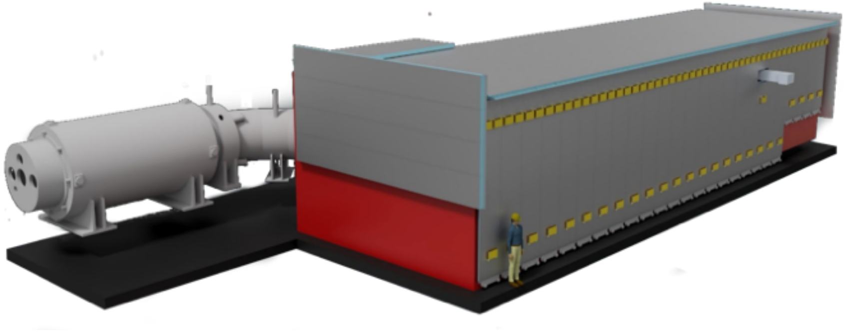
CRV AT MU2E II OVERVIEW

Slides heavily influenced by Yuri's past presentations,
Work from many contributors



SIMON CORRODI
Argonne National Laboratory

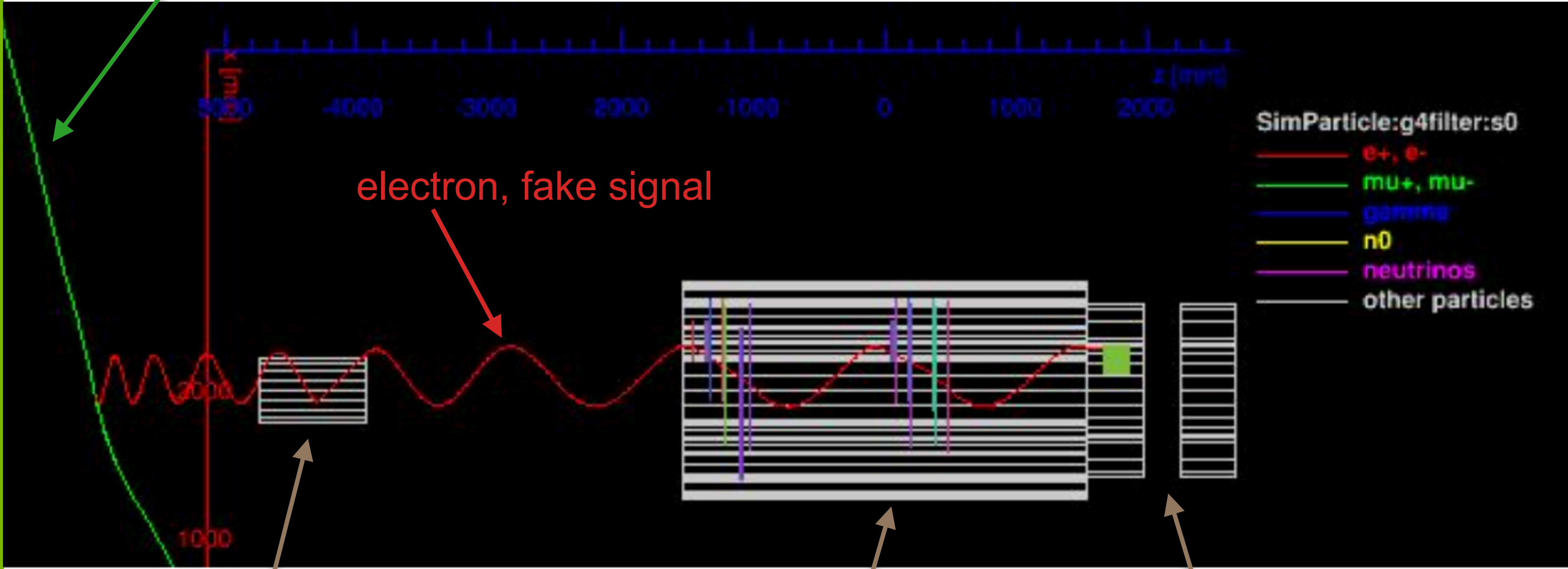
on behalf of the Mu2e II CRV group

Workshop on the Future Muon Program at Fermilab
March 26 to 29, 2023
Caltech, Pasadena

COSMIC RAY BACKGROUND: EXAMPLE

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

cosmic ray (muon)



electron, fake signal

stopping target

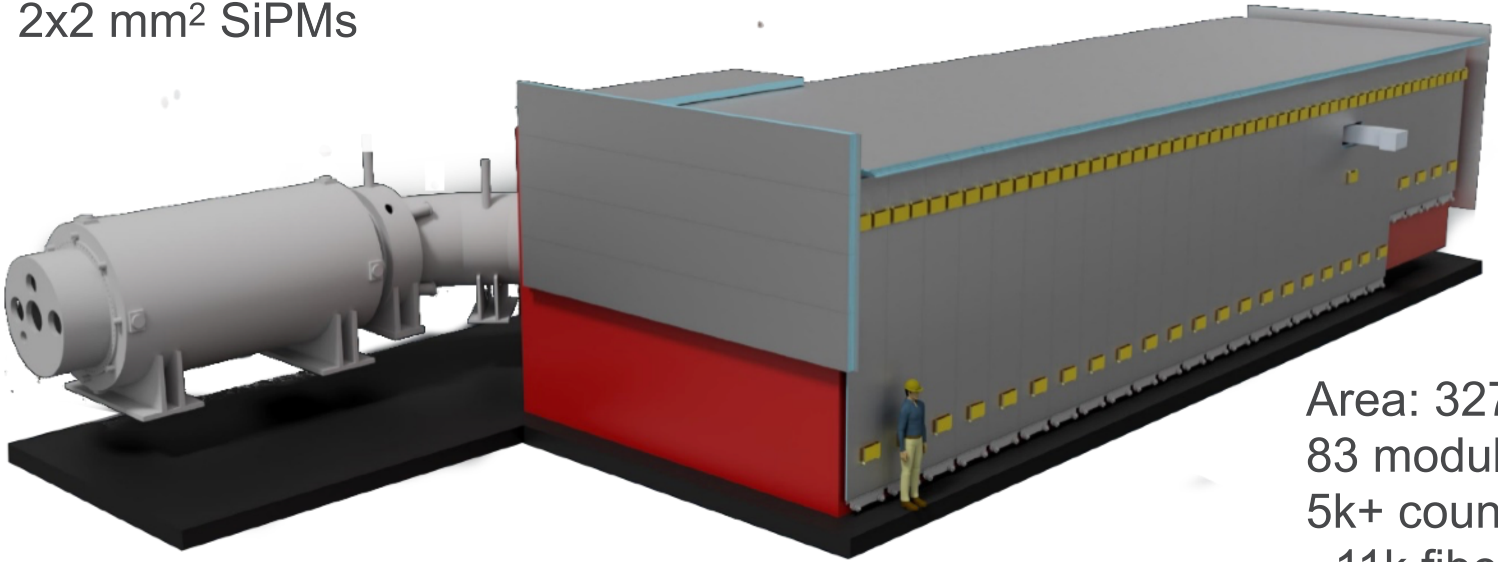
tracker

calorimeter

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

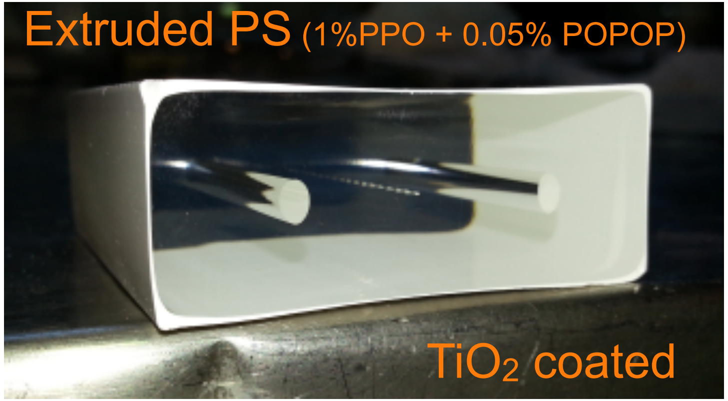
4-layer scintillating 5x2 cm^2 counters, read-out through wavelength-shifting fibers by 2x2 mm^2 SiPMs

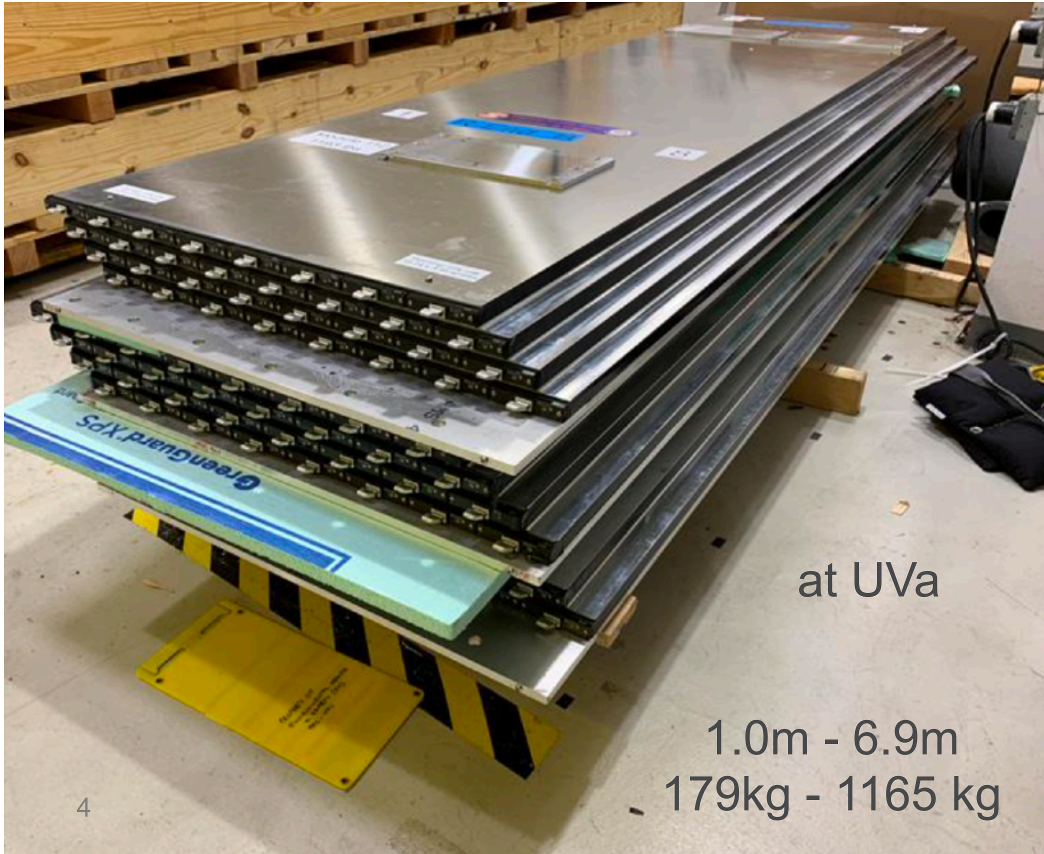


Area: 327 m^2
83 modules, 10 types
5k+ counters
~11k fibers
~19k SiPMs
~300 Front-end Boards

THE MU2E COSMIC RAY VETO (CRV)

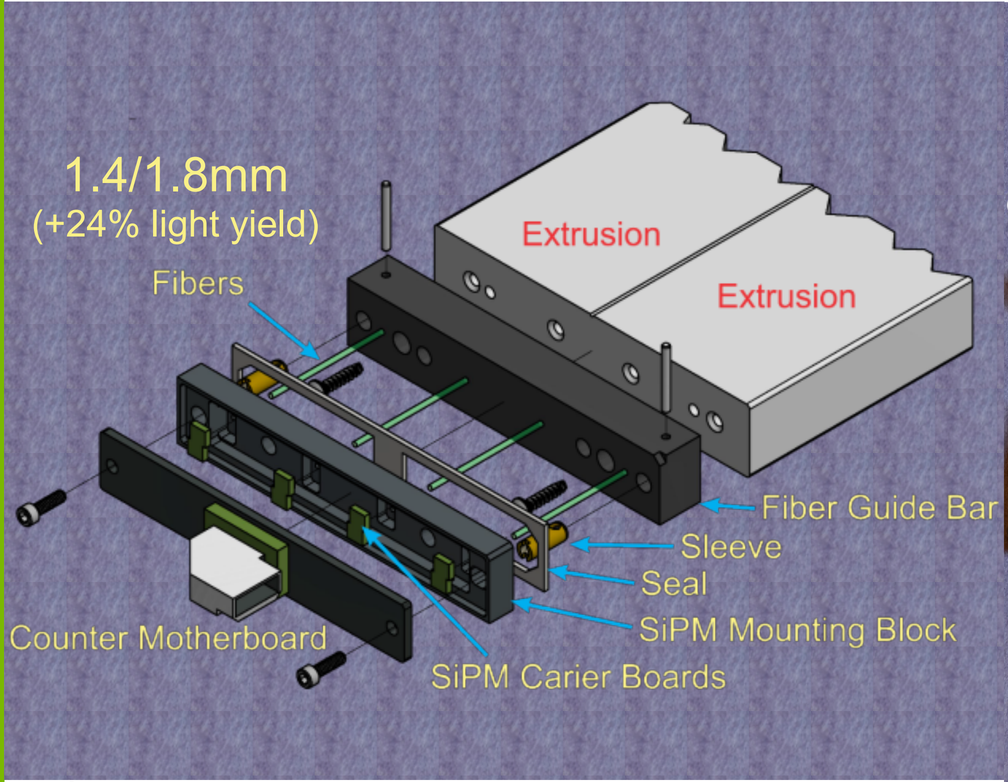
4-layer scintillating 5x2 cm² counters, read-out through wavelength-shifting fibers by 2x2 mm² SiPMs

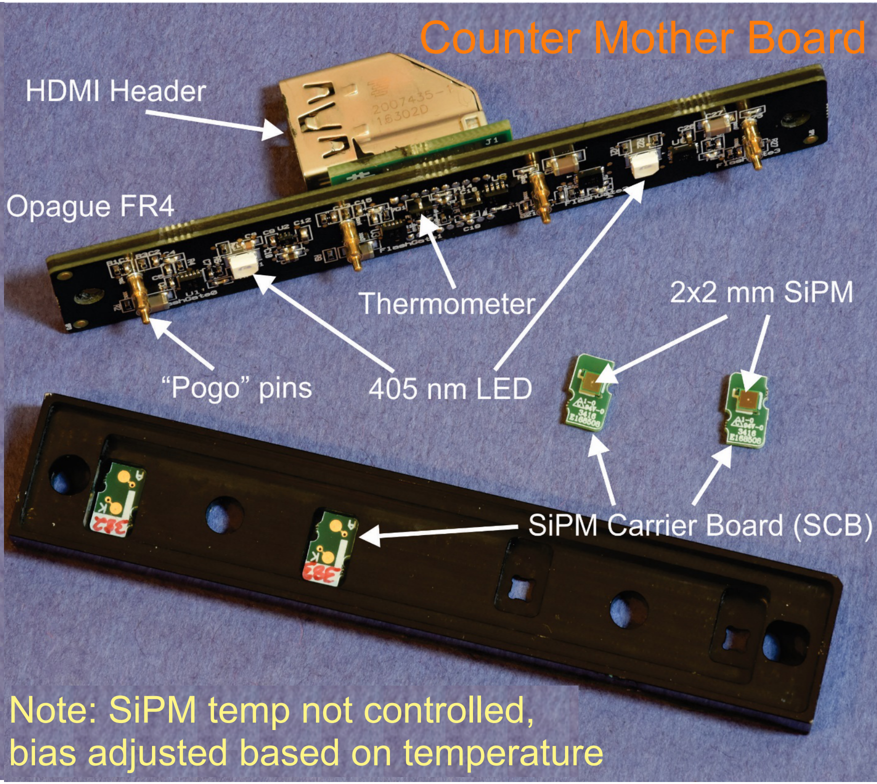




THE MU2E COSMIC RAY VETO (CRV)

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





CRV REQUIREMENT: A BACKGROUND FREE EXPERIMENT

Cosmic Rays: 1 background event per day (mu2e) ~3x higher in mu2e II

Mu2e:

- SES **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
    - -> needs ~few 1000x suppression
    - => needs efficiency of up to 99.99% in some areas
    - => low dead time (data rates)

Mu2e II challenges:

- live time for Mu2e II: 3x [5 years + duty cycle]
  -> suppression needs ~ 3x
- Higher beam intensity -> higher non-cosmic ray noise (>3x)
  -> higher dead time, data rates, radiation damage

CRV REQUIREMENT: A BACKGROUND FREE EXPERIMENT

Expected mu2e CRV performance in 2025. -> >2 background events in mu2e II

Results	Mu2e	Mu2e-II (5-year)
Backgrounds		
DIO	0.144	0.263
Cosmics	0.209	
RPC (in-time)	0.009	0.033
RPC (out-of-time)	0.016	< 0.0057
RMC	< 0.004	< 0.02
Antiprotons	0.040	0.000
Decays in flight	< 0.004	< 0.011
Beam electrons	0.0002	< 0.006
Total	0.41	0.47
N(muon stops)	6.7×10^{18}	5.5×10^{19}
SES	3.01×10^{-17}	3.25×10^{-18}
$R_{\mu e}$(discovery)	1.89×10^{-16}	2.34×10^{-17}
$R_{\mu e}$(90% CL)	6.01×10^{-17}	6.39×10^{-18}

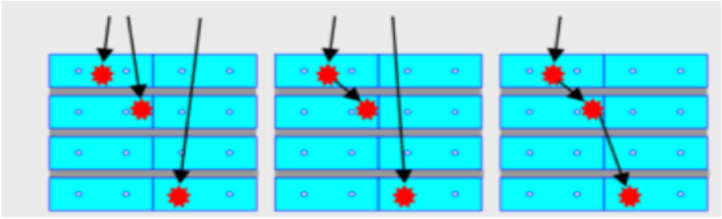
?

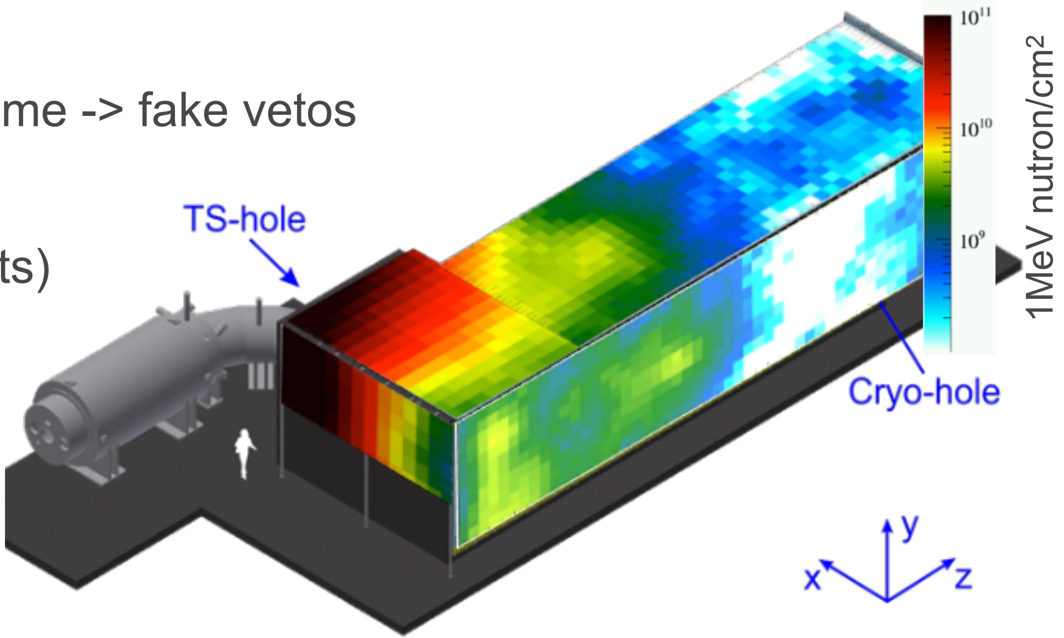
Mu2e II Snowmass: https://arxiv.org/pdf/2203.07569.pdf

CHALLENGES: DEAD TIME

"Fake CR events" introduce dead time -> fake vetos

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





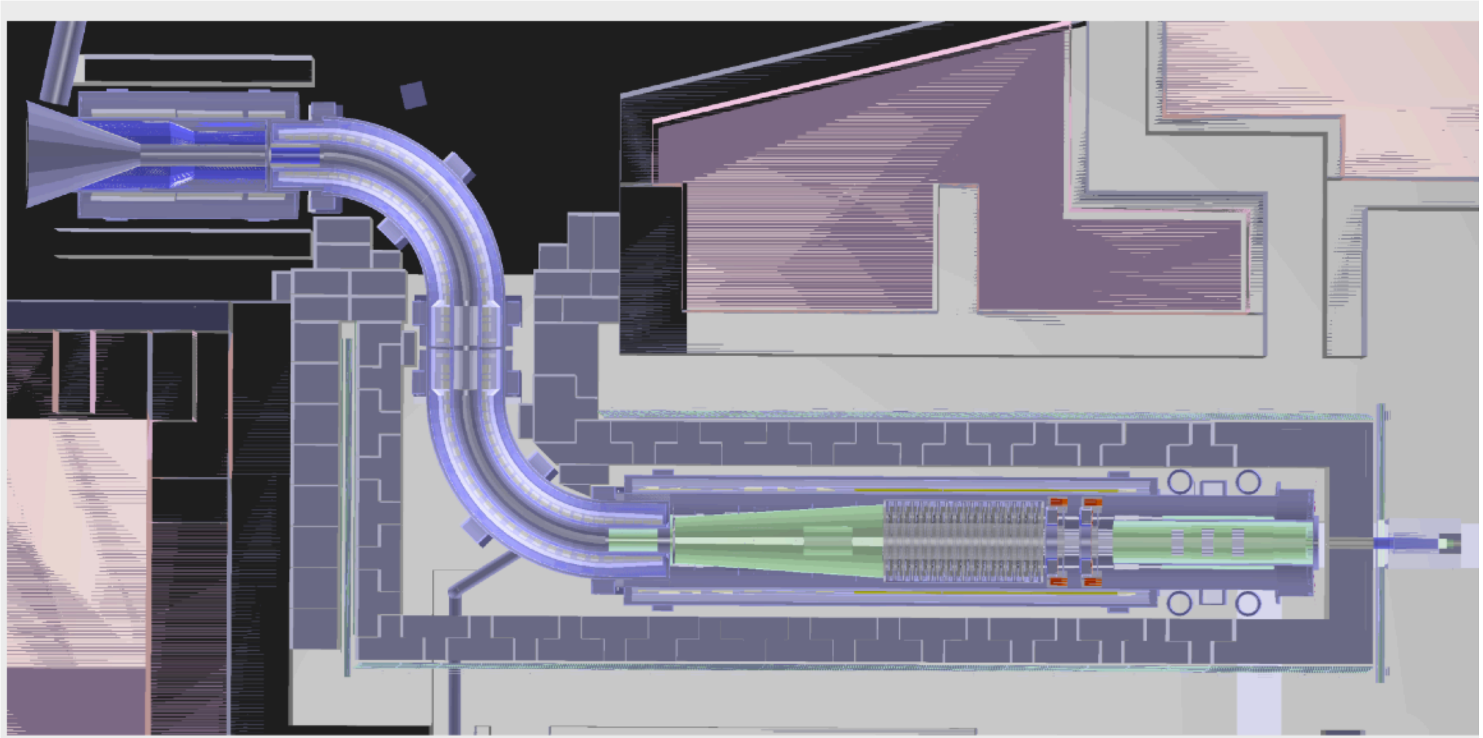
Source I: primary production beam
->Improved shielding Barite and boron loaded concrete

Current design:
50% dead time in Mu2e II

Source II: Stopped Muon produced secondaries
-> reducing the single channel rates
-> reducing false coincidence rates -> reducing dead time

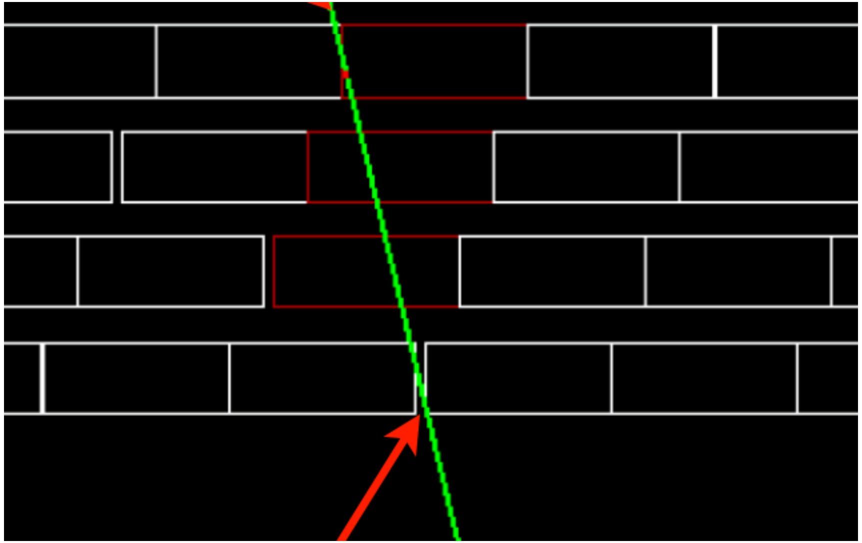
SOLUTIONS/ONGOING R&D: SHIELDING

Yuri simulated high-Z (Barite) enriched with 1% Boron carbide: capture neutrons
=> reduce dead time close to 0



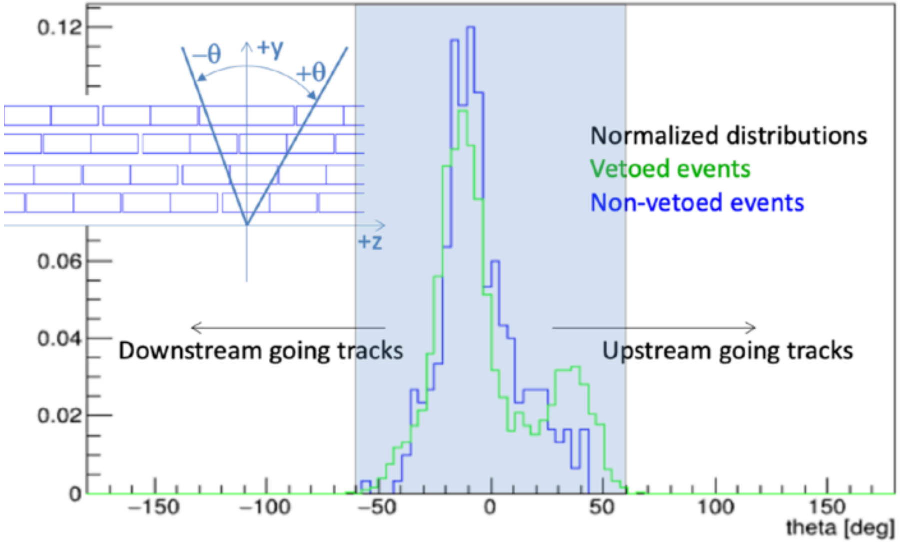
CHALLENGES: INEFFICIENCIES I: HOLES AND EDGE EFFECTS

Geometry/Edge Effects



already a staggered design
to minimize gaps

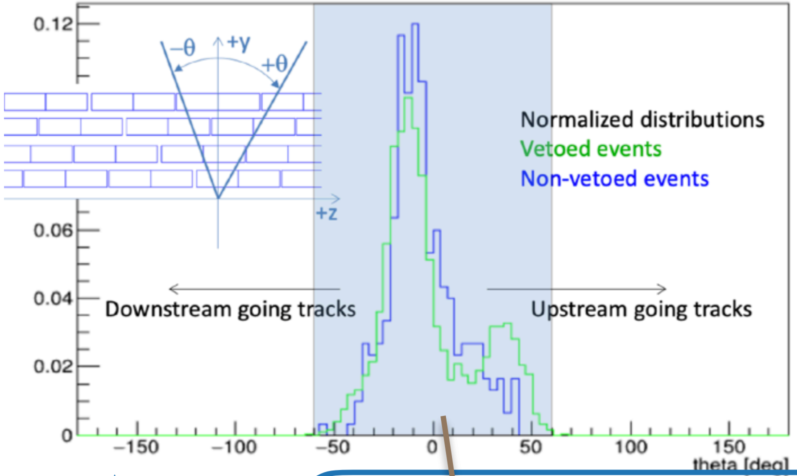
most of the CR come from "above"



CR moun background estimate from "gaps": 0.22 ± 0.15

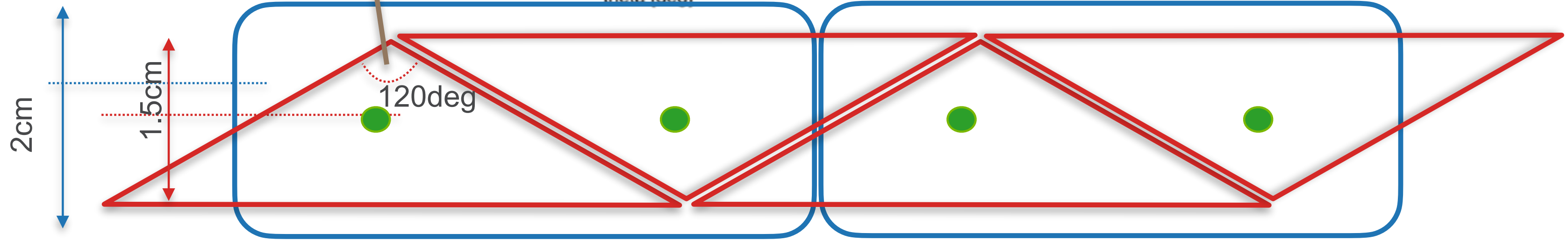
SOLUTIONS/ONGOING R&D: ALTERNATIVE CRY DESIGN

most of the CR come from “above”



- improved efficiency due to reduced gaps
- finer granularity, 3x resolution
-> lower rate per channel
- simplifies design of future modules

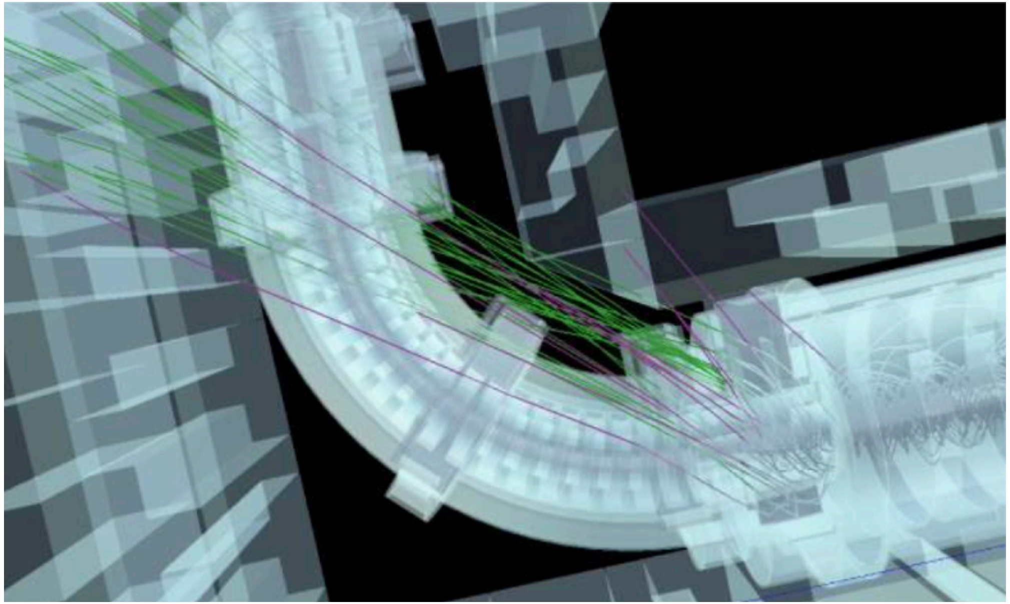
- ~45deg particles that “hit a gap" deposit more energy in the other layers

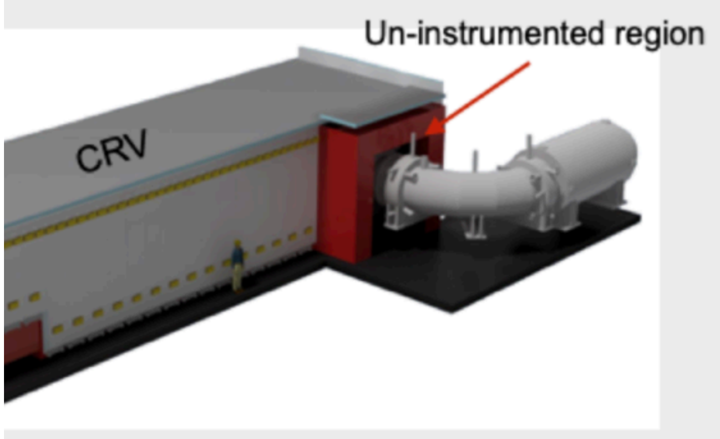


CR background estimate from “gaps”: 0.22 ± 0.15 -> below 0.1

CHALLENGES: INEFFICIENCIES II: UNINSTRUMENTED

Example: No shielding at the TS opening





Solutions/Ongoing R&D:
Ideas needed
-> new instrumentation?

=> mitigation with passive absorbers, pitch angle cuts

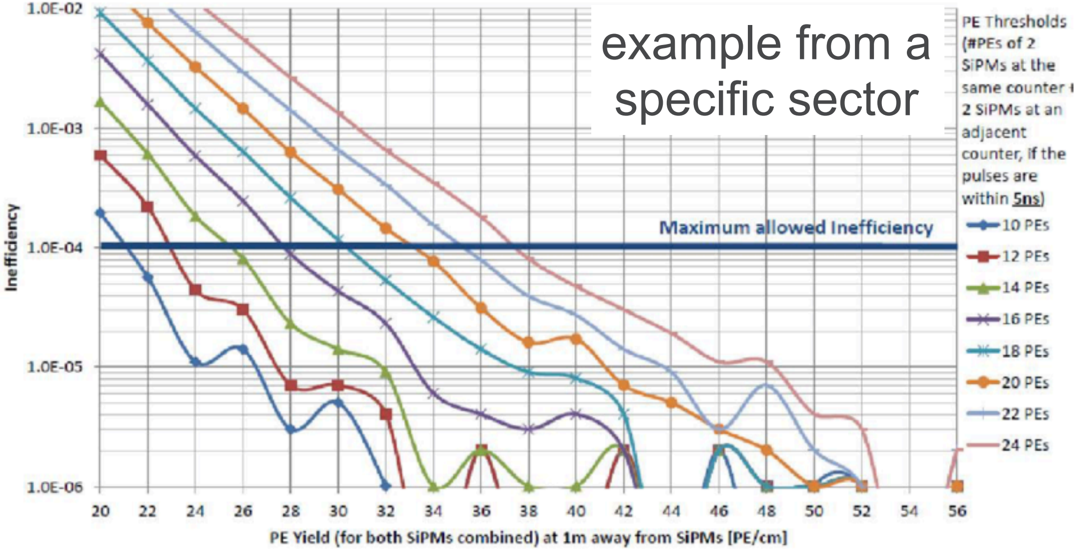
background estimate 0.08 ± 0.02 (dominant CR)

Ray Culbertson (docdb 8322): explored more shielding
-> a factor 2 reduction seems possible

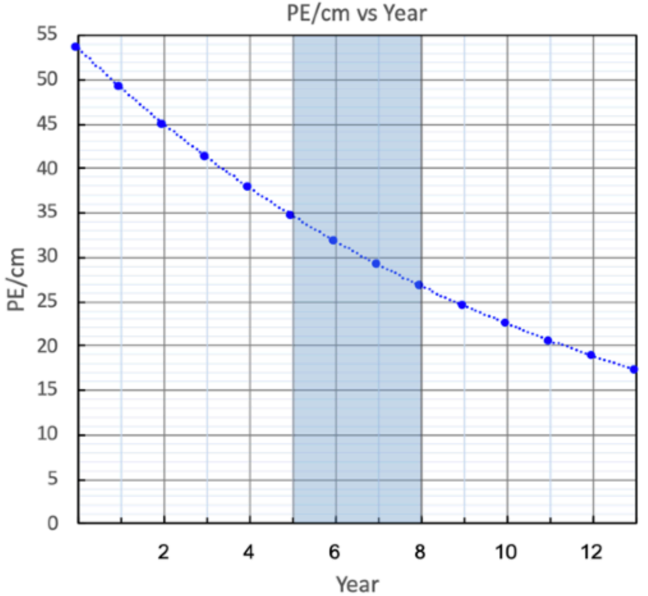
Argonne NATIONAL LABORATORY

CHALLENGES: INEFFICIENCIES III: LIGHT YIELD

efficiency scales with light (photo electron) yield



aging needs to be monitored and understood well



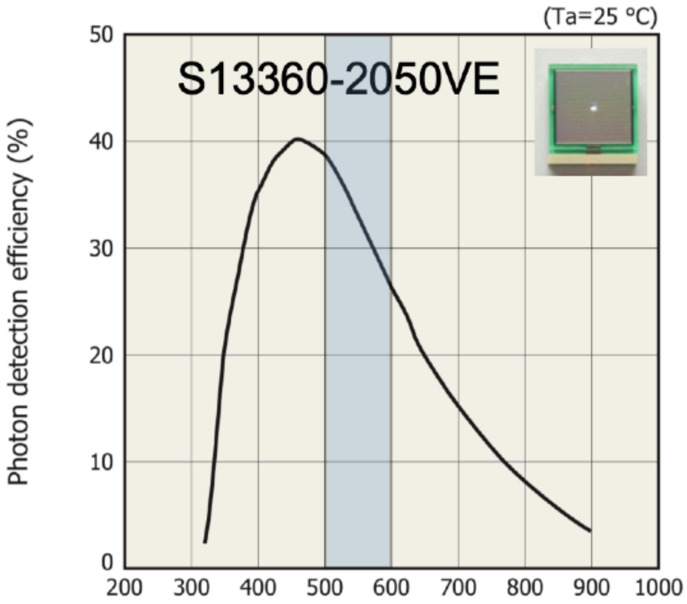
=> extensive efforts to monitor and understand aging

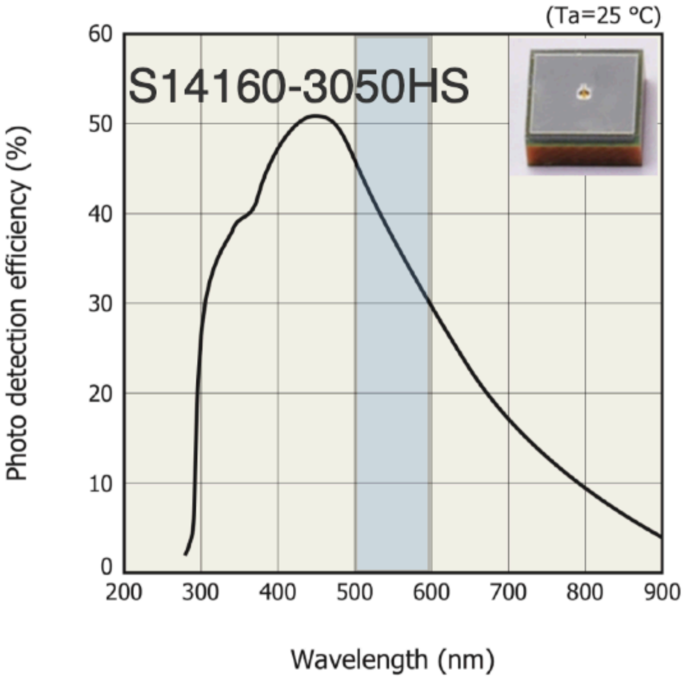
-> mu2e CRV can not be used for mu2e II

SOLUTIONS/ONGOING R&D: NEW SIPMS

Light yield increase of 24% by switching from 1.4 to 1.8 mm fibers

Mu2e CRV uses “old” SiPMS, new SiPMs have significant higher PDE

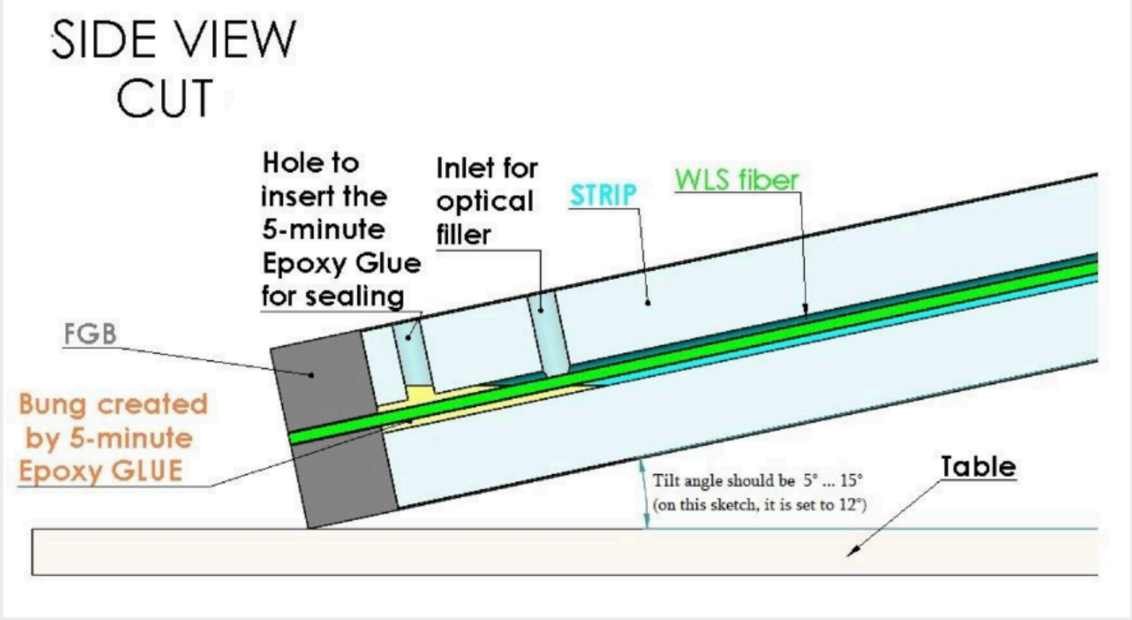




SOLUTIONS/ONGOING R&D: POTTING FIBERS

Light collection: an increase by 40% by potting the fibers channels with silicon resin

Disadvantage: leaking resin might damage read-out



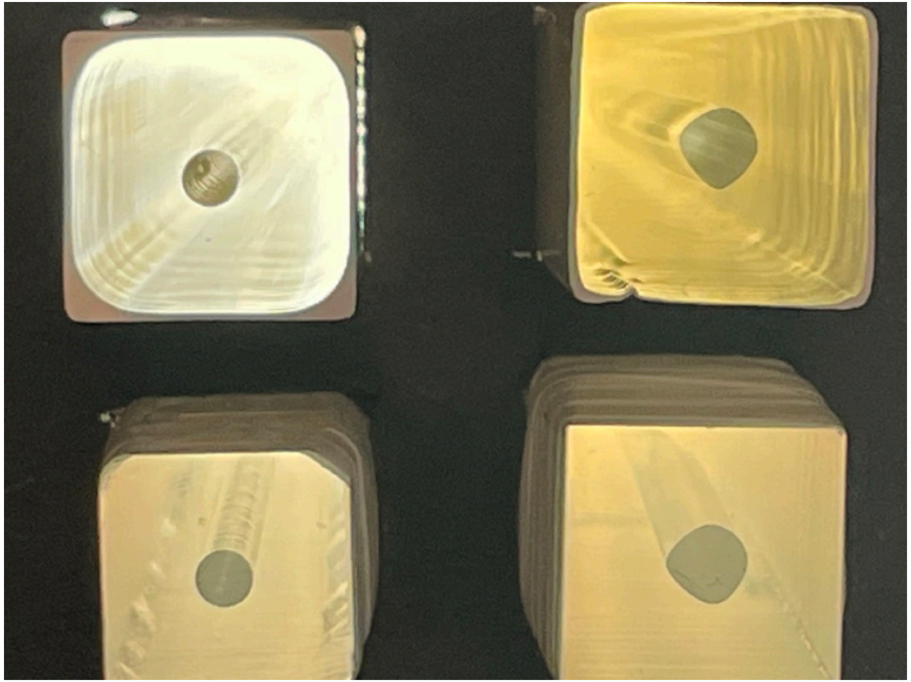
Dubna team:
Fill with epoxy to seal?

SOLUTIONS/ONGOING R&D: POTTING FIBERS

from Alan Bross

Light collection: optimized holes/channels for wavelength shifting fibers

A) Canadian company B) FNAL



- Potting fibers yield 40% to 60% light yield increase in B not in A
- A showed ~5% higher light yield than potted B

=> does well controlled holes/chan. give the same effect as potting?

CHALLENGES: DAQ DATA RATES

Event building
Mu2e
Challenge in mu2e to get 2x factor above nominal beam intensity:
-> sparsity channels
  2% highest rate channels -> 1/4
  5% highest rate channels -> 1/2
-> ADC value compression

Mu2e II:
event builder possibility already exhausted the highest rate channels will need detector side changes

Data transfer
Mu2e
The bottle neck is the 10MB/s FEB-ROC link

Use the off-spill times to transfer (requested) on-spill data, ~100 suppression expected

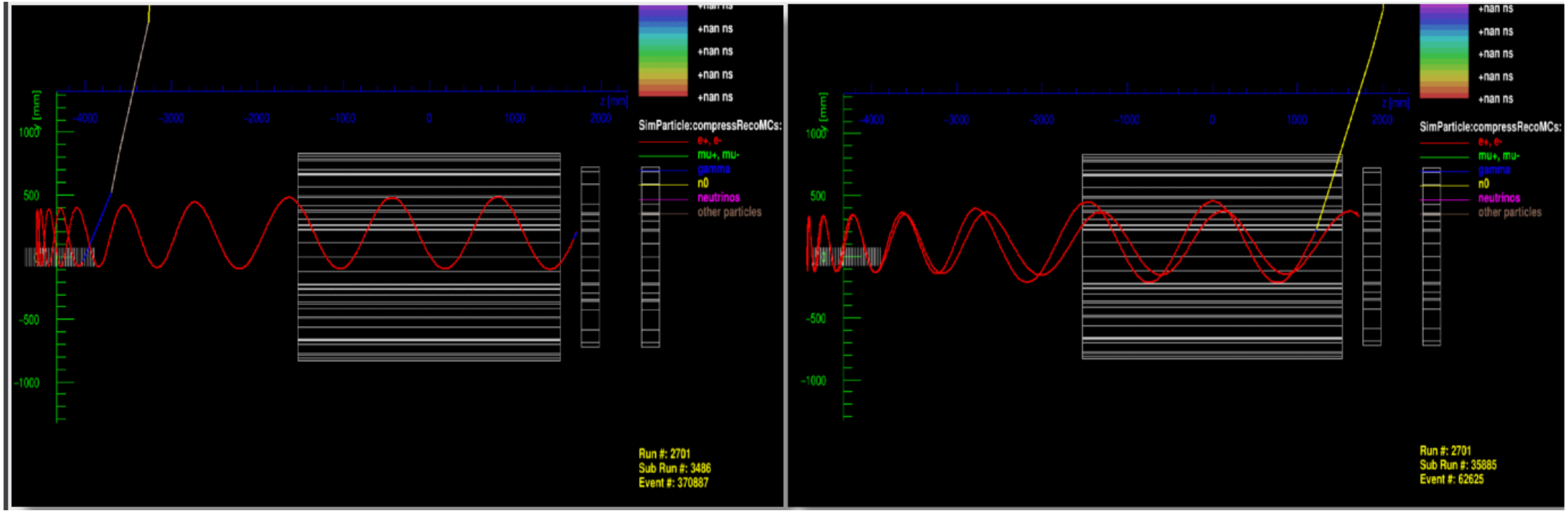
Mu2e II:
No off-spill time available to get data out
-> ~3x faster data transfer needed
  (or higher suppression from triggers)

CHALLENGES: CR BG FROM NEUTRONS

Not neglectable for mu2e II:
- estimated to be 0.007 BG events per 1M seconds
- Mu2e II (~25M seconds) -> 0.175 BG events

Solutions: shielding? (Active veto around the target?)

6' concrete shielding above target
-> 0.02±0.002



OTHER SOLUTIONS?

RPC in high rate areas?
Advantages:
- "arbitrary" readout segmentation
-> lower rate, lower dead time
- signal compatible with current CRV readout

Disadvantages:
- complicated: additional gas/HV system
- hard rate limits?

Active shielding around the target?
- very thin tracker? HV-MAPS style?
-

RPC: Resistive Plate Chambers

SUMMARY

Mu2e CRV can not be used

- detector degradation, high noise rate

CRV design with a finer granularity

- reduce high rates, dead time, while improving efficiency (triangular shaped)
- most critical regions can be enhanced with additional layers

Light output can be enhanced

- new SiPMs with higher PDE, potting thicker fibers

Additional Shielding will be needed

- reduce readout noise, suppress background from TS-opening and neutrons

Explore other technologies

- for hot regions

SUMMARY

CR backgrounds:

from “gaps”: below 0.1

uninstrumented 0.08 ± 0.02

neutrals 0.02 ± 0.002

total: 0.20 ± 0.08

+ optimized momentum cuts:
  => 0.17

Mu2e: 103.85 < p < 104.90 MeV/c
700 < t < 1697ns

Mu2e II: 104.05 < p < 104.90 MeV/c
690 < t < 1650ns

Results	Mu2e	Mu2e-II (5-year)
Backgrounds		
DIO	0.144	0.263
Cosmics	0.209	0.171
RPC (in-time)	0.009	0.033
RPC (out-of-time)	0.016	< 0.0057
RMC	< 0.004	< 0.02
Antiprotons	0.040	0.000
Decays in flight	< 0.004	< 0.011
Beam electrons	0.0002	< 0.006
Total	0.41	0.47
N(muon stops)	6.7×10^{18}	5.5×10^{19}
SES	3.01×10^{-17}	3.25×10^{-18}
$R_{\mu e}$(discovery)	1.89×10^{-16}	2.34×10^{-17}
$R_{\mu e}$(90% CL)	6.01×10^{-17}	6.39×10^{-18}

REQUIRED WORK

Shielding improve to minimize the increased dead time, rates and radiation dose

Improved design to keep the experiment background free
- seek funding to build a triangle prototype (aging, could be installed in mu2e)
- more simulation work needed

Explore Ideas on how to veto backgrounds events entering through the muon beam gap

Discussion
NEXT STEPS?
PLANS?
INVOLVED PEOPLE?

R&D program

Mu2e II Snowmass: https://arxiv.org/pdf/2203.07569.pdf

REQUIRED WORK

CRV prototype: to be installed during shutdown

Improved counters:
- R&D to improve the profile of counter extrusions
- R&D to improve coating reflectivity
- R&D to fill fiber holes -> potting
- aging studies

Shielding Prototypes:
- Procure high-Z shielding: few small blocks to be installed in mu2e
- optimize the shielding design

DAQ:
- demonstrate mu2e-II feasibility

…. …..

MORE MATERIAL

MU2E EXPECTED BACKGROUNDS

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Backgrounds		
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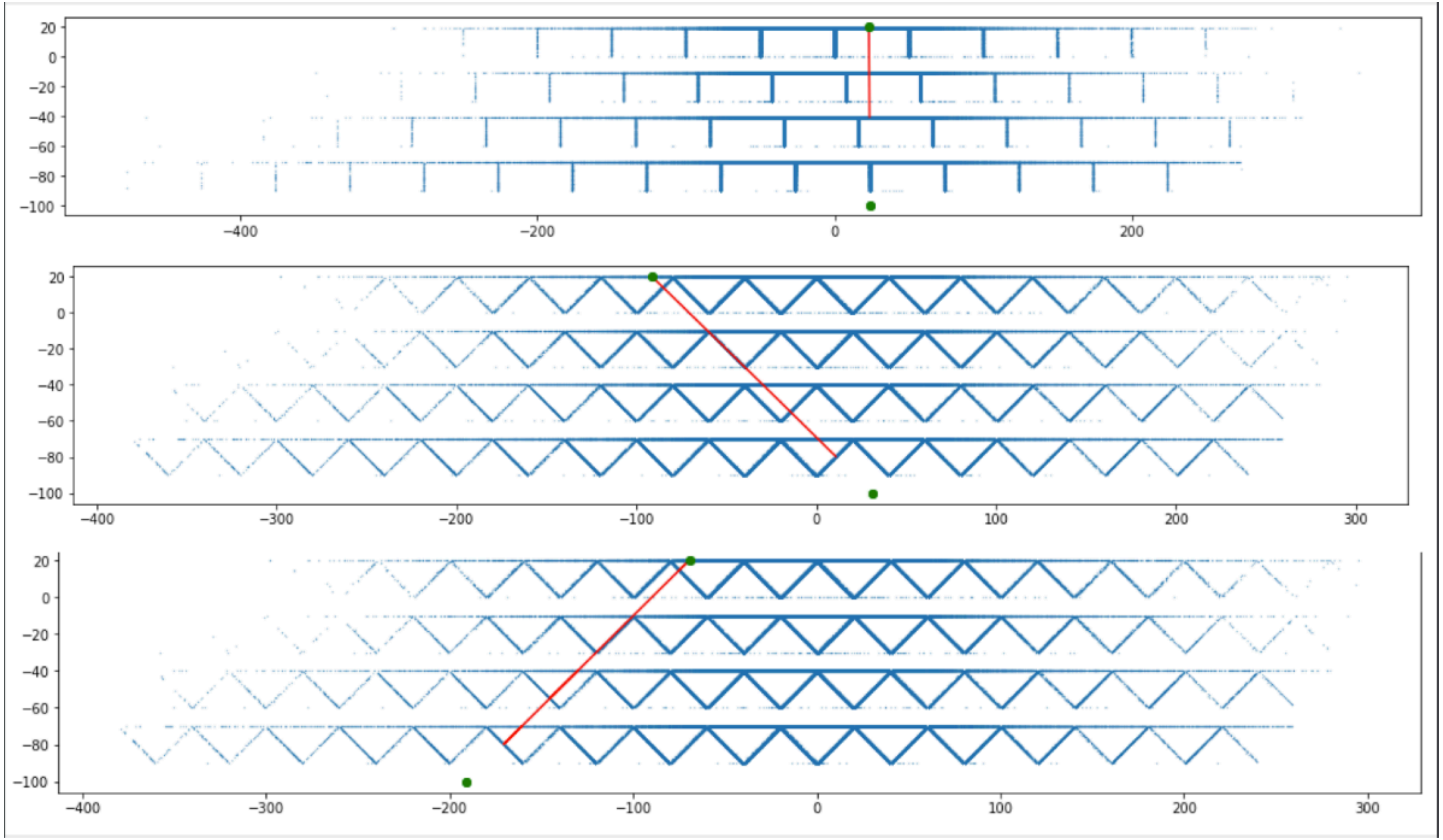
Improved tracker res., thinner ST
Improved veto efficiency

Beam below $\bar{p}$ threshold

MU2E EXPECTED BACKGROUNDS



READOUT ELECTRONICS: FRONT END BOARD (FEB)

64 (4 x 16) channels

HDMI connecting to the CMB

80 MSPS Digitization
TI AFE5807

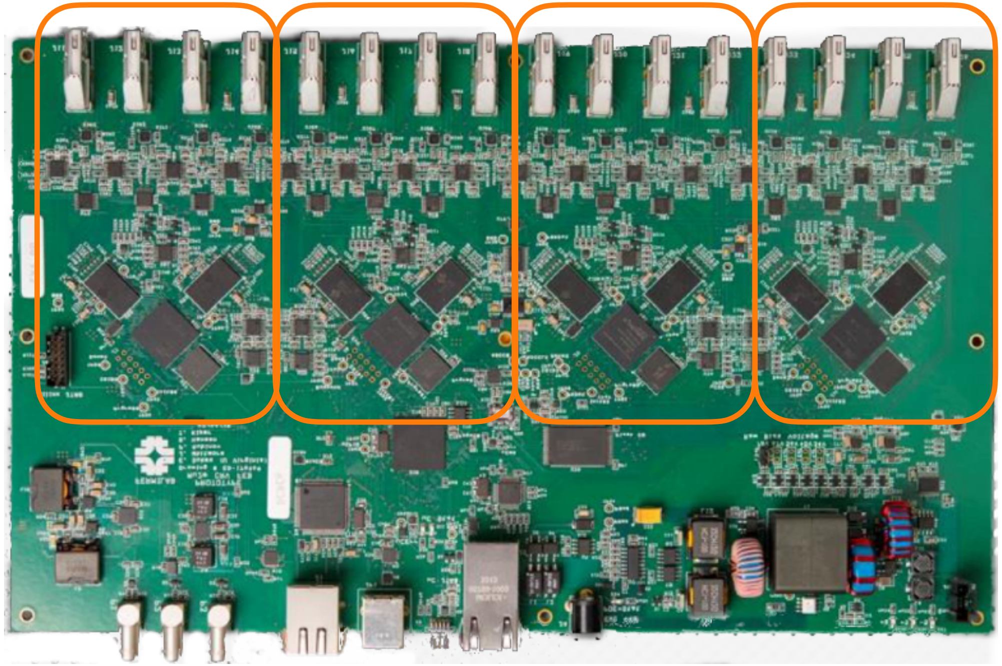
FPGA & DDR
zero-suppressed/self-triggered,
paged (event window tag) memory

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,
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 x 4

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

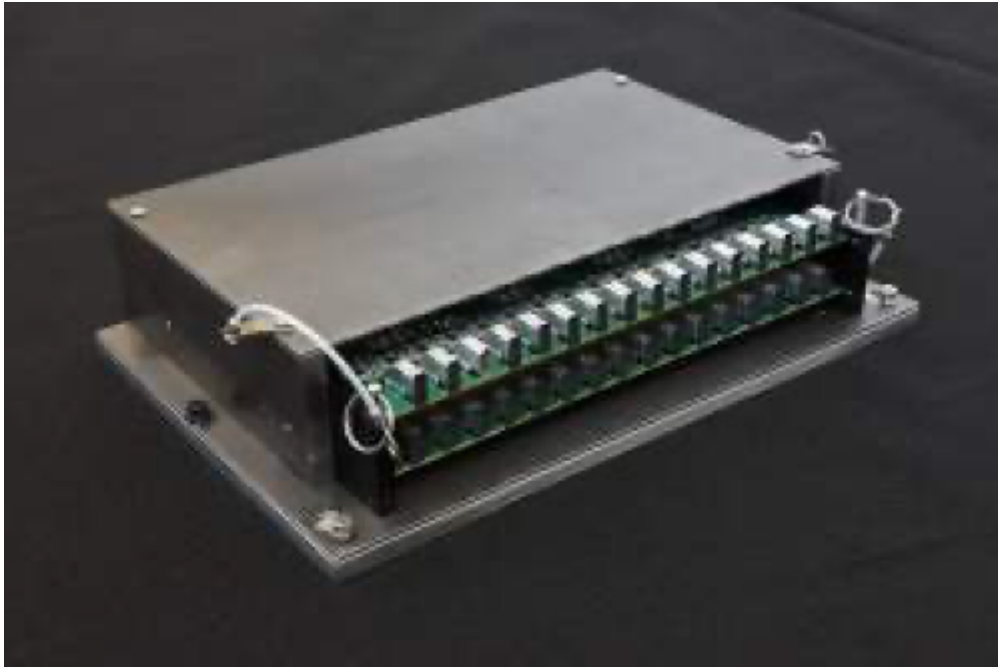
uC (ARM A8, 200MHz)
control and housekeeping

power over ethernet (POE):
12bit DAC to fine tune each SiPM

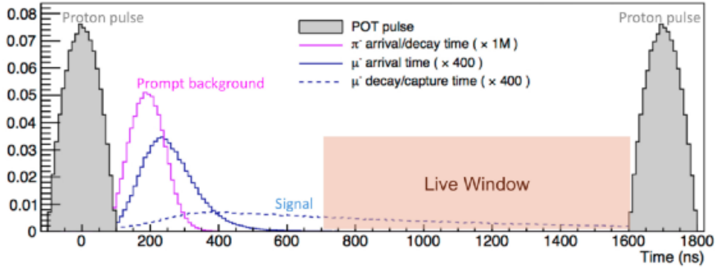
data, communication,
clock/event-tags, power

READOUT ELECTRONICS: FRONT END BOARD (FEB)

64 (4 x 16) channels

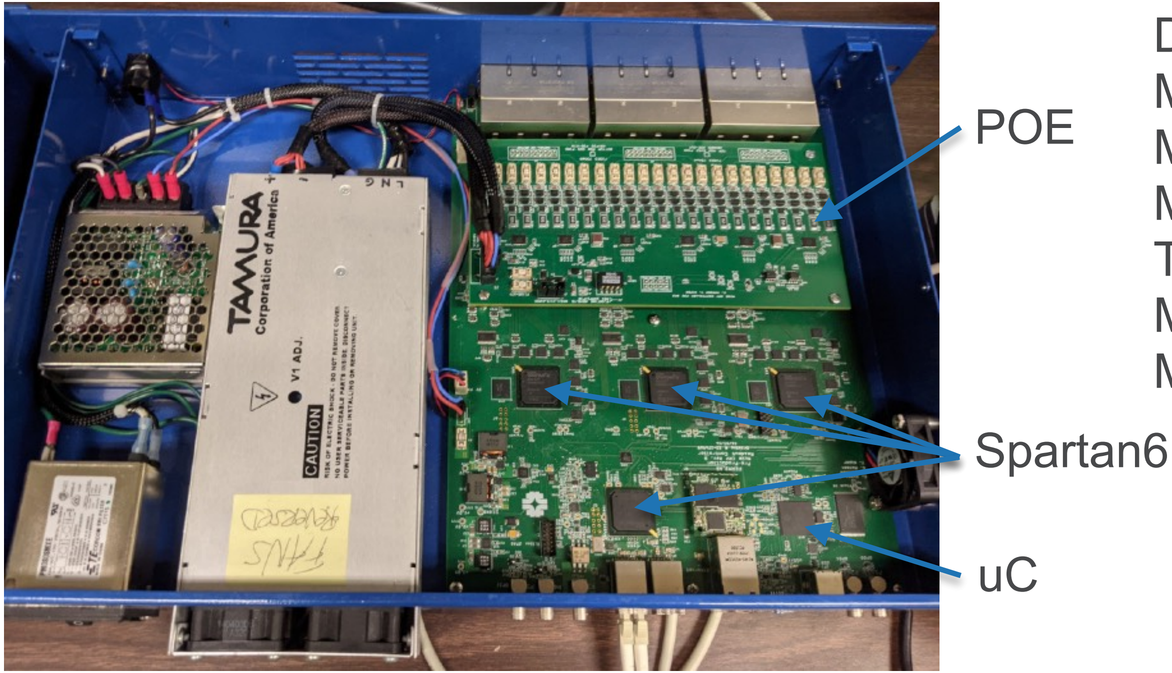


Unique features:
- (cheap) off-the-self components, no dedicated ASICs
- Flash-gate: Lower the SiPM bias voltage: ~2V (current + after pulsing suppression)



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