

Legacy Run 2 measurements of the Higgs boson cross-section in $\tau\tau$ and other final states with ATLAS

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IFIC Scientific Days: Origin of mass. L1 Higgs Force
December 2nd, 2024

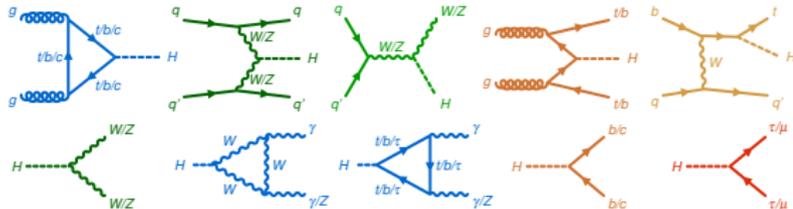
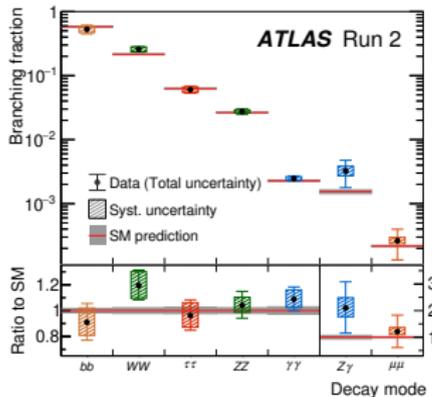
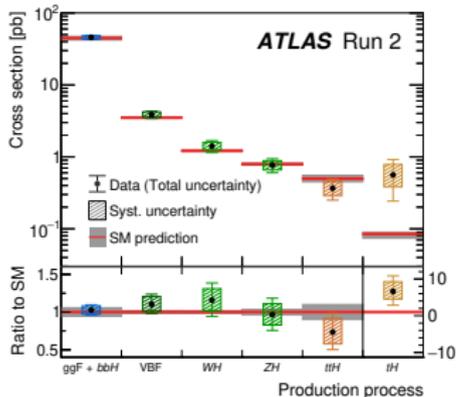


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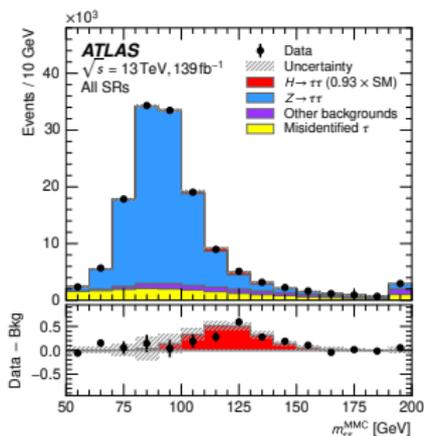
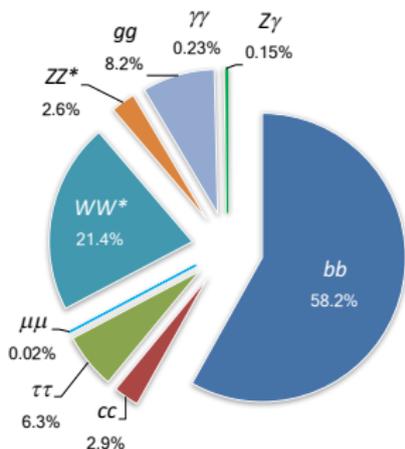
Introduction



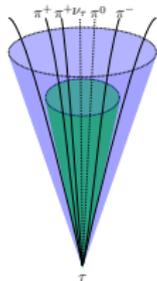
- All main Higgs boson production and decay mechanisms have been observed experimentally
- ... and in a remarkable agreement with the Standard Model (SM) predictions
- ATLAS Run 2 results summarized in [Nature 607 52 \(2022\)](#) (10th anniversary of the discovery)
- Work has continued to extract the most out of the Run 2 dataset
- ... and with the first Higgs boson results at $\sqrt{s} = 13.6$ TeV in Run 3

Introduction: Why $H \rightarrow \tau\tau$?

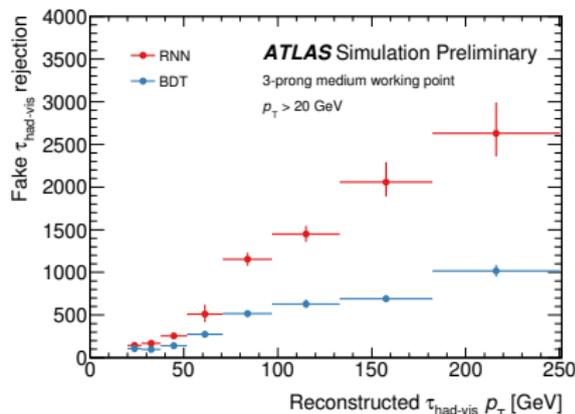
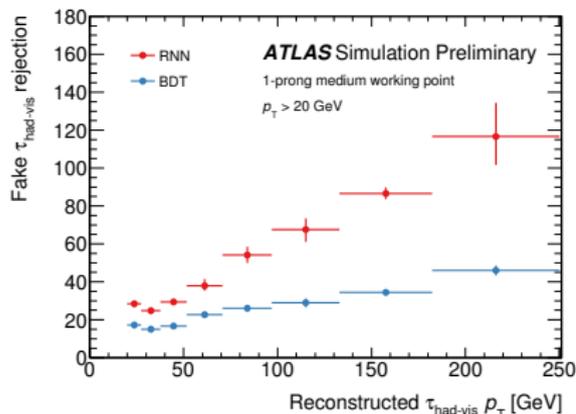
- Run 1: $H \rightarrow \tau\tau$ reached 5σ significance in the ATLAS+CMS combination \rightarrow First observation of the Higgs boson Yukawa couplings to fermions
- $H \rightarrow \gamma\gamma, H \rightarrow 4\ell$: best mass resolution (1-2%) but low branching ratio (BR)
- $H \rightarrow WW^* \rightarrow e\nu\mu\nu$: clean, but with worse mass resolution and BR below 1%
- $H \rightarrow \tau\tau$: mass resolution of $\sim 10\%$, BR of $\sim 6\%$
 - Main difficulty: large irreducible $Z \rightarrow \tau\tau$ background
 - Need to handle different τ -lepton decays (τ_{had} or τ_{ℓ})



Performance interlude: τ_{had}

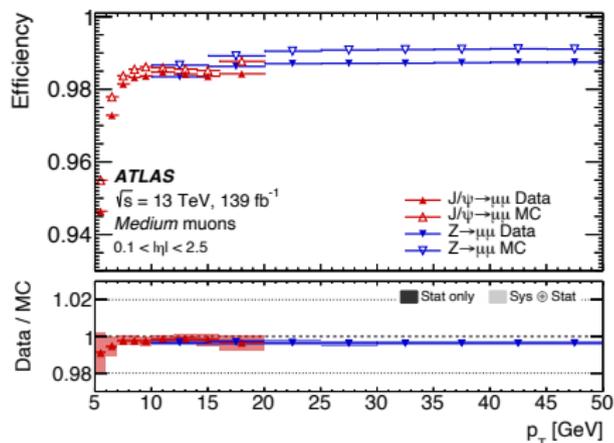
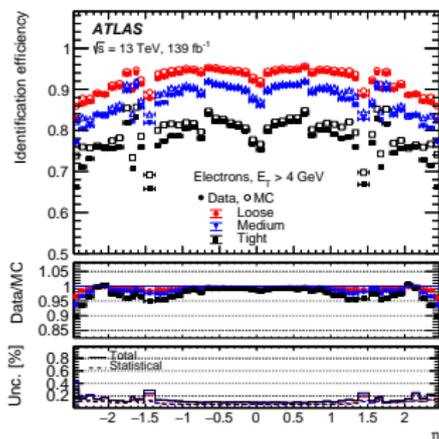


- Hadronically decaying τ -leptons produce 1(72%) or 3(22%) charged pions + neutrinos + often neutral pions
- Signature: narrow jet with one or three tracks in the detector
- Identification of τ_{had} greatly improved in Run 2 with a **new RNN-based ID**: rejection against fakes increased by $>75\%$ (ATL-PHYS-PUB-2019-033)



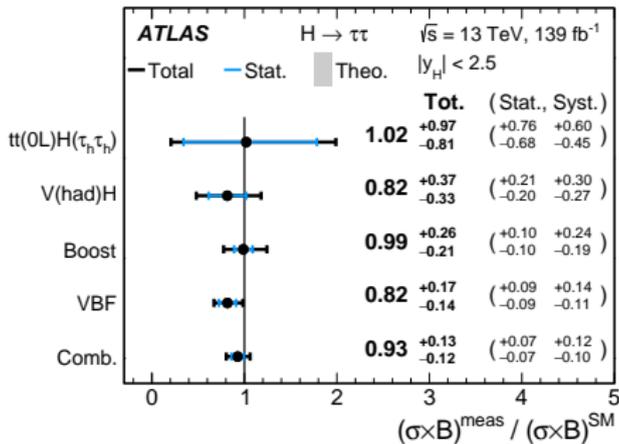
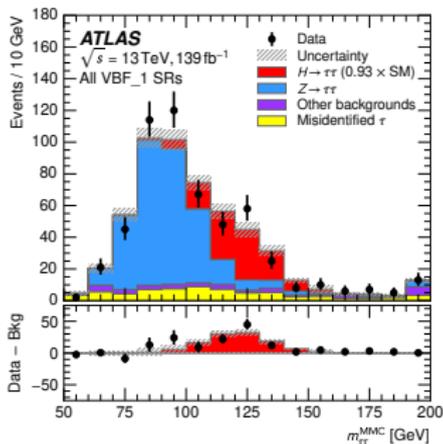
Performance interlude: Electrons and Muons

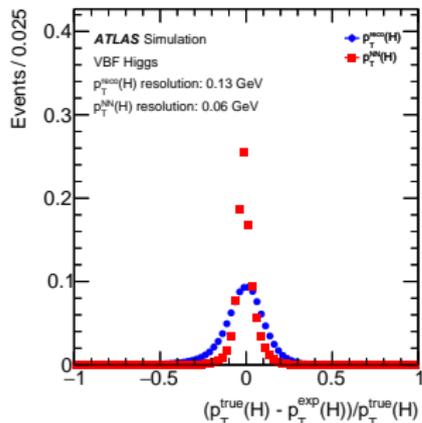
- Decays of τ -leptons to e/μ with a BR of $\sim 35\%$
- Impressive improvements in both electrons and muon performance during Run 2
- Efficiency measured in data using well-known $Z \rightarrow \ell\ell$ and $J/\psi \rightarrow \ell\ell$ resonances
- **Electrons:** better pile-up subtraction for isolation, identification efficiencies uncertainties reduced by up to 50%
- **Muons:** identification and isolation measured with accuracy of $O(0.1\%)$ in the bulk of the phase space, up to the $O(1\%)$ in complex kinematic configurations



Run 2 $H \rightarrow \tau\tau$ measurements

- ATLAS full Run 2 $H \rightarrow \tau\tau$ results in JHEP 08 (2022) 175, Physics Briefing
- Main novelties:
 - Adding $V(qq)H$ and $t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}}) \rightarrow$ Measured all main production mechanisms
 - New MVAs to increase the sensitivity to VBF \rightarrow Well above 5σ VBF observation
 - Control regions based on object-level embedding (replace e/μ by τ -lepton) \Rightarrow Correct $Z(\tau\tau)$ background normalization
 - Measured overall $H \rightarrow \tau\tau$ cross-section with a precision of 12% + first results in the simplified template cross-section (STXS) framework



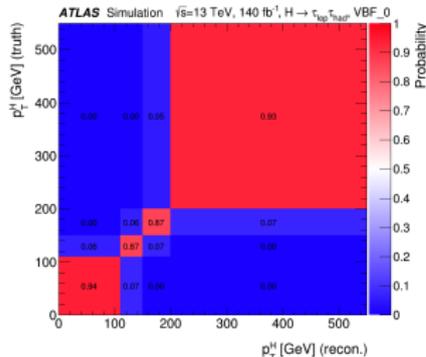


- Larger $H \rightarrow \tau\tau$ branching ratio than the high-resolution channels \rightarrow Better sensitivity to high $p_T(H)$ phase space
- Neural Network (NN) for $p_T(H)$ reconstruction:

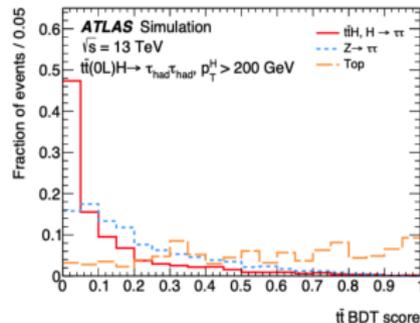
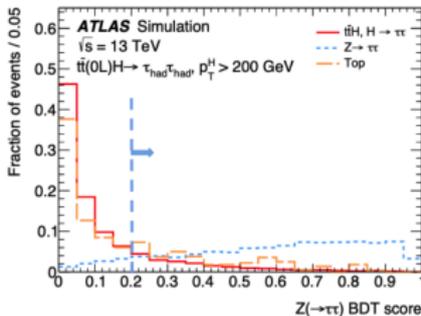
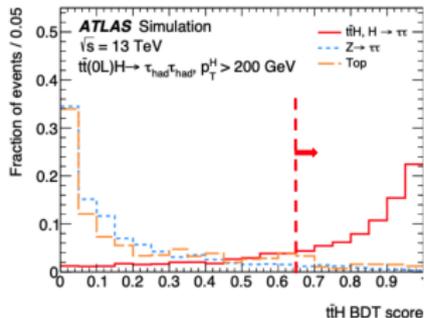
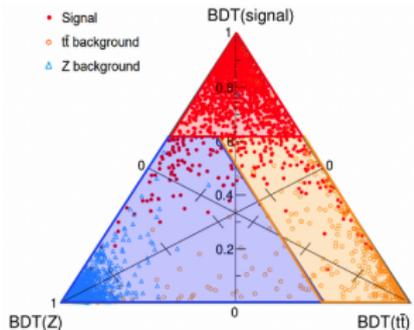
- Input variables for NN:

- $\Delta R(\tau\tau)$, $\Delta\phi(\tau\tau)$: angular distances between the two τ -leptons
- E_T^{miss} : missing transverse energy
- $p_T(\tau\tau)$: built from the four-momenta of the two τ -leptons and E_T^{miss}
- $m_{\tau\tau}^{\text{coll}}$: di- τ invariant mass in the collinear approximation

- Improves resolution, reduces event migration between STXS bins



- $t\bar{t}H$ categories in first Run-2 analysis:
 - Event selection: 5-6 jets + 1-2 b -tagged jets
 - Binomial BDTs: $t\bar{t}H$ vs. $Z(\tau\tau)$ and $t\bar{t}H$ vs. $t\bar{t}$
- Legacy analysis: Multiclass BDT classifiers trained using $t\bar{t}H$, $Z(\tau\tau)$ and $t\bar{t} \Rightarrow 25\%$ sensitivity improvement
- SRs and CRs defined with the 3 BDT scores

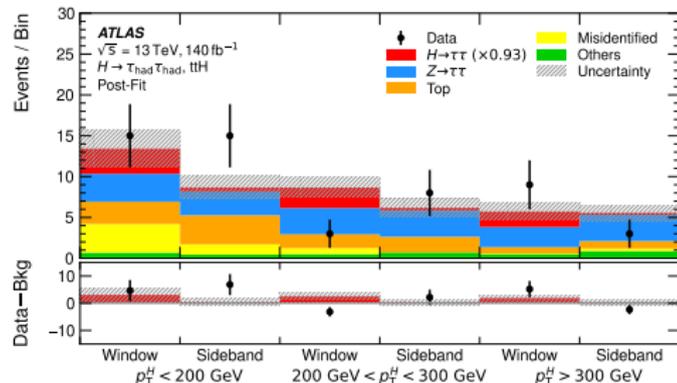
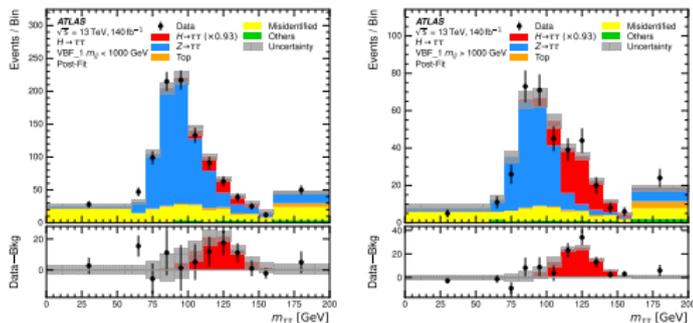


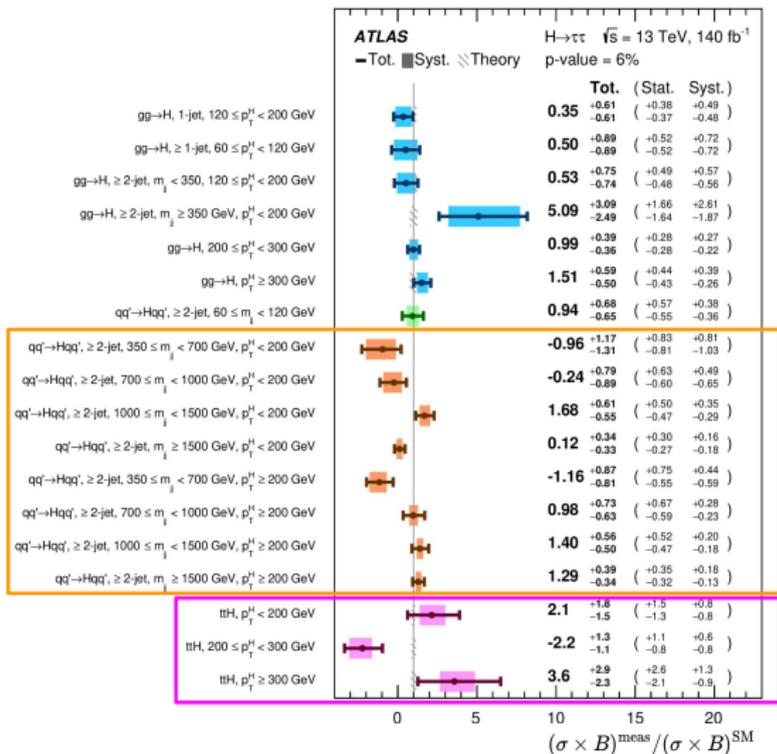
• VBF:

- Same BDT from previous round (VBF vs. $ggF+Z(\tau\tau)$)
- Define VBF_1 (signal enriched) and VBF_0 SRs
- Selection optimized to enhance VBF sensitivity in each STXS bin

• ttH:

- 6 SRs defined, based on the multiclass scores and the $m_{\tau\tau}$ (window/sideband regions)
- All other categories unchanged





- Fit combining all regions and channels ($\mathcal{T}_{\ell\ell\ell}, \mathcal{T}_{\text{had}\mathcal{T}\ell}, \mathcal{T}_{\text{had}\mathcal{T}\text{had}}$)
- No significant deviations observed from SM predictions
- **STXS VBF (8 bins):**
 - First measurement at $m_{jj} > 1500 \text{ GeV}$ and $p_T(H) > 200 \text{ GeV}$
 - Most precise measurement for $m_{jj} > 1500 \text{ GeV}$ and $p_T(H) < 200 \text{ GeV}$
- **STXS $t\bar{t}H$ (3 bins):** statistically limited \rightarrow Also derived upper limits

- Besides updated STXS results, Legacy analysis also features unfolded differential cross-sections in a VBF-enhanced phase space

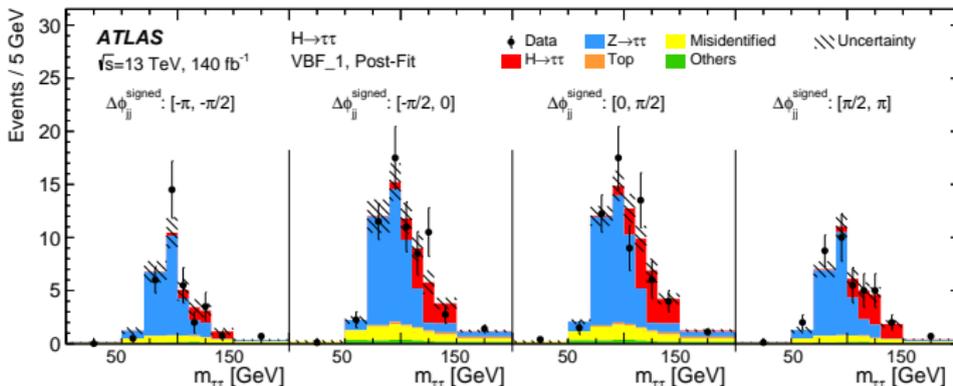
- Basic fiducial particle-level event selection:

$$m_{jj} > 600 \text{ GeV}, |\Delta\eta_{jj}| > 3.4, \eta(j_0) \times \eta(j_1) < 0$$

- Measured in bins of 4 variables sensitive to VBF kinematics:

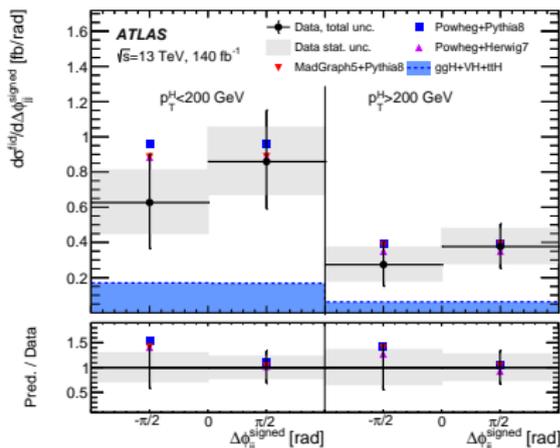
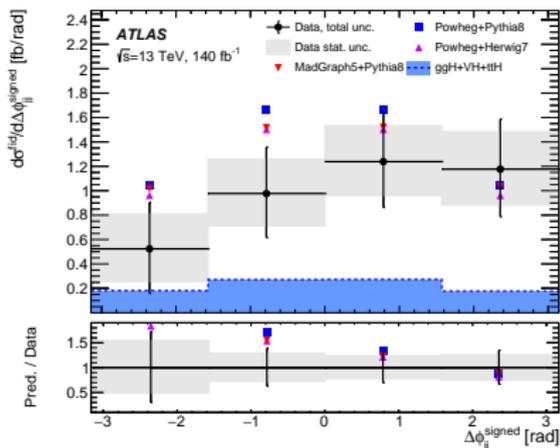
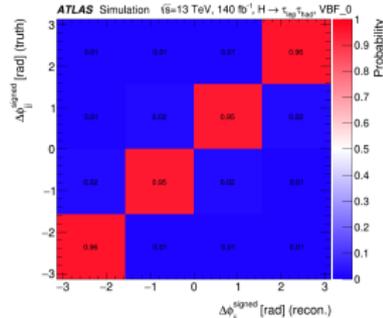
$$p_T(j_0), p_T(H), \Delta\phi_{jj}^{\text{signed}} \text{ and } \Delta\phi_{jj}^{\text{signed}} \text{ vs. } p_T(H)$$

- Strategy: define VBF_0 and VBF_1 regions using the same BDT as in the STXS measurement, and fit $m_{\tau\tau}$ distributions



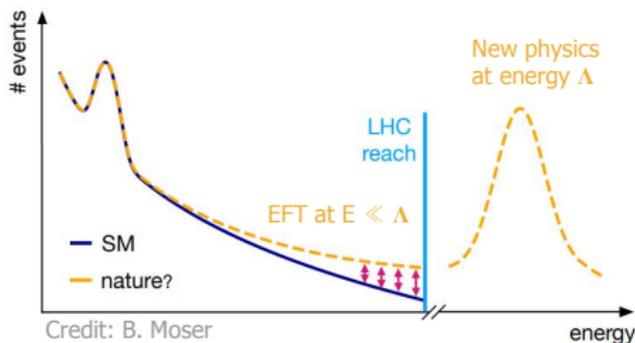
Legacy Run-2 $H \rightarrow \tau\tau$: Differential results arXiv:2407.16320

- Using a profile-likelihood unfolding
- All distributions in good agreement with the SM
- Uncertainties in the measurements of 30%–50%, dominated by the statistical uncertainty of the data
- Measured variables are sensitive to BSM effects \rightarrow SMEFT interpretation



SM Effective Field Theory (EFT)

- Estimate potential impact of high-mass BSM contributions in our observables



- Model-independent way to parametrize the effect of New Physics at a high energy $\Lambda (\gg \text{vev})$ at lower experimentally accessible energy scales ($\Lambda \gg E$)

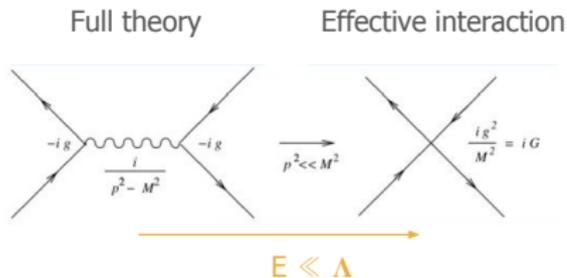
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d=6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

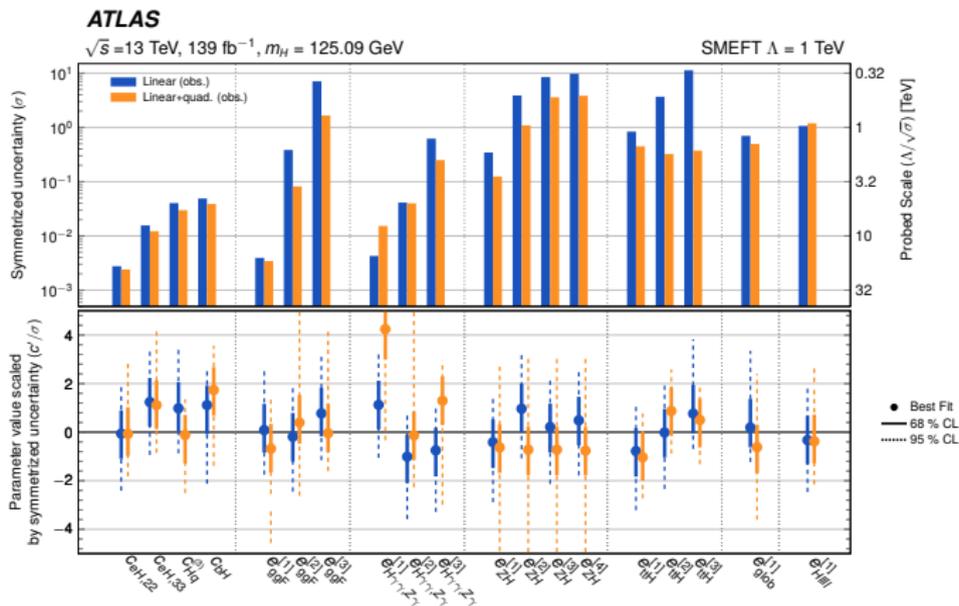
Λ - Assumed energy scale (1 TeV)

c_i - Wilson coefficients

\mathcal{O}_i - SMEFT Operators

- Linear terms: interference between dim-6 operators and SM
- Quadratic terms: Pure BSM, product of two dim-6 amplitudes





- Comparison with results for SMEFT **Linear+quadratic model** (Λ^{-4} terms included)
- Constraints on the coefficients generally stronger compared to the **Linear model**
- Compatibility p -value with the SM: 98.2%

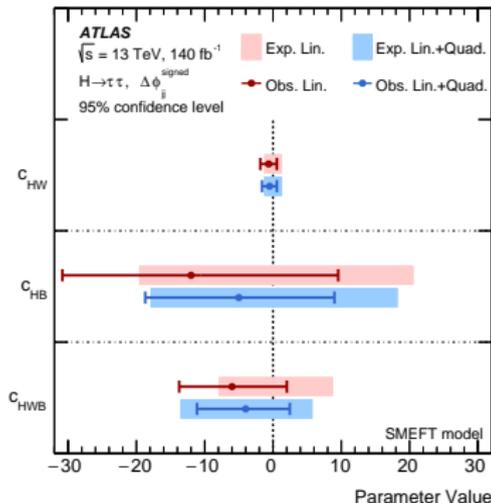
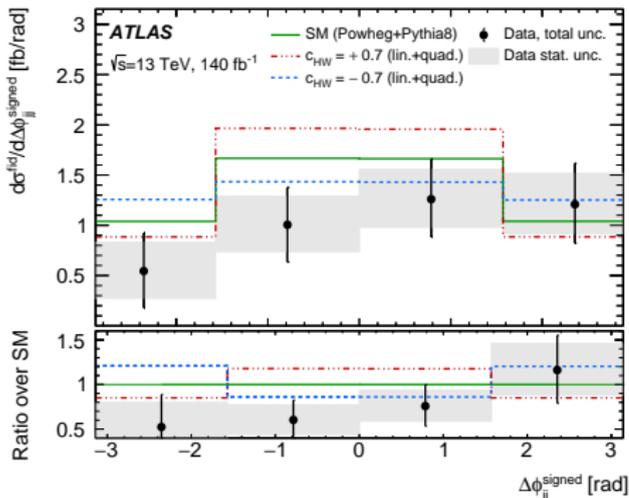
$H \rightarrow \tau\tau$ Differential: EFT interpretation

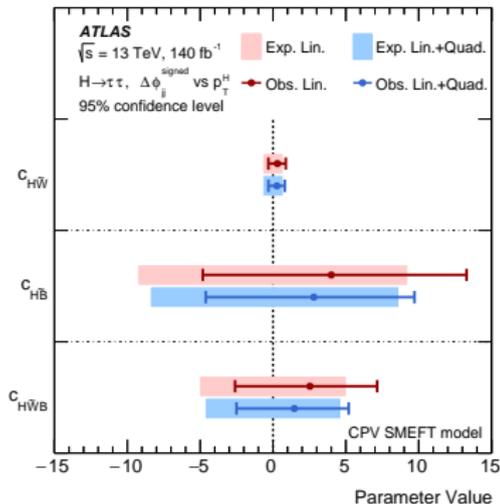
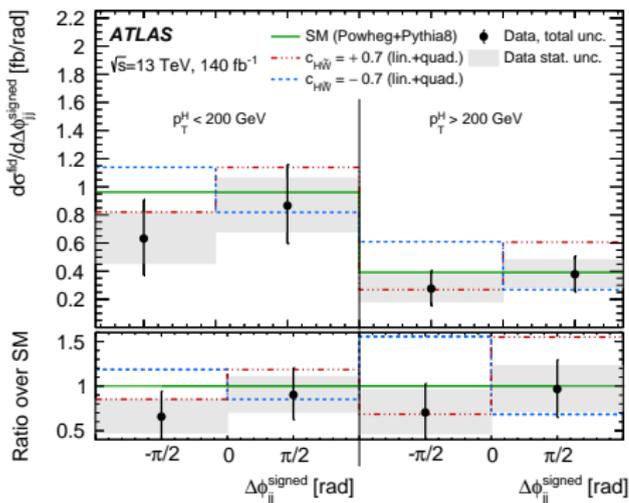
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- $H \rightarrow \tau\tau$ analysis proved good sensitivity for VBF production

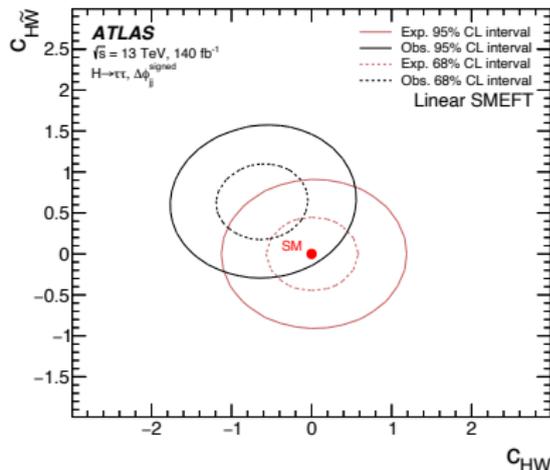
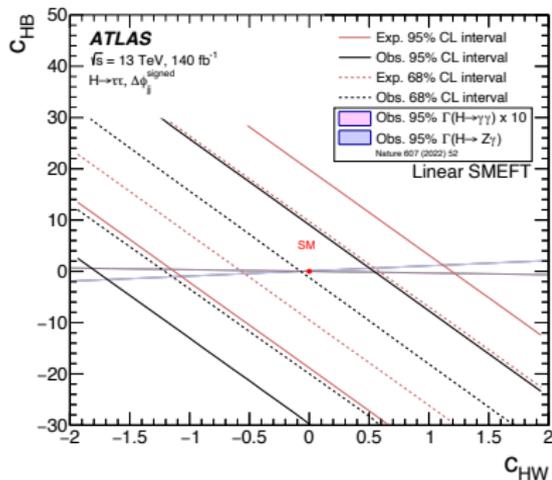
→ Set constraints on the Wilson coefficients affecting the VBF production vertex (c_{HW} , c_{HB} , c_{HWB}) with the $\Delta\phi_{jj}^{\text{signed}}$ differential measurement

c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$	





- Also constraining CP-odd Wilson coefficients $c_{H\tilde{W}}, c_{H\tilde{B}}, c_{H\tilde{W}\tilde{B}}$ with the $\Delta\phi_{jj}^{\text{signed}}$ vs. $p_T(H)$ differential measurement
- Strongest limits to date on the CP-odd Wilson coefficient $c_{H\tilde{W}}$ at $(-0.31, +0.88)$,



- Also derived constraints over multiple Wilson coefficients
- C_{HW} VS. C_{HB} : very similar effects from both coefficients \rightarrow ‘Flat direction’ where the effects of the two Wilson coefficients cancel each other out
- Complementarity of this measurement with other Higgs boson studies, such as from the $H \rightarrow \gamma\gamma, Z\gamma$ decay width
- C_{HW} VS. $C_{H\tilde{W}}$: the two operators induce different effects \rightarrow No flat directions

In lieu of Summary...

- $H \rightarrow \tau\tau$: powerful channel to explore Higgs boson physics, with unique sensitivity to VBF production and high $p_T(H)$ phase space
- ATLAS $H \rightarrow \tau\tau$ Run-2 analyses led by the IFIC group:
 - XP: analysis contact and paper editor
 - Editors of two Physics Briefings
 - PhD theses of Antonio J. Gómez (just submitted!) and Enrique Valiente (due next year)
 - Talk at LHCP 2023: “Higgs boson couplings at ATLAS” by Luca Fiorini
 - Talk at Higgs 2023: “Property measurements of the Higgs boson production in association with top quark at the ATLAS detector” by Ximo Poveda
 - Talk at LHCP 2024: “Higgs boson coupling measurements in ATLAS” by Antonio J. Gómez
 - Topical talk at Higgs Hunting 2024: “Improvements in the measurement of VBF and ttH production with $H \rightarrow \tau\tau$ in ATLAS” by Enrique Valiente
 - Talk at Higgs 2024: “Measurements of Higgs boson coupling properties to leptons with the ATLAS detector” by Enrique Valiente
- **Looking forward to adding Run 3 data to the results!**

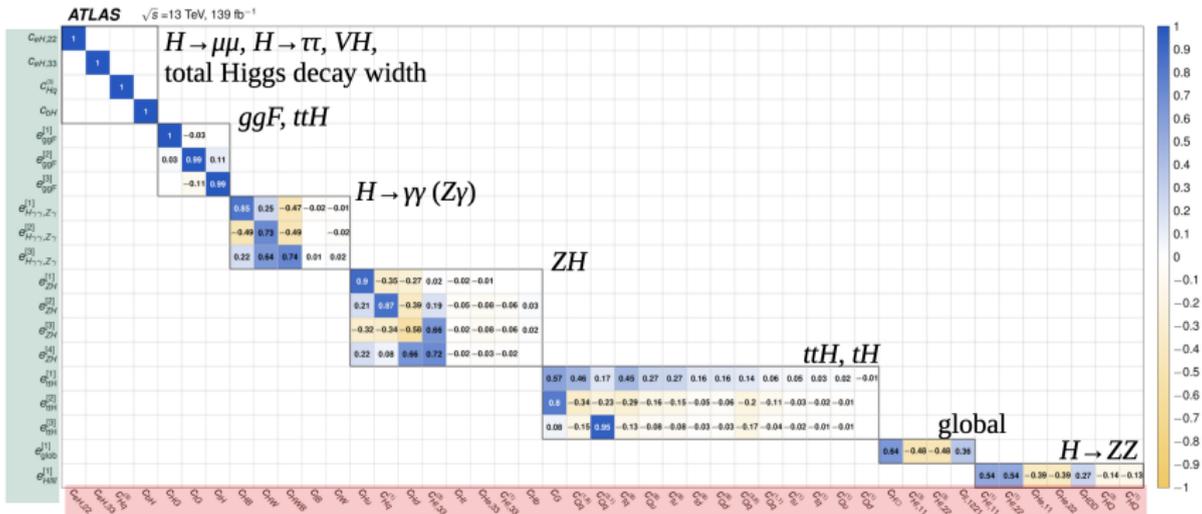
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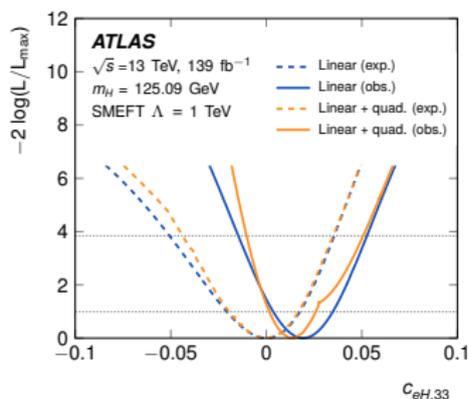
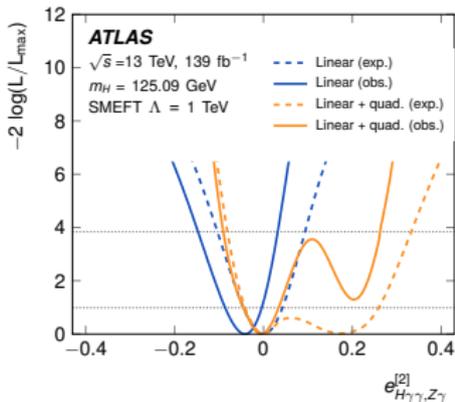
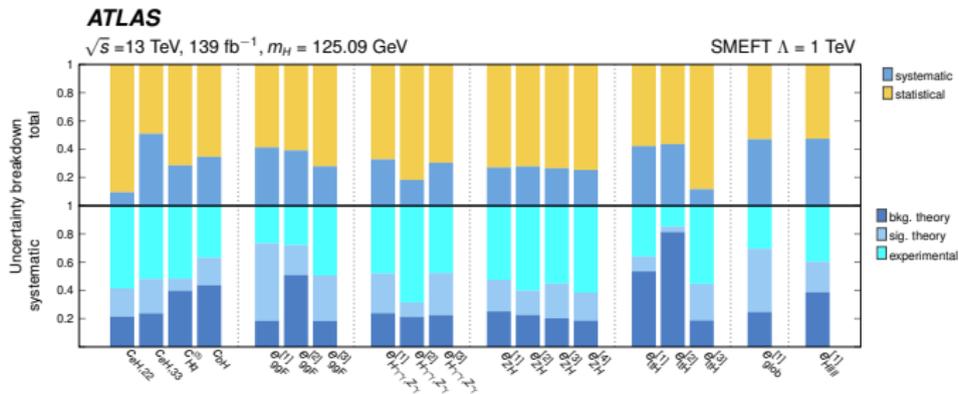
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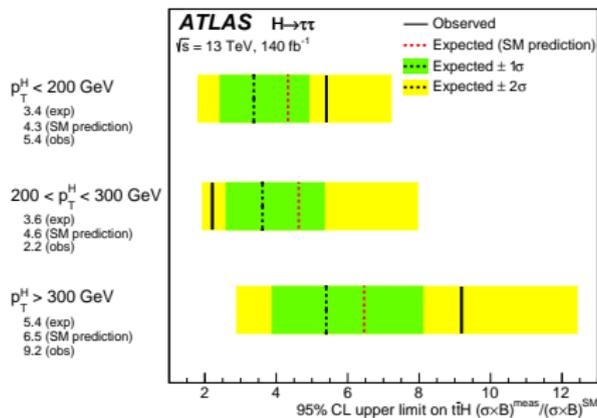
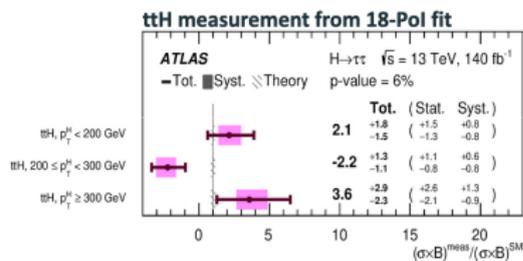
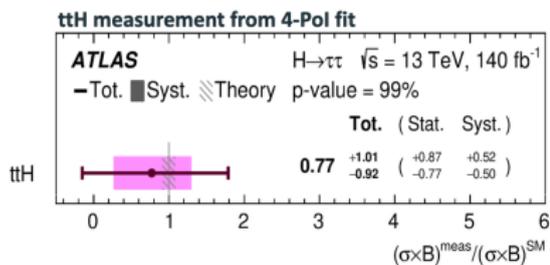


Backup Slides

- Definition of the fit basis coefficients in terms of the Warsaw basis Wilson coefficients.
- Achieves both fit stability and fit-parameter interpretability.







- ▶ New CMS measurement with differential $t\bar{t}H$ measurement
- ▶ Focus on two most sensitive channels 2LSS+0 τ and 3L+0 τ

