Study of the Higgs boson CP properties in vector-boson fusion production and ditau final state with the ATLAS detector

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Introduction

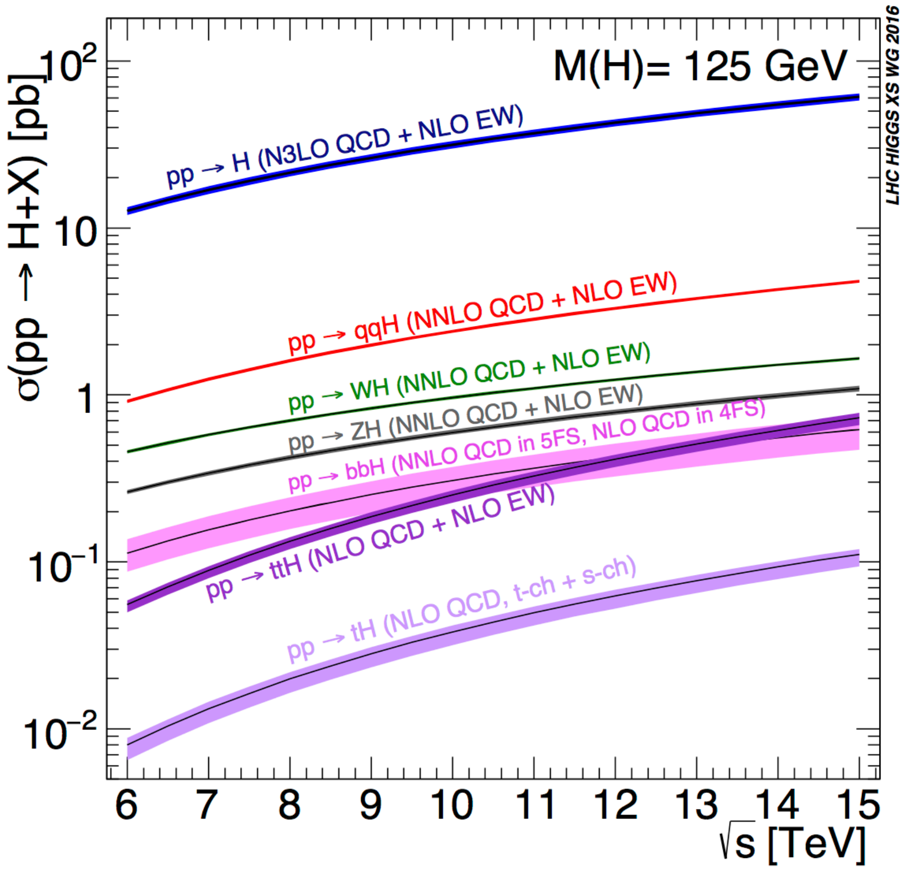
- Baryons asymmetry observed in the universe
- Sakharov condition: Charge-Parity (CP) symmetry has to be violated to have different reaction rates for baryons and anti-baryons

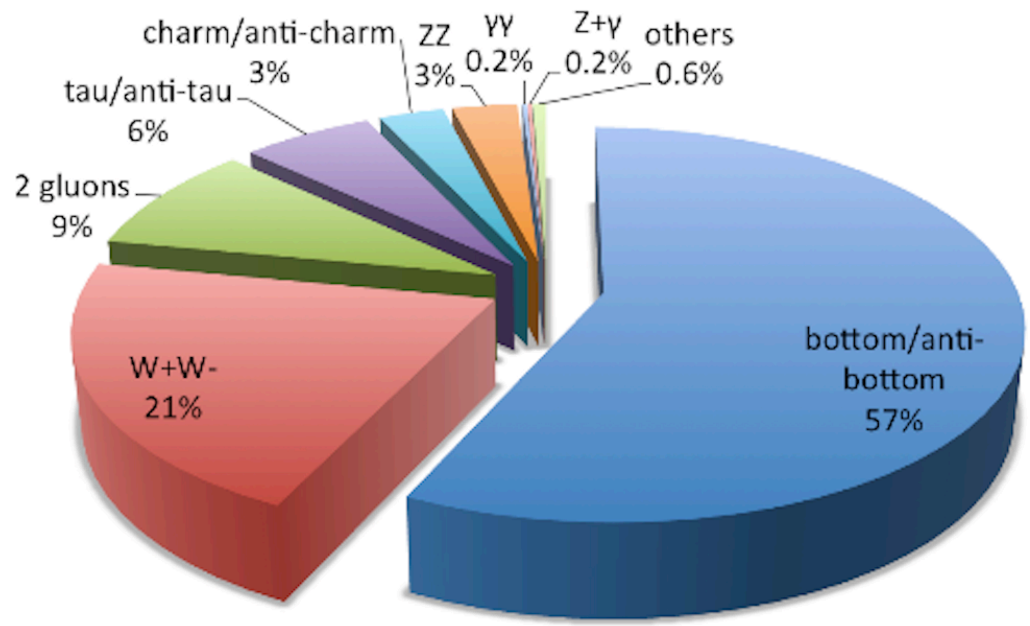
$$\Gamma(N \xrightarrow{\mathcal{L}(\Delta n_{\text{Bar}} \neq 0)} f) \neq \Gamma(\bar{N} \xrightarrow{\mathcal{L}(\Delta n_{\text{Bar}} \neq 0)} \bar{f})$$

- In the Standard Model (SM), CP violation is encoded in the CKM (PMNS) matrix for quarks (leptons)
  - Source of CP violation only appears in the charged current couplings
  - Effect too small to generate the observed matter-antimatter asymmetry

- Higgs boson predicted to be a scalar ($J^{CP} = 0^{++}$) in SM with no CP-violating interactions:
  - The measurement of a CP-odd contribution in the Higgs boson couplings would be a sign of physics beyond the SM (BSM)

Higgs production mode and decays

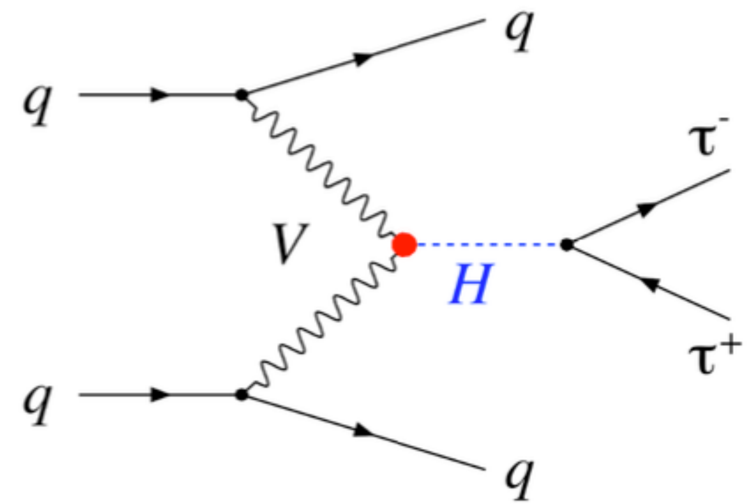




- Higgs boson production mostly through gluon-gluon fusion (ggF) and vector-boson fusion (VBF)
- For the Higgs boson decay, largest branching ratio is for $H \to bb$ and $H \to WW$. Among the decays, $H \to \tau\tau$ has good branching ratio and relatively high signal/background, so it's suited for studying the CP of the Higgs boson

Study of the Higgs CP in VBF and $H \rightarrow \tau\tau$ final state

- Search for possible CP violating effects in HVV vertex for VBF production mode



- EFT Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{f_{\tilde{B}B}}{\Lambda^2} H^\dagger \hat{B}_{\mu\nu} \hat{\tilde{B}}_{\mu\nu} H + \frac{f_{\tilde{W}W}}{\Lambda^2} H^\dagger \hat{W}_{\mu\nu} \hat{\tilde{W}}_{\mu\nu} H$$

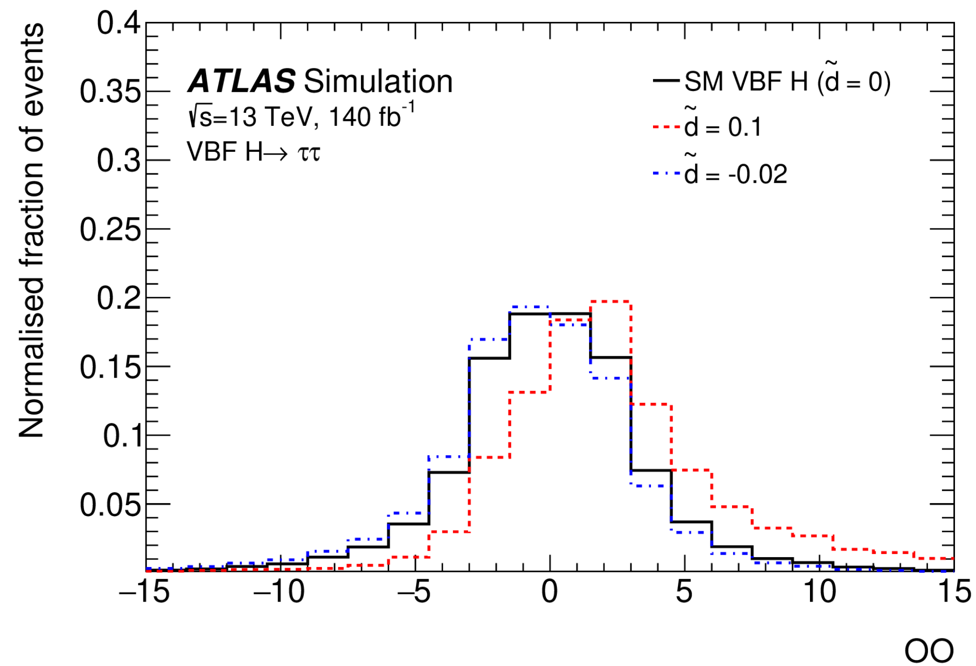
- Simplify using only one CP-violating parameter:

$$\tilde{d} = -\frac{m_W^2}{\Lambda^2} f_{\tilde{W}W} = -\frac{m_W^2}{\Lambda^2} \tan^2(\theta_W) f_{\tilde{B}B}$$

- Use Optimal Observable to measure $\tilde{d}$:

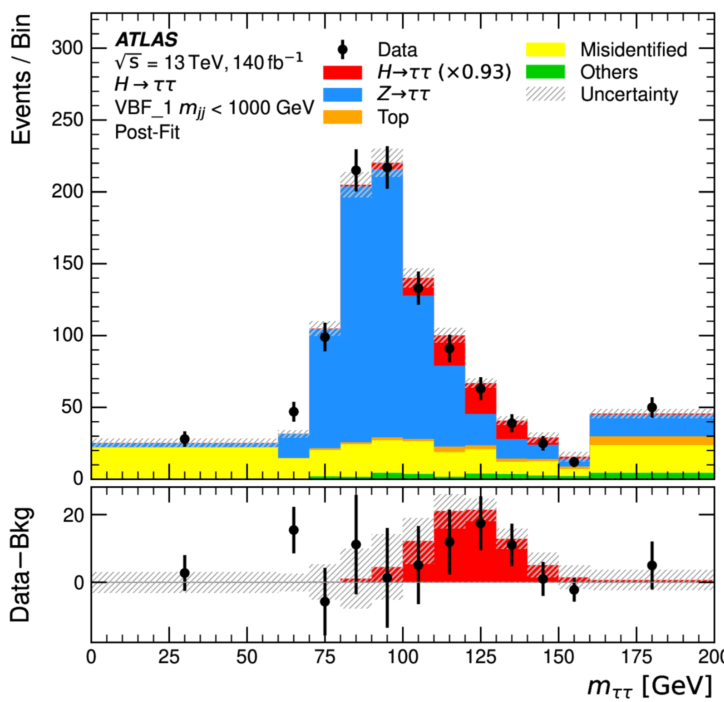
$$OO = \frac{Re(M^*_{SM} M_{CP-Odd})}{|M^2_{SM}|}$$

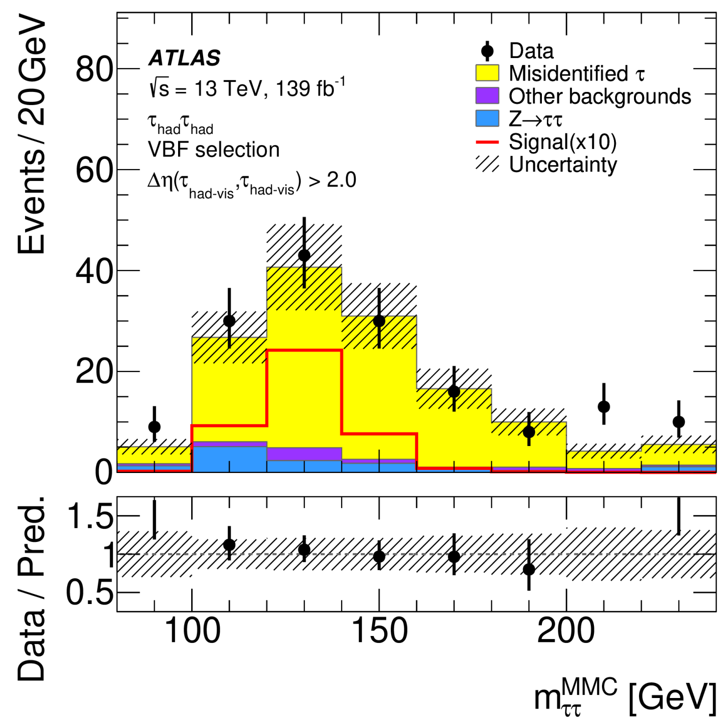
- Full phase space information in 1-dim. observable for small $\tilde{d}$. $< OO > \neq 0 \rightarrow$ CP violation neglecting re-scattering effects by new light particles in loops

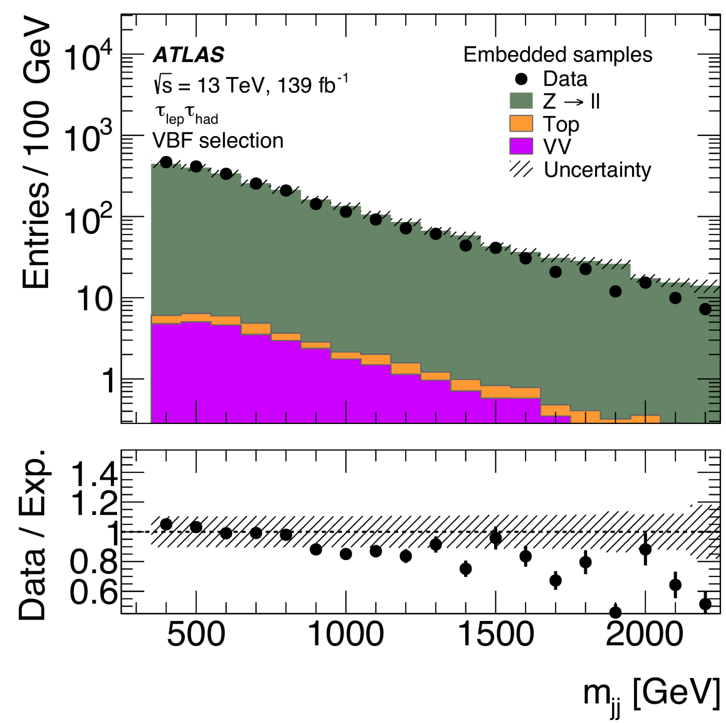


Background estimation

- Analysis considers all ditau final states, $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$
- Mostly based on simulation except for misidentified τ, which is estimated using data-driven method
- $Z \rightarrow \tau\tau$ is the largest and irreducible background; validated and normalised through the kinematic embedding procedure
- Mis. τ estimated using the Matrix Method ($\tau_{lep}\tau_{lep}$) and the Fake Factor method ($\tau_{lep}\tau_{had}/\tau_{had}\tau_{had}$)

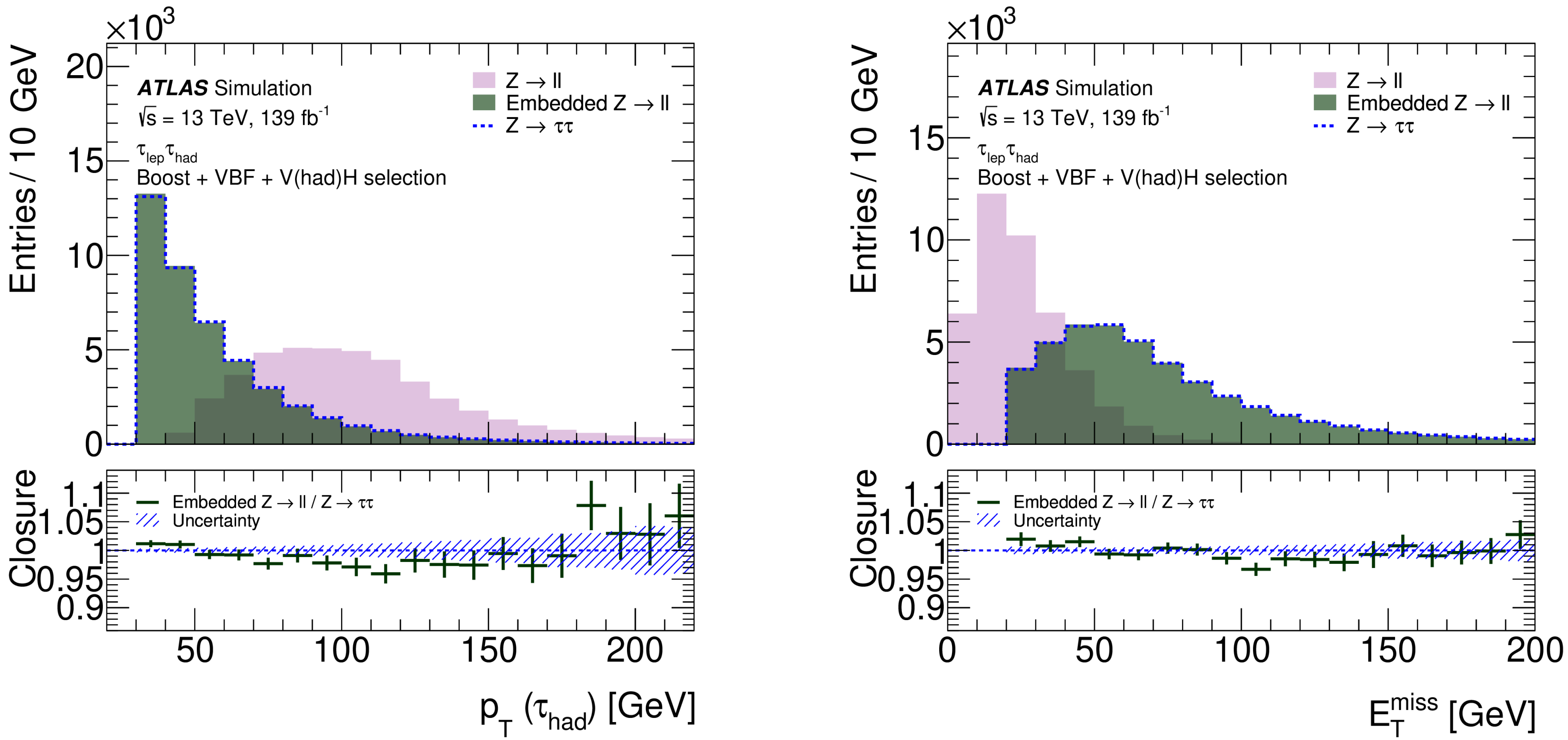






Kinematic Embedding (JHEP 08 (2022) 175)

- Select $Z \rightarrow ll$ events in control regions defined to be orthogonal to the signal regions
- Unfold $Z \rightarrow ll$ events taking into account the lepton reconstruction/identification efficiencies
- Mimic $Z \rightarrow \tau\tau$ events through kinematics parameterisation of the τ decay products



MVA analysis strategy

- Neural Networks implemented in Keras using TensorFlow, with separate network across different channels
- Each channels uses a different set of input observables, taking into account the peculiar jets back-to-back topology for VBF; most important features are the reconstructed masses and the p_T of the ditau, E^T_{miss} and jets system
- Binary classifier for $\tau_{lep}\tau_{had}/\tau_{had}\tau_{had}$ while multi-classifier for $\tau_{lep}\tau_{lep}$ due to different relevant background composition
- The Networks are trained assuming SM predictions, then tested with different CP-violating hypotheses and no bias found

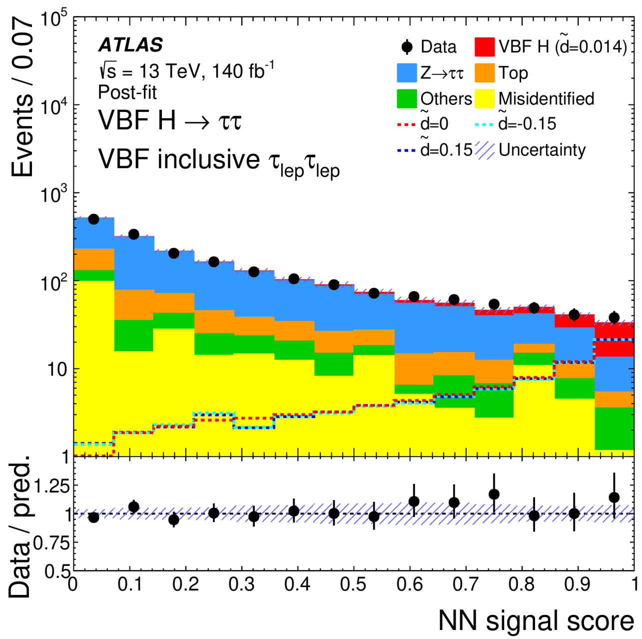
	Variable	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
τ-lepton properties	$\eta(\tau_1), \eta(\tau_2)$		•	
	$p_{\text{T}}(\tau_1), p_{\text{T}}(\tau_2)$		•	
	$\phi(\tau_1), \phi(\tau_2)$		•	
	$E(\tau_1), E(\tau_2)$		•	
	$C_{jj}(\tau_1)$	•	•	•
	$C_{jj}(\tau_2)$	•	•	•
Mass	$m_{\tau\tau}^{\text{MMC}}$	•	•	•
	$m_{\tau\tau}^{\text{vis}}$	•	•	•
	m_{jj}	•	•	•
	$m_{\text{T}}(\tau_1, E_{\text{T}}^{\text{miss}})$	•	•	•
	$m_{\text{T}}(\tau_2, E_{\text{T}}^{\text{miss}})$	•	•	•
	$m\,(\tau_1, \tau_2, j_1)$	•	•	•
Angular distances	$\eta^{j_1} \times \eta^{j_2}$	•	•	•
	$\Delta R_{\tau_1\tau_2}$	•	•	•
	$\Delta\eta_{\tau_1\tau_2}$	•	•	•
	$\Delta\phi_{\tau_1\tau_2}$	•	•	•
	$\Delta\eta_{jj}$	•	•	•
	$\Delta\phi_{H,j_1}$	•	•	•
Jet properties	$p_{\text{T}}(\tau_1, \tau_2, j_1, j_2)$		•	
	$p_{\text{T}}\,(j_1, j_2)$	•	•	•
	$p_{\text{T}}(\tau_1, \tau_2, j_1, j_2, E_{\text{T}}^{\text{miss}})$	•	•	•
	$p_{\text{T}}(j_2), p_{\text{T}}(j_3)$	•		•
	$\eta(j_1), \eta(j_2)$		•	
	$\phi(j_1), \phi(j_2)$		•	
	$E(j_1), E(j_2)$		•	
	$p_{\text{T}}(\tau_1) + p_{\text{T}}(\tau_2)$	•		•
	$p_{\text{T}}(\tau_1, \tau_2)$	•	•	•
	$p_{\text{T}}(\tau_1, \tau_2, E_{\text{T}}^{\text{miss}})$	•	•	•
	$p_{\text{T}}(\tau_1, \tau_2, j_1, E_{\text{T}}^{\text{miss}})$	•	•	•
	$p_{\text{T}}(\tau_1)/p_{\text{T}}(\tau_2)$	•		•
	$\Delta p_{\text{T}}(\tau_1, \tau_2)/(p_{\text{T}}(\tau_1) + p_{\text{T}}(\tau_2))$	•		•
Missing transverse energy	$E_{\text{T}}^{\text{miss}}$		•	
	$E_{\text{T}}^{\text{miss}}\phi$		•	
	$E_{\text{T}}^{\text{miss}}/p_{\text{T}}(\tau_1)$	•	•	•
	$E_{\text{T}}^{\text{miss}}/p_{\text{T}}(\tau_2)$	•	•	•
	$E_{\text{T}}^{\text{miss}} - \phi\text{–centrality}/\sqrt{2}$	•	•	•
	$E_{\text{T,HPTO}}^{\text{miss}}$	•		•

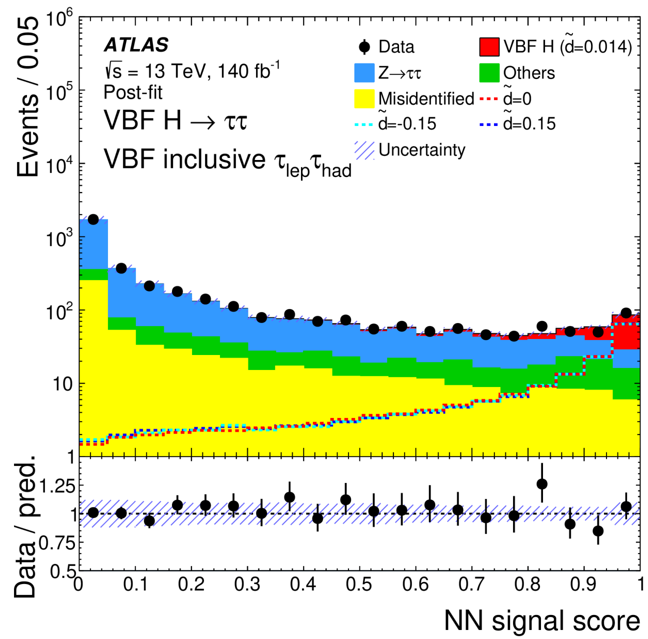
MVA score distribution and signal region selection

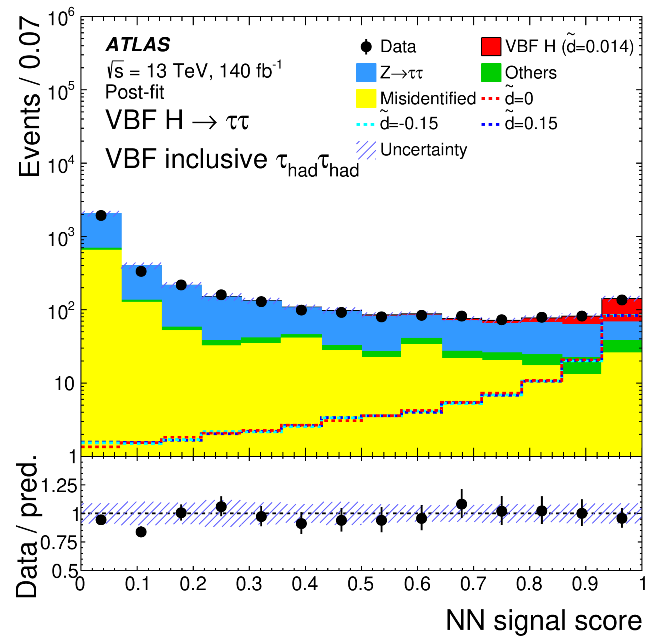
- Selection over MVA Score to classify events in SR high/ Low and Validation region. Optimal value for SR high definition is chosen to give the strongest expected 68% C.L. on $\tilde{d}$ interval

- $S/\sqrt{S+B} > 6.8\ (3.5)$ for $\tau_{had}\tau_{lep}/\tau_{had}\tau_{had}\ (\tau_{lep}\tau_{lep})$ for SR high regions

Channel	Region	NN signal score	$s/\sqrt{s+b}$
$\tau_{\text{lep}}\tau_{\text{lep}}$	$\text{SR}^{\text{HighNN}}$	> 0.91	3.50
	SR^{LowNN}	$0.67 - 0.91$	1.98
	VR^{LowNN}	< 0.67	0.51
$\tau_{\text{lep}}\tau_{\text{had}}$	$\text{SR}^{\text{HighNN}}$	> 0.91	6.93
	SR^{LowNN}	$0.63 - 0.91$	2.69
	VR^{LowNN}	< 0.63	0.30
$\tau_{\text{had}}\tau_{\text{had}}$	$\text{SR}^{\text{HighNN}}$	> 0.93	6.86
	SR^{LowNN}	$0.60 - 0.93$	2.42
	VR^{LowNN}	< 0.60	0.34

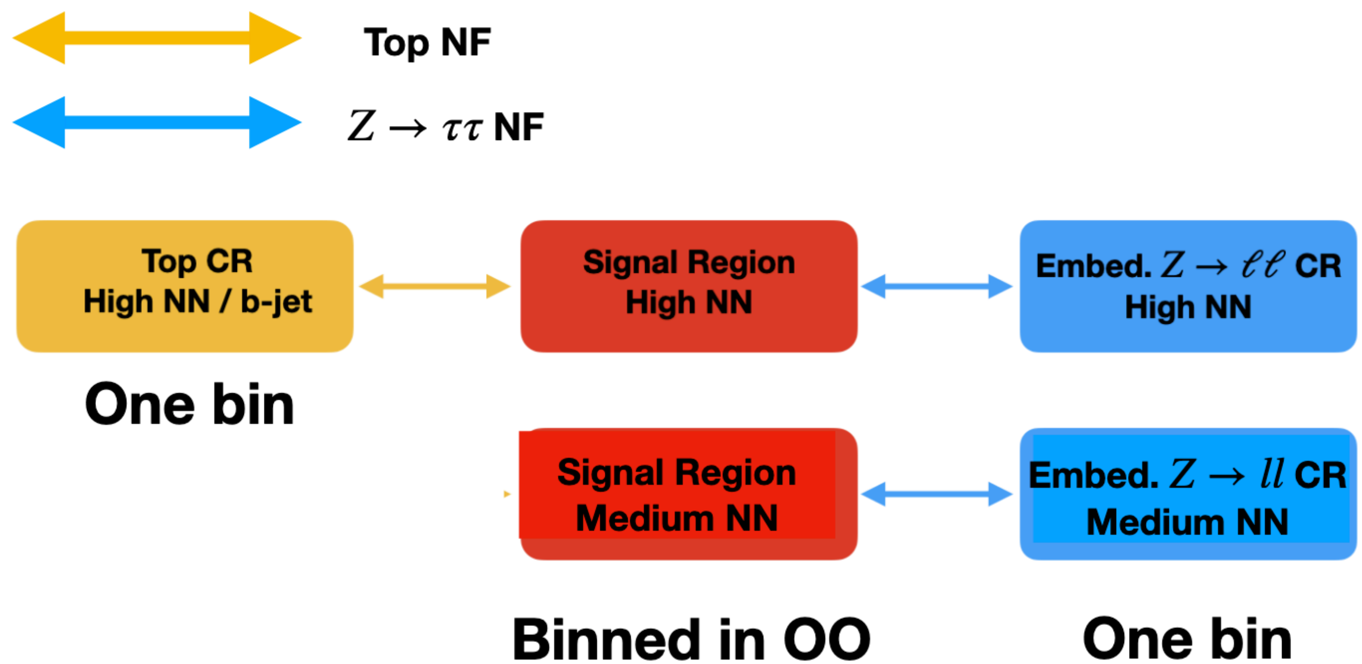






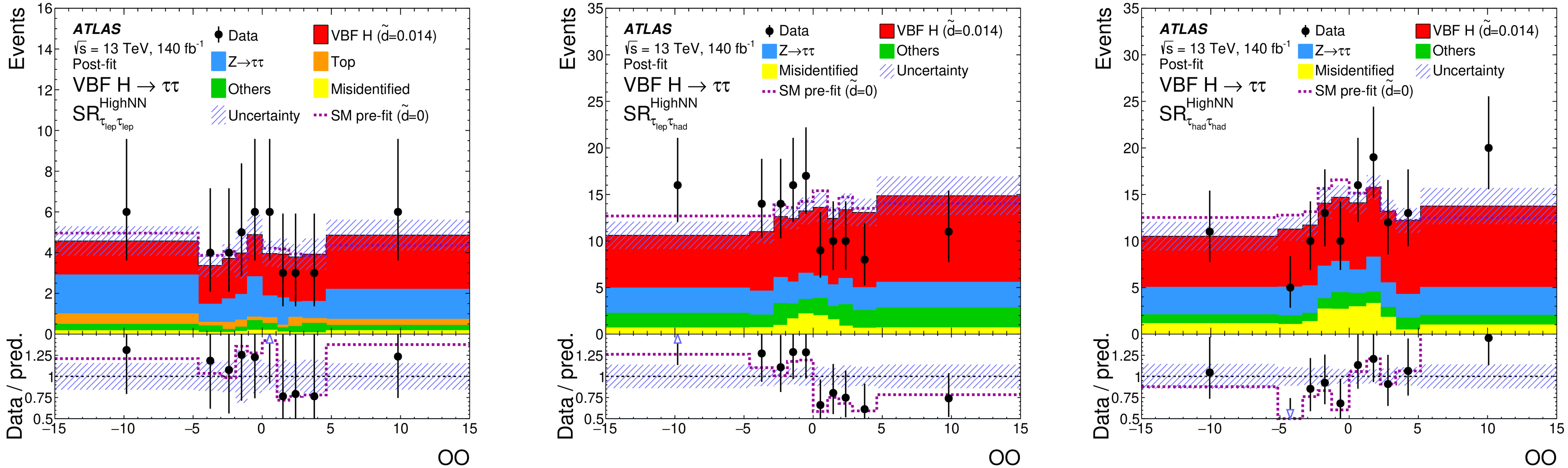
Fit model and signal extraction

- Fit includes SRs High/Low from all the channels using OO distribution as fitting variable. For each signal region, a control region is defined though embedding to constrain the $Z \rightarrow \tau\tau$ background
- Signal normalisation is added as common free floating normalisation factor, since this analysis is only interested in the OO shape changes and not to overall cross-section effects
- Results extracted by doing a negative log-likelihood scan for different hypotheses of the parameter of interest, using signal templates constructed by reweighing the SM VBF Higgs sample

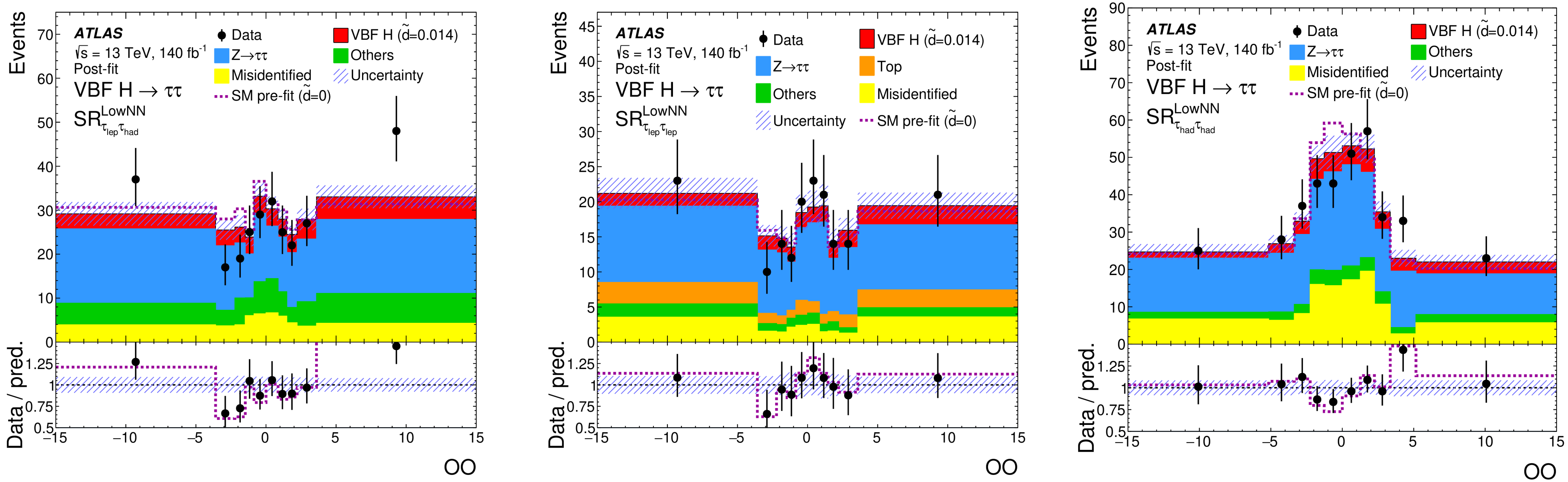


Optimal Observable distributions in signal regions

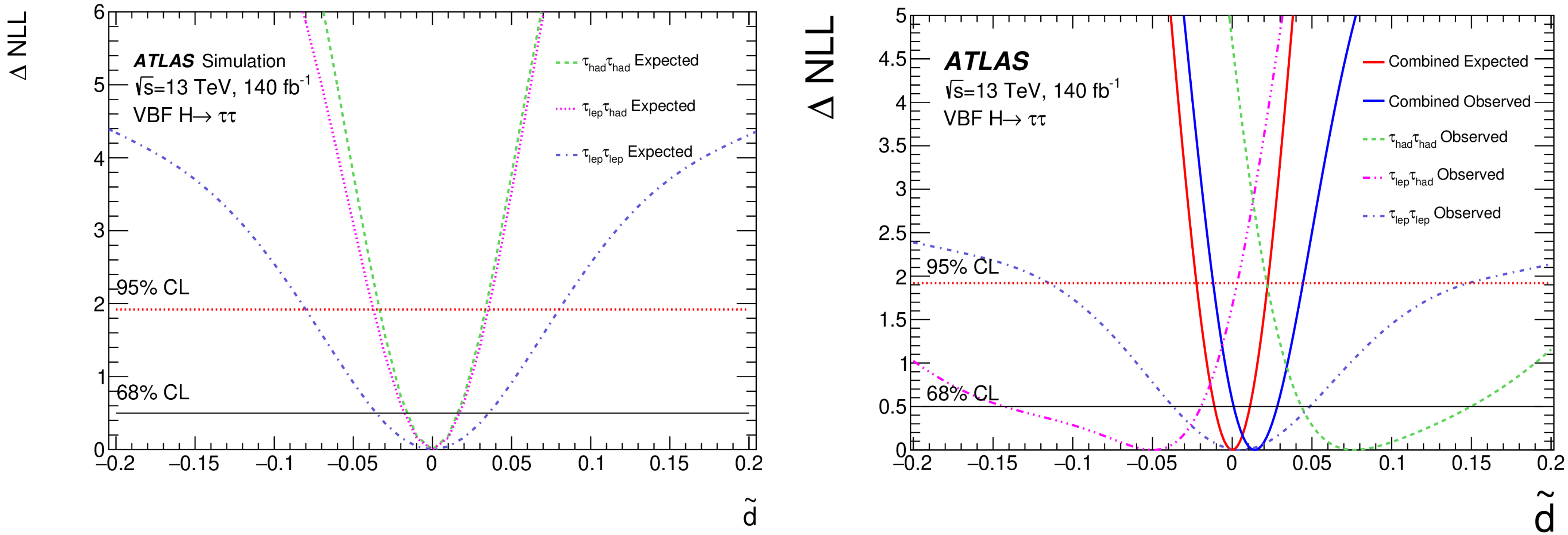
SRs High



SRs Low



Results for $\tilde{d}$ interpretation (HISZ basis)



Parameter	Observed best value	68% CL (Exp.)	95% CL (Exp.)	68% CL (Obs.)	95% CL (Obs.)
$\tilde{d}$ (lin.+quad.)	0.014	[−0.011, 0.011]	[−0.022, 0.022]	[0.001, 0.028]	[−0.012, 0.044]
$\tilde{d}$ (lin. only)	0.011	[−0.011, 0.011]	[−0.021, 0.022]	[0.000, 0.023]	[−0.012, 0.034]

- Great improvement with respect to previous analysis using partial Run2 dataset, now being able to set constraints also at 95% C.L.

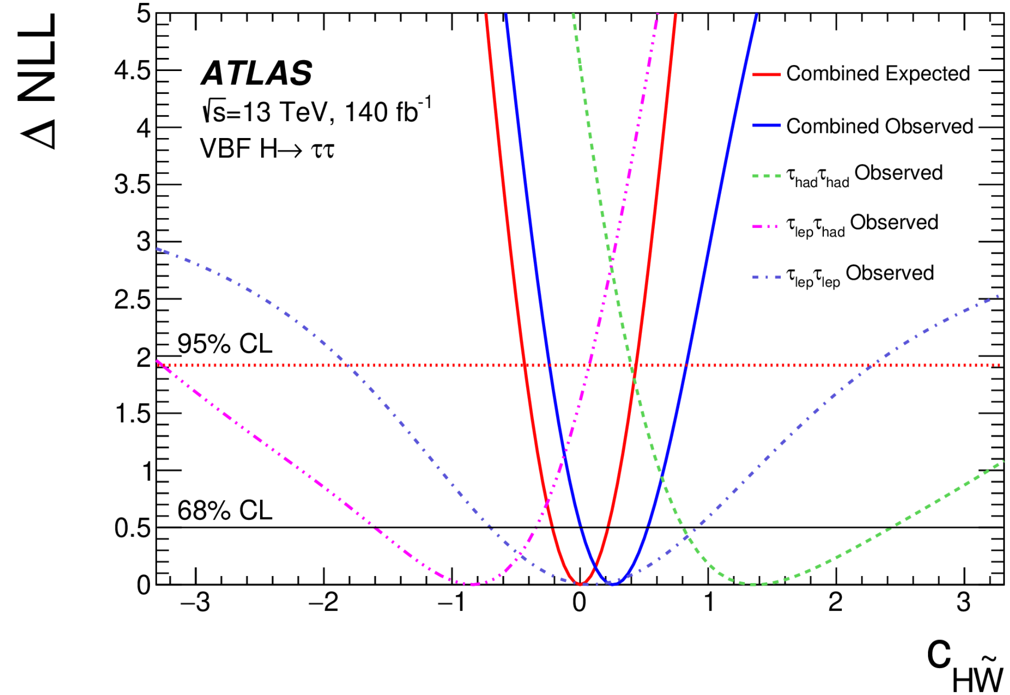
Results for Warsaw basis interpretation

- "Convert" the results from HIGZ to Warsaw basis; results for most sensitive EFT CP-odd operators for VBF production process, $c_{H\tilde{W}}$, $c_{H\tilde{B}}$ and $c_{H\tilde{W}B}$

- Both linear and linear+quadratic EFT parameterisation are tested. Small differences between the two will ensure that the EFT interpretation is correct

- Agreement between the combined fit and the single-channel fits is 2.8 σ, due to statistical fluctuations

- Very stringent results for $c_{H\tilde{W}}$



Parameter	Observed Best Value	68 % CI (Exp.)	95 % CI (Exp.)	68 % CI (Obs.)	95 % CI (Obs.)
$c_{H\tilde{W}}$ (lin.+quad.)	0.26	[−0.22, 0.22]	[−0.43, 0.44]	[0.01, 0.53]	[−0.24, 0.83]
$c_{H\tilde{W}}$ (lin. only)	0.21	[−0.21, 0.22]	[−0.41, 0.44]	[−0.02, 0.45]	[−0.23, 0.70]
$c_{H\tilde{B}}$ (lin.+quad.)	7.2	[−3.8, 3.6]	[−8.0, 7.2]	[2.0, 12.7]	[−3.8, 19.0]
$c_{H\tilde{B}}$ (lin. only)	4.0	[−3.6, 3.7]	[−7.0, 7.5]	[−0.3, 7.7]	[−4.0, 11.9]
$c_{H\tilde{W}B}$ (lin.+quad.)	4.0	[−2.1, 2.0]	[−4.4, 3.9]	[1.1, 7.0]	[−2.1, 10.4]
$c_{H\tilde{W}B}$ (lin. only)	2.0	[−2.0, 2.0]	[−3.8, 4.1]	[−0.2, 4.2]	[−2.2, 6.5]

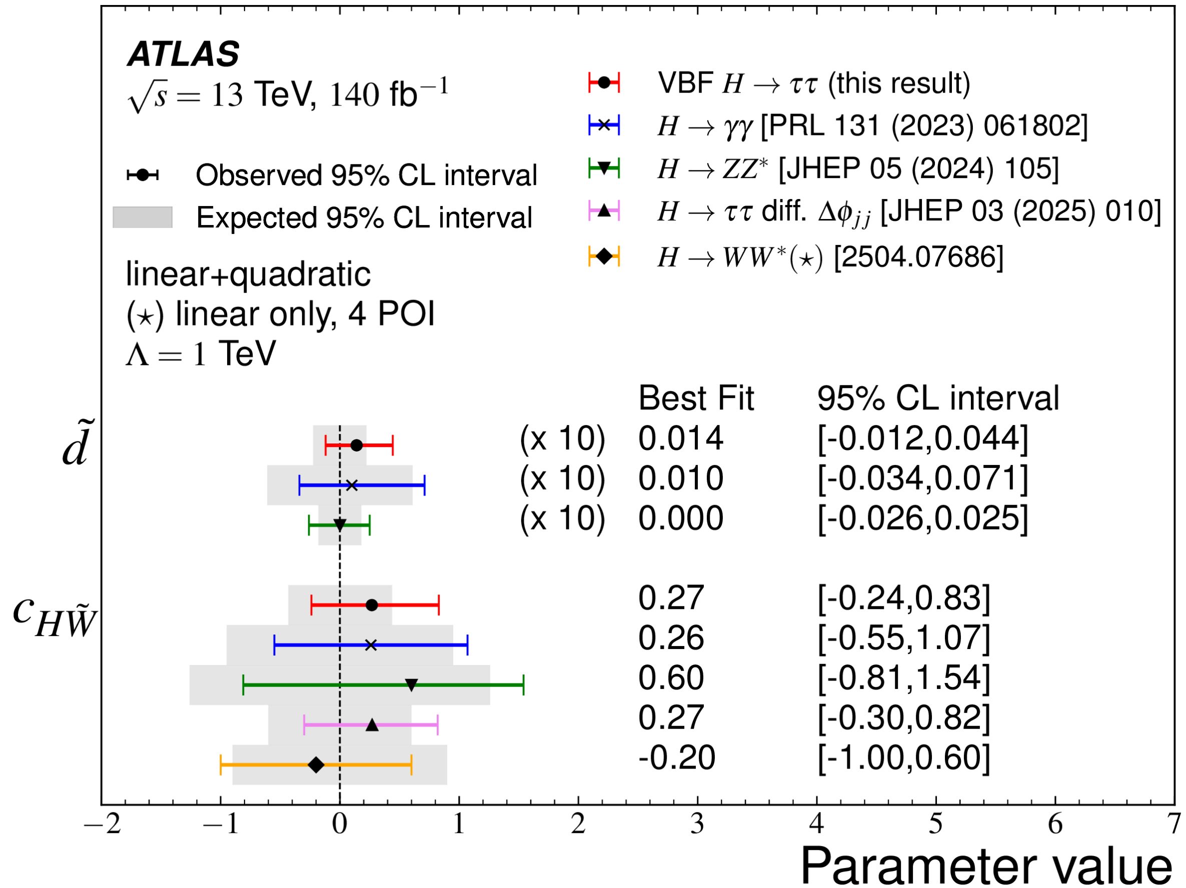
Uncertainty breakdown on $\tilde{d}$ estimation

- Impact of the main systematic uncertainties in the final $\tilde{d}$ 68% C.L. interval
- Main limitations on the sensitivity comes from the statistical uncertainties in the actual observed data
- Among the systematic uncertainties, large impact coming from Jet/E_T^{miss} (expected because of jet selection to target VBF Higgs boson production mode). High impact also from Signal theory uncertainties, driven by Parton Shower uncertainty

Systematic source	Uncertainty [%]
Jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	± 20
Signal theory	± 15
Background theory	± 11
Normalisation factors	$^{+6.0}_{-5.5}$
Misidentified τ-leptons	± 4.8
τ-leptons reconstruction	± 4.0
Sample size	± 3.0
Leptons reconstruction	± 2.4
Luminosity	± 0.4
Flavour tagging	± 0.3
Embedding	± 0.2
Total systematic uncertainty	± 30
Total statistical uncertainty	± 95

Comparison with other analyses

- Results in both HISZ and Warsaw basis interpretations are compared with similar measurements for other Higgs boson decays
- In both interpretations, this analysis provides among the most stringent limits on the CP odd Higgs boson hypothesis
- Results coming from orthogonal measurements and harmonised between them will lead to future combination results



Summary

- The measurement of a CP-odd contribution in the Higgs boson couplings would be a sign of physics beyond the Standard Model

- Search for possible CP violating effects in HVV vertex for VBF production mode and $H \to \tau\tau$ final state is promising due to relatively large branching ratio and signal over background

- Use Multivariate Analysis to select high purity regions and fit the Optimal Observable distribution to look for possible CP-odd Higgs component

- Results interpreted both in HISZ and Warsaw basis, imposing among the stringent limits on CP-odd operators:
  - $\tilde{d}$ constrained to a 95% C.L. interval of [-0.012,+0.044], while the Warsaw basis parameter $c_{H\tilde{W}}$ is constrained to [-0.24, +0.83] for new physics scale $\Lambda = 1$ TeV
  - Main limitations on the sensitivity comes from the statistical uncertainties in the actual observed data

Thanks a lot for your attention