Preliminary investigations towards the measurement of the Higgs boson self-coupling with $hh \rightarrow bb^{-}\tau^{+}\tau^{-}$

Christos Paraskevopoulos (NTU Athens/BNL)

HEP 2021 38th Conference on Recent Developments in High Energy Physics and Cosmology, Thessaloniki, 16-19 June 2021
**Higgs boson self-coupling modifier**

- The BEH mechanism not only predicts the existence of a massive scalar particle, but also requires this scalar particle to couple to itself.

\[ V(\phi) = \frac{1}{2} m_h^2 h^2 + \lambda v h^2 + \frac{\lambda}{4} h^4 = m_H^2 \frac{h^2}{2} + \frac{\lambda_{HHH} h^3}{3!} + \frac{\lambda_{HHHH} h^4}{4!} \]

- The Higgs boson self-coupling modifier due to BSM scenarios is defined as \( \kappa \lambda = \frac{\lambda_{HHH}}{\lambda_{SM}} \).

- In the SM, pairs of Higgs bosons at the LHC are dominantly produced in gluon-gluon fusion (ggF) processes, namely via a loop of top quarks.

A direct probe to \( \lambda_{HHH} \) is to measure the non-resonant di-Higgs production via the triangle diagram.

BSM theories predict heavy resonances that could decay into a pair of the SM Higgs bosons, such as a heavy spin-0 scalar \( X \) in two-Higgs-doublet models.
Experimental Signatures

- Relatively small background
- Relatively high branching ratio
- High trigger efficiency

**Kinematics** depend on Higgs self-coupling
- Additional handle to $\kappa_\lambda$

**HH: multiple final states**
- $H \rightarrow bb$ is the protagonist

$bb\tau\tau$ is the most sensitive decay channel with 36 fb$^{-1}$ data
Event Selection and Background Estimation

The $b\bar{b}\tau^+\tau^-$ analysis looks for final states with two $b$-tagged jets and two $\tau$-leptons. In the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, events are triggered by single lepton triggers (SLT), requiring an electron or a muon in the final state, or by the coincidence of a lepton trigger with a hadronic $\tau$ trigger, Lepton Tau Triggers (LTT).

- **Single Lepton Triggers (SLT)**
  - $e/\mu$ triggers >26GeV
  - Lepton tau triggers (LTT)
    - Thresholds between 15-18GeV
    - Opposite sign between the $\tau$ and the lepton
    - Exactly two $b$-tagged jets

The background due to a jet faking the $\tau_{\text{had}}$ is estimated by a data driven fake factor method:
- FFs computed separately for each process ($t\bar{t}$, $W$+jets, multi-jets) in a dedicated CR
- Contribution from true taus and other backgrounds is subtracted
- $FF = \frac{N_{\text{tau}}}{N_{\text{anti-tau}}}$, $NA = FF \times NB$
  - FF is calculated for each CR, depends on channel/targeted process

Lephad: a combined FF is calculated for combining the Gluon initiated and quark initiated FFs.
From each particle 4-vector, we extract useful variables such as $P_t, \eta, \phi, M$ and the 4-vector of the system of particles.

- Keeps particles that at the same event contain Higgs that decay to $b\bar{b}$ and $\tau\tau$.
Generator Level level $bb\tau\tau$

- Tlorentzvectors of $bb$ to calculate the $m_{bb}$ and other variables of their system from the 4 vector of it
- DeltaR is calculated between the two $b$-jet, Phi and M of the $bb$ system which is calculated too
- Print out all the useful variables into an ntuple

- From each tau and child we keep pdgId, status, barcode and $pt$
- From $t_{lep}$ and $t_{had}$ we need $pt$, eta, phi, $m$, E and get their 4 vectors
Pre-Selection useful variables

**ATLAS Work In Progress**
\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]

- \( kL \rightarrow 1 \)
- \( kL \rightarrow 10 \)
Pre-Selection useful variables

ATLAS Work In Progress

\[ \sqrt{s} = 13 \text{ TeV, } 139 \text{ fb}^{-1} \]

- \( kL \rightarrow 1 \)
- \( kL \rightarrow 10 \)

\[ b \text{ leading pt, Gev} \]

\[ b \text{ subleading pt, Gev} \]
Pre-Selection useful variables

ATLAS Work In Progress

\( \sqrt{s} = 13 \text{ TeV, 139 fb}^{-1} \)

- kL -> 1
- kL -> 10

mHH, GeV

# of events
Reweighting Tool

DiHiggs analyses need simulations of many $\kappa_\lambda$
- Computationally expensive (full simulation)
- Reweighting only requires fully simulated $\kappa_\lambda = 1$

$$pp \rightarrow HH$$

Events used to generate the arbitrary $\kappa_\lambda$ at generator level

$$\frac{d\sigma}{dm_{HH}}(m_{HH}) = A(m_{HH}) + B(m_{HH})\kappa_\lambda + C(m_{HH})\kappa_\lambda^2$$

Validate using remaining generated $\kappa_\lambda$

- Use of $m_{HH}$ branches to generate the different $\kappa_\lambda$
- Generated $\kappa_\lambda$ from -30 to 30, increments of 0.2

Look at statistical errors for 5, 10 and 20 GeV bins
Selection useful variables

- $m_{bb}$ is calculated from the 4-Vector of the di-$b$-jet system
Selection useful variables

- $m_{HH}$: The invariant mass of the di-Higgs system is reconstructed from the di-τ and di-b-jet 4-vectors.

![Graph 1](https://via.placeholder.com/150)

**LTT**

![Graph 2](https://via.placeholder.com/150)

**SLT**
Reweight from $\kappa_\lambda = 1$ and $10 \, m_{HH}$ comparison:

- Use KLambdaReweightTool for truth-level reweighting of samples towards other $\kappa_\lambda$ hypotheses
- Use of specific weight factors (Filter Efficiency, Luminosity, Cross Section, WeightGeneralMC)
Reweight from $\kappa_\lambda = 1$ and $10 \ m_{HH}$ comparison:
Summary

• SM HH production cross-section is very small: 33.41 fb at 13 TeV
• To study a rare process like HH production need to look at the H decay channels with high BRs
• bbττ has the third highest accessible BR is the most sensitive decay channel
• It is relatively clean compared to other channels with higher BR but also larger background and more difficult reconstruction
  → very promising !!!

• Focusing on obtaining the best possible result for the non-resonant SM di-Higgs production through τ_{lep}τ_{had} channel