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Search for associated production of a Higgs boson and a single top quark

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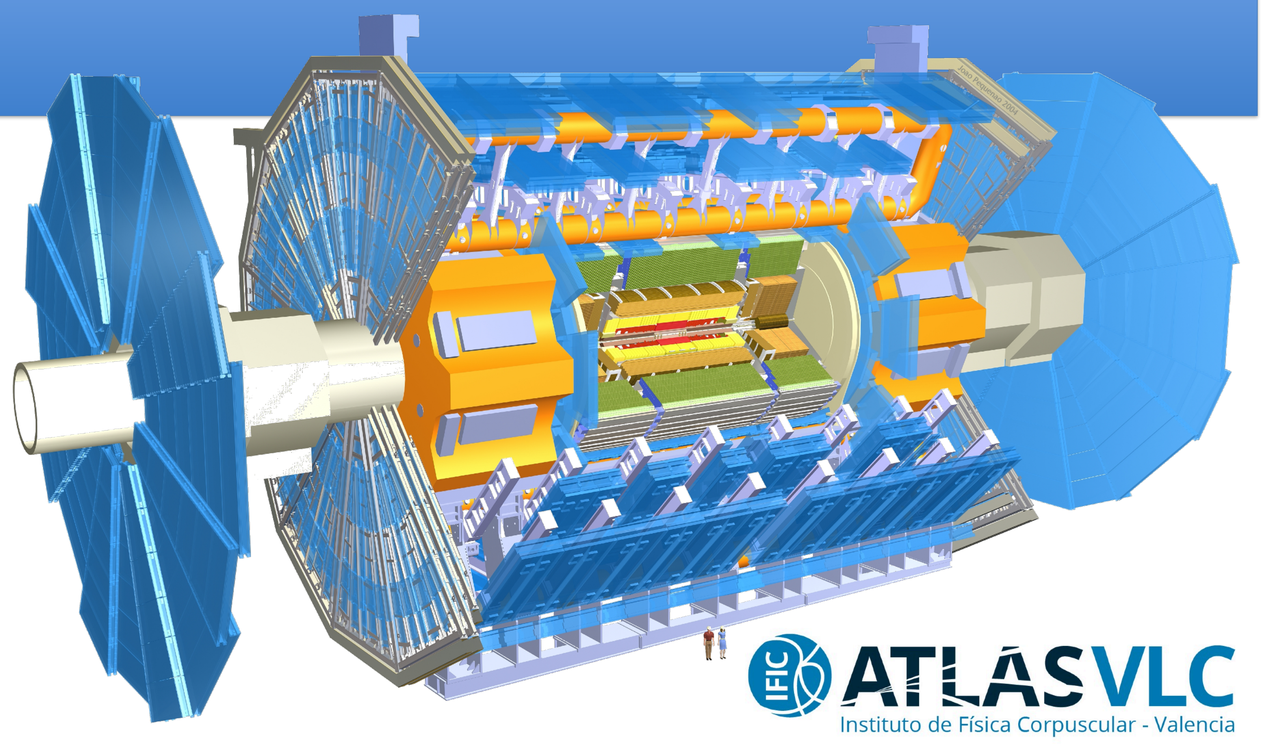
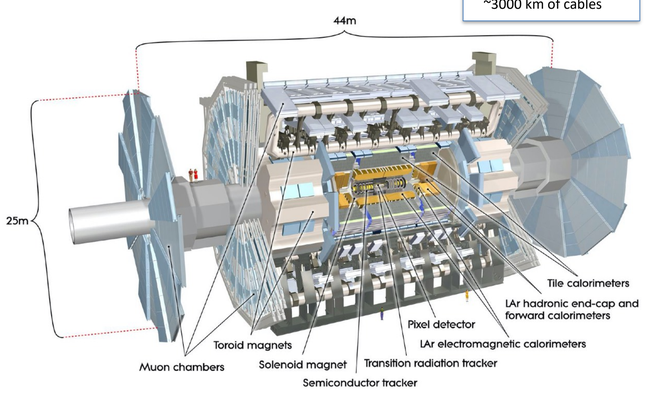
The Large Hadron Collider (LHC) at CERN is the **largest** and **most powerful** particle **collider** built up to date. It has extended the frontiers of high energy particle physics with its unprecedented 13 TeV proton-proton collisions with 40 MHz rate at the design luminosity of 10^{34} cm^{-2} s^{-1}. **ATLAS** (A Toroidal LHC ApparatuS) is one of the four LHC experiments. It is a **general purpose detector** which was build to find the Higgs boson.



ATLAS (A Toroidal LHC ApparatuS)

Length: ~44.0 m
Radius: ~12.5 m
Weight: ~7000 tons
10^8 electronic channels
~3000 km of cables



Magnets
- 2T central solenoid
- Air cored toroids (peak field in the coil windings of 4 T)

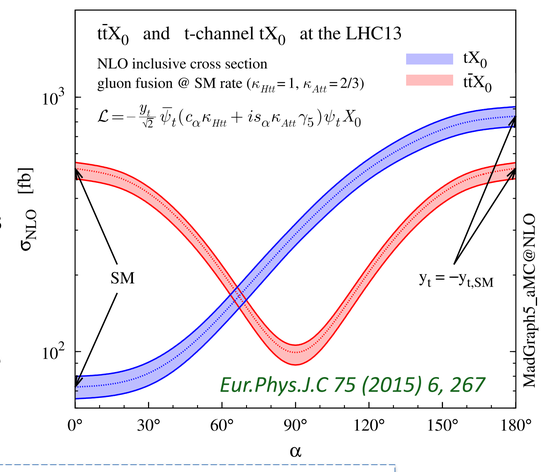
Inner Detector (ID): Tracker ($|\eta|<2.5$)
- Silicon Pixels
- Silicon microstrips (SCT)
- Transition Radiation Tracker (TRT)

Calorimeters ($|\eta|<4.9$)
- EM: Pb-LAr
- HAD: Fe/Scintillators (central), Cu/W-LAr (foward)

Muon Spectrometer ($|\eta|<2.7$)
- Monitored Drift Tubes (MDT)
- Cathode Strip Chambers (CSC)
- Resistive Plate Chambers (RPC)
- Thin Gap Chambers (TGC)

Theoretical motivation

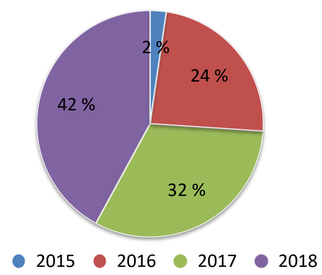
- In the Standard Model (SM) the Higgs field couples to fermions through a Yukawa interaction with a coupling strength proportional to the mass of the fermion.
- The Yukawa coupling between the **top** quark and the **Higgs** boson (y_t) is the **strongest coupling** of the SM, almost unity.
- The **only process sensitive to** both the **sign** and magnitude of y_t is the associated tHq production. Its observation would allow to probe the CP properties of the y_t coupling.



Object definition and event selection

Physical objects: electrons, muons, jets, b-tagged jets, and missing transverse energy.
Using:
- Acceptance for electrons: $p_T < 10$ GeV and $|\eta^{clust}| < 2.47$
- Acceptance for muons and taus: $p_T < 10$ GeV and $|\eta^{clust}| < 2.5$
- Single lepton and single muon triggers with $p_T(\ell_{leading}) > 27$ GeV and $p_T(\ell) > 20$ GeV thresholds.
- For identifying taus a recursive neural network is used.
- Jets (stream of particles from quark hadronisation) find with clustering algorithms.
- *b*-tagging with secondary vertex search.
- MET from calo clusters.

Analysing an integrated luminosity of 139 fb^{-1} corresponding to the Run 2 data taking period (from 2015 to 2018).

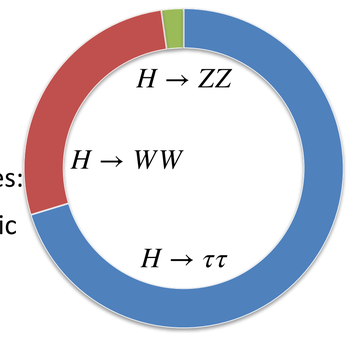


Search of the associated tHq production

The search of the tHq production is performed in several channels which are defined according to the multiplicity of light-flavoured leptons (ℓ) and hadronically decaying taus (τ_{had}) in the final state.

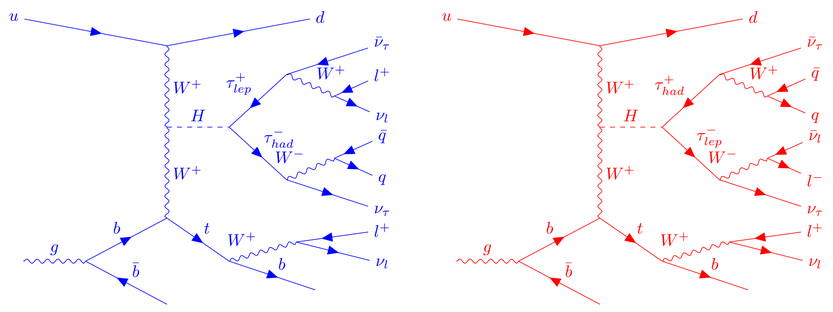
This analysis is exceptionally **challenging** due to the extremely **small inclusive cross section** of the tHq process (~73 fb).

arXiv:1610.07922 [hep-ph]



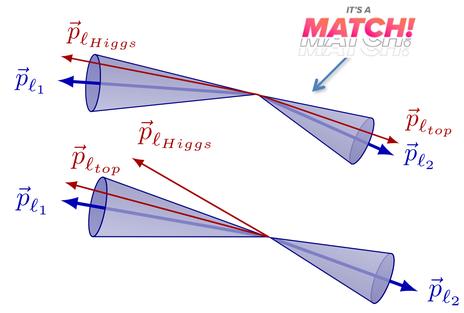
Three Higgs-boson decays contribute to these final states:

Focus on the signature of two light leptons and one hadronic tau ($2\ell + \tau_{had}$) and distinguishing between the channel in which the light leptons have the same (**SS**) or opposed (**OS**) electrical charge.

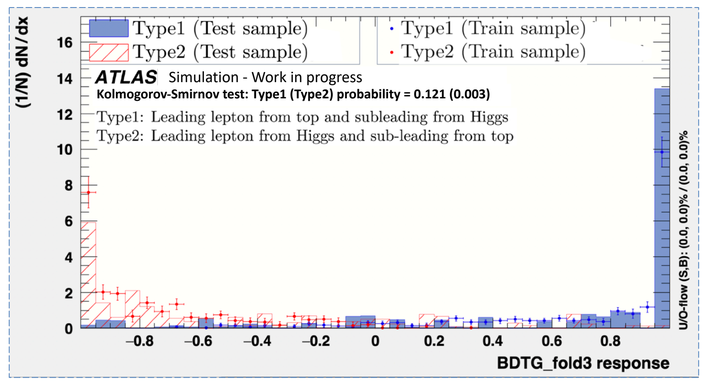


Lepton assignment

The knowledge of which light lepton is originated from the Higgs boson and which from the top quark is **crucial to discriminate** the tHq signal from the background.



- **OS**: The light lepton whose charge is the same as the τ_{had} is the one from the top-quark and the other comes from the Higgs boson.
- **SS**: When both light leptons have the same electrical charge is not possible to know the parent particle a priori. Solution:
  - Particle and reconstruction levels are compared using ΔR cones to match particles to its true origin and define a label.
  - Define **Boosted Decision Tree** (BDT) to associate the leptons to the Higgs boson and the top quark.
    - Cross validation with k-folding
    - Gradient boosting
    - Optimisation via grid search

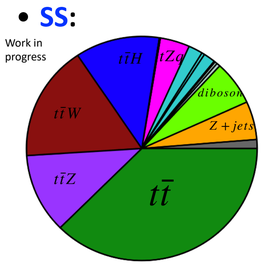


Background estimation

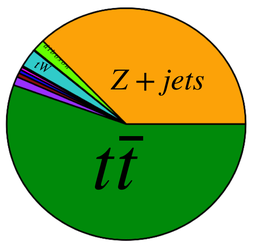
There are several processes mimicking the signature of the $2\ell + \tau_{had}$ production. The background estimation is done with Monte Carlo (MC) simulations

Suppression of jets wrongly identified as leptons is achieved by demanding to pass tight **identification** and **isolation** requirements.

- **SS**:



- **OS**:



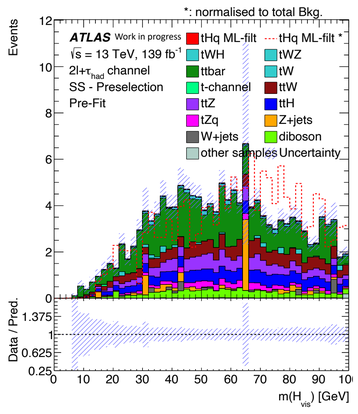
Main background process: top quark-antiquark pair production ($t\bar{t}$). Other backgrounds: Z+jets, $t\bar{t}H$, $t\bar{t}Z$, $t\bar{t}W$, tW, diboson or triboson

Event Selection

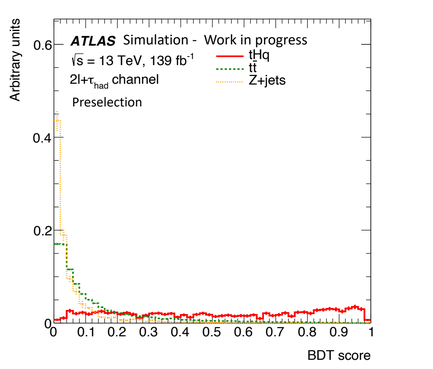
A signal-enriched region is achieved by separating the tHq events from the backgrounds by using a BDT for both **SS** and **OS** :

- Using IFIC's **GPU cluster** for ML: Artemisa.
- Preselection region events as input for training.
- Feature importance ranking for variables.
- Hyperparameters optimisation via genetic algorithm.
- Using information from Lepton assignment.

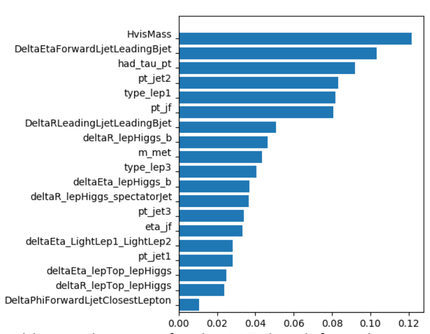
- Additional BDTs are built and optimised in order to define control regions that target specific backgrounds.



The mass of the visible decay products of the Higgs boson, $m(H_{vis})$, is a variable with high separation power.



A cut on the BDT score is used to discriminate the process of interest from the others.



Variables used as input for the BDT that defines the **SS** signal region ranked according to its impact in the training.

Final step: Perform a binned **profile likelihood fit** of the SM predictions to the collected data to extract, considering the signal and control regions, the signal strength $\left(\frac{observed}{predicted}\right)$.

Conclusion and next steps

ATLAS and CMS experiments are deeply exploring the top-quark-Higgs-boson Yukawa coupling y_t through an exhaustive study of the associated production of Higgs bosons with top quarks.
Next steps:
- MC only fit (Asimov)
- Evaluation of the uncertainties (statistical and systematic)
- Data fit
- Combine the results of all channels

Goal: Set the best limits on the tHq production.

This analysis with Run 2 data (139 fb^{-1}) sets the base for future studies with **more statistics** in the LHC Run 3.

The observation of an excess of signal with respect to the SM prediction, would be an **evidence** of new physics in terms of **CP-violating** y_t coupling.

Looking forward to finish the Run 2 analysis and study the tHq process with Run 3 data!!!