Cosmic Muon Station for Outer Tracker Module Testing

Mentees: Elena Vlašković, Luan Hernández
Mentors: Kiley Kennedy, André Frankenthal

Princeton University
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Abstract

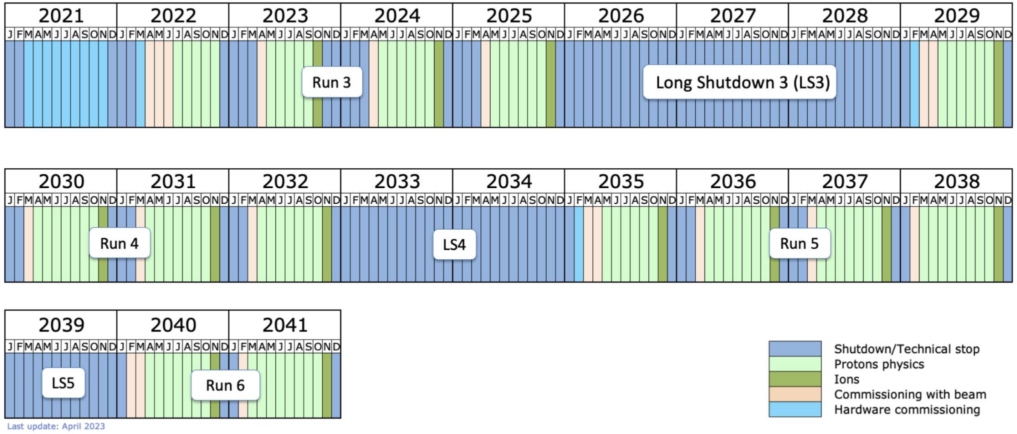
The Outer Tracker (OT) is an essential component of the CMS HL-LHC upgrade project. OT module performance measurements typically rely on internal charge injection in lieu of an external source, limiting the extent to which the entire end-to-end system can be tested. By using cosmic muons as a real source of ionizing particles, we fill this gap and assess the synchronous performance of the modules. A cosmic muon station interfaced with simple scintillators/photomultiplier tubes (PMTs) allows us to understand the behavior of the module in the presence of an external trigger and characterize key metrics such as position-dependent efficiency and resolution. The main task involves working on the hardware setup (e.g., detector setup, frontend-backend connection, DAQ) and the analysis software (e.g., DAQ, data analysis, script automation).

Overview

1. Introduction
2. Module Test Bench
3. Silicon Modules
4. External Trigger
5. Data Analysis
6. Conclusion

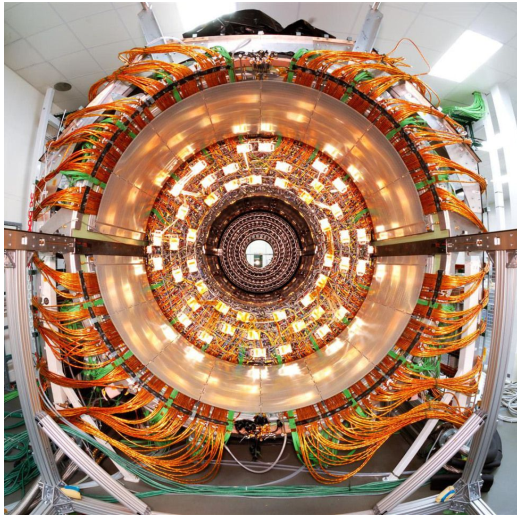
Motivation

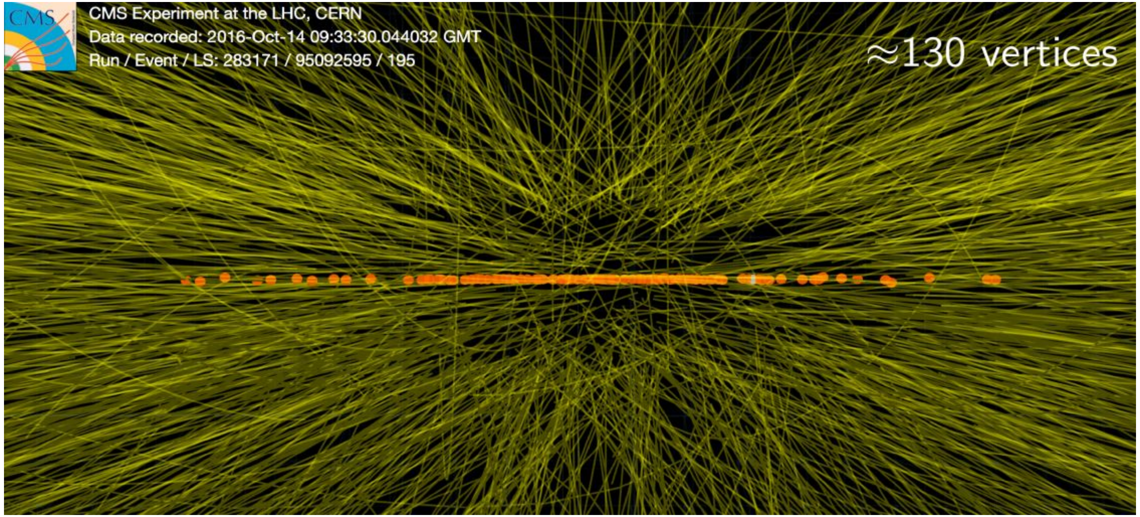
- ❖ Our project focuses on the CMS OT High Luminosity upgrade that will be implemented during Long Shutdown 3 in 2026.
- ❖ The OT measures the trajectories of charged particles and their momentum, and utilizes a Level 1 trigger to make selection on meaningful data.



HL-LHC Outer Tracker

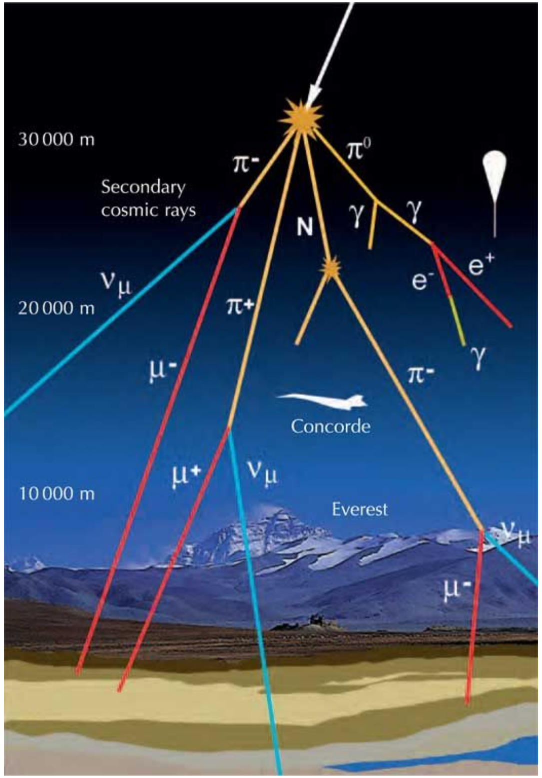
- Pileup simulation within the OT
- For HL-LHC there will be over ~200 collisions per bunch crossing due to increased luminosity after the upgrade.



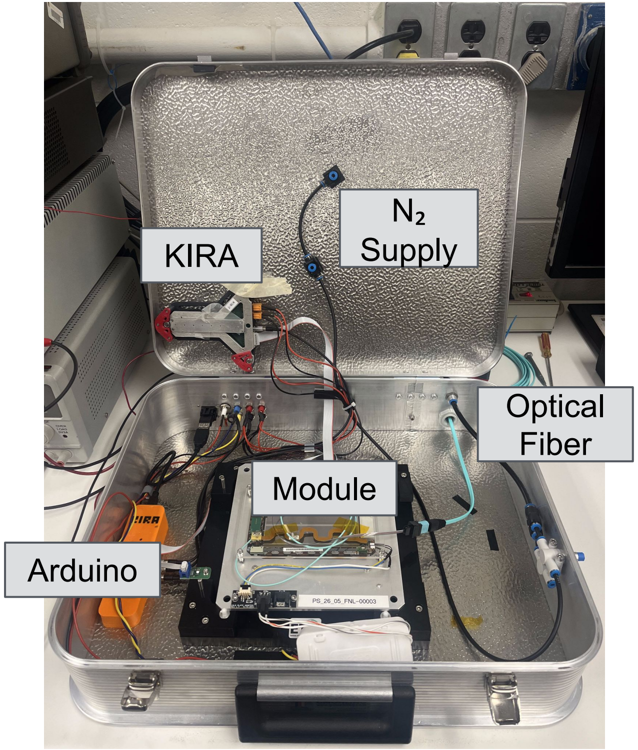


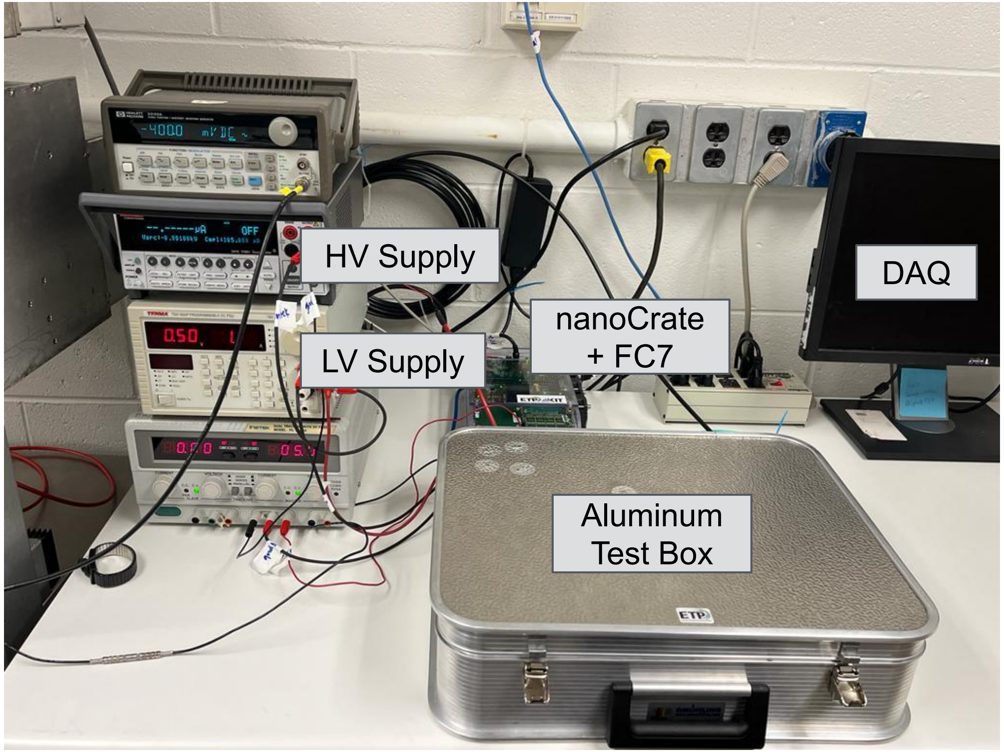
Cosmic Muons

- Cosmic rays, high-energy protons and atomic nuclei, interact with molecules in our atmosphere.
- These interactions lead to the creation of pions, that quickly decay into muons.
- These muons are then captured by our modules and these data can be used to test the position-dependent efficiency and resolution of the module.



Outer Tracker Module Test Bench Setup



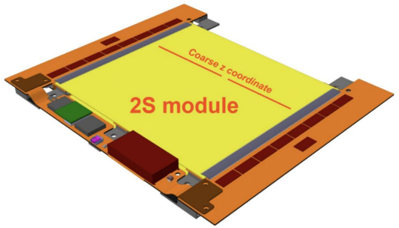


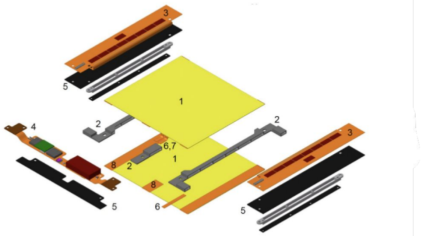
Outer Tracker Module Test Bench Setup

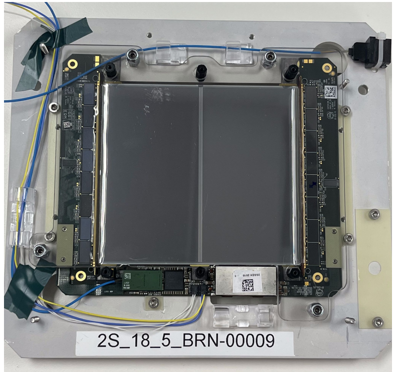
- The aluminum box serves to prevent light leakage onto the module.
- There is a line that supplies **nitrogen** into the box to remove oxygen molecules and maintain internal temperature and prevent condensation.
- The **KIRA/Arduino** system injects external signals to test the module using LED lights.
- The **high voltage** powers the electronics around the module, while **low voltage** powers the electronics on the module.
- The **optical fiber** transfers the data captured on the module to the **Data Acquisition System (DAQ)** where it is analyzed through the use of the **Graphical User Interface (GUI)**.

2S (Strip-Strip) Module

- Surface area of sensor: 10 x 10 cm²
- Two strip sensors separated by 1.8 mm
- Each sensor is divided in two halves with a 70 μm gap between them
- Each half consists of 1016 strips of 5 cm length
- 2 x 8 CMS Binary Chips
- Each chip corresponds to 254 strips of the sensors

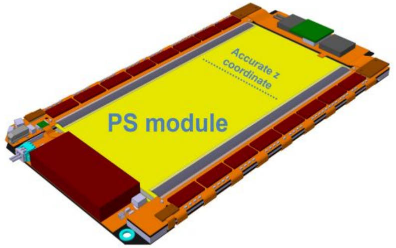


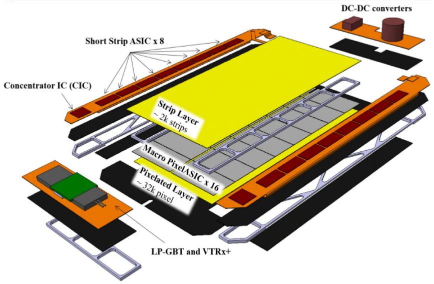


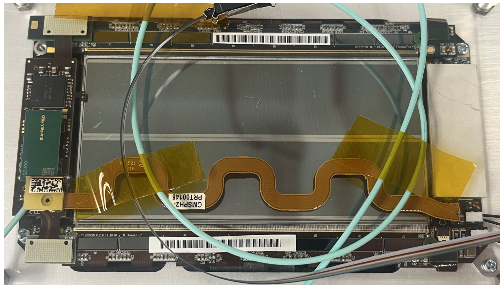


PS (Pixel-Strip) Module

- Surface area of sensor: 5 x 10 cm²
- Pixel and strip sensors separated by 1.6 mm
- Finer granularity
- Pixel layer is made up of macro pixels of 100 µm x 1446 µm
- 120 strips per chip, 2 x 8 strip-chips (SSA)
- 16 x 120 pixels per chip, 2 x 8 pixel-chips (MPA)
- Strips in the other layer measure 100 µm x 23136 µm
- More technologically challenging design

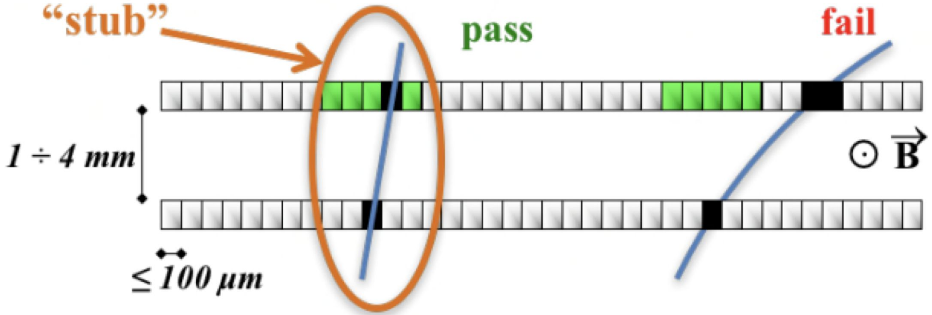






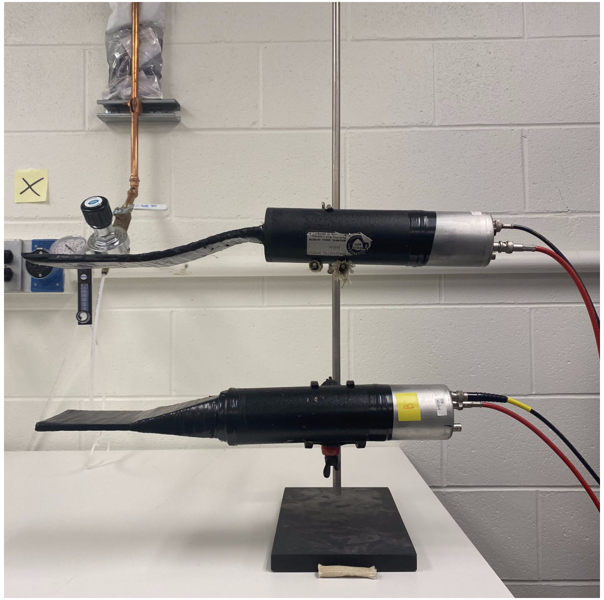
Tracking Information of Trigger

- The purpose of the overlapped layers of the module is to measure the bend of a particle's trajectory due to the magnetic field.
- The stub window is the accepted range of deviation.
- The stub of the module is the pair of strips that fall within the stub window.



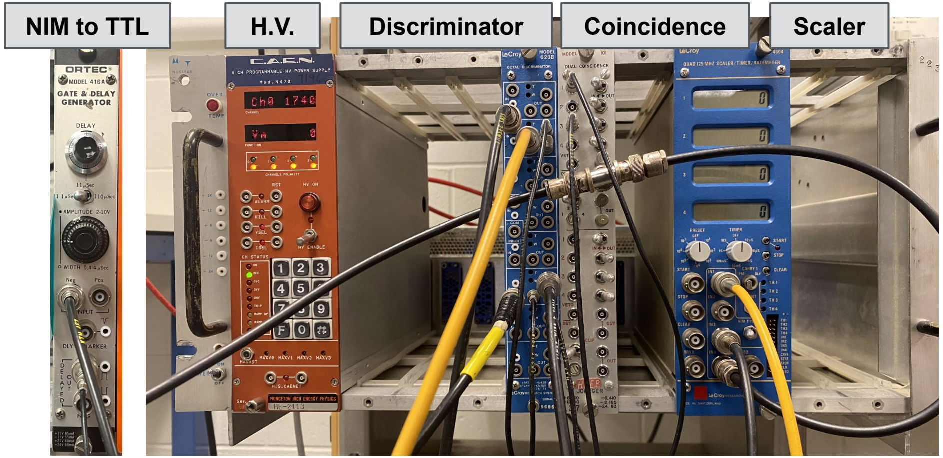
Development of External Trigger

- The external trigger consists of two scintillators bound to **photomultiplier tubes (PMTs)** that are vertically overlapping each other.
- As a cosmic muon passes through, it ionizes molecules within the scintillators creating photons that travel through the PMTs.
- As they enter the PMTs, the photons get converted into electrons.



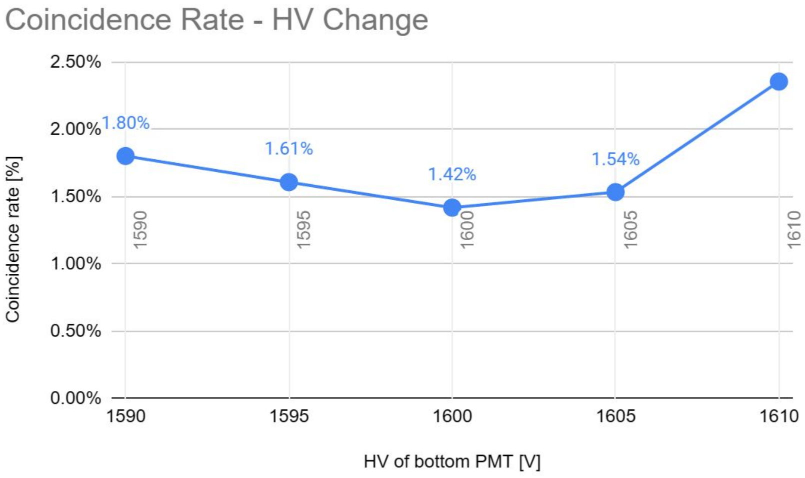
Development of External Trigger

- ❖ The outputs of the PMTs are sent to a discriminator with a minimum signal threshold.
- ❖ If the signal passes the threshold, a logic pulse is outputted by the discriminator and sent to the coincidence trigger.
- ❖ If both discriminator outputs occur simultaneously, the coincidence trigger will output a pulse.
- ❖ The coincidence output is negative NIM logic and is sent to a delay generator to be converted into positive TTL logic.



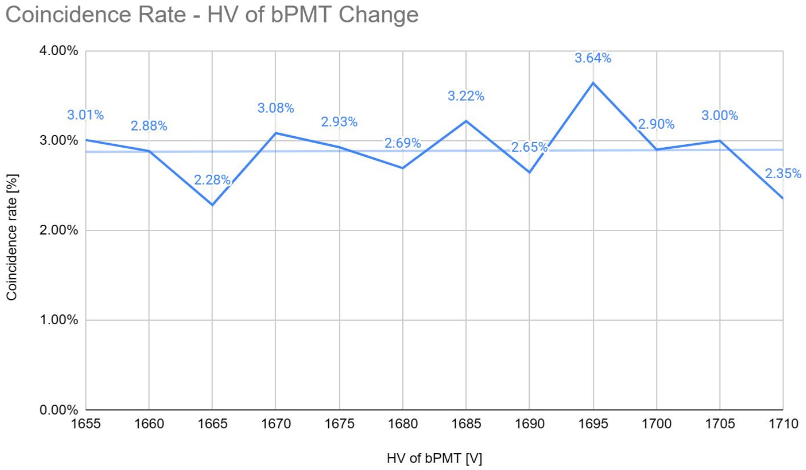
Data Analysis on External Trigger

- ❖ Due to a higher number of pulses in the bottom PMT, they were set at different voltages in order to minimize the asymmetry between their counts.
- ❖ Recorded a change in coincidence rate in relation to the voltage of the bottom PMT from 1590 - 1610 V by fixing the H.V. of the top PMT at 1740 V as the maximum value.



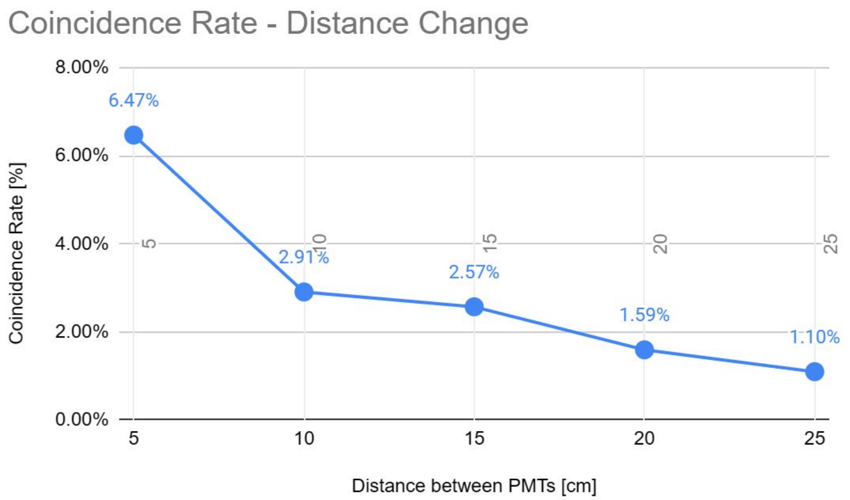
Data Analysis on External Trigger

- ❖ With new measurements, the optimal voltage for the bottom PMT was determined to be 1690 V.
- ❖ The graph below shows the coincidence rate in relation to the change of bottom PMT's voltage, while the top PMT's voltage remained fixed at 1740 V.



Data Analysis on External Trigger

- ❖ Additionally, a test was conducted to measure how the distance between the PMTs affects the coincidence rate.
- ❖ The graph shows that as the distance becomes larger, the coincidence rate rapidly decreases.

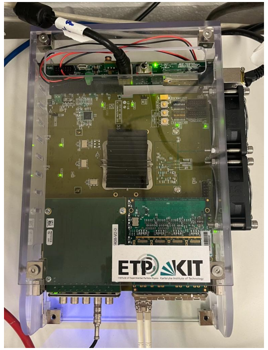


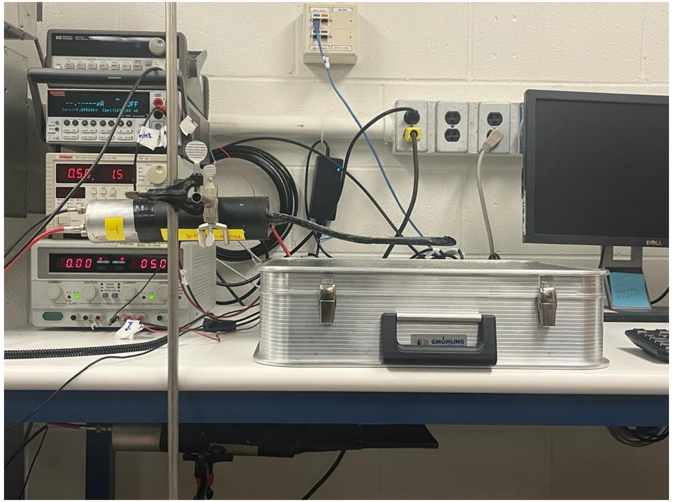
Cosmic Muon Rate

- One muon hits every square centimeter of the Earth every minute, according to the Department of Energy.
- Taking the surface area of the scintillators into account, the theoretical value was calculated at ~2 muons that should interact with our setup per second.
- Experimentally, it was determined that this setup was detecting ~0.3 muons/sec. This is ~15% trigger efficiency.
- PMTs that can be pushed to higher voltages and also have minimal noise creation should approximate the theoretical value much better.

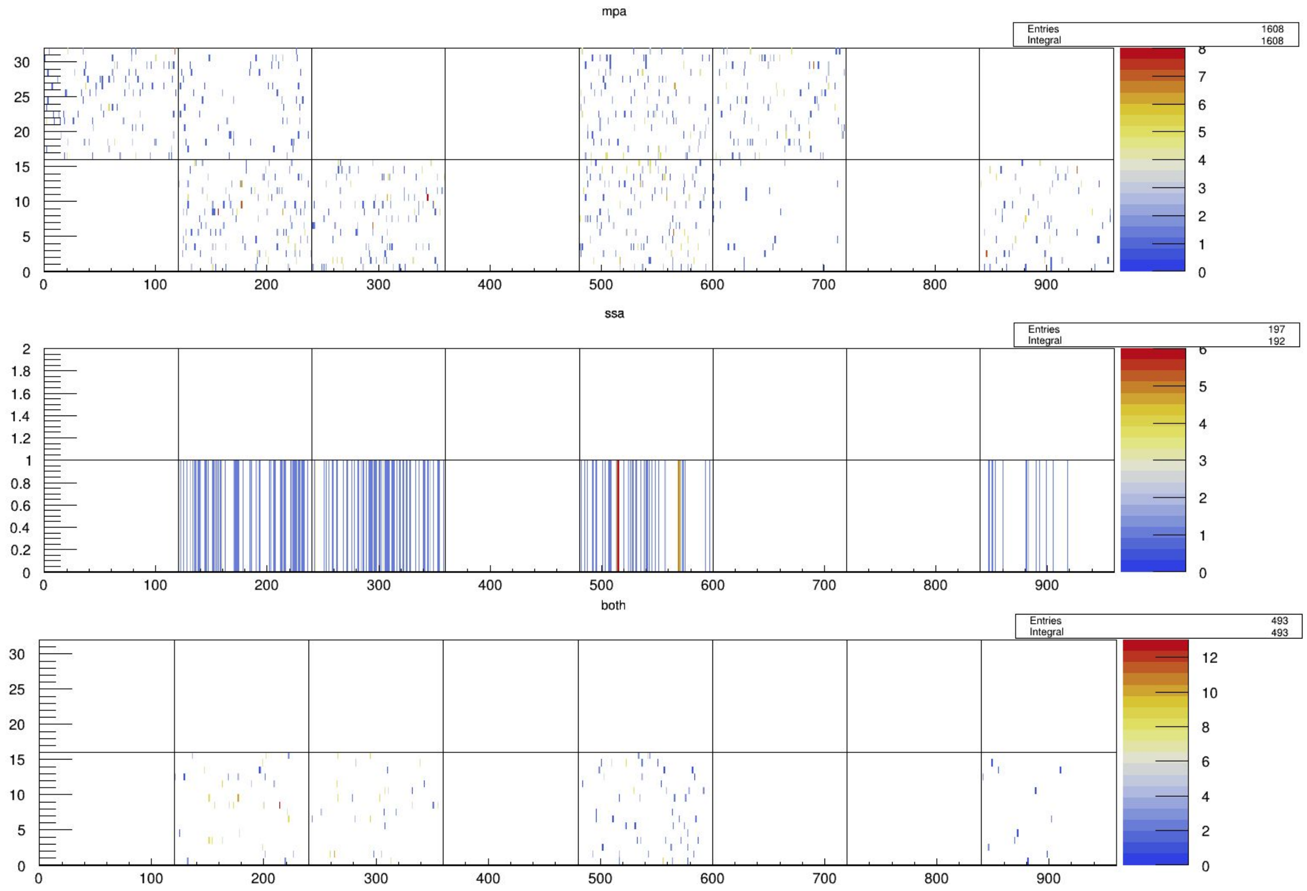
Implementing External Trigger on the Test Bench

- After optimizing the performance of PMTs, the setup was finalized by placing the module inside the aluminum box between the scintillators.
- This allows for correlation between the triggers on the module and the triggers on the cosmic muon setup.
- This correlation is the way to test the efficiency of the module.





Example Run on PS Module

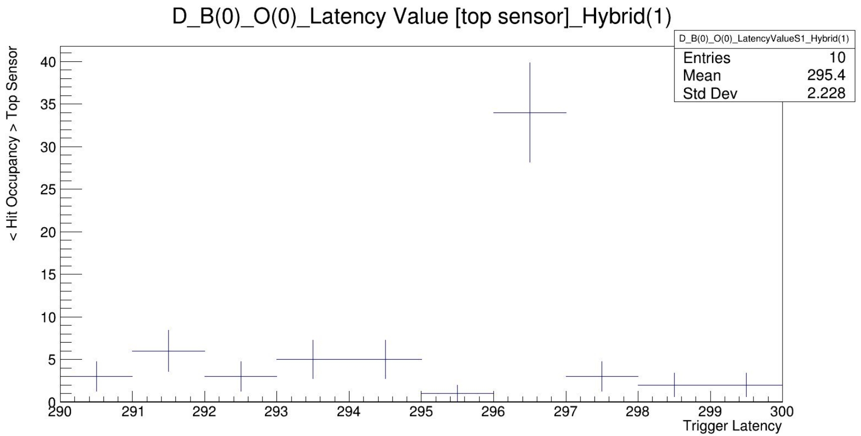


Data Analysis on PS Module

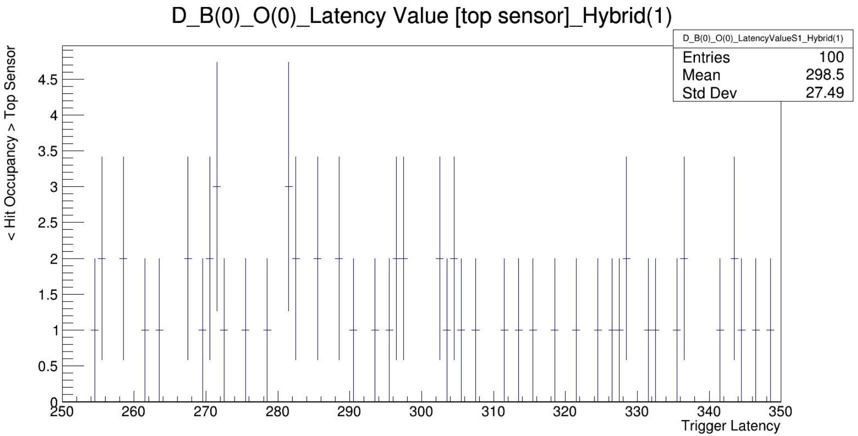
- Once the PyROOT script is run, the module begins to capture data from incident cosmic muons.
- The data are outputted in the form of histograms, depicting exactly where the muon interacted with the module's sensor layers.
- The two sides of the strip sensor have different thresholds that still need to be optimized.
- The optimized trigger was lined up with the test bench and calculations show that the module coincidences make up ~50% of the total number of events before any module optimizations and noise removal.

Latency Optimization

❖ Internal Trigger



❖ External Trigger



The clear peak shown on the graph for the internal trigger (module) signifies that the latency is correct, and further studies need to be done to find out the latency for the external trigger (PMTs).

Future Work

- The next step would be to optimize the module thresholds to increase the number of coincidences and efficiency.
- Take longer runs and incorporate a radioactive source to increase the particle rate and speed up testing for modules.
- Test multiple modules at once with the use of a light-locked insulator crate that stores them vertically.

Conclusion

- The CMS Outer Tracker is a critical component of the HL-LHC upgrade.
- This is the first cosmic muon test developed to assess OT module performance, and offers a unique opportunity to test external triggering without a test beam.
- The future optimizations of the module and the external trigger will increase the measured cosmic muon rate and yield a higher module efficiency.

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Backup Slides

Silicon Detectors

- Silicon detectors are semiconductors that are n- or p-doped (electrons or holes are added).
- **Reverse bias** creates a depletion zone without free charges so that when an ionized particle passes through, it will create free charges that lead to a measurable current and detect the signal.