ATLAS measurement of CP-invariance in VBF $H \rightarrow \tau\tau$

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http://arxiv.org/pdf/1602.04516.pdf

Why is CP-invariance interesting?

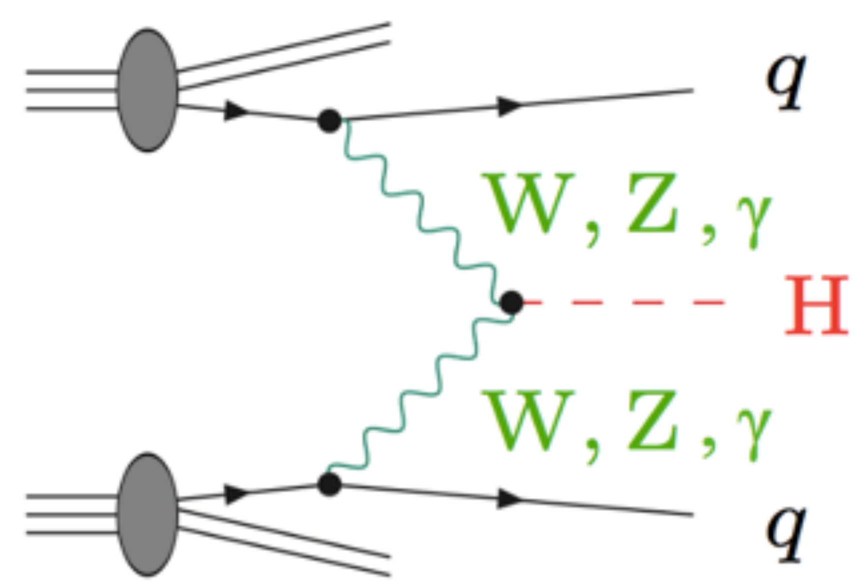
3 conditions needed to to explain observed baryon asymmetry in the Universe

Sakharov conditions:
- B violation
- C and CP violation
- non-thermal equilibrium

CP-violation in the quark sector not large enough!

with Higgs discovery opportunity to search for new sources of CP violation
- pure CP-odd Higgs boson couplings already unlikely
- how about CP-mixing?

Probe tensor structure of HVV coupling in VBF
– CP-odd contribution is clear indication of new physics



Parametrisation of CP-odd coupling

Effective field theory Lagrangian with CP-odd terms:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

- CP-mixing parametrised in terms of $\tilde{d}$ and $\tilde{d}_B$

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W)$$
$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W)$$
$$\tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$
$$\tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d}\,.$$

- contributions from the various electroweak gauge-boson fusion processes cannot be distinguished experimentally

—> set $\tilde{d} = \tilde{d}_B$

$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$$
$$\tilde{g}_{HAZ} = 0$$

- Because of this assumption, can directly compare with results from HWW/HZZ CP-analyses (arXiv:1506.05669)

$$\tilde{d} = -\hat{\kappa}_W = -\tilde{\kappa}_W/\kappa_{SM}\tan\alpha$$

Parametrisation of CP-odd coupling

Using $\tilde{d}$ as strength parameter, we can look at deviations in ME:

Matrix element $M_{\text{tot}} = M_{\text{SM}} + \tilde{d} \cdot M_{\text{odd}}$

~Cross-section

$$|M_{\text{tot}}|^2 = |M_{\text{SM}}|^2 \qquad \text{(CP-even)}$$
$$+\tilde{d} \cdot 2\,\text{Re}[M_{\text{SM}}^* M_{\text{odd}}] \qquad \text{(CP-odd)}$$
$$+\tilde{d}^2 \cdot |M_{\text{odd}}|^2 \qquad \text{(CP-even)}$$

Interference term $\tilde{d} \cdot 2\,\text{Re}[M_{\text{SM}}^* M_{\text{odd}}]$

CP-odd, no contribution to xsection, source of CP violation

Quadratic term $\tilde{d}^2 \cdot |M_{\text{odd}}|^2$

CP-even, quadratic contribution to xsection, no contribution to CP violation

Measuring CP-invariance

Assuming a CP conserving interaction, the expectation value of a CP odd observable $\mathcal{A}$ integrated over the whole CP-symmetric phase space Ω will be zero:

$$\langle \mathcal{A} \rangle = \int \frac{\mathcal{A}\,\mathrm{d}\Omega}{\mathrm{d}\Omega} = 0 \tag{2.52}$$

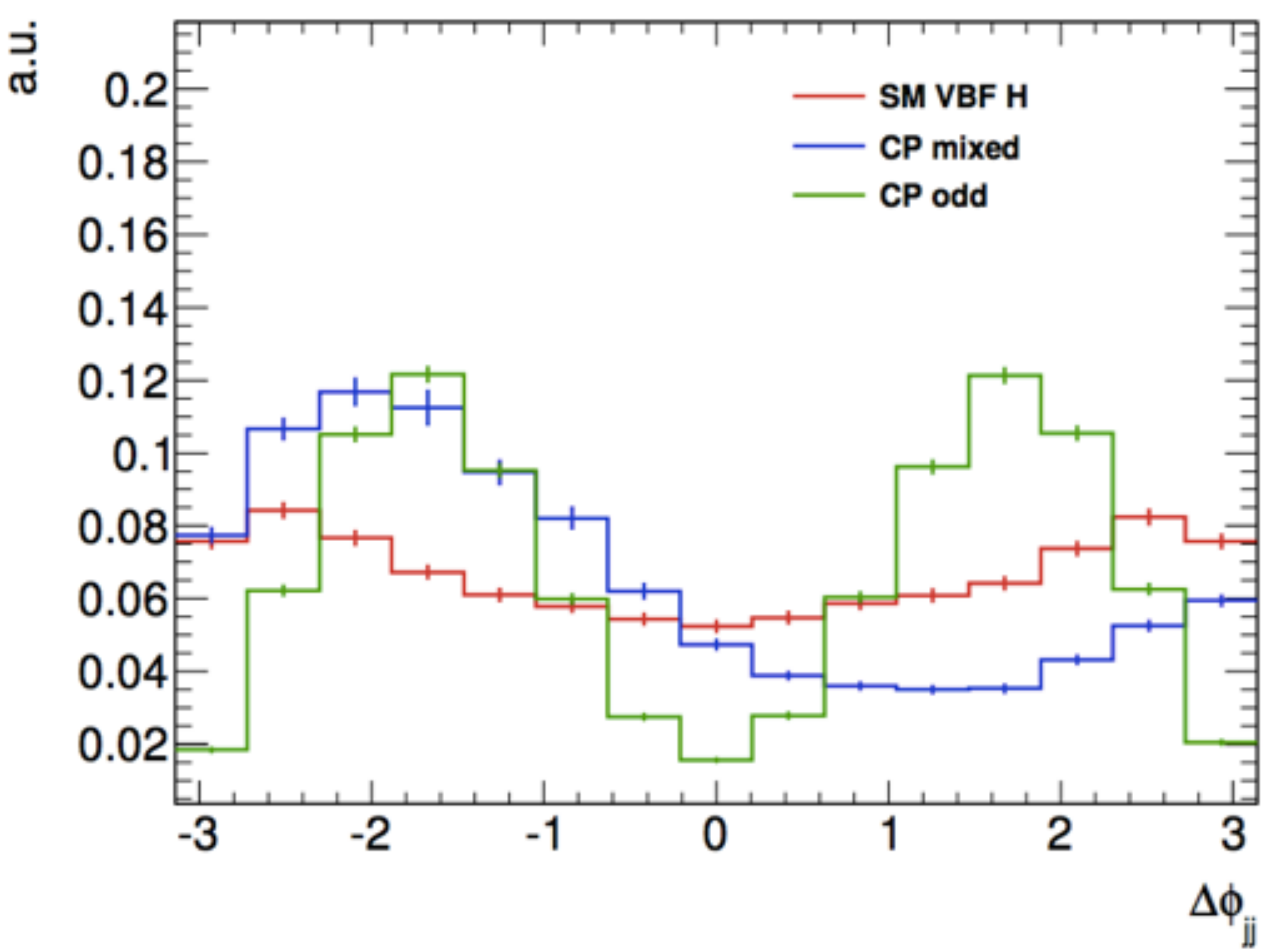
if CP is violated: $\langle \mathcal{A} \rangle \neq 0$ **← model independent test of CP-invariance!**

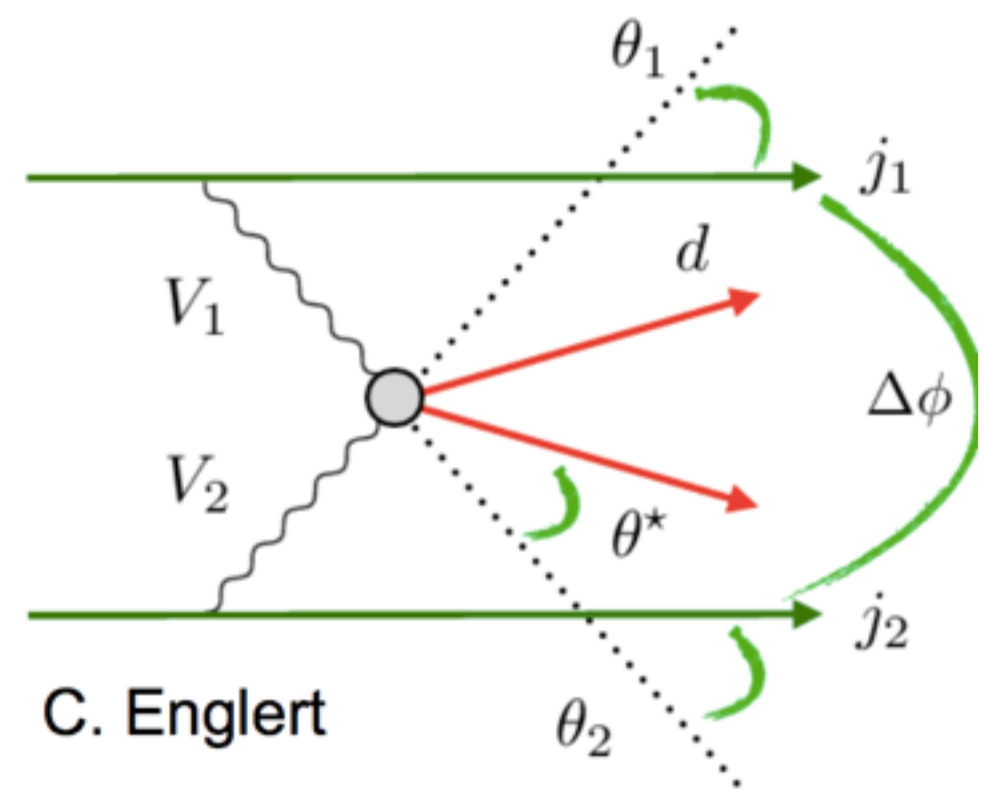
CP-odd observable: signed $\Delta\phi_{jj}$

First proposed by Hankele, Klamke, Zeppenfeld and Figy in 0609075 [hep-ph]

$$\epsilon_{\mu\nu\rho\sigma} b_+^\mu p_+^\nu b_-^\rho p_-^\sigma = 2 p_{T+} p_{T-} \sin(\phi_+ - \phi_-) = 2 p_{T+} p_{T-} \sin \Delta\phi_{jj} \,. \qquad (11)$$

Here b_+^μ and b_-^μ denote the normalised four-momenta of the two proton beams, circulating clockwise and anti-clockwise, and p_+^μ (ϕ_+) and p_-^μ (ϕ_-) denote the four-momenta (azimuthal angles) of the two tagging jets, where p_+ (p_-) points into the same detector hemisphere as b_+^μ (b_-^μ). This ordering of the tagging jets by hemispheres removes the sign ambiguity in the standard definition of $\Delta\phi_{jj}$.





C. Englert

Optimal Observable

In principle highest sensitivity via ML fit to multidimensional phase space

$$\vec{\Phi} = (\Phi_1, \ldots, \Phi_n)$$ (VBF H 6+1 phase space observables)

Requires many simulated events for binned ML fit (curse of dimensionality)

$$d\sigma(\vec{\Phi}) = d\sigma_0 + \eta \cdot d\sigma_1 + \eta^2 \cdot d\sigma_2$$

$$\mathcal{L} = \prod_{i=1}^{N_{data}} d\sigma_i$$

$$\log \mathcal{L} = \sum_{i=1}^{N_{data}} \log \left(d\sigma_0 + \eta \cdot d\sigma_1 + \eta^2 \cdot d\sigma_2\right)$$

$$\frac{d \log \mathcal{L}}{d\eta} = \sum_{i=1}^{N_{data}} \frac{d\sigma_1 + \eta \cdot \sigma_2}{d\sigma_0 + \eta \cdot d\sigma_1 + \eta^2 \cdot d\sigma_2} = 0$$

$$\sum_{i=1}^{N_{data}} \frac{O_1 + \eta \cdot O_2}{1 + \eta \cdot O_1 + \eta^2 \cdot O_2} = 0$$

Same sensitivity in fit to one dimensional optimal observable OO distributions

$$O_1 = \frac{d\sigma_1}{d\sigma_0}, \qquad O_2 = \frac{d\sigma_2}{d\sigma_0}$$

for small η only
1st order observable O_1 = OO

Optimal Observable techniques used extensively at LEP!

First order Optimal Observable

Neglecting squared term in ME (or assuming $\tilde{d}$ small), fit to one-dimensional optimal observable has same power as full multi-dimensional fit

$$OO = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

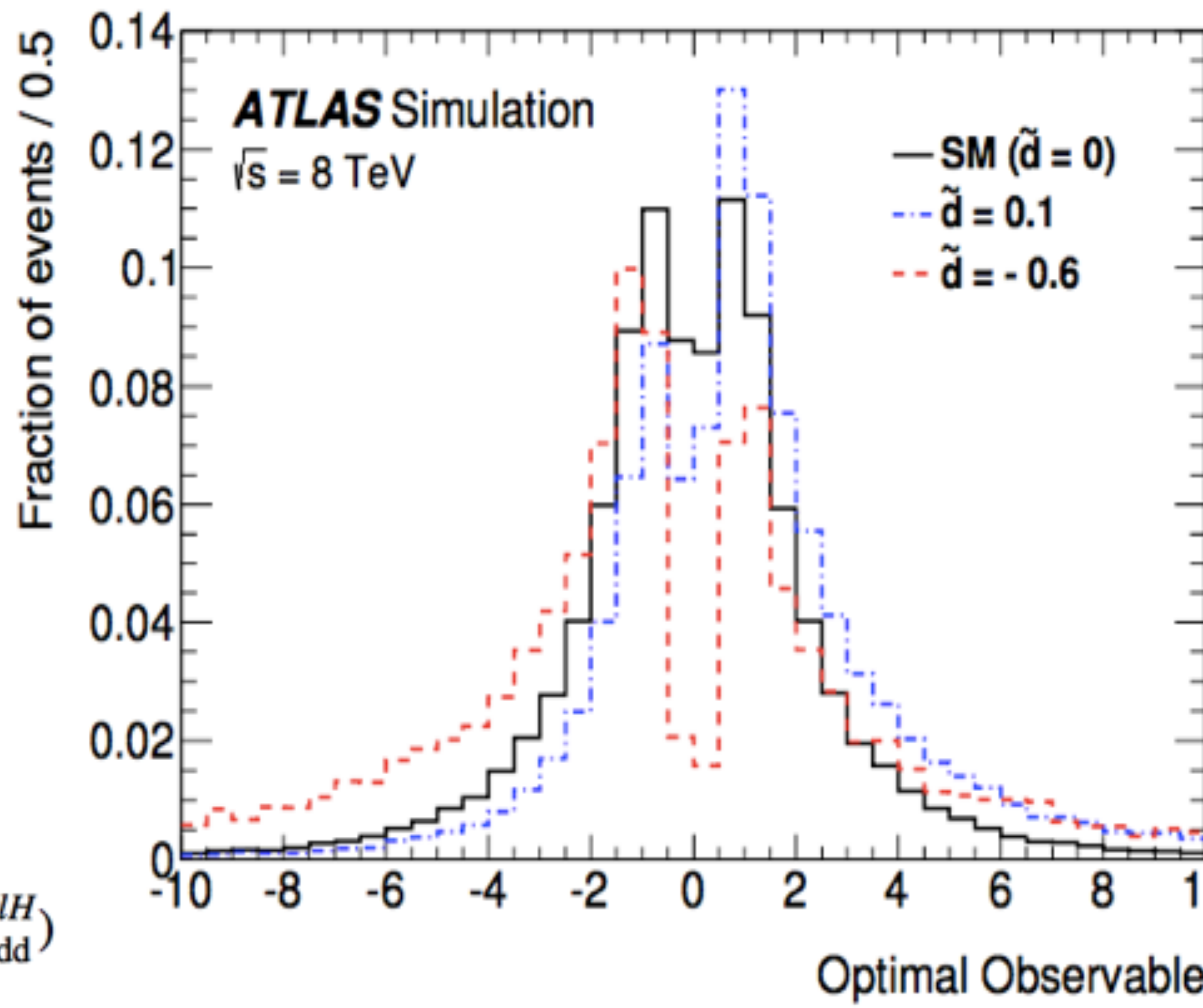
LO ME from HAWK

Calculated with:

- Higgs 4-vector, as sum of 4-vectors of reconstructed taus from MMC
- two reconstructed anti-kt jets (p_T ordered)
- Bjoerken x of initial-state partons:

$$x_{1/2} = \frac{M(jjH)}{\sqrt{s}} e^{\pm y(jjH)}$$

also include 3rd jet, if present



Flavour of the initial- and final-state partons unknown —> sum over all possible flavour configurations (CT10, LO)

$$2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}}) = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) 2\,\mathrm{Re}((\mathcal{M}^{ij\to klH}_{\mathrm{SM}})^* \mathcal{M}^{ij\to klH}_{\mathrm{CP\text{-}odd}})$$

$$|\mathcal{M}_{\mathrm{SM}}|^2 = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) |\mathcal{M}^{ij\to klH}_{\mathrm{SM}}|^2 .$$

method independent of decay mode!

Signal Modelling

- No full-simulation MC sample available for $\tilde{d} \neq 0$ —> use reweighing

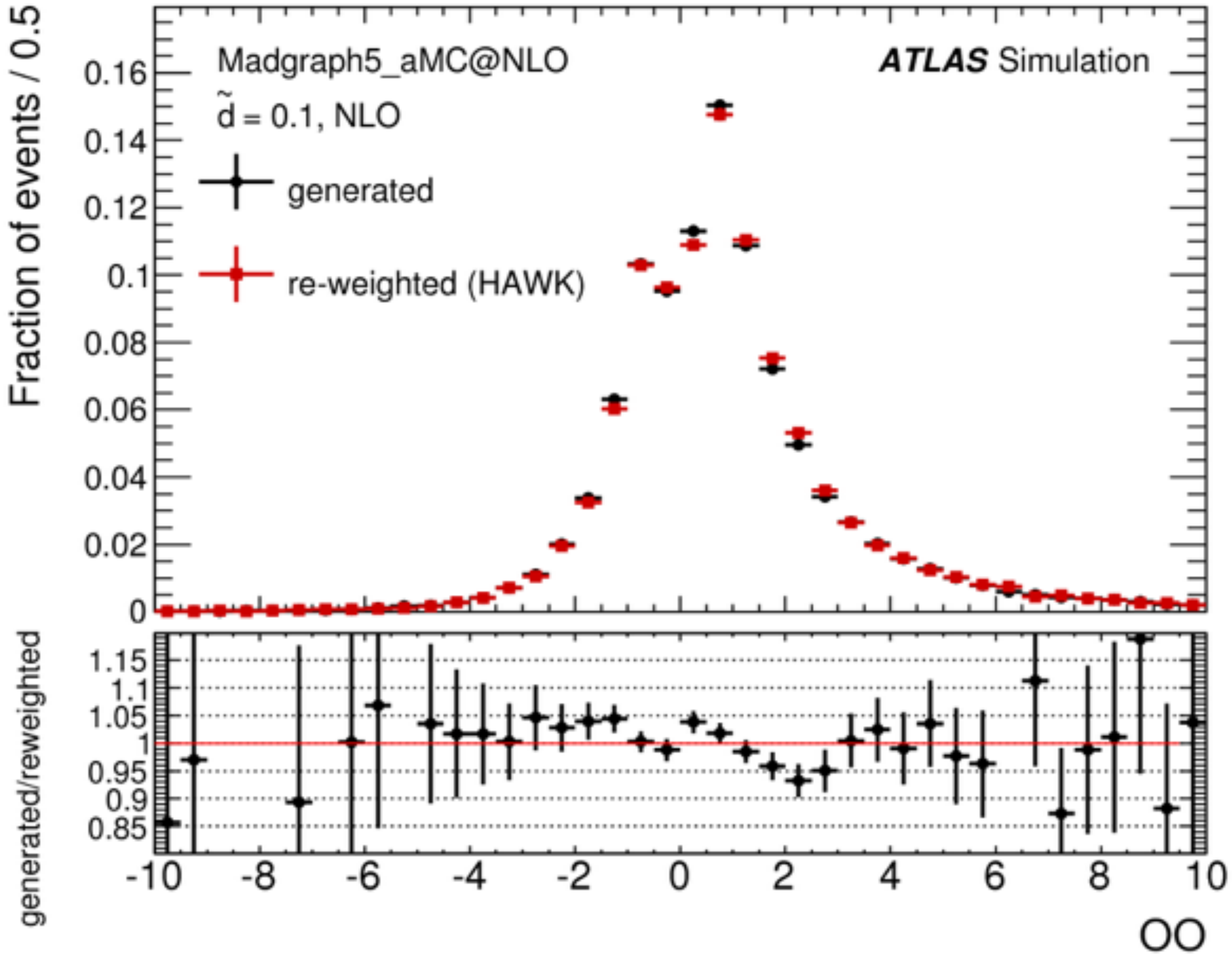
$$w = M^2(\tilde{d}) / M^2_{SM}$$

- MEs from HAWK (same code used for OO calculation)
- SM VBF Higgs signal sample: NLO POWHEG+PYTHIA
  - three possible processes: qq → qqH, qg → qq q-barH, qq → qqgH
- use appropriate ME at LO for the 2 → 2 or the 2 → 3 process, taking into account ingoing and outgoing parton flavours

Signal Modelling Validation

Reweighting validated with MG5_aMC@NLO. Compare:

- NLO SM MG5_aMC@NLO sample re-weighted
- NLO BMS MC5_aMC@NLO generated sample



shape difference used as systematic uncertainty in ML fit

Why CP-invariance in VBF H → $\tau\tau$?

H → $\tau\tau$ channel has large VBF sample

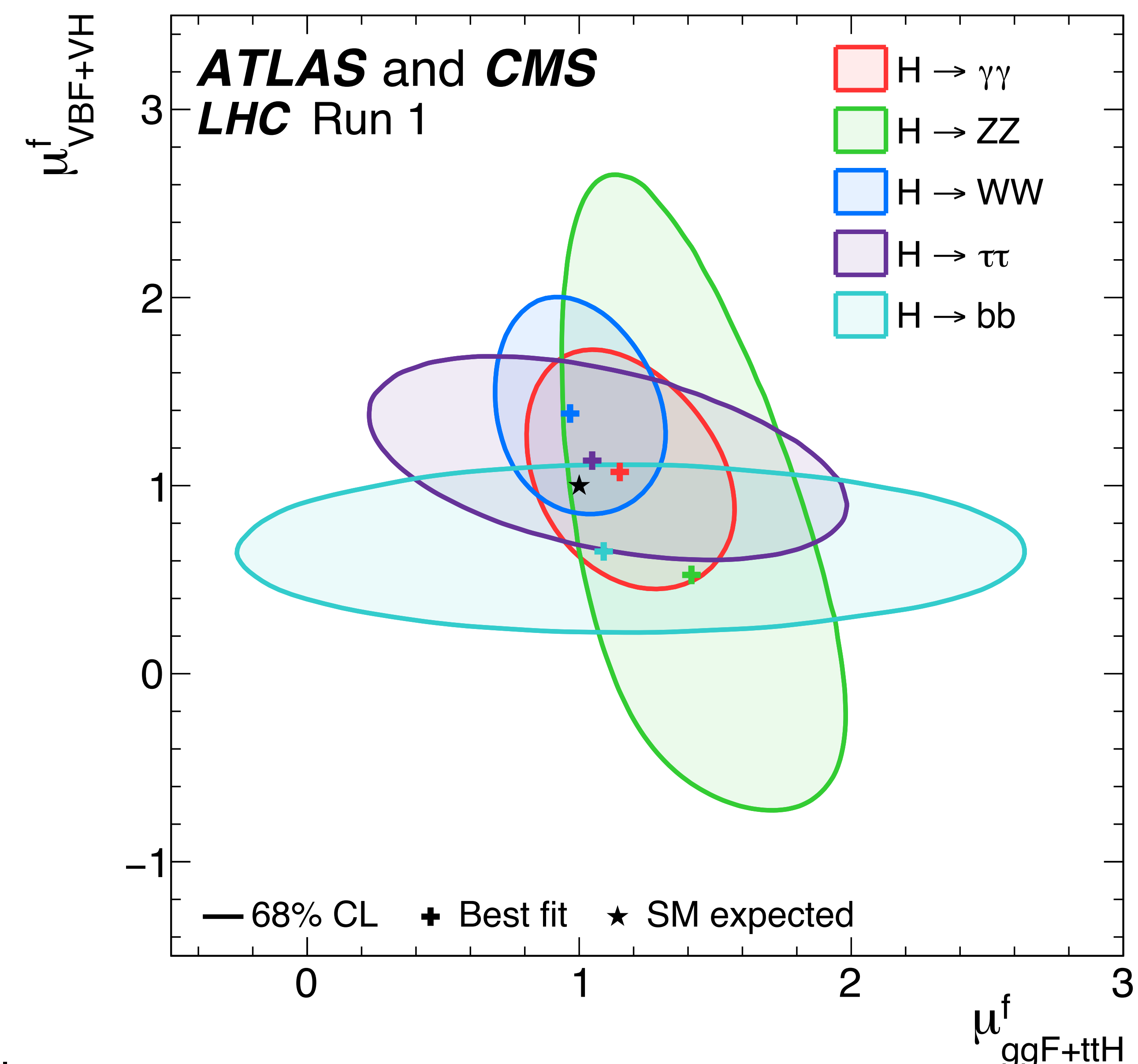
- use 8 TeV dataset from run 1
- use it for a proof of principle

Method can be extended to any decay mode that is sensitive to VBF production!

- good project for run 2

Build on H → $\tau\tau$ evidence analysis (JHEP 04 (2015) 117)

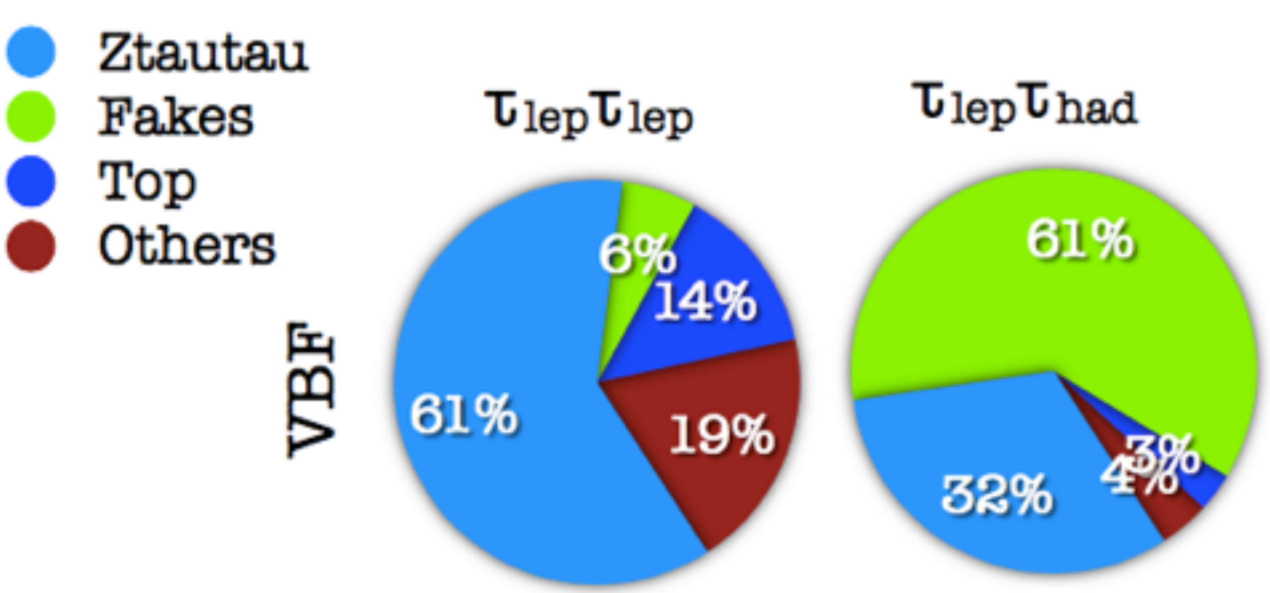
- use same background estimation, categories, BDT and systematics
- include only lep-had and lep-lep channels



VBF region definition

$\tau_\ell\tau_\ell$	At least two jets with $p_T^{j_1} > 40$ GeV and $p_T^{j_2} > 30$ GeV $\Delta\eta(j_1, j_2) > 2.2$ $\text{BDT}_{\text{score}} > 0.68$ $\mid O_1 \mid < 15$
$\tau_\ell\tau_{\text{had}}$	At least two jets with $p_T(j_1) > 50$ GeV and $p_T(j_2) > 30$ GeV $\Delta\eta(j_1, j_2) > 3.0$ $m_{\tau\tau}^{\text{vis}} > 40$ GeV $\text{BDT}_{\text{score}} > 0.3$ $\mid O_1 \mid < 15$

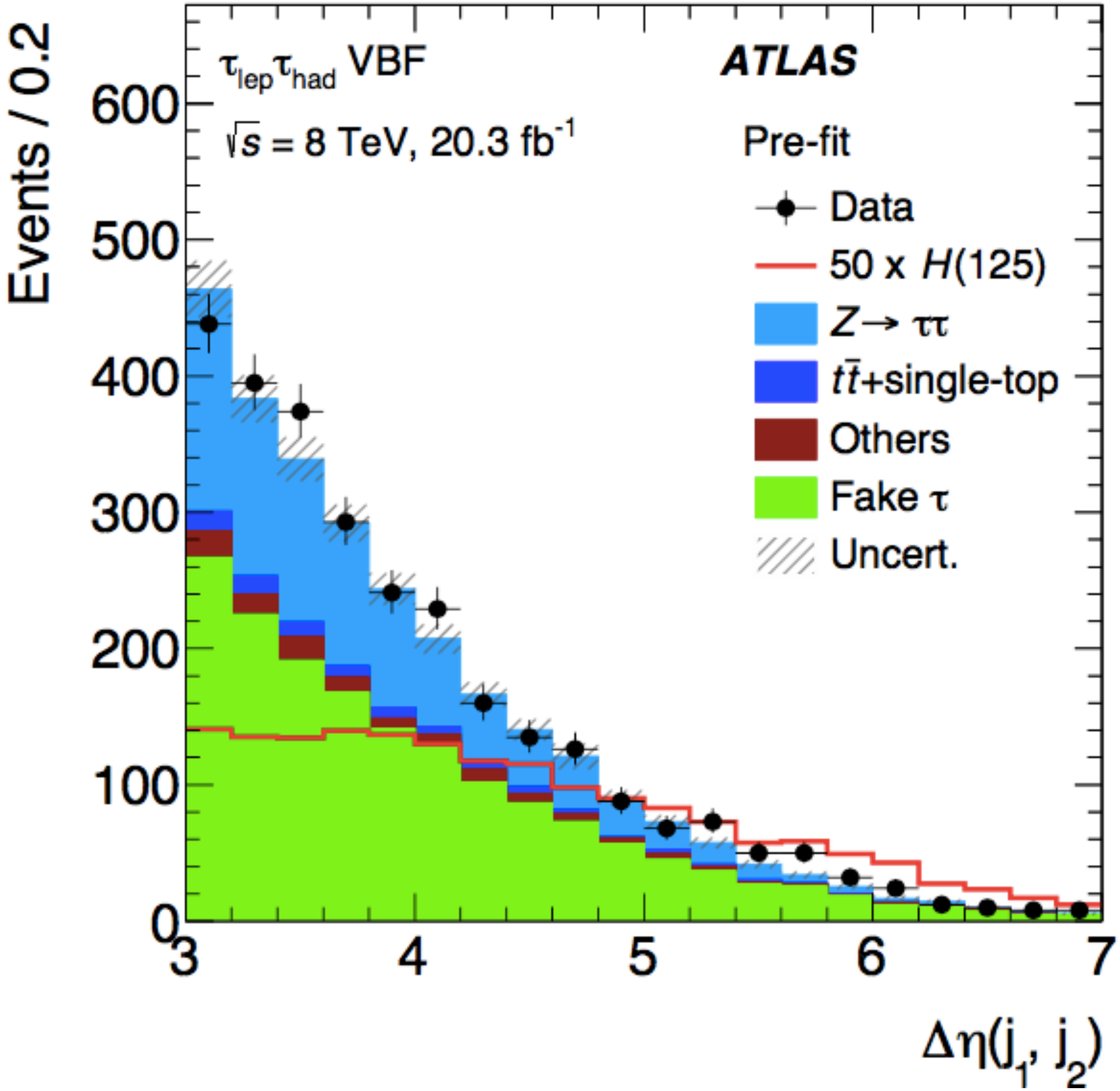
VBF region (before BDT cut):



Category	ggF	VBF	S/B
lep-lep	41%	55%	0.023
lep-had	33%	64%	0.017

Multivariate analyses based on boosted decision tree to enhance signal/bkg separation

Background model



Z $\rightarrow\tau\tau$ from embedding

arXiv:1506.05623

Z →μμ data events, subtract μ and replace it with simulated τ

Fakes:

use data-driven methods, use anti-isolated leptons/taus

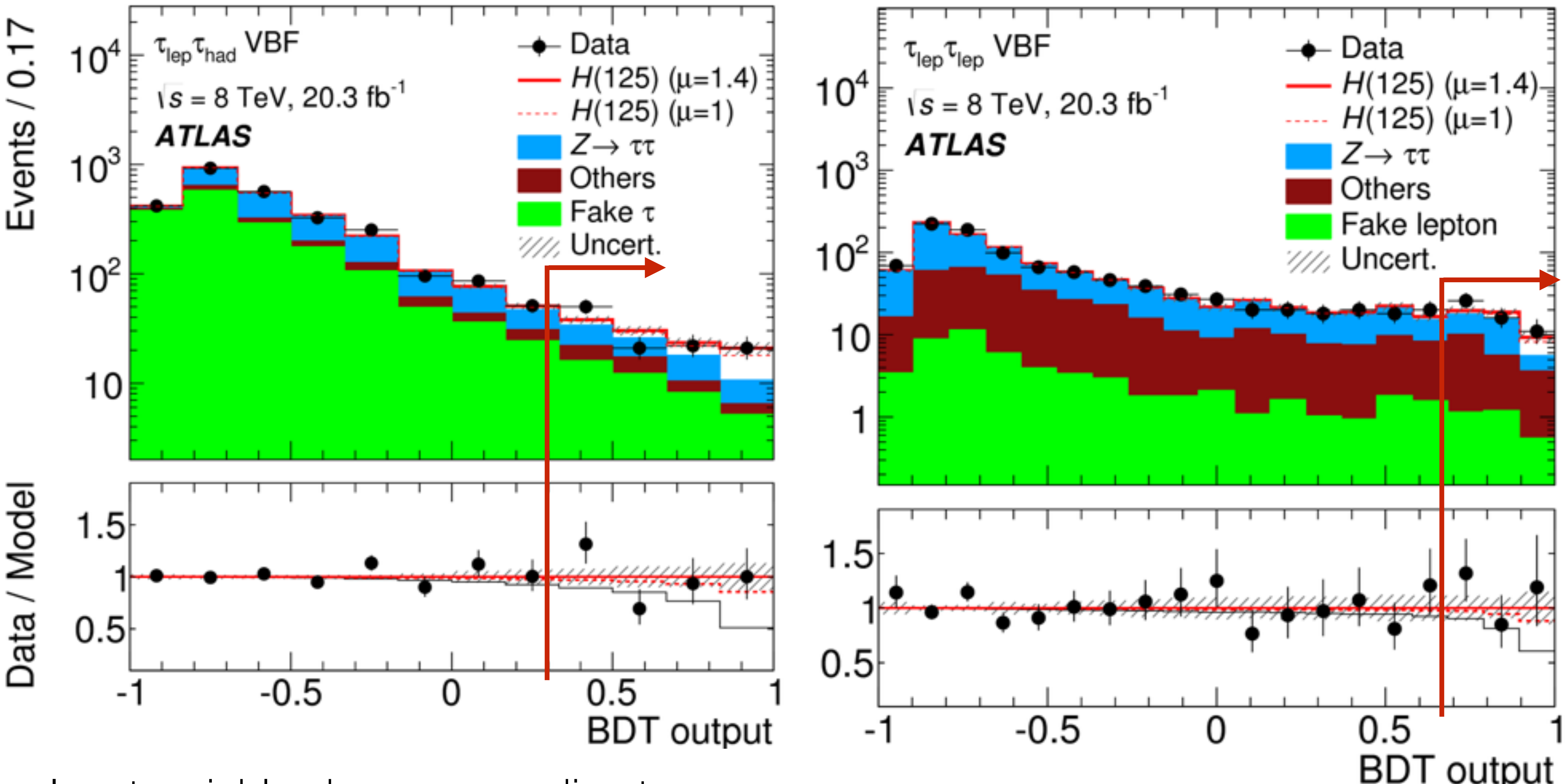
t-tbar + single-top

Shape from MC
normalisation from top CR (inverted bveto)

Other:

Diboson and Z →μμ/ee (lep-lep) from MC, both shape and normalisation

Signal regions

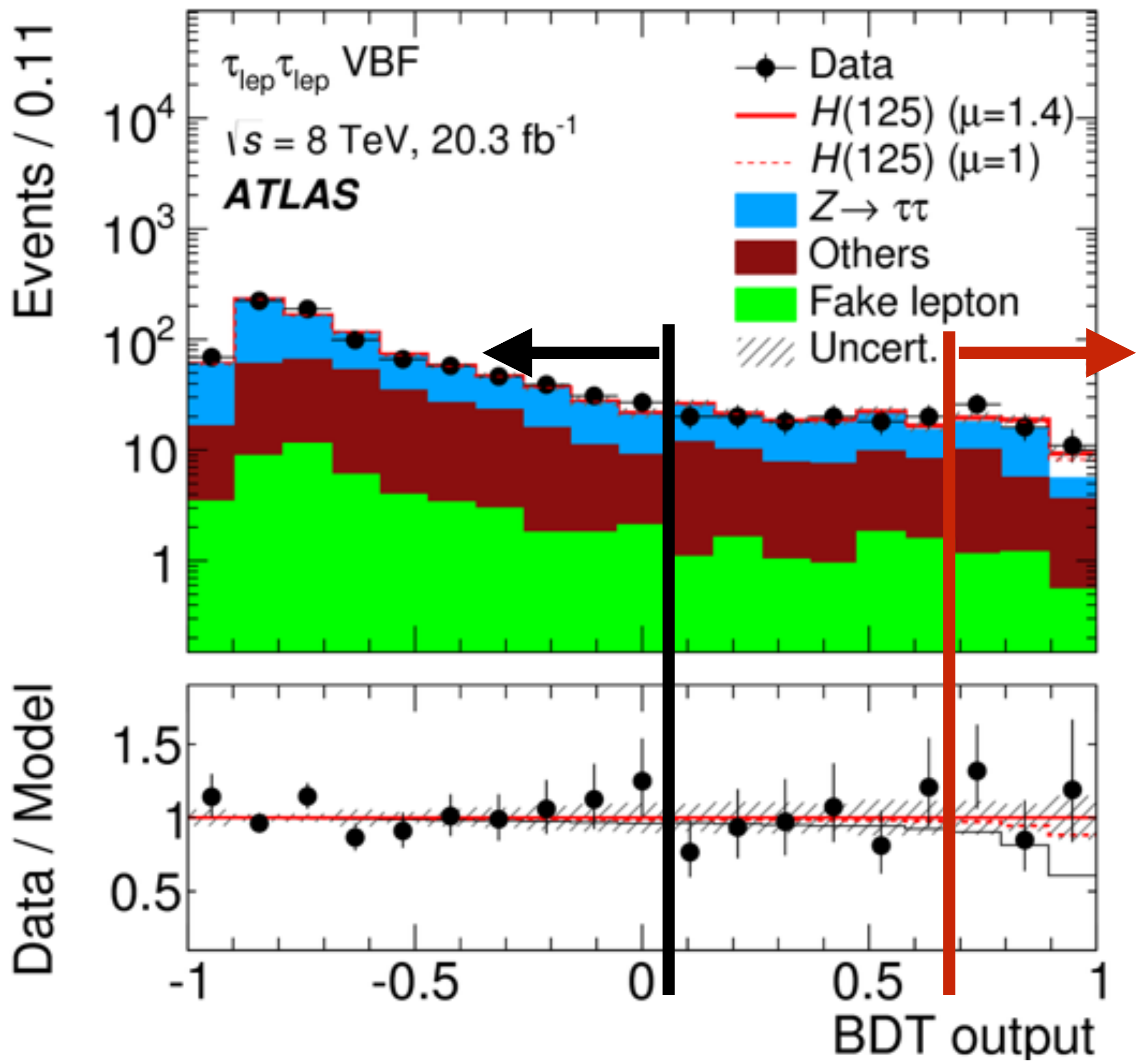


Input variable chosen according to:

- resonance properties: m(ττ), ΔR(ττ),
- VBF topology: m(jj), Δη(jj), $\eta_{j1} \times \eta_{j2}$,
- event activity: vector p_T-sum.
- event topology: m_T ,object centralities

Lep-Lep fit model

Region	$\tau_\ell \tau_\ell$
$Z \to \ell\ell$	$80 < m_{\tau\tau}^{\rm vis} < 100$ GeV same-flavour events
Top	Invert b-jet veto
Low $\mathrm{BDT_{score}}$	$\mathrm{BDT_{score}} < 0.05$



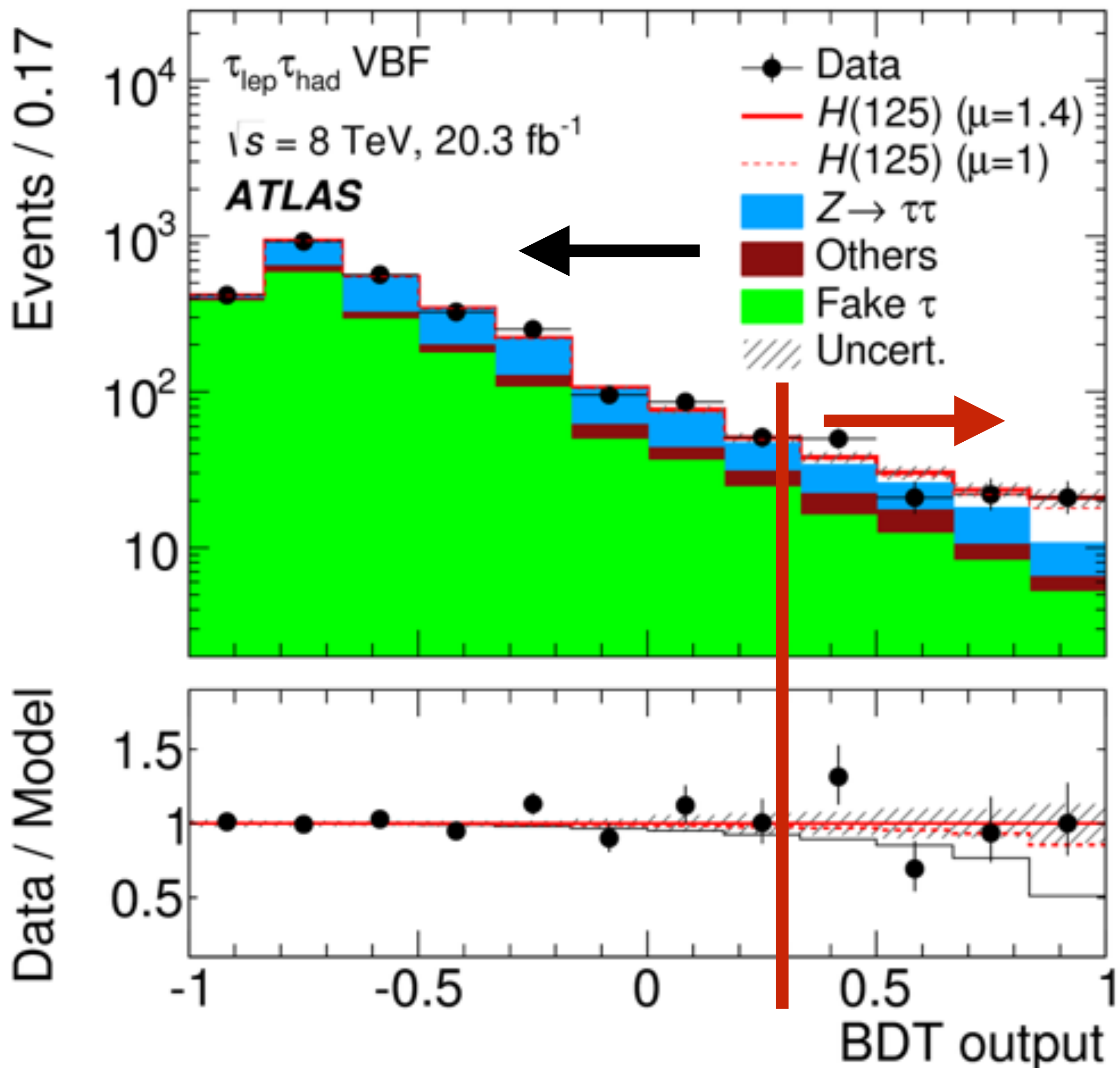
Bkg control region
Low BDT bins
BDT shape

Zll control region
Z mass window
Single bin

Signal Region
High BDT bins
OO_1

Top control region
bTag
Single bin

Lep-Had fit model



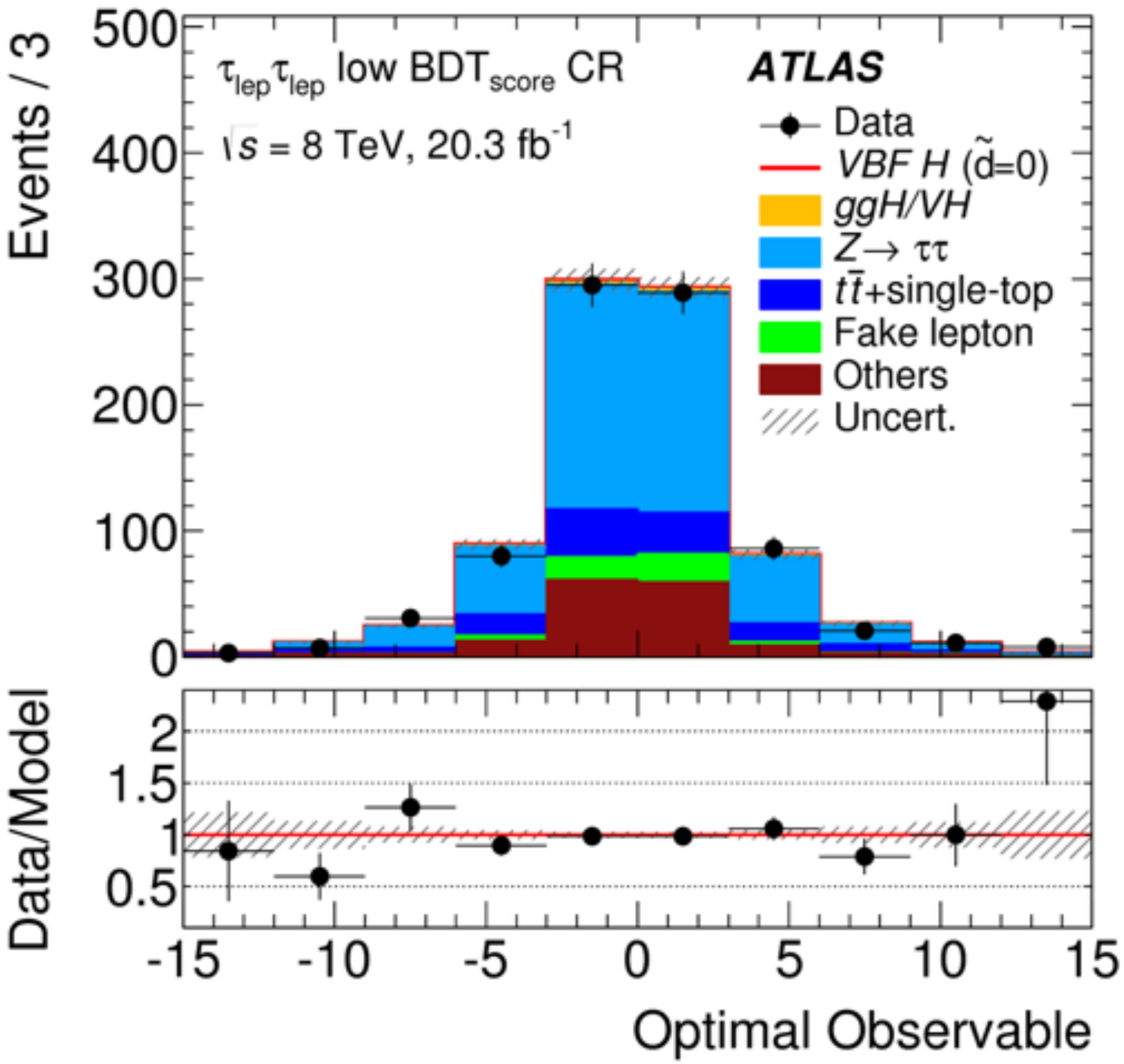
Region	$\tau_\ell \tau_{had}$
$Z \to \ell\ell$	
Top	Invert b-jet veto $m_T > 40$ GeV
Low BDT$_{score}$	BDT$_{score}$ < **0.3**

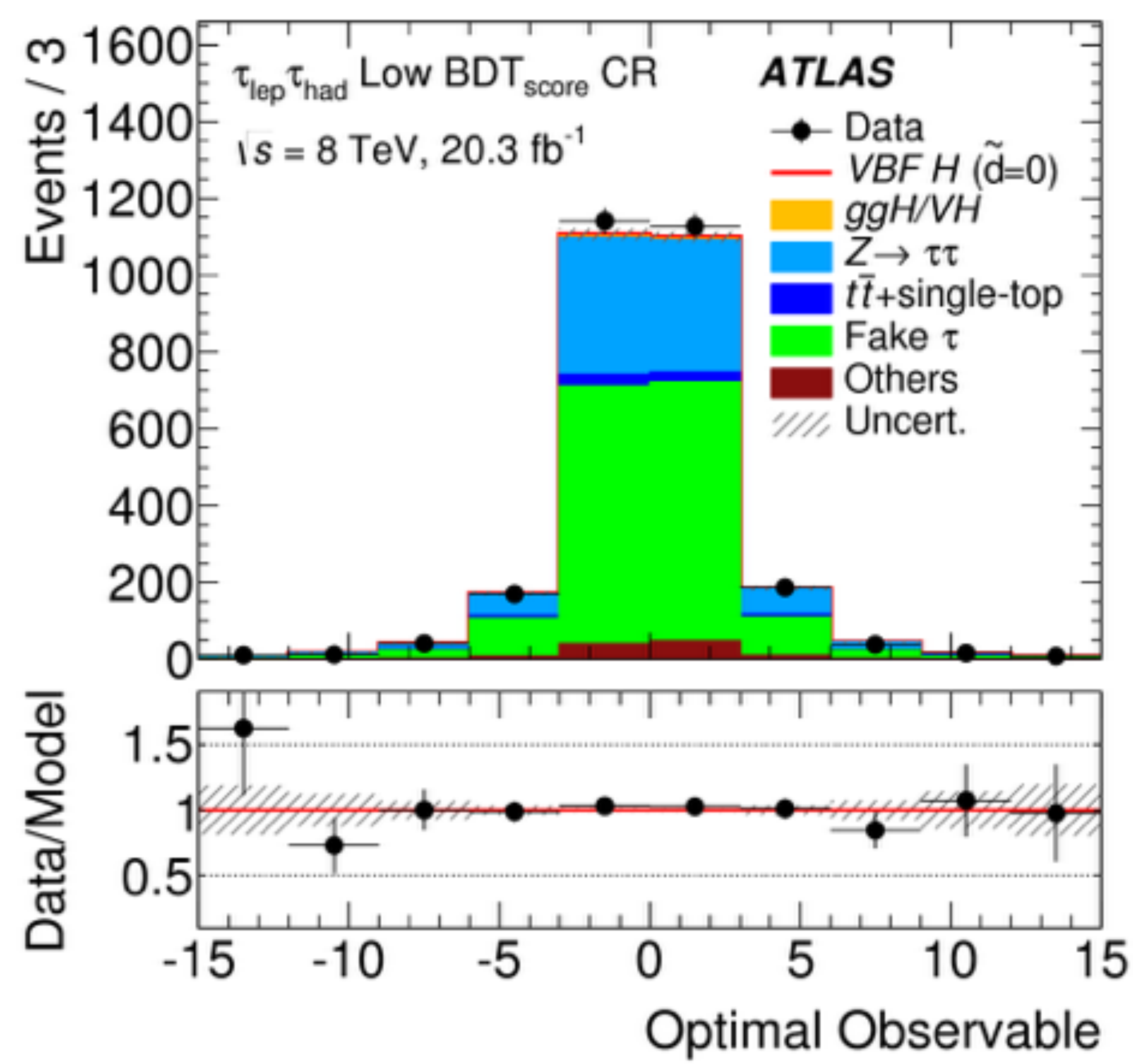
Bkg control region
Low BDT bins
BDT shape

Signal Region
High BDT bins
OO_1

Top control region
bTag
Single bin

OO in low BDT control region





Fit

Generate signal hypotheses in a range of CP-odd coupling strength values (d-tilde)

- Calculate negative log likelihood (NLL) for each signal hypothesis including signal region and all control regions (one NLL value per signal hypothesis)

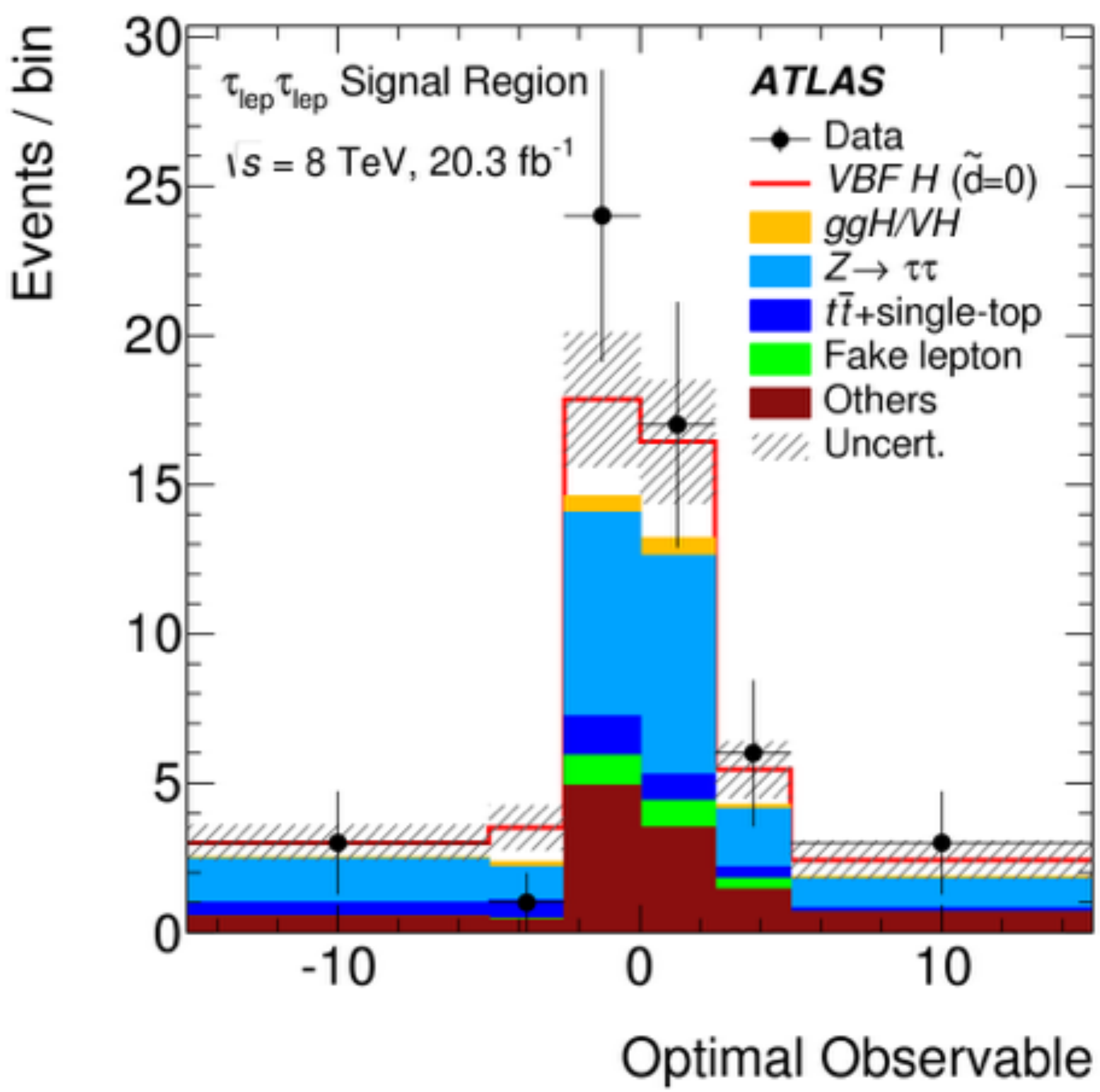
- NLL built using binned maximum likelihood (HistFactory)

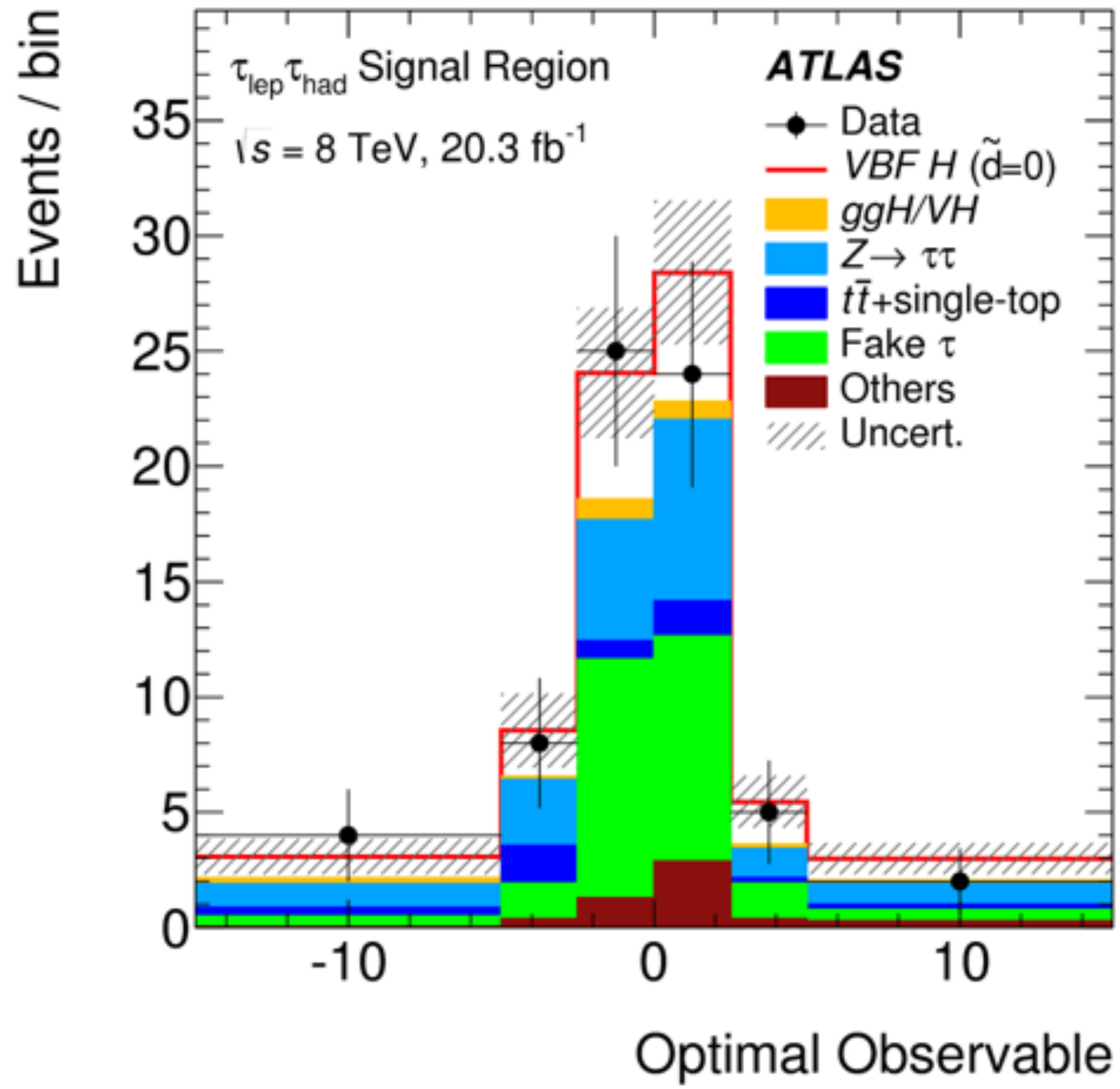
- VBF signal normalisation free in fit, only shape information is used

- All other Higgs production modes treated as background
    - VBF H —> WW (lep-lep final state) considered signal

- include all source of sys unc used in the coupling papers
    - add uncertainties to OO shape for signal due to UE/PS and to re-weighting
    - largest ones are related to JES/JER, hadronically decaying tau and electron energy scales; the most important theoretical uncertainty is due to the description of the underlying event and parton shower in the VBF signal sample.

Results



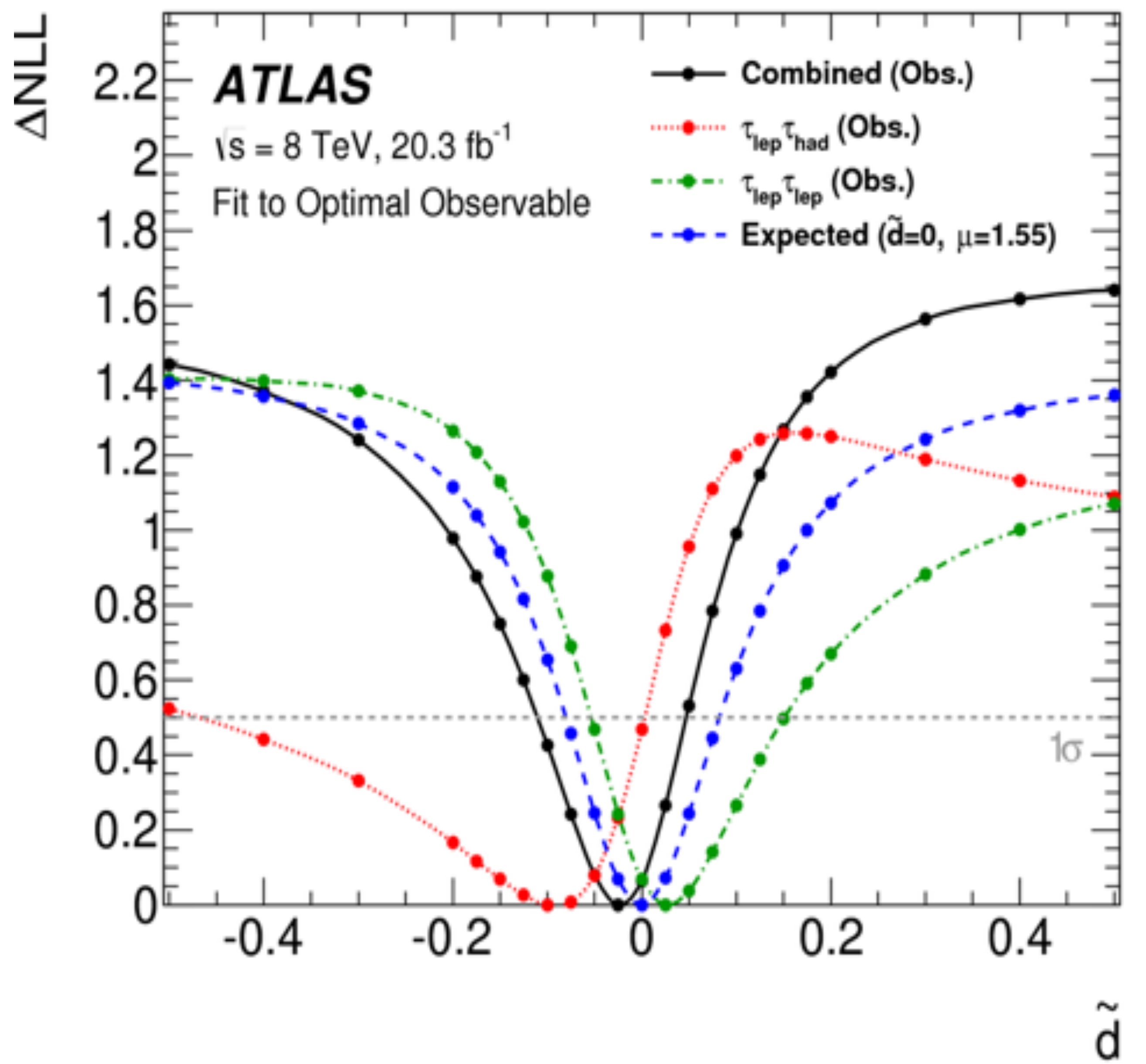


- fit only shape
- signal normalisation free to float

Process	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$
Data	54	68
VBF $H \to \tau\tau/WW$	9.8±2.1	16.7±4.1
$Z \to \tau\tau$	19.6±1.0	19.1±2.2
Fake lepton/τ	2.3±0.3	24.1±1.5
$t\bar{t}$ +single-top	3.8±1.0	4.8±0.7
Others	11.5±1.7	5.3±1.6
ggH/VH, $H \to \tau\tau/WW$	1.6±0.2	2.5±0.7
Sum of backgrounds	38.9±2.3	55.8±3.3

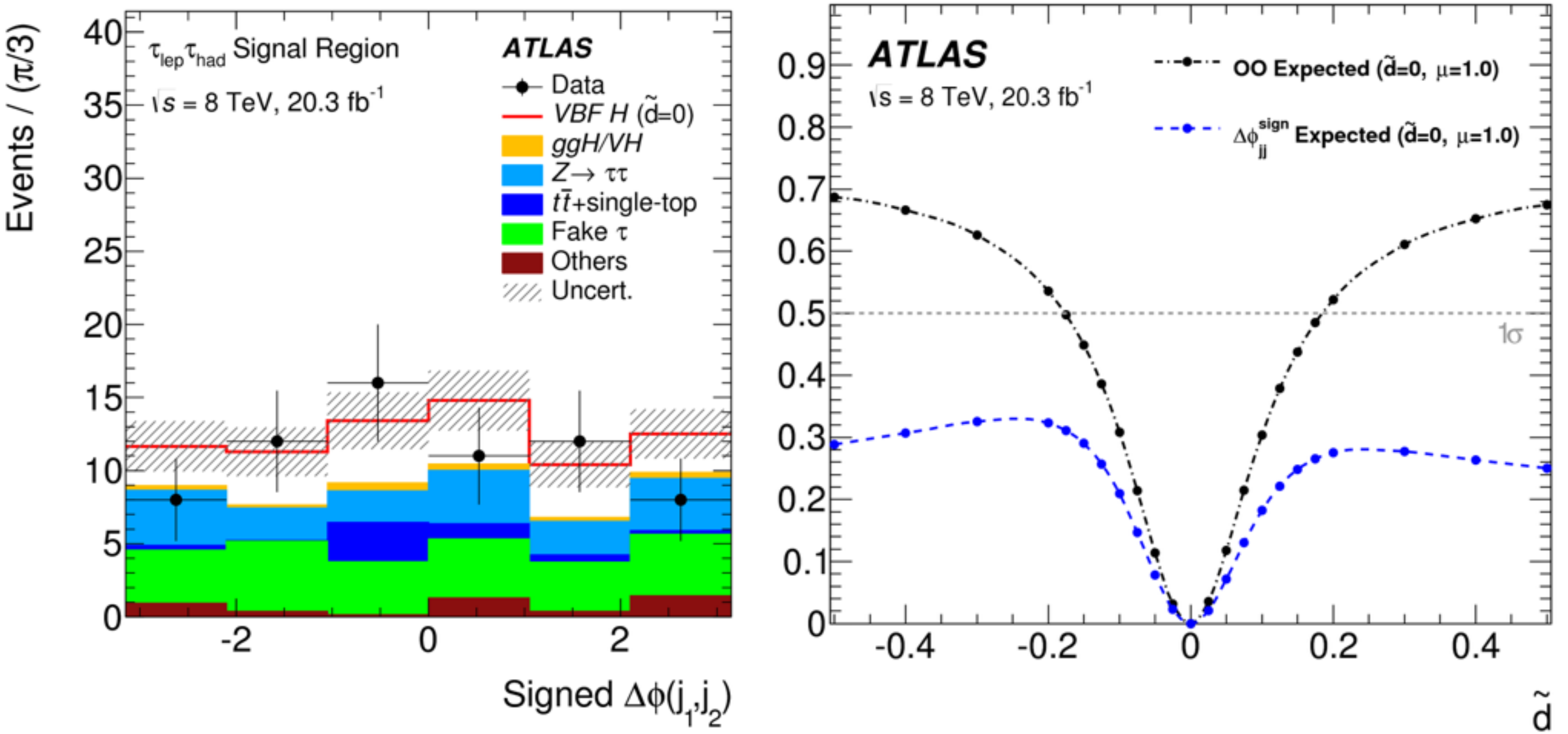
Results

- Signal strength left free in the fit
  - Analysis relies only on OO shape, not on (possibly more model-dependent) signal yield
- Perform fit for various $\tilde{d}$ scenaria, to obtain case with minimum NLL.
- Pure CP-odd and high mixing values already excluded – analysis focuses on small $\tilde{d}$ values
- $\tilde{d}$ values of [-0.11,0.05] are found to be consistent with the data at the 1σ level.
  - Values obtained via interpolation between discreet $\tilde{d}$ points evaluated
  - Same result (within rounding) for both linear and quadratic interpolation



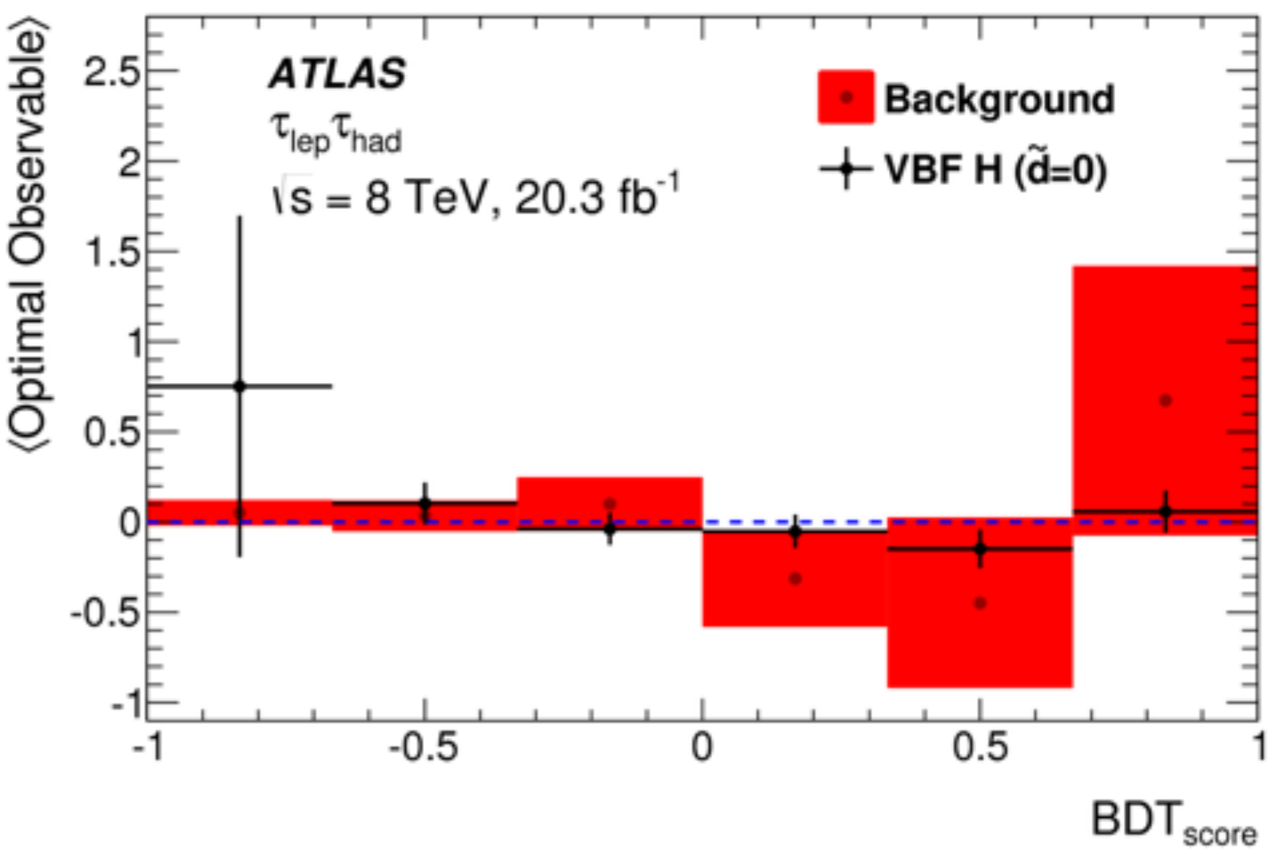
Comparing to signed $\Delta\phi_{jj}$

- is OO really better than using signed $\Delta\phi_{jj}$?

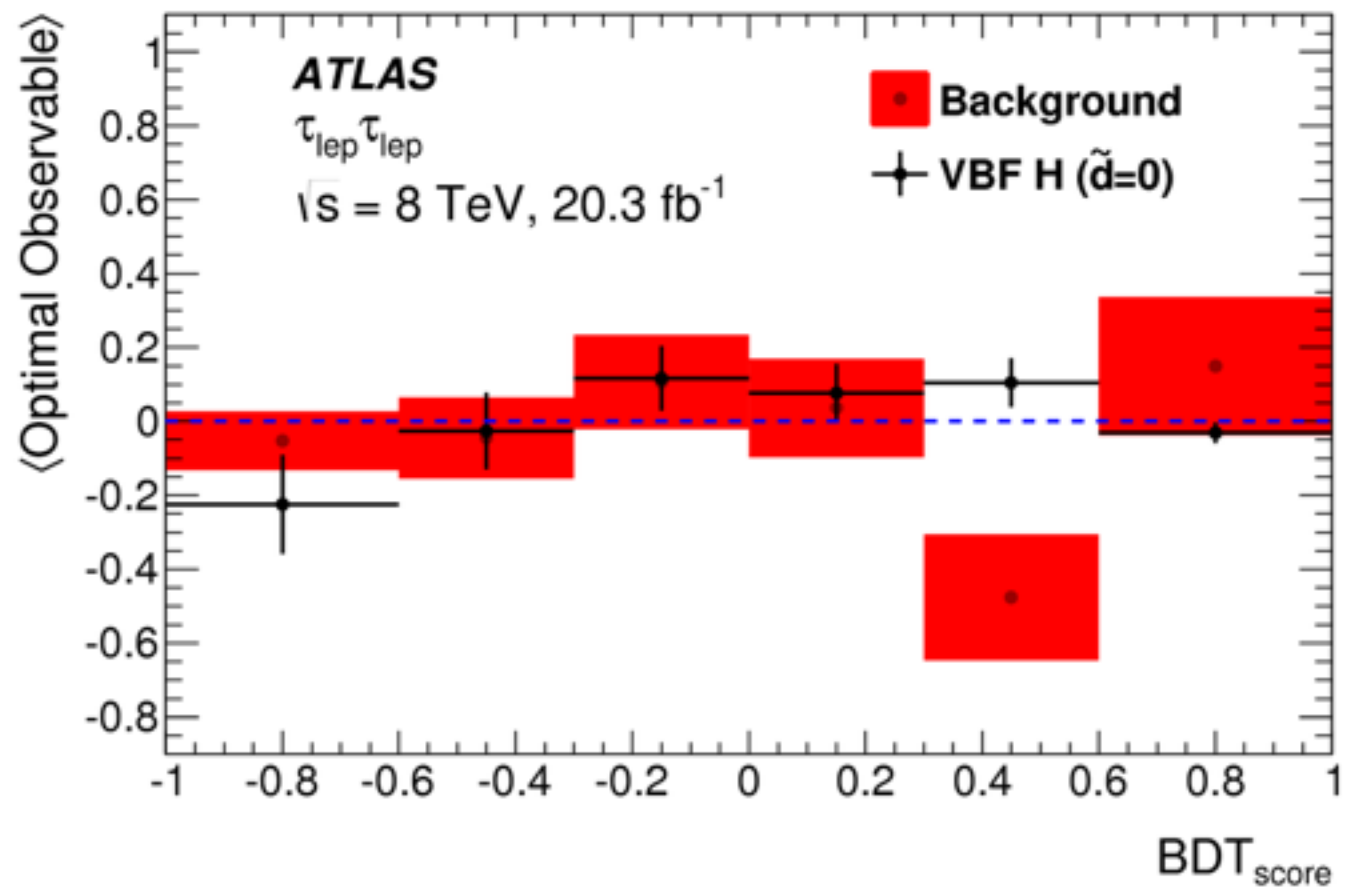


Direct test of CP-invariance

- SM background are CP-invariant
  - check that <OO>$_{bkg}$ = 0



pre-fit bkg model



<OO> measured in data:

0.3 ± 0.5 lep-lep

–0.3 ± 0.4 lep-had

Consistent with zero → No sign of CP-violation

Conclusion

- first test of CP-invariance in the VBF production
  - use CP-odd optimal observable
  - proven to be much more powerful than $\Delta\phi_{jj}$
  - approach is independent of the decay, can be used by other decay channels!

- only set 68% C.L. interval, not enough sensitivity with 20/fb to reach 2 sigma exclusion
  - proof of principle of the method

- 68% C.L. interval is10 times better than H—>ZZ/H—>WW combined analysis
  - also better then H —> $\gamma\gamma$ EFT constraint from differential cross sections

Back Up

Extra assumptions

The effective $U(1)_Y$- and $SU(2)_{I_W,L}$-invariant Lagrangian is then given by (following Ref. [21, 22]):

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{f_{\tilde{B}B}}{\Lambda^2} O_{\tilde{B}B} + \frac{f_{\tilde{W}W}}{\Lambda^2} O_{\tilde{W}W} + \frac{f_{\tilde{B}}}{\Lambda^2} O_{\tilde{B}} \qquad (1)$$

with the three dimension-six operators

$$O_{\tilde{B}B} = \Phi^+ \hat{\tilde{B}}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \qquad O_{\tilde{W}W} = \Phi^+ \hat{\tilde{W}}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \qquad O_{\tilde{B}} = (D_\mu \Phi)^+ \hat{\tilde{B}}^{\mu\nu} D_\nu \Phi \quad . \qquad (2)$$

and three dimensionless Wilson coefficients $f_{\tilde{B}B}$, $f_{\tilde{W}W}$ and $f_{\tilde{B}}$; Λ is the scale of new physics.

Here D_μ denotes the covariant derivative $D_\mu = \partial_\mu + \frac{i}{2} g' B_\mu + i g \frac{\sigma_a}{2} W^a_\mu$, $\hat{V}_{\mu\nu}$ ($V = B, W^a$) the field-strength tensors and $\tilde{V}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$ the dual field-strength tensors, with $\hat{B}_{\mu\nu} + \hat{W}_{\mu\nu} = i \frac{g'}{2} B_{\mu\nu} + i \frac{g}{2} \sigma^a W^a_{\mu\nu}$.

The last operator $O_{\tilde{B}}$ contributes to the CP-violating charged triple gauge-boson couplings $\tilde{\kappa}_\gamma$ and $\tilde{\kappa}_Z$ via the relation $\tilde{\kappa}_\gamma = -\cot^2 \theta_W \tilde{\kappa}_Z = \frac{m_W^2}{2\Lambda^2} f_{\tilde{B}}$. These CP-violating charged triple gauge boson couplings are constrained by the LEP experiments [23–25] and the contribution from $O_{\tilde{B}}$ is neglected in the following; i.e. only contributions from $O_{\tilde{B}B}$ and $O_{\tilde{W}W}$ are taken into account.

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

MC Samples

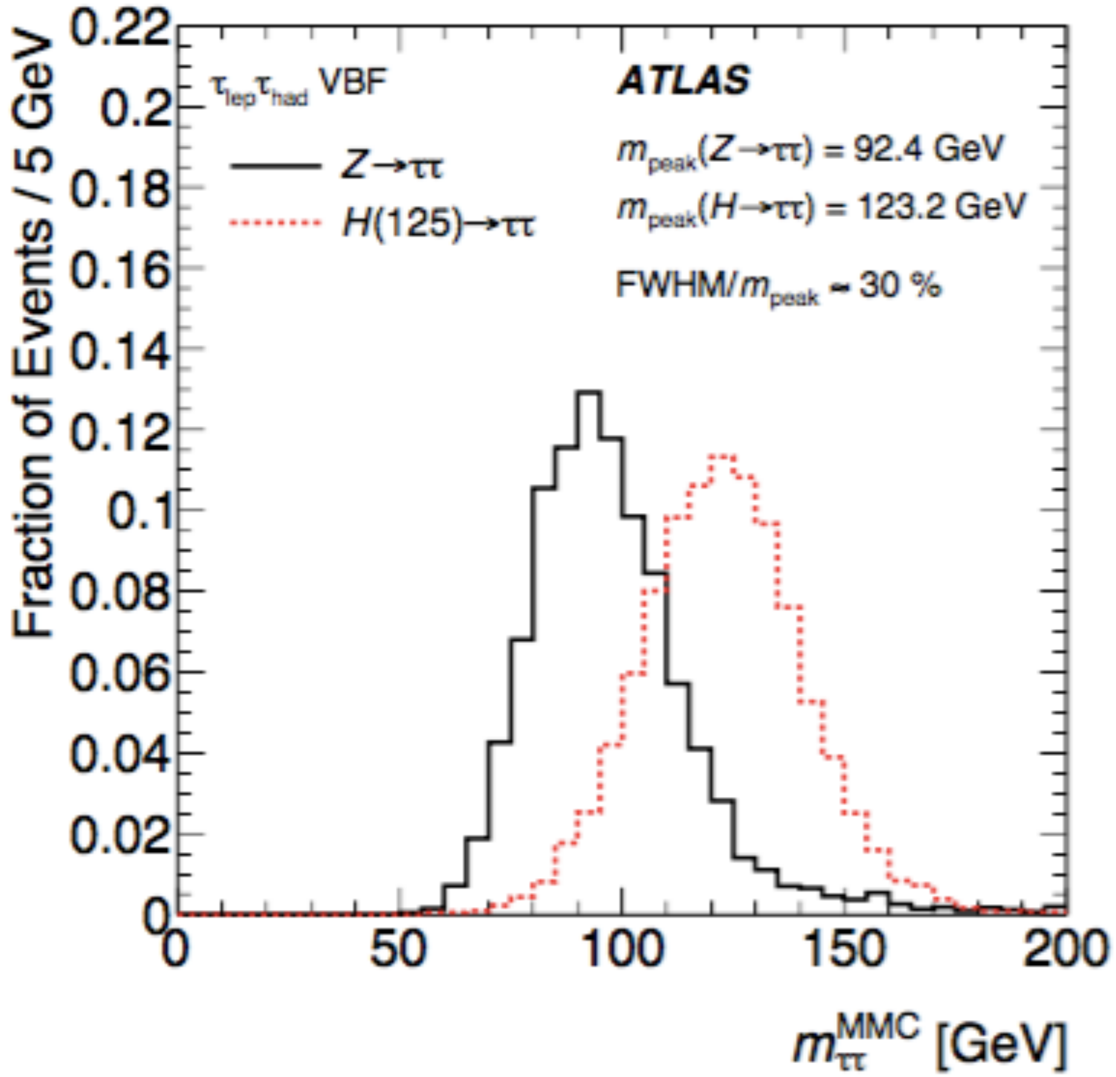
Signal	MC generator	$\sigma \times \mathcal{B}$ [pb] $\sqrt{s} = 8$ TeV		
VBF, $H \to \tau\tau$	Powheg-Box [47–50] Pythia8 [51]	0.100	(N)NLO	[41, 42, 52–54]
VBF, $H \to WW$	same as for $H \to \tau\tau$ signal	0.34	(N)NLO	[41, 42, 52–54]
Background	**MC generator**	**$\sigma \times \mathcal{B}$ [pb] $\sqrt{s} = 8$ TeV**		
$W(\to \ell\nu)$, $(\ell = e, \mu, \tau)$	Alpgen [55]+Pythia8	36800	NNLO	[56, 57]
$Z/\gamma^*(\to \ell\ell)$, 60 GeV$< m_{\ell\ell} <$ 2 TeV	Alpgen+Pythia8	3910	NNLO	[56, 57]
$Z/\gamma^*(\to \ell\ell)$, 10 GeV$< m_{\ell\ell} <$ 60 GeV	Alpgen+Herwig [58]	13000	NNLO	[56, 57]
VBF $Z/\gamma^*(\to \ell\ell)$	Sherpa [59]	1.1	LO	[59]
$t\bar{t}$	Powheg-Box + Pythia8	$253^{\dagger}$	NNLO+NNLL	[60–65]
Single top : Wt	Powheg-Box + Pythia8	$22^{\dagger}$	NNLO	[66]
Single top : s-channel	Powheg-Box + Pythia8	$5.6^{\dagger}$	NNLO	[67]
Single top : t-channel	AcerMC [68]+Pythia6 [69]	$87.8^{\dagger}$	NNLO	[70]
$q\bar{q} \to WW$	Alpgen+Herwig	$54^{\dagger}$	NLO	[71]
$gg \to WW$	gg2WW [72]+Herwig	$1.4^{\dagger}$	NLO	[72]
WZ, ZZ	Herwig	$30^{\dagger}$	NLO	[71]
ggF, $H \to \tau\tau$	HJ MINLO [73, 74] + Pythia8	1.22	NNLO+NNLL	[54, 75–80]
ggF, $H \to WW$	Powheg-Box [81] + Pythia8	4.16	NNLO+NNLL	[54, 75–80]

Table 1: MC event generators used to model the signal and the background processes at $\sqrt{s} = 8$ TeV. All Higgs boson events are generated assuming $m_H = 125$ GeV. The cross sections times branching fractions ($\sigma \times \mathcal{B}$) used for the normalisation of some processes (many of these are subsequently normalised to data) are included in the last column together with the perturbative order of the QCD calculation. For the signal processes the $H \to \tau\tau$ and $H \to WW$ SM branching ratios are included, and for the W and Z/γ^* background processes the branching ratios for leptonic decays ($\ell = e, \mu, \tau$) of the bosons are included. For all other background processes, inclusive cross sections are quoted (marked with a †).

H→WW

- Non-negligible amount of VBF, H→WW events in the leplep signal region
  - No such contribution in lephad
- These are also treated as signal since an anomalous coupling in VBF would equally show up there
- Possible concern: an anomalous HVV coupling would also affect the decay in these events
  - Used a MG5-based reweighting provided by the HWW group to obtain a sample with anomalous coupling in the decay
  - Very small differences in OO distribution
  - For final analysis: neglect effect of anomalous coupling on the decay
  - Use same reweighting procedure for VBF Htautau and HWW

Missing Mass Calculator



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- Good m(ττ) resolution most effective tool against Z→ττ.
  - m(ττ): most highly ranked BDT input variables.
- m(ττ) reconstructed by Missing Mass Calculator (MMC).
  - MMC is sophisticated technique to reconstruct m(ττ) in presence of neutrinos from τ-decays.
    - Requirement that mutual orientations of the neutrinos and other decay products are consistent with the mass and decay kinematics of a tau lepton.
  - Better than the collinear mass (collinear approximation not always holds).

Pre-selection

Channel	Preselection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	Exactly two isolated opposite-sign leptons Events with $\tau_{\rm had}$ candidates are rejected $30\ \ {\rm GeV} < m_{\tau\tau}^{\rm vis} < 100\ (75)$ GeV for DF (SF) events $\Delta\phi_{\ell\ell} < 2.5$ $E_{\rm T}^{\rm miss} > 20\ (40)$ GeV for DF (SF) events $E_{\rm T}^{\rm miss, HPTO} > 40$ GeV for SF events $p_{\rm T}^{\ell_1} + p_{\rm T}^{\ell_2} > 35$ GeV Events with a b-tagged jet with $p_{\rm T} > 25$ GeV are rejected $0.1 < x_{\tau_1}, x_{\tau_2} < 1$ $m_{\tau\tau}^{\rm coll} > m_Z - 25$ GeV
$\tau_{\rm lep}\tau_{\rm had}$	Exactly one isolated lepton and one medium $\tau_{\rm had}$ candidate with opposite charges $m_{\rm T} < 70$ GeV Events with a b-tagged jet with $p_{\rm T} > 30$ GeV are rejected