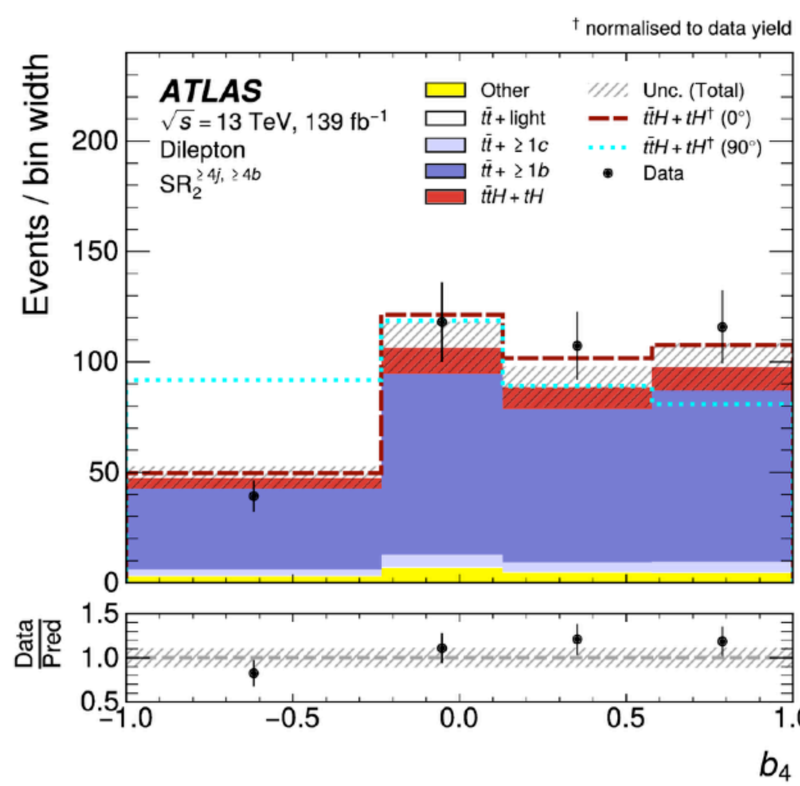
‘boosted’ region with a high-pT Higgs identified using a DNN.

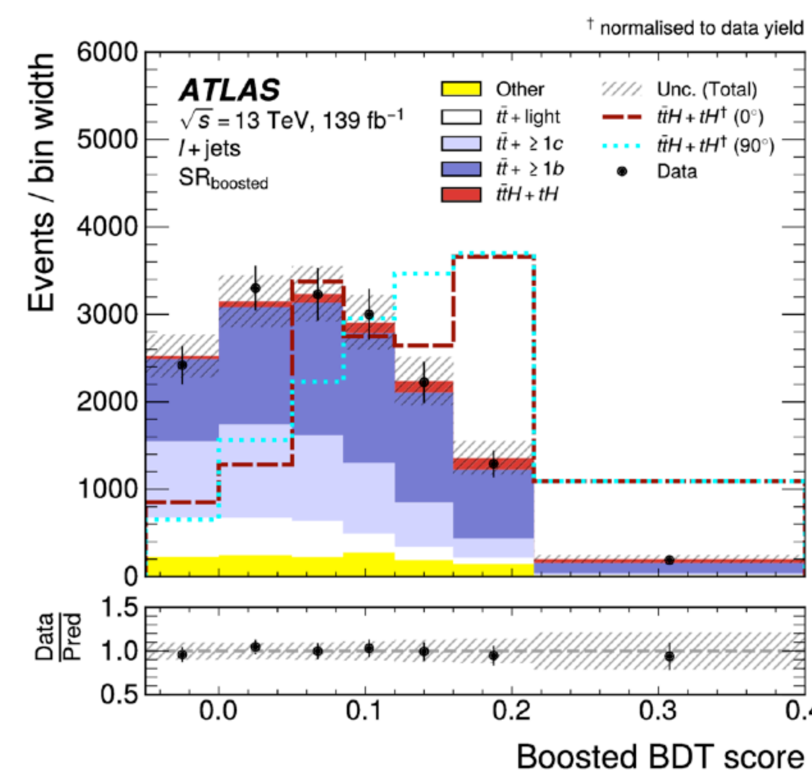
Two sets of BDTs reconstruction BDTs and classification BDTs.

$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}, \text{ and } b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|},$$



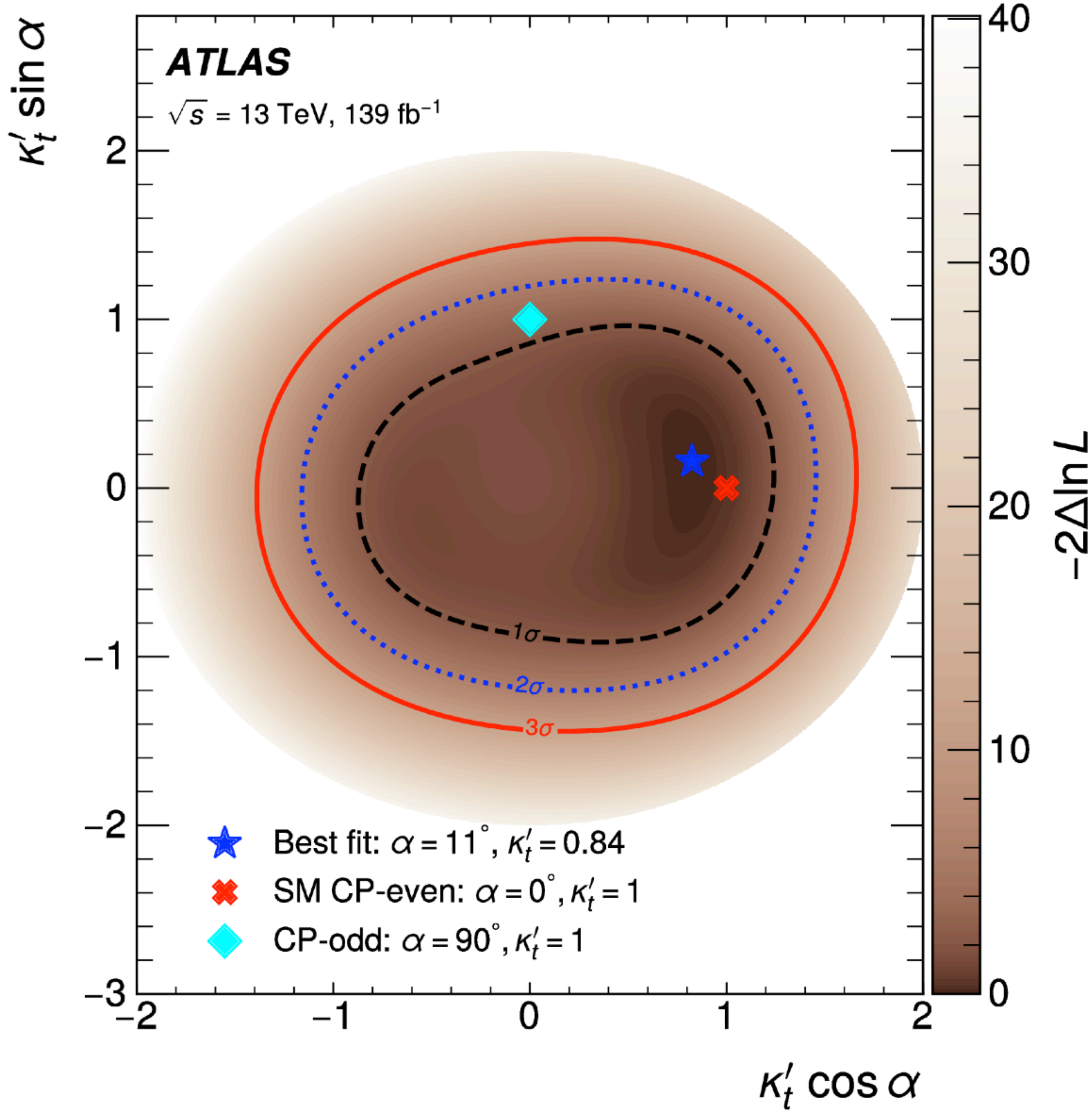






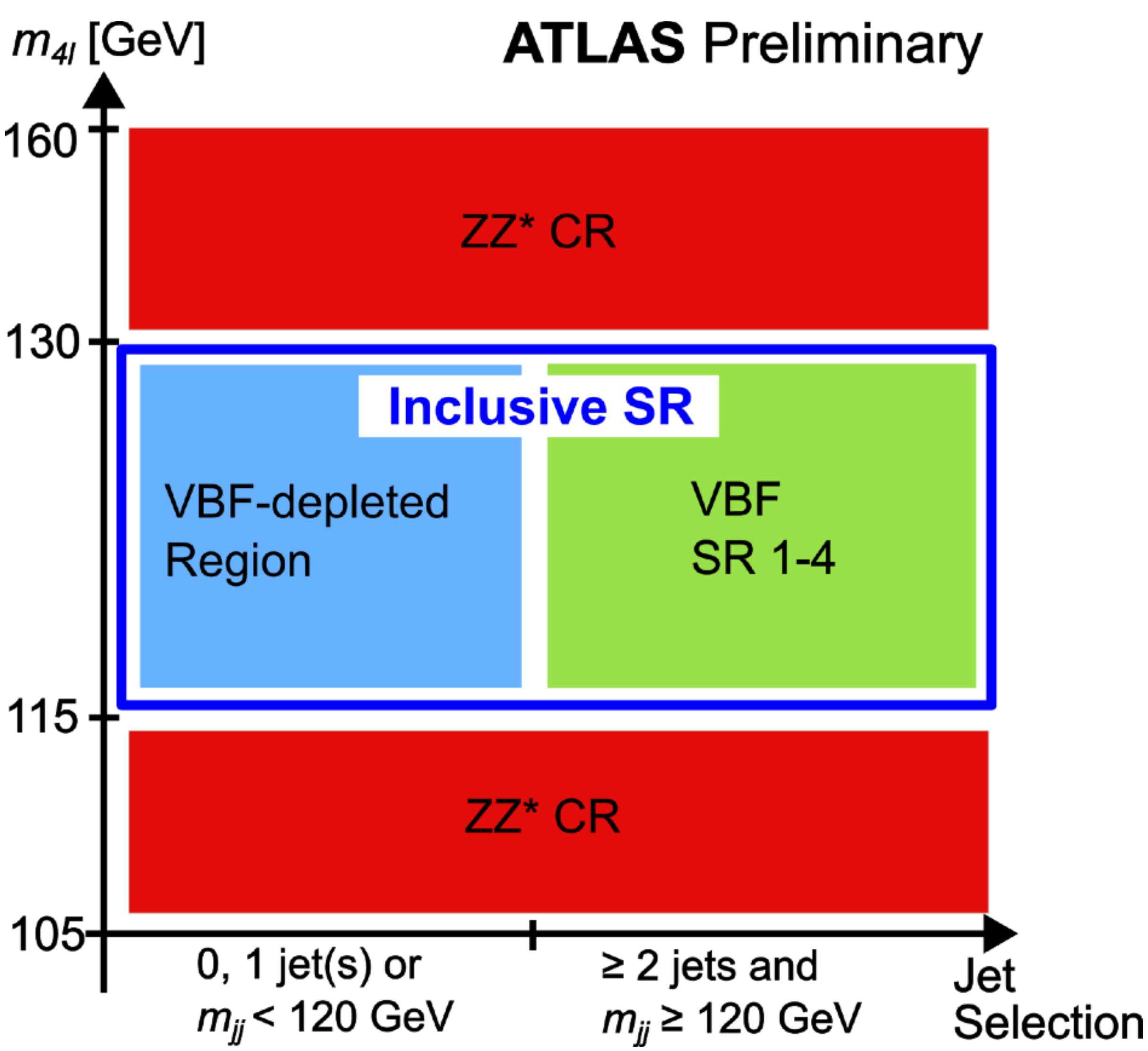
Probing the CP nature of the top-Higgs Yukawa coupling in tt-H and tH events with H→bb- decays

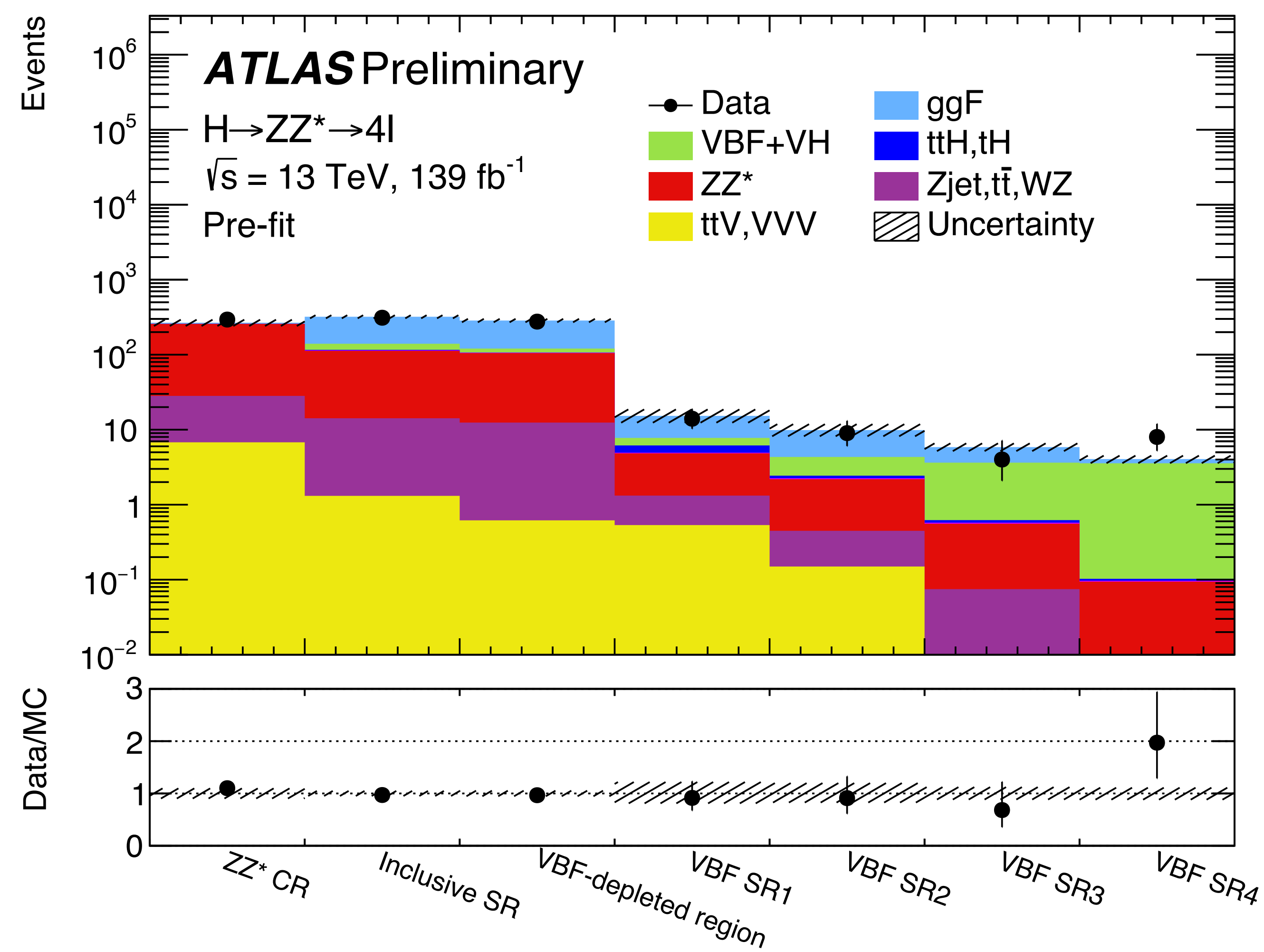
$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$



Test of CP-invariance of the Higgs boson in Vector Boson Production and its decay to Four Leptons

Optimal observables symmetric for CP-even Higgs, become asymmetric if CP-odd BSM couplings.
SMEFT framework is used to guide the analysis strategy and interpret the results
Optimal Observables (OO) , asymmetry in their distribution evidence for CP violation





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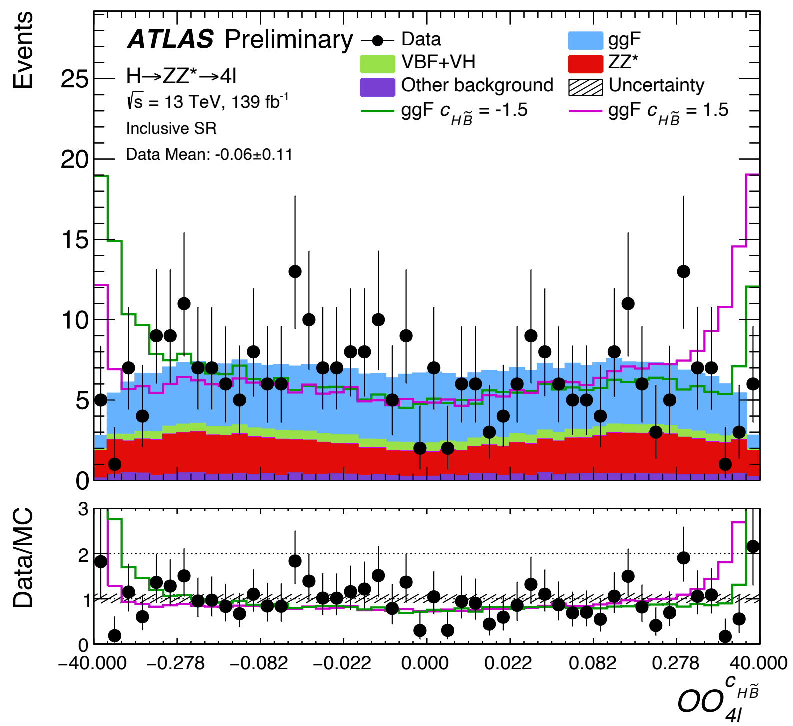
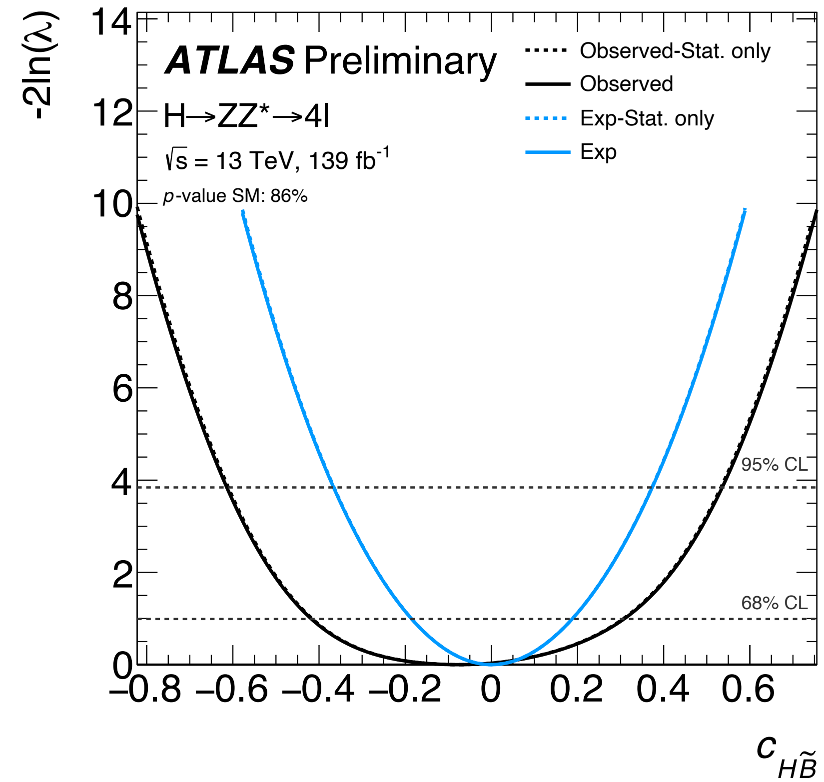
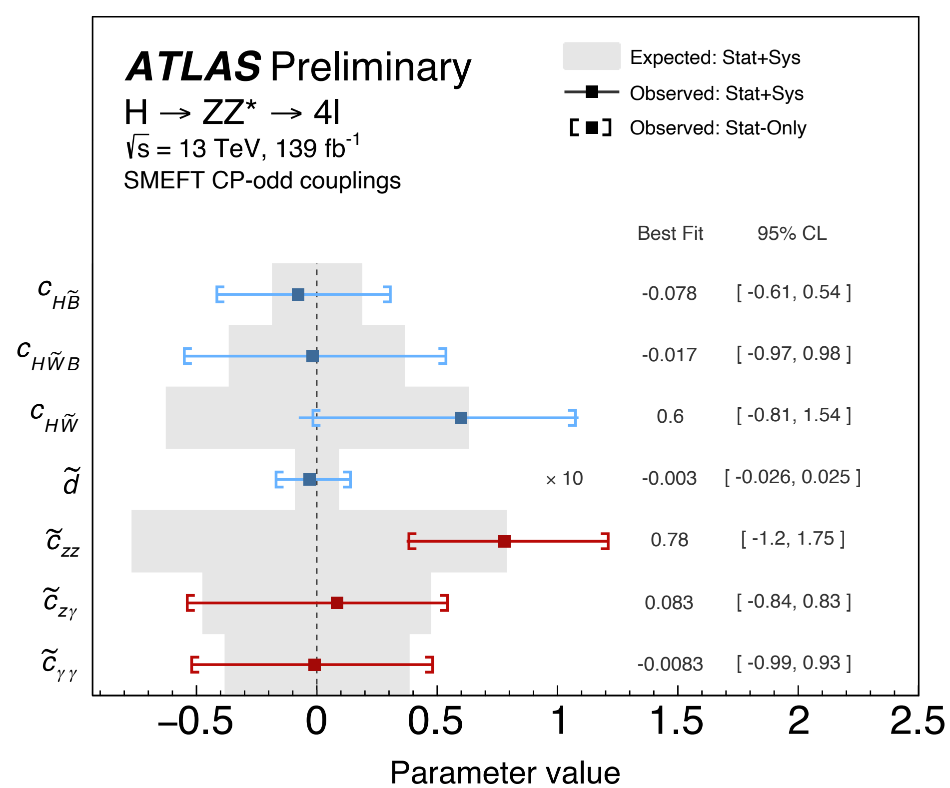


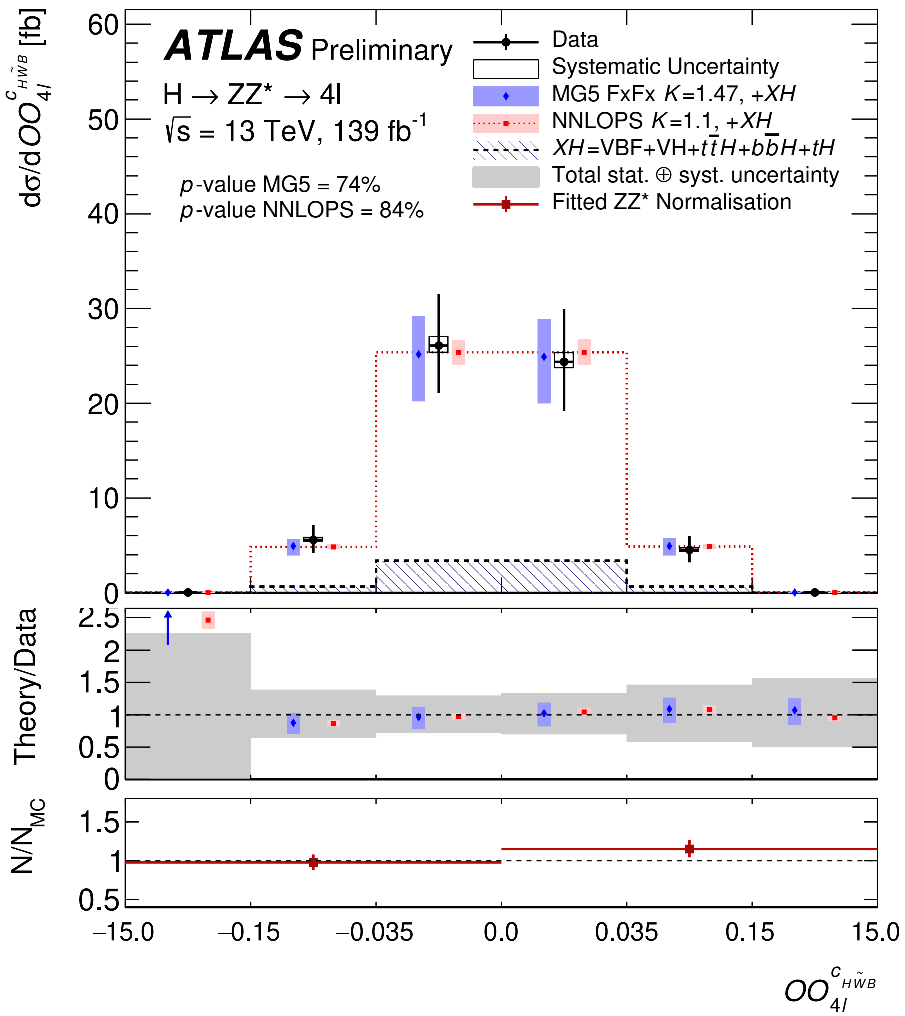


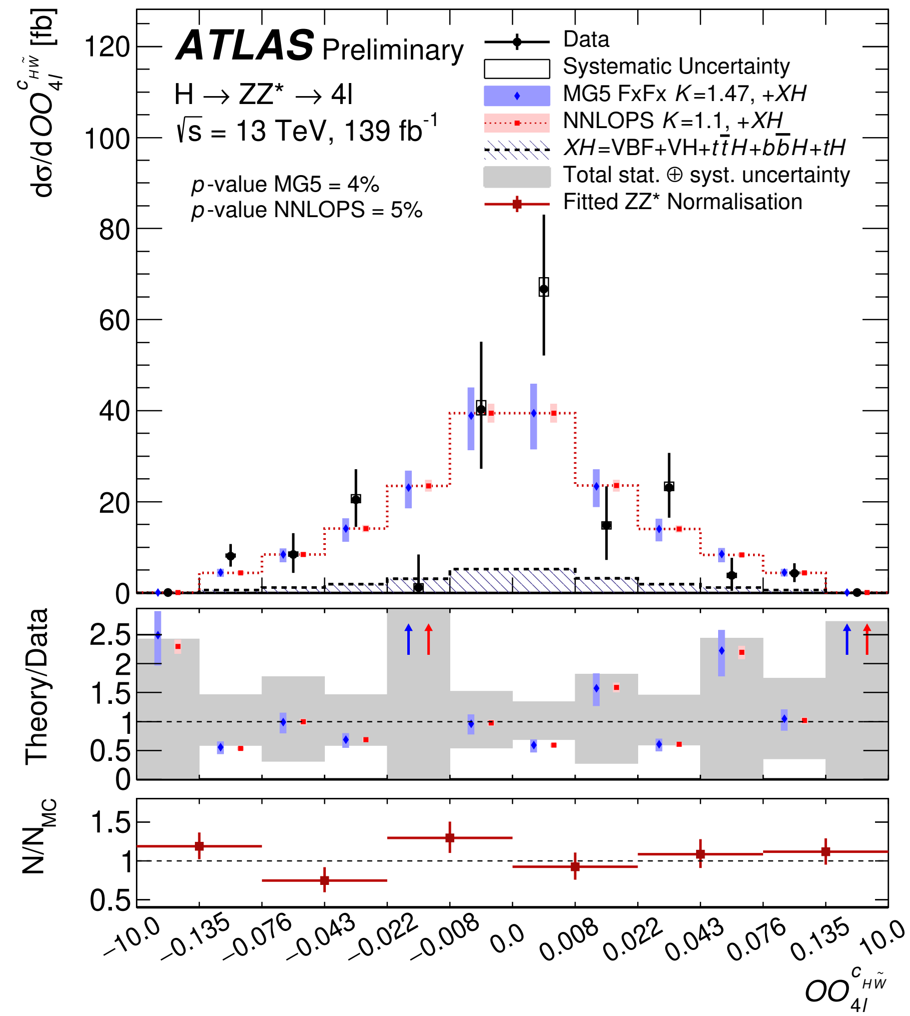
“Warsaw basis”

“Higgs basis”



Test of CP-invariance of the Higgs boson in Vector Boson Production and its decay to Four Leptons

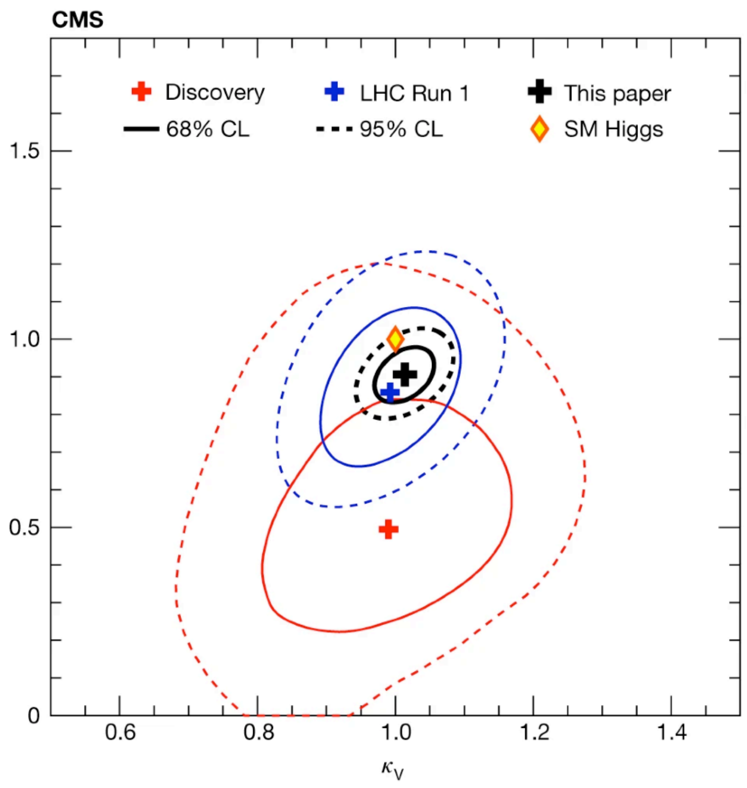


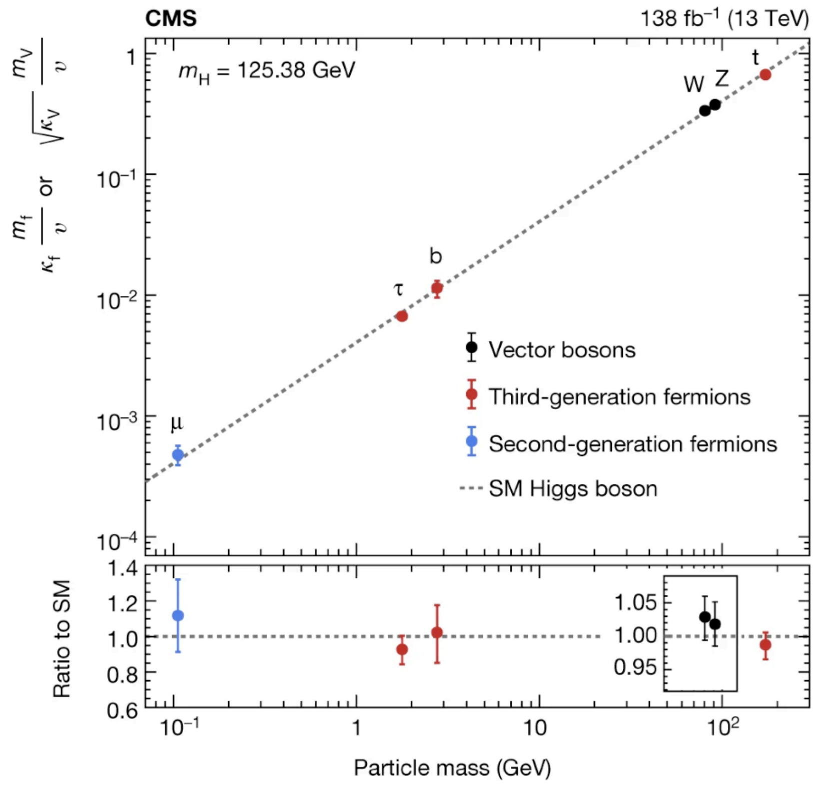


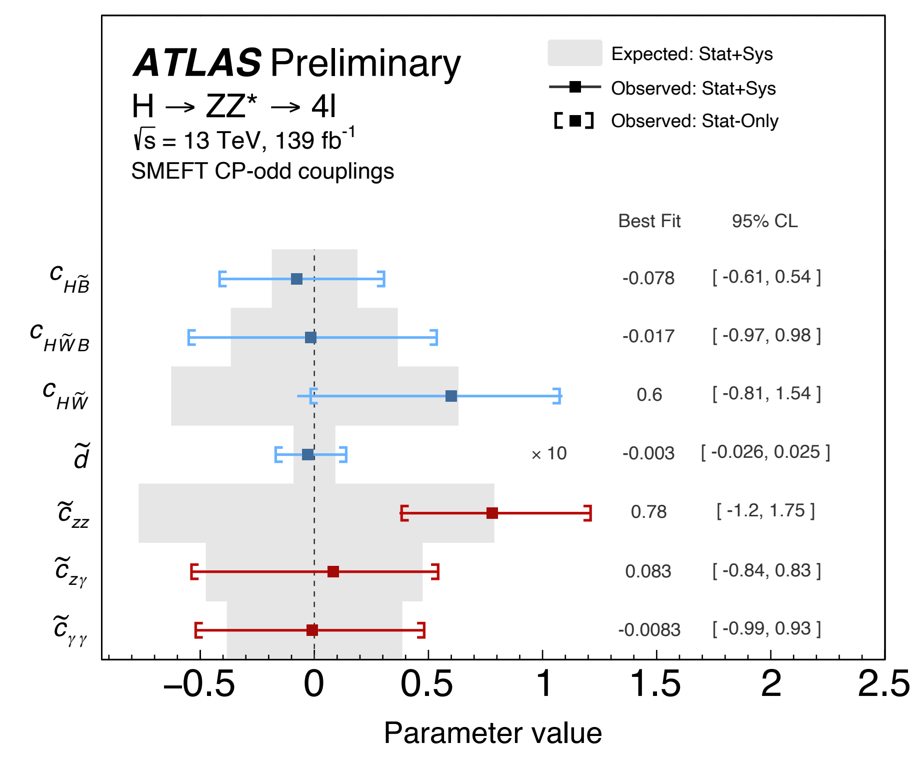
Conclusions

Measurement of fermion couplings and Higgs CP mostly compatible with the Standard Model.

These measurements push the limits in our understanding of the Standard Model and still provide opportunities to probe new physics.

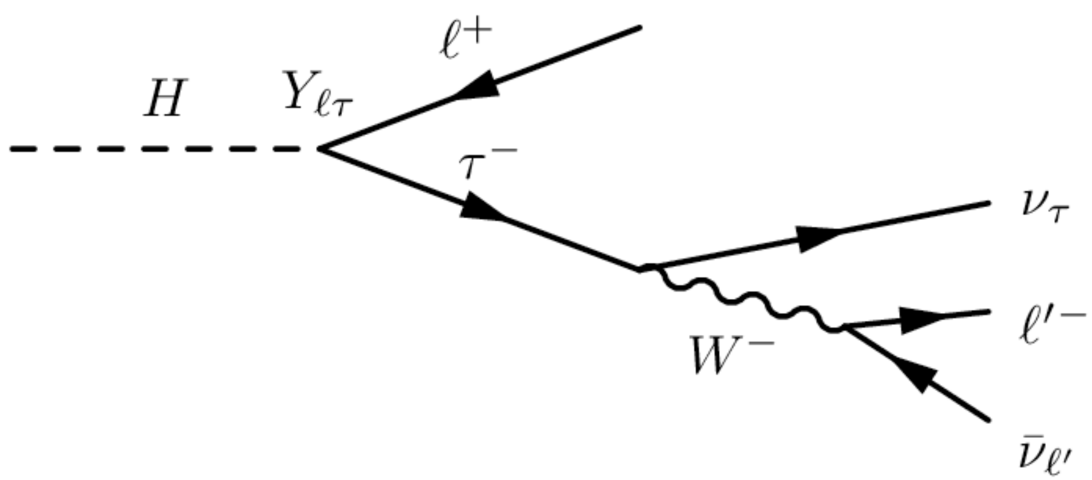


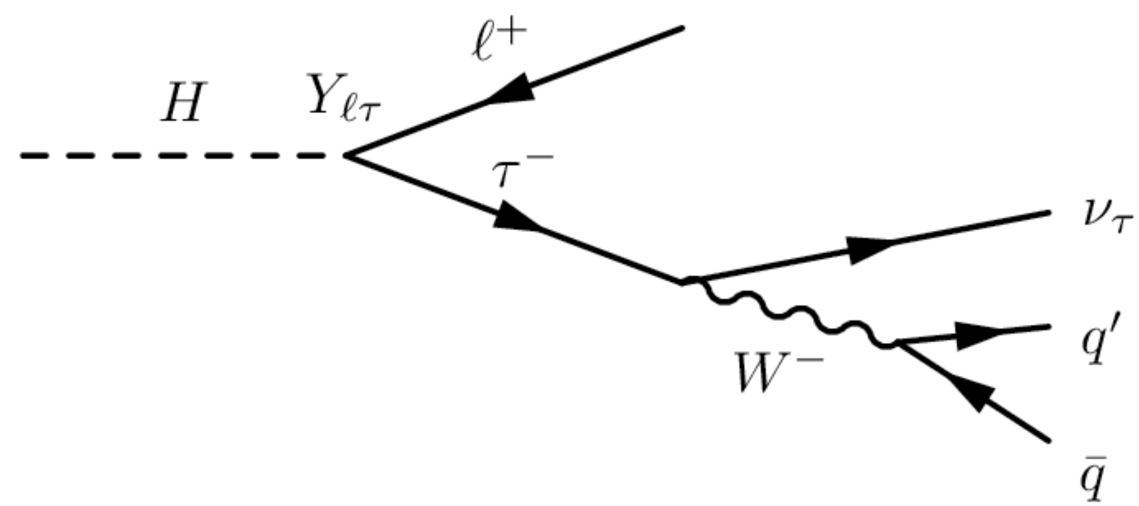




BACKUP

Searches for lepton-flavour-violating decays of the Higgs boson into eτ and μτ





Two complementary background estimation techniques are exploited. The first relies on simulation and is used in both the $\ell\tau_\ell$and $\ell\tau$had channels. The second one relies on the Symmetry method and is applied in the $\ell\tau_\ell$ channel.

1. SM processes are symmetric under the exchange of prompt electrons with prompt muons to a good approximation. As a consequence, the kinematic distributions of prompt electrons and prompt muons are approximately the same;
2. Flavour-violating decays of the Higgs boson break this symmetry.

According to the e/μ-symmetry assumption, the SM background is split equally between the $\mu\tau_e$ and $e\tau_\mu$ datasets. However, the $H \to \mu\tau$ signal is mostly present in the $\mu\tau_e$ dataset, since the p_T of the muon originating from the Higgs boson is typically larger than the p_T of the electron originating from the decay of the τ-lepton. Similarly, the $H \to e\tau$ signal is mostly present in the $e\tau_\mu$ dataset. Thus, in a search for $H \to \mu\tau$ decays, the SM background can be estimated using the $e\tau_\mu$ dataset, and vice versa.

Test of CP-invariance of the Higgs boson in Vector Boson Production and its decay to Four Leptons

Finally, a common parametrisation used in existing experimental searches for CP-violation in the HVV vertex [10, 30] assumes that the BSM CP-odd Higgs boson coupling to a $Z\gamma$ pair is zero and that the two remaining CP-odd couplings in the Warsaw basis, which mix to form the two couplings of the Higgs boson to ZZ^* and $\gamma\gamma$ decays, are the same. The single remaining effective coupling is denoted as $\widetilde{d}$. It is related to the Warsaw basis couplings by the parametrisation $c_{H\widetilde{W}B} = 0, c_{H\widetilde{W}} = c_{H\widetilde{B}} = \frac{\Lambda^2}{v^2}\widetilde{d}$, where v is the Higgs boson vacuum expectation value. In the Higgs basis, it is equivalent to the direction $\widetilde{c}_{z\gamma} = 0$, $\widetilde{c}_{\gamma\gamma} = \sin^2\theta_W \cos^2\theta_W \widetilde{c}_{zz}$, where θ_W is the Weinberg angle.

Normalising the interference term by the SM term forms a so-called 'optimal observable' for each coupling, which can be used to detect a CP asymmetry:

$$OO = \frac{2\Re\left(\mathcal{M}^*_{SM}\mathcal{M}_{BSM}\right)}{|\mathcal{M}_{SM}|^2}. \tag{3}$$

These observables are CP-odd by construction, implying a symmetric distribution with a vanishing mean in the absence of CP violation. Any asymmetry observed in the distribution of the optimal observables would be direct evidence for CP-violation in the HVV coupling. The matrix elements entering the