A High Efficiency Cosmic Ray Veto Detector for the Mu2e Experiment at Fermilab

and a Search for Hidden Chambers in the Great Pyramid

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The Holy Grail of Particle Physics: What Lies Beyond the Standard Model
Probes for New Physics: $\mu + N \rightarrow e + N$ Outstanding

Different SUSY and non-SUSY BSM models

<table>
<thead>
<tr>
<th>Observable</th>
<th>AC</th>
<th>RVV2</th>
<th>AKM</th>
<th>$\delta LL$</th>
<th>FBMSSM</th>
<th>LHT</th>
<th>RS</th>
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<tr>
<td>$D^0 - \bar{D}^0$</td>
<td>★★★</td>
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<td>$\epsilon_K$</td>
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<td>$S_{\psi\psi}$</td>
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<td>$S_{\phi\kappa}$</td>
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<td>$A_{CP}(B \rightarrow X_s\gamma)$</td>
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<td>$A_{9}(B \rightarrow K^*\mu^+\mu^-)$</td>
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<td>$B \rightarrow K^*(\nu\bar{\nu})$</td>
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<td>$B_s \rightarrow \mu^+\mu^-$</td>
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<td>$K^+ \rightarrow \pi^+\nu\bar{\nu}$</td>
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<td>$K_L \rightarrow \pi^0\nu\bar{\nu}$</td>
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<td>$\mu \rightarrow e\nu\bar{\nu}$</td>
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<td>$\tau \rightarrow \mu\nu\bar{\nu}$</td>
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Altmannshofer et al., NPB 830, 17 (2010)

Table 8: “DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Muons can be produced copiously, conversion electrons are distinctive, BSM effects are large.

- ★★★★★ Large effects
- ★★★ Visible, but small
- ★ No sizable effect
Pushing the Limits: Where we are Now

- $\mu N \rightarrow eN$
- $\mu \rightarrow e\gamma$
- $\mu \rightarrow eee$

![Graph showing branching fraction upper limit vs year for different experiments like TRIUMF, MEGA, MEG, SINDRUM, SINDRUM II.](image-url)
Pushing the Limits: Where we Plan to be

- $\mu N \rightarrow eN$
- $\mu \rightarrow e\gamma$
- $\mu \rightarrow eee$

Branching Fraction Upper Limit vs Year

- TRIUMF
- MEGA
- MEG
- MEG-II
- SINDRUM
- SINDRUM II
- DeeMe
- COMET
- Mu2e
- Mu3e
Probing new physics through lepton flavor violation through muon-to-electron conversion using a novel detector design

Signal: delayed emission of a single $\sim$105 MeV electron in an Aluminum stopping target

$\mu^- N \rightarrow e^- N'$
Two biggest backgrounds are Muon decay-in-orbit and cosmic-ray induced electrons.
Mu2e Experiment: Cosmic Ray Veto

- CRV identifies cosmic ray muons that produce conversion-like backgrounds.
- Design driven by need for excellent efficiency, large area, small gaps, high neutron and gamma rates, access to electronics, and constrained space.
- Technology: Four layers of extruded polystyrene scintillator counters with embedded wavelength shifting fibers, read out with SiPM photodetectors.
- Track stub in 3/4 layers, localized in time/space produces a veto in offline analysis.
- **Overall efficiency of 99.99% is needed to keep the background to less than 1 evt**
Mechanical Design: Counter

• Fundamental element of the CRV (5,344 total)
• Counters are extruded at the Fermilab NICADD facility
• Each counter has two 1.4/1.8 mm wavelength-shifting fibers placed in channels in extruded PS doped with 1% PPO + 0.05% POPOP and coated with with TiO$_2$
• All counters, except a handful where the radiation doses are too high, or if they are too short, are read out on both ends by silicon photomultipliers (SiPMs)
• Counters range from 1045 mm to 6900 mm long
• Counter profile: 51.3 x 19.8 mm$^2$
Mechanical Design: Di-counter Manifold

• Counters grouped in pairs to form a di-counter
• Each di-counter end served by a single counter motherboard with 4 2x2 mm² SiPMs, 2 flasher LEDs, 1 thermometer
• Designed to minimize pressure damage to SiPMs, eliminate light leaks, facilitate SiPM-fiber registration, provide easy removal/installation, and have a low profile
• Opaque counter motherboard forms manifold top; SiPM mounting block of anodized aluminum
• Pogopins connect counter motherboard and SiPM carrier boards
• SiPM temp not controlled, but bias adjusted based on temperature
• HDMI header can have vertical and horizontal orientation
Mechanical Design: Di-counter Manifold

- HDMI Header
- Opaque FR4
- "Pogo" pins
- 405 nm LED
- 2x2 mm SiPM
- Counter Mother Board
- SiPM Carrier Board (SCB)
- SiPM Mounting Block (SMB)
Mechanical Design: Modules

• Fundamental mechanical element of the CRV
• 4 layers of counters with 3 layers of Al absorbers sandwiched between them: 16 counters (8 di-counters) /layer
• Layers are offset to avoid projective gaps between counters
• Total: 83; of 10 different types
• Mechanical tolerances very tight and critical
• Weight: 179 kg - 1165 kg.
• Lengths range from 1.0 m – 6.9 m
We chose this photodetector type because:

• Good effective quantum efficiency
• Ability to measure absolute light yield
• Small size: facilitates on detector mounting
• Works in high magnetic fields
• Low cost: $9.56/ch mounted on carrier board

Hamamatsu MPPC S13360-2050VE

All values at 25° C at overvoltage of 2.5V:
1) 2mm x 2mm, 50 μm pixel
2) Surface-mount, TSV packaging
3) PDE > 35% (530 nm)
4) Gain ≥ 1.0x10^6
5) Pulse rise time < 5 nsec
6) Dark rate < 250 kHz @ 0.5 PE threshold
7) X-talk (inter-pixel) < 2%
8) Bias spread: ±0.5V (within batch); ±1.5V (all)
9) Temperature dependence ≤ 50 mV/°C
SiPM Delivery and Testing

SiPMs are mounted on small 8.4 x 4.9 mm$^2$ “SiPM carrier boards” (SCBs). They are delivered and tested on “waffle” pack boards, each with $4 \times 4 = 16$ SCBs. Punched out of the waffle pack when needed.

SiPM side of “waffle pack”

Pogopin pad side of “waffle pack”
Electronics: Block Diagram

Four components: (1) Mounted SiPMs (SCB w SiPM: 19,456, $9.56 ea), (2) Counter Motherboards (CMB: 4864, $32.71 ea), (3) Front-end Boards (FEB: 316, $1750 ea), (4) Readout Controllers (ROC: 16, $2000 ea)

All commercial-off-the-shelf parts (80 MHz ultrasound octal amp/ADC)

Dynamic range: 2000
Max rate/SiPM: 1 MHz
Max rate FEB-ROC: 10 MB/s
Max rate ROC-DTC: 250 MB/s
Time resolution: ~ 2 ns
Magnetic field: ~ 0.1 T
Max dose: $10^{10}$ n/cm$^2$
Front End Board: Amplifier, Digitizer, Shaper

• Serves 64 SiPMs
• Takes SiPM signals from 16 CMBs over HDMI cables
• Individual bias for all 64 SiPMs
• Amplifies, shapes, digitizes in amplitude and time, zero-suppresses, and buffers signals
• Power provided by Ethernet
• Can be read out (& powered) locally or through a readout controller

The core of the readout is a commercial ultrasound chip

TI AFE5807: Eight channels of low noise preamp, variable gain amp, programmable gain amp, programmable low pass filter, 80msps 12 bit ADC. $7 per channel, 120mW per channel. Adjust gain such that 1p.e. = 10 ADC counts.
Readout Controller

- Powers entire system
- Serves up to 24 FEBs (PoE)
- Interface to the DAQ computer
Electronics: Features

- All COTs parts: system can be reproduced inexpensively by others
- PoE from ROC to FEB eliminates need for any power supplies (other than 110V wall power)
- Histogramming firmware in FPGA allows fast dark-noise spectra to be obtained within seconds to calibrate the PE spectrum
- In-situ IV curves can be taken (100 pA precision, 1 mA max) that rivals commercial test equipment
Performance

Light yield from 120 GeV protons normally incident 1 m from readout end
- ~53 PE/SiPM
- 1.4 mm fibers

Reconstructed position using TOF from readout on both ends of a counter
- $\sigma = 15$ cm
- 1.4 mm fibers
Simulation Code

- A huge effort has gone into developing a detailed, fast, soup-to-nuts MC with a complete simulation of the counter response to incident particles.
- MC includes timing jitter, SiPM crosstalk, and afterpulsing, Front-end Board digitization, etc.
- MC has been extensively tuned to agree with test-beam data.

Response to 120 GeV protons along a 3-m long counter

Transverse response to 120 GeV protons for a 3-mm wide counter. Only data from left fiber used.
Other Experiments Exploring Similar Systems

Light Dark Matter eXperiment (LDMX) hadronic calorimeter
- quadcounter with 1 fiber/50-mm wide extrusion rather than di-counter

Exploring the Great Pyramid Experiment (EGP)
- Quadcounter with 1 fiber/extrusion rather than di-counter
- Better resolution needed: triangular counter: 40 x 20 mm² (base x height) gives ~1 mm

Exploring the Temple of Kukulcan at Chichen Itza
- Same design as EGP

Mu2e-II
- Exploring using same design as EGP

DUNE
- Exploring similar design for Near Detector
Summary

• We have developed a complete detector system based on scintillator counters with embedded wavelength-shifting fibers read out by SiPMs
• The detector is simple to fabricate using modest resources and is inexpensive
• A fast, inexpensive readout system using all COTS parts and that needs only wall power has been designed: it can be reproduced with ease
• The design is flexible and is being used or considered for multiple experiments

Many thanks to my colleagues on Mu2e