Calorimeter Studies for BIB mitigation

IMCC and MuCol Annual Meeting 2024

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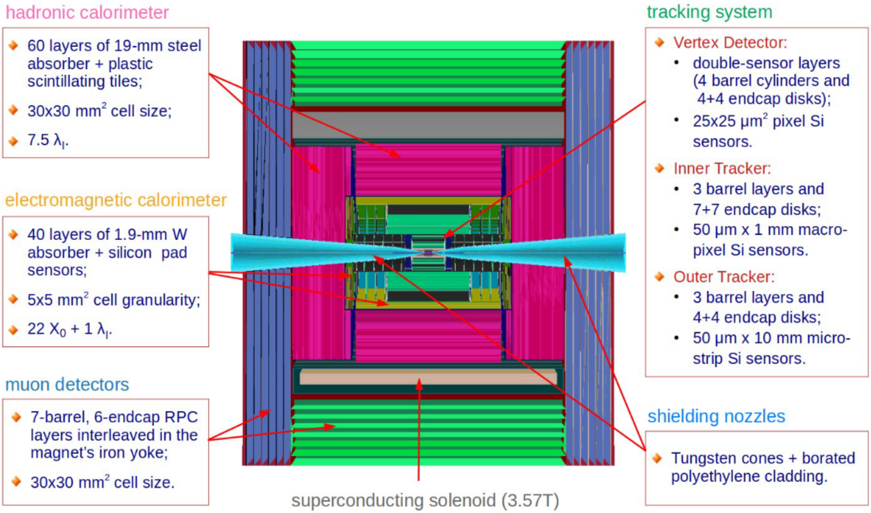
Introduction

- Current muon collider detector design shows good jet reconstruction performance. Plenty of room for further optimization.
- This talk focuses on using the W-Si calorimeter.
- An optimized strategy to mitigate BIB in the ECAL barrel is discussed.
- Use shower profile information of hard scatter process vs BIB to implement energy thresholds in calorimeter cells, instead of a flat 2MeV cut.

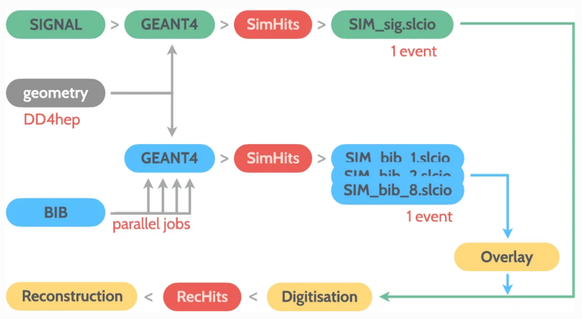
Detector



This talk focuses on electromagnetic calorimeter

Full Simulation Framework

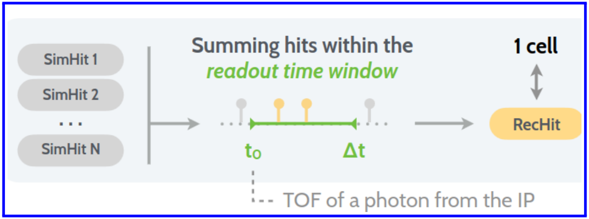
Signal process $\mu^+\mu^- \rightarrow \nu\bar{\nu}H, H \rightarrow b\bar{b}$ at $\sqrt{s}$ =3 TeV (1k events)
BIB simulation at $\sqrt{s}$ =1.5 TeV (1 full BX)



We focus on studying SimHit distributions and use hit features to modfiy the digitization stage

Digitization process

Each calorimeter hit has a cell ID, timestamp, E deposit

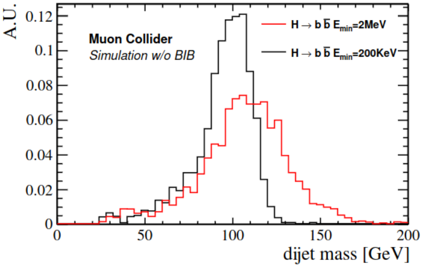


- In each ECAL cell, the simulated hit energy deposits within an integration time window are summed together
- This collection is required to pass energy threshold
- The time of the earliest hit is assigned to the digitized hit (RecHit)

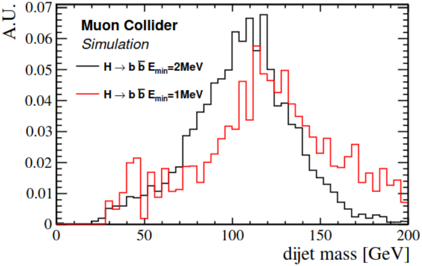
Jet reconstruction performance

Performance is limited by BIB. Jet reconstruction depends on calorimeter thresholds. Without BIB, reducing the threshold improves invariant mass width. However, in presence of BIB, the performance degrades.

without BIB



with BIB

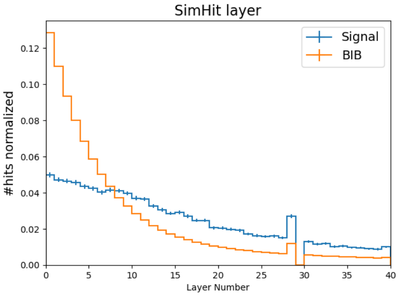


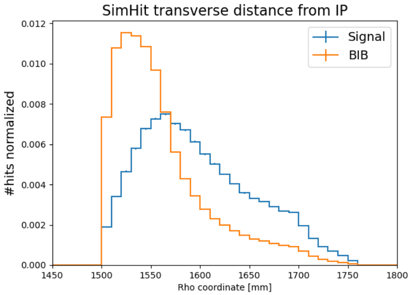
Reference: Simulated Detector Performance at the Muon Collider [2203.07964]

Idea: use differences in shower profiles of BIB and hard interaction to implement energy thresholds that depend on cell location.

Sensor Depth Dependence

Hit occupancy in ECAL barrel (40 layers of W absorber + Si pad sensor)

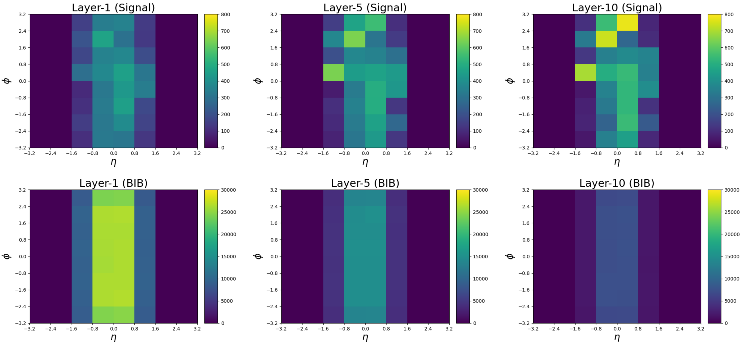




BIB hits have highest occupancy in initial layers, signal distribution extends to larger radius.

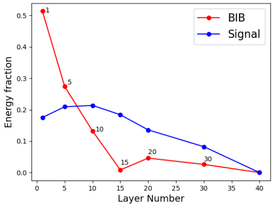
Layer Dependence of Shower Profile

SimHit energy deposit (in keV) in $\eta - \phi$ towers of 0.8x0.8 for layer 1, 5, 10:



$$\text{Energy fraction} = \frac{E_{layerN}}{\sum_N (E_{layerN})}$$

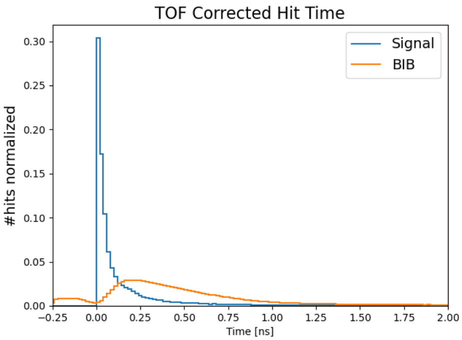
50% of BIB energy is in layer-1. Can use tight cell thresholds for initial layers.



Hit Timing and Integration Window

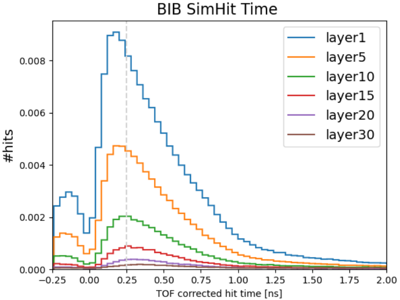
Time of Flight correction:

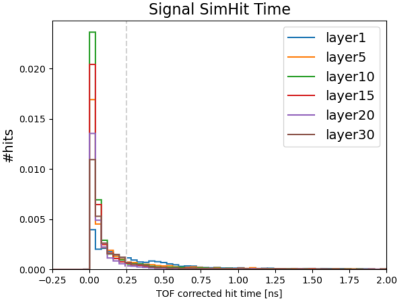
$$T_{corrected} = T_{absolute} - D/c, \text{ where } D = \sqrt{X^2 + Y^2 + Z^2}$$



A common time window of 0.25 ns is used for all layers.

Hit Timing Layer Dependence

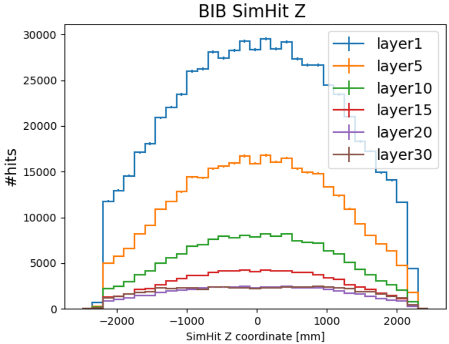




BIB timing peaks shifted for deeper layers.
Make readout time window depend on layer number to further reduce BIB hits while keeping signal hits. (Work in progress)

Hit Occupancy Z-coordinate Dependence

For initial layers, hits occupancy highest in central region and flattens out for deeper layers.



Use tighter energy thresholds for central Z and initial layers.

Implementing this strategy

Readout time window: $\Delta T = g(Layer)$

Energy threshold: $E_{th} = f(Layer, Z)$

Working on implementing a layer dependent readout time window, and studying the SimHit energy distributions. This will influence our choice of cell threshold function to use.

We may need different functions for different physics object reconstruction (photon, jet, etc).

Check L. Sestini's talk for CRILIN case.

Summary and Discussion

- An optimized BIB mitigation strategy is discussed to further improve jet reconstruction performance.
- Hit timing, sensor depth and Z-coordinate are promising features which can be utilized to implement variable thresholds in calorimeter cells.
- Using a variable readout timing window for different layers is explored for the first time.
- The project is in early stages, stay tuned for updates.
- Feedback and suggestions are very welcome!

MuCol Calorimeter BIB mitigation using Machine Learning

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Overview

Goal:

- Can we distinguish BIB hits from Hbb signal hits?
- Can we do it using only Calorimeter Hits information?
- How fast can we do it?

Why do we want to do this?

- We expect a large fraction of BIB hits compared to signal hits
- Leads to an exponential increase in the object reconstruction time and complexity

Approach

- Split an event(100% BIB overlaid) into several blocks of (η x ϕ x r). Block size = (0.5,0.5,3000)
- Analyze each block to see if it is BIB or contains Hbb hits
- Using 3D Convolutional Neural Networks. Features are the hit position and energy

Example hit blocks for BIB and Hbb

Each point corresponds to an energy deposition in the Calo at that location

Figure: BIB block

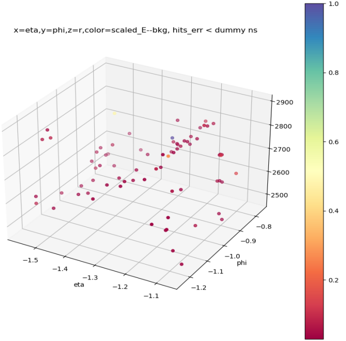
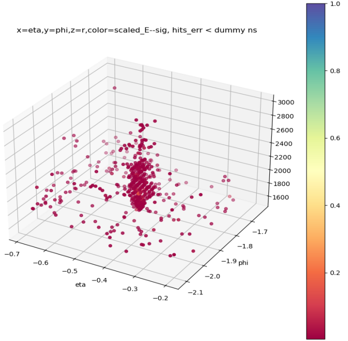


Figure: Hbb block



The difference in hit distribution for BIB vs Hbb can be learnt

Preliminary Model performance and future steps

Model Performance:

- Evaluated on events which are not used for training
- The blue color is BIB blocks and the orange color is Hbb blocks
- Good separation between the 2 normalized distributions implying the model is able to learn
- Demonstrates proof of concept
- Performance expected to improve

Future steps:

- Speed up the training using GPUs
- Include timing info of the hits
- Iterate:
  - Optimize the network architecture
  - Implement the network using hls4ml on FPGAs for fast inference
- All hits in BIB blocks can be set to 0, resulting in a clean event and this can speed up reconstruction