Software For the Mu2e Experiment

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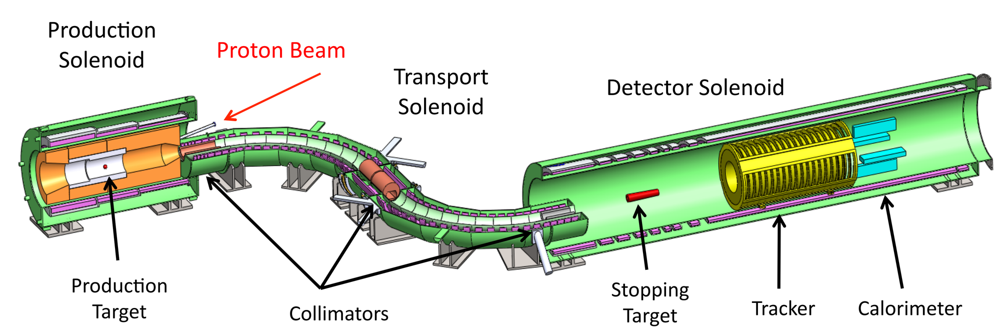
http://mu2e.fnal.gov

Introduction

The Mu2e experiment at Fermilab is in the midst of its R&D and approval processes. To aid and inform this process, a small team has developed an end-to-end Geant4-based simulation package and has developed reconstruction code that is now at the stage of an advanced prototype. Having these tools available at an early stage allows design options and tradeoffs to be studied using high level physics quantities. A key to the success of this effort has been, as much as possible, to acquire software and customize it, rather than to build it from scratch in-house.

The Experiment

Within the Standard Model, muon decays to final states that violate lepton family number (LFN) are too rare to be observed. Therefore any observation of an LFN violating muon decay is direct evidence for physics beyond the Standard Model. One such decay mode may occur when a negative muon is bound to an atomic nucleus, forming a muonic atom: coherent, neutrino-less muon to electron conversion in the Coulomb field of a nucleus. The final state is a mono-energetic electron plus an unobserved, recoiling, intact nucleus; all background processes produce electrons with a continuous energy spectrum. The Mu2e experiment will form muonic Aluminum, measure the energy spectrum of electtrons from its decay and ask if an excess is observed at the conversion energy, about 105 MeV.



The above figure shows Mu2e apparatus. An 8 GeV proton beam enters from the right and strikes a production target, producing pions that decay to muons. A system of of three graded-field solenoids captures the backwards going muons and directs them onto a stopping target, a set of thin Al foils. Most muons range out in these foils and are captured to form muonic atoms. Electrons from the decay of the muonic atoms are directed by a graded magnetic field onto a tracking system and an electromagnetic calorimeter. Not shown are a system to monitor the extinction of the proton beam, a cosmic ray veto system and a system to measure the muonic X-ray spectrum from the stopping targets.

The Software Tools

G4beamline

- A layer on top of GEANT4; hides most G4 complexity from end users
- Easy-to-learn language for geometry and run-time configuration
- Output: ROOT ntuples and text files
- Vital for a fast turn around for early designs of the muon beamline.
- Not sufficiently powerful for design of the detector and the extinction monitor, or for advanced studies of the muon beamline.

MARS

- Low energy neutrons critical for Mu2e: use MARS+MCNP
- Mu2e pioneered running MARS+MCNP on the grid
- Study heat and radiation load at the cryogenic solenoids, neutron sky-shine, and neutron fluxes throughout the detector.
- Critical calculations will be done with both MARS and GEANT4.

FastSim

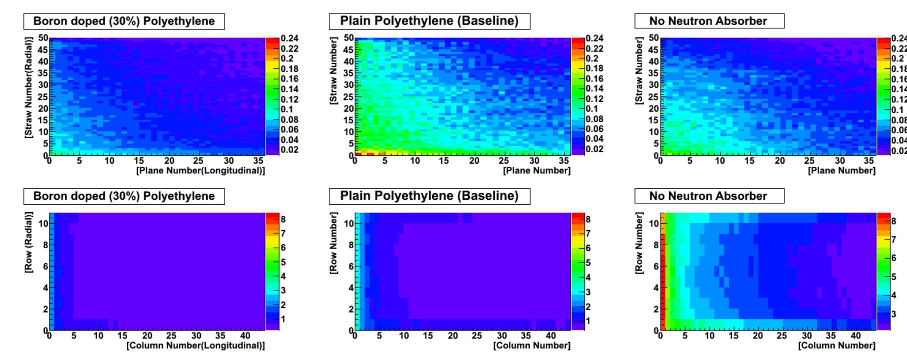
- A surface based, fast, parameterized simulation and track fitting package.
- Pedigree: BaBar and SuperB.
- Mu2e improved treatment of very thin materials and improved navigation for curling tracks.
- Fast turn-around studies of: acceptance and resolution for variants of tracking system, optimal size and dimensions of the calorimeter, tolerance of tracker momentum resolution to B-field misalignment.

Mu2e Offline

- The workhorse for detector simulations and advanced beamline studies. Taking over from G4beamline for routine beamline studies.
- Calibration, reconstruction and analysis will be done in his environment.
- Goal: use this software everywhere from the lowest level non-real-time layer in the trigger/DAQ, through calibration and reconstruction to final analyses.
- Acquired infrastructure software supported by Fermilab Computing Division (CD): the art framework, which drives the event loop; an event-data model, including persistency; run-time configuration; message logging; maintenance of random number engine state; management of singleton-like entities used for geometry and conditions data
- These tools are an evolution, starting from CMSSW. See talk for abstract 354 by Chris Green in "Event Processing (track 2)", Monday afternoon.
- Acquired the battle-tested BaBar track fit code (Kalman filter based) and ported it to run in in this environment. All tracker results use this code.
- Authoritative geometry representation is optimized for reconstruction; the GEANT4 geometry is derived from this representation. Planning to derive MARS and G4beamline geometries from this same source.
- G4 used as an engine that creates a complete parent-child history plus collections of track steps in sensitive volumes. Conversion of G4 steps into DIGIs is done by Mu2e modules outside of G4.
- Merging in pileup events: in collaboration with the art team, Mu2e developed the technology to split the task into one part requiring detailed knowledge of persistency, but none of Mu2e, and a second part requiring detailed knowledge of Mu2e, but none of persistency. This process preserves complete MC truth information.
- Pileup is accumulated before analog to DIGI conversion
- Event displays: G4 display plus a ROOT based display that runs within art.
- Under construction: interfaces to file catalogs and other databases. Will leverage extensive CD experience; see poster for abstract 61 by Adam Lyon.

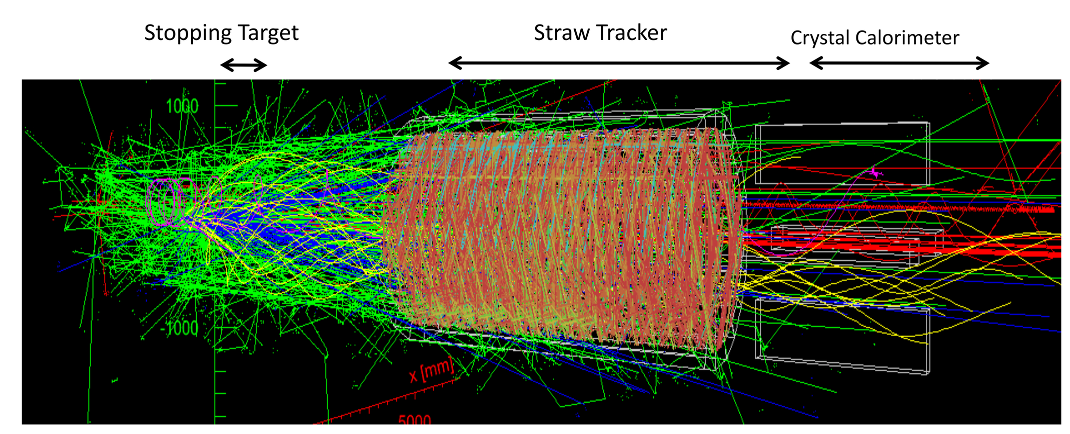
Selected Results

Rates in the Tracker and Calorimeter

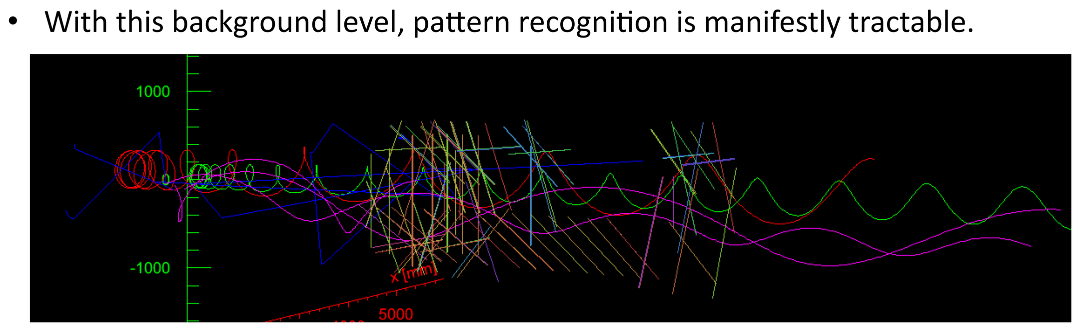


The above figures show a study of detector rates for hits that arise from neutrons produced when muonic Al in the stopping target undergoes muon nuclear capture. The units are the number of hits in one straw(crystal) during one cycle of the muon beam line; a signal event is live for about 10% of one cycle. The top row shows the hit rates in the tracker for 3 different options for the neutron absorber, a doped polyethylene shield that lives inside the vacuum of the Detector Solenoid. The second row shows the hit rates in the calorimeter for the same variants of the neutron absorber

Track Pattern Recognition

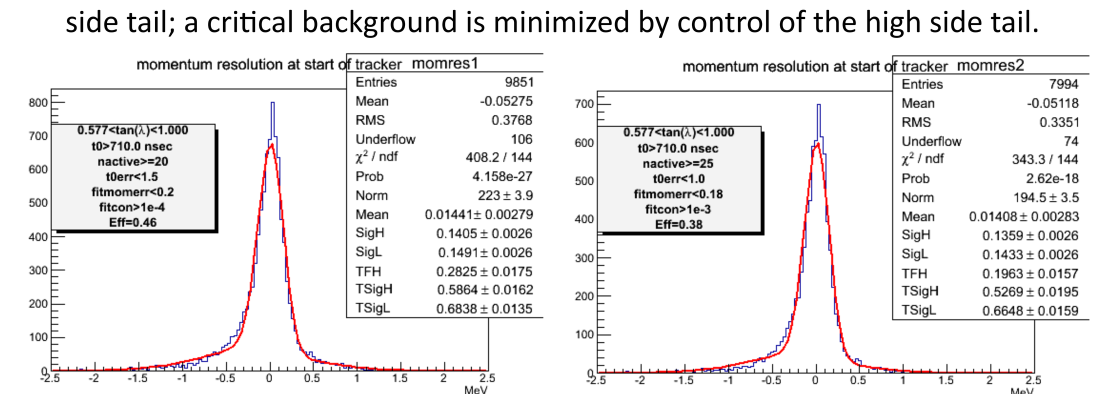


- The figure above shows a simulated event of one conversion electron plus all of the pileup associated with one cycle of the muon beamline.
- The figure shows the trajectories of all simulated particles that made at least one hit in the tracking system during the live gate during one cycle of he muon beamline. It also shows the individual hit wires in the tracker. The calorimeter vanes are shown in outline only.
- How well will the pattern recognition code do with such an event?
- The pattern recognition code, when run on this event, correctly identified a ±50 ns window around the conversion electron (red helix, below).
- The figure below shows the same event as above but it only shows the trajectories of, and hits from, those simulated particles that made a hit in the tracking system during the reconstructed ±50 ns window.
- With this background level, pattern recognition is manifestly tractable.

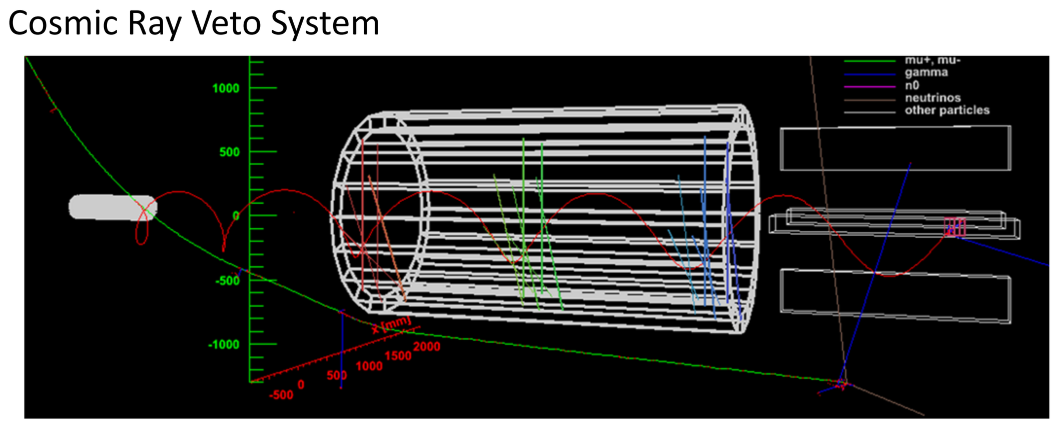


Tracker Momentum Resolution

- The figures below show the tracker efficiency and momentum resolution for two sets of track quality cuts. Reconstruction run on events with the best available simulation of pile up. No use of MC truth in reconstruction.
- Illustrates possible tradeoffs between efficiency and the amount of high side tail; a critical background is minimized by control of the high side tail.



Cosmic Ray Veto System



In the above figure, a cosmic ray muon (green) is incident on the earth above the detector. It penetrates into the hall from the left and interacts in a stopping target foil; one of the products of this interaction is an electron with an energy near the conversion energy (red helix). Such an electron can fake the signal. This event comes from a study done to determine the required rejection power of the cosmic ray veto system

Summary and Conclusions

- A small team has made rapid progress in the development of software for the Mu2e experiment: an end to end simulation and advanced prototype track reconstruction codes are in place.
- Calorimeter and Cosmic Ray Veto reconstruction in progress.
- Rapid progress was enabled by leveraging the work of others: as much as possible the software has been acquired and configured, not built.

[1] Representing the Mu2e Collaboration and the Scientific Software Infrastructure group within the Scientific Computing Division of Fermilab.

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