Study of the $\mathrm{H} \to \tau\tau$ decay channel with ATLAS

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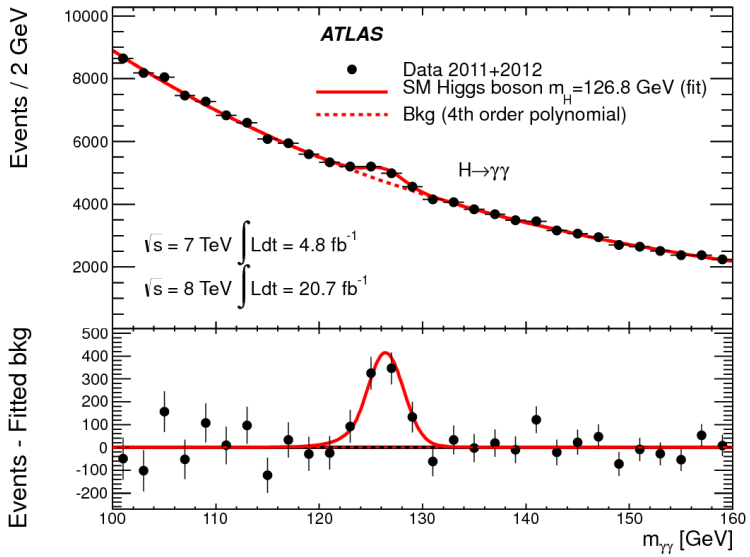
Introduction

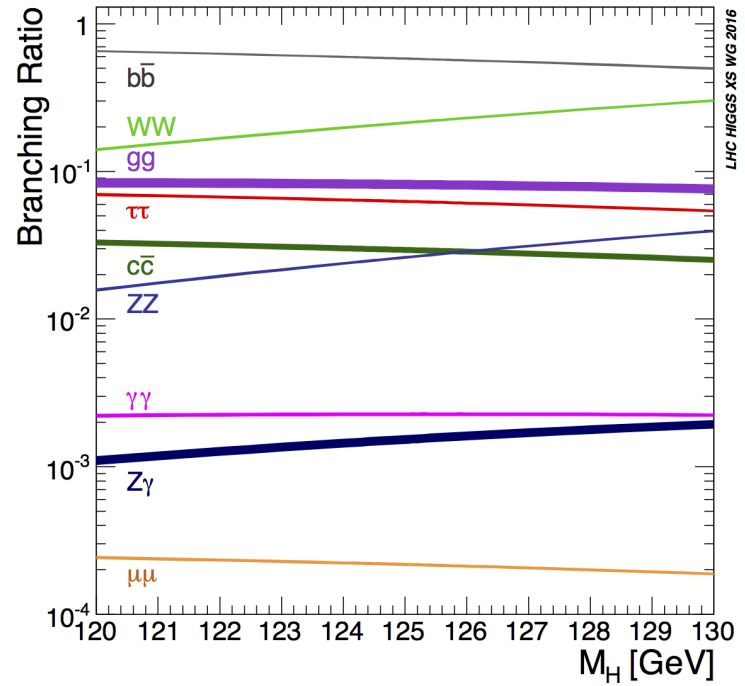
Higgs boson discovered in 2012

- $H \to \gamma\gamma$
- $H \to ZZ^* \to 4\ell$

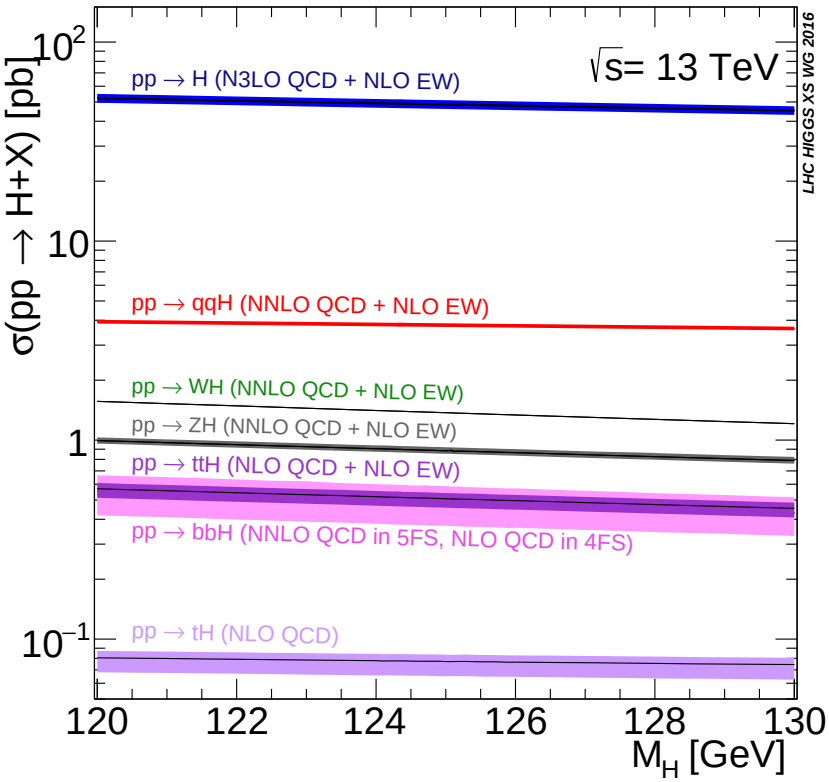


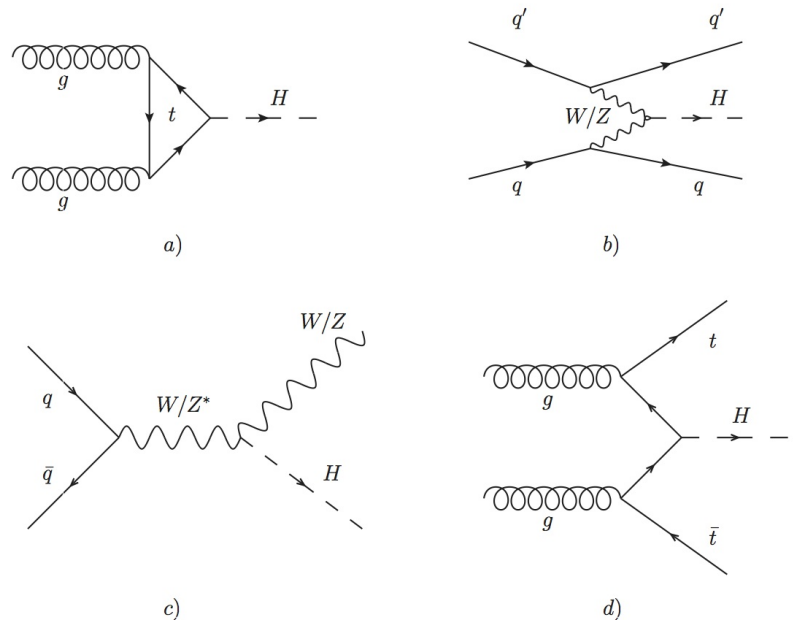
Establishing SM **mass generation** mechanism for **fermions** at LHC

- measure direct coupling
- $H \to \tau\tau$ promising candidate (good signal to background ratio)
- direct access to Higgs-fermion vertex: Higgs CP measurements



Higgs boson production at LHC





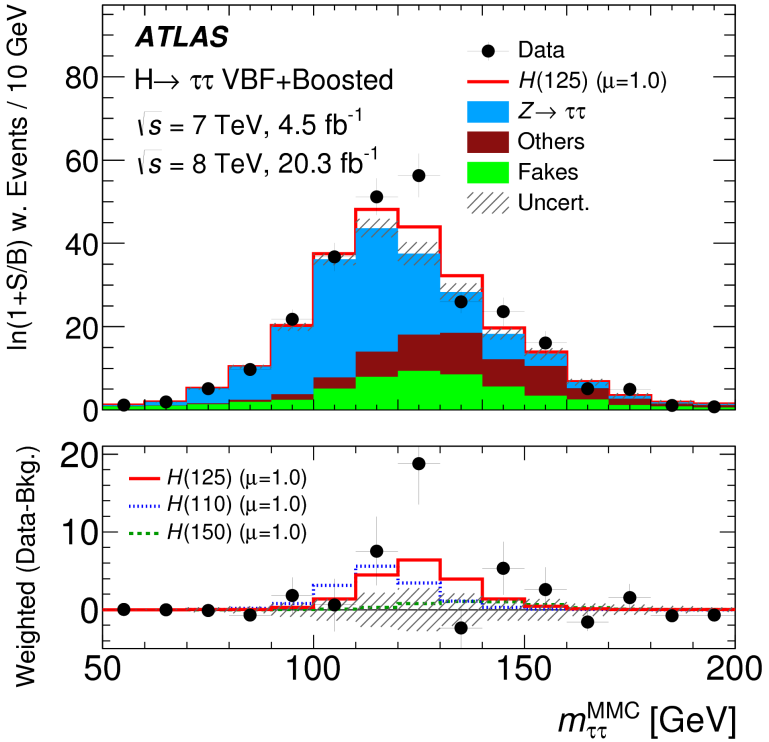
All accessible production modes are explored

- gluon-gluon fusion (ggH) and vector boson fusion (VBF)
- Higgs-strahlung (WH/ZH)
- ttH is considered in a combined ttH analysis in ATLAS, therefore not considered in our analysis – talk "ttH at LHC" by Daniele Madaffari

H $\rightarrow \tau\tau$ searches

ATLAS Run I analysis – will be presented

- search in 7+8 TeV datasets ($\sim 25\text{fb}^{-1}$)
- observation of H $\rightarrow \tau\tau$ in combination with CMS, ref. JHEP 04 (2015) 117
- **evidence** for direct H $\rightarrow \tau\tau$ coupling
- first significant signature for H to fermion coupling



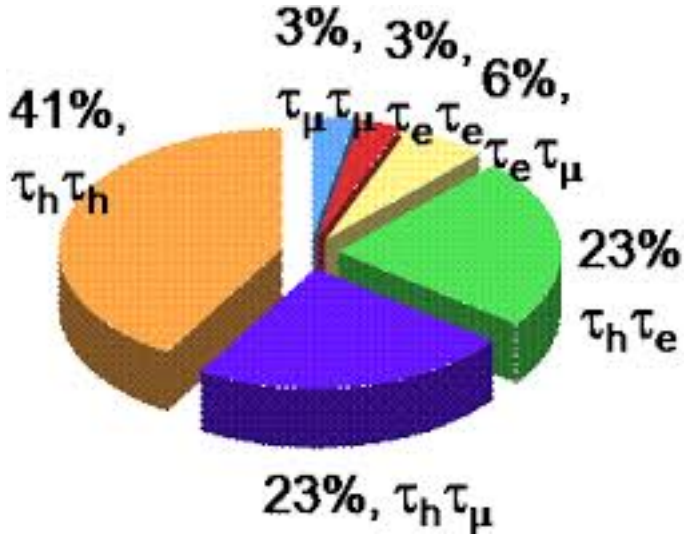
ATLAS Run II analysis – ongoing

- search in 13 TeV 2015+2016 datasets ($\sim 36\text{fb}^{-1}$)
- cross-section measurement
- more precise measurement of the Higgs boson coupling to τ leptons
- Higgs CP measurements

$H \to \tau\tau$ decay modes

Similar analysis for three decay channels:

- di-lepton channel: $H \to \tau\tau \to 2\ell + 4\nu$
- semi-lepton channel: $H \to \tau\tau \to \ell + n\pi + 3\nu$
- hadronic channel: $H \to \tau\tau \to n\pi + 2\nu$



Signatures in the detector:

- isolated electron(s) and/or muon(s)
- missing transverse energy
- reconstructed hadronic τ decay
- accompanying jets (reflect the production mechanism)

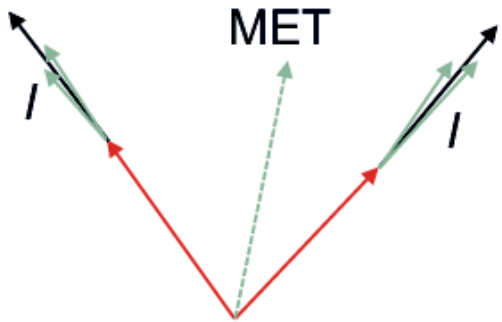
Background modeling

Backgrounds considered:

- Monte Carlo (MC) simulations based
  - Z+jets (with $Z \to \ell\ell$, where $\ell = \mathrm{e}, \mu$)
  - W+jets
  - top (ttbar + single top production)
  - diboson (WW/ZZ production)
  - contribution from other Higgs boson decays ($\mathrm{H} \to WW \to \ell\nu\ell\nu$ for ll)
- data-driven
  - $Z \to \tau\tau$ (the most important background in all sub-channels)
    - **Embedding** procedure
  - fakes (one/two jets/electrons are misidentified as leptons/τ_{had})
    - estimation depends on the final state

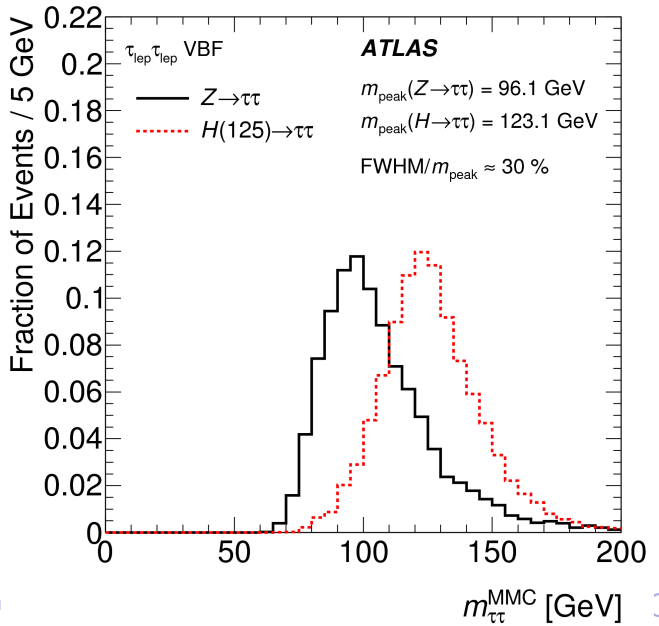
Higgs boson mass reconstruction

Invariant mass cannot be properly reconstructed due to neutrinos



- **Collinear mass approximation**
  - assumes all τ-decay products are collinear

- **Missing Mass Calculator (MMC)**
  - takes into account the probability of the angular distribution between the τ-decay products
  - nearly 100% reconstruction efficiency, critically depends on the MET resolution



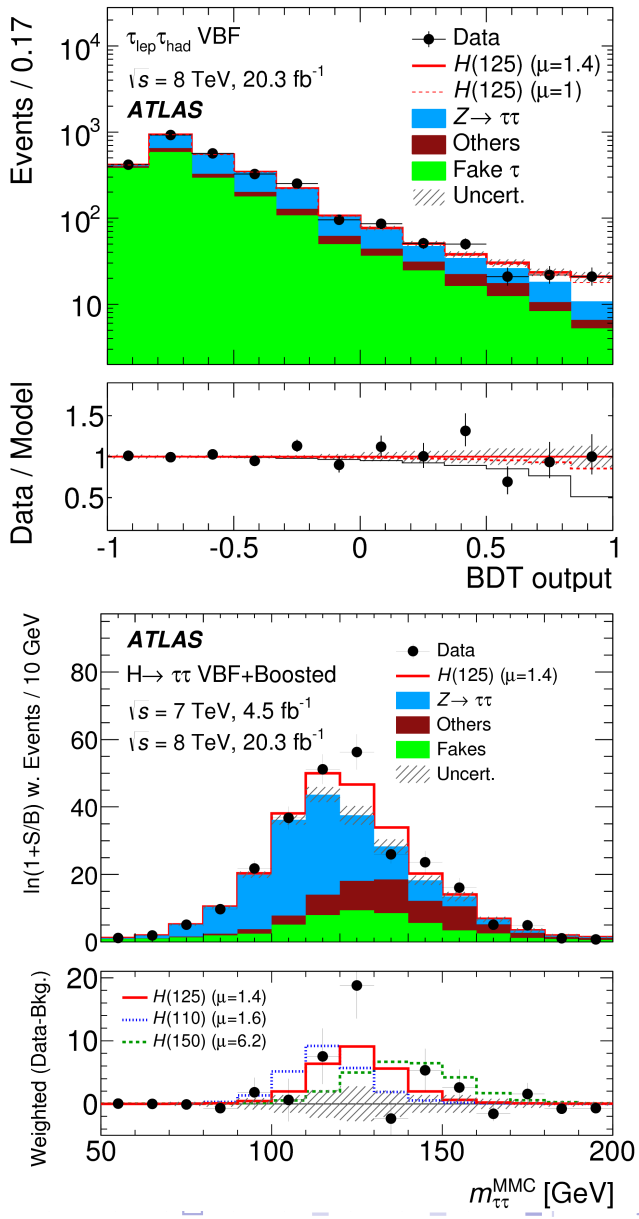
Analysis strategy

Multivariate analysis (MVA)

- based on boosted decision tree (BDT) with several inputs (MMC being the most important one)
- BDT discriminants from each channel x category (VBF, Boosted) x dataset (7, 8 TeV) x region (signal, control) are further used as input variables for the likelihood fits

Cut-based analysis (CBA)

- evaluates binned likelihood from MMC distributions
- used as a cross-check; lower sensitivity than MVA, but results compatible within uncertainties



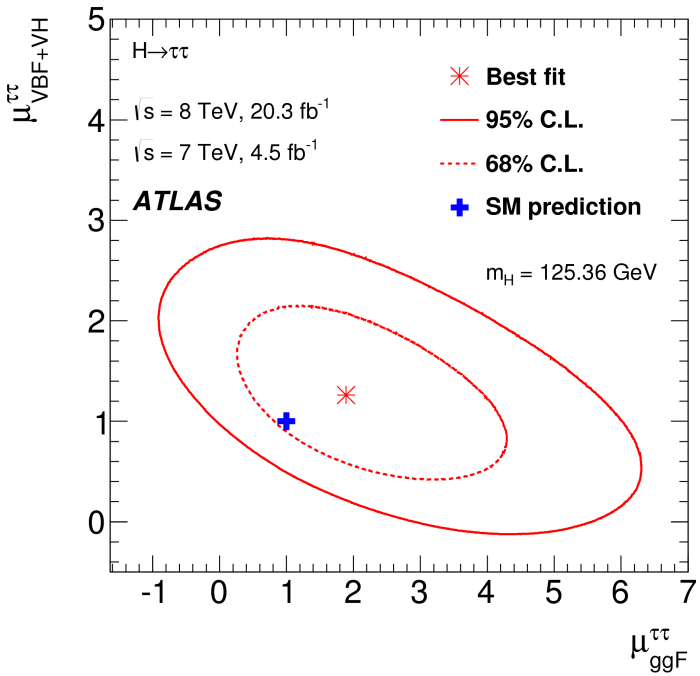
$H \to \tau\tau$ results

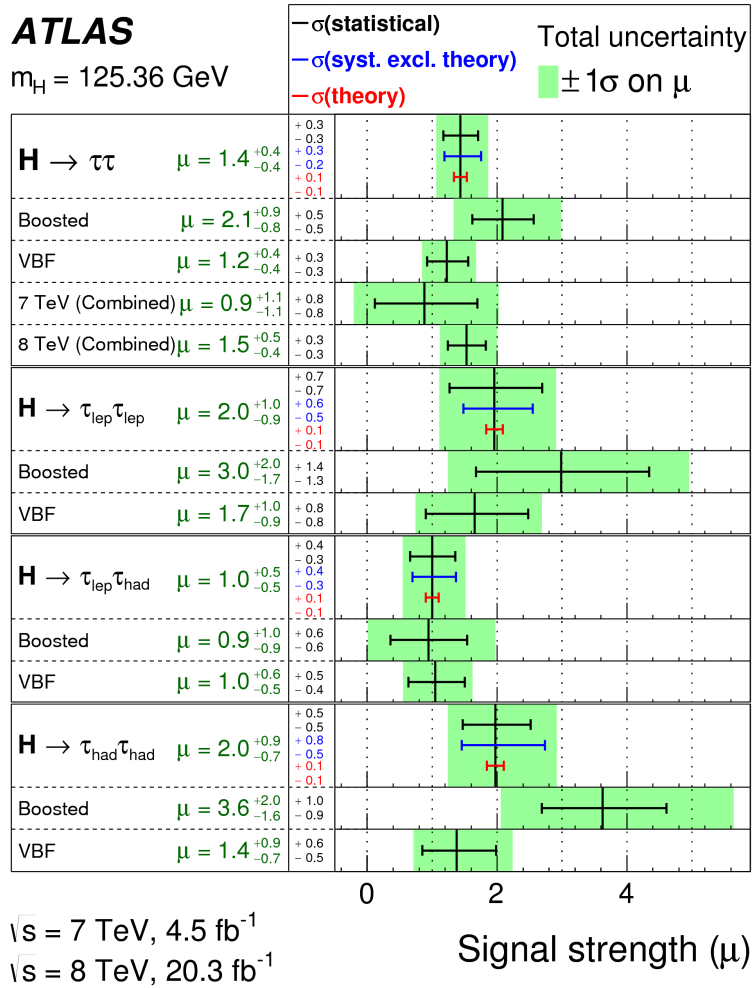
Excess observed in all three channels

- **Expected** significance: 3.4σ
- **Observed** significance: 4.5σ

signal strength

$$\mu = 1.43^{+0.27}_{-0.26}(stat)^{+0.32}_{-0.25}(syst) \pm 0.09(theo)$$





$H \to \tau\tau$ is the most powerful channel for the VBF production mode

Conclusion

- Higgs boson decay to a pair of tau leptons is proven above 5σ significance when combining ATLAS and CMS Run-1 results
  - ATLAS Run-1 significance: 4.5σ, ATLAS paper JHEP 04 (2015) 117
- The goal in Run-2 is to achieve better sensitivity with new data and better tau reconstruction
- Run-2 results are expected to come by May 2018
- Apart from Higgs boson decays predicted by the Standard model, searches for other decay modes as well as for possible other Higgs bosons (e.g. MSSM Higgs) continue

BONUS SLIDES

Background modeling

$Z \to \tau\tau$ is modeled using data to ensure event topology as realistic as possible (especially jets and MET)

- Everything (Z kinematics; jet multiplicity and topology) except τ decays is obtained from data

Embedding procedure

- selected $Z \to \mu\mu$ events in data
- replace μ with simulated τ
- τ decayed w/TAUOLA; polarization and spin-correlations taken into account

Object and event selection (I)

- Object selection
  - e/μ - well identified isolated electrons/muons with $p_T > 15$ (10) GeV in fiducial volume of the inner detector (and muon spectrometer)
  - τ_{had} - hadronic tau decay products identified using the multivariate technique (BDT classifier)
  - jets - $p_T > 25$ GeV, imposing jet vertex fraction for $p_T < 50$ GeV to mitigate the impact of pile-up
- Object overlap removal is applied, removing close objects ($\Delta R < 0.2$) with the order of priority $\mu \rightarrow e \rightarrow \tau_{had} \rightarrow jet$

Run-1 datasets:

- 7 TeV data, 4.5fb^{-1}
- 8 TeV data, 20.3fb^{-1}

Object and event selection (II)

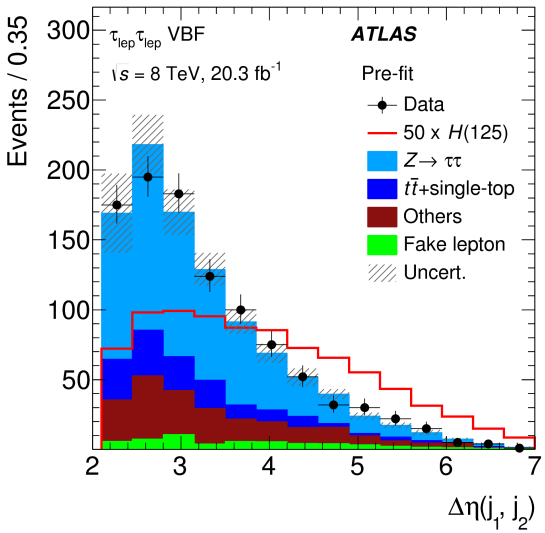
- Event pre-selection is different for each sub-channel

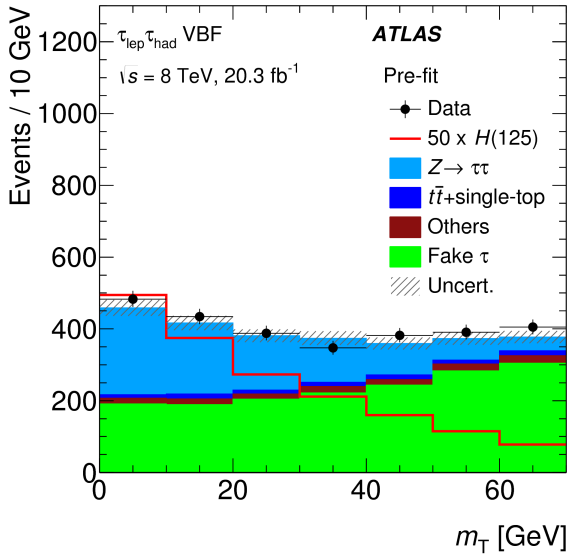
Had-Had channel
2 opposite charge (OS) isolated τ_{had} candidates
no leptons
MET $>$ 20 GeV
MET points between two τ_{had} in ϕ or min$[\Delta\phi(\tau_{had}, MET)] < \pi/4$
$0.8 < \Delta R(\tau_1, \tau_2) < 2.4$
$\Delta\eta(\tau_1, \tau_2) < 2.4$
Lep-Had channel
1 isolated ℓ, 1 τ_{had} candidate with opposite charge
transverse mass $m_T(\ell, MET) < 70$ GeV
no b-tagged jets
Lep-Lep channel
2 OS isolated ℓ, no τ_{had}
$p_T(\ell_1) + p_T(\ell_2) > 35$ GeV
$30 < m(\ell\ell) < 100(75)$ GeV for DF (SF)
MET $>$ 20 (40) GeV for DF (SF)
MET_HPTO $>$ 40 GeV for SF (high-pT objects only)
no b-tagged jets
$\Delta\phi(\ell\ell) < 2.5$
$0.1 < x_1, x_2 < 1$ (lepton momentum fractions from collinear approximation)

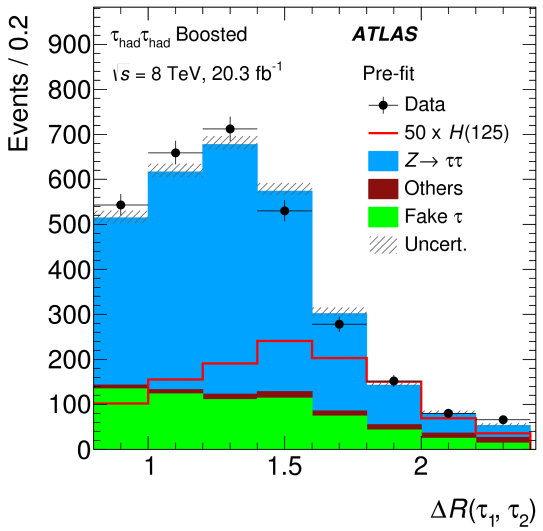
- Background modeling is checked in several control regions

Object and event selection (III)

- Two event categories optimized for different Higgs production mechanisms are used in all three channels
  - **VBF** – optimized for VBF production mode, basically requiring two forward jets with large rapidity gap
  - **Boosted** – optimized for ggF production mode, basically requiring high reconstructed Higgs p_T ($p_T > 100$ GeV)
- Examples of discriminating variables in each sub-channel

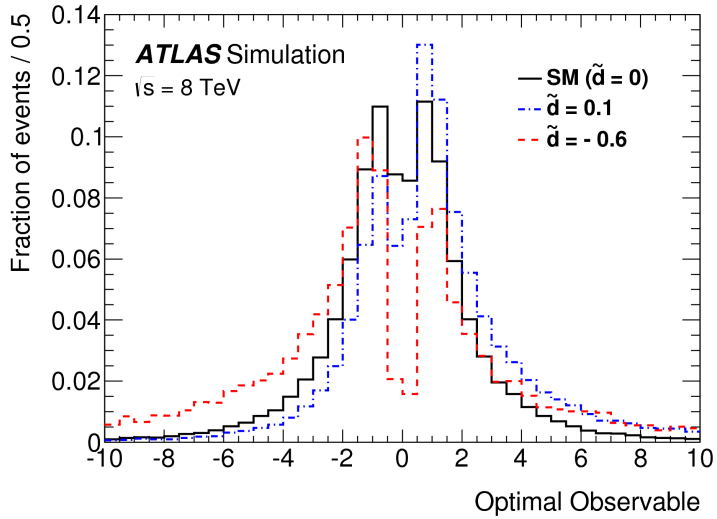


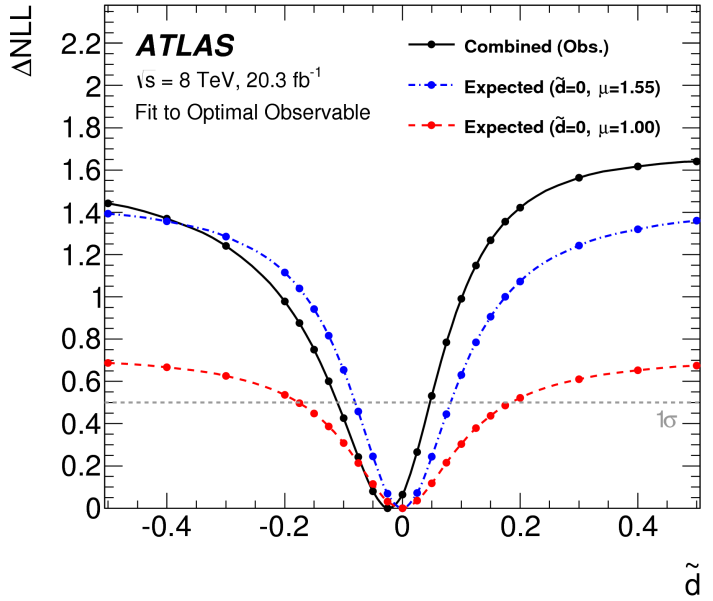




Higgs CP invariance in HVV coupling

- Utilise VBF $H \rightarrow \tau\tau$ sample to test CP-invariance in the HVV coupling (method independ of Higgs decays)
- Use CP-odd Optimal Observable (OO)
  - Mean value $\neq 0 \rightarrow$ CP violation
  - Calculated using ME code from HAWK; inputs:
    - Reconstructed Higgs 4-vector
    - Tagging Jets 4-vectors
- Fit OO for various scenaria and place limits on CP mixing parameter ($\tilde{d}$)
- Run-1 results : values of $\tilde{d}$ outside [-0.11,0.05] excluded at 68 % CL
  - Better limits at 68 % CL than ATLAS Run-1 HWW/HZZ measurement





Higgs CP invariance test in H$\to \tau\tau$ decay

- Information about CP violation encoded in the correlation between tras. spin components of the taus
- Access the spin correlation by reconstructing the angle ϕ^*_{CP} between the tau decay planes
  - distribution of the angle has a sine shape and the phase depends on the mixing parameter CP even/odd
- Two method to reconstruct the τ decay planes:
  - Impact parameter method (used in 1p0n decay); uses info from track momentum and impact parameter
  - Rho decay plane method (used in 1p1n decay); uses the charged and neutral decay products
- Main contribution from hadronic tau decays (less neutrinos in the final state)