Design and simulation of particle identification and exotic muon decay searches using HIAF muon beam

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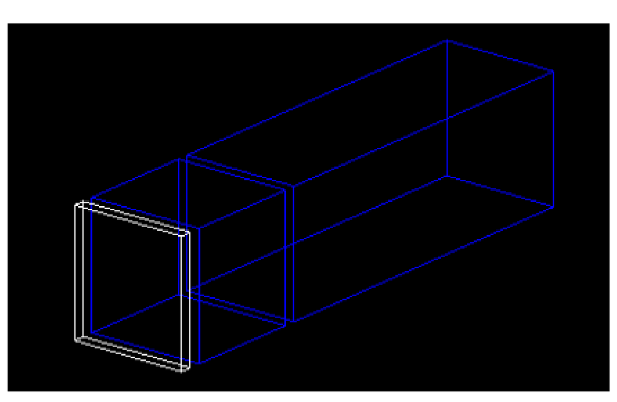
Introduction

Muon physics and detector design have always been a key focus of particle physics research. We designed two experiments based on the muon beam provided by HIAF. One primarily focused on particle identification in the beam and, based on this, proposed some muon dark matter scattering experiments. The other experiment mainly simulated the decay channels of exotic muons, providing relatively good sensitivity and offering a concept for detector design.

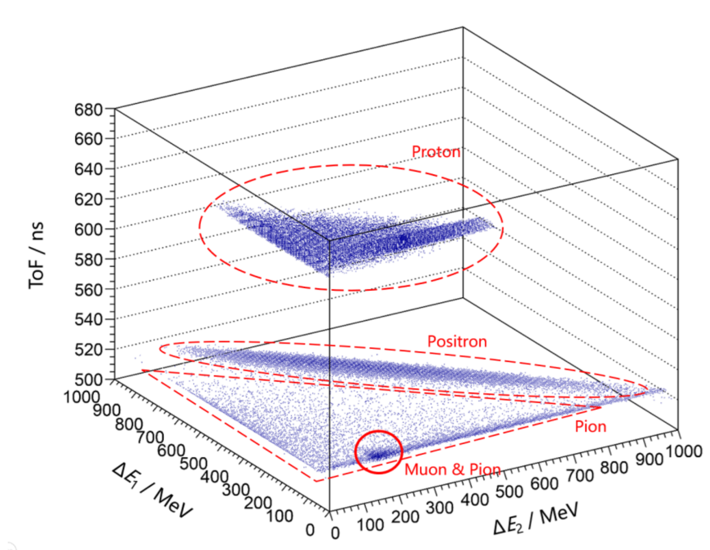
Particle Identification

During beam production, particles such as pions, electrons, and protons with the same momentum as muons may be mixed in due to decay, magnetic rigidity selection, and other factors. To perform muon scattering experiments, identification must be performed.

We first used Geant4 to simulate the time of flight (ToF) and energy deposition (dE) of the beam passing through scintillator detectors.



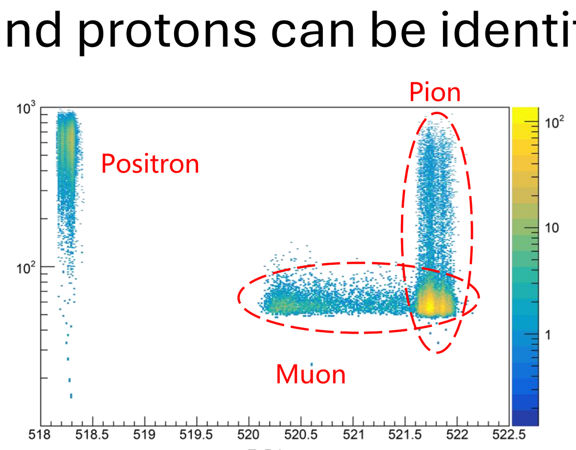
For 1.2GeV/c μ^+ beam, 0.2ns time resolution, 2% energy resolution

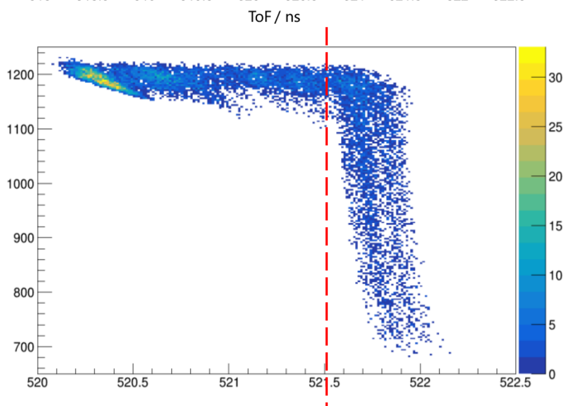


1cm Plastic (ToF end) +10cm CsI (dE_1) +30cm CsI (dE_2)

ToF start detector is a thin plastic scintillator ~155m far away.

From the resulting plots, electrons (positrons) can be distinguished by dE, and protons can be identified by ToF.

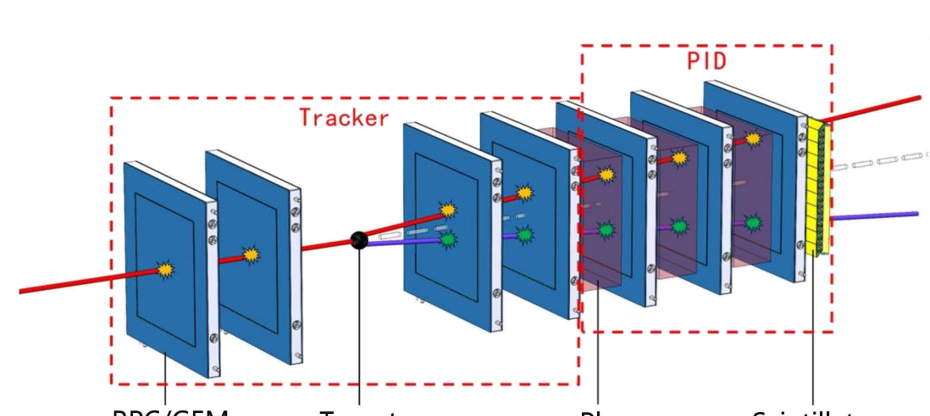




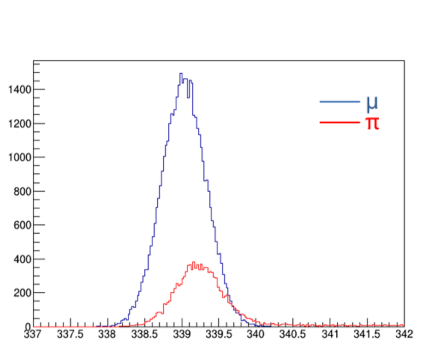
Pions are mixed with muons due to their similar masses. In the ToF-dE distribution, pions can be distinguished by combining both variables, and a tail in the muon ToF is also observed. From the p_z-ToF distribution of muons, the tail becomes more pronounced, which is caused by muons from pion decay during the process and can also be removed.

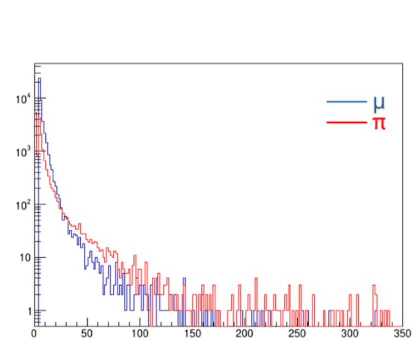
Thus, muons, pions, electrons, protons, and the muon tail in low-energy beam components can be distinguished via ToF and dE analysis.

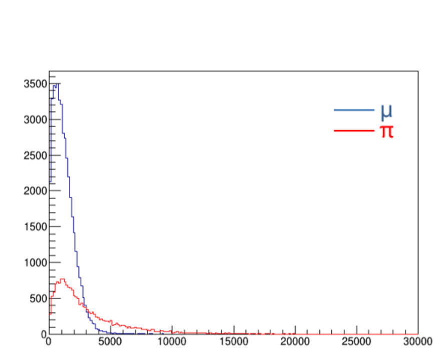
For higher-energy mixed muon-pion beams, the time of flight is too short and the energy deposition is similar, making them difficult to distinguish. Therefore, track simulation must be combined for identification.

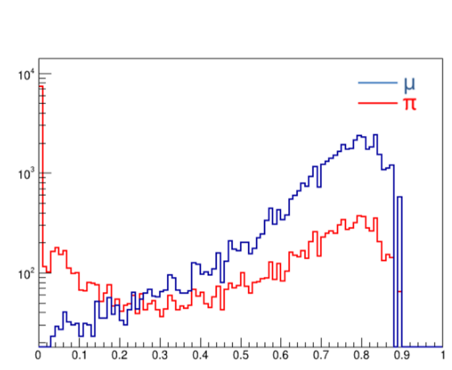


We performed simulations on mixed muon-pion beams （3GeV momentum) by recording positions via scattering in multiple lead plates (10cm thick) to fit linear tracks, using cesium iodide at the downstream end to record energy deposition, while retaining ToF detectors.









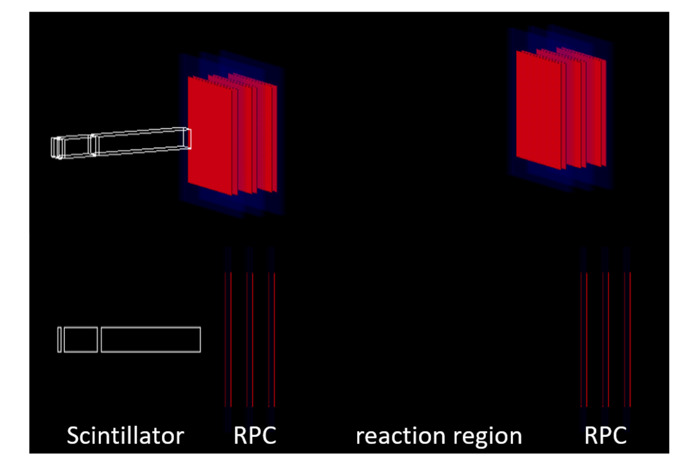
Assuming the distributions of the above three variables are independent, a multivariate likelihood method is used for identification. If Lμ>0.7 is taken as the muon selection criterion, the muon identification efficiency is about 70.7%.

L_μ>0.7		
\	True Muon	True Pion
Identified Muon	30756	4815
Identified Muon	12778	13321

Exotic Muon Decay

Within the Standard Model, the dominant decay channel of the muon is $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$. However, exotic decays may exist, producing an electron and a heavy neutral X_0 with a mass close to that of the muon (taken as 105 MeV).

We used Geant4 to simulate the decay of the HIRF beam in vacuum, and recorded the decay electron signals on the RPC located behind the reaction region.

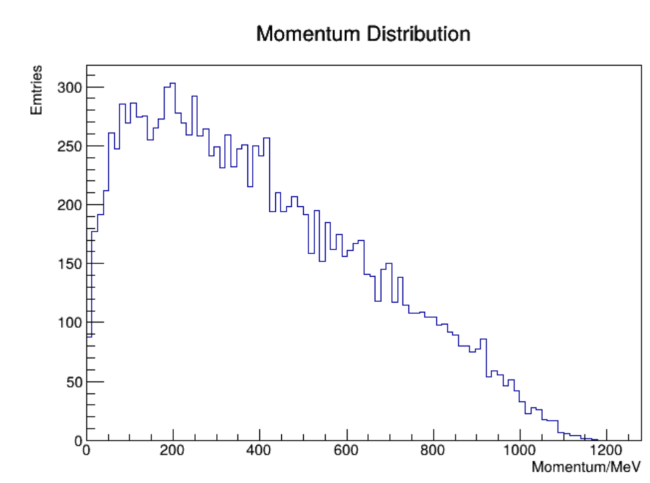


Scintillator: Width 1+10+30 cm
Cross-section 3 cm × 3 cm
Spacing 1+1 cm

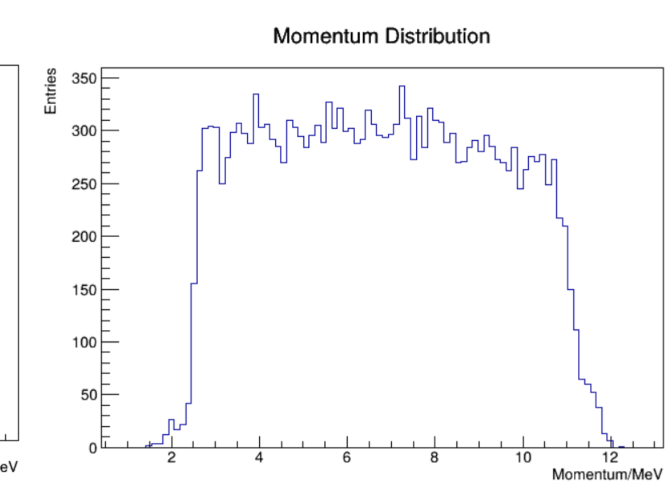
RPC: Width 4 cm
Cross-section 28 cm × 28 cm
Spacing 2.5×2 cm

Reaction region length: 90 cm
(about 10^{-4} of the muons decay.)

Total: 1m



$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

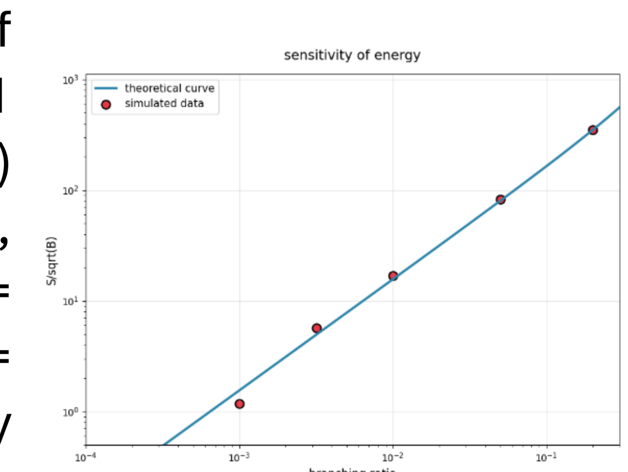


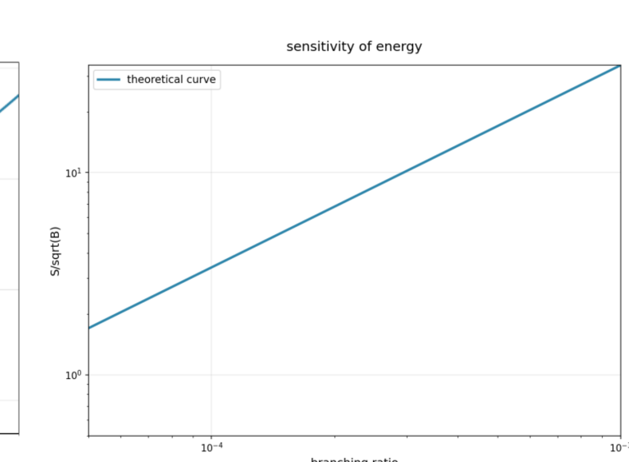
$\mu^- \rightarrow e^- + X_0$

Theoretically, there is a significant difference in the electron energy produced by the two decay channels, which is also confirmed by the simulation results.

The sensitivity can be simulated with a momentum cut of 2– 10 MeV. Using a sample size of 10^{10} (about 10^6 decays), it is verified that the variation of sensitivity under different decay branching ratios is consistent with theoretical expectations.

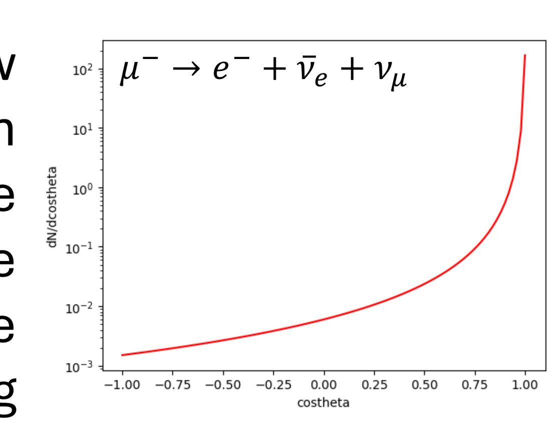
Using a sample size of 10^{12} (beam time about 1 month, about 10^8 decays) with 0.1% branching ratio, simulation yields signal = 9578 and background = 77725 . The sensitivity drops to 5σ at a branching ratio of 0.01%.

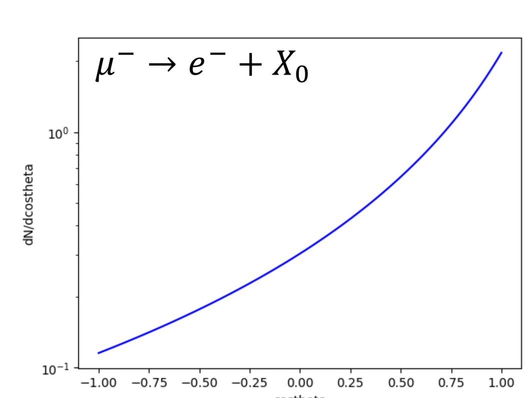


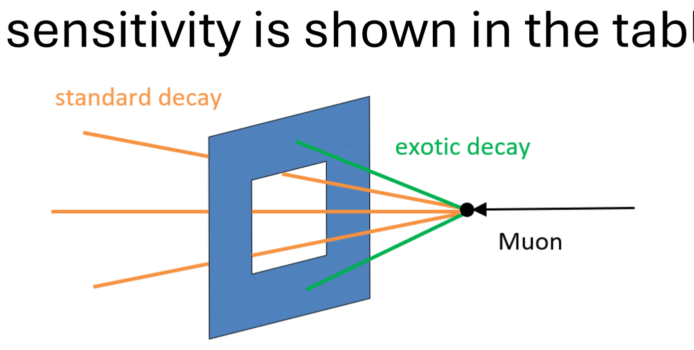


The electron decay angular distributions of two modes also show significant differences. To achieve higher sensitivity, a combination with the decay angular distribution is required.

One design uses a hollow detector to accept signals, which can reject most of the more concentrated background. The required hollow size of the detector for corresponding sensitivity is shown in the table.

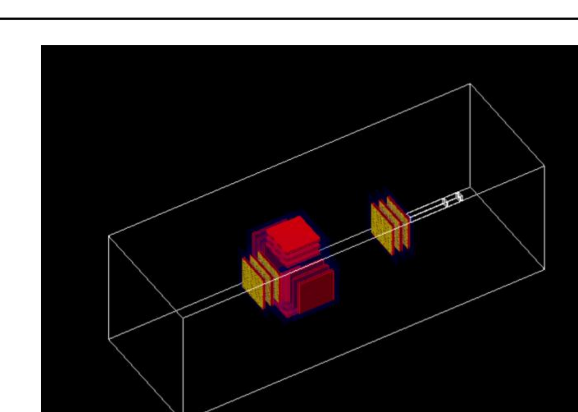






branching ratio limit	sample size	background rejection	detector radius
10^{-6}	10^{13}	99.7%	> 35 cm
10^{-5}	10^{12}	66.7%	> 10 cm
10^{-5}	10^{12}	97.3%	> 20 cm

The other design is to surround the reaction region with detectors, which can effectively increase the signal count rate. If fully recorded, the number of signals can be improved by one order of magnitude, and so can the sensitivity.



Summary

For low-energy (1.2 GeV) muon beams, we use ToF and dE for identification, which achieves good separation of beam components. We also discuss the muon-pion identification for high-energy (3 GeV) beams.

We design a detector to search for exptic muon decay, discuss the sensitivity on branching ratio under vacuum conditions, obtain a world-leading sensitivity, and propose feasible detector geometries for improving sensitivity.