Muon Collider simulations studies

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June 17, 2021

Introduction

Muon colliders have potential for very high energy collisions, in the multiple TeV range.

We aim to study feasibility of detecting four Higgs signals in a 3 TeV muon collider.

Signals: $\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu HH$ $\mu^+\mu^- \to \mu^+\mu^- HH$

$\mu^+\mu^- \to ZHH$ $\mu^+\mu^- \to H \to HH$

Backgrounds:

$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu b\bar{b}b\bar{b}$ $\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu b\bar{b}H$ $\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu b\bar{b}Z$

Generator level MC Samples

MADGRAPH5 was used to generate the MC level samples for the signals and backgrounds. Specific instructions on how to generate and store the output files is here:
`https://github.com/agandotra611/MuC_Simulation_Workflow`

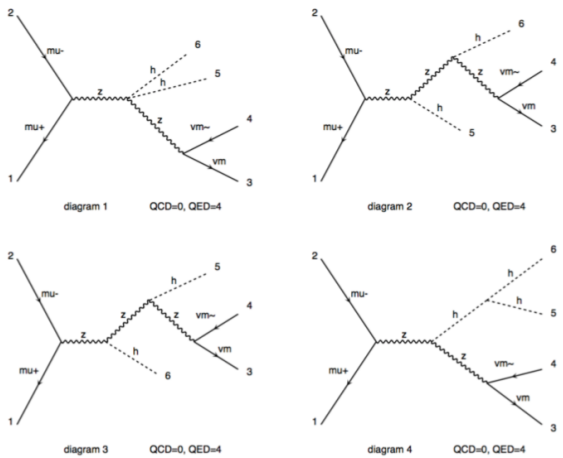


Figure: For the $\mu^+\mu^- \to \nu_\mu \bar{\nu_\mu} HH$ signal, there were 8 possible Feynman diagrams that MADGRAPH generated.

Generator level validation plots

The Higgs pT, η, ϕ are plotted at the MC level for validation for $\approx 10^4$ events.

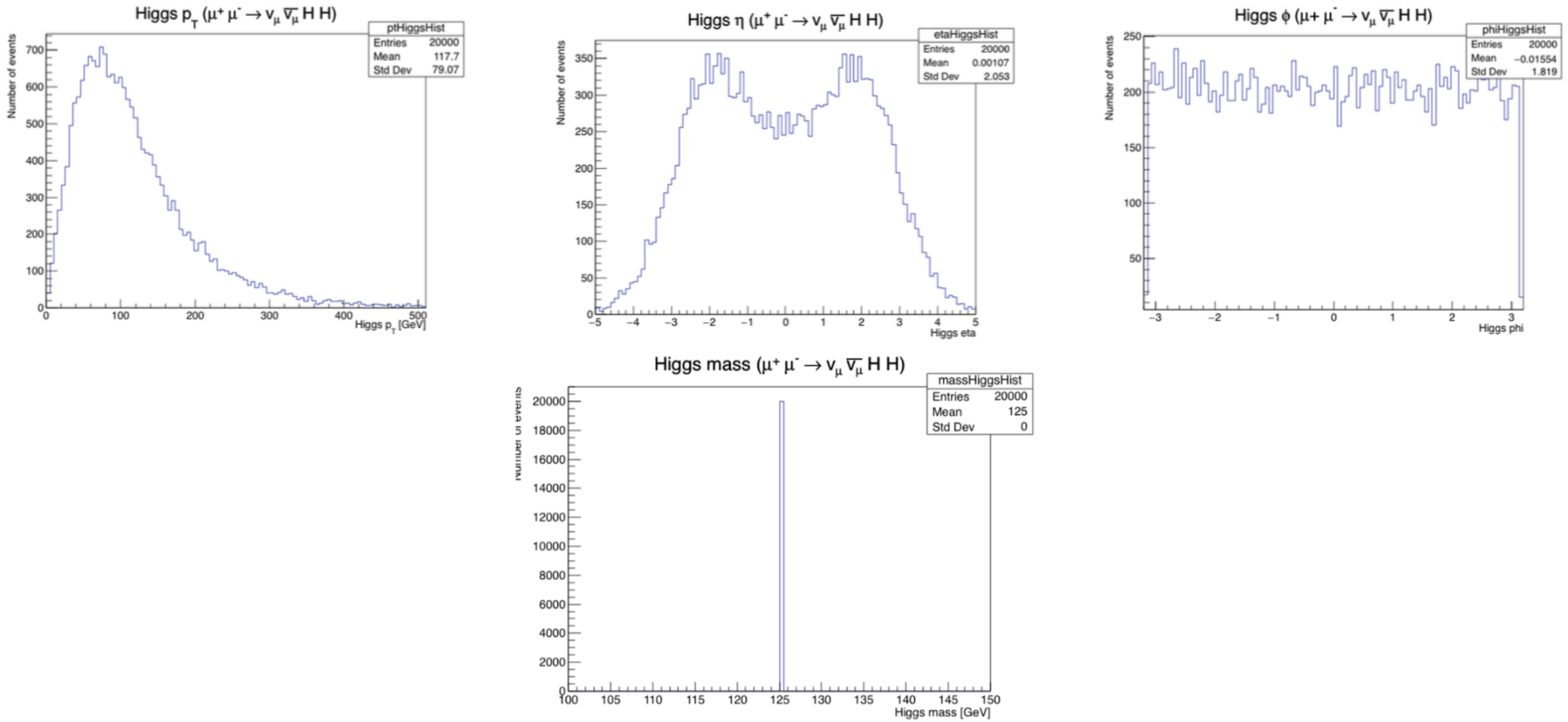


Figure: Generator level validation plots

Simulation workflow

1. Generate MC samples using MADGRAPH5 (.hepmc format).
2. Use sim_steer.py with ddsim to simulate the MC samples and get simulation level plots (.slcio format).
3. Then we reconstruct these files using reco_steer.xml using Marlin to get reconstructed plots (.slcio format).
4. Reconstructed files can be inputted into lctuple_steer.xml producing a root file with relevant variables.

The above files and how to run them are given in more detail in the git linked before.

Simulator level plots

The Higgs pT, η, ϕ are plotted at the simulator level for validation for $\approx 10^4$ events.

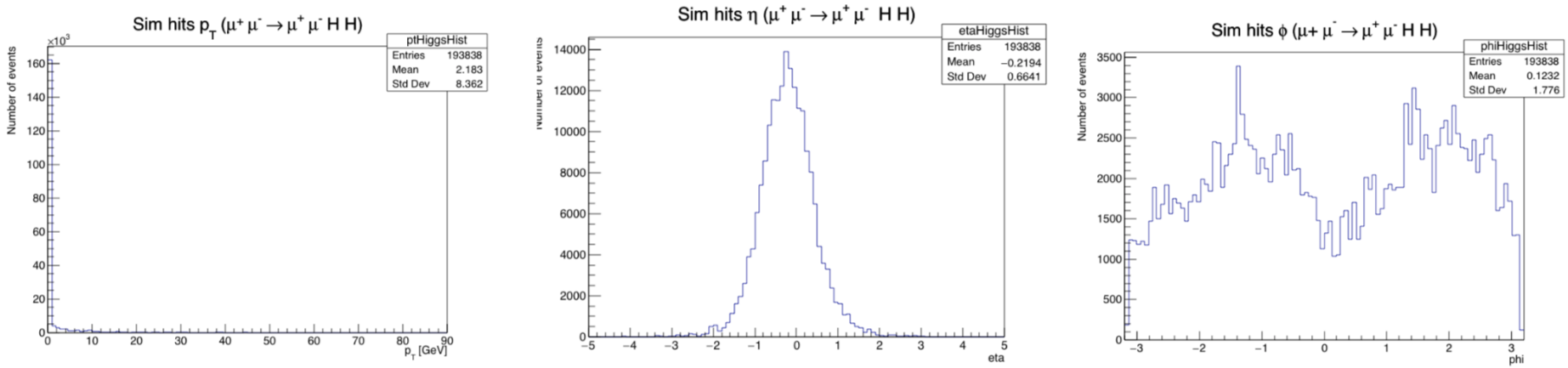
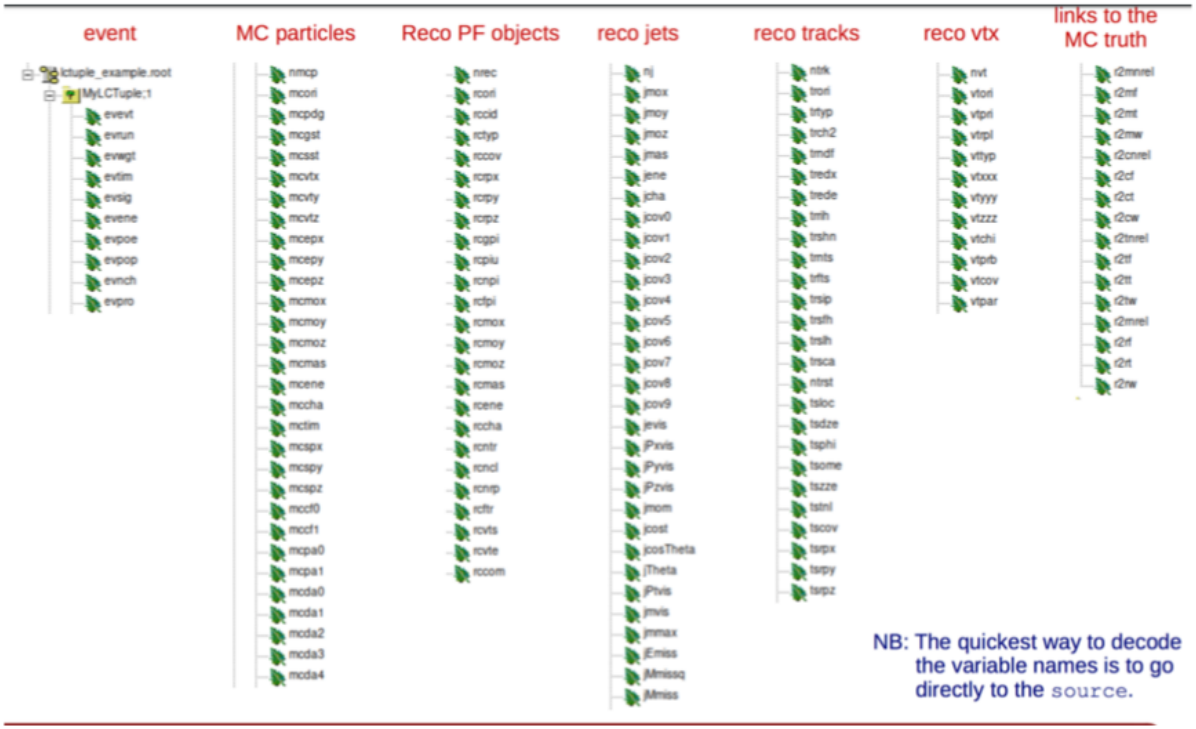


Figure: Simulator level validation plots

Details of steering files

Figure: The simulation and reconstruction steering files respectively

LCTuple Output



To understand what these variables represent, one should look at the .cc and header files in

https://github.com/iLCSoft/LCTuple/blob/master/src/

```
// Write default jet parameters
_jmox[ i ] = jet->getMomentum()[0];
_jmoy[ i ] = jet->getMomentum()[1];
_jmoz[ i ] = jet->getMomentum()[2];
_jmas[ i ] = jet->getMass();
_jene[ i ] = jet->getEnergy();
_jcha[ i ] = jet->getCharge();
_jcov0[ i ] = jet->getCovMatrix()[0];
_jcov1[ i ] = jet->getCovMatrix()[1];
_jcov2[ i ] = jet->getCovMatrix()[2];
_jcov3[ i ] = jet->getCovMatrix()[3];
_jcov4[ i ] = jet->getCovMatrix()[4];
_jcov5[ i ] = jet->getCovMatrix()[5];
_jcov6[ i ] = jet->getCovMatrix()[6];
_jcov7[ i ] = jet->getCovMatrix()[7];
_jcov8[ i ] = jet->getCovMatrix()[8];
_jcov9[ i ] = jet->getCovMatrix()[9];
```

A useful thing to do is to switch off MC Particles in the reco_steer.xml file, so you can save space by keeping only the reconstructed events

This is an example from JetBranches.cc

Reconstructed invariant mass distributions

After reconstruction, we get the jet momenta and energies, which can be used to calculate the invariant mass $m = \sqrt{E^2 - p^2}$. We define $m1$ and $m2$ are the invariant masses of the highest and lowest jet pT pairs. We stack the signals on the background normalised by cross section.

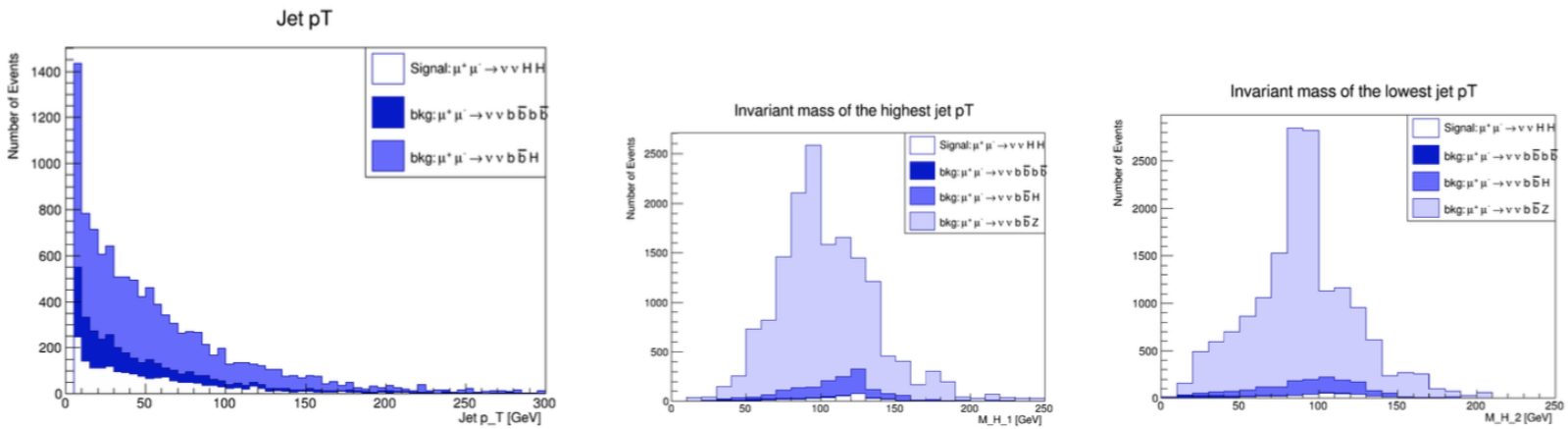


Figure: Invariant mass distributions

Optimising $S/\sqrt{S+B}$ ratio

We aim to improve the signal-background ratio by making some cuts on the jet pT and m1. The most effective ones we found were $m1 > 100$ and $pT > 20$. After the cuts we get the plots below.

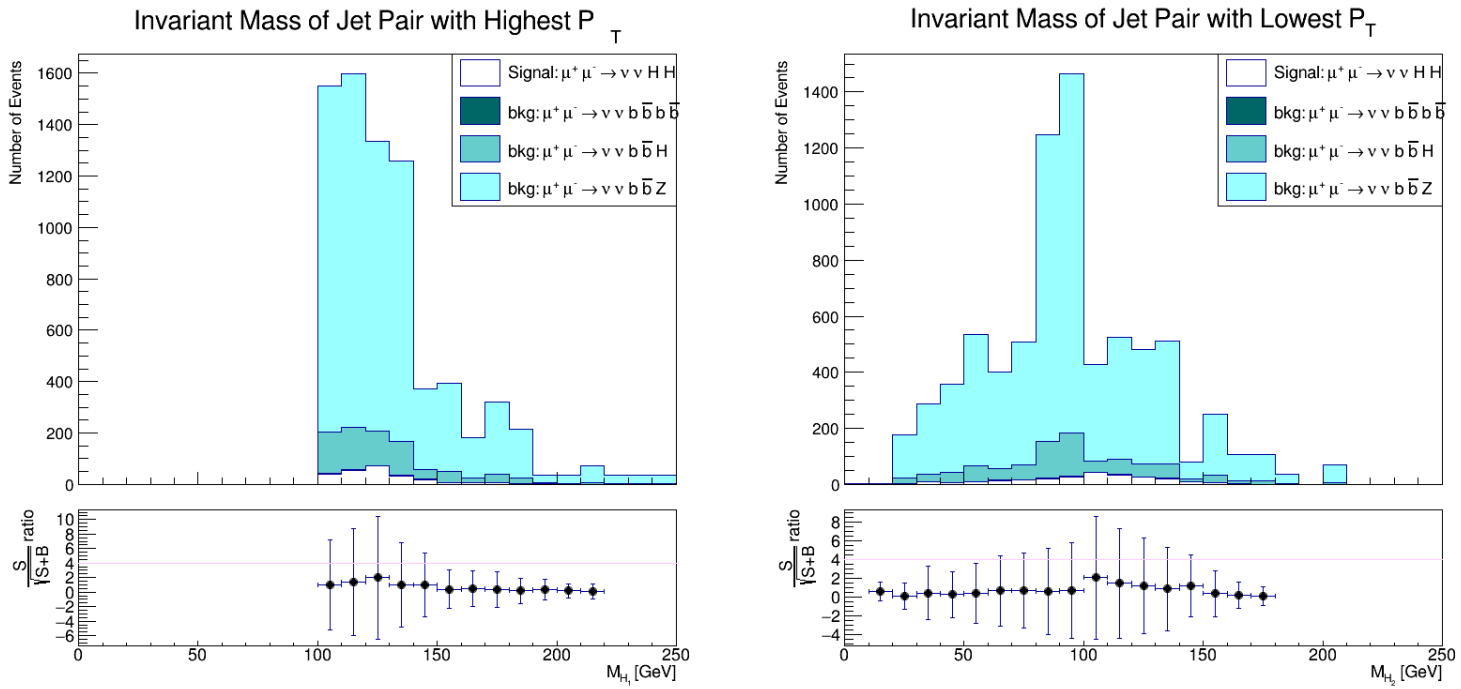


Figure: Invariant mass plots with $m1 > 100$ and $pT > 20$

Kinematic fitter

The kinematic fit uses the reconstructed variables and imposes a mass constraint on the jets, i.e. that we need two diHiggs jets. It minimizes the χ^2 and calculates the probability of goodness of fit per event, $P_{gof} = e^{-\chi^2/2}$.

Considered three permutations for jet combinations and picked events with lowest χ^2 value.

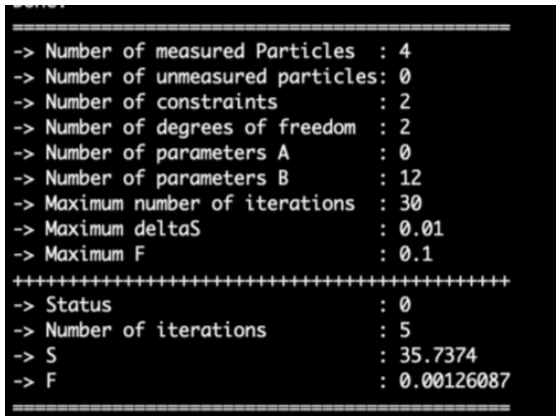


Figure: Output of the kinematic fit on an event

P_{gof} and χ^2

From the plots, it seems ideal cuts would be $P_{gof} > 0$ and $S < 20$.

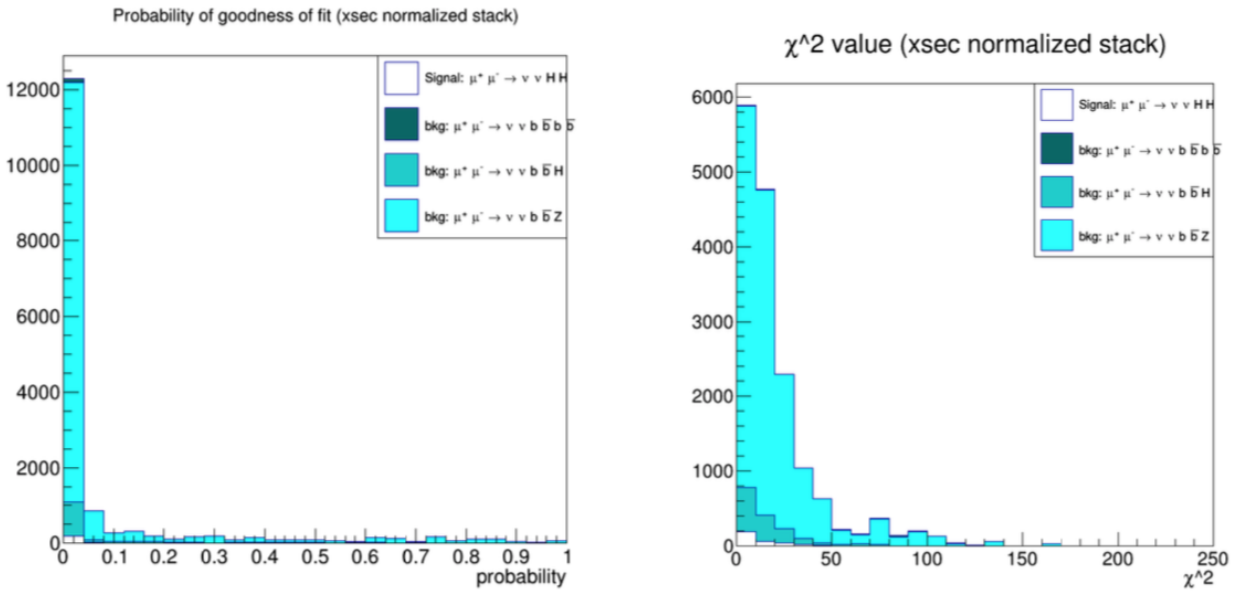


Figure: P_{gof} and χ^2 plots

m1, m2 after kinematic fit cuts

Performing the kinematic fit while calculating the invariant mass to pick the jet combination with lowest χ^2, yields corrected m1, m2 plots.

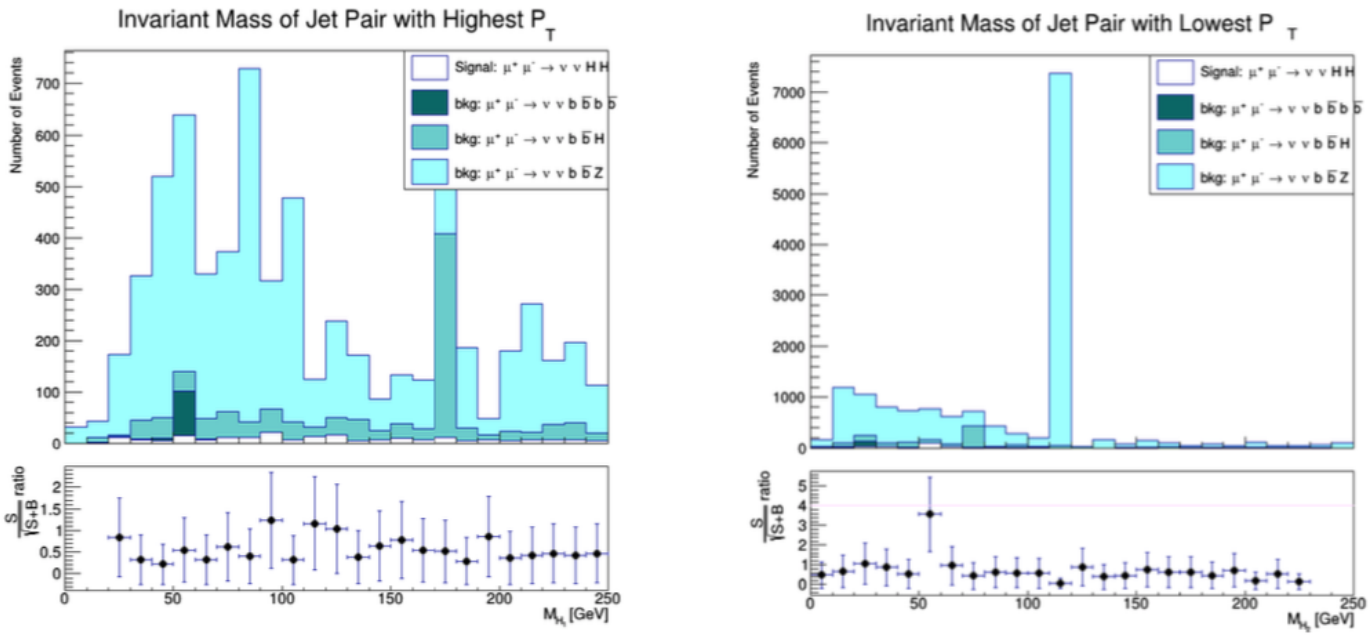


Figure: m1, m2 plotted using kinematic fit to pick best combinations

$\chi^2 < 20$ cut

Source of peaks needs to be diagnosed from the ntuples.

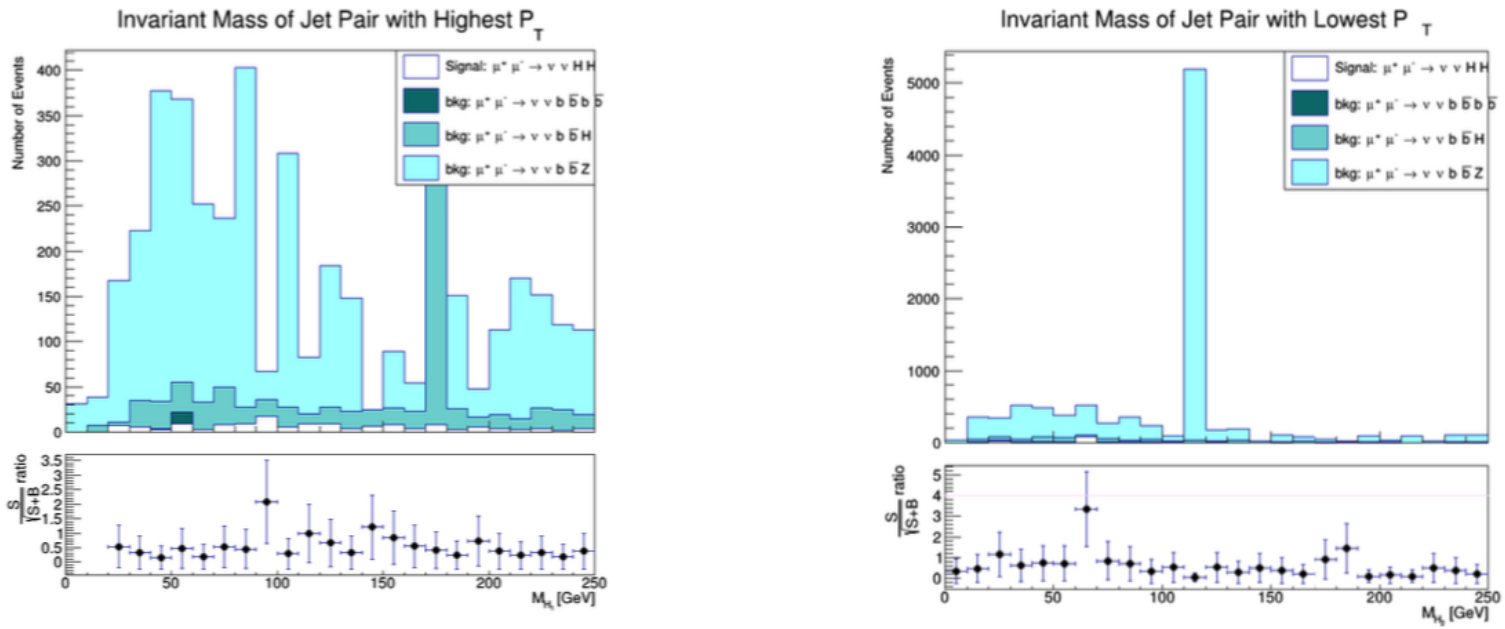


Figure: m1, m2 plotted using kinematic fit to pick best combinations with $\chi^2 < 20$ cut