Properties of the Higgs boson measured by ATLAS collaboration

ATLAS EXPERIMENT

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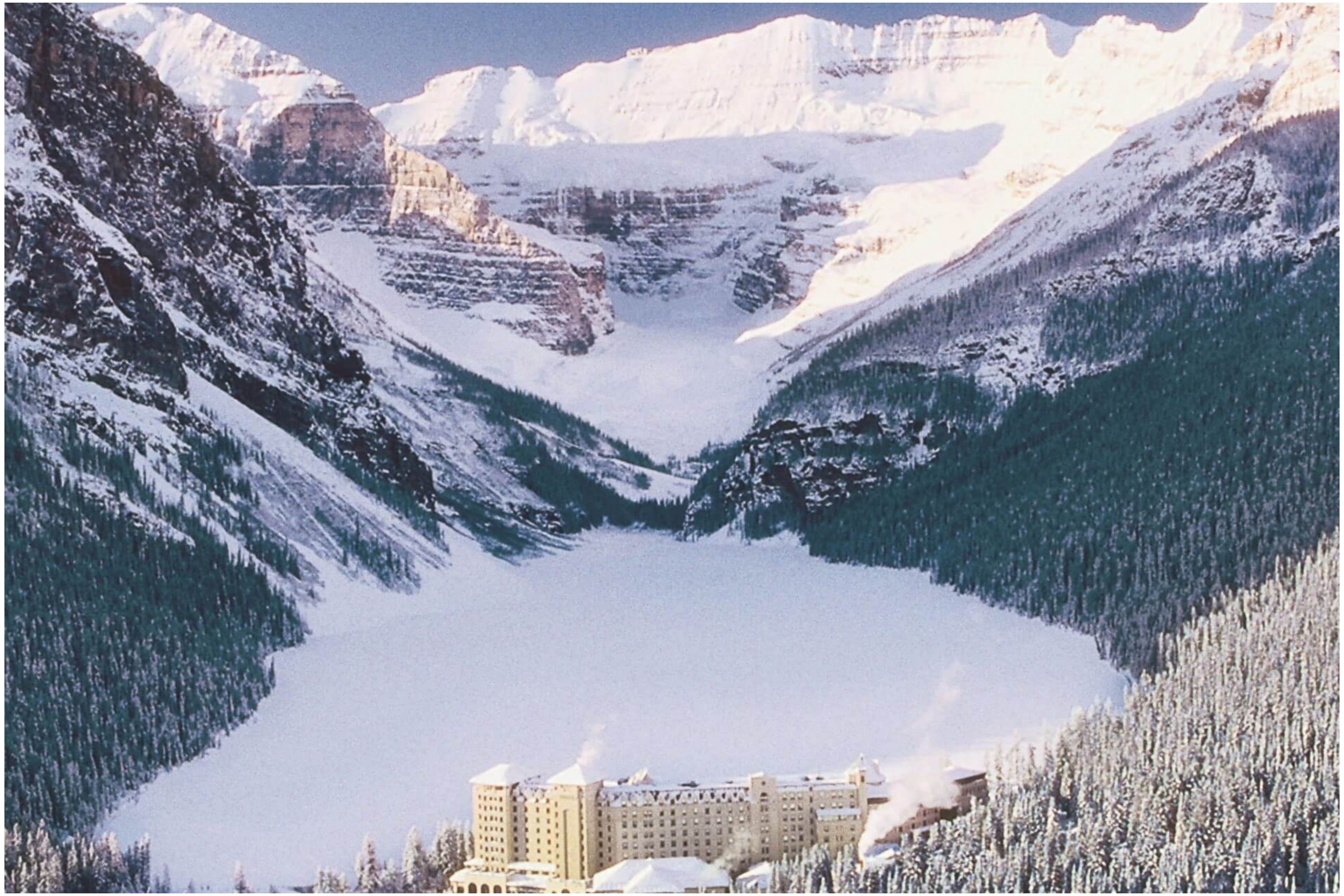
LLWI: 18 Feb 2024



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Higgs properties

- Measurements of Higgs boson properties are one of our most promising windows into new physics
  - **Higgs mass:** free parameter to be measured, and dependent on Higgs potential parameters
    - Covered analyses: $H \to ZZ^* \to 4\ell$ (link), $H \to \gamma\gamma$ (link) and their combination (link)
  - **Higgs width:** predicted SM total width is 4.1 MeV, accessible with off-shell production
    - Covered analyses: $H^* \to ZZ$ off-shell production (link)
  - **Higgs CP:** Sakharov conditions for a matter-dominated Universe require CP violation, and known SM cannot explain this asymmetry → CP violation in the Higgs sector is an enticing possibility
    - Covered analyses: $H \to WW^* + 2\text{jets}$ (link), $H \to \tau\tau$ (link), and $H \to bb$ (link), VBF $H \to \gamma\gamma$ (link) and $H \to ZZ^* \to 4\ell$ (link)
  - Not mentioned but in backup: $t\bar{t}H/tH$ with $H \to \gamma\gamma$ (link)

Higgs Mass: $H \rightarrow ZZ^* \rightarrow 4\ell$

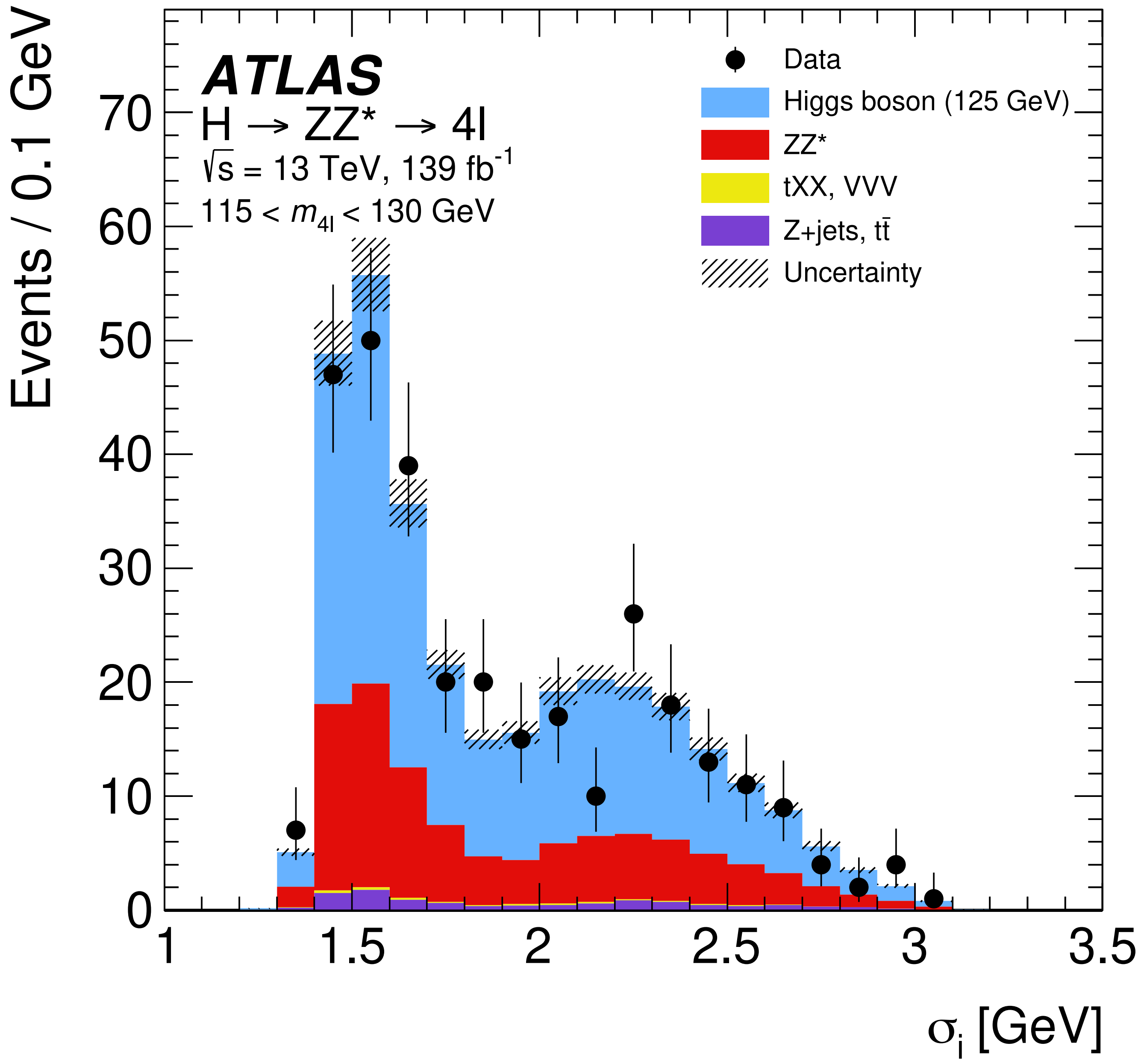
ATLAS EXPERIMENT

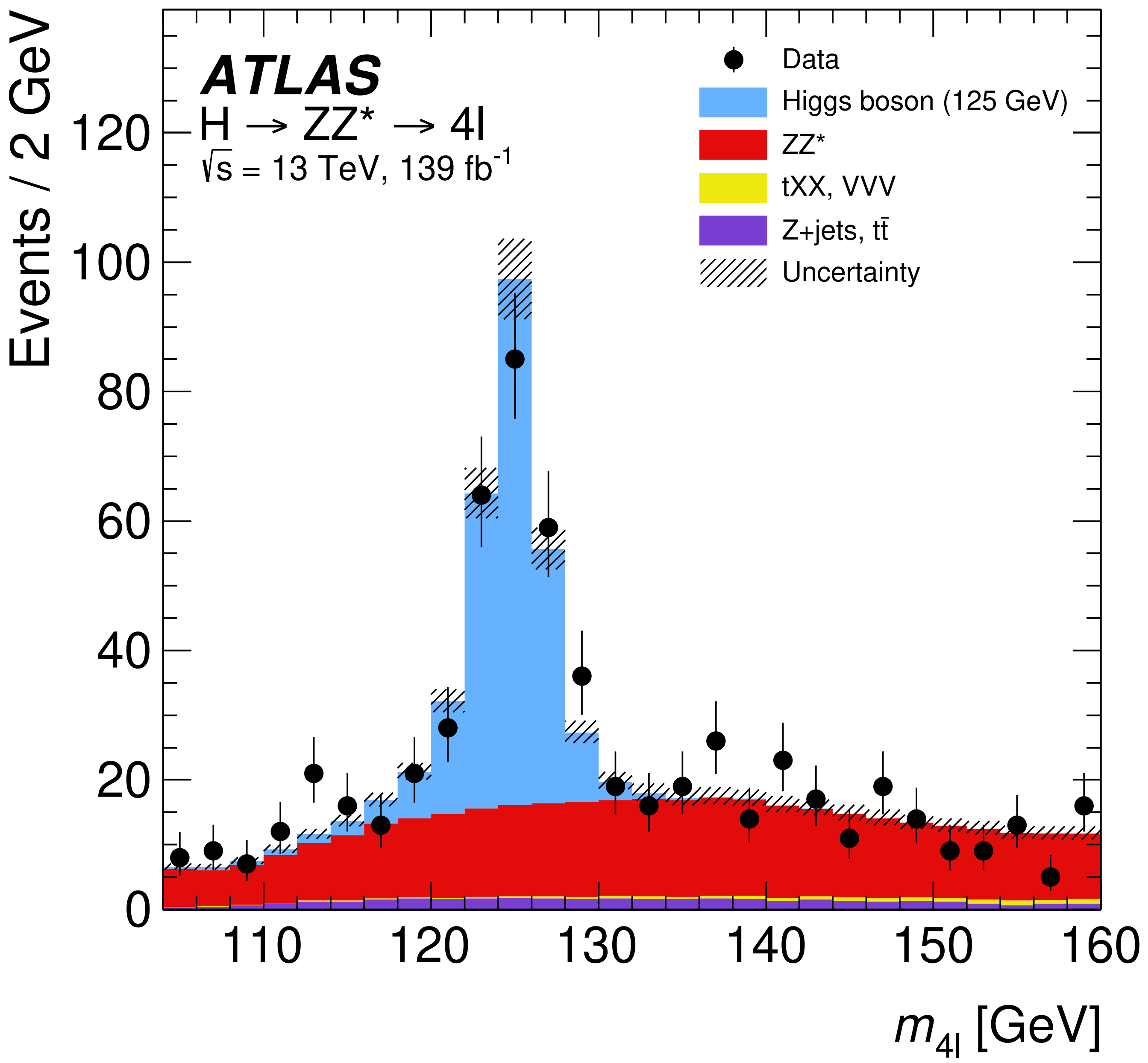
- Improved muon momentum scale calibrations (link)
- Sig vs. Bkg DNN discrimination: p_T & η of 4ℓ and $\ln(|M_{HZZ^*}|^2/|M_{ZZ^*}|^2)$
- Per-event resolution σ_i trained quantile-regression neural network output
- Uses 2D likelihood to capture dependencies from $m_{4\ell}$, DNN and σ_i under categorization of 4μ, $4e$, $2\mu2e$, $2e2\mu$ channels

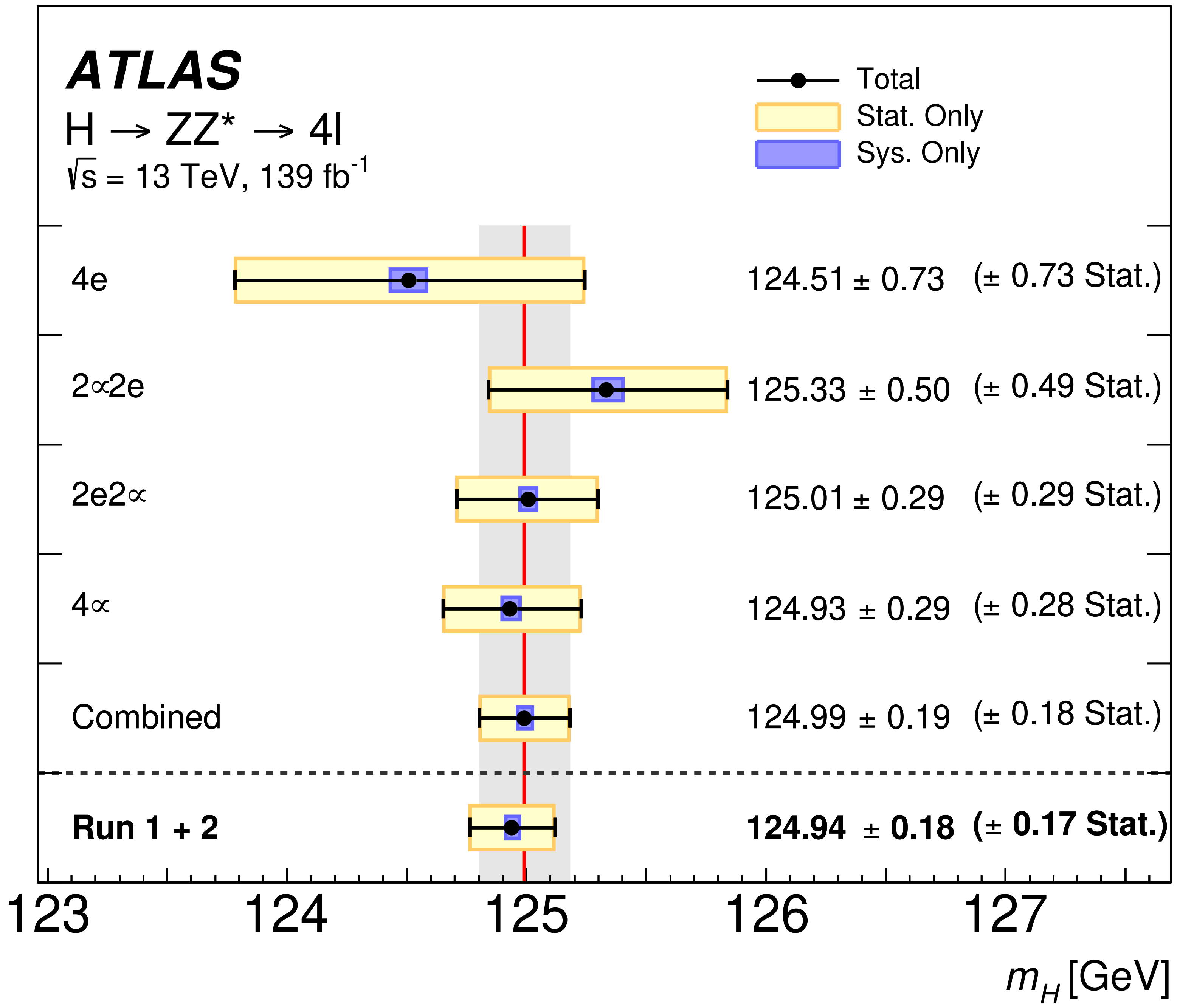
Largest unc. on m_H

Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	±28
Electron energy scale	±19
Signal-process theory	±14

Run 2: $m_H = 124.99 \pm 0.18\ \text{(stat.)} \pm 0.04\ \text{(syst.)}\ \text{GeV}$







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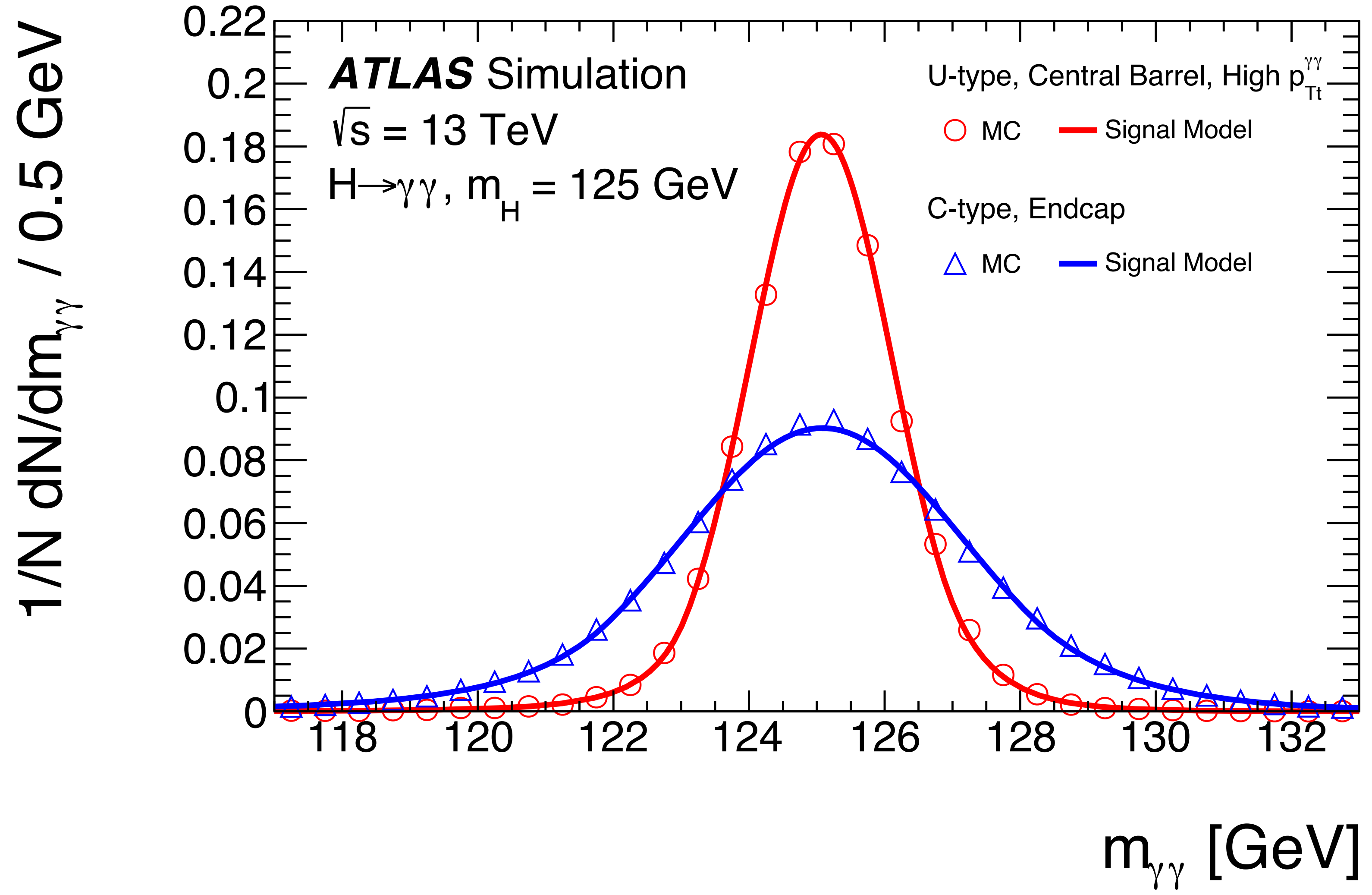
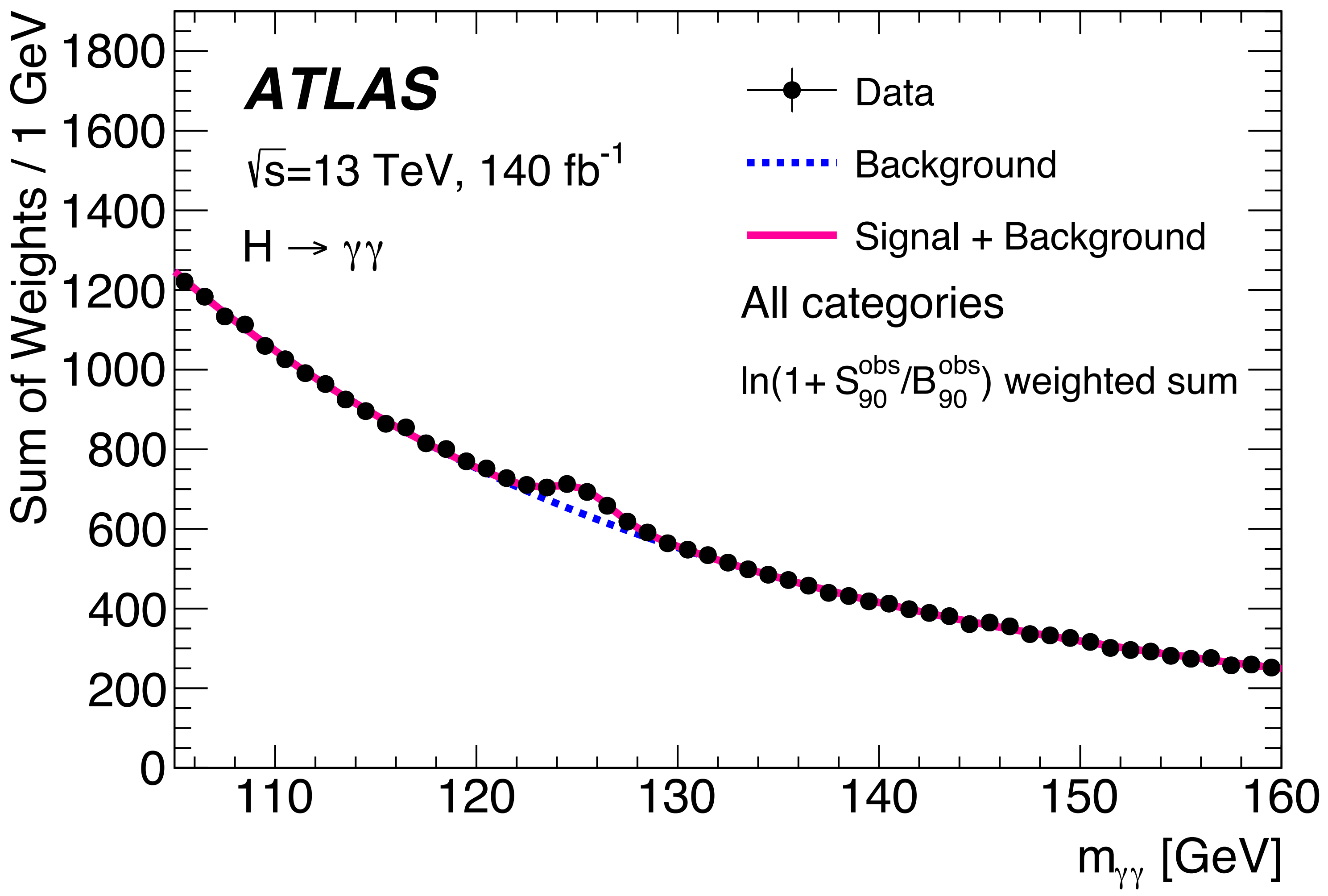
Higgs Mass: $H \rightarrow \gamma\gamma$

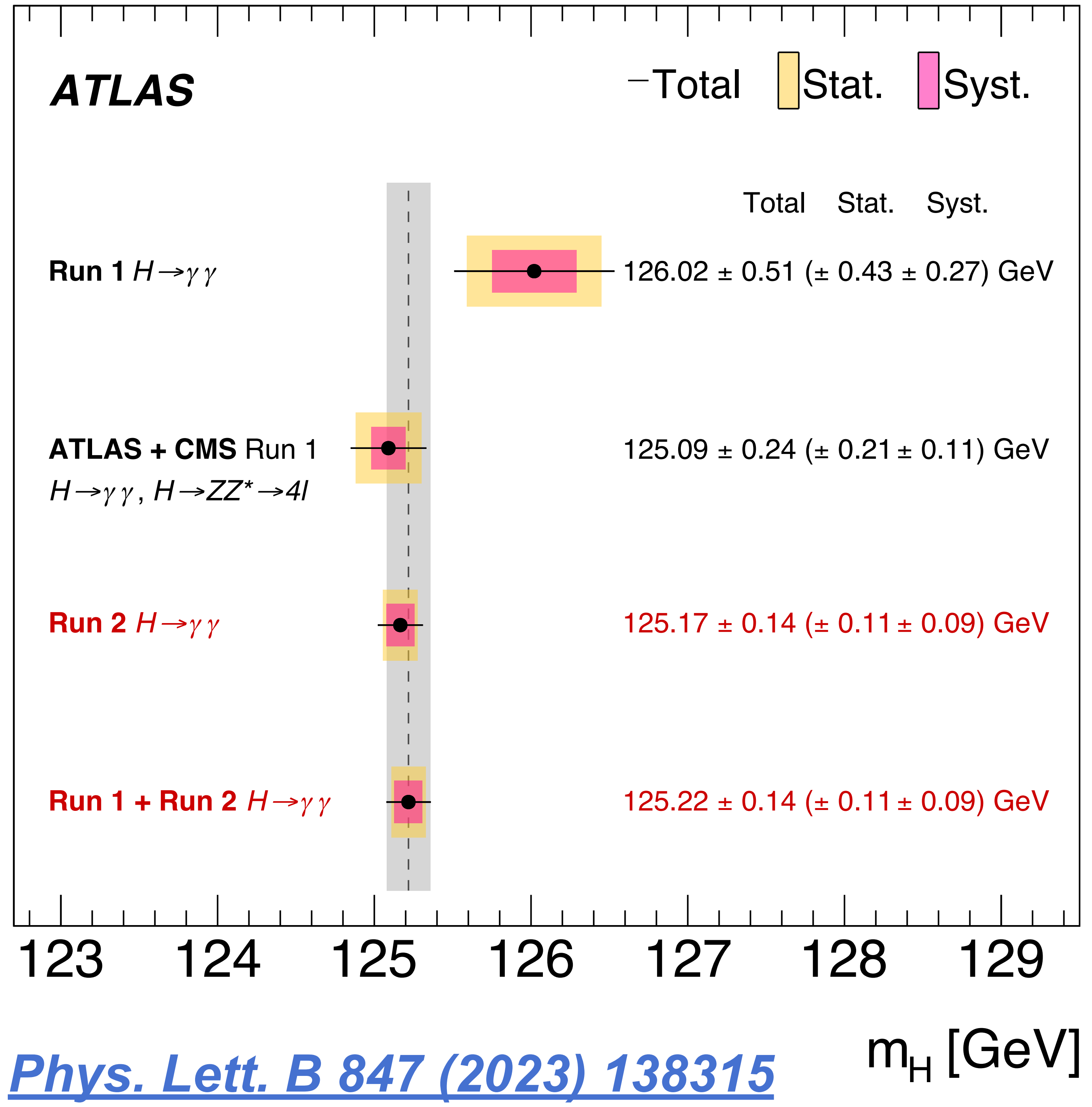
- Event selection based on cross-section measurement (link)
- New photon reconstruction with improved energy resolution and calibration
- Signal modeling described by Double-sided Crystal-Ball with dependency on m_H absorbed in mean and width
- Background modeling with fit model (Exponential, power-law or Exponentiated 2nd order polynomial) chosen empirically for each category based on goodness-of-fit
- Floated normalization in 14 categories (defined by $\gamma_{\text{conv.}}$, pseudorapidity of photon pairs, and magnitude of pair transverse momentum) with dependency on m_H parametrized

Largest unc. on m_H

Source	Impact [MeV]
Photon energy scale	83
$Z \to e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^{\pm} \to \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5
Signal model	1
Total	90







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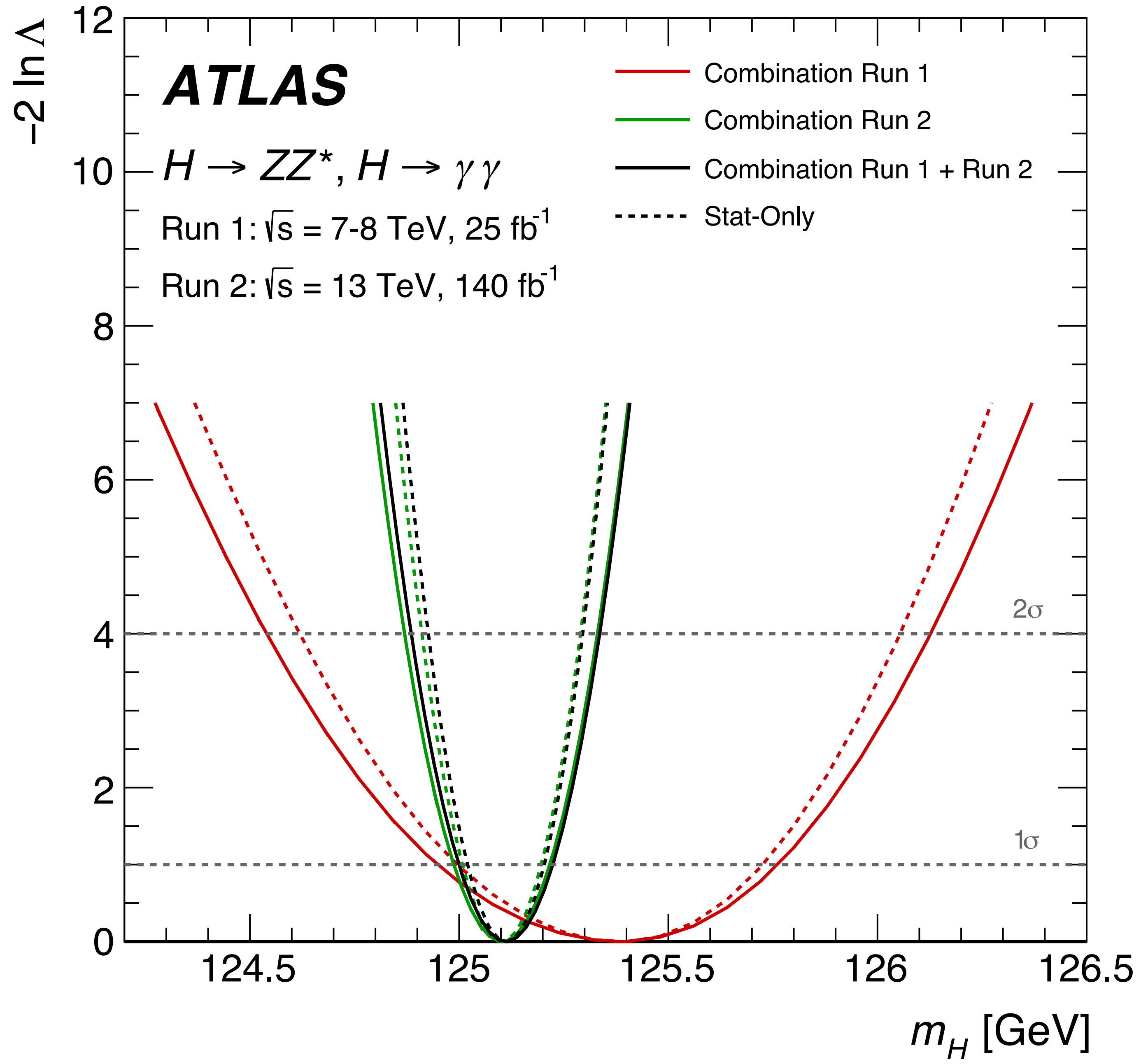
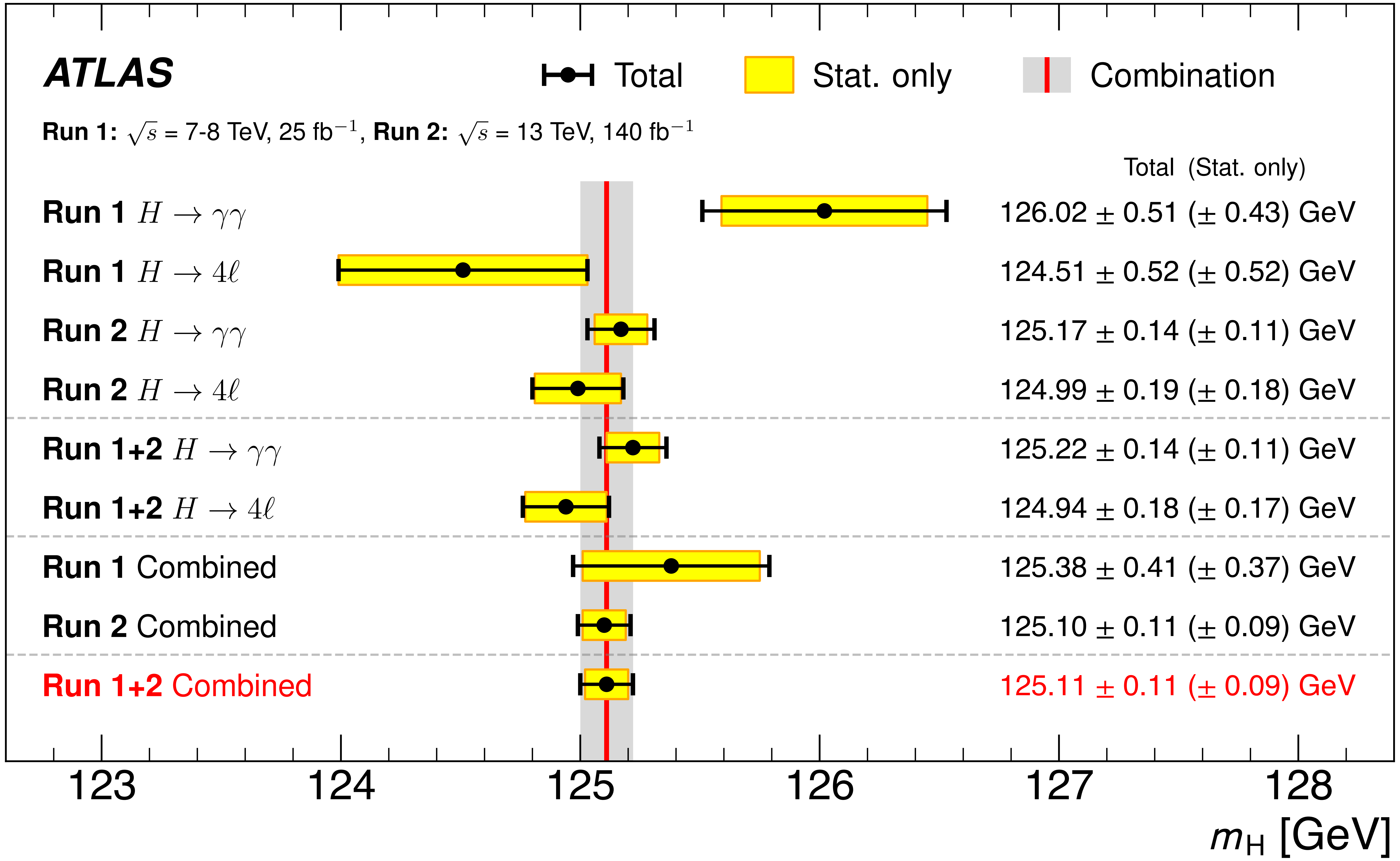
Run1 & 2 combination of Higgs Mass

Source	Systematic uncertainty on m_H [MeV]	
e/γ E_T-independent $Z \to ee$ calibration	44	≈ as in Run 1
e/γ E_T-dependent electron energy scale	28	≈ 30% better
$H \to \gamma\gamma$ interference bias	17	
e/γ photon lateral shower shape	16	≈ 3x better
e/γ photon conversion reconstruction	15	≈ 3x better
e/γ energy resolution	11	≈ 2x better
$H \to \gamma\gamma$ background modelling	10	≈ 4x better
Muon momentum scale	8	≈ 20% better
All other systematic uncertainties	7	> 5x better

Both channels performed statistical combination with Run 1 with simultaneous fit on m_H

0.09% precision on the Higgs mass on both channels!





Higgs Width: $H^* \to ZZ$

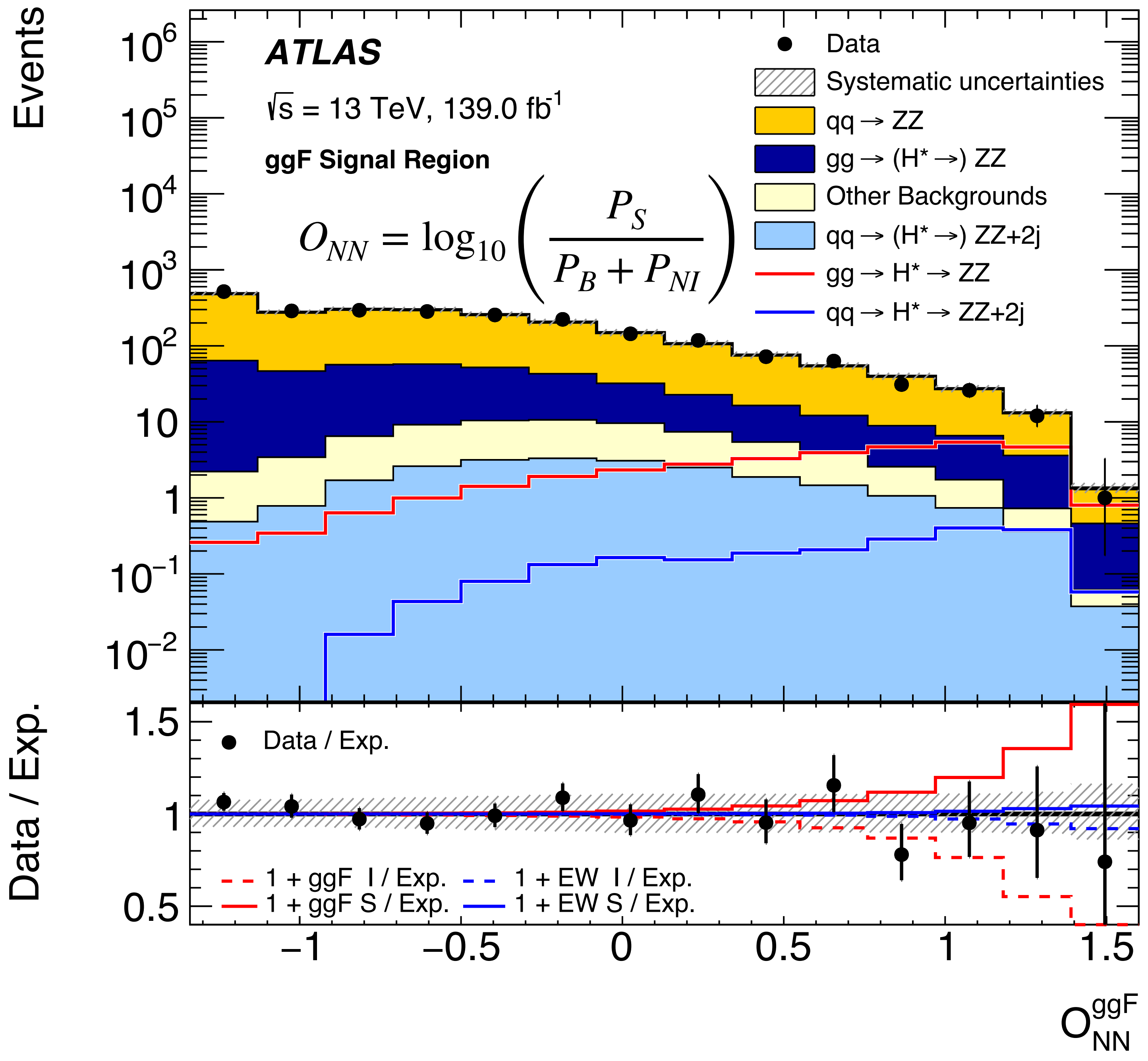
- Higgs width is inferred by measuring $H^* \to ZZ$ on-shell and off-shell signal due to the difference of cross section relation
- Include ggF and EW $H^* \to ZZ$ signals, and their backgrounds with destructive interference
- Simultaneously fit with signal strength and bkg NF in all SRs and CRs

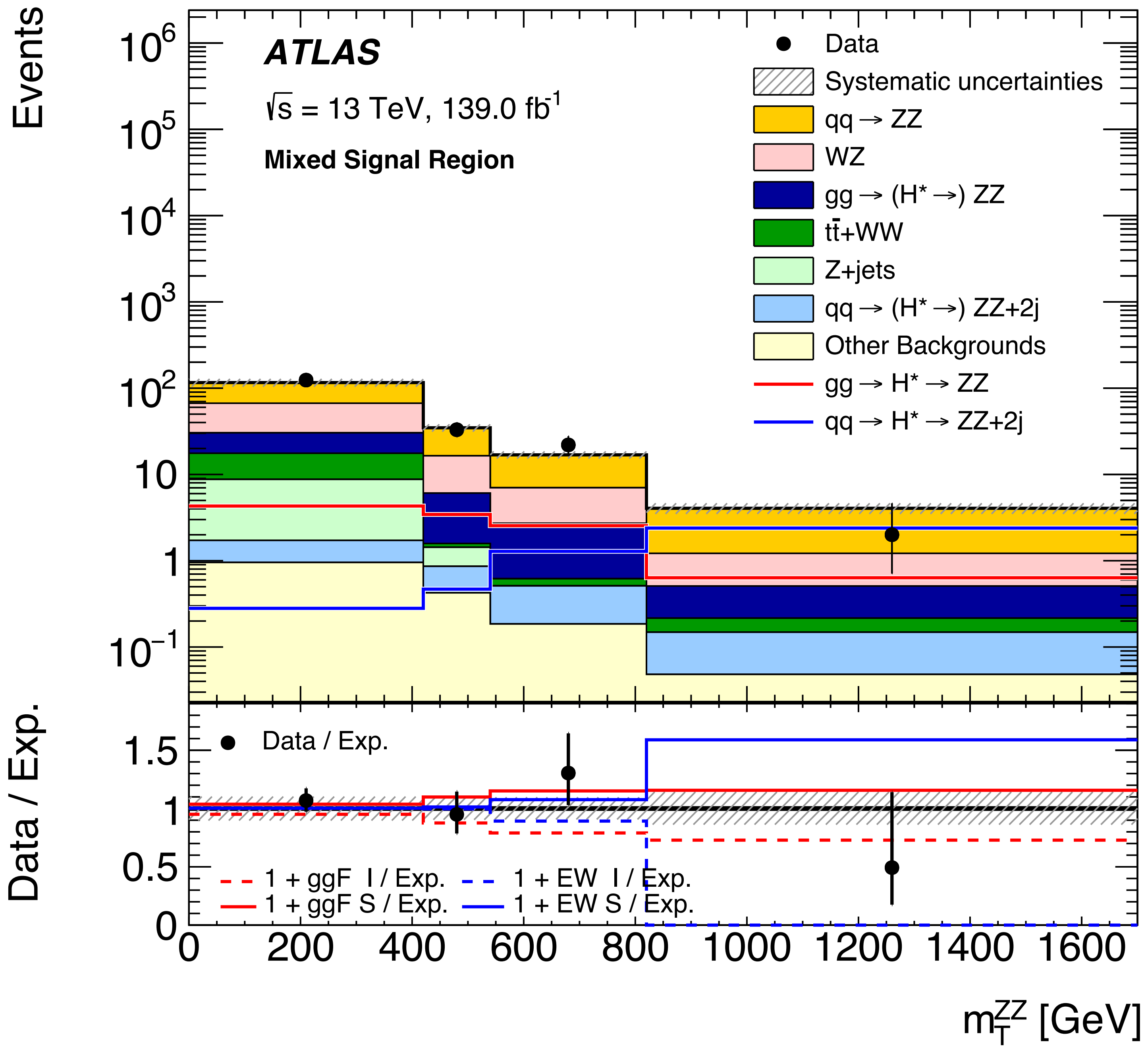
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m^2_{ZZ}}$$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m_H \Gamma_H}$$

$$\to \Gamma_H \propto \frac{\sigma_{gg\to H^*\to ZZ}}{\sigma_{gg\to H\to ZZ}}$$

- Targeting two final states with 3 signal regions (ggF, EW, and mixed) in each final state:
  - 4ℓ: SR with $m_{4\ell} > 220$ GeV constrained with multi-class NN
  - $2\ell 2\nu$: SR with E_T^{miss} and lepton kinematics constrained with m_T^{ZZ}
- Similar sensitivity in both channels

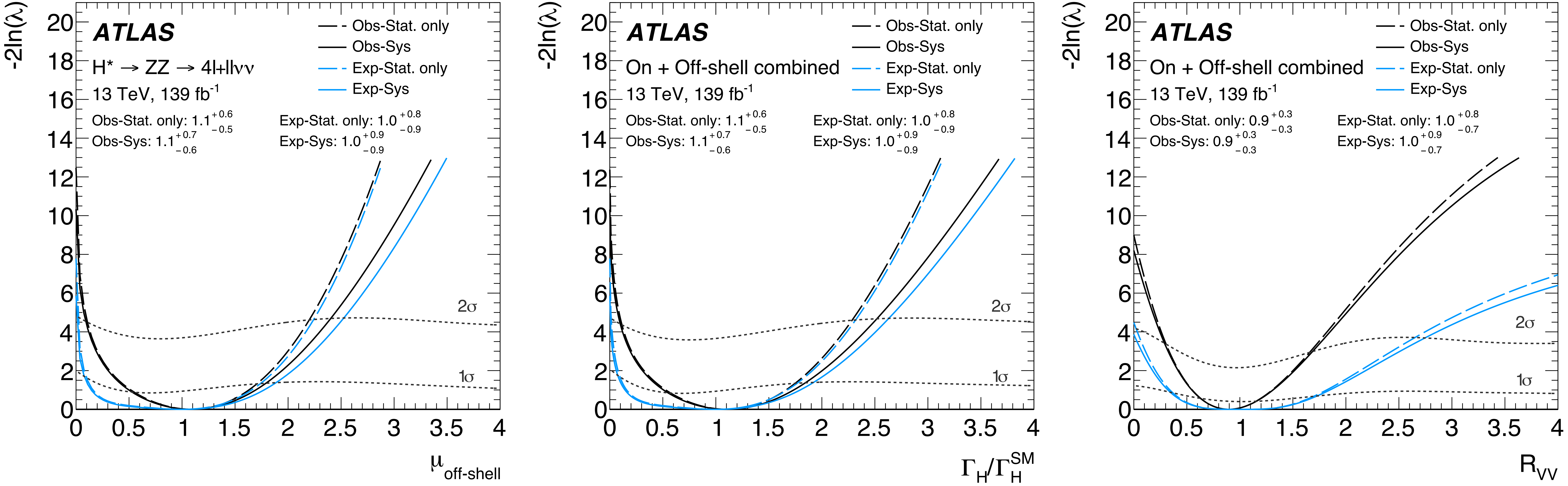




Higgs Width: $H^* \to ZZ$

- Direct measurement of off-shell signal strength
- Combined with on-shell measurement to measure Γ_H with correlated exp syst and decorrelated theory syst
- Further interpretation on the ratio of off-shell to on-shell couplings

Observed (expected) $\Gamma_H = 4.5^{+3.3}_{-2.5}$ (4.1) MeV



CP: $H \to WW^* + 2\text{jets}$

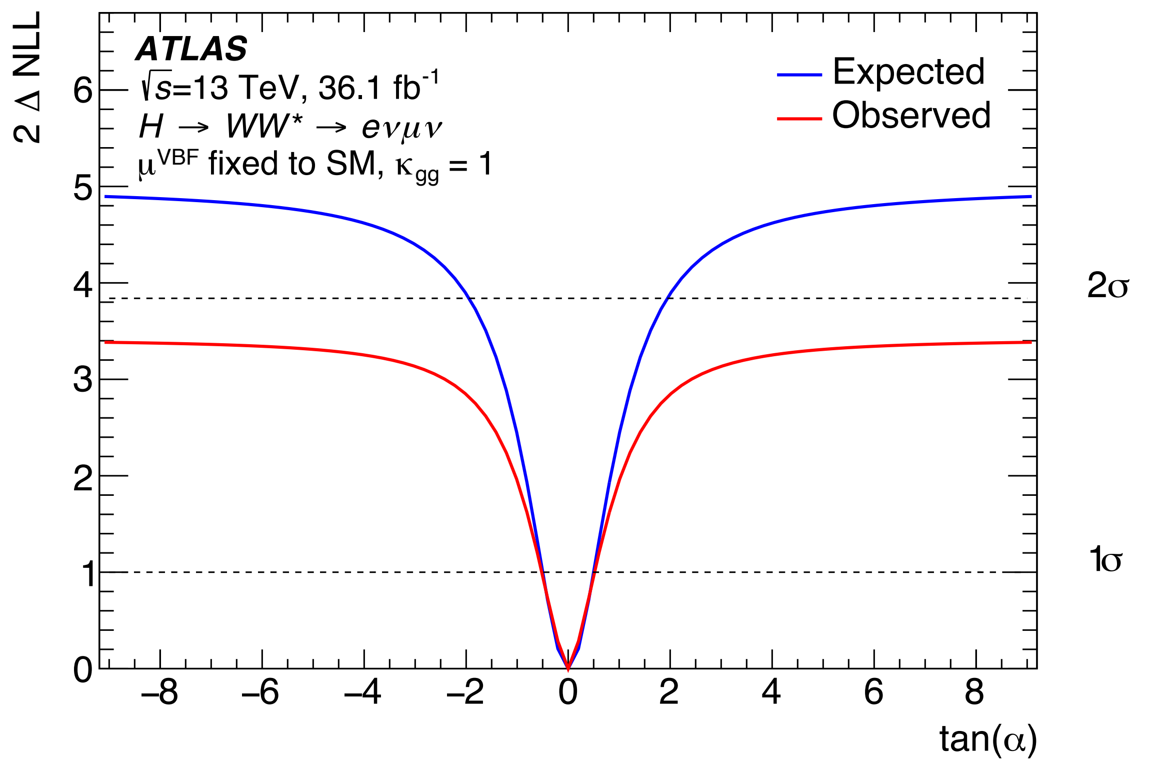
$$\mathcal{L}_0^{\text{loop}} = -\frac{g_{Hgg}}{4}\left(\kappa_{gg}\cos(\alpha)G^a_{\mu\nu}G^{a,\mu\nu} + \kappa_{gg}\sin(\alpha)G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)H$$

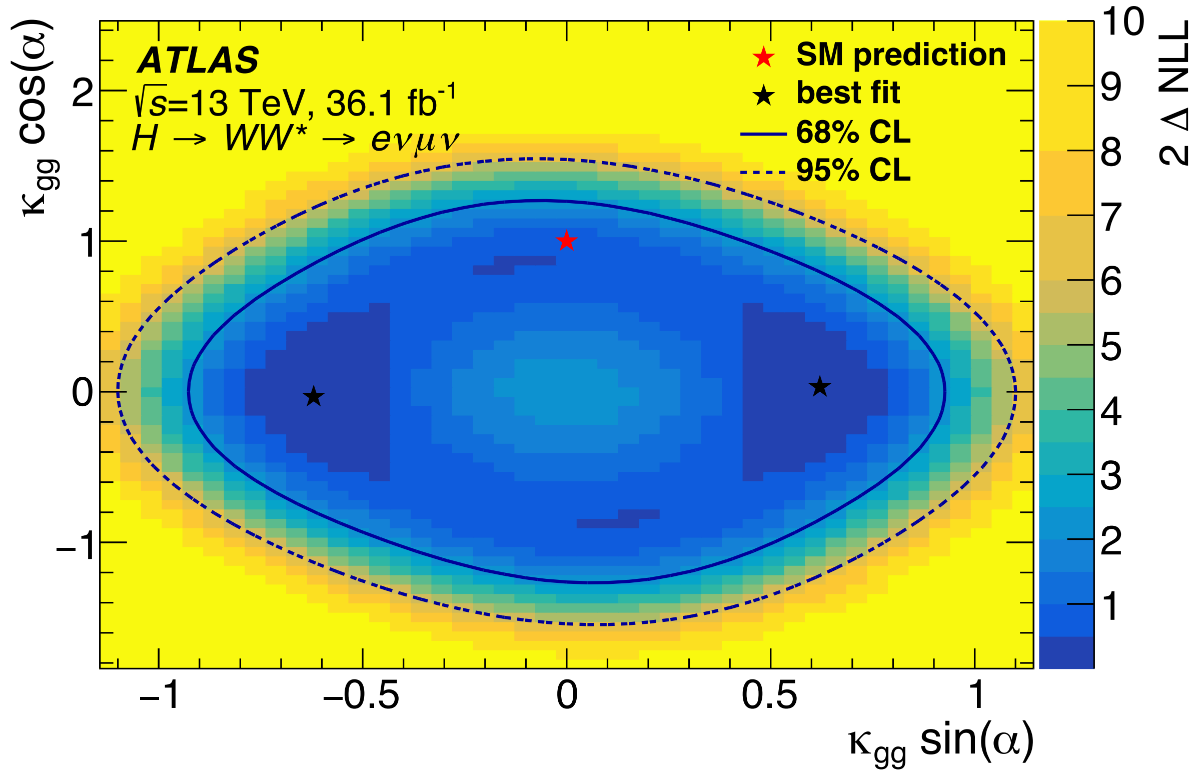
ATLAS EXPERIMENT

- $ggH + 2\text{jets}$ to probe CP properties of Higgs-top Yukawa coupling through Higgs-gluon effective coupling (in heavy-top mass limit) assuming SM HVV coupling
- $\tan(\alpha)$ sensitivity limited by under-fluctuation of signal strength

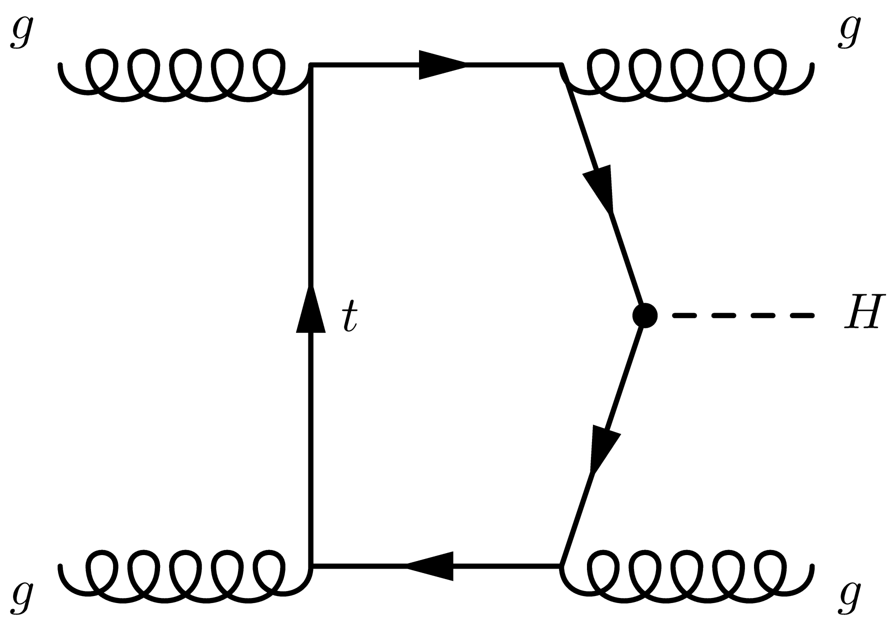
$\mu^{ggF+2jets} = 0.5 \pm 0.4\,(\text{stat.})^{+0.7}_{-0.6}\,(\text{syst.})$

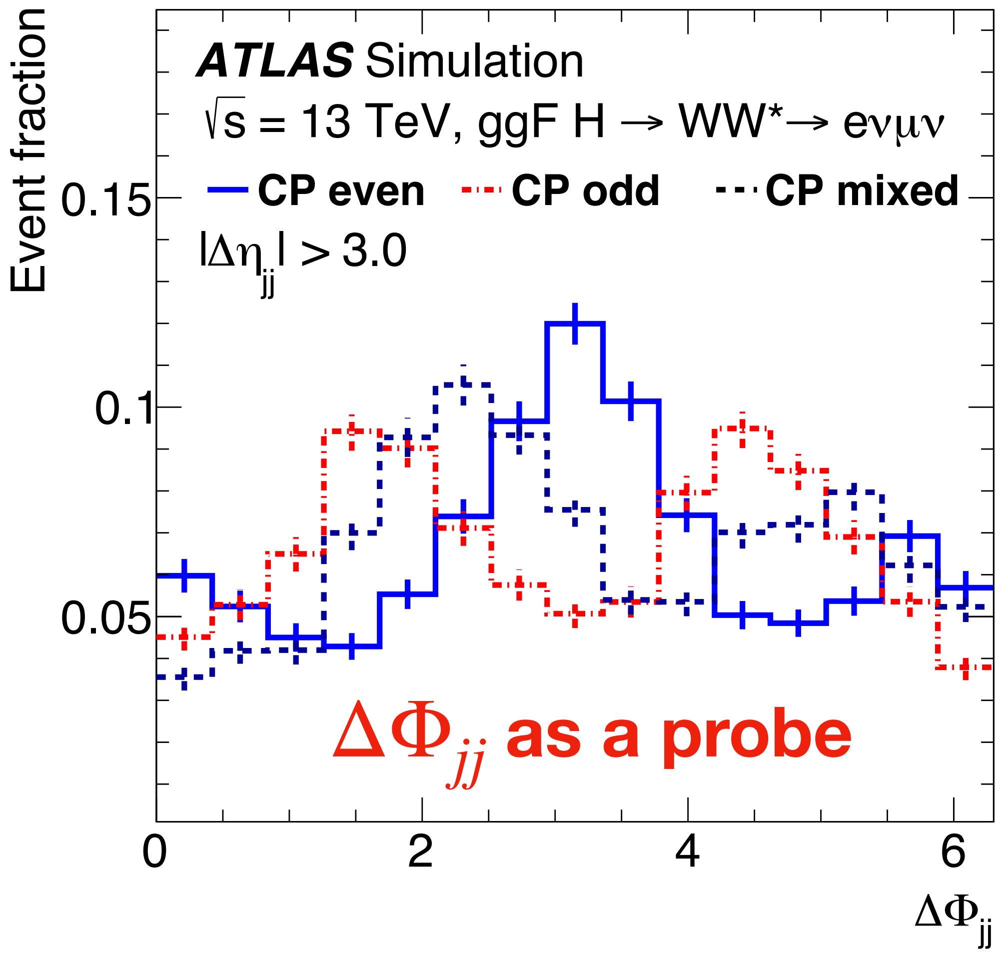
$\tan(\alpha) = 0.0 \pm 0.4\,(\text{stat.}) \pm 0.3\,(\text{syst.})$



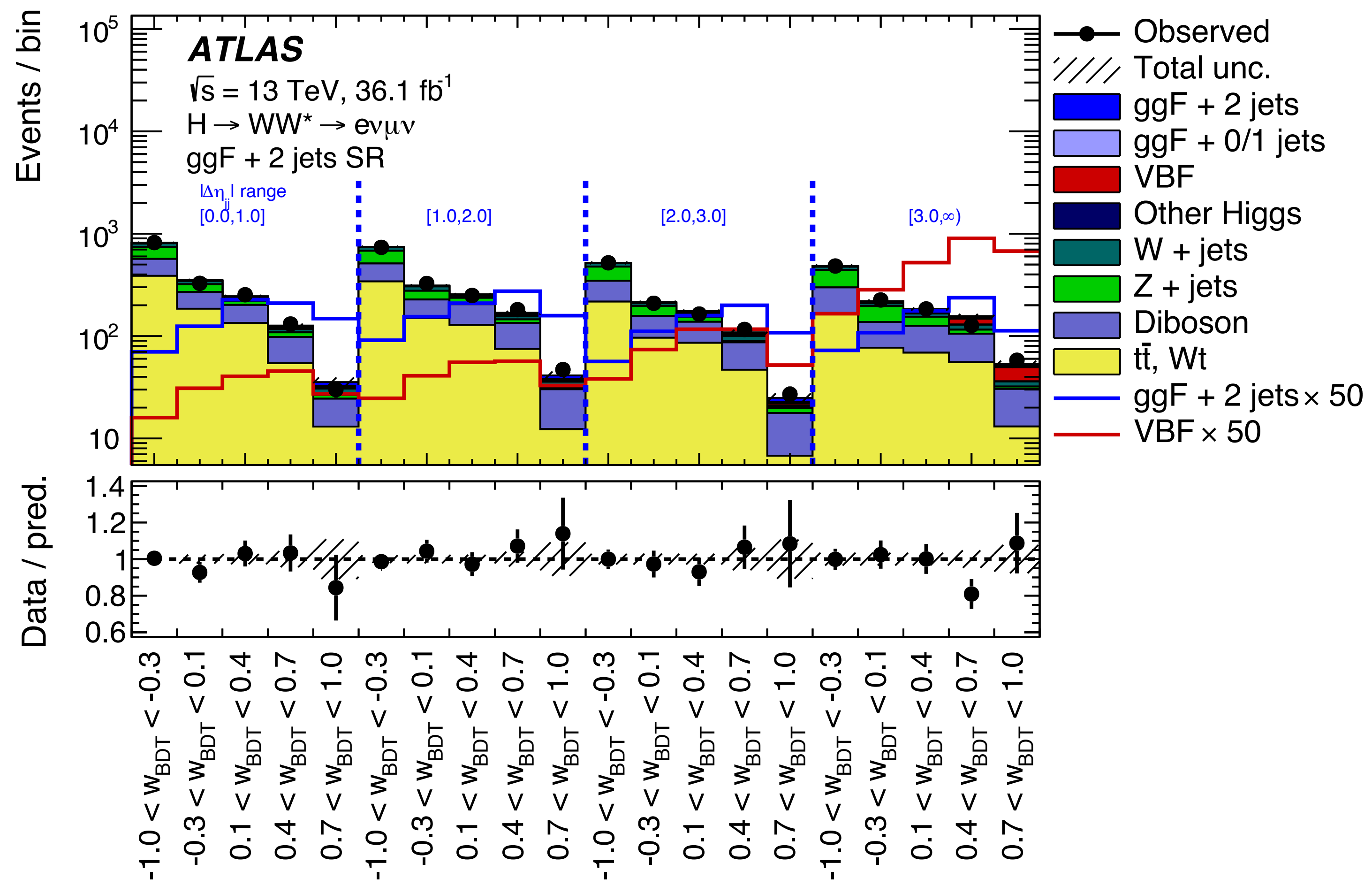


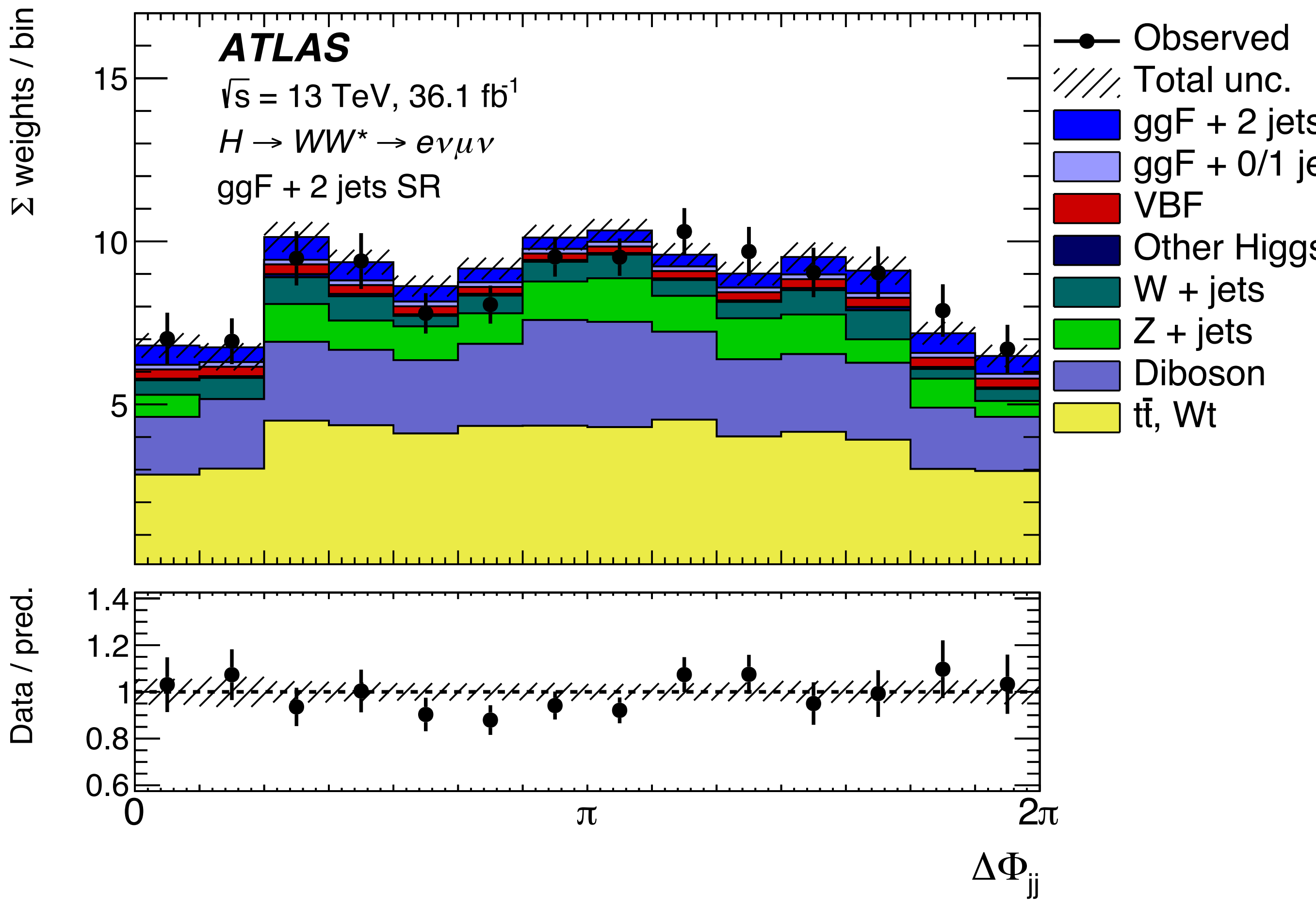
Source	$\Delta(\tan(\alpha))$
Total data statistical uncertainty	0.4
SR statistical uncertainty	0.33
CR statistical uncertainty	0.10
MC statistical uncertainty	0.14
Total systematic uncertainty	0.28
Theoretical uncertainty	0.23
Top-quark bkg.	0.15
ggF signal	0.14
WZ, ZZ, $W\gamma$, $Z\gamma$ bkg.	0.06
WW bkg.	0.06
Z/γ^* bkg.	0.016
VBF bkg.	0.015
Experimental uncertainty	0.21
b-tagging	0.16
Modelling of pile-up	0.10
Jets	0.07
Misidentified leptons	0.04
Luminosity	0.034
Total	0.5





Simultaneous fit with categories split by BDT and $|\eta_{jj}|$ using $\Delta\Phi_{jj}$ as observation

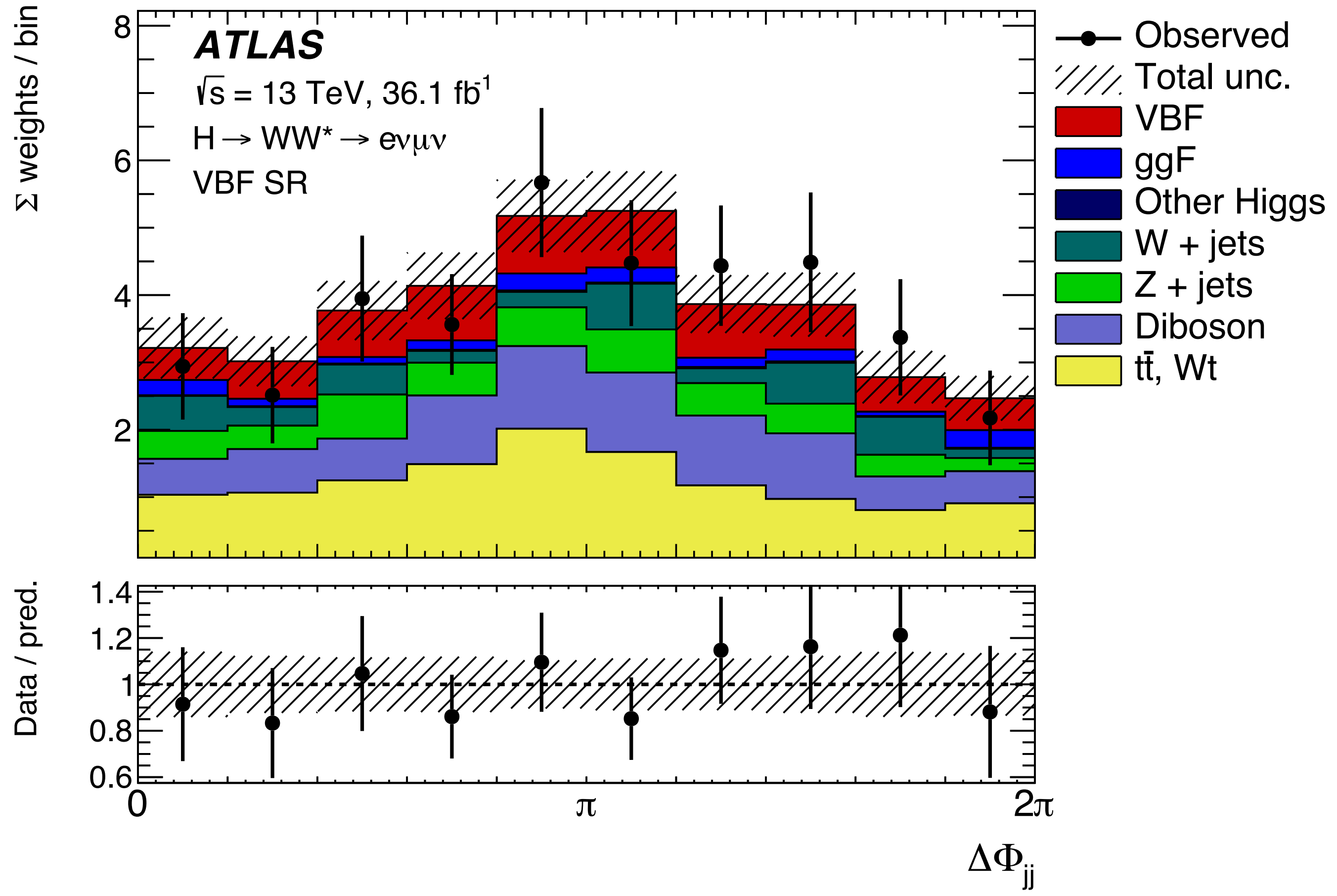




CP: $H \to WW^* + 2$jets

- VBF to constrain HVV coupling to longitudinally and transversely polarized W and Z bosons (a_L, a_T) and $(\kappa_{VV}, \epsilon_{VV})$ assuming SM Hgg coupling
- Results are consistent with the SM

Fit with categories split by BDT with $\Delta\Phi_{jj}$ as observation



(a) κ_{VV} fit, $\varepsilon_{VV} = 0$

Source	$\Delta\kappa_{VV}$
Total data statistical uncertainty	0.11
SR data statistical uncertainty	0.10
CR data statistical uncertainty	0.019
MC statistical uncertainty	0.035
Total systematic uncertainty	0.12
Theoretical uncertainty	0.10
Top-quark bkg.	0.072
WW bkg.	0.062
ggF bkg.	0.033
Z/γ^* bkg.	0.017
VBF signal	0.019
Experimental uncertainty	0.050
Jet	0.026
b-tagging	0.014
Luminosity	0.011
Misidentified leptons	0.007
Total	0.17

Different scenarios are performed to estimate (a_L, a_T) and $(\kappa_{VV}, \epsilon_{VV})$

Type	Expected	Observed
a_T shape-only fit ($a_L = 1$)	$1.0 \pm 0.5(\text{stat.})^{+0.3}_{-0.4}(\text{syst.})$	$1.3^{+0.8}_{-0.4}(\text{stat.})^{+0.3}_{-0.2}(\text{syst.})$
a_L shape + rate fit ($a_T = 1$)	$1.00^{+0.08}_{-0.10}(\text{stat.})^{+0.07}_{-0.13}(\text{syst.})$	$0.90^{+0.09}_{-0.13}(\text{stat.})^{+0.08}_{-0.18}(\text{syst.})$
a_T shape + rate fit ($a_L = 1$)	$1.00^{+0.36}_{-0.49}(\text{stat.})^{+0.19}_{-0.27}(\text{syst.})$	$1.19^{+0.27}_{-0.32}(\text{stat.})^{+0.12}_{-0.14}(\text{syst.})$
a_L shape + rate fit (a_T profiled)	$1.00^{+0.08}_{-0.10}(\text{stat.})^{+0.08}_{-0.13}(\text{syst.})$	$0.91^{+0.10}_{-0.18}(\text{stat.})^{+0.09}_{-0.17}(\text{syst.})$
a_T shape + rate fit (a_L profiled)	$1.0^{+0.4}_{-0.5}(\text{stat.})^{+0.2}_{-0.4}(\text{syst.})$	$1.2 \pm 0.4(\text{stat.})^{+0.2}_{-0.3}(\text{syst.})$

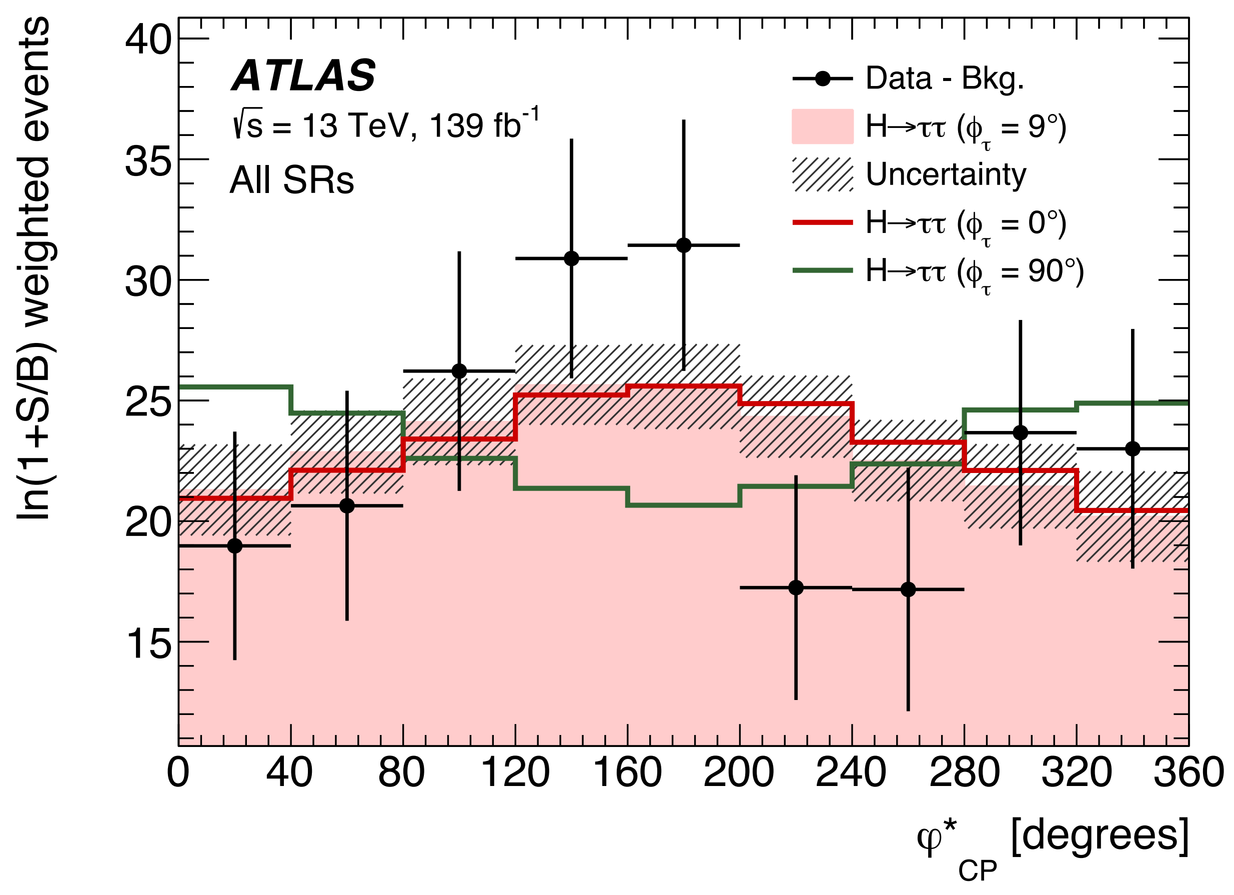
Type	Expected	Observed
ε_{VV} shape-only fit ($\kappa_{VV} = 1$)	$0.00^{+0.23}_{-0.25}(\text{stat.})^{+0.14}_{-0.17}(\text{syst.})$	$0.14^{+0.39}_{-0.22}(\text{stat.})^{+0.16}_{-0.12}(\text{syst.})$
κ_{VV} shape + rate fit ($\varepsilon_{VV} = 0$)	$1.00^{+0.08}_{-0.10}(\text{stat.})^{+0.08}_{-0.13}(\text{syst.})$	$0.91^{+0.09}_{-0.12}(\text{stat.})^{+0.09}_{-0.18}(\text{syst.})$
ε_{VV} shape + rate fit ($\kappa_{VV} = 1$)	$0.00^{+0.18}_{-0.24}(\text{stat.})^{+0.08}_{-0.13}(\text{syst.})$	$0.09^{+0.13}_{-0.16}(\text{stat.})^{+0.06}_{-0.07}(\text{syst.})$
κ_{VV} shape + rate fit (ε_{VV} profiled)	$1.00^{+0.08}_{-0.10}(\text{stat.})^{+0.08}_{-0.13}(\text{syst.})$	$0.91^{+0.10}_{-0.18}(\text{stat.})^{+0.09}_{-0.17}(\text{syst.})$
ε_{VV} shape + rate fit (κ_{VV} profiled)	$0.00^{+0.22}_{-0.24}(\text{stat.})^{+0.11}_{-0.15}(\text{syst.})$	$0.13^{+0.28}_{-0.20}(\text{stat.})^{+0.08}_{-0.10}(\text{syst.})$

CP: $H \to \tau\tau$

$$\mathscr{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau \left(\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i\gamma^5 \tau\right) H$$

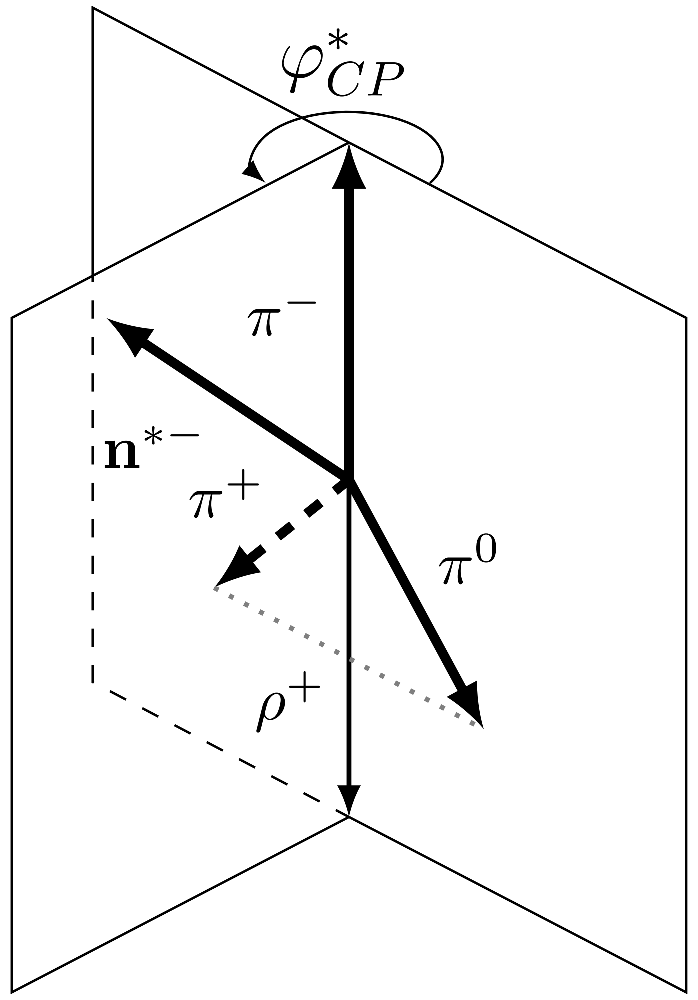
ATLAS EXPERIMENT

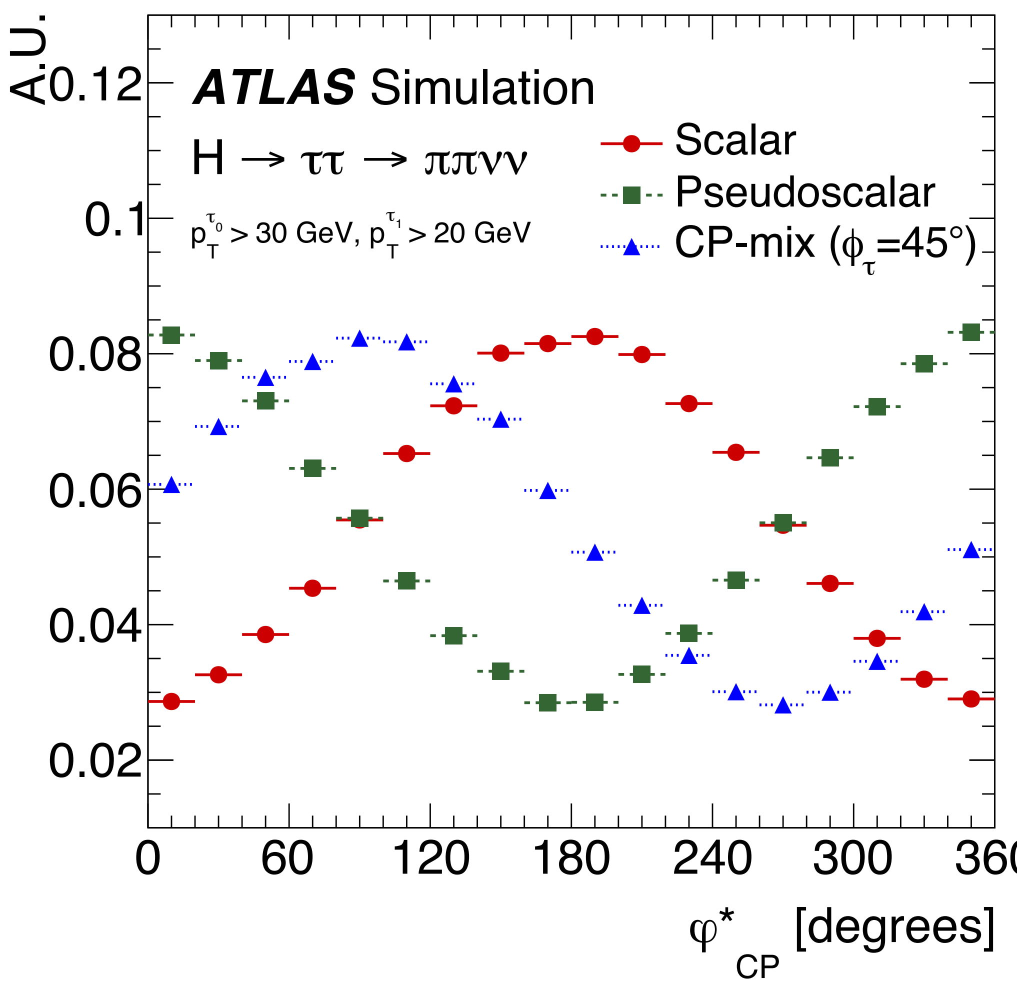
- Probe the CP of Higgs-tau Yukawa coupling with ggF, VBF, VH, and $t\bar{t}H$ productions
- φ^*_{CP} is constructed with combinations of τ decays ($\tau_\ell\tau_h$ and $\tau_h\tau_h$, and $\pi^\pm$ and π^0 multiplicity from τ_h) → Phase of φ^*_{CP} directly related to mixing angle ϕ_τ
- Observed ϕ_τ is consistent with SM, with largest impact on ϕ_τ comes from data statistics



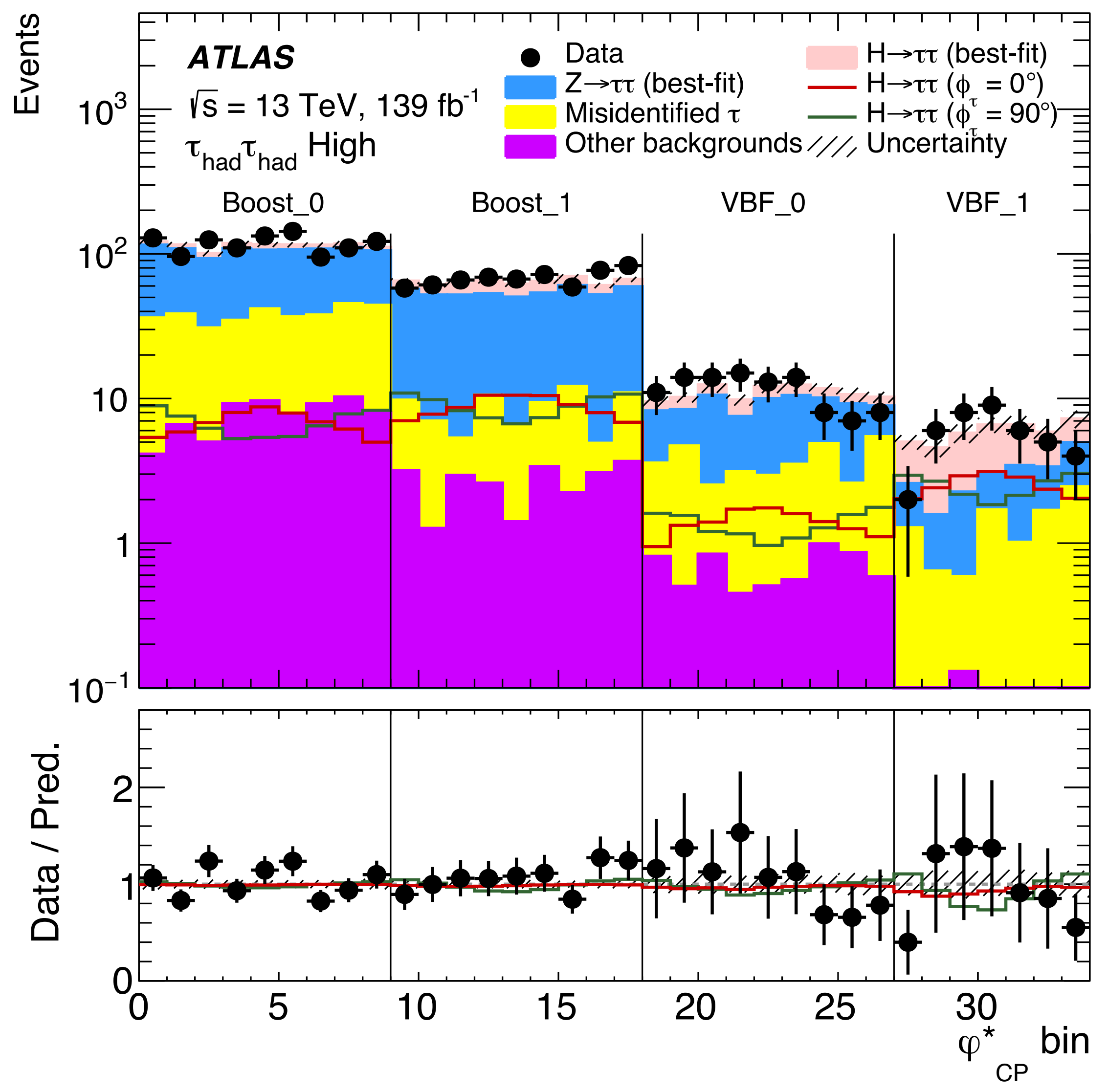
φ^*_{CP} is sensitive to Higgs CP properties!

$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau),$$

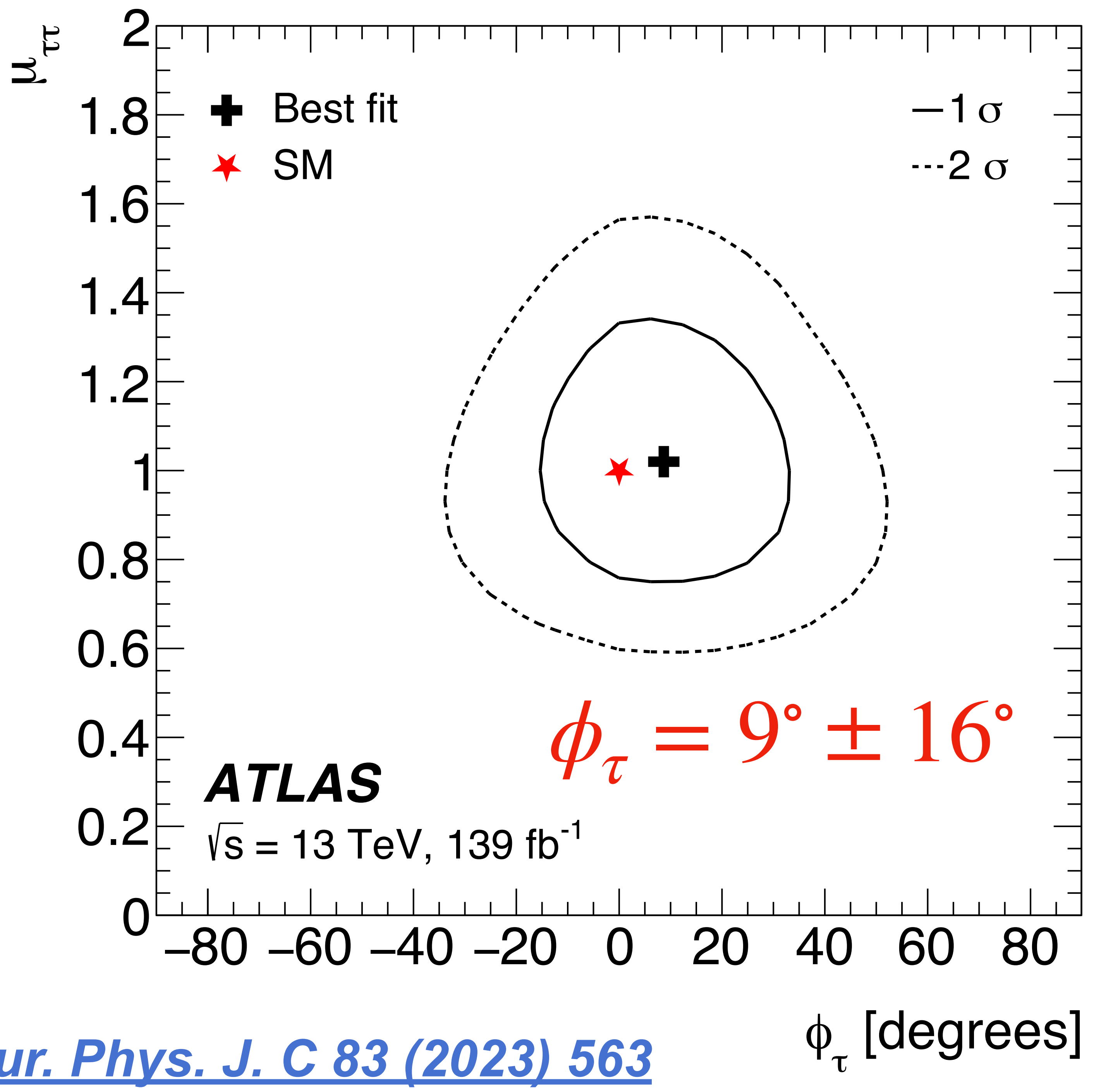




SR are categorized with combination of "$\tau_\ell\tau_h/\tau_h\tau_h \otimes d_0^{sig}/y^\rho \otimes$ VBF/Boost"



Pure CP-odd disfavored at 3.4 σ



$\phi_\tau = 9^\circ \pm 16^\circ$

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CP: $t\bar{t}H/tH$ with $H \to bb$

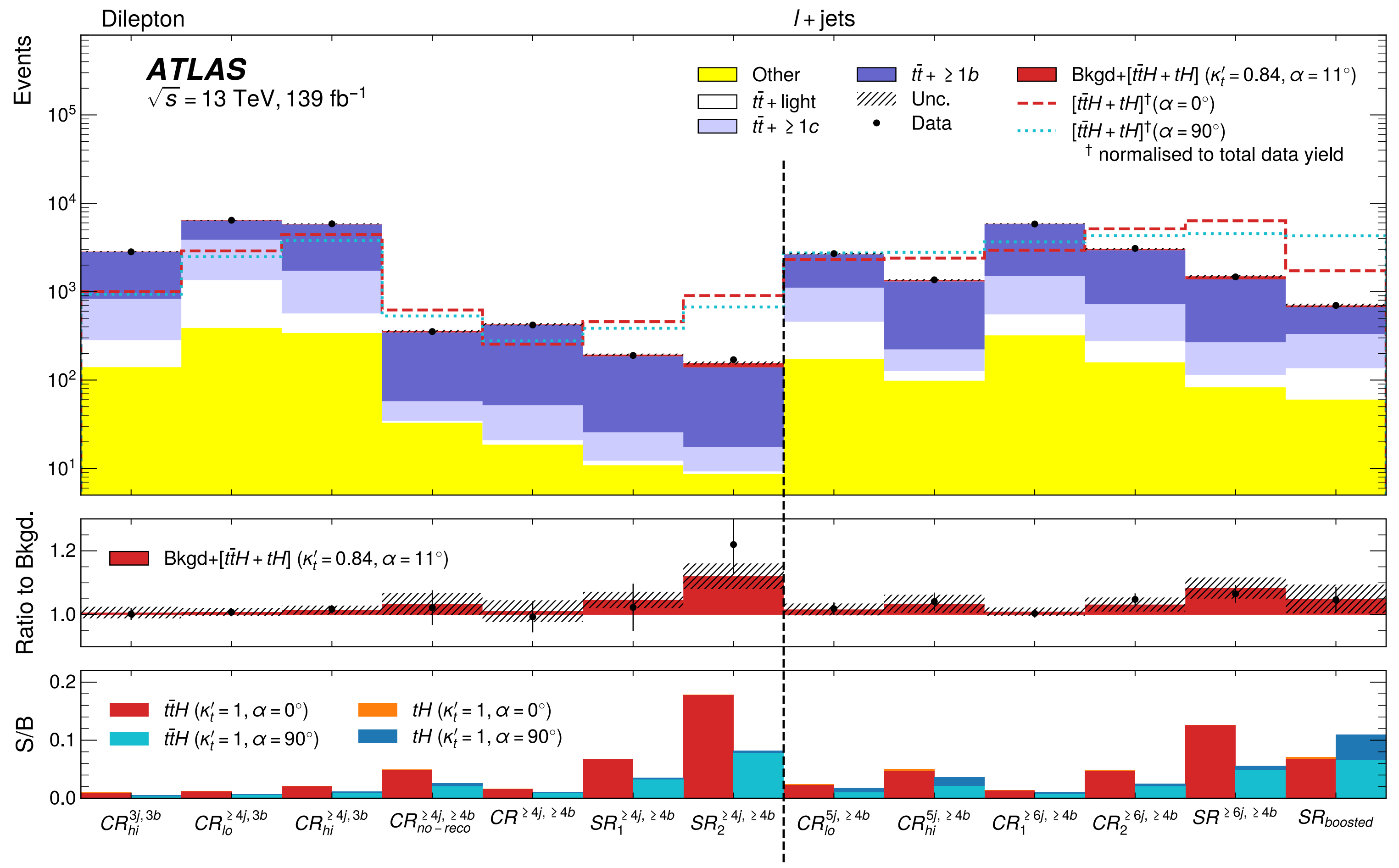
$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

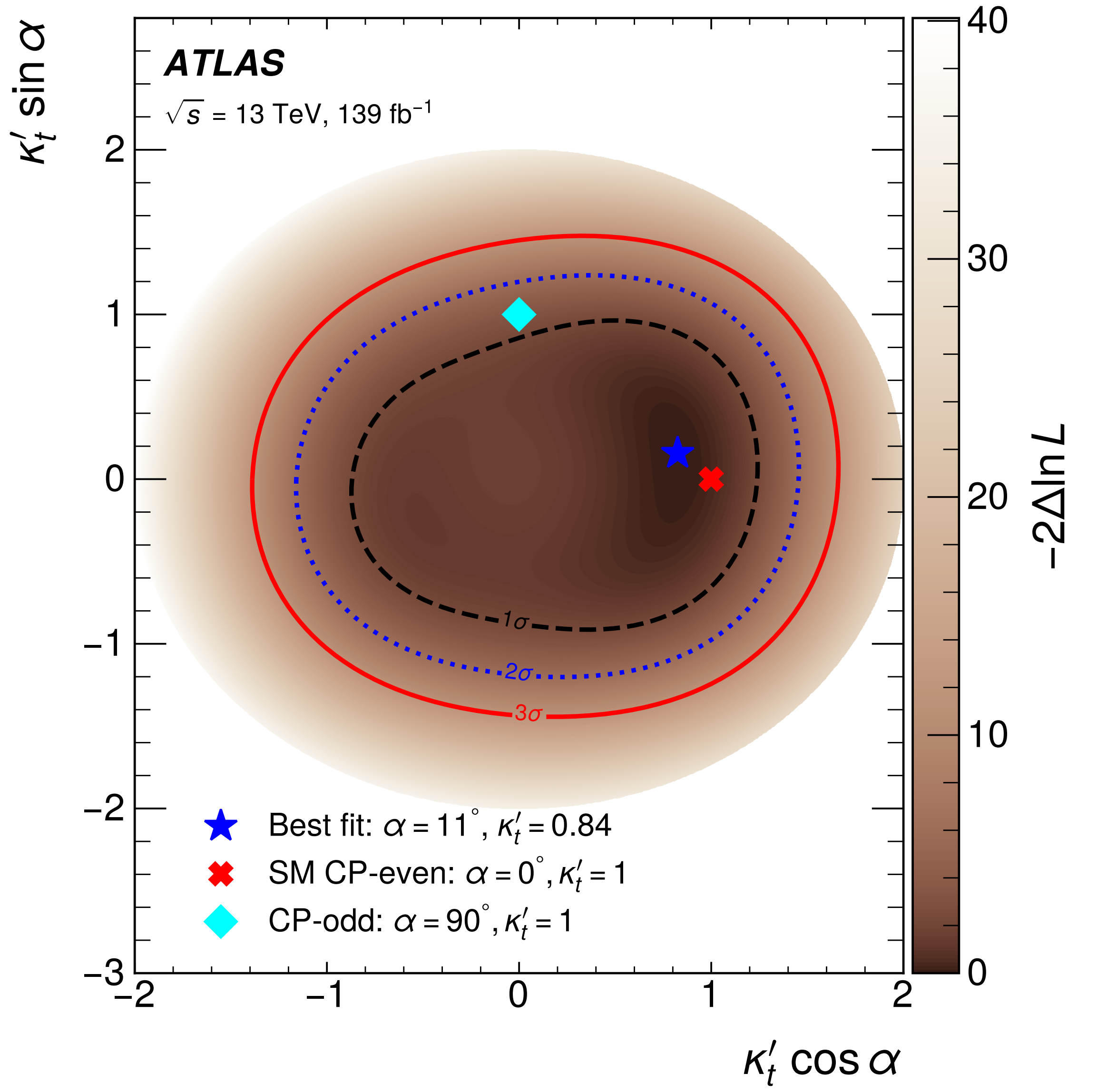
ATLAS EXPERIMENT

- Strategy based on $t\bar{t}H \to bb$ STXS measurement
- $\alpha = 11^\circ\,{}^{+52^\circ}_{-73^\circ}$ and $\kappa_t' = 0.84^{+0.30}_{-0.46}$ consistent with SM
- Limited by low signal yield and background modeling

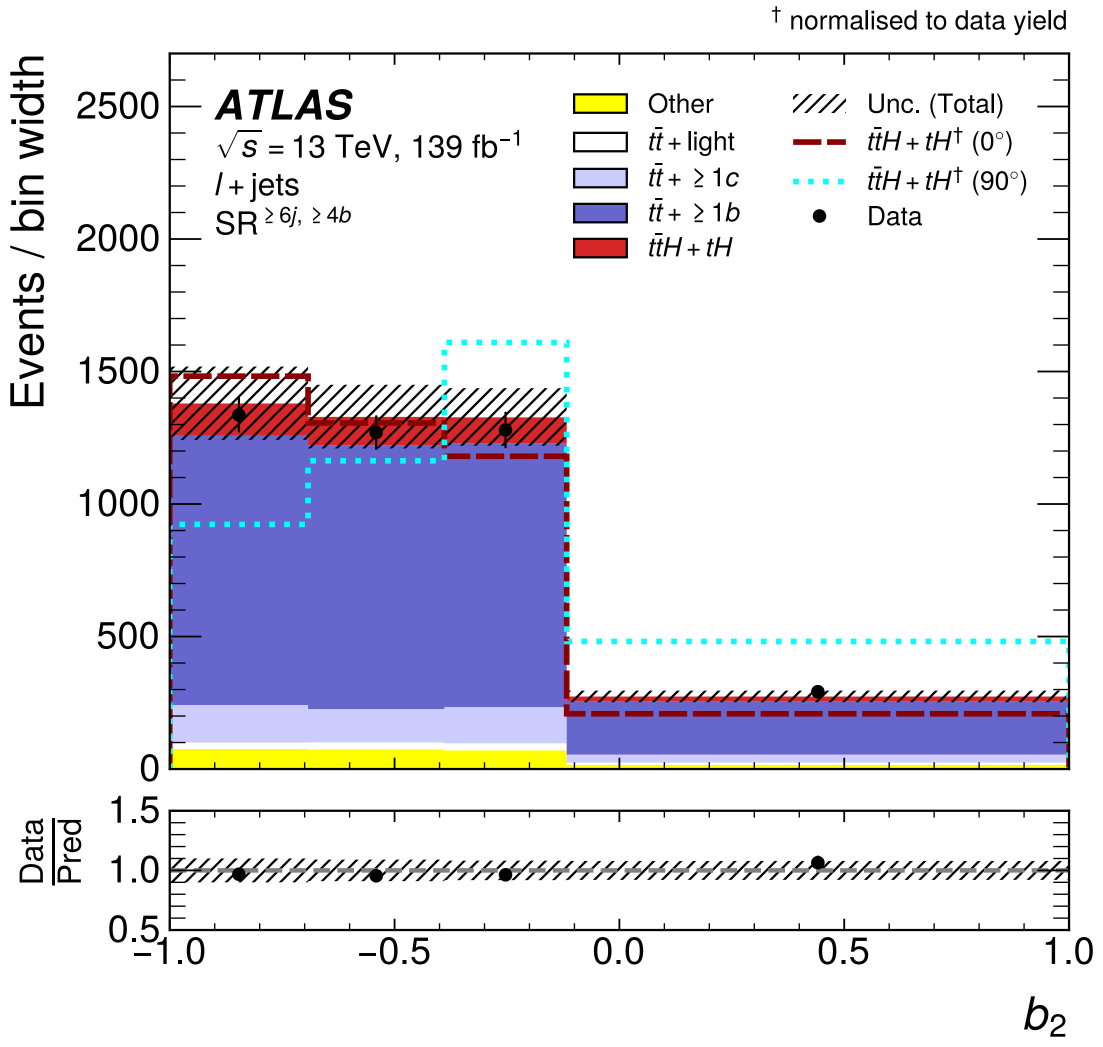
$$b_2 = \frac{(\vec{p}_1 \times \hat{z})\cdot(\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|} \qquad b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

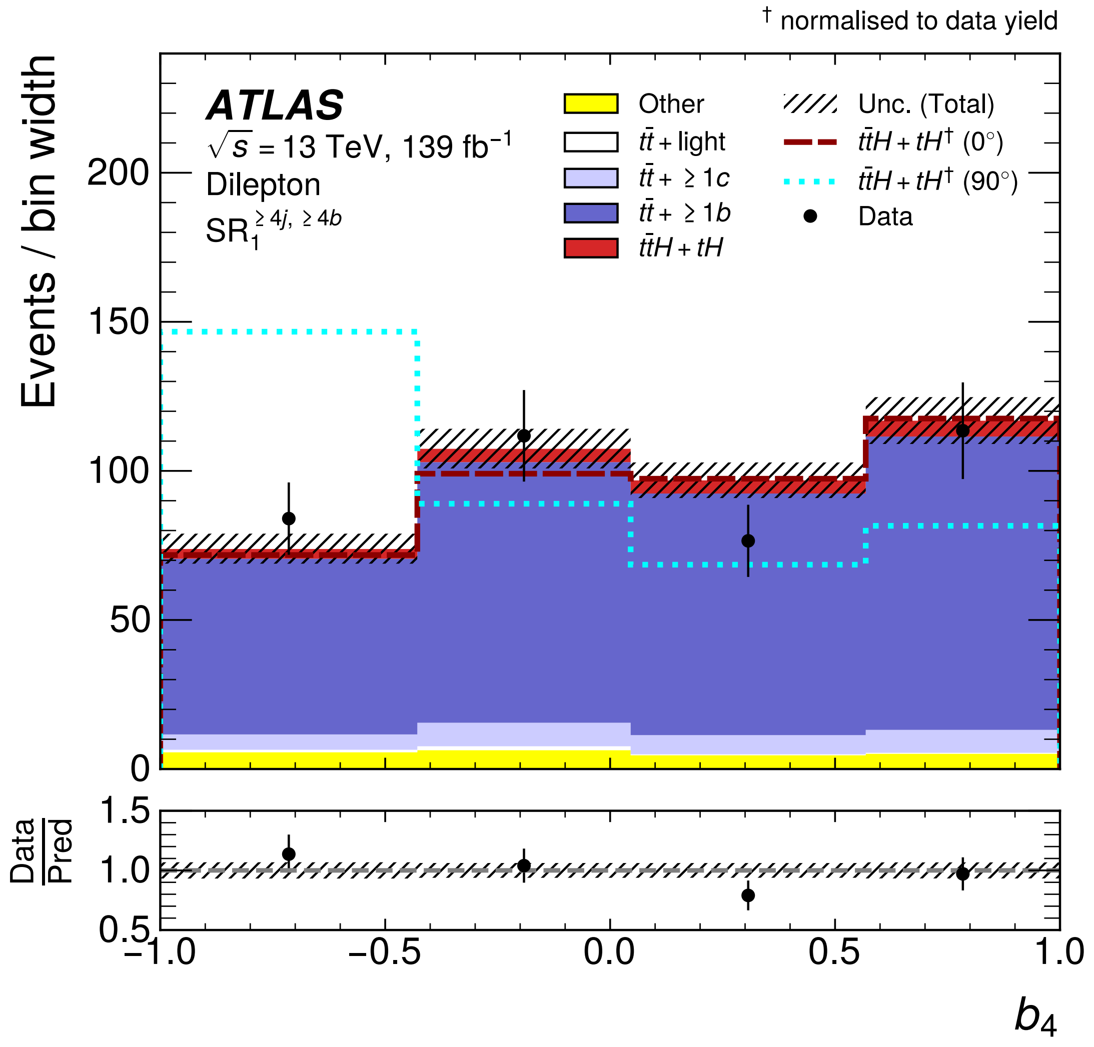
- NN for boosted Higgs, BDT to reconstruct Higgs/Top
- BDTs (w/ reco MVA as input) to classify S and B

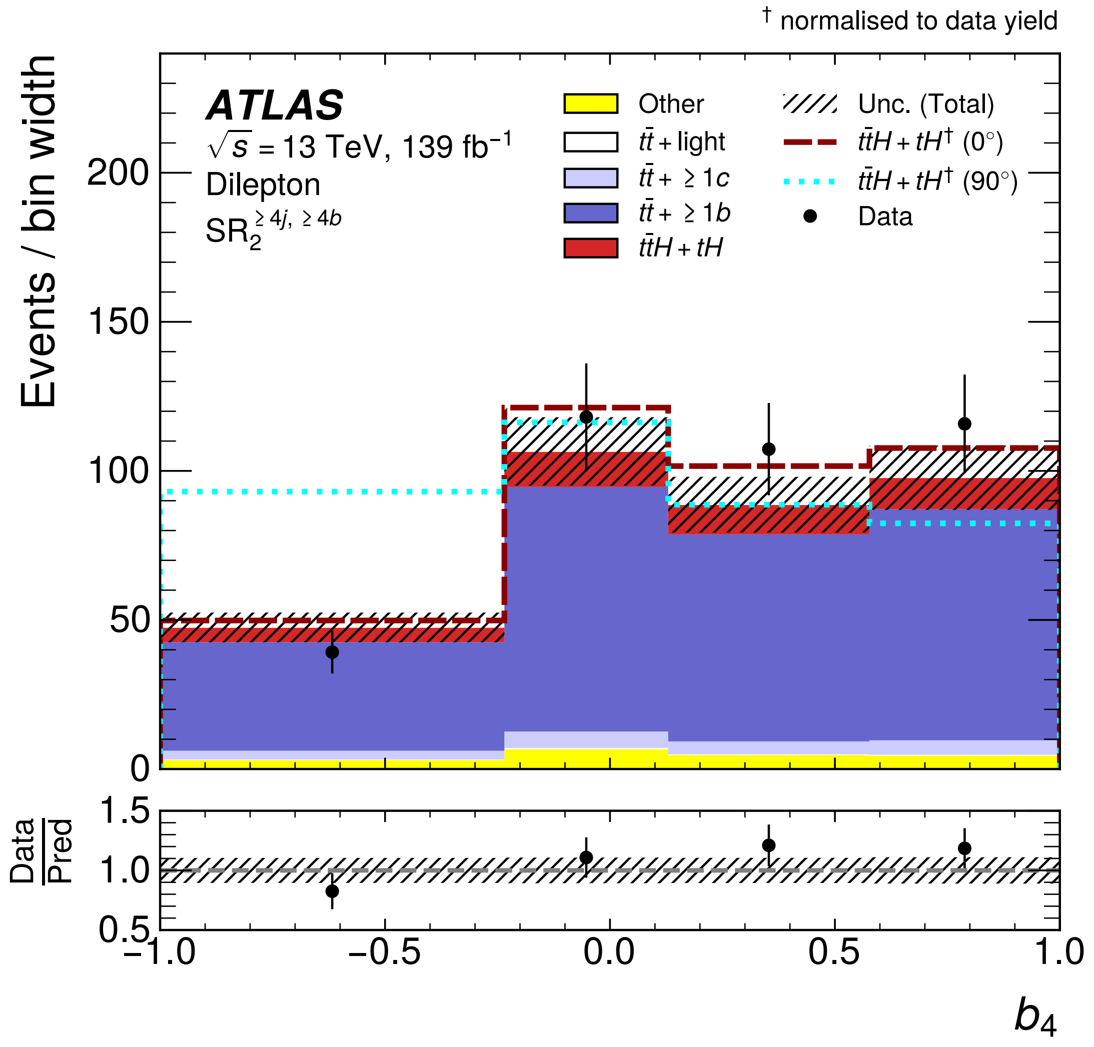


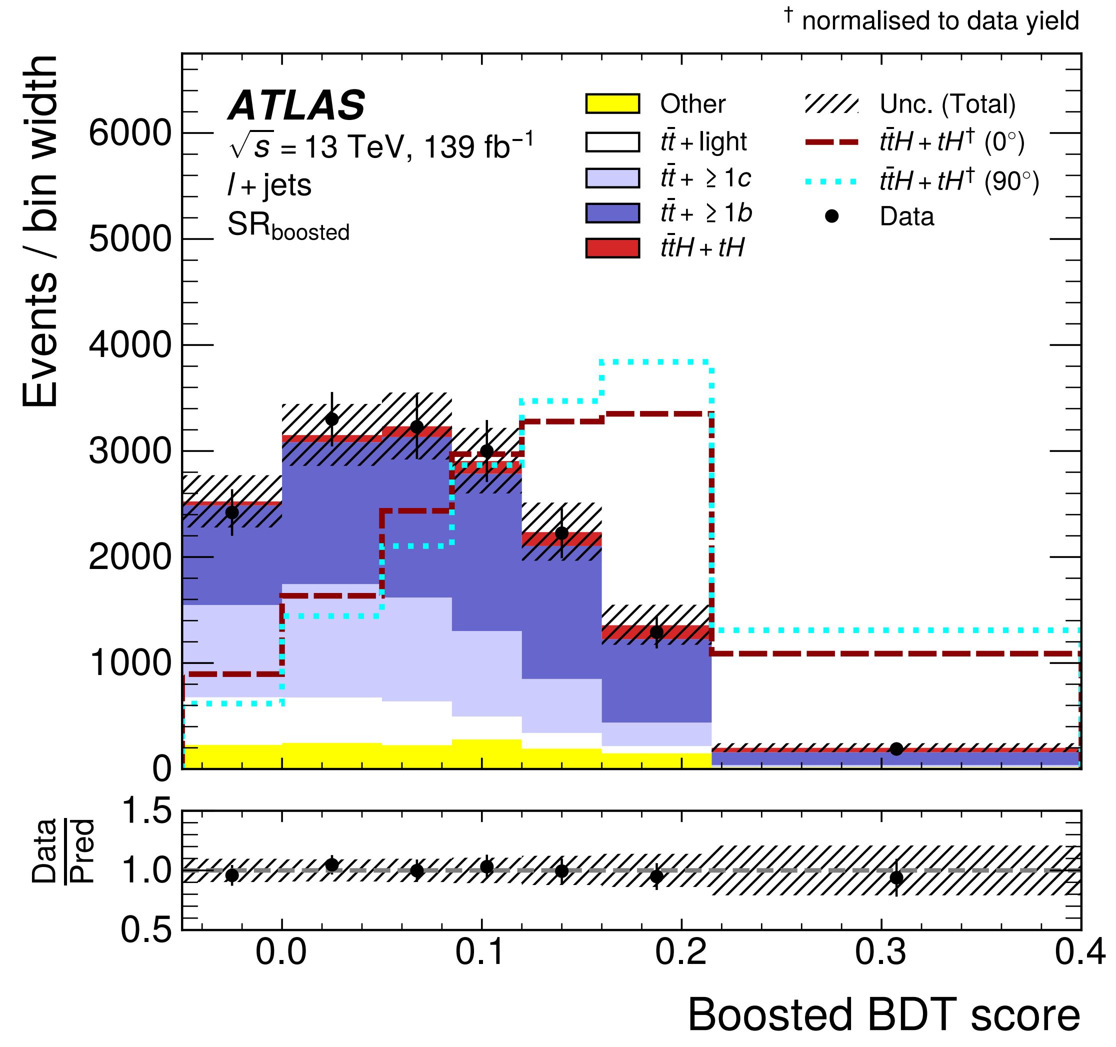


Boosted BDT score, b_2 and b_4 constructed as CP-sensitive observables









CP: VBF $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$

- EFT to include CP-odd operators with different EFT bases chosen for interpretation (Warsaw, Higgs and HISZ bases)
- Optimal Observables ($\mathcal{O}\mathcal{O}$) to probe CP-admixture in HVV coupling
- Observable is symmetric for CP-even contributions → any asymmetry indicates CP-odd contributions

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i^2}{\Lambda}\mathscr{O}_i^{(6)}$$

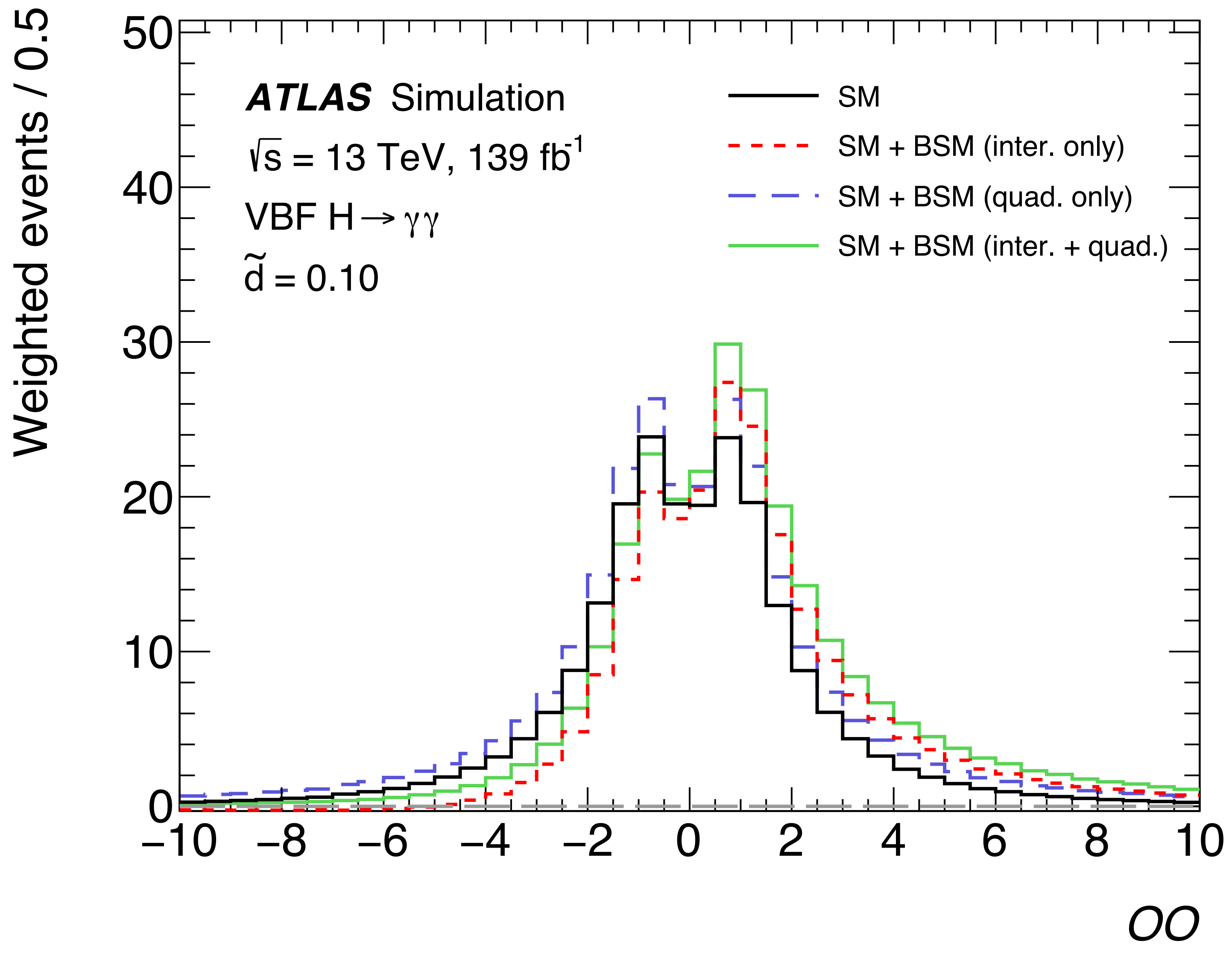
A CP-odd operators added as $\mathscr{O}^{(6)}$

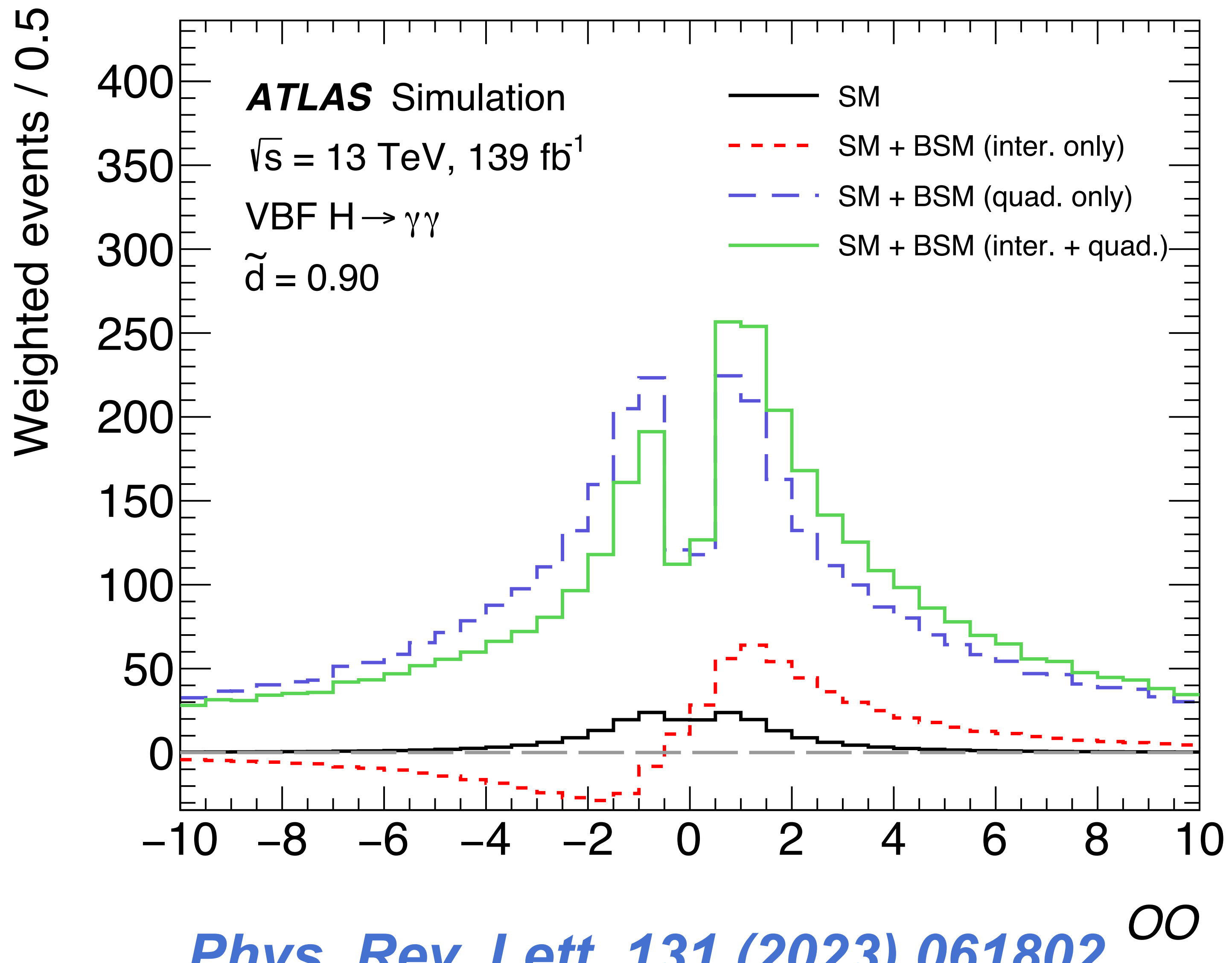
$$|\mathscr{M}|^2 = |\mathscr{M}_{\rm SM}|^2 + 2c_i{\rm Re}(\mathscr{M}^*_{\rm SM}\mathscr{M}_{CP\text{-odd}}) + c_i^2|\mathscr{M}_{CP\text{-odd}}|^2.$$

Optimal Observables

$$OO = 2{\rm Re}(\mathscr{M}^*_{\rm SM}\mathscr{M}_{\rm CP-odd})/|\mathscr{M}_{\rm SM}|^2$$

Operator	Structure	Coupling
Warsaw Basis		
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
Higgs Basis		
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$



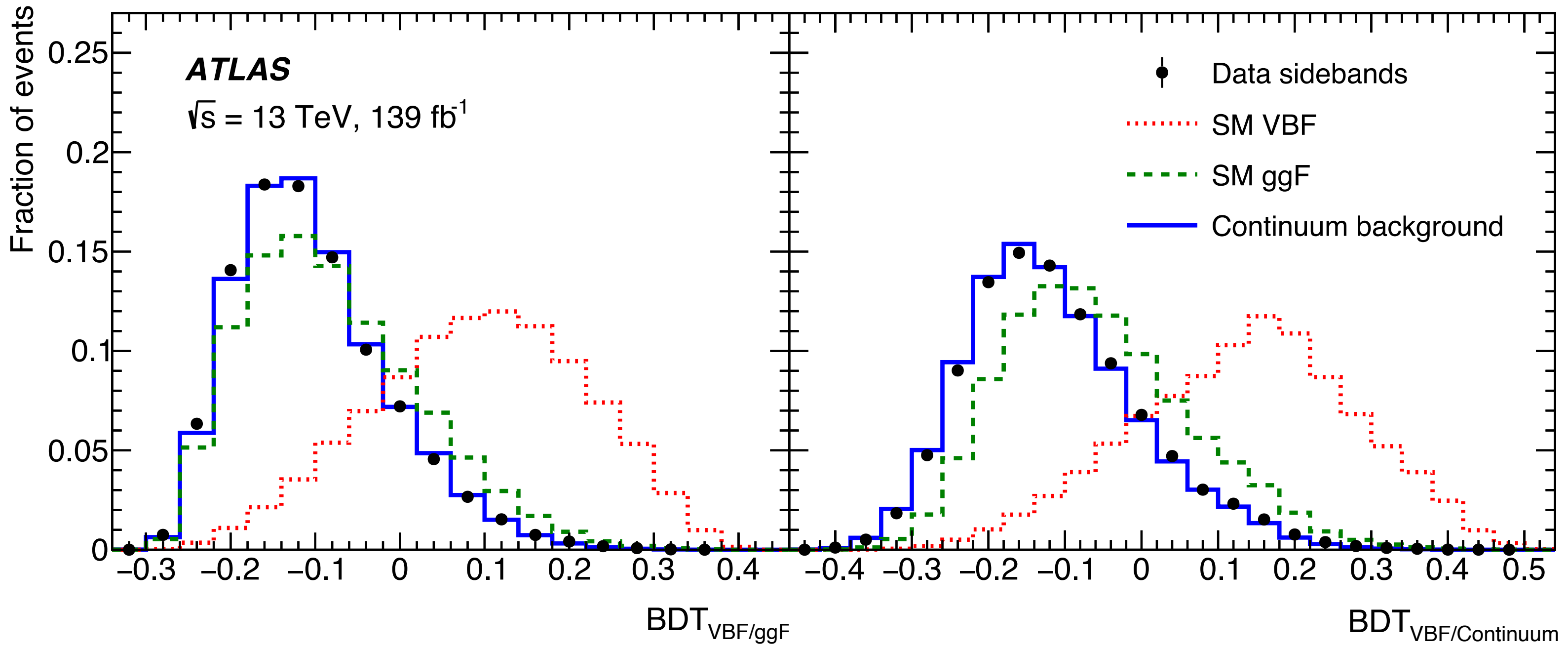


Phys. Rev. Lett. 131 (2023) 061802
arXiv:2304.09612

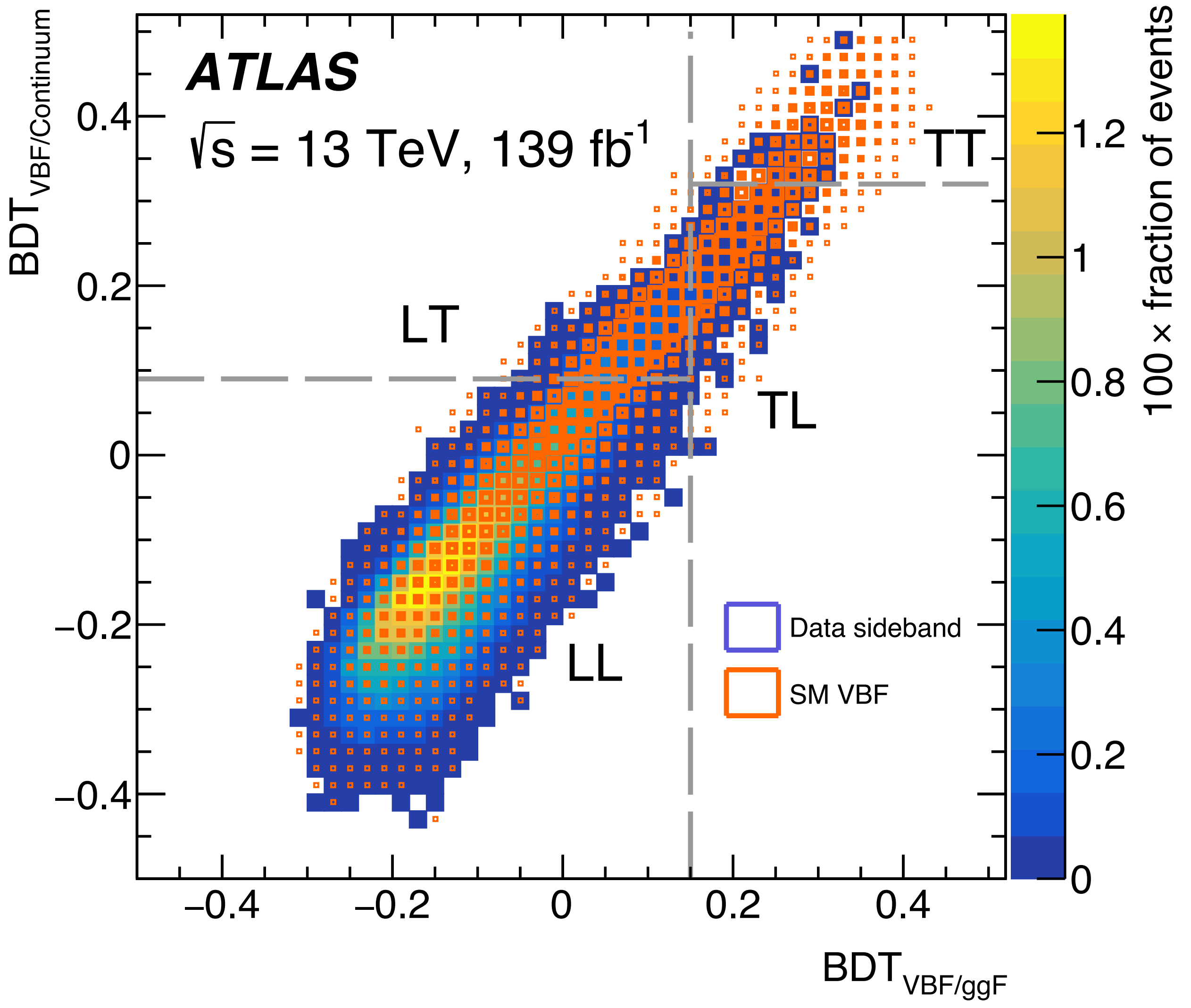
CP: VBF $H \rightarrow \gamma\gamma$

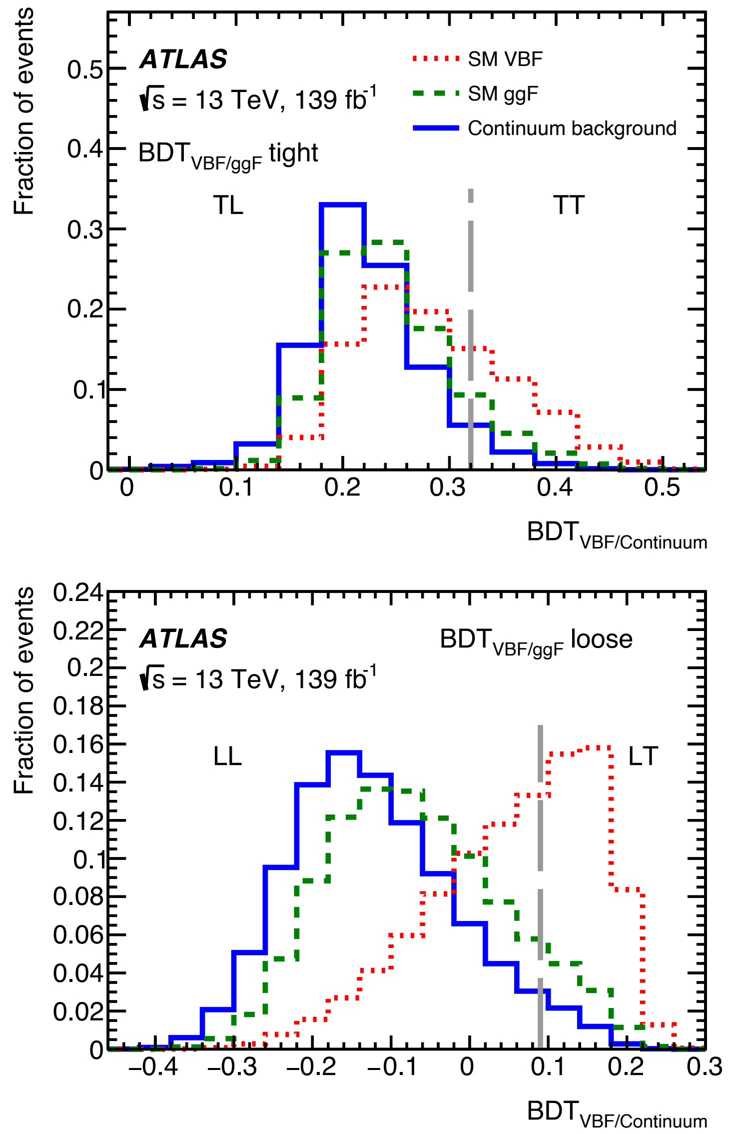
- Selecting 2 tight photons with 2 jets having $|\eta_{jj}| > 2$ with BDT
- Probing different values of $\tilde{d}$ (assuming $\tilde{d} = \tilde{d}_B$) or $c_{H\tilde{W}}$ (assuming $c_{H\tilde{B}} = c_{H\tilde{W}B} = 0$) sensitive to CP-odd components
- Results are compatible with SM

BDT to select VBF enriched phase-space + BDT to suppress continuum background from $\gamma\gamma$, $j\gamma$, and jj

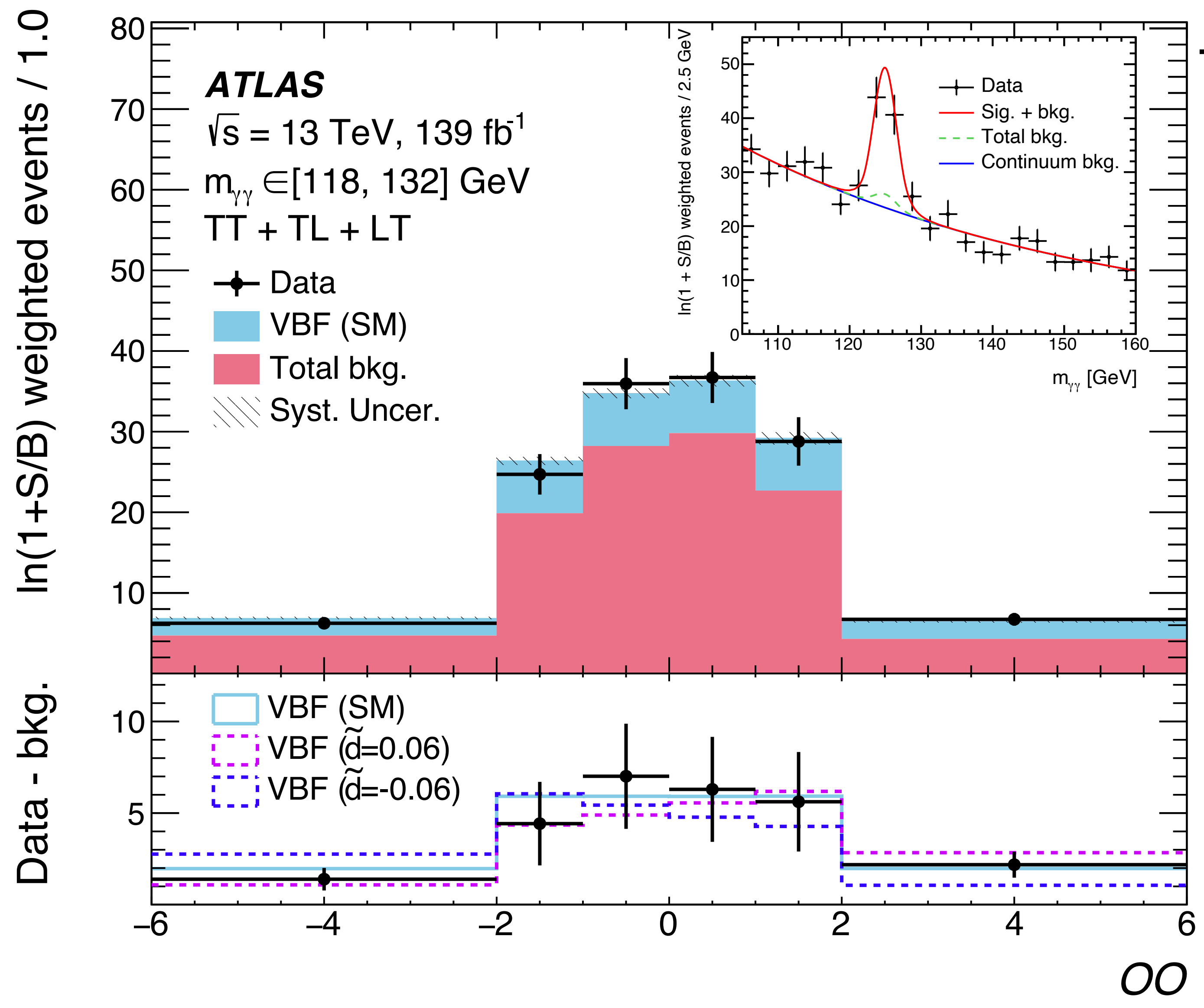


3 SRs (TT, LT, LL) constructed in 2D BDT plane → 10% improvement on VBF significance than previous analyses

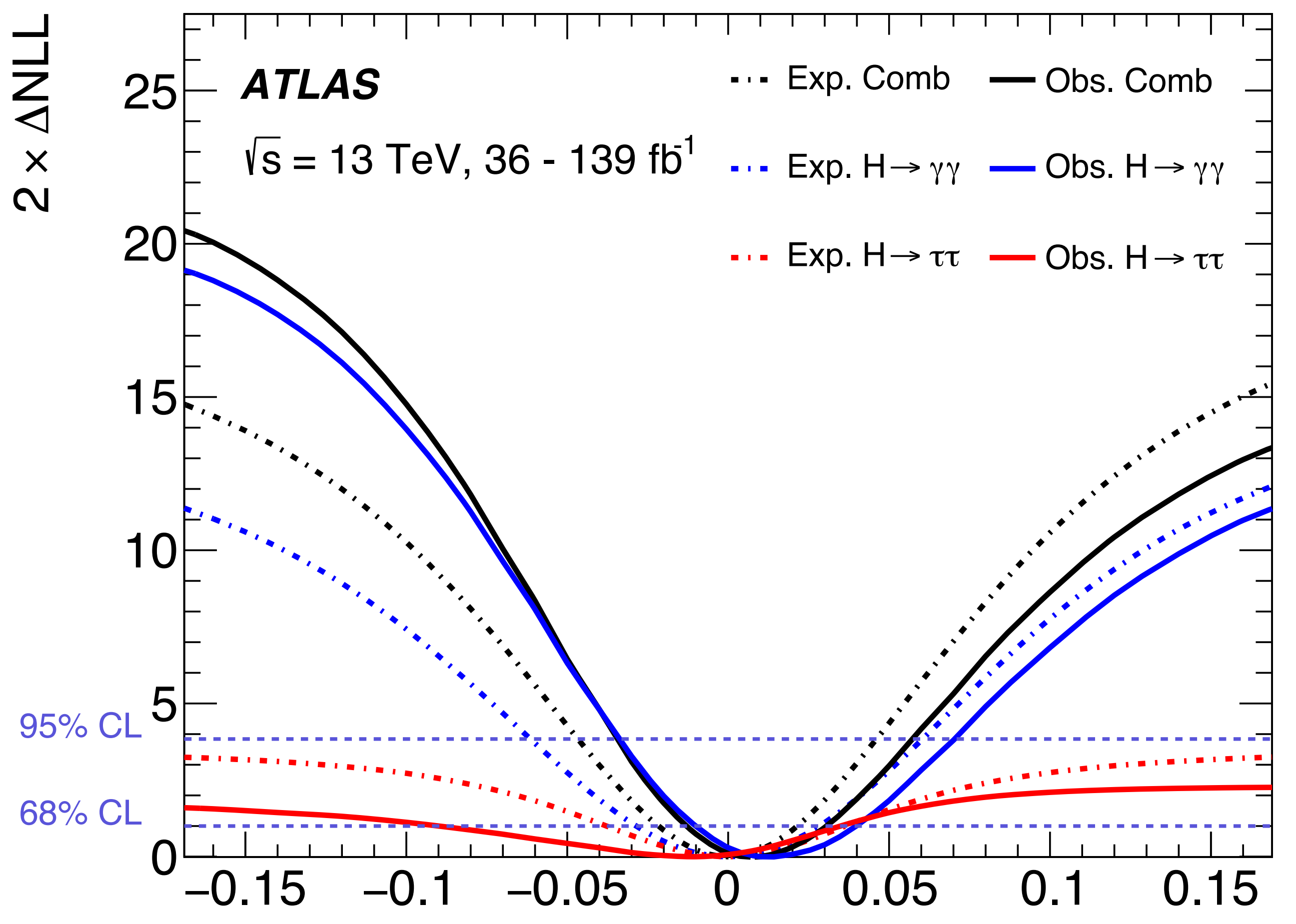




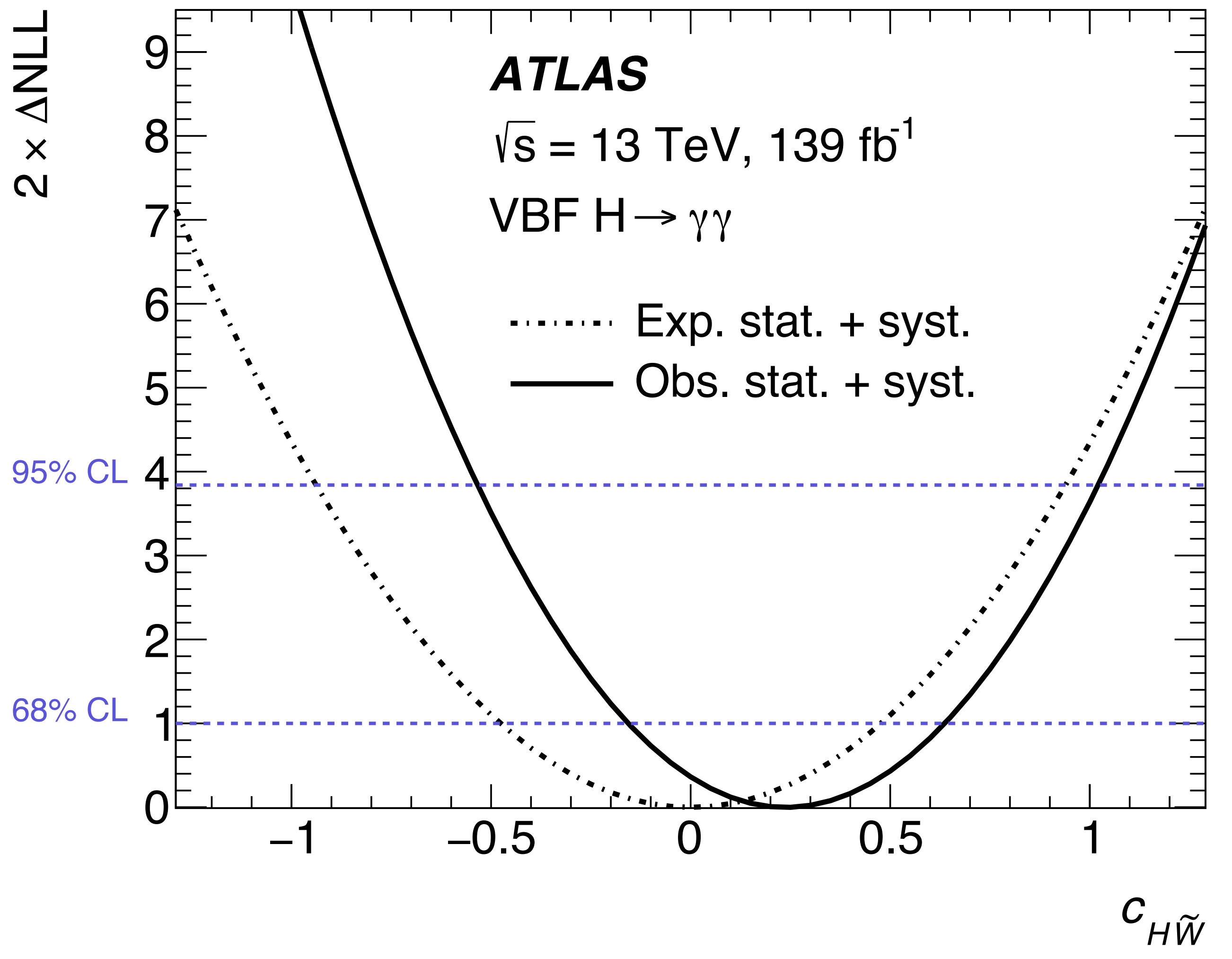
Signal extracted by combined maximum LLH fit of the spectrum in each bin



$\tilde{d}$ interpretation to combine with VBF $H \rightarrow \tau\tau$ (link)

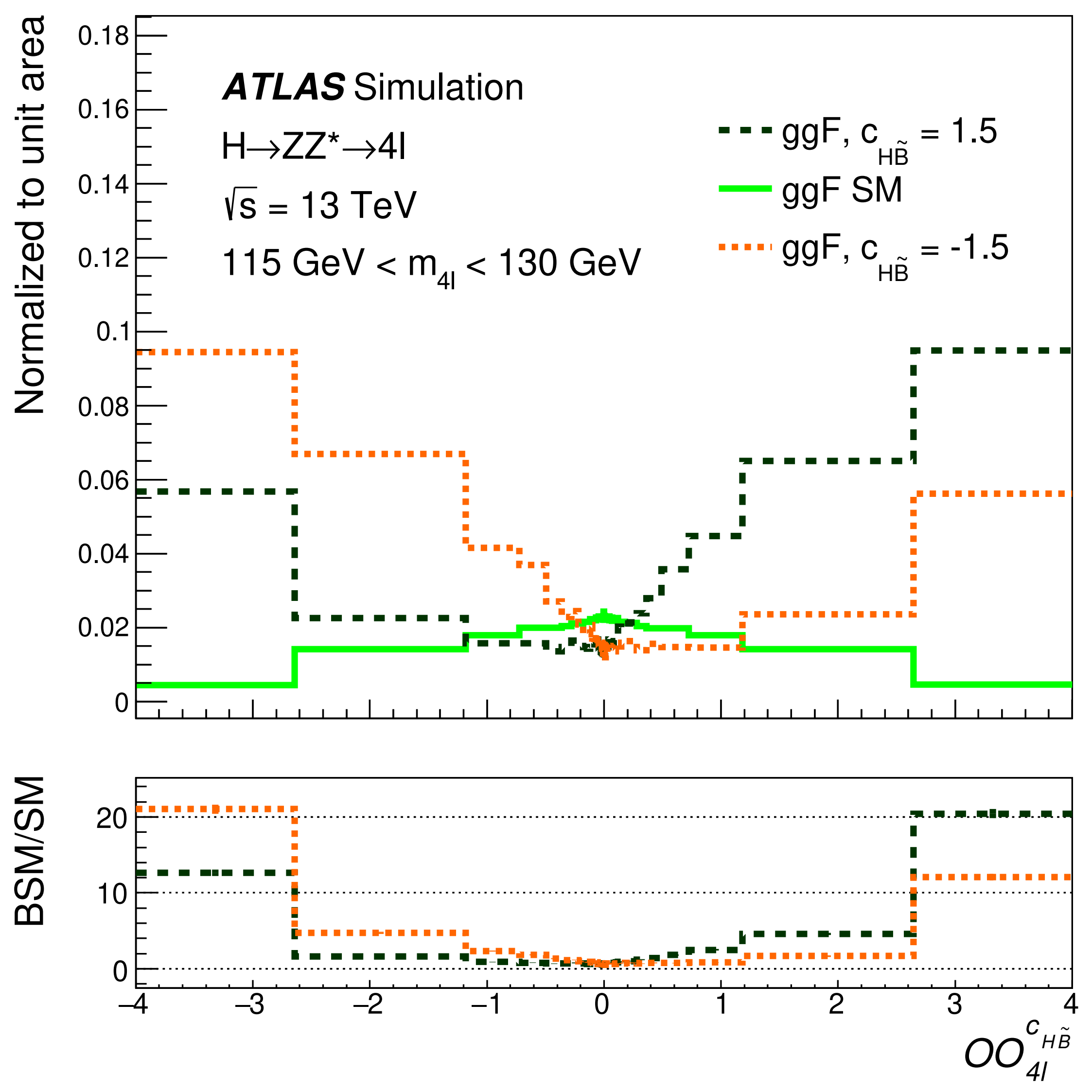


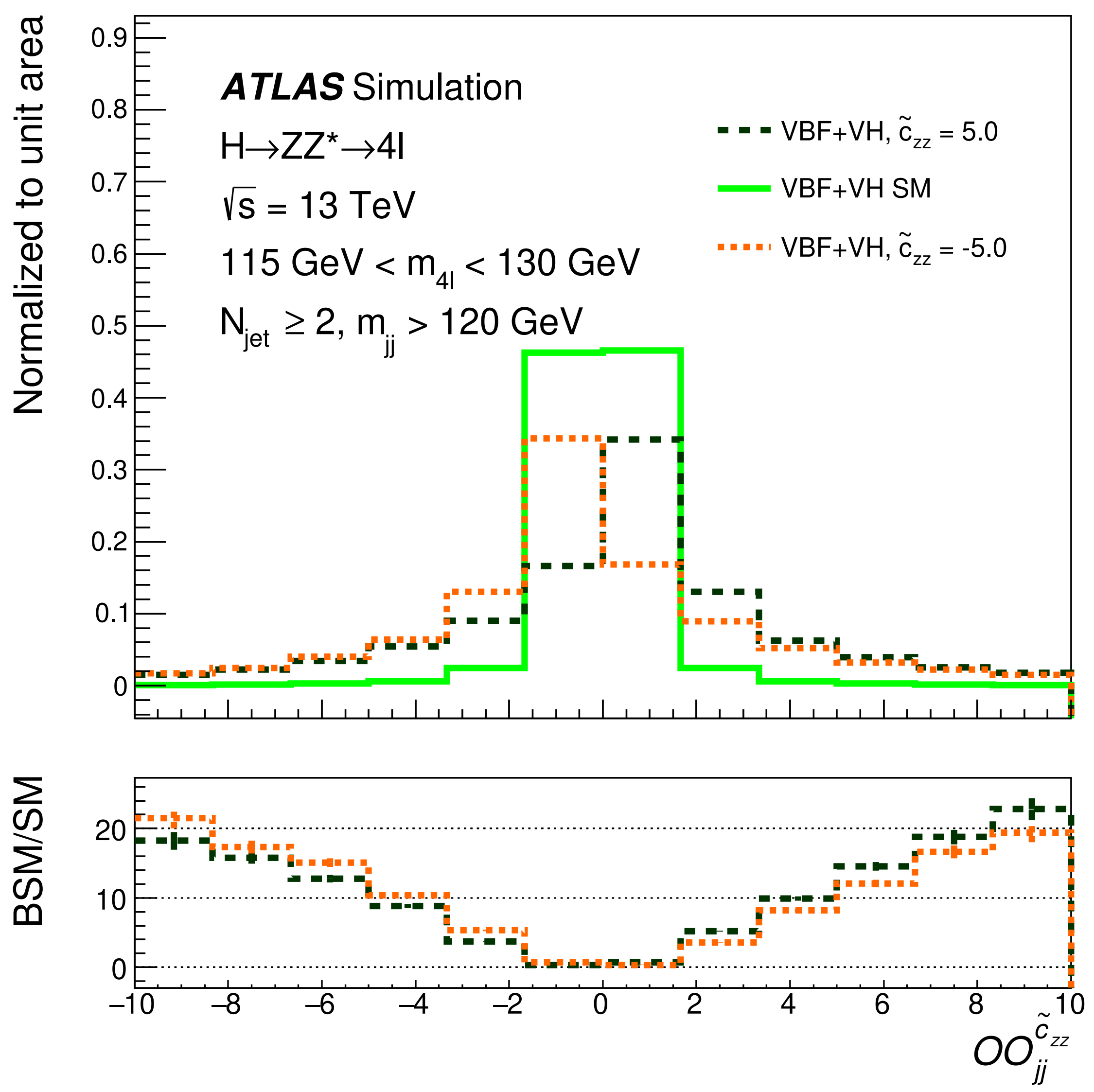
$c_{H\tilde{W}}$ interpretation to combine with other analysis

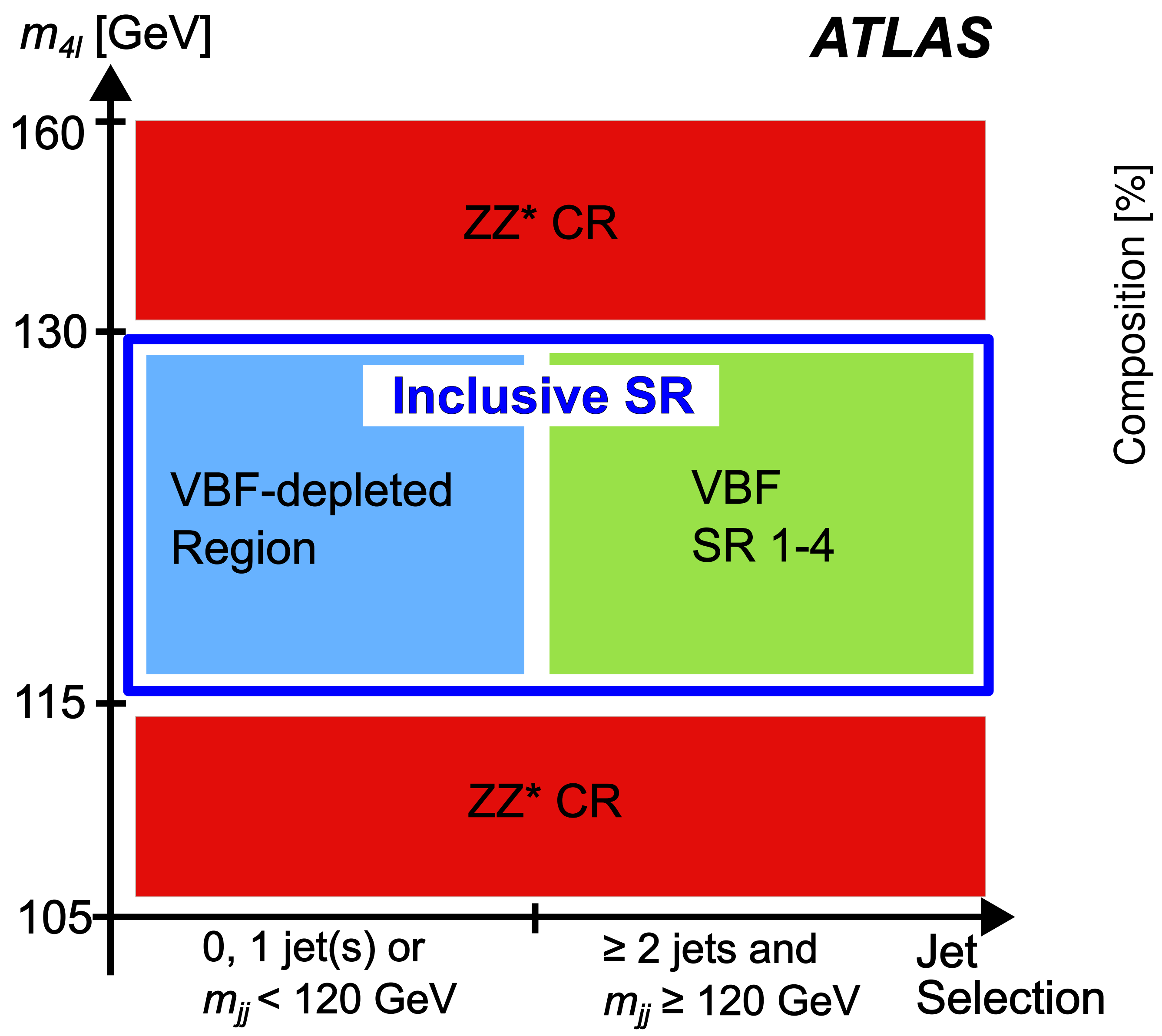


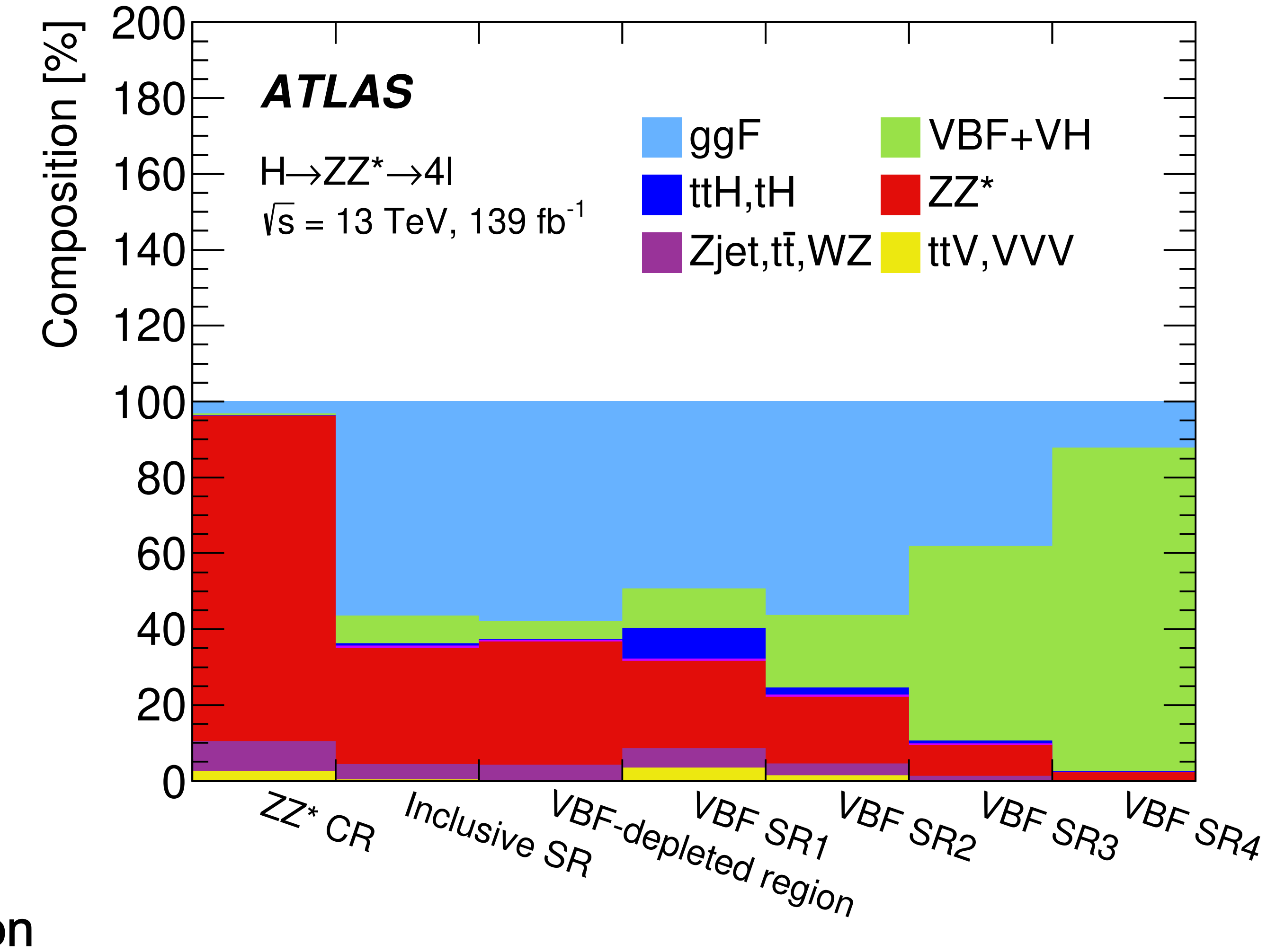
CP: VBF $H \to ZZ^* \to 4\ell$

- Measurements are performed to probe the coupling strength of CP-odd operators and differential cross-section
- Constrain HVV CP-odd effects from both production and decay in all 3 bases: $\tilde{d}$ in HISZ, Warsaw and Higgs bases → Build $\mathcal{OO}$ for each coefficients and vertices as fitted variables: $\mathcal{OO}^{c_i}_{jj}$ and $\mathcal{OO}^{c_i}_{4\ell}$
- 4 VBF SRs (with NN classifying VBF, VH and ggF) for VBF production, and 1 VBF-depleted region for $H \to ZZ$ decay (ggF dominant)



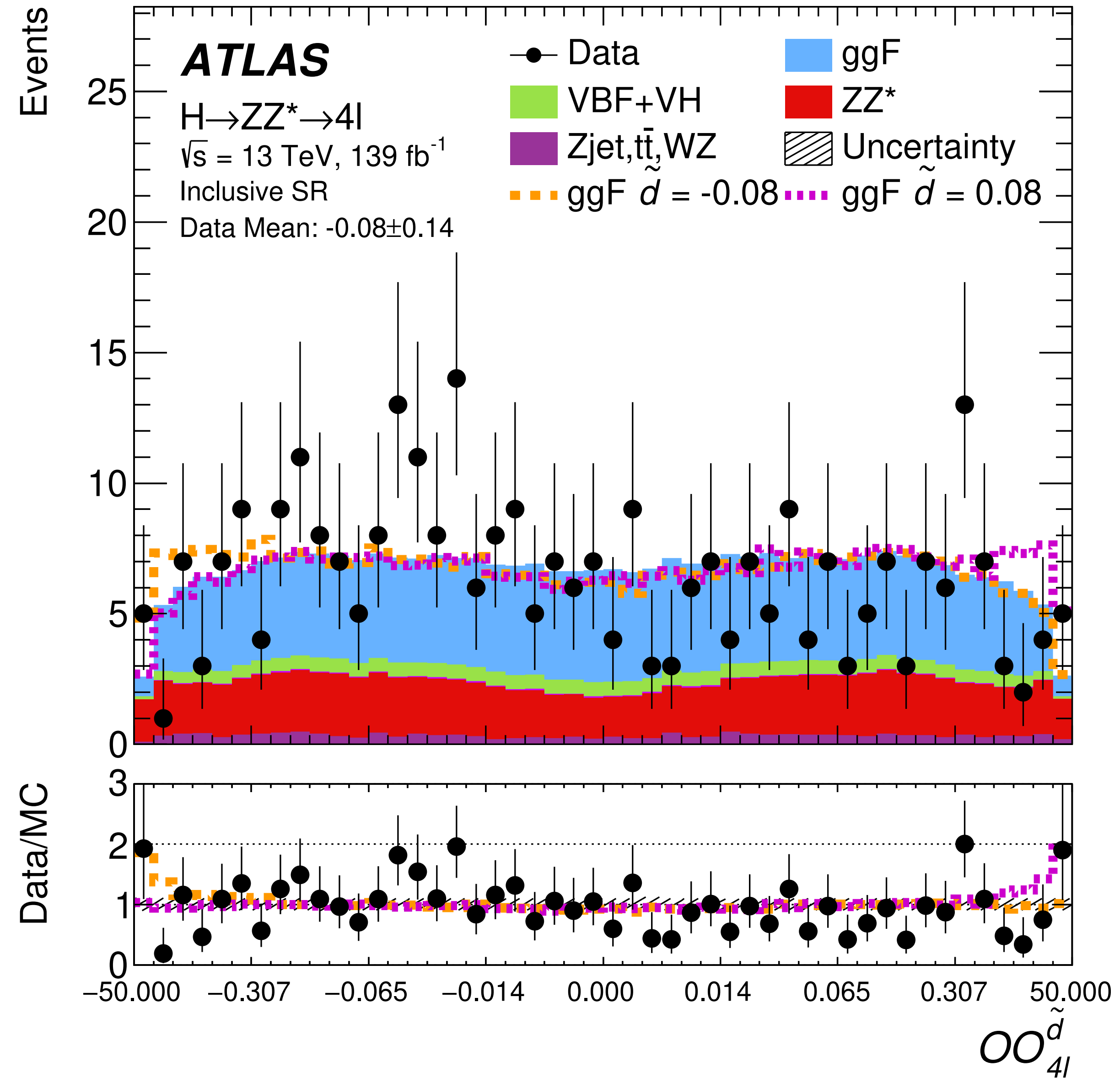


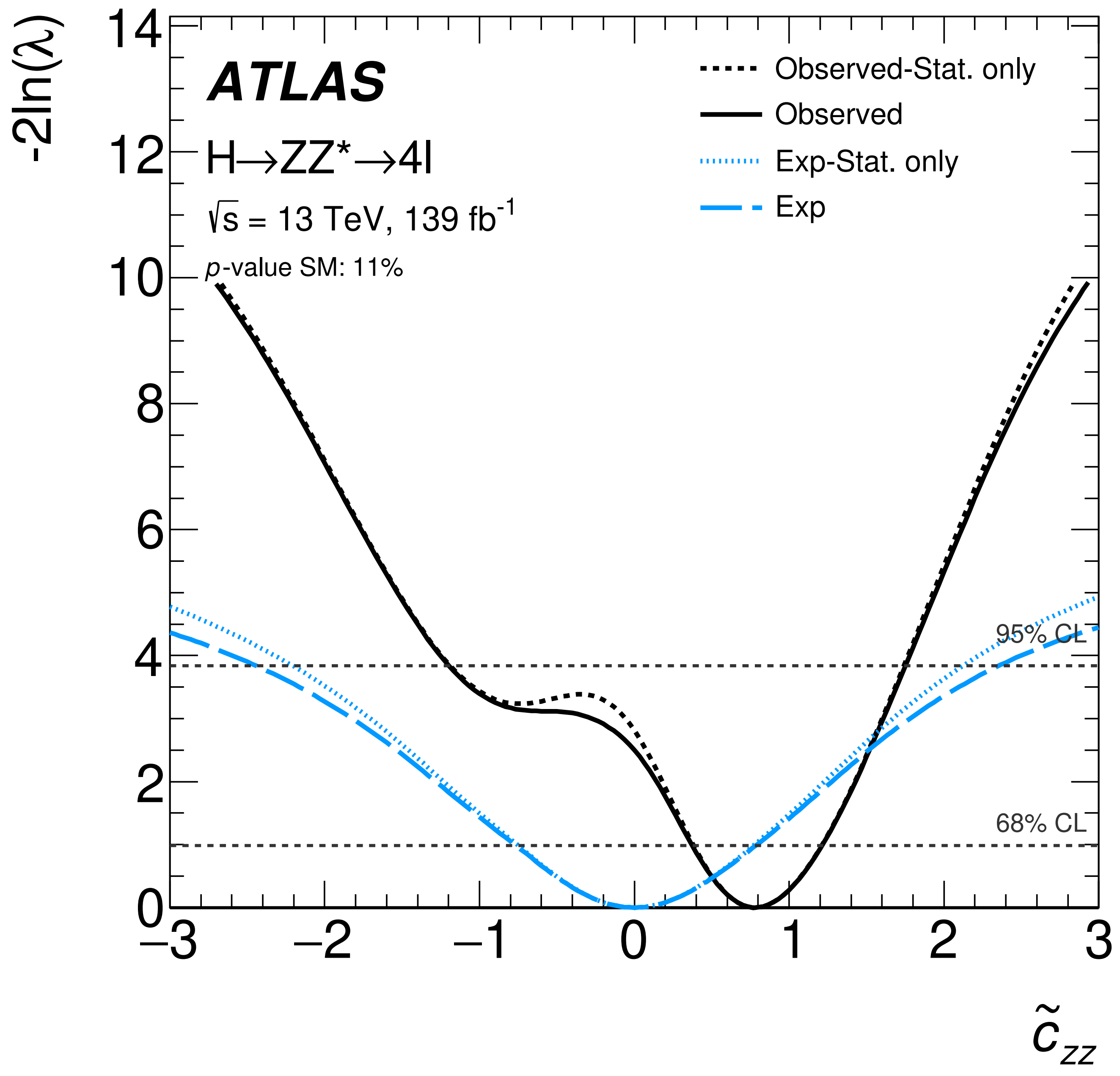


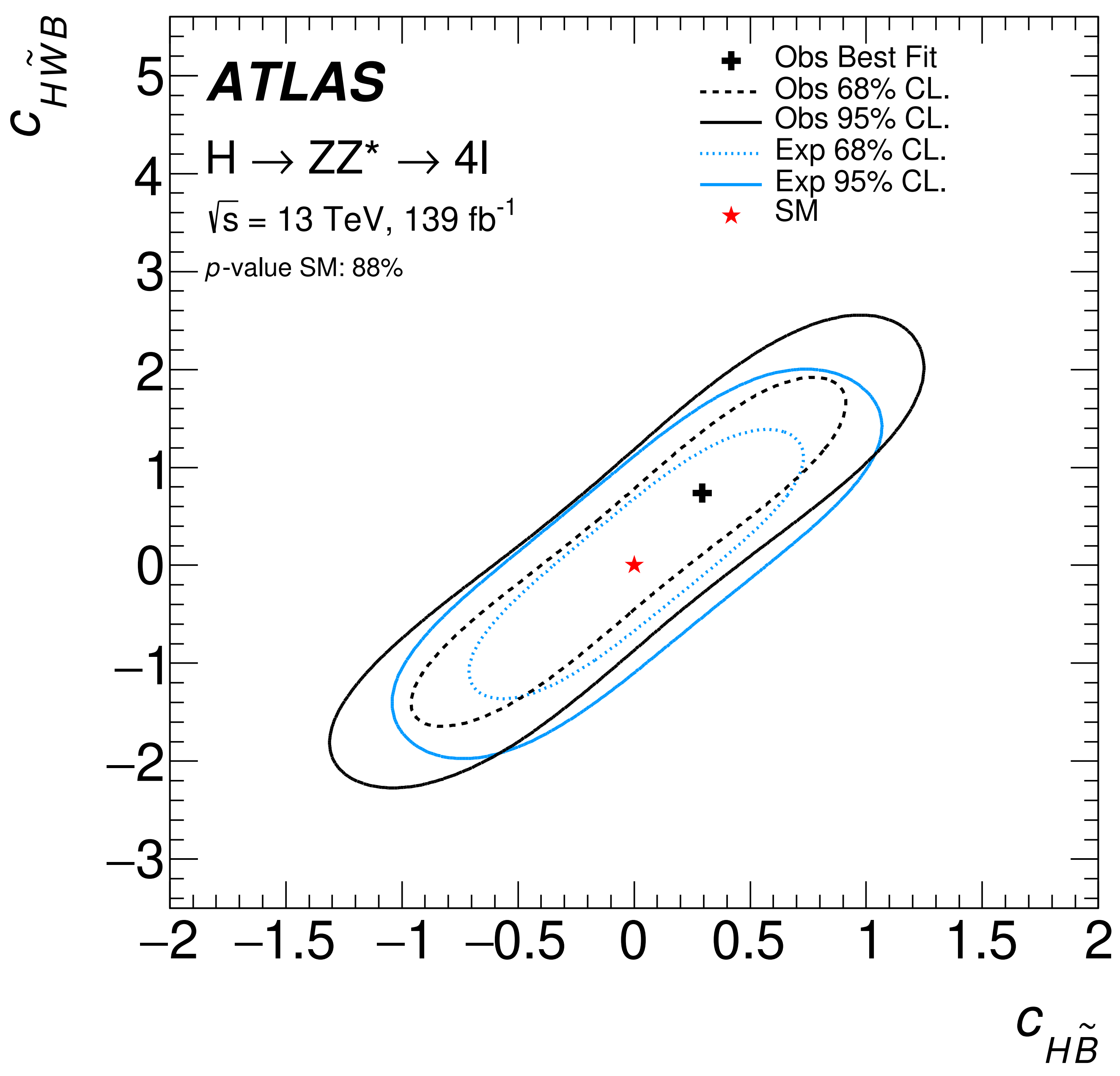


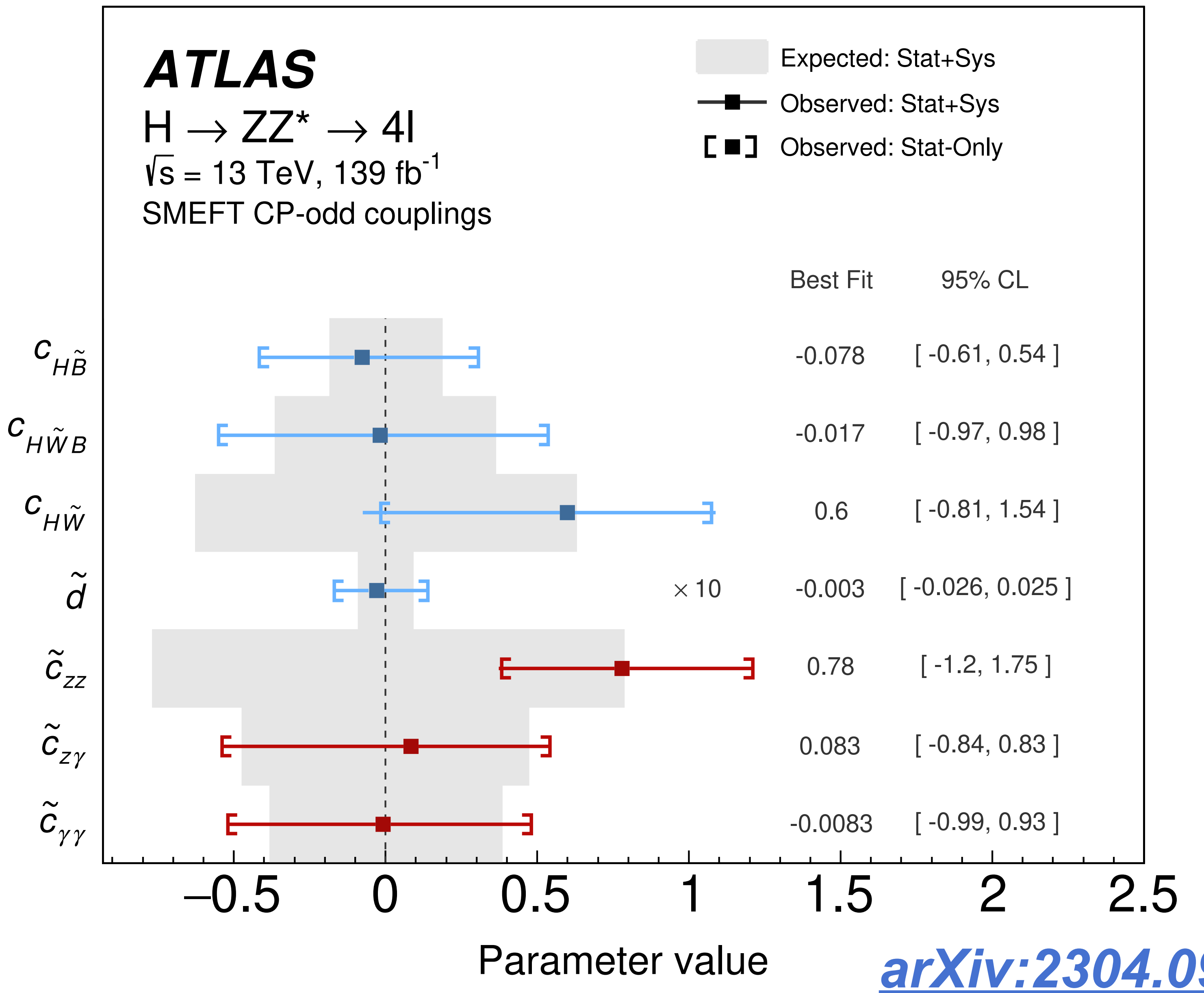
CP: VBF $H \to ZZ^* \to 4\ell$

- Maximum LLH fit performed for 3 CP-odd coupling parameters in Warsaw and Higgs basis, and for Different CP-odd hypothesis are tested using morphing
- Coupling parameters are scanned individually and in 2D



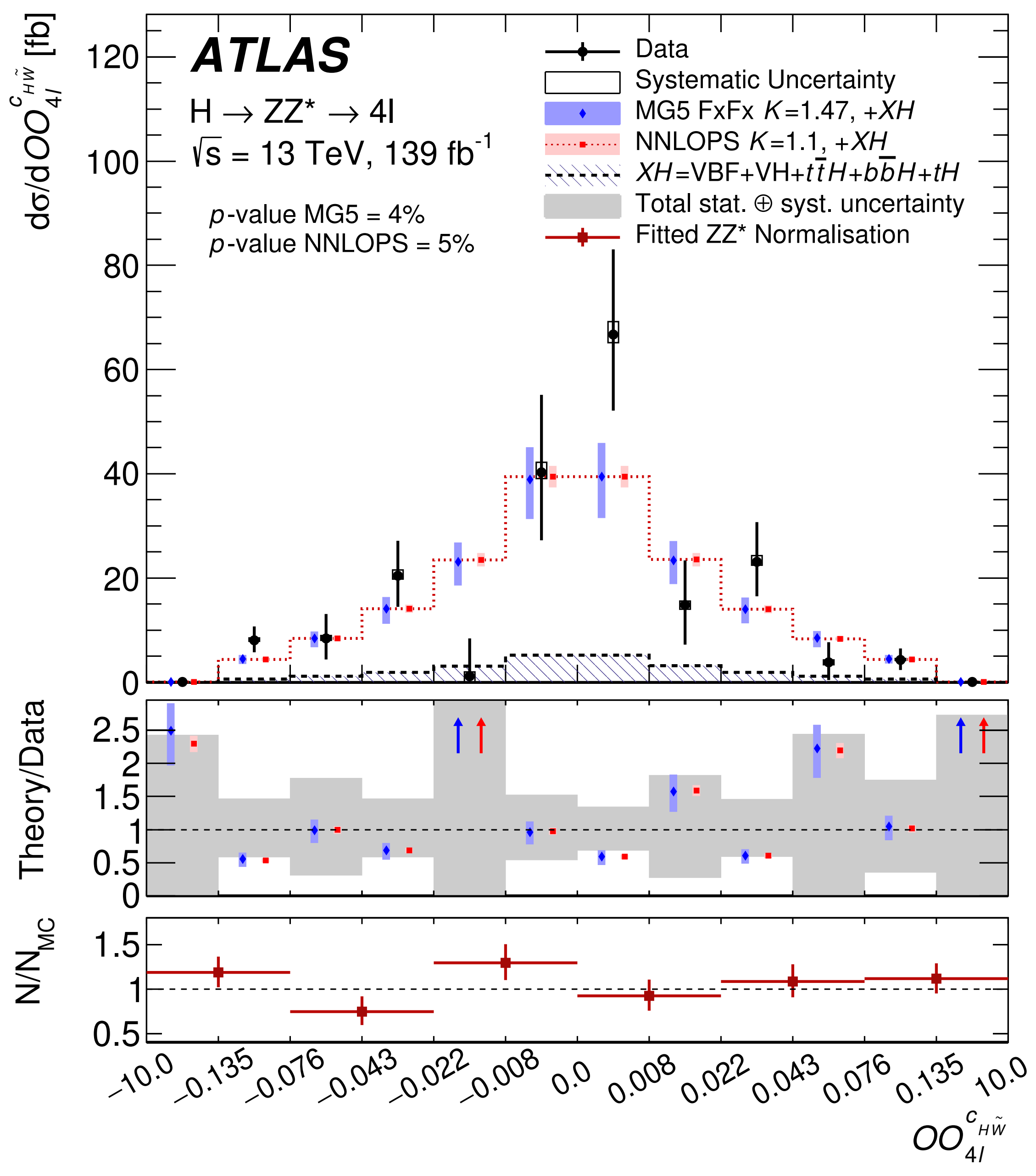


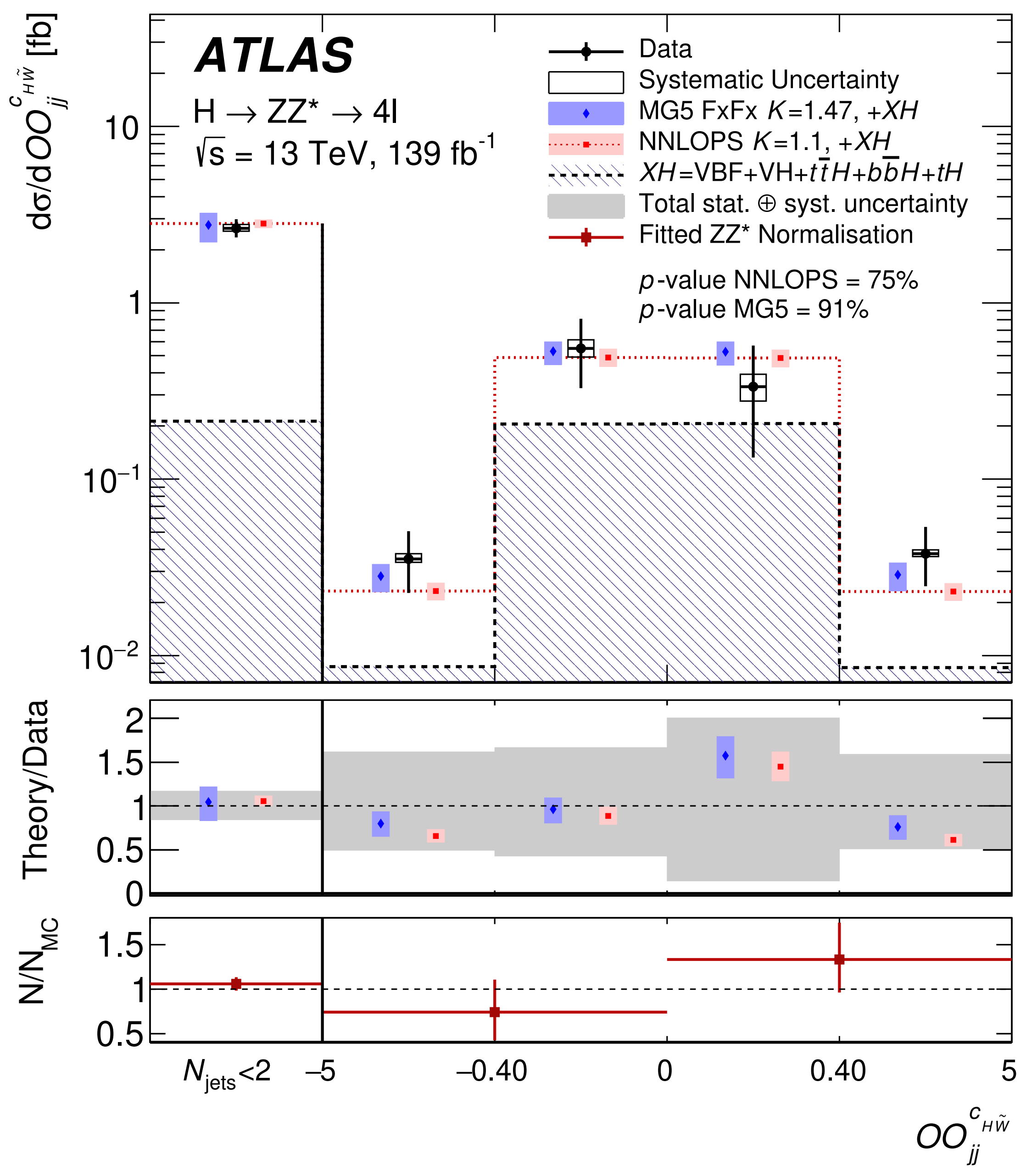


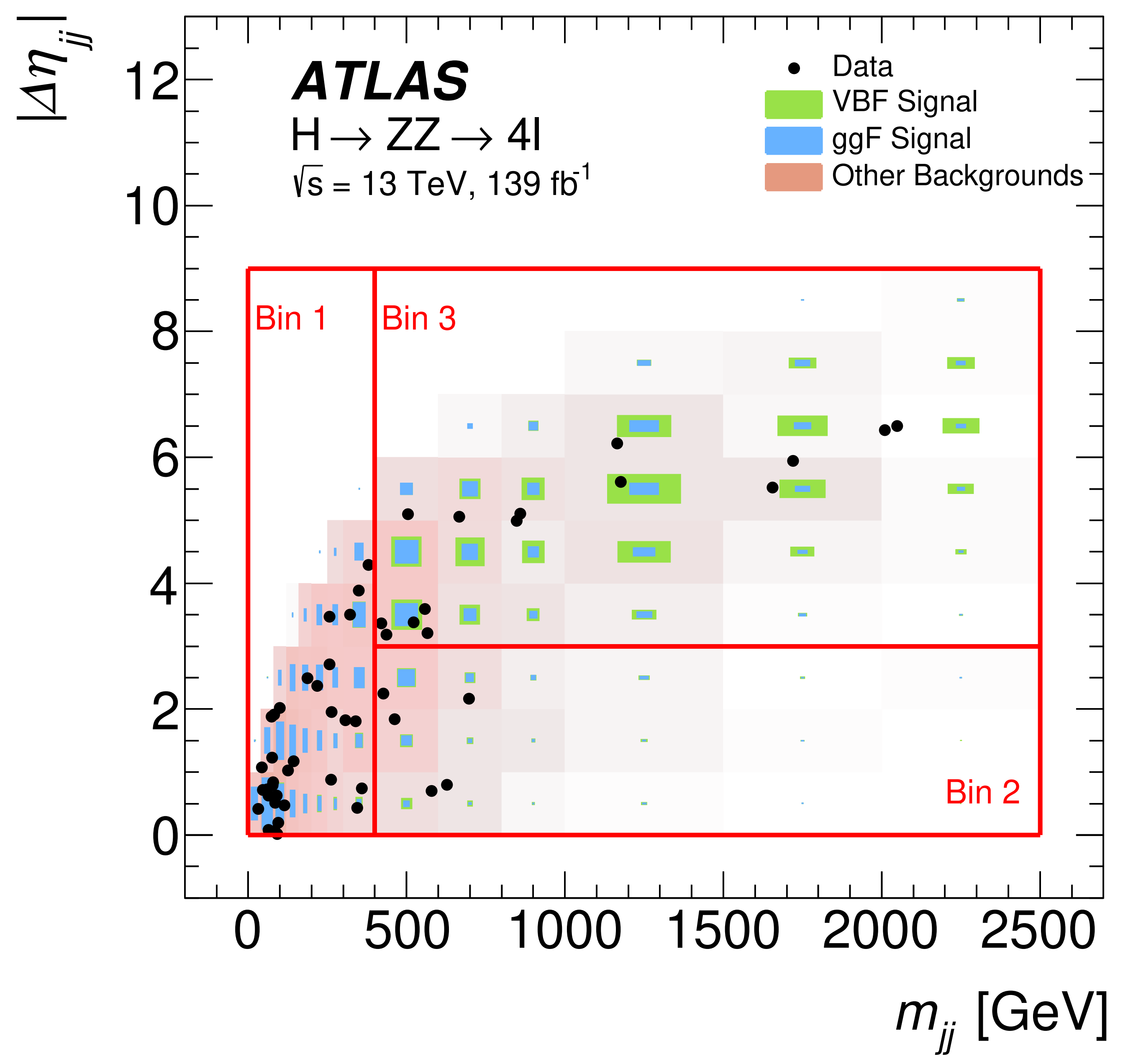


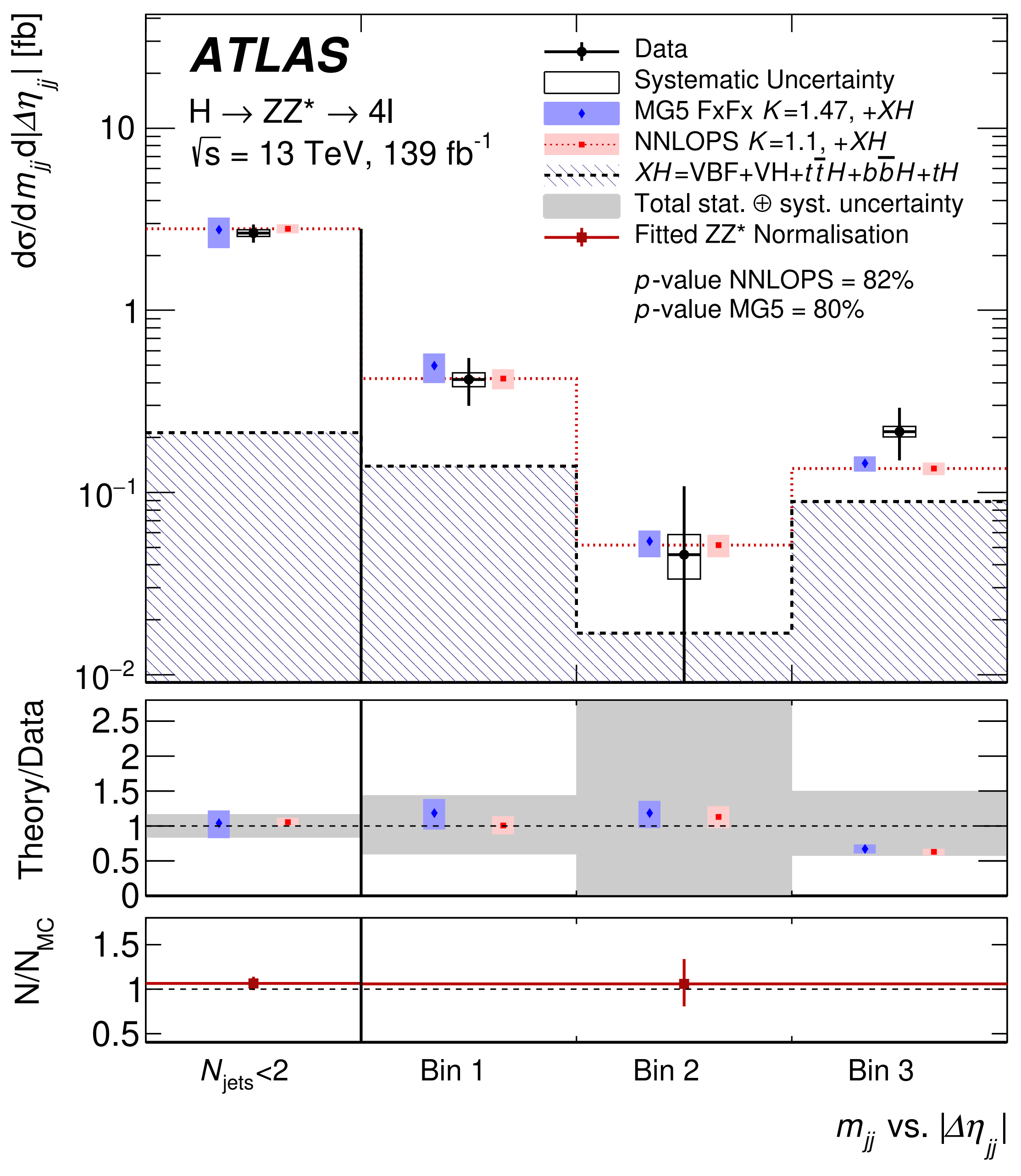
CP: VBF $H \to ZZ^* \to 4\ell$ differential

- Differential cross-section measurements for model-independent results sensitive to possible deviations from the SM
- Fiducial cross sections measured in 3 bins in the $|\eta_{jj}|$ and m_{jj}
- Probe different $\mathcal{O}\mathcal{O}$ with signal strength is extracted by fitting the $m_{4\ell}$ spectrum in each bin









Conclusion and Outlook

- Higgs mass is measured close to 0.1% level precision
- Higgs width measurements push the limits closer to SM expectation
- CP-structure of the Higgs couplings are studied in multiple final states with different coupling parameters
- Stronger exclusion limits on pure CP-odd Higgs and so far no sign of any significant CP-odd component in HVV or Hff couplings
- VBF coupling results reported in Warsaw and Higgs basis, and for easier comparisons and combination. First differential cross-section results for different $\mathcal{O}\mathcal{O}$
- Looking forward to analyses including Run 3 data with 66 fb^{-1} on tapes so far, and two more years of data taking ahead of us

Backup

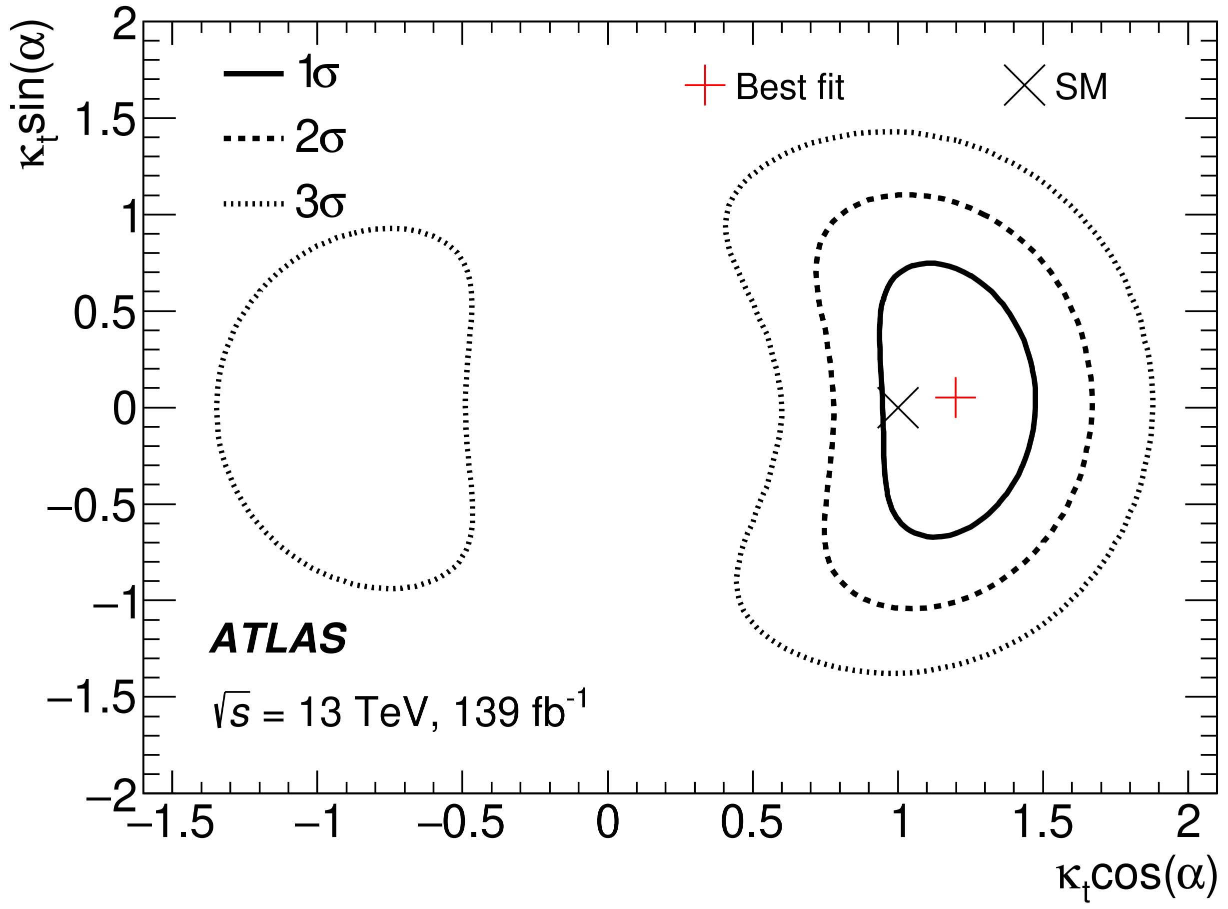
CP: $t\bar{t}H/tH$ with $H \to \gamma\gamma$

$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t\kappa_t[\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\}H$$

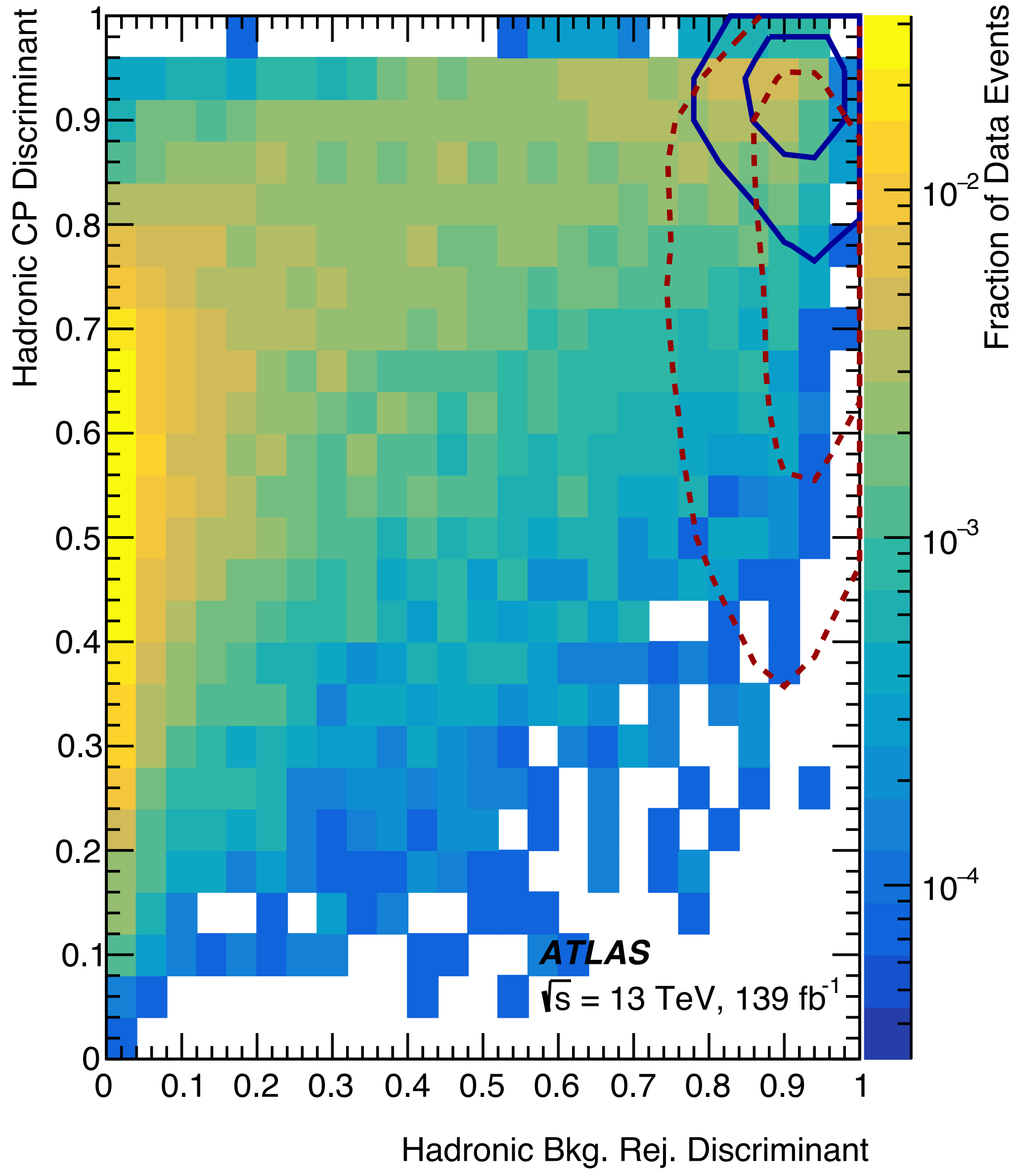
ATLAS EXPERIMENT

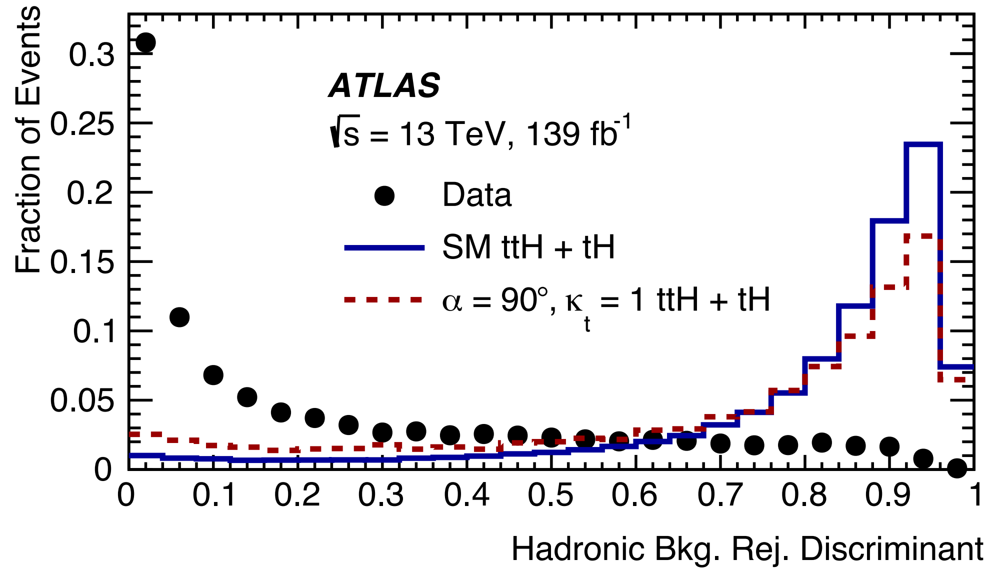
- $t\bar{t}H/tH$ processes are directly sensitive to Higgs-top Yukawa coupling
- Two BDTs to define 20 categories, which maximizing sensitivity, in leptonic and hadronic channels
- Observed $\mu_{t\bar{t}H} = 1.43^{+0.33}_{-0.31}\,(\text{stat})^{+0.21}_{-0.15}\,(\text{syst})$ with 5.2 σ significance
- The 95% CL limit of 12 times of SM expectation is set for tH
- CP-odd coupling of Higgs-top is constrained, with $|\alpha| > 43°$ excluded at 95% CL.

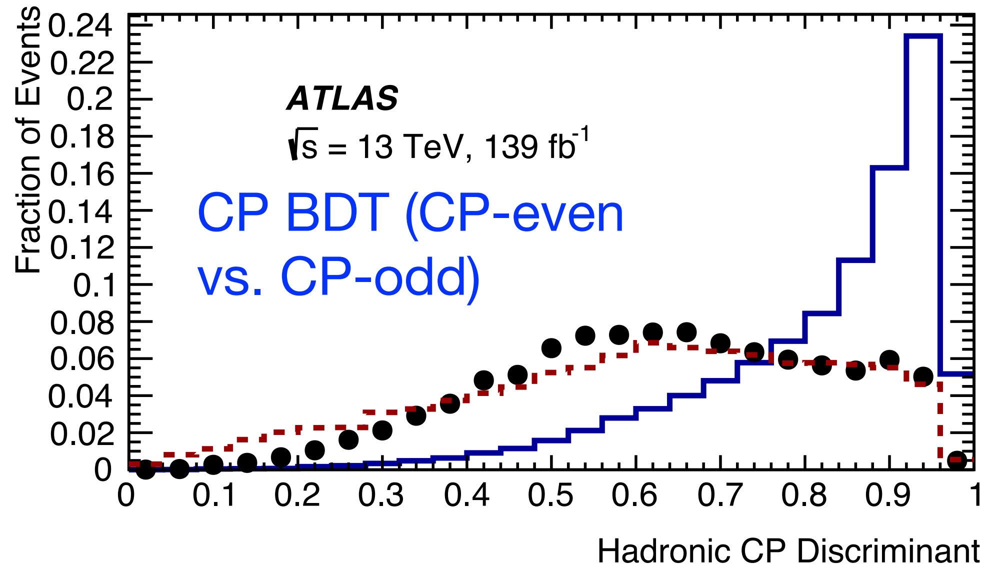
Pure CP-odd disfavored at 3.9 σ



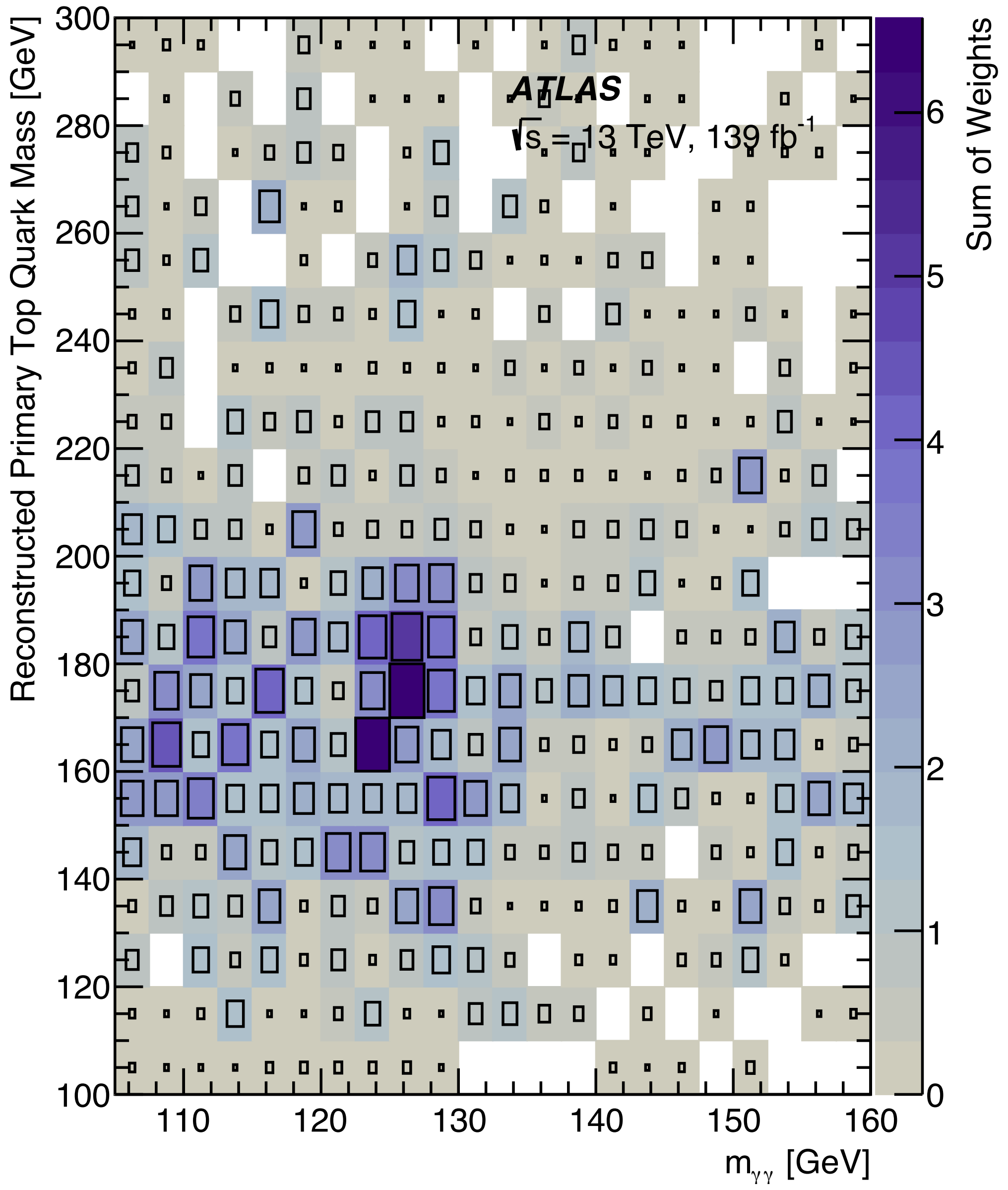
Background rejection BDT ($t\bar{t}H$ vs. Bkg)

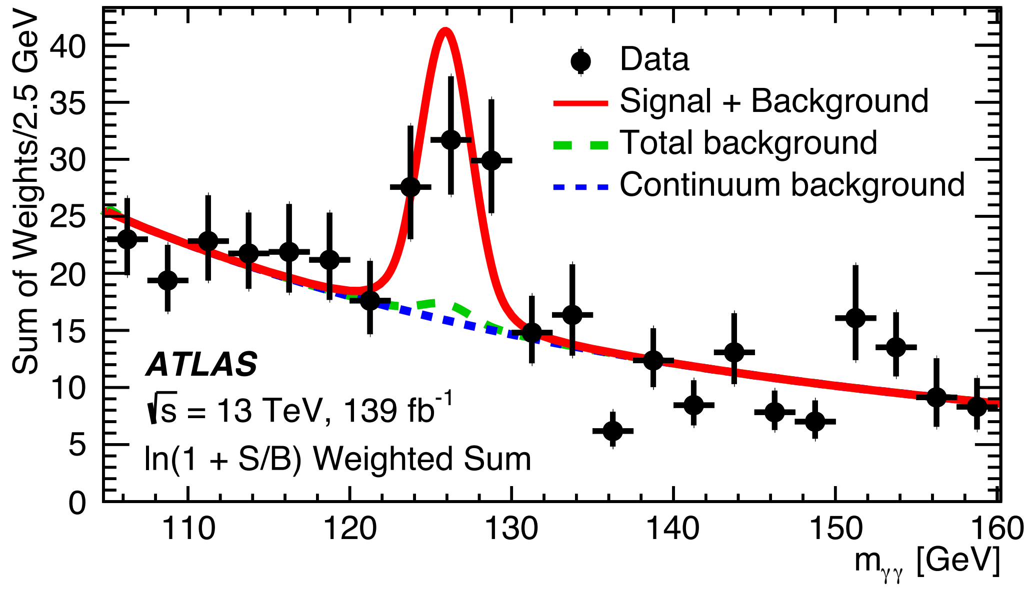


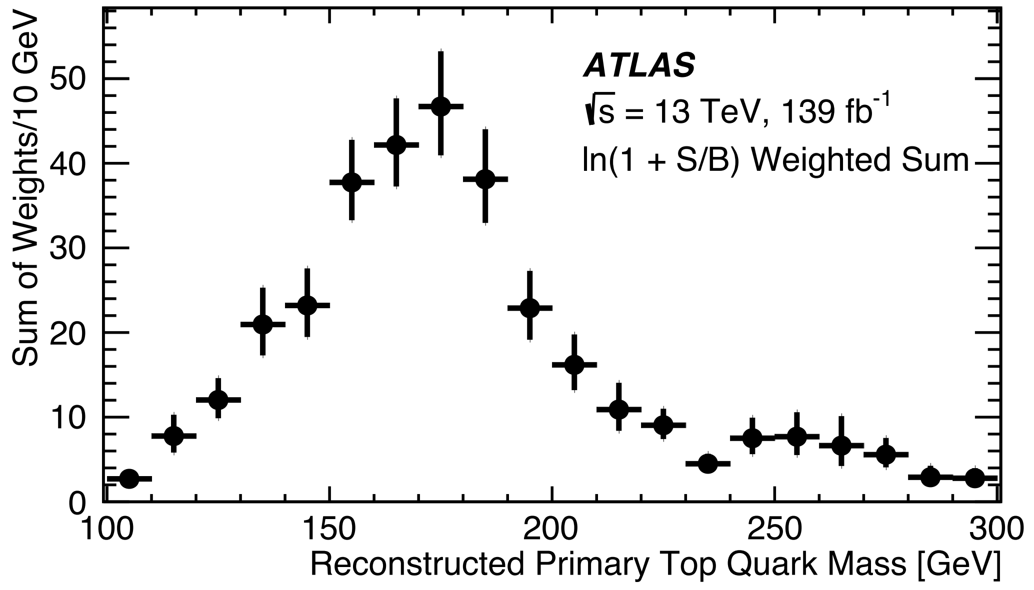




Top reconstruction by a Top Reco BDT







Matrix element method

ATLAS EXPERIMENT

- Matrix element method calculates the matrix element (probability) that the event with reconstructed kinematics $\vec{x}$ matches the hypothesis α
- Therefore, $KD(ZZ*)$ provides a ratio of two terms
  - Matrix element for an event to be likely from Higgs production (signal would have larger probability)
  - Matrix element for an event to be likely from ZZ background production (background would have larger probability)

$$KD\left(ZZ^{*}\right) = ln\left(\frac{\left|M_{ggH}\right|^{2}}{\left|M_{ZZ}\right|^{2}}\right)$$