New Frontiers in Lepton Flavor

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Background Studies and Normalization of Signal Events in the Mu2e Experiment

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HZDR

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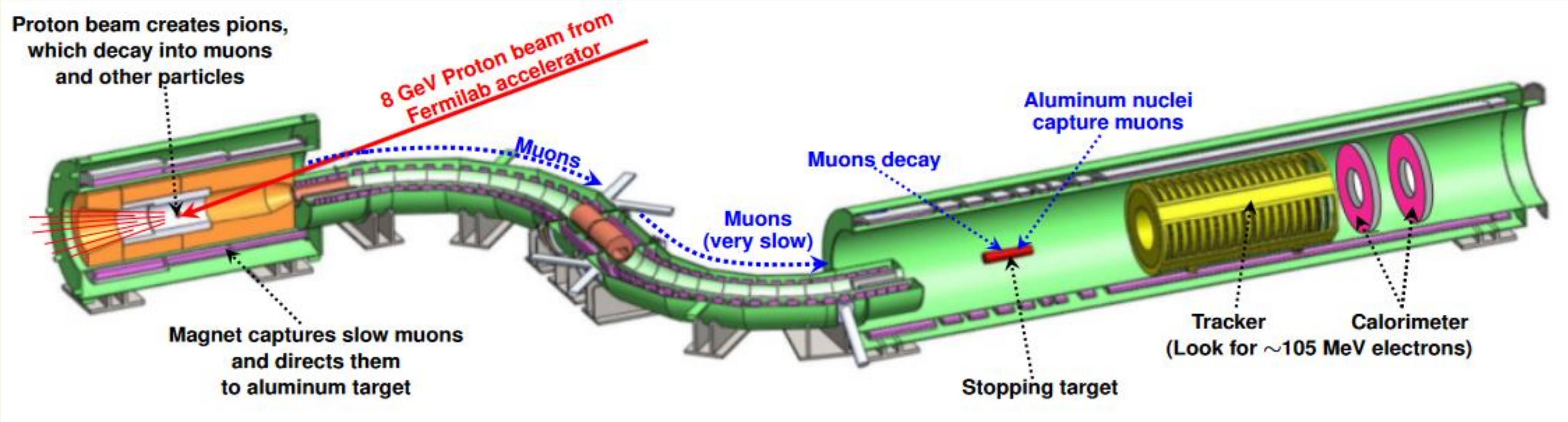
The Mu2e Experiment

- The Mu2e experiment is currently being constructed at Fermilab in the USA
- Goal: to search for the neutrino-less conversion of negative muons into electrons in the field of an aluminum nucleus ($\mu^- + Al \rightarrow e^- + Al$)

The principle of the Mu2e experiment



- 8 GeV proton beam hits a tungsten target and produces pions
- The pions are guided by a magnetic field toward the transport solenoid, where they decay into muons
- The muons hit the aluminum-stopping target, where they either decay or undergo a capture reaction
- Detectors (tracker and calorimeter) search for the conversion electrons

The Mu2e Experiment

- The muon-to-electron conversion process results in a monochromatic electron with an energy of 104.97 MeV

- The goal is to reach a single event sensitivity of 3×10^{-17} on the conversion ratio ($R_{\mu e} = \frac{\mu^- + Al \rightarrow e^- + Al}{\mu^- + Al \rightarrow nuclear\ capture}$)
  - four orders of magnitude higher than previous related experiments

- To reach the desired sensitivity, two important tasks should be accomplished:
  - all backgrounds that could mimic the conversion signal should be controlled
  - the signal events should be normalized accurately

Objectives

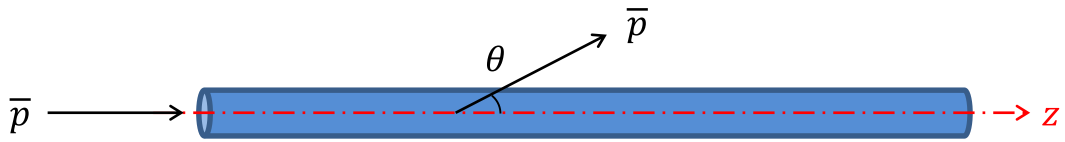
- to investigate the beam-related and cosmic rays-related backgrounds using several Monte Carlo (MC) codes
  - MC code: MCNP6, FLUKA2021, MARS15, and GEANT4 (the official Mu2e simulation code)
  - focus on the prediction credibility of each code
- to evaluate the performance of the detector system used for the signal events normalization

Background Investigation: MC Simulation Studies

Antiprotons beam-related background

- Protons hitting the tungsten target produce antiprotons that could reach the aluminum stopping target, annihilate and produce background electrons
- Pions created in the transport solenoid by antiproton interactions can produce background electrons via radiative pion capture
  - a part of this background can be rejected by a cut on the signal time window

- MC Investigation: antiproton yields from a 1.9 GeV/c and a 2.1 GeV/c antiproton pencil beam hitting a tungsten cylindrical target (R=0.315 cm, L=16 cm)

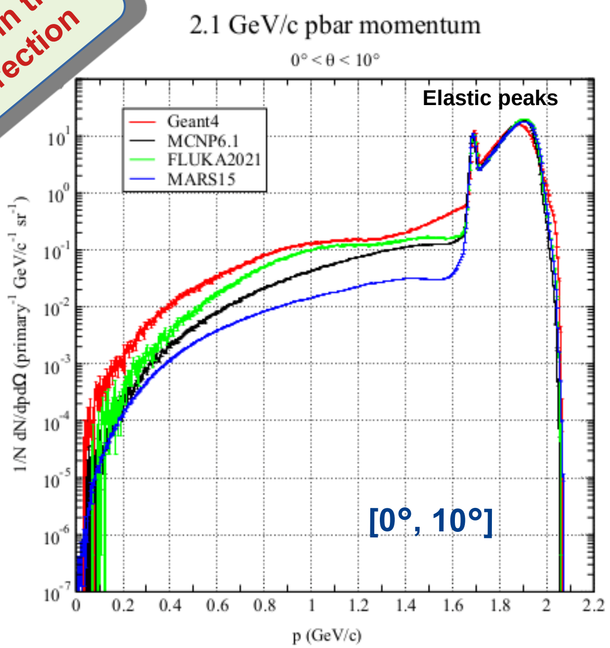


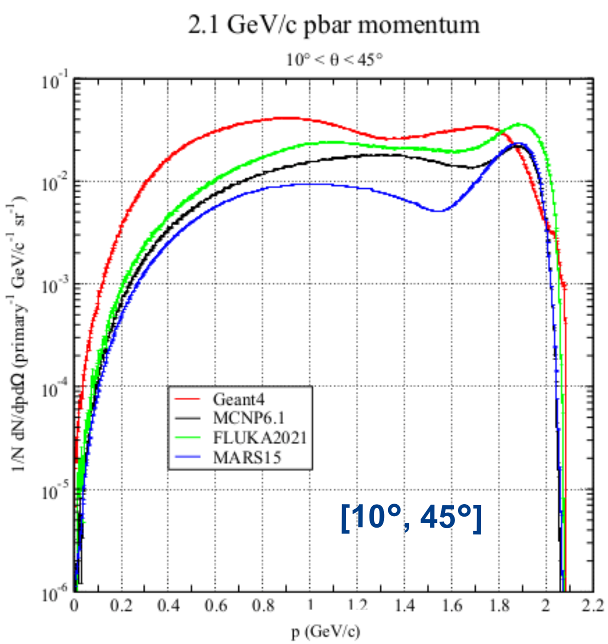
Background Investigation: MC Simulation Studies

$\overline{p}$ beam momentum of 1.9 GeV/c							
θ	Geant4	MCNP6	Δ	FLUKA	Δ	MARS15	Δ
$0° - 10°$	3.11	3.23	3.7%	3.38	8.5%	3.19	2.4%
$10° - 45°$	$5.38{\cdot}10^{-2}$	$2.28{\cdot}10^{-2}$	-57.5%	$2.52{\cdot}10^{-2}$	-53.2%	$1.47{\cdot}10^{-2}$	-72.6%

$\overline{p}$ beam momentum of 2.1 GeV/c							
θ	Geant4	MCNP6	Δ	FLUKA	Δ	MARS15	Δ
$0° - 10°$	3.01	3.04	1.0%	3.22	7.1%	3.01	0.1%
$10° - 45°$	$5.03{\cdot}10^{-2}$	$2.27{\cdot}10^{-2}$	-55.0%	$3.30{\cdot}10^{-2}$	-34.4%	$1.46{\cdot}10^{-2}$	-70.9%

Good agreement in the very forward direction





Background Investigation: MC Simulation Studies

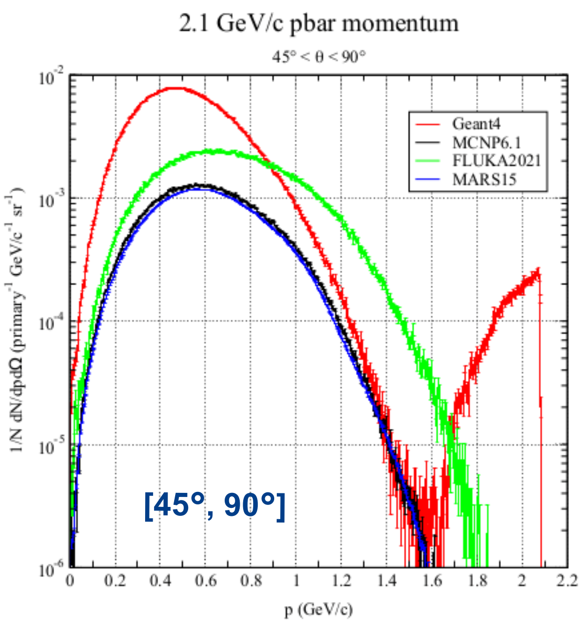
$\overline{p}$ beam momentum of 1.9 GeV/c

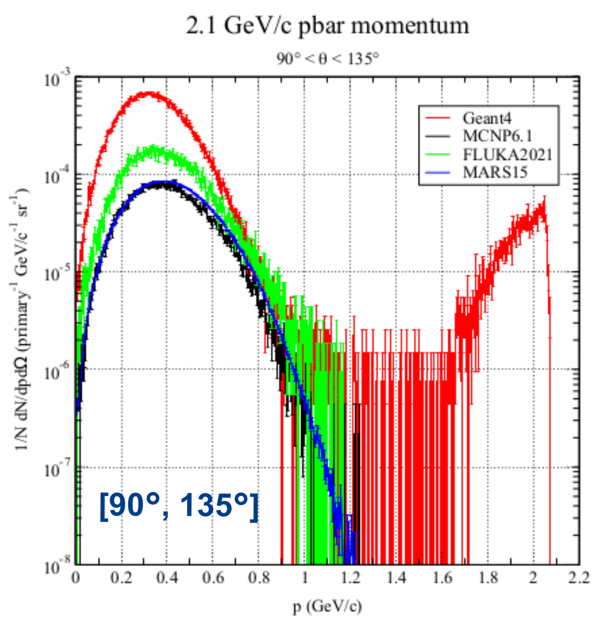
θ	Geant4	MCNP6	Δ	FLUKA	Δ	MARS15	Δ
$45° - 90°$	$4.43 \cdot 10^{-3}$	$7.34 \cdot 10^{-4}$	-83.4%	$1.47 \cdot 10^{-3}$	-66.9%	$6.42 \cdot 10^{-4}$	-85.5%
$90° - 135°$	$7.87 \cdot 10^{-5}$	$3.13 \cdot 10^{-5}$	-60.3%	$5.47 \cdot 10^{-5}$	-30.4%	$3.28 \cdot 10^{-5}$	-58.3%
$135° - 180°$	$8.26 \cdot 10^{-6}$	$4.57 \cdot 10^{-6}$	-44.7%	$1.71 \cdot 10^{-6}$	-79.3%	$6.02 \cdot 10^{-6}$	-27.1%

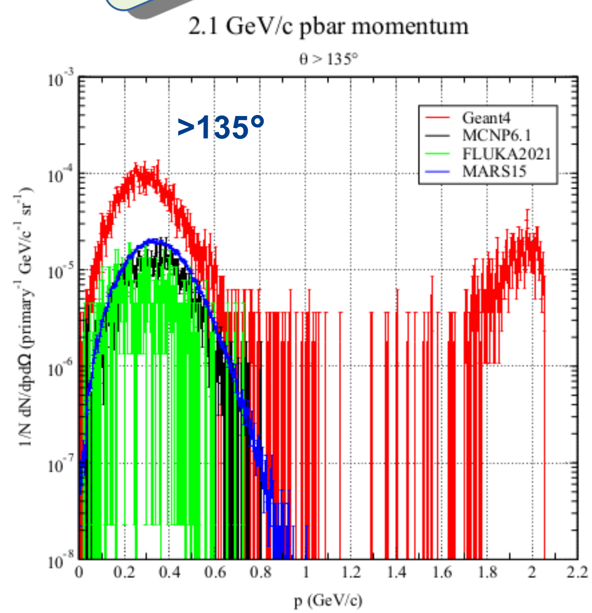
$\overline{p}$ beam momentum of 2.1 GeV/c

θ	Geant4	MCNP6	Δ	FLUKA	Δ	MARS15	Δ
$45° - 90°$	$4.12 \cdot 10^{-3}$	$7.80 \cdot 10^{-4}$	-81.1%	$1.78 \cdot 10^{-3}$	-56.8%	$7.09 \cdot 10^{-4}$	-82.8%
$90° - 135°$	$2.35 \cdot 10^{-4}$	$3.17 \cdot 10^{-5}$	-86.5%	$6.70 \cdot 10^{-5}$	-71.5%	$3.53 \cdot 10^{-5}$	-84.9%
$135° - 180°$	$3.06 \cdot 10^{-5}$	$4.20 \cdot 10^{-6}$	-86.3%	$2.24 \cdot 10^{-6}$	-92.7%	$6.23 \cdot 10^{-6}$	-79.7%

GEANT4 overestimate the $\overline{p}$ yield at large angles



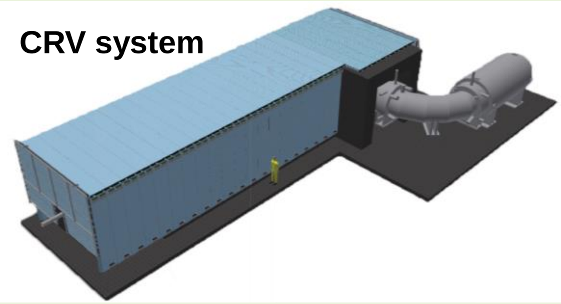


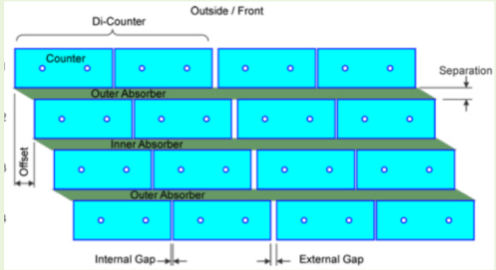


Background Investigation: MC Simulation Studies

Cosmic rays-related background

- The experiment has a cosmic ray veto (CRV) system, suppressing the background due to the cosmic rays that could hit the stopping target
- The CRV system is shielded by 1 m of (standard) concrete
- The concrete absorbs <u>cosmic neutrons</u>, forming an additional possible background source

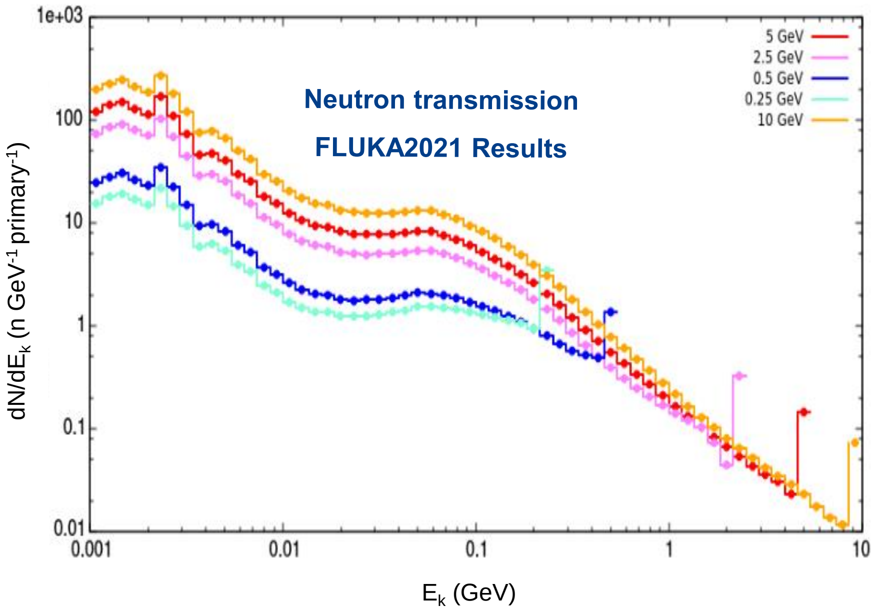


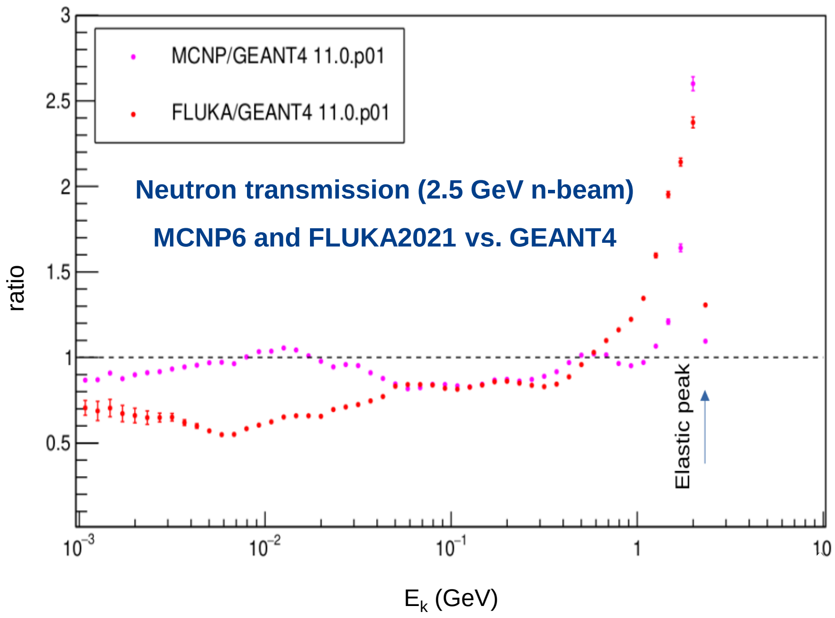


4 overlapping layers of scintillator bars with 2 wavelength-shifting fibers

Background Investigation: MC Simulation Studies

- MC Investigation: transmission of cosmic neutrons in a 10x10x1 m^3 block of concrete
  - neutron source: monoenergetic neutron pencil beams
    - Ekin = 0.25 GeV, 0.5 GeV, 2.5 GeV, 5.0 GeV, and 10 GeV

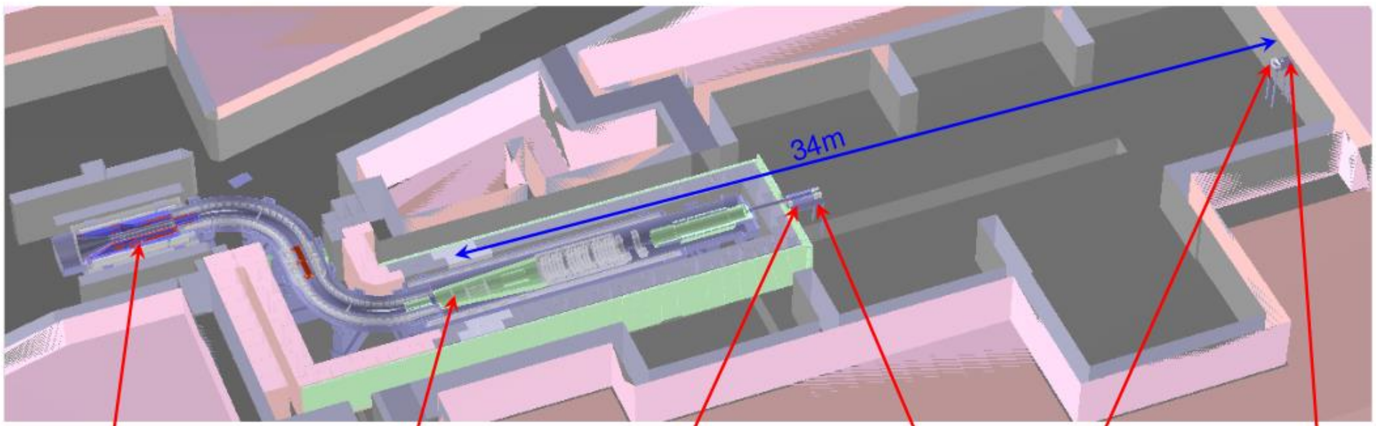




- **Spectra of neutrons after 1 m concrete generally differ by less than a factor 2**
- **The elastic peak: GEANT4 is about 2.5 lower than MCNP6 and FLUKA2021**

Normalization of Signal Events: Detector Studies

- The normalization of the signal events is planned to be done using a detector system made of an HPGe detector and a Lanthanum Bromide detector
  - will measure the rate of muons stopped on the aluminum target
    - looking at the emitted characteristic X-and γ-rays of energies up to 1809 keV

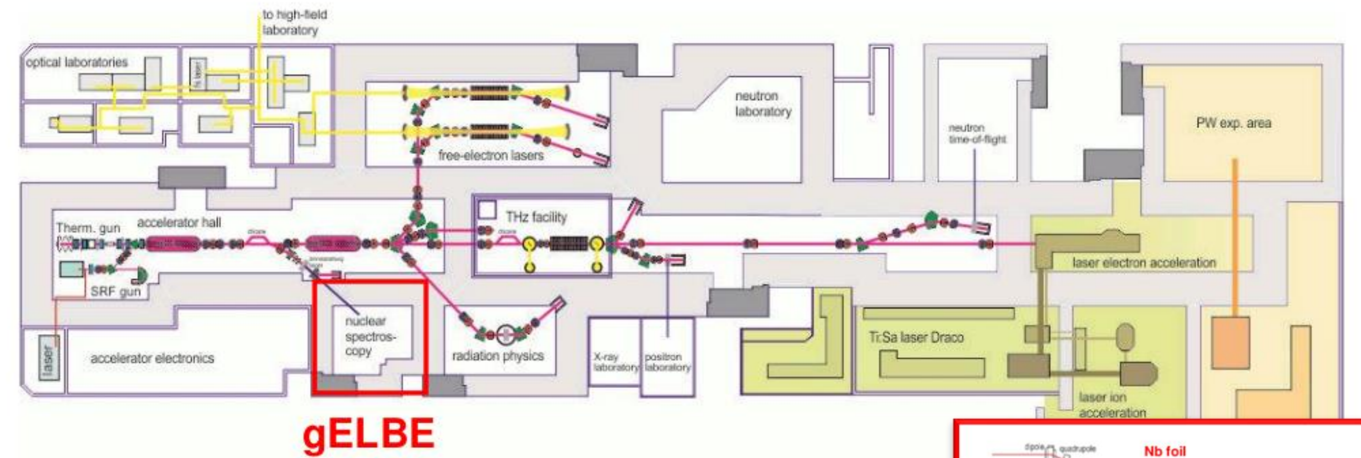


- The detector system was tested at the ELBE facility (HZDR)
  - under conditions similar to the ones expected at the Mu2e experiment

Normalization of Signal Events: Detector Studies

Mu2e@HZDR: The ELBE radiation source

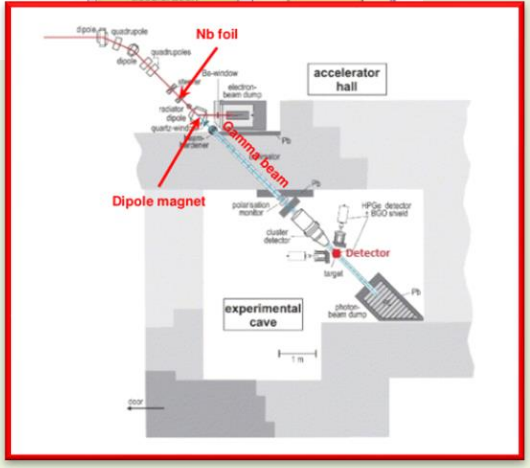
$E_e \leq 40$ MeV; $I_e \leq 1$ mA; Micropulse duration 10 ps $< \Delta t <$ 1 μs



– gELBE produces bremsstrahlung from an electron beam impinging on niobium radiator foils

– Using the gELBE pulsed bremsstrahlung spectrum and calibration sources (^{137}Cs, ^{60}Co, ^{88}Y) allows to simulate the Mu2e conditions

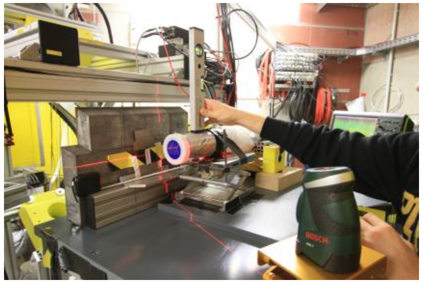
– **3 Irradiation Campaigns:** HPGe test (2017), $LaBr_3$ test (2021), Test of full system (2022)

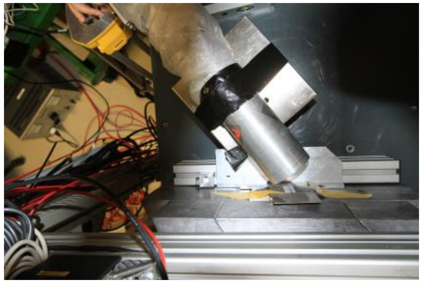


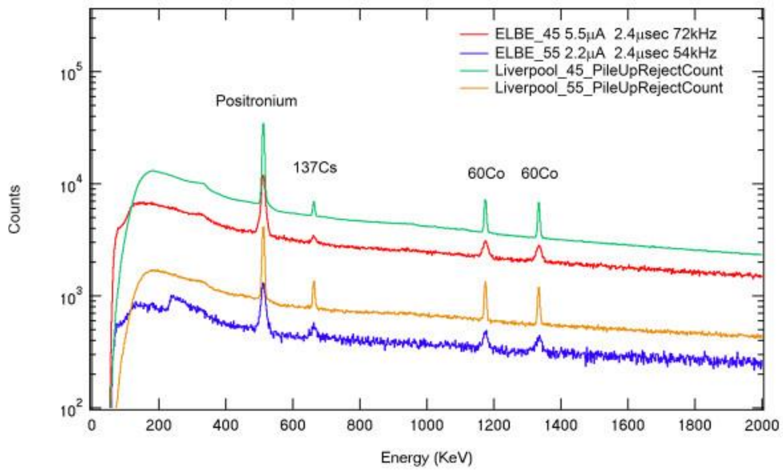
Normalization of Signal Events: Detector Studies

August 2017: Test of a HPGe detector

- <u>Aim</u>: to measure HPGe detector performance in terms of energy resolution and radiation damage and to understand the best detector geometry and position







Energy resolution from spectrum analysis between 3 keV and 6 keV

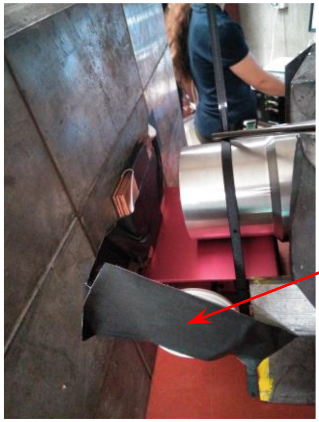
- No radiation damage on the detector found after beamtime
- No degradation in energy resolution after beamtime
- The data has been used to exercise and test reconstruction algorithms
- Observation of single spectral lines over high-rate bremsstrahlung background with high average photon energy is possible

Normalization of Signal Events: Detector Studies

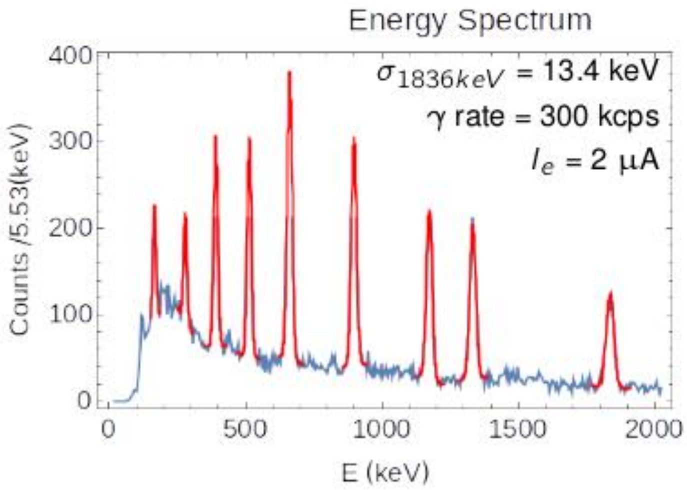
Sept 2021: Test of the $LaBr_3$ detector

- Aim: to test whether the $LaBr_3$ detector system could deal with the rate fluctuations anticipated at the Mu2e experiment

- A calibration source including Y-88 line at 1836 keV was used to mimick the muon capture on aluminum emission at 1809 keV
  - determine energy resolution for 1836 keV line over Bremsstrahlung spectrum at increasing levels of gELBE electron current



- "Nominal" expected Mu2e conditions were found at a pulse frequency of 813 kHz and 1.1 µA electron current
  - 150 kcps with 3.8 MeV average photon energy



- Detector system can handle data taken at twice the expected photon rate (813 kHz pulse frequency)

Summary

- Two tasks for supporting the Mu2e experiment design were performed:
  - investigation of the backgrounds via MC simulations
  - testing of the detector system for the signal events normalization

- The MC simulations were performed using GEANT4, FLUKA2021, MCNP6, and MARS15 codes
  - to evaluate the prediction credibility of the codes and tune the simulation setup

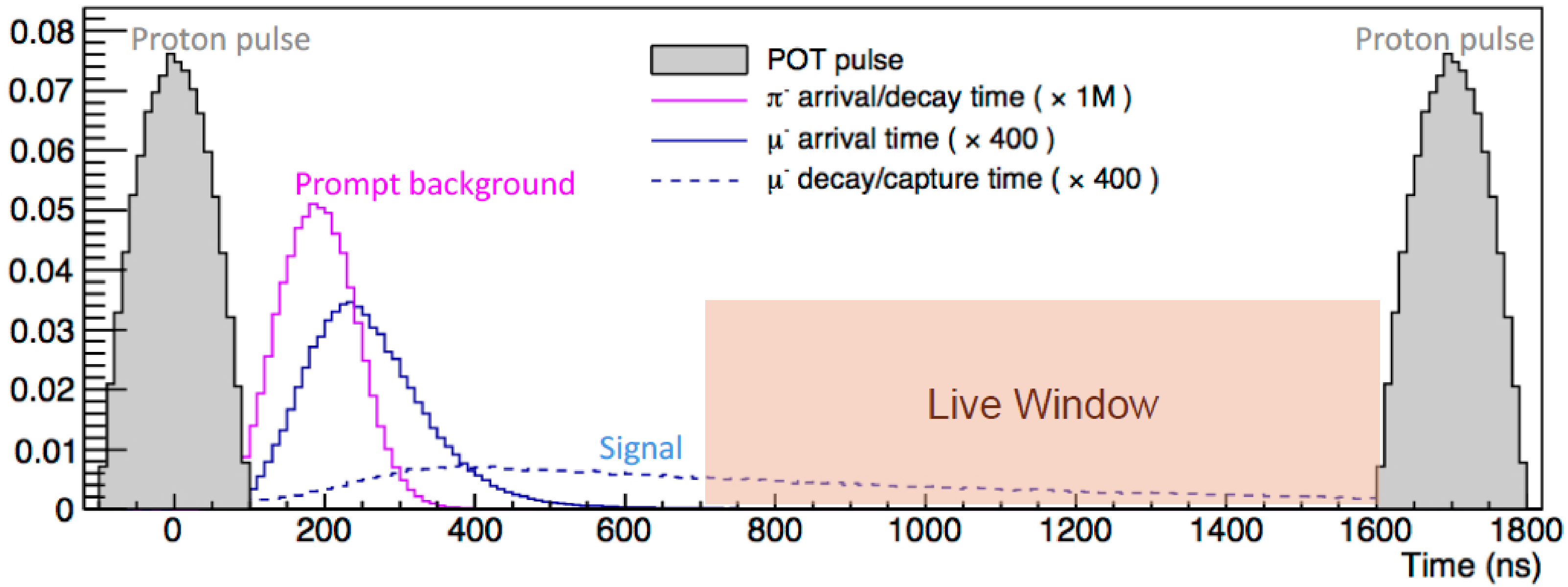
- The normalization will be provided by measuring the total number of muon captures via a system of HPGe + $LaBr_3$ detectors
  - will measure the rate of 1809 keV γ -rays emitted from the stopping target's aluminum discs when muons are captured

- The detectors are currently being set up in Mu2e building

Thank you for your attention!

The Mu2e experiment

Pulsed proton beam allows definition of a “Live Window” for the signal to suppress prompt background (1695 ns peak-to-peak):



- Fermilab accelerator complex provides optimal pulse spacing for Mu2e
- 700 ns delay allows to suppress prompt background from pions by $\sim 10^{-11}$
- Must achieve extinction (N_{p^+} out of bunch)/(N_{p^+} in bunch) $\leq 10^{-10}$