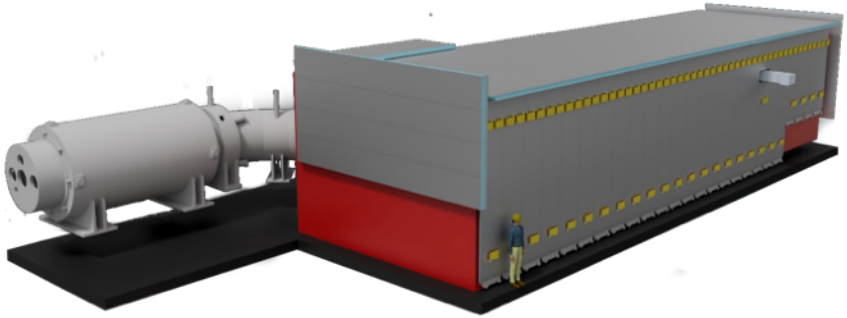
THE HIGH-EFFICIENCY COSMIC RAY VETO DETECTOR FOR THE MU2E EXPERIMENT AT FERMILAB

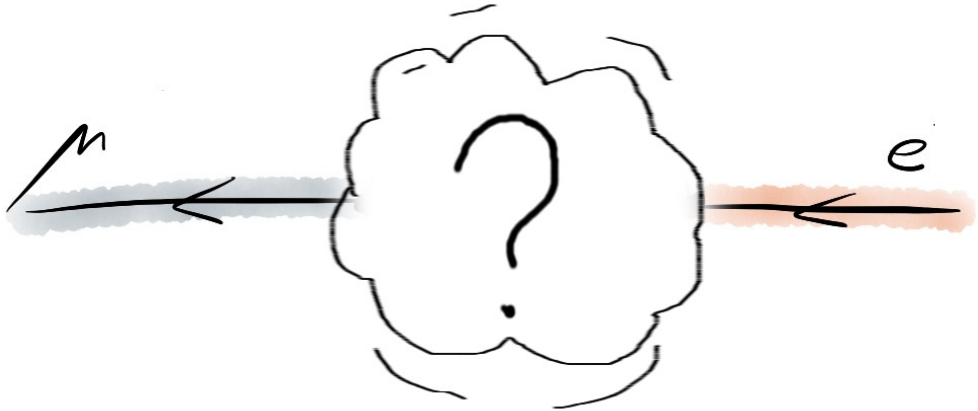


SIMON CORRODI
Argonne National Laboratory

on behalf of the Mu2e CRV group

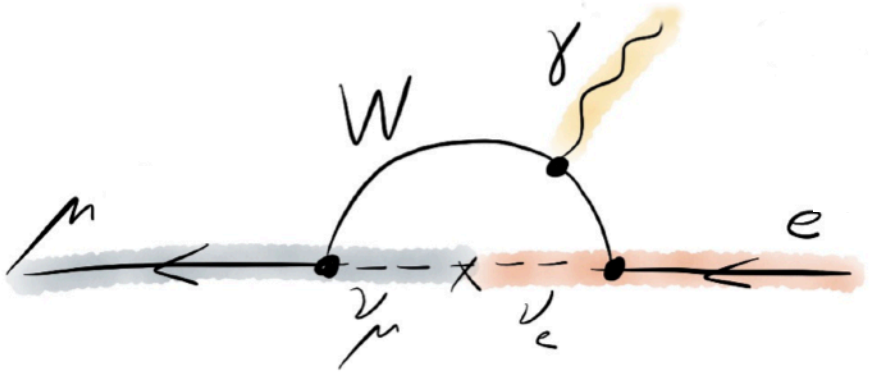
NuFact 2022
July 31 - August 6, 2022
Salt Lake City

CHARGED LEPTON FLAVOR VIOLATION



*sketches from Niklaus Berger

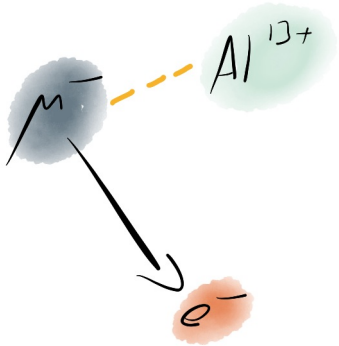
CHARGED LEPTON FLAVOR VIOLATION



Standard Model branching fraction
$< 10^{-54}$
any observation is **new physics**

$$\sim \left(\frac{\Delta m_\nu^2}{m_W^2} \right)^2$$

CHARGED LEPTON (MUON) FLAVOR VIOLATION



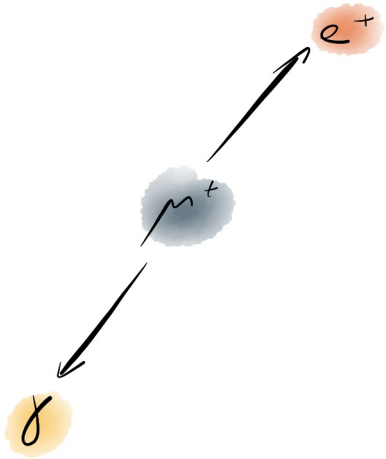
$$\mu^- N \to e^- N$$

SINDRUM II (PSI, 2006)

$Br < 7 \cdot 10^{-13} \quad (N = Au)$

Mu2e, COMET, DeeMe
(Fermilab, J-PARC)

$Br \lesssim 3 \cdot 10^{-15} - 2.6 \cdot 10^{-17}$



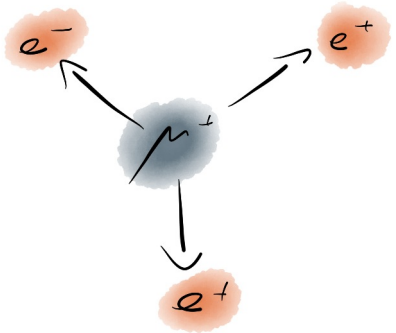
$$\mu^+ \to e^+ \gamma$$

MEG (PSI, 2016)

$Br < 4.2 \cdot 10^{-13}$

MEG II (PSI)

$Br \lesssim 5 \cdot 10^{-14}$



$$\mu^+ \to e^+ e^- e^+$$

SINDUM (PSI, 1988)

$Br < 1.0 \cdot 10^{-12}$

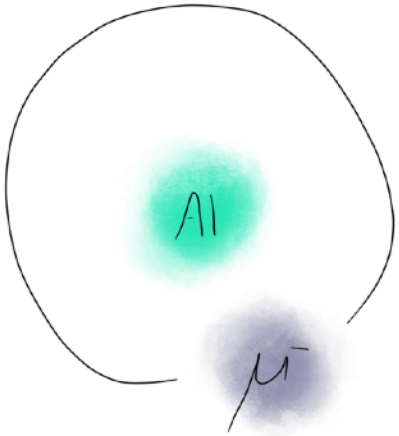
Mu3e (PSI)

$Br \lesssim 2.0 \cdot 10^{-15} - 1.0 \cdot 10^{-16}$

THE MU2E SIGNAL (ALUMINUM TARGET)

Delayed emission of a single ~105 MeV electron in an Aluminum stopping target.

$$\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))$$



Signal

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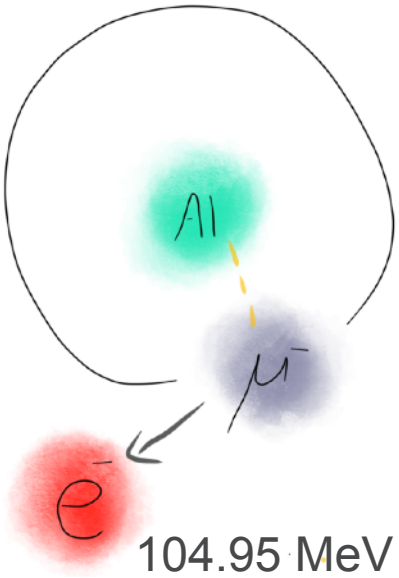

Signal

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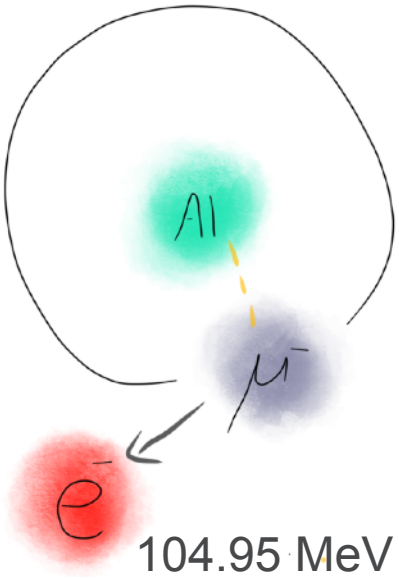
Delayed emission of a single ~105 MeV electron in an Aluminum stopping target.

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{}$$



104.95 MeV

Signal

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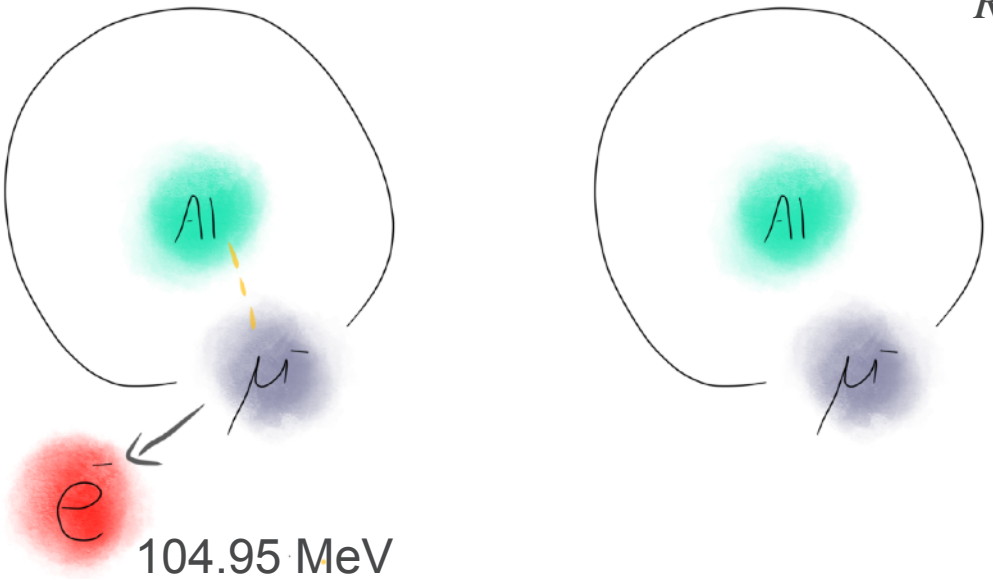

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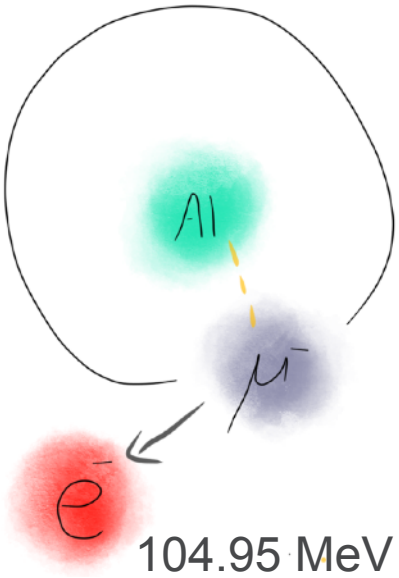

104.95 MeV

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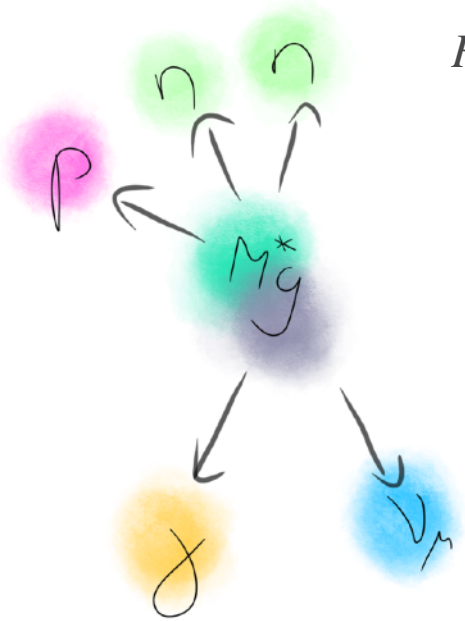
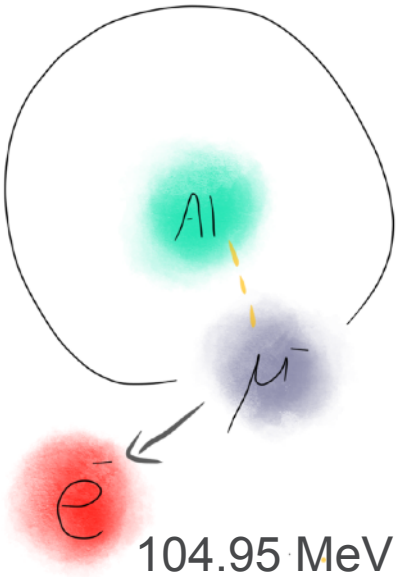


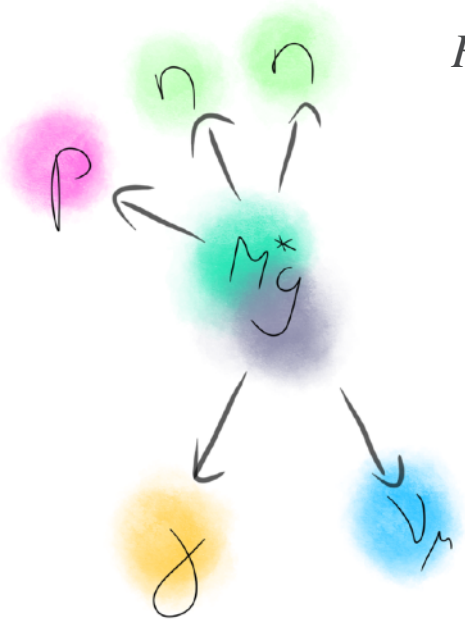
Nuclear Capture
(BR = 61%)

THE MU2E SIGNAL (ALUMINUM TARGET)

Delayed emission of a single ~105 MeV electron in an Aluminum stopping target.



Signal



Nuclear Capture
(BR = 61%)

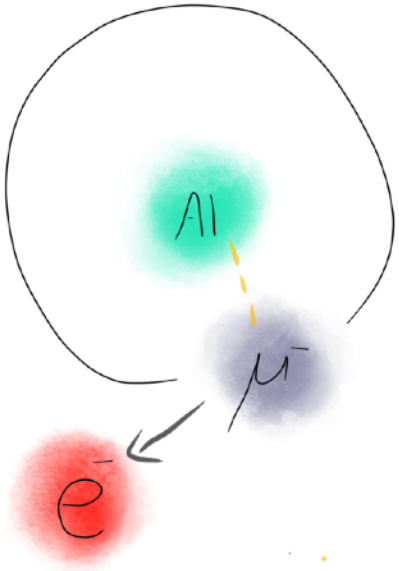
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$

THE MU2E BACKGROUNDS: DECAY IN ORBIT

Decay in Orbit (DIO)

Beam

Cosmic Rays



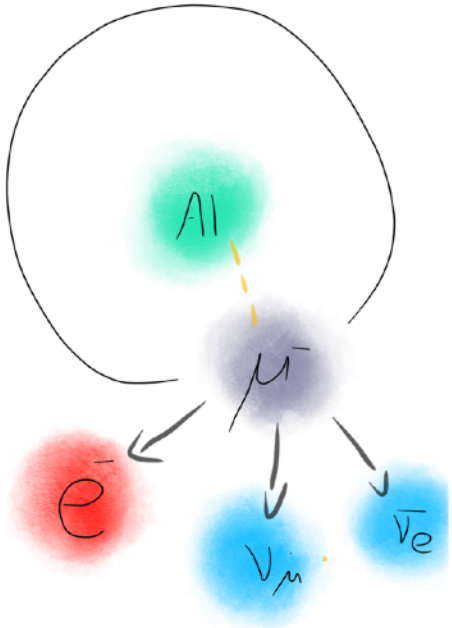
=> energy resolution

THE MU2E BACKGROUNDS: DECAY IN ORBIT

Decay in Orbit (DIO)

Beam

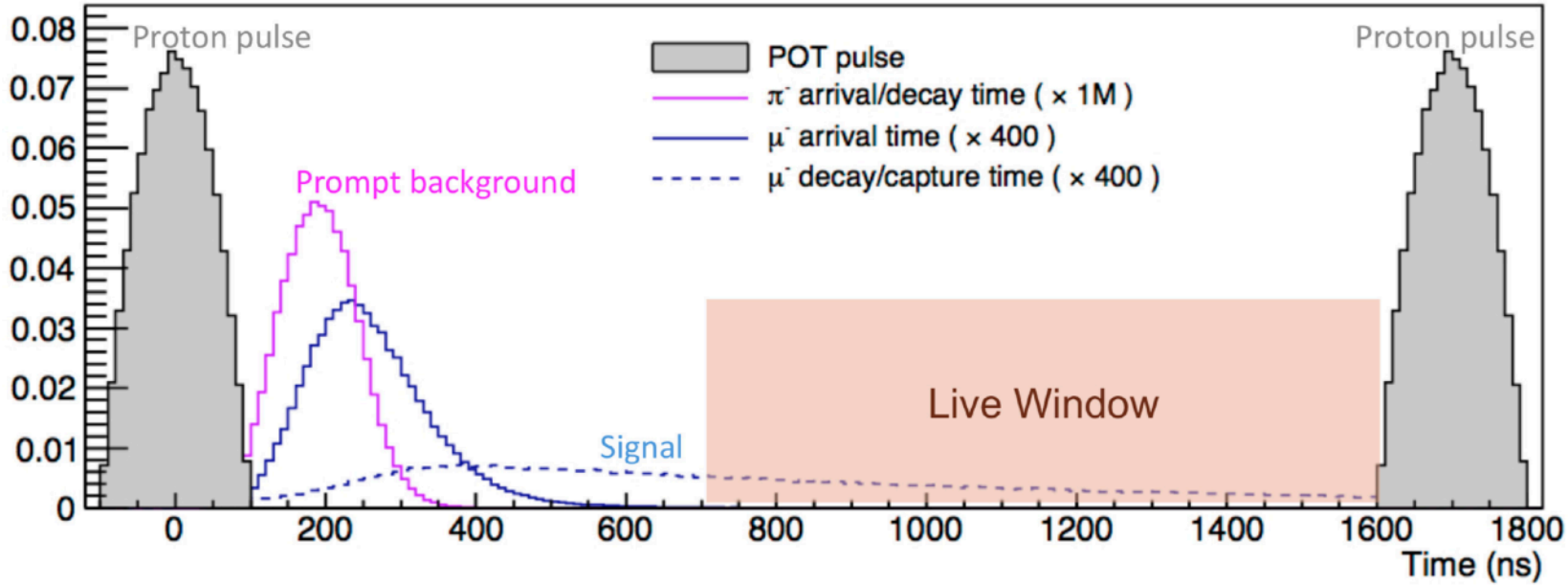
Cosmic Rays



=> energy resolution

THE MU2E BACKGROUNDS: BEAM

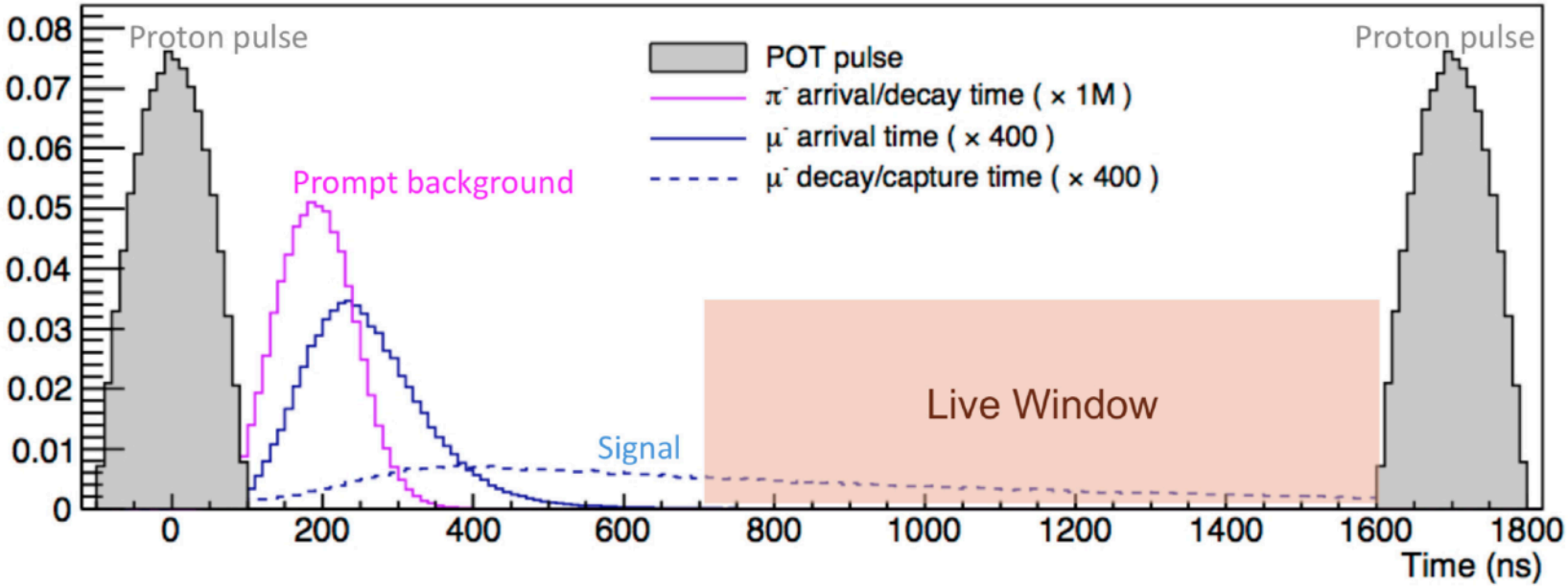
Decay in Orbit (DIO) **Beam** Cosmic Rays



=> Pulsed beam with excellent distinction

THE MU2E BACKGROUNDS: BEAM

Decay in Orbit (DIO) **Beam** Cosmic Rays

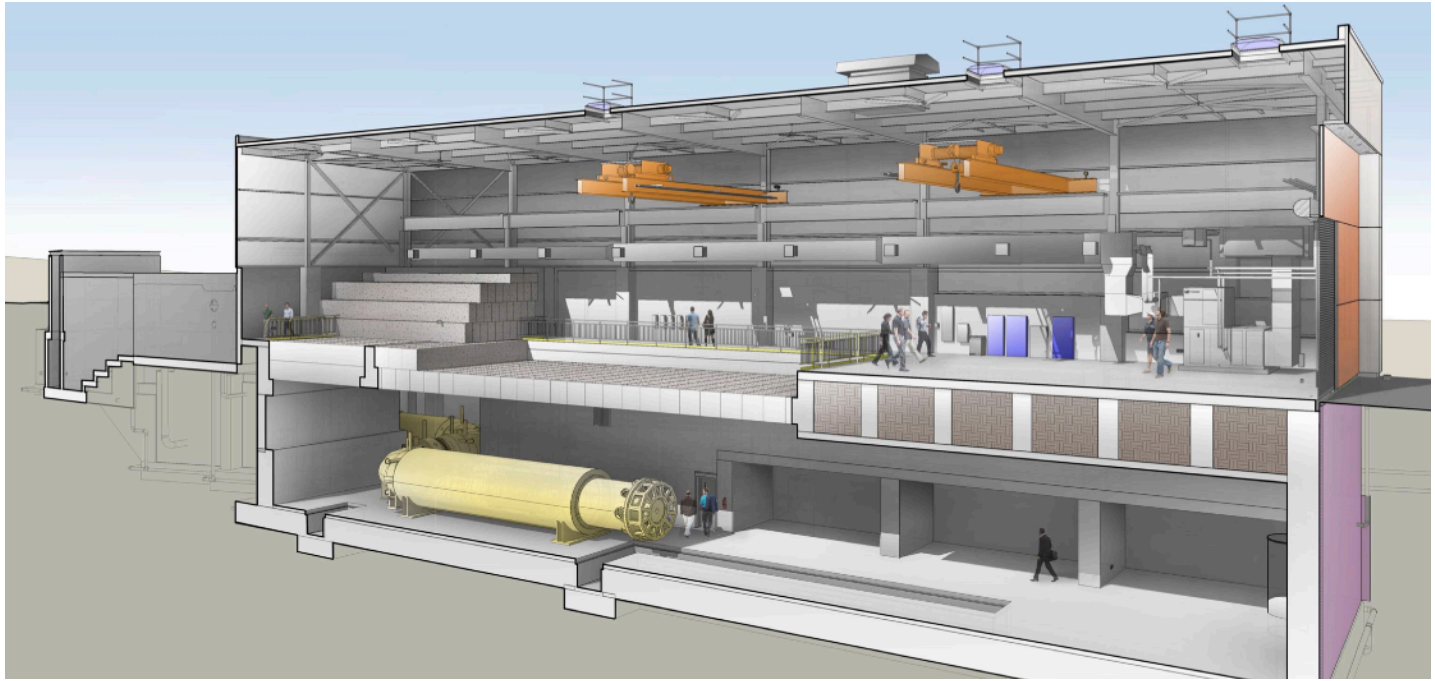


=> Pulsed beam with excellent distinction

-> the detector is live “most” of the time

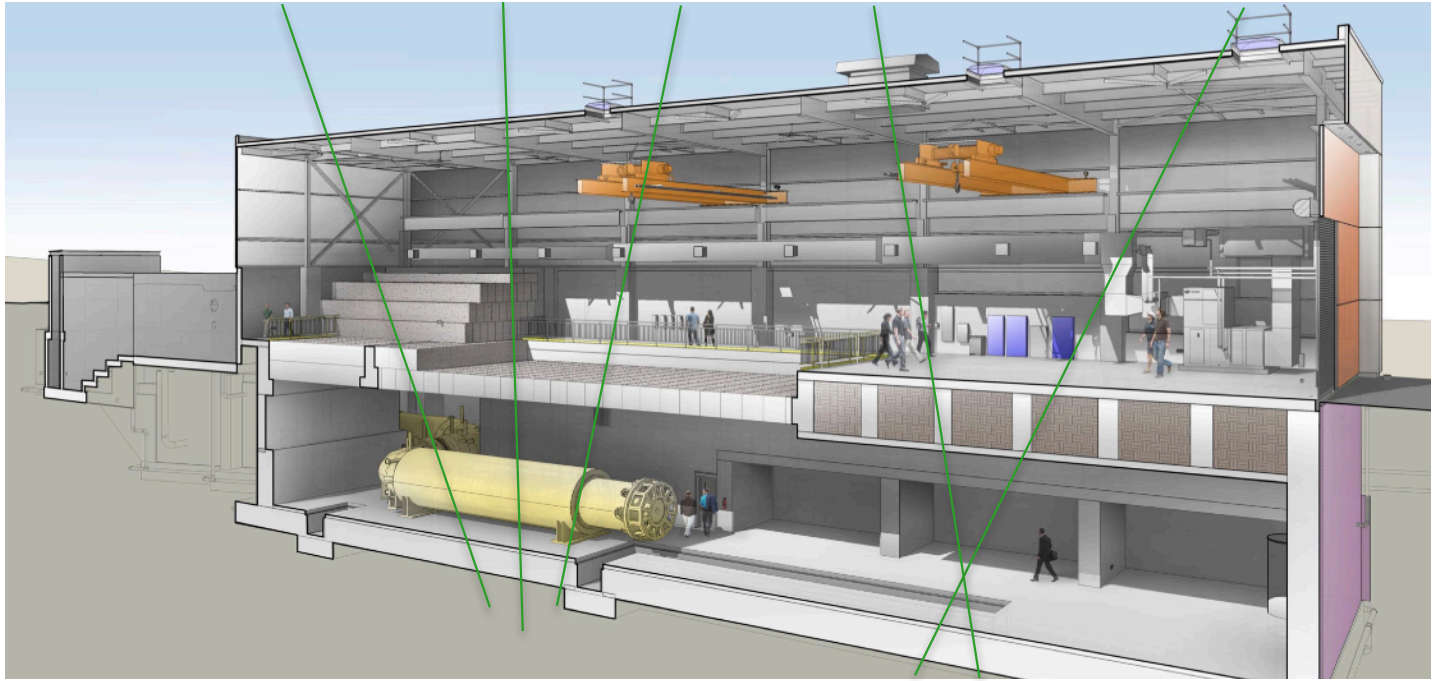
THE MU2E BACKGROUNDS: COSMIC RAYS

Decay in Orbit (DIO) Beam **Cosmic Rays**

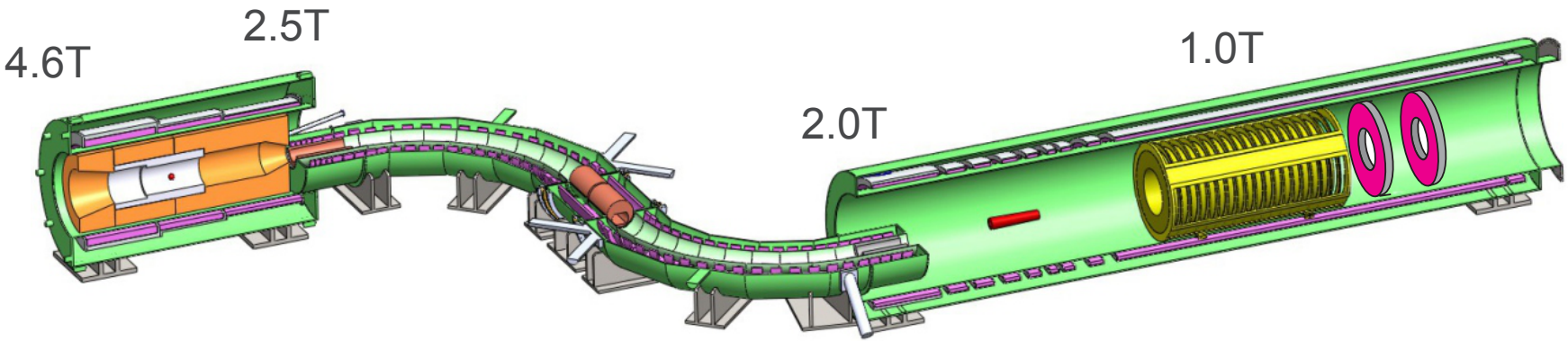


THE MU2E BACKGROUNDS: COSMIC RAYS

Decay in Orbit (DIO) Beam **Cosmic Rays**

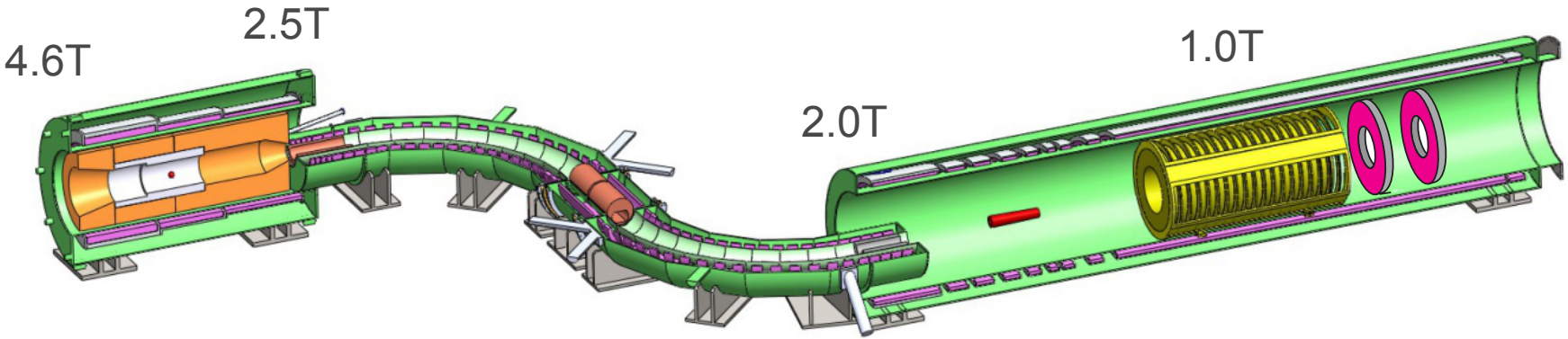


THE MU2E EXPERIMENT AT FERMILAB



THE MU2E EXPERIMENT AT FERMILAB

(PS: Production Solenoid)



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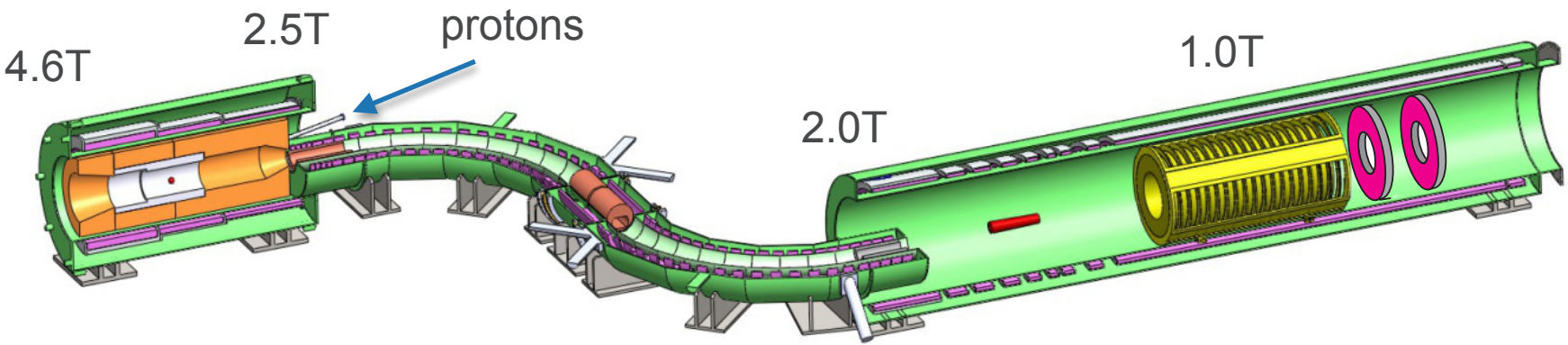

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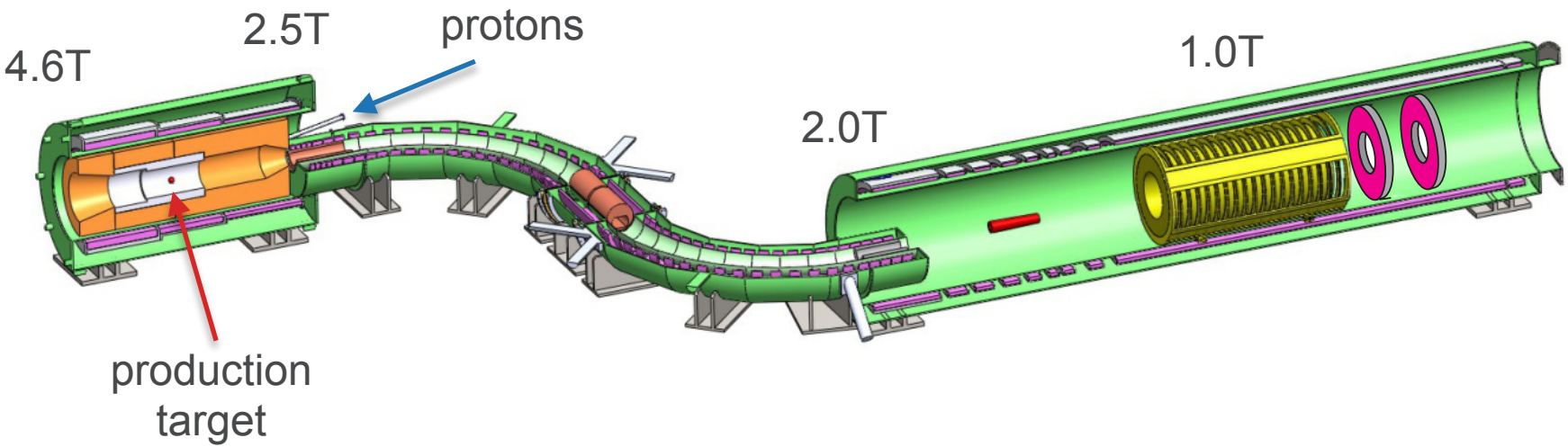

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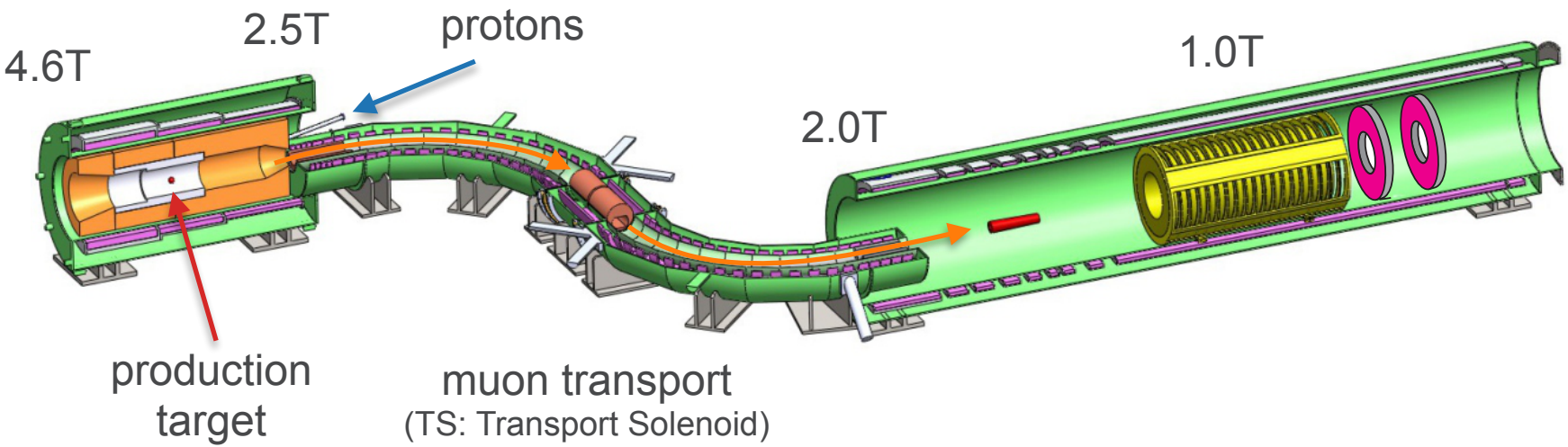
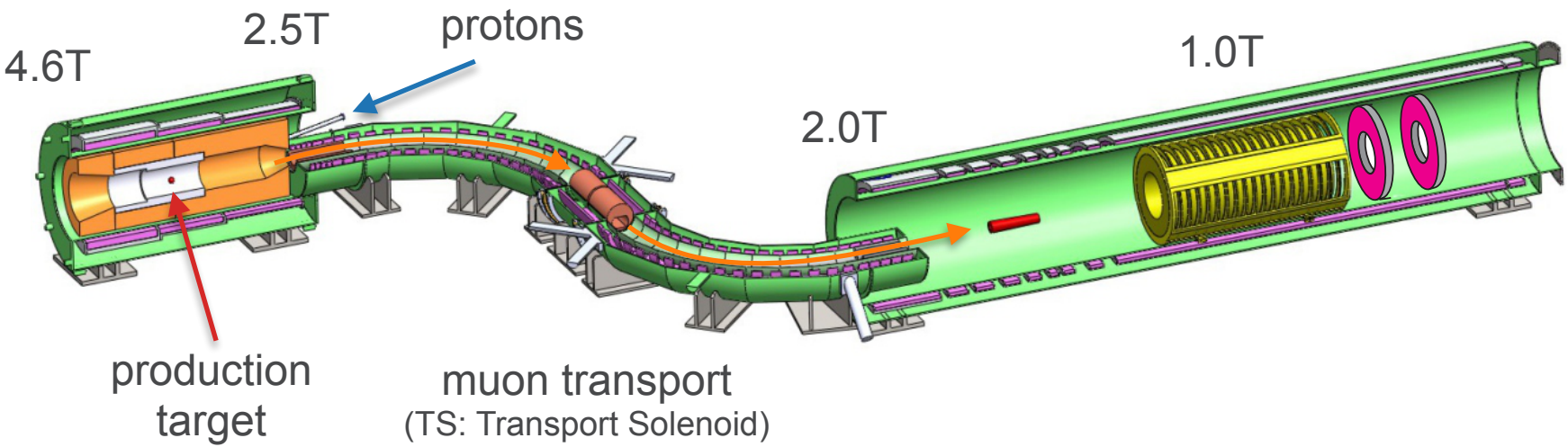


THE MU2E EXPERIMENT AT FERMILAB

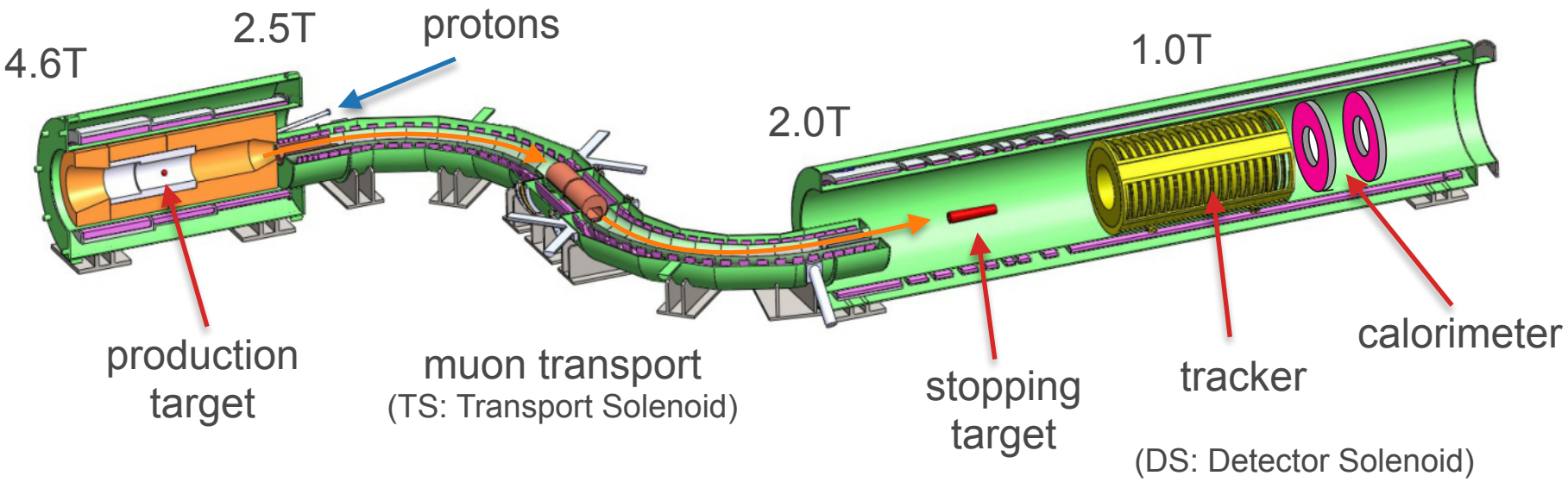
(PS: Production Solenoid)



(DS: Detector Solenoid)

THE MU2E EXPERIMENT AT FERMILAB

(PS: Production Solenoid)



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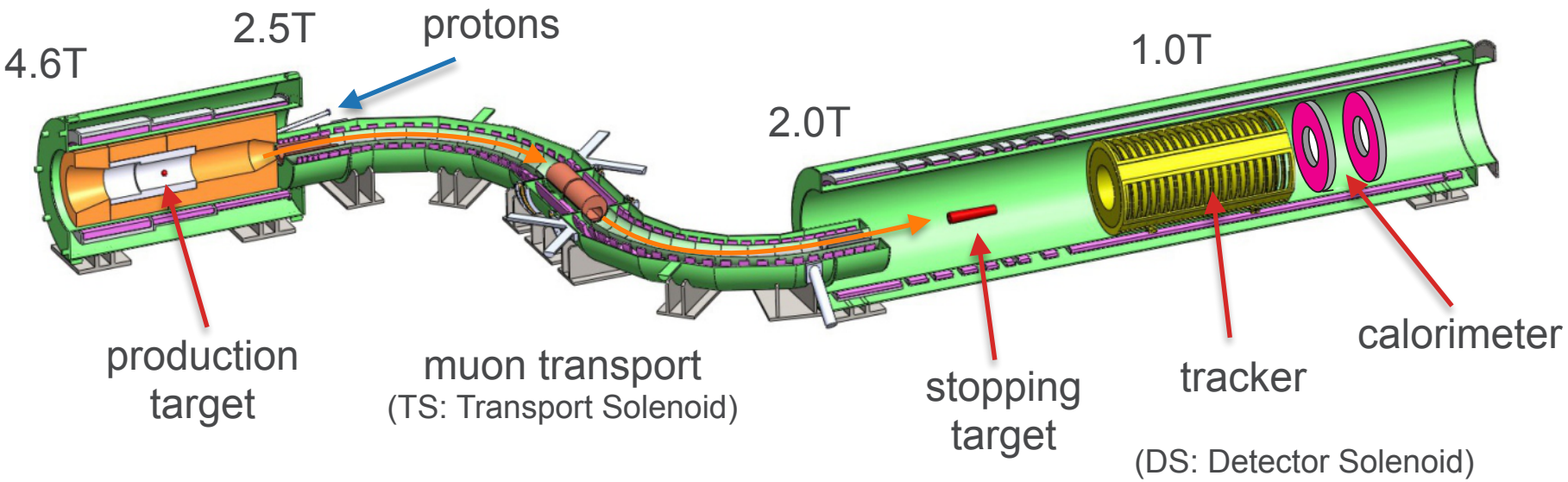
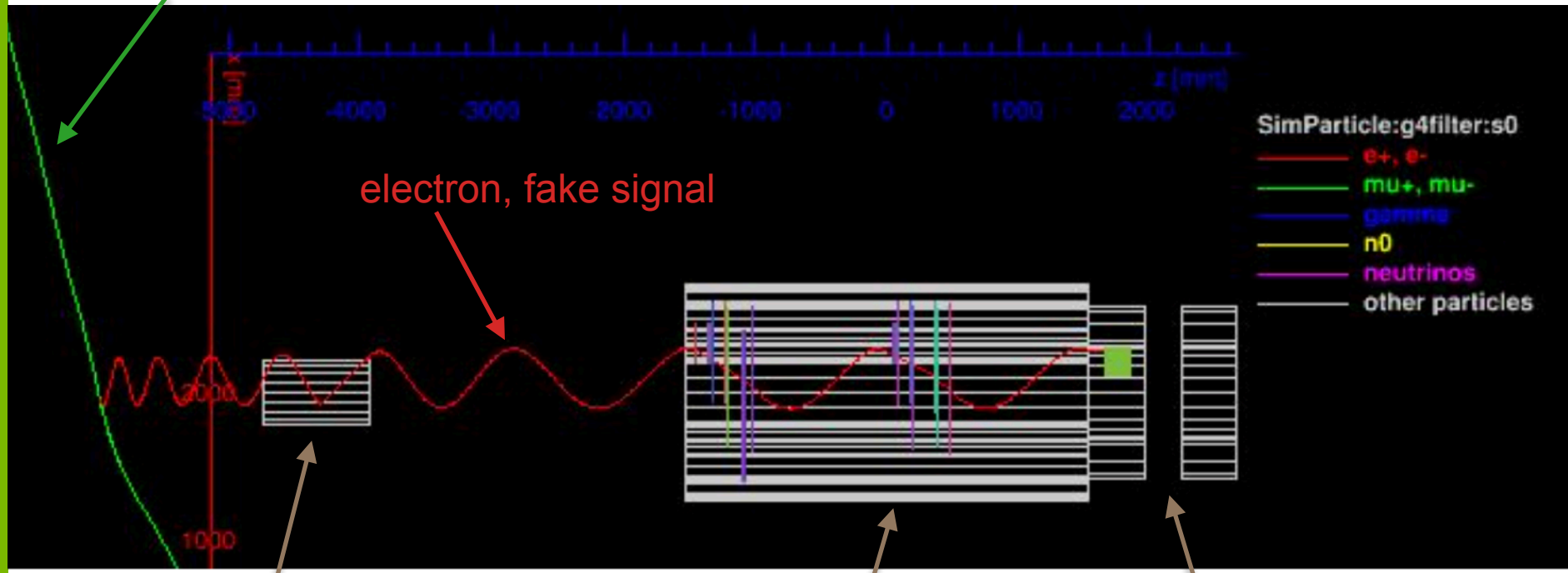


See talk 9: "Design, construction, and vertical slice performance tests of the Mu2e straw tracker", by Richard Bonventre

COSMIC RAY BACKGROUND: EXAMPLE

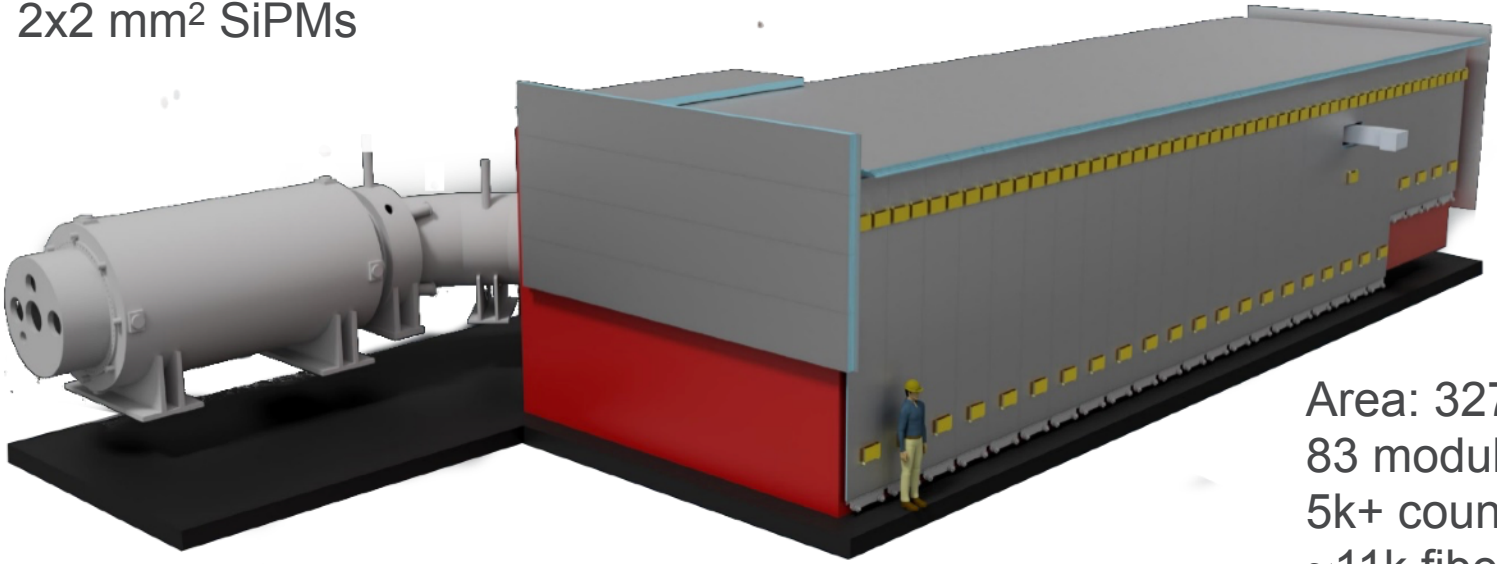
Mu2e expects 1 signal-like event per day induced by cosmic rays



THE MU2E COSMIC RAY VETO (CRV)

Localized hits (space and time) coincidence in multiple (3/4 or 4/4) layers trigger a (offline) ~125 ns vetoed in the signal window

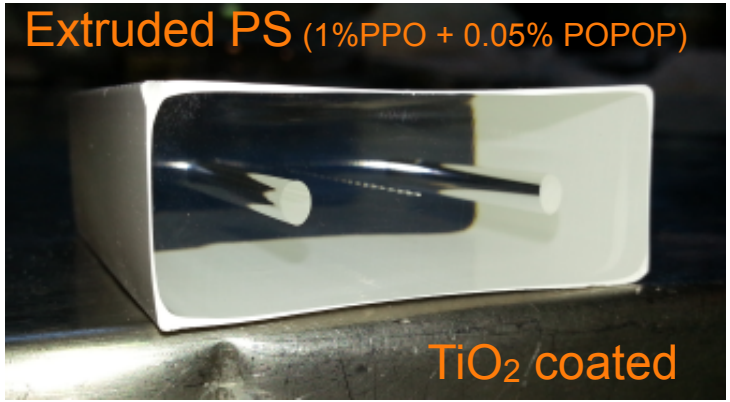
4-layer scintillating 5x2 cm^2 counters, read-out through wavelength-shifting fibers by 2x2 mm^2 SiPMs

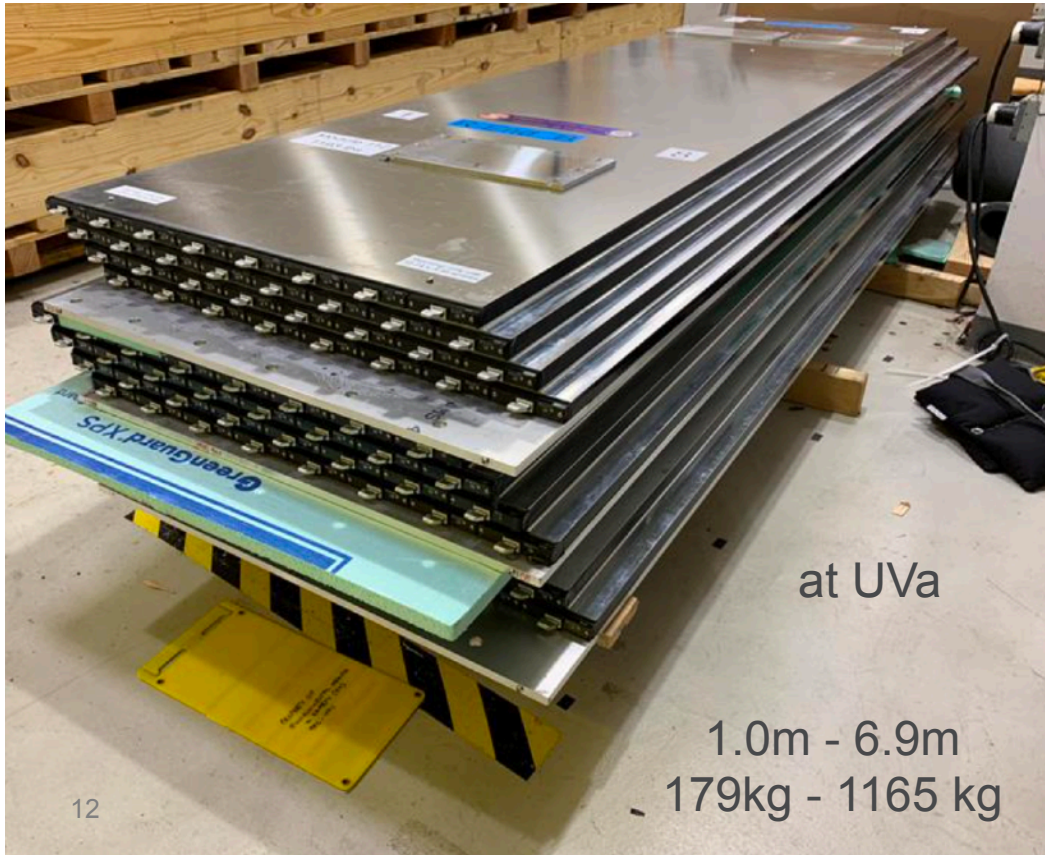


Area: 327 m^2
83 modules, 10 types
5k+ counters
~11k fibers
~19k SiPMs
~300 Front-end Boards

THE MU2E COSMIC RAY VETO (CRV)

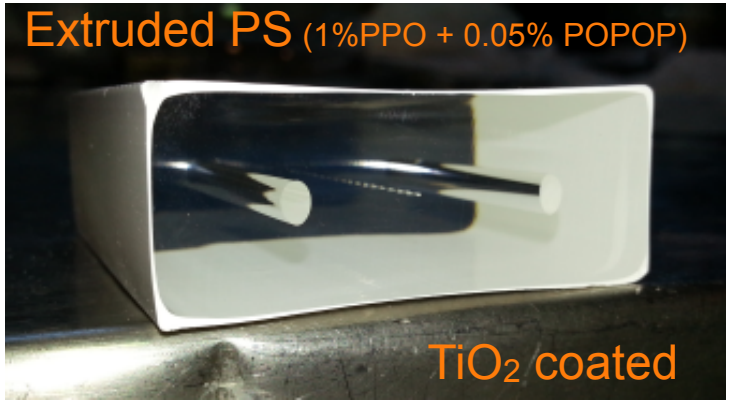
4-layer scintillating 5x2 cm^2 counters, read-out through wavelength-shifting fibers by 2x2 mm^2 SiPMs



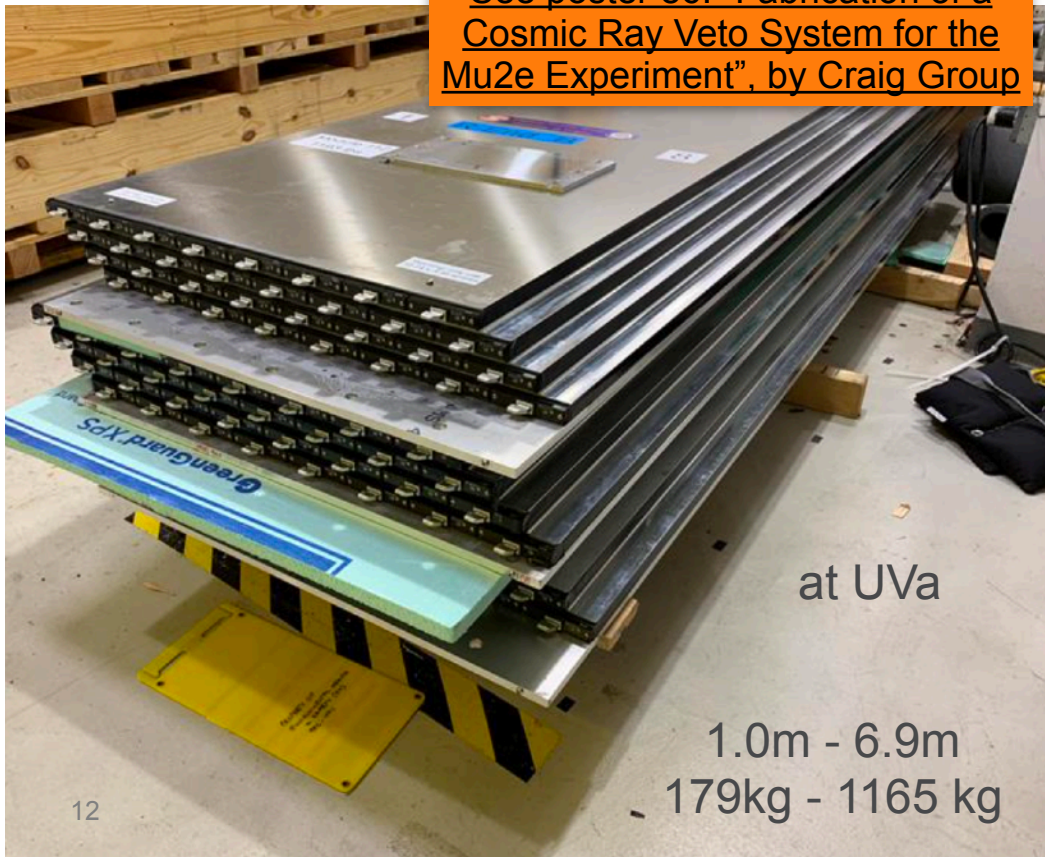


THE MU2E COSMIC RAY VETO (CRV)

4-layer scintillating 5x2 cm² counters, read-out through wavelength-shifting fibers by 2x2 mm² SiPMs

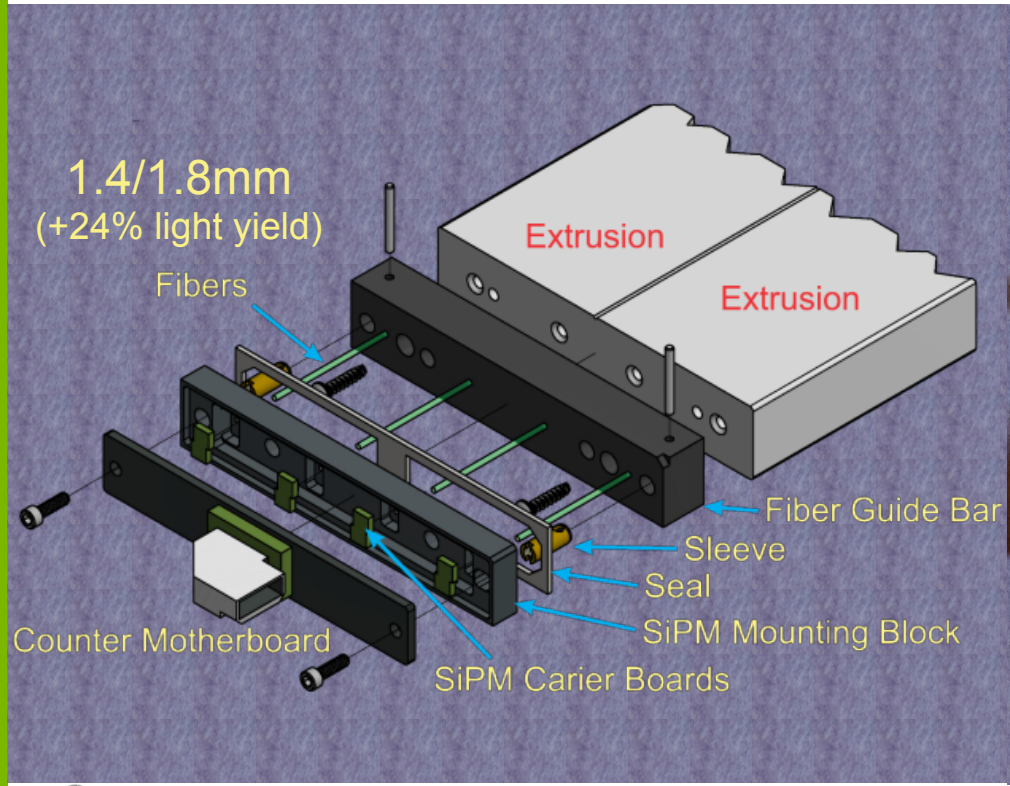


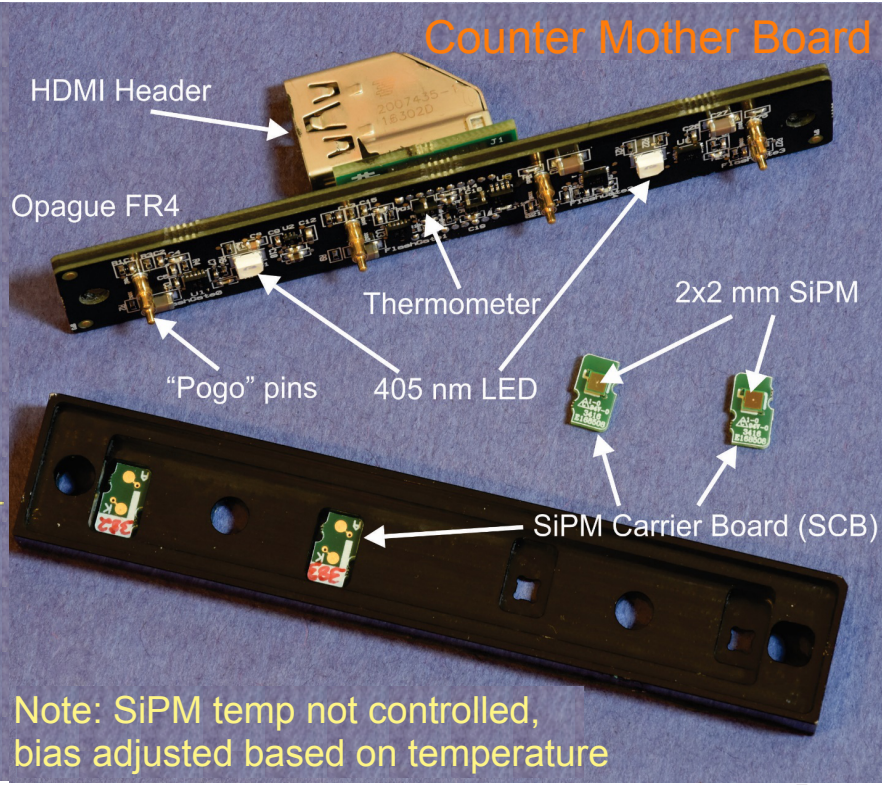
See poster 86: “Fabrication of a Cosmic Ray Veto System for the Mu2e Experiment”, by Craig Group



THE MU2E COSMIC RAY VETO (CRV)

4-layer scintillating 5x2 cm^2 counters, **read-out through wavelength-shifting fibers by 2x2 mm^2 SiPMs**





CRV REQUIREMENTS

Goal: single event sensitivity of **2.5×10^{-17}** (6×10^{-17} 90%CL)
~10^{18} stopped muons, 3.6×10^{20} protons on target within 3 years of running

=> requires a **background free experiment** (expected total of 0.4, 0.2 from CR)

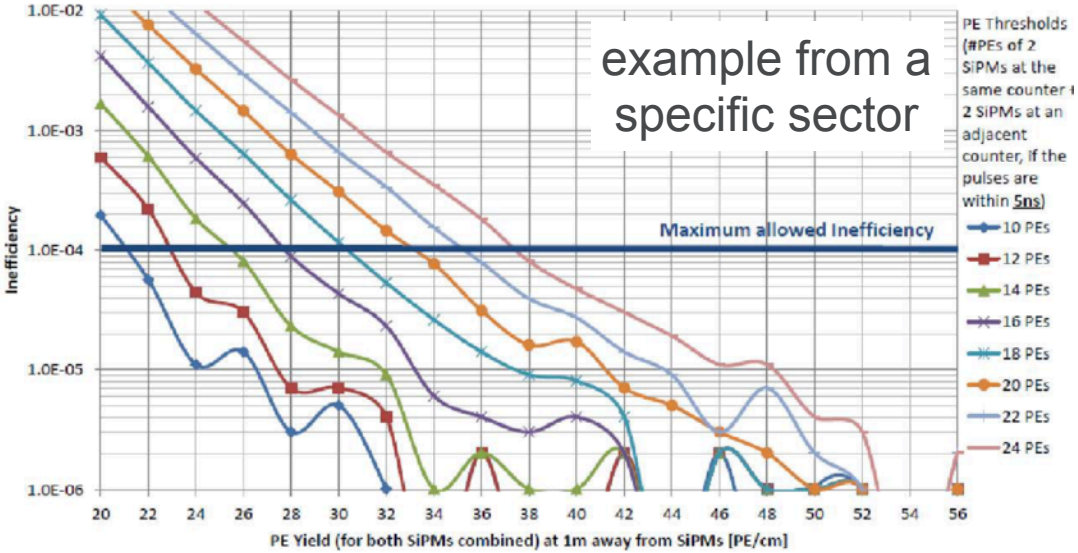
Cosmic Rays: 1 background event per day -> needs ~few 1000x suppression
few km deep under ground or veto detector: CRV

CRV Requirements:
- **efficiency of up to 99.99%** is needed to keep the background to less than 1 event
- **very low dead time**

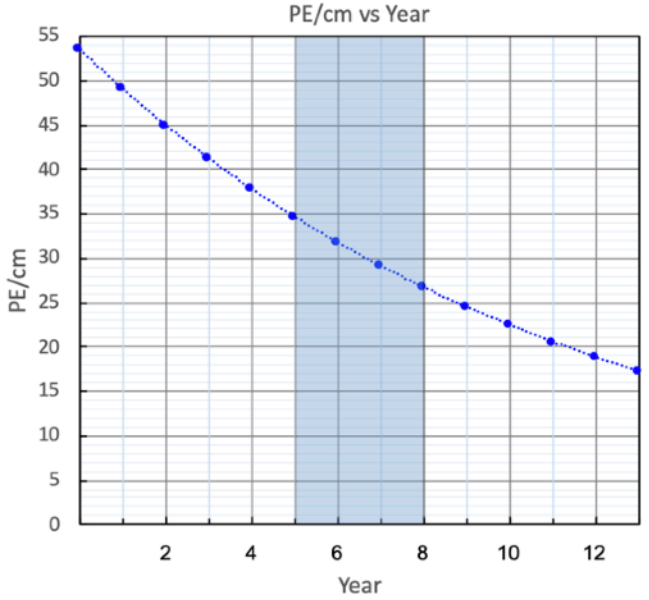
CHALLENGES: INEFFICIENCIES I

The maximally allowed inefficiency is 1×10^{-4}

efficiency scales with light (photo electron) yield



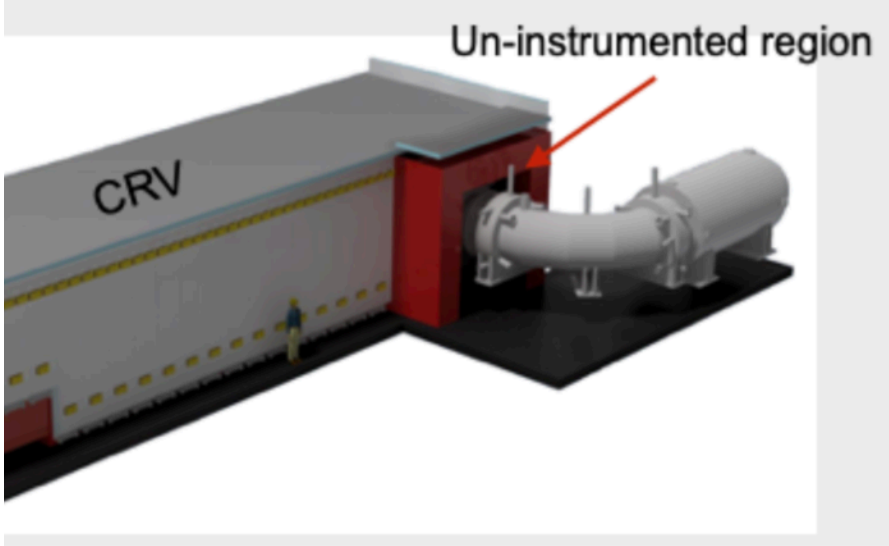
aging needs to be monitored and understood well



=> extensive efforts to monitor and understand aging

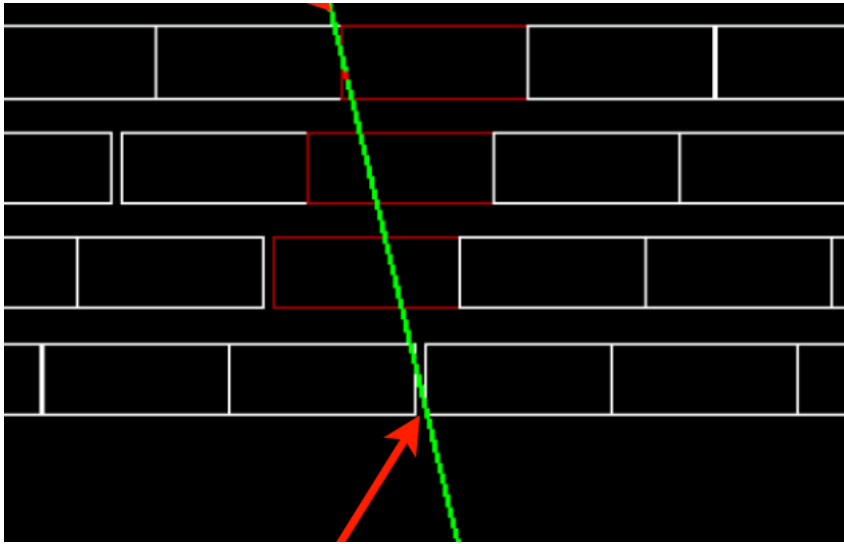
CHALLENGES: INEFFICIENCIES II: HOLES AND EDGE EFFECTS

Example: No shielding at the TS opening



=> mitigation with passive absorbers (expensive)

Example: Geometry/Edge Effects

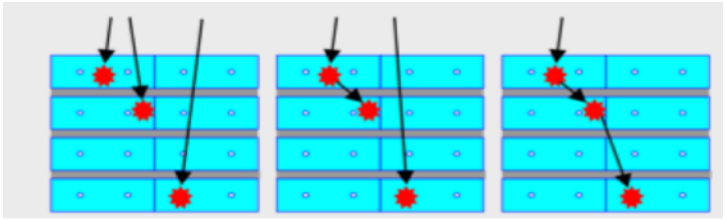


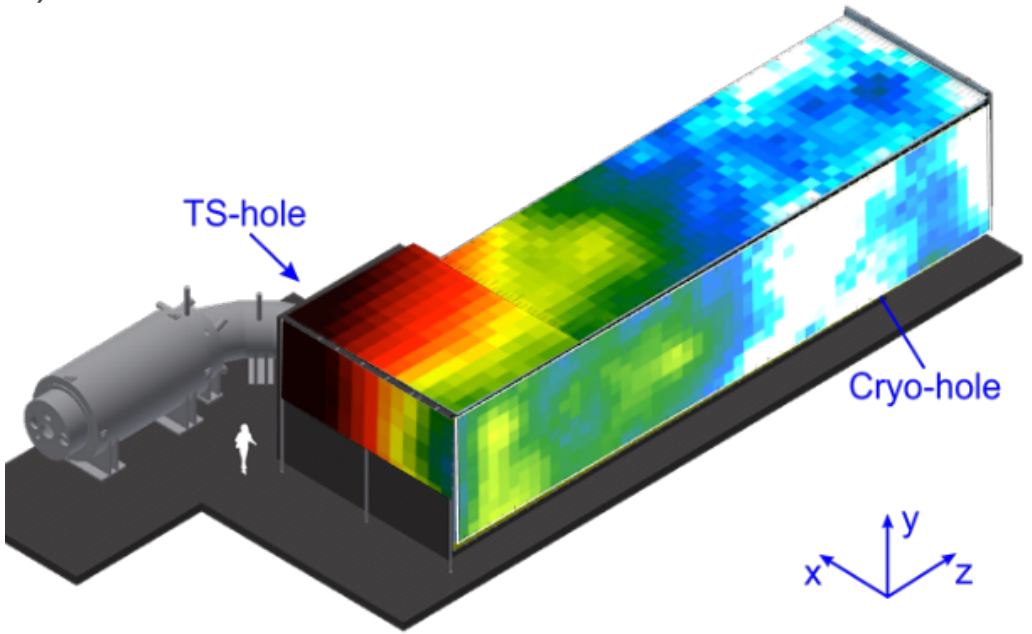
=> staggered design to minimize gaps

CHALLENGES: DEAD TIME

“Fake CR events” introduce dead time -> fake vetos

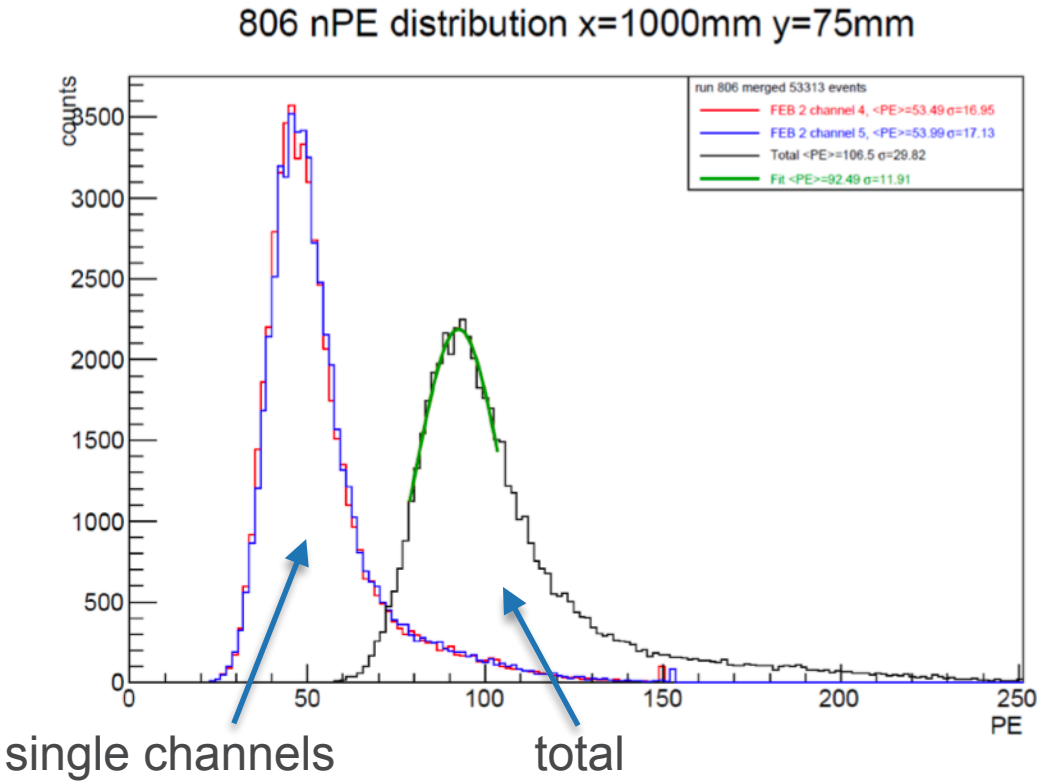
Superposition of different sources:
-> detector noise (SiPM dark counts)
-> “radiation”





PERFORMANCE

Testbeam: 120 GeV protons normally, 1m from the readout end

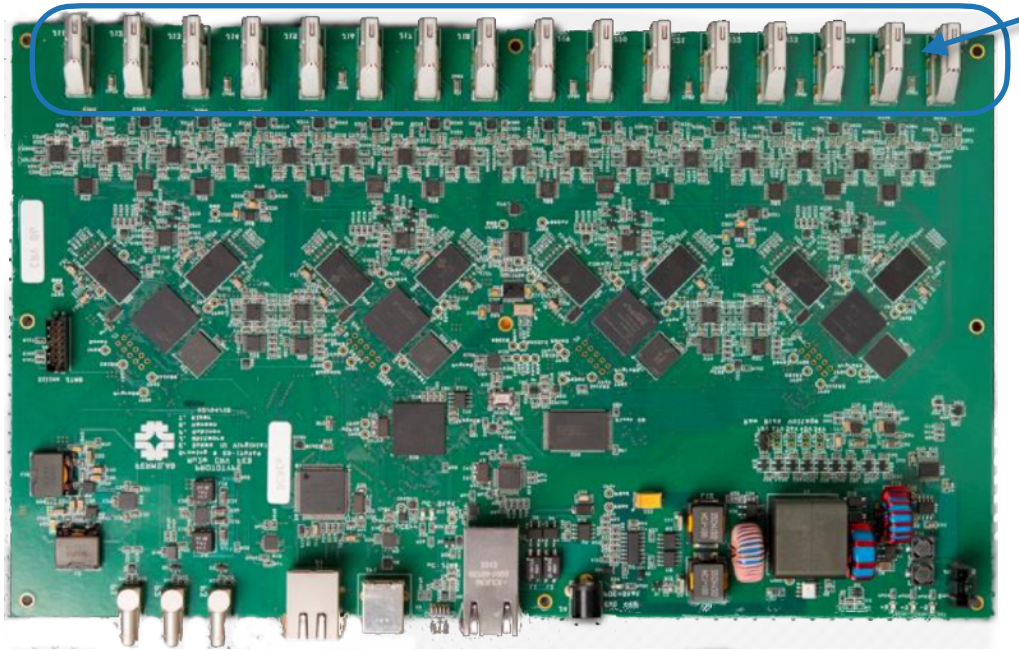


READOUT ELECTRONICS: FRONT END BOARD (FEB)

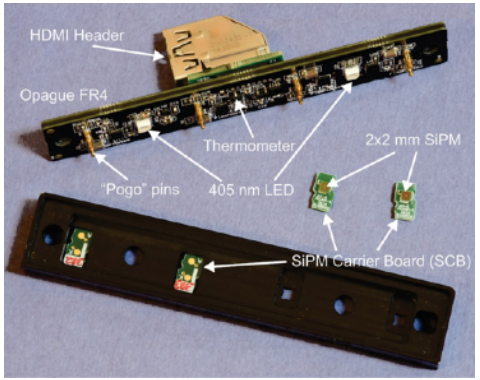
64 (4 x 16) channels

READOUT ELECTRONICS: FRONT END BOARD (FEB)

64 (4 x 16) channels



HDMI connecting to the CMB



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80 MSPS Digitization
TI AFE5807

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64 (4 x 16) channels

HDMI connecting to the CMB

80 MSPS Digitization
TI AFE5807

FPGA & DDR
zero-suppressed/self-triggered,
paged (event window tag) memory

READOUT ELECTRONICS: FRONT END BOARD (FEB)

64 (4 x 16) channels

HDMI connecting to the CMB

80 MSPS Digitization
TI AFE5807

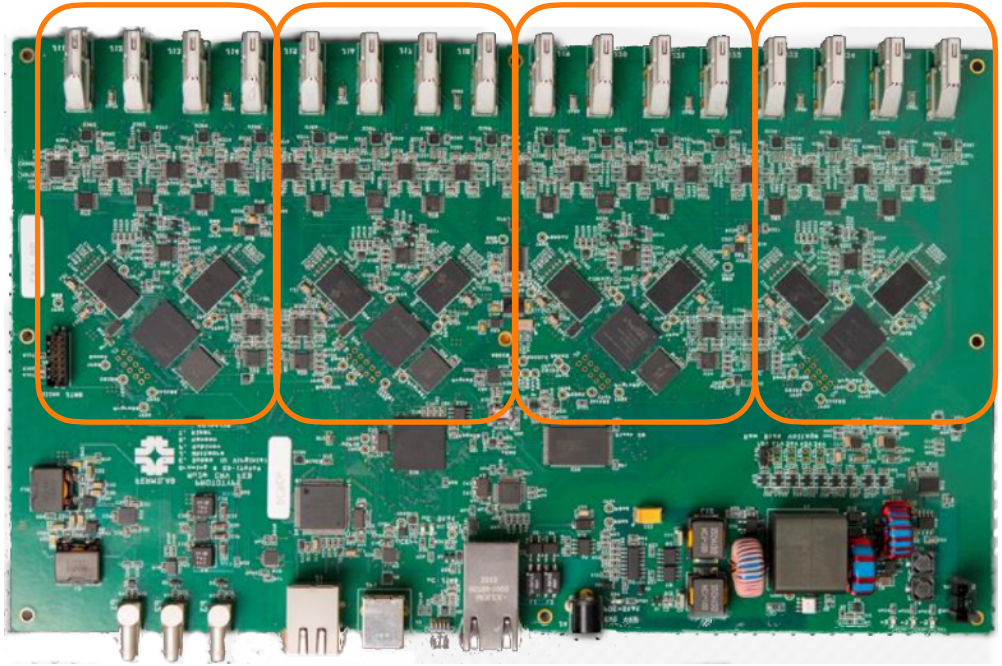
FPGA & DDR
zero-suppressed/self-triggered,
paged (event window tag) memory

Current board:
Spartan 6 & LPDDR

Spartan 6: early end of life:
=> currently migrating to spartan 7

READOUT ELECTRONICS: FRONT END BOARD (FEB)

64 (4 x 16) channels



HDMI connecting to the CMB

80 MSPS Digitization
TI AFE5807 x 4

FPGA & DDR
zero-suppressed/self-triggered,
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data, communication,
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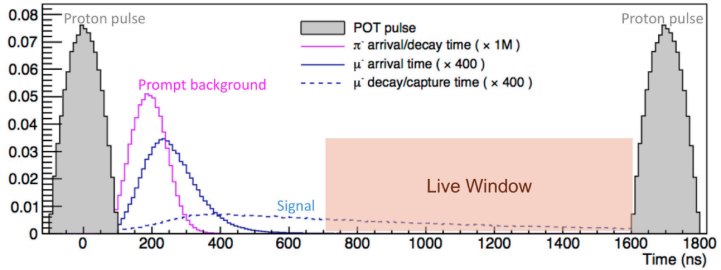
power over ethernet (POE):
12bit DAC to fine tune each SiPM

READOUT ELECTRONICS: FRONT END BOARD (FEB)

64 (4 x 16) channels

Unique features:
- (cheap) off-the-self components, no dedicated ASICs
- Flash-gate:
  Lower the SiPM bias voltage: ~2V (current + after pulsing suppression)



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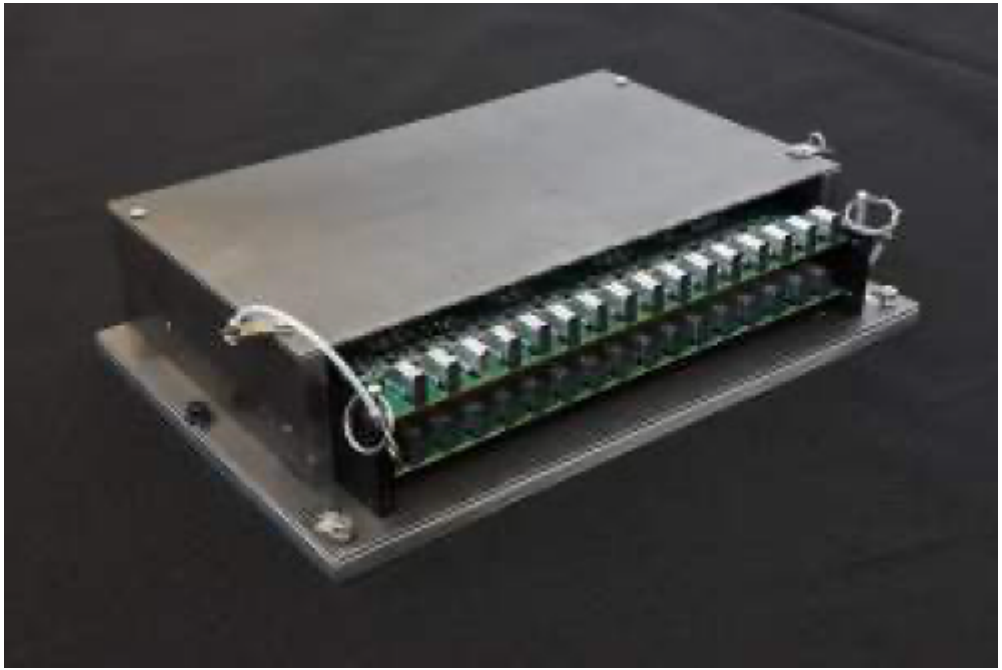

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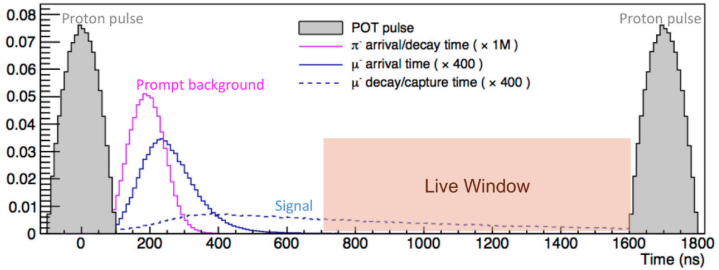
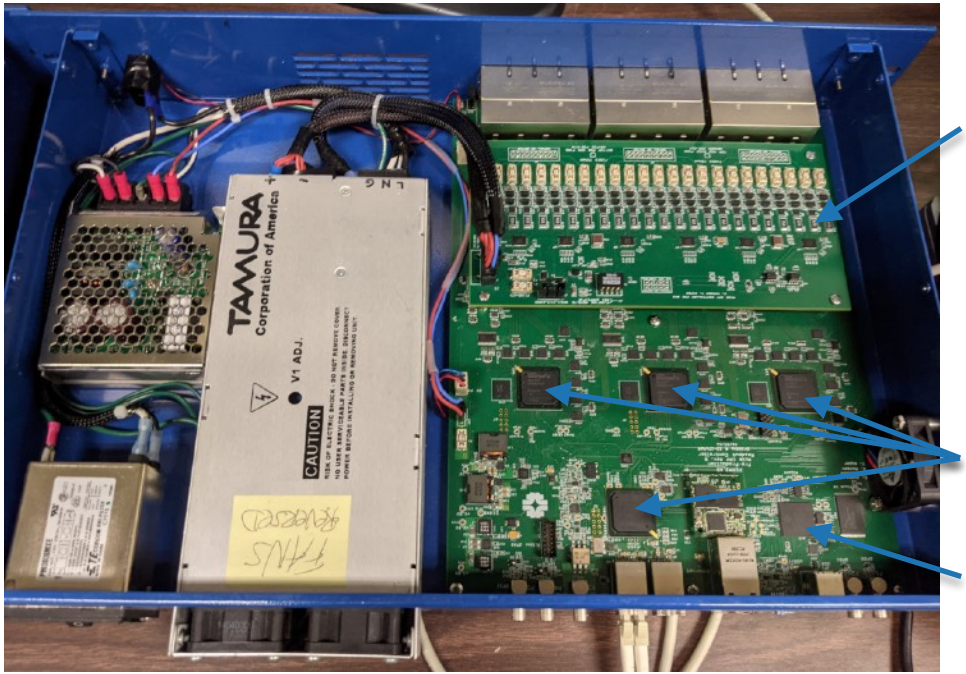


READOUT ELECTRONICS: READOUT CONTROLLER (ROC)

24 (3 x 8) FEBs



TDAQ (DTC): fiber communication (3.125 GBPS),
copper clock/timing (event-tag)

Overall Readout-System

Dynamic range:	2000
Max rate/SiPM:	1 MHz
Max rate FEB-ROC:	10 MB/s
Max rate ROC-TDC:	250 MB/s
Time resolution:	~ 2 ns
Magnetic field (FEB):	~ 0.1 T
Max dose (FEB):	10^{10} n/cm^2

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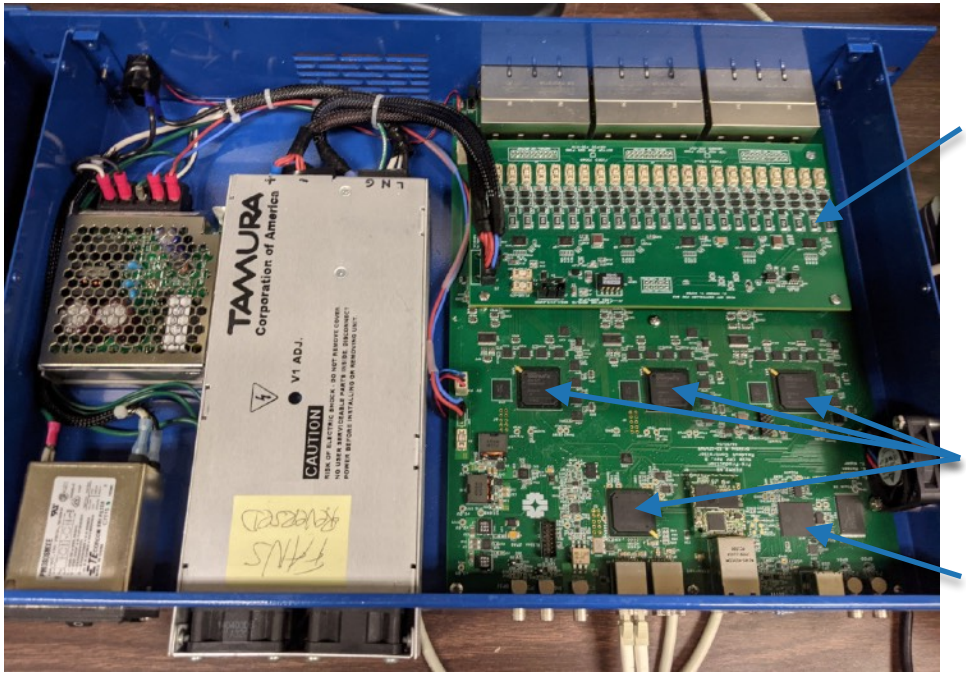

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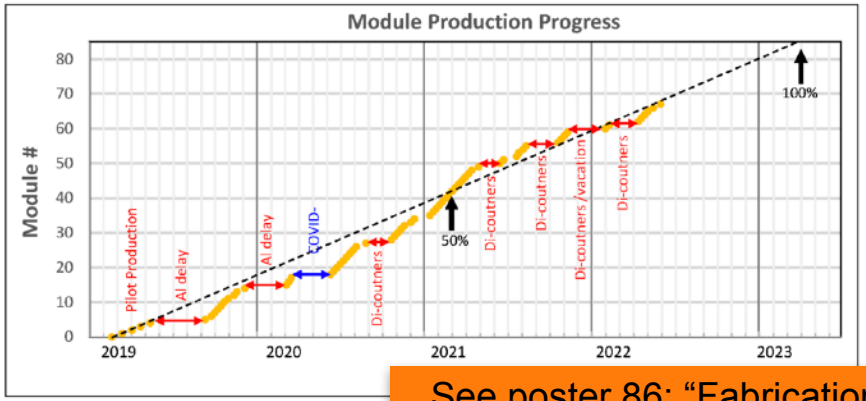
See poster 103: "A High Rate Readout System for a High-Efficiency Cosmic Ray Veto for the Mu2e Experiment", by Simon Corrodi

STATUS

CRV module production (68/83, 82%)



See poster 86: “Fabrication of a Cosmic Ray Veto System for the Mu2e Experiment”, by Craig Group

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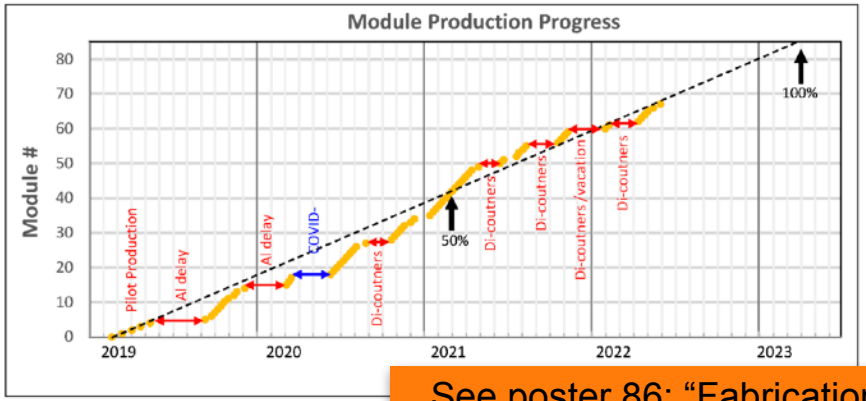

See poster 86: "Fabrication of a Cosmic Ray Veto System for the Mu2e Experiment", by Craig Group

CRV Electronics:

- Vertical Slice Test: completed, DAQ integration ongoing
- FEB: Spartan 6->7 migration
- ROC: ready for production

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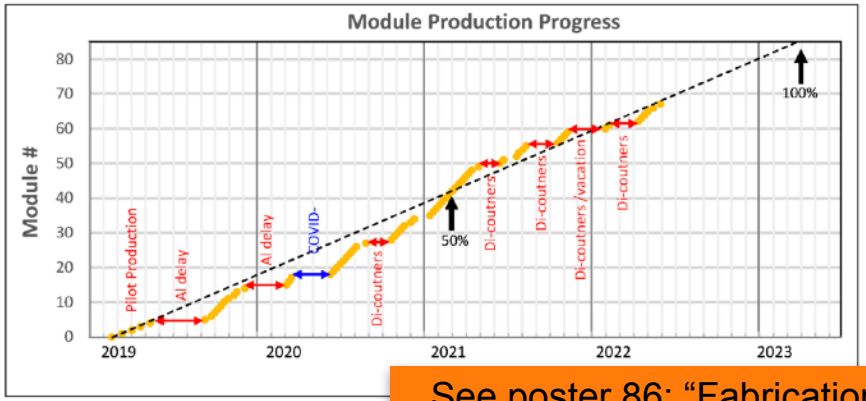

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CRV Electronics:

- Vertical Slice Test: completed, DAQ integration ongoing
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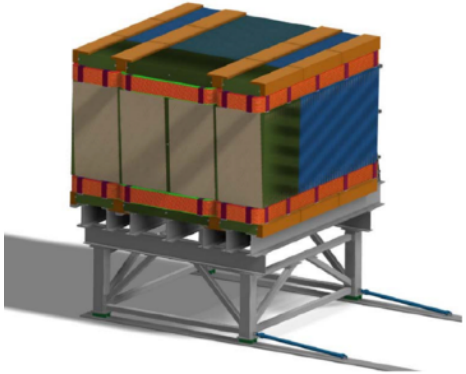
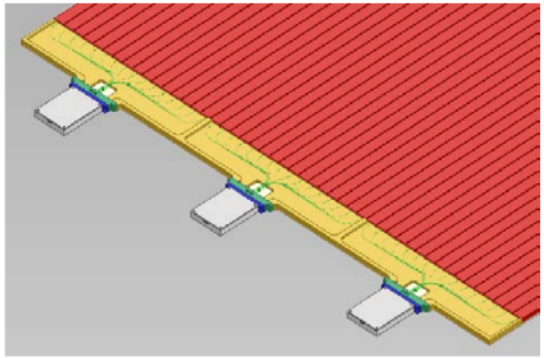
Mu2e Schedule

- detector commissioning through late 2024
- Run1 data taking 2025/2026 until LBNF/PIP-II shutdown
- Resume data collection in 2029 after long shutdown

SIMILAR SYSTEMS - OTHER EXPERIMENTS

Dune: Temporary Muon Spectrometer (TMS)





- PS Extrusions
  + wavelength shifting fibers
- very similar digitization (TI AFE)

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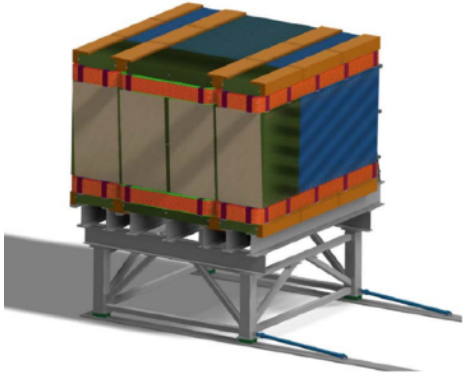

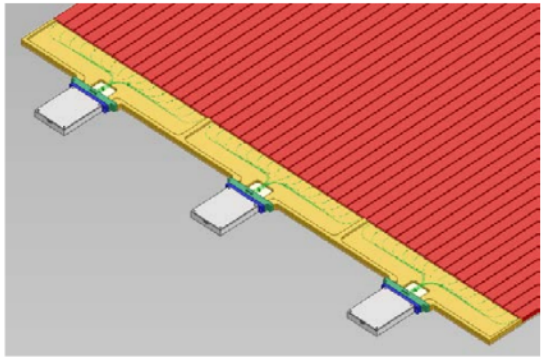

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- inspired by mu2e FEB design
=> SBND: plans to use DAPHNE and mu2e-ROC

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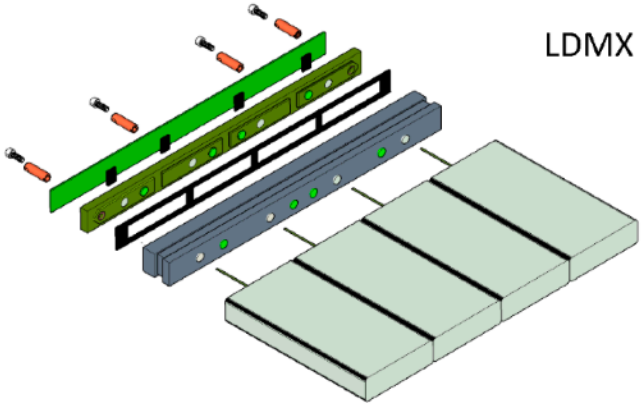
LDMX (Light Dark Matter eXperiment):

- quad counter, 1 fiber/50cm



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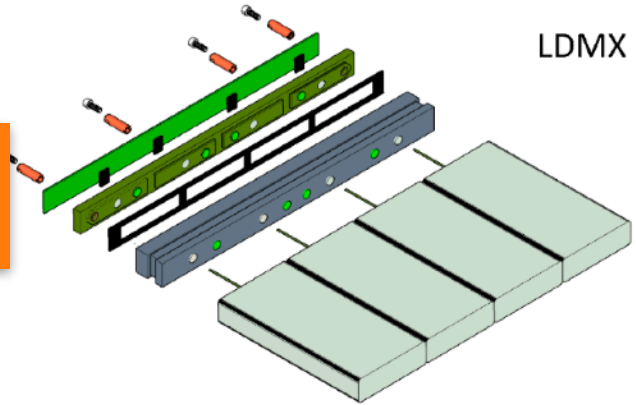
LDMX (Light Dark Matter eX

- quad counter, 1 fiber/50cm

See talk 88: “LDMX: The Light Dark Matter eXperiment", by Matt Solt



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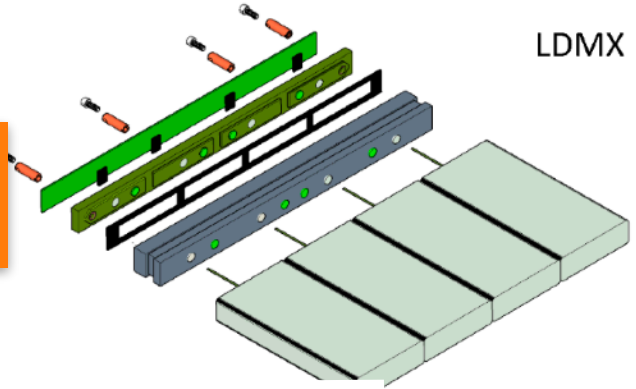
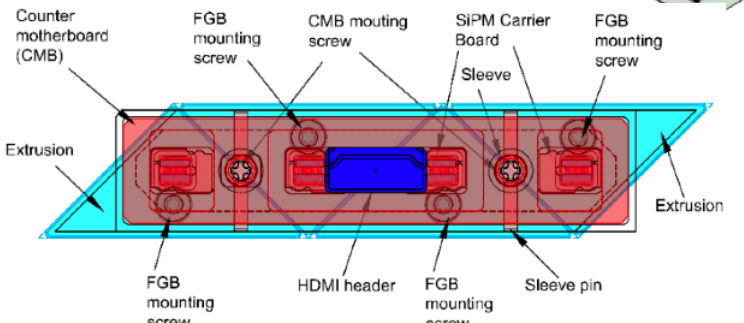


Exploring the Great Pyramid Experiment (EGP)

- triangular quad counter

- also: potentially Mu2e-II



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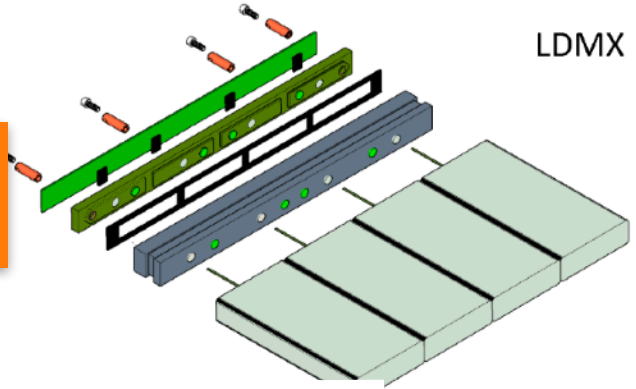

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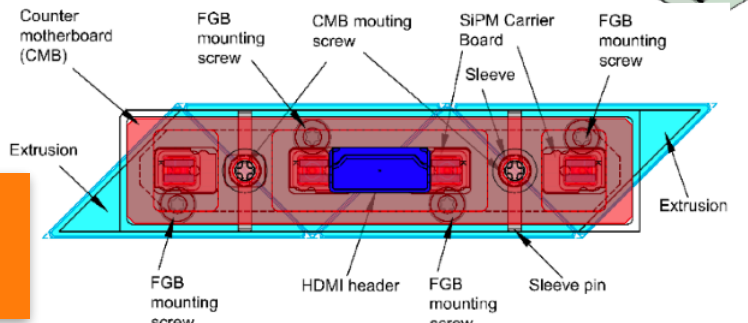
See talk 263: "Mu2e-II : next generation muon conversion experiment", by Yuri Oksuzian



SUMMARY

- The Mu2e CRV is a detector system based on scintillator counters with embedded wavelength-shifting fibers read out by SiPMs…

- …with an efficiency above 99.99% and low dead times.

- The detector is inexpensive and only uses modest resources to build

- A fast, inexpensive readout system with POE has been designed

- Flexible design: that is used and copied for multiple experiments

- On track to be completed (KPP) by 2024.