Measurement of CP-violation in the $H \rightarrow \tau\tau$ channel using Vector Boson Fusion events

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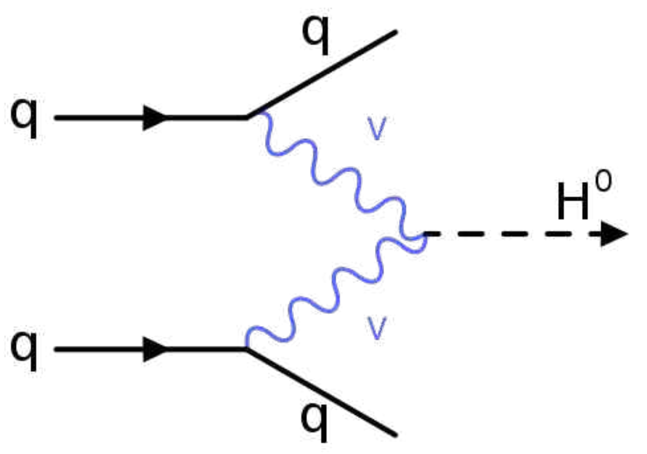
1. Introduction

- Higgs Boson discovery at the LHC in 2012 by ATLAS and CMS experiments
  $m_H = 125.09 \pm 0.21\,(stat) \pm 0.11\,(syst)$ GeV
- The Higgs seems to be Standard-Model like, however further precision measurements are necessary, like measurements of its spin and CP eigenvalues
- CP-violation
  → the Higgs sector has been recently discovered, it is interesting to search for CP-violation in this new sector
  → it is one of the three Sakharov conditions for explaining baryon asymmetry in the universe

2. Theoretical overview

- The analysis aims to study the vertex where the Higgs couples to two vector bosons through Vector Boson Fusion (VBF)

$V = W, Z, \gamma$



- Effective Field theory framework

General Lorentz-invariant parametrization of the HVV vertex

$$T^{\mu\nu}(q_1,q_2) = a_1(q_1,q_2)g^{\mu\nu} \quad \text{SM: CP EVEN}$$
$$+ a_2(q_1,q_2)[q_1 \cdot q_2 g^{\mu\nu} - q_2^{\mu} q_1^{\nu}] \quad \text{CP-EVEN}$$
$$+ a_3(q_1,q_2)\varepsilon^{\mu\nu\rho\sigma}q_{\rho,1}q_{\sigma,2} \quad \text{CP-ODD}$$

- Consider a CP-odd perturbation to the Standard Model (SM)

$$a_1 = \frac{2m_V^2}{v}, \quad a_2 = 0, \quad a_3 \neq 0 \quad \longrightarrow \quad \begin{cases} a_3^{HZZ} = \frac{2e}{M_W sin\theta_W}(\tilde{d}\,cos^2\theta_W + \tilde{d}_B sin^2\theta_W) \\ a_3^{HWW} = \frac{2e}{M_W sin\theta_W}\tilde{d} \\ a_3^{HZ\gamma} = \frac{2e}{M_W}cos\theta_W(\tilde{d} - \tilde{d}_B) \\ a_3^{H\gamma\gamma} = \frac{2e}{M_W sin\theta_W}(\tilde{d} sin^2\theta_W + \tilde{d}_B cos^2\theta_W) \end{cases}$$

Inspired from SUSY models → $\tilde{d}$ and $\tilde{d}_B$ parameters can be measured

3. Optimal observable

For testing the CP violation one should use a discriminant variable which is experimentally sensitive to the presence of the additional CP-odd contribution

↓

Optimal Observables

In the analysis it is assumed $\tilde{d} = \tilde{d}_B$

$$M_{BSM} = M_{SM} + \tilde{d} \cdot M_{CP-odd}$$

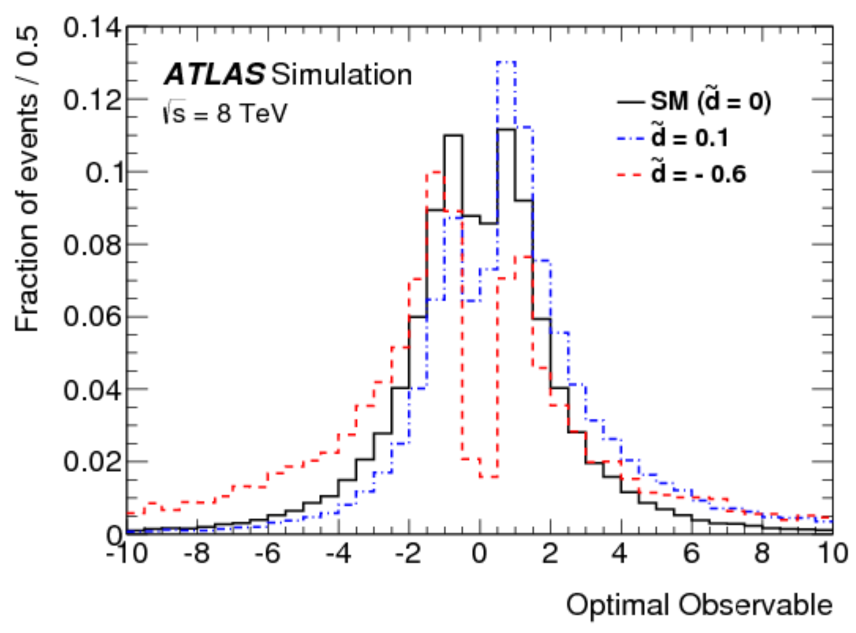
$$|M_{BSM}^2| = |M_{SM}^2| + \tilde{d} \cdot 2\,Re(M_{SM}^* M_{CP-odd}) + \tilde{d}^2 |M_{CP-odd}^2|$$

$$O_1 := \frac{2\,Re(M_{SM}^* M_{CP-odd})}{|M_{SM}^2|}$$

$< O_1 > = 0$ SM

$< O_1 > \neq 0$ CP-ODD contribution

First order Optimal Observable, sensitive to the CP-odd coupling for the linear term ($\tilde{d}$)



Recontstructed with the four-momenta of final state jets, Higgs and the Bjorken x

$$O_2 := \frac{|M_{CP-odd}^2|}{|M_{SM}^2|} \longrightarrow$$

Second order Optimal Observable, sensitive to the CP-odd coupling for the quadratic term ($\tilde{d}^2$), not used in the analysis

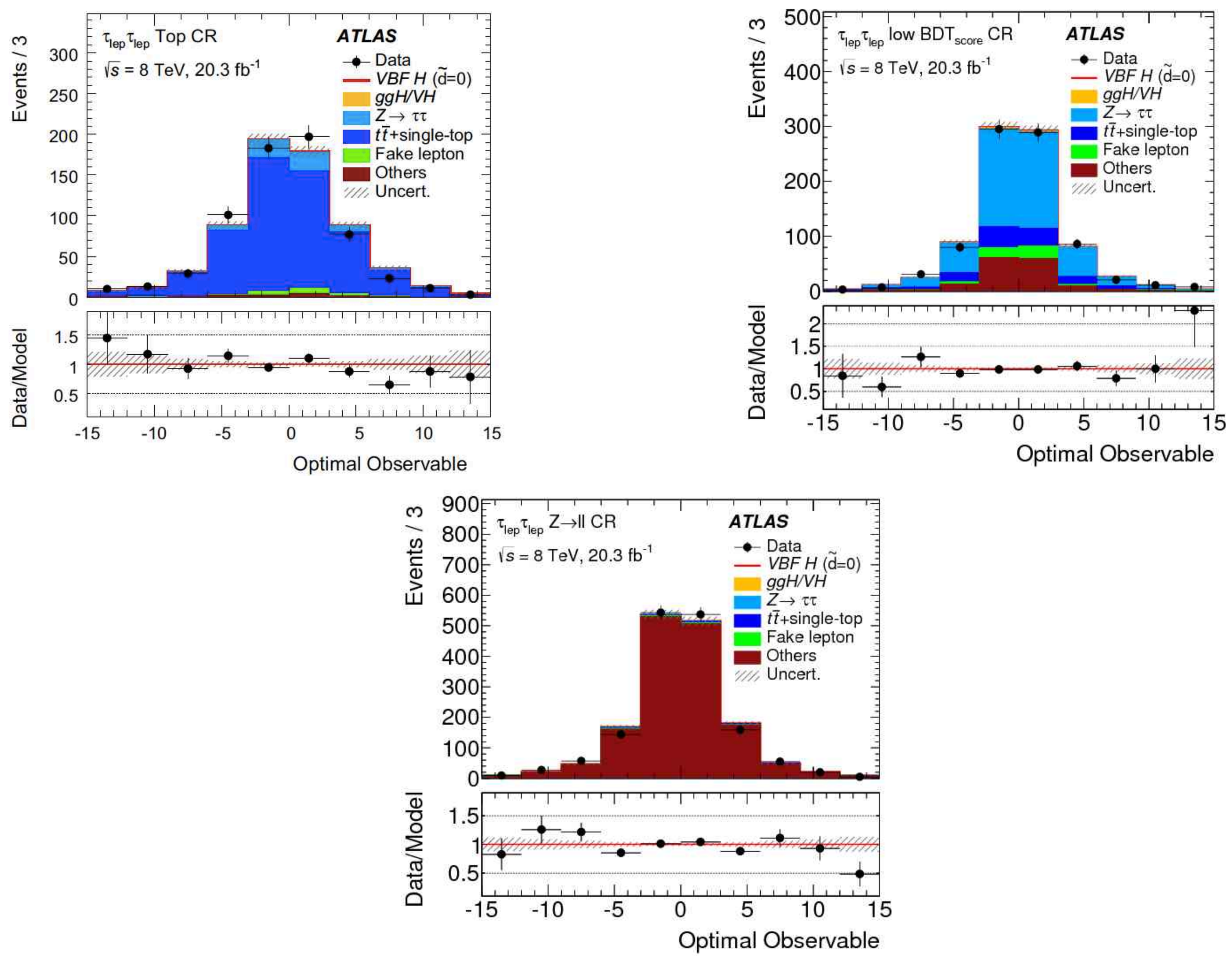
4. Analysis

- RUN 1 data collected by ATLAS 20 fb^{-1}
- This measurement can be performed in every Higgs decay channel, however the $\boldsymbol{H \rightarrow \tau\tau}$ channel allows to select a sizeable amount of VBF events
- 2 channels depending on the reconstructed decay modes of the τ: dileptonic ($\tau_{lep}\tau_{lep}$) and semileptonic ($\tau_{lep}\tau_{had}$)

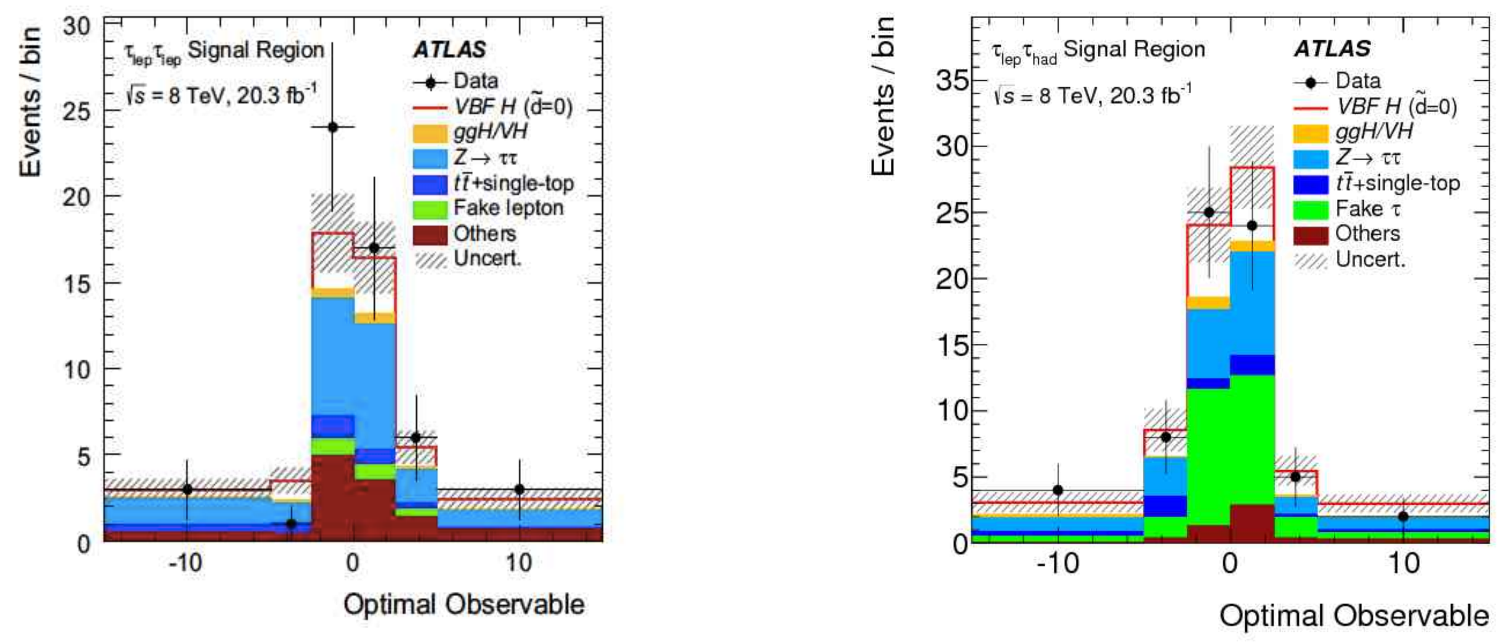
Signal region → a VBF region is identified requiring typical VBF cuts, two high-pT jets well separated in rapidity, then a Boosted Decision Tree (BDT) is used for separating Higgs events produced via VBF from all the other backgrounds including other Higgs production modes

Optimal Observable → used in each signal region for $\tilde{d}$ measurement

Control region → the Optimal Observable is modelled for different background processes using dedicated control regions: Top, low BDT and $Z \rightarrow l\,l$ in $\tau_{lep}\tau_{lep}$ channel



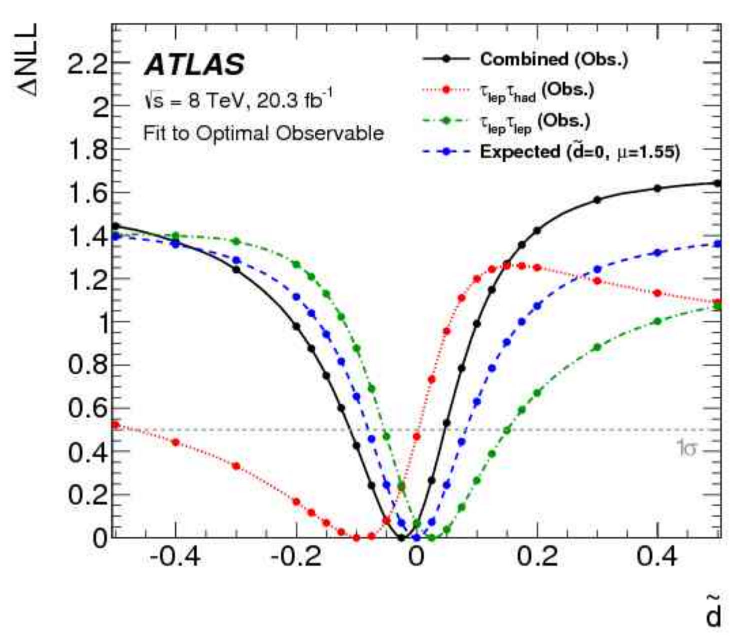
- For the estimation of $\tilde{d}$ a maximum-likelihood fit is performed on the Optimal Observable using also information from CRs
- The likelihood is evaluated for different $\tilde{d}$ values → all the CP-violating simulated samples are obtained with the technique of reweighting



Optimal observables distribution in the signal regions after the global fit for the $\tilde{d} = 0$ hypothesis

5. Results

- $\tilde{d} < 0.11$ and $\tilde{d} > 0.05$ excluded at 68% C.L.
- The 68% C.L. is 10 times better than another result in ATLAS in the Higgs decay to vector bosons
- The statistic of RUN 1 cannot allow to reach higher significance but with the statistic of RUN 2 (36 fb^{-1} of data collected only in 2015-2016) and the combination with other Higgs decay channels this method will be highly competitive. In addition the second order Optimal Observable can be used to increase sensitivity



[1] "Test of CP invariance in vector-boson fusion production of the Higgs boson using the Optimal Observable method in the ditau decay channel with the ATLAS detector", ATLAS Collaboration, Eur. Phys. J. C (2016) 76:658