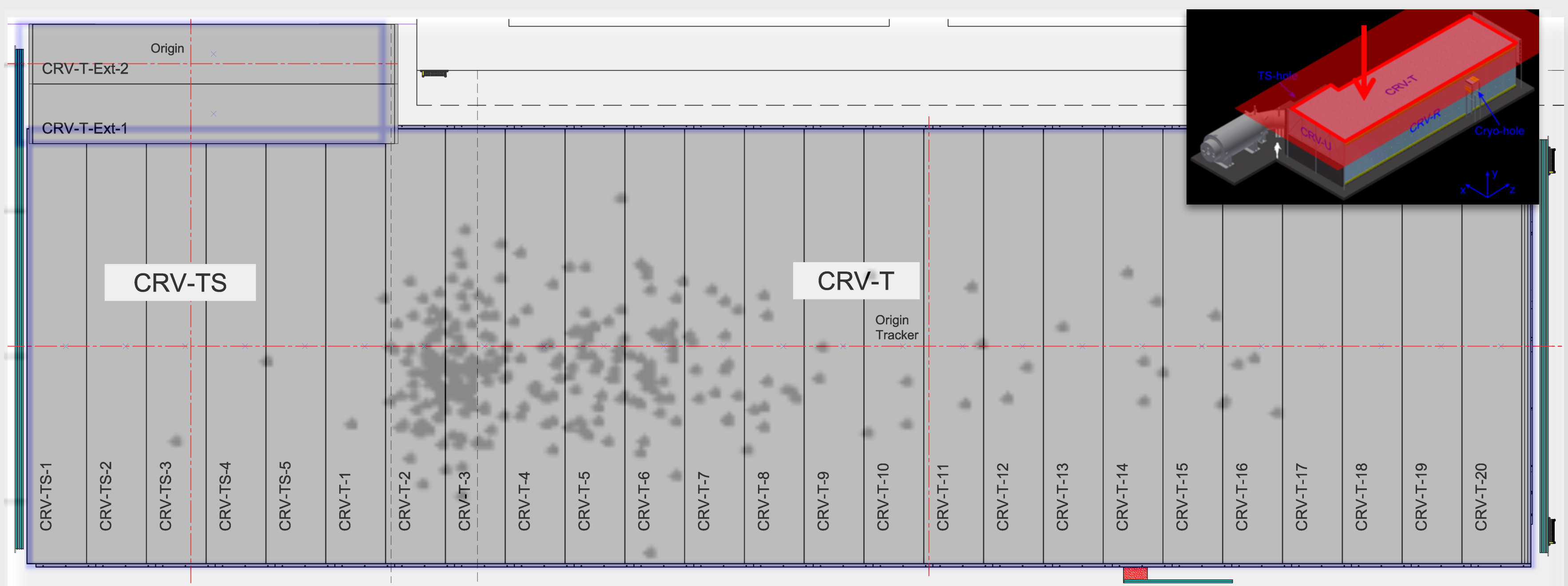
CRV at Mu2e-II

Members and workshop

- Conveners: Yuri Oksuzian, Craig Dukes
- Group members: current CRV team members
- We've had the workshop on 12/11/2020
  - Overview - Yuri (40 min)
  - Electronics - Lei (20 mins)
  - Mu3e tracker overview - Simon (20 min)
  - Discussion - all (30 min)

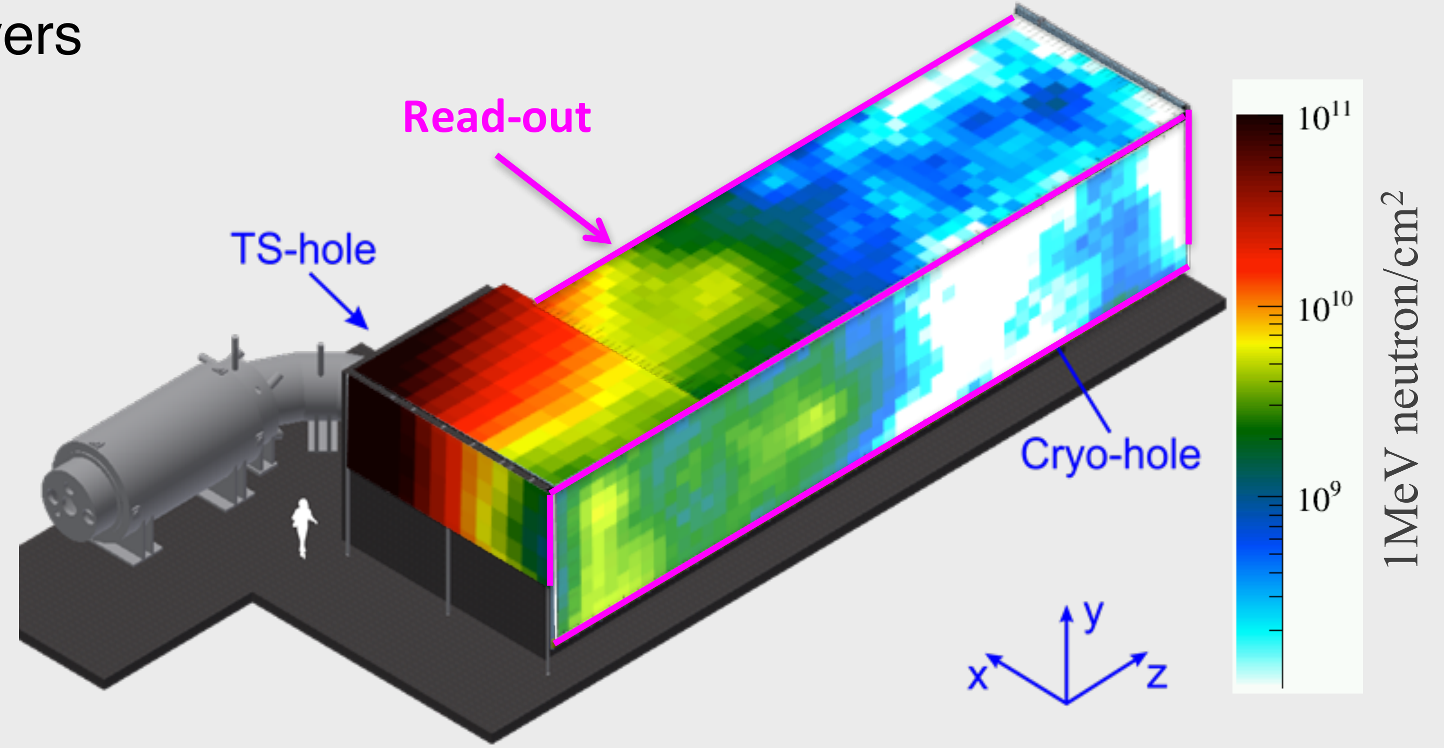
Enhancing CRV performance

- Expected live-time and therefore CR background will be ~3x higher for Mu2e-II
  - Need to enhance the CRV performance in the most critical regions
- The light yield degradation impacts the CRV performance
  - Large (all?) portion of CRV needs to be replaced for Mu2e-II
  - Rebuild the CRV and enhance the light yield in critical regions
- Gaps between di-counters and modules impact the CRV performance
  - Reduce gaps
  - Use different counter geometry
  - Extra layers



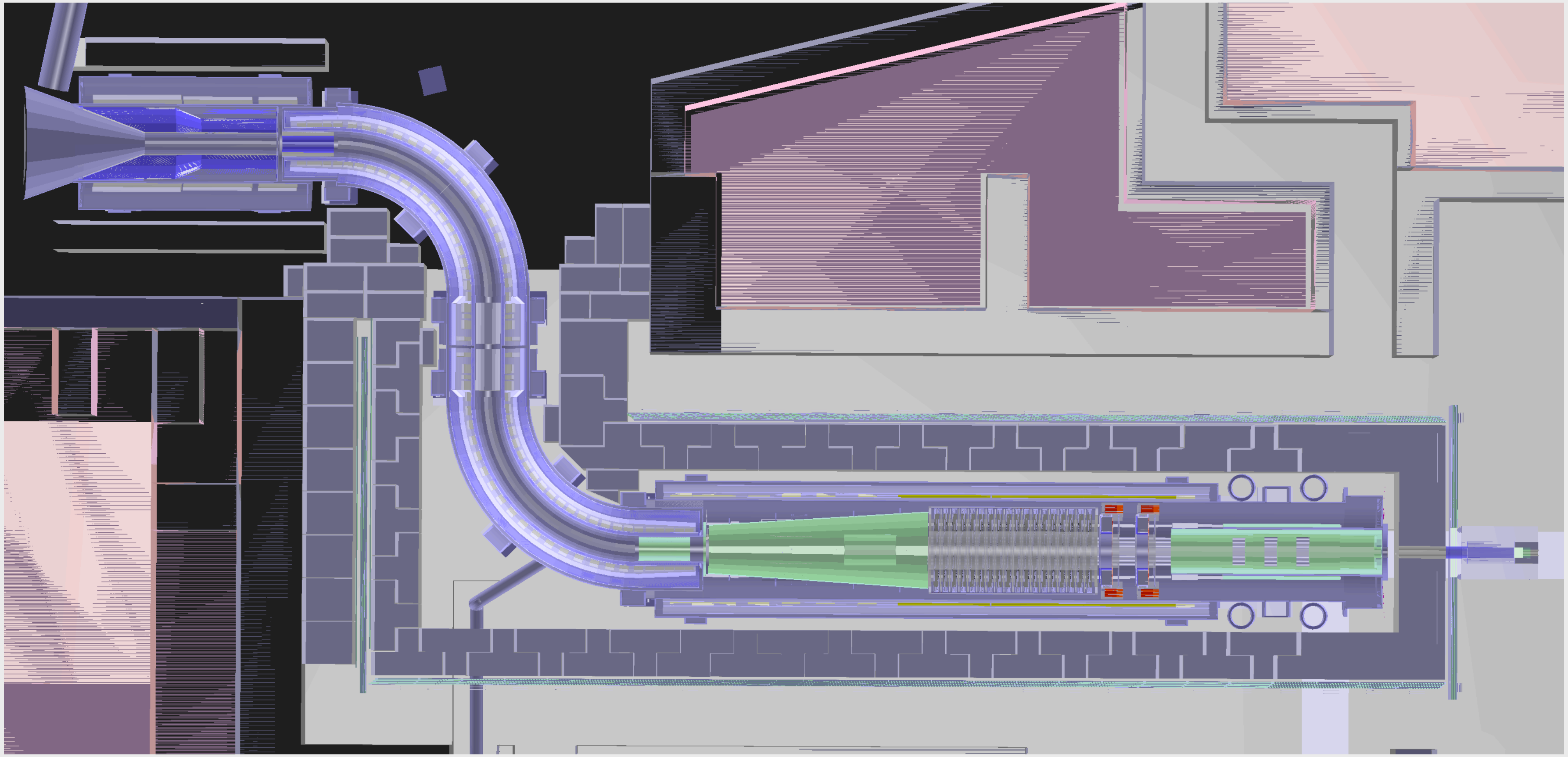
Cosmic Ray Veto

- Higher (x2-3) noise rates impose challenges: higher DAQ rates, rad damage to electronics and induced dead-time by CRV
  - Consider enhanced shielding: tungsten PS and high-Z boron doped concrete
    - However, for this exercise we'll use the same Mu2e-type PS geometry
  - Explore other detector technologies to withstand higher rates in 'hot' regions
  - Fine-granular layers



Shielding

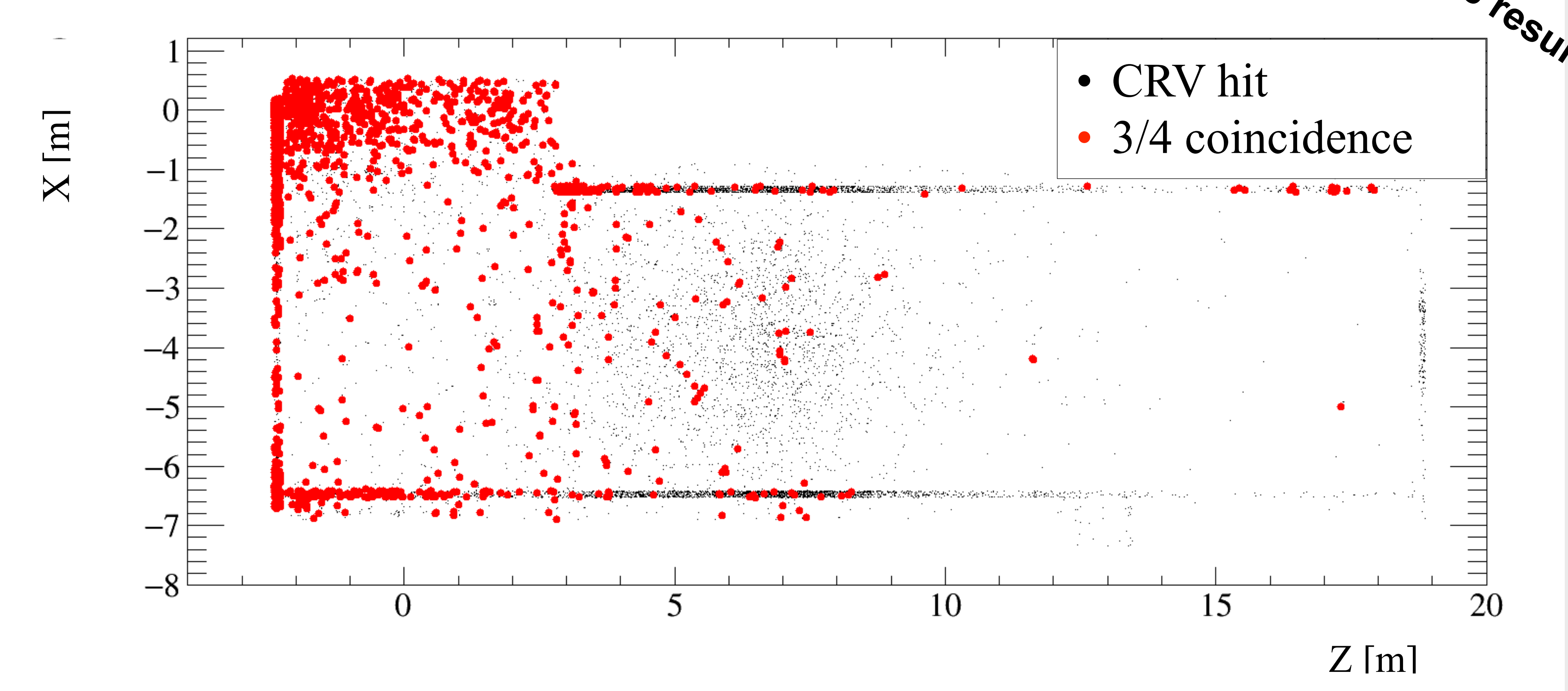
- I have implemented high-Z (Barite) enriched with 1% Boron carbide
- I have simulated stages 1 and 2
- Need to study CRV rates and dead-time



Dead-time at Mu2e II

- I simulated 800 MeV protons to estimate the rates and dead-time in CRV
  - The total simulated POT of 10E9 is only sufficient for ~10 ubunches
- The total dead-time > 50%
- Finer granularity detector and/or enhanced shielding are required to suppress the dead-time

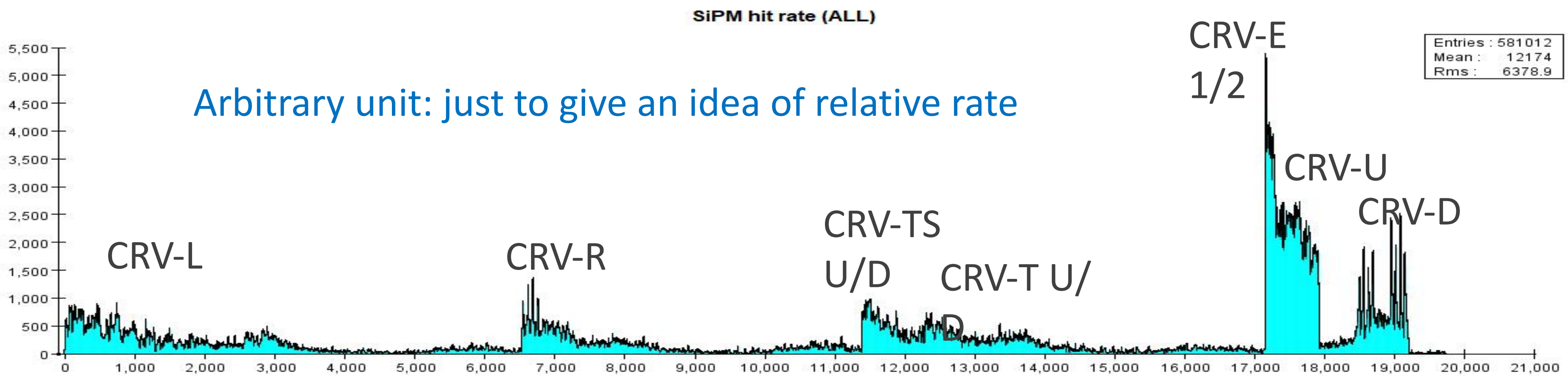
2018 results



Current CRV rate limitation

Lei Xia

- Readout system rate limitation: tight to loose
  - FPGA event builder in FEB: (*)
    - ~ 13/hits/μ-bunch if fully populate 16 input channels
    - ~ 16/hits/μ-bunch if populate half of 16 input channels
    - ~ 26/hits/μ-bunch if fully populate 16 input channels and use compression
  - FEB to ROC link: ~10MB/s (*)
  - ROC to DTC fiber: ~250MB/s
- For mu2e: FPGA event builder is the major bottleneck; try to manage ~ x2 headroom over nominal beam intensity (not final yet…)
  - Highest rate channels (<2%): 1/4 of input channels + ADC value compression
  - High rate channels (<5%): 1/2 of input channels + ADC value compression
  - Other channels: fully populated input channels (+ ADC value compression?)



Mu2e II: ~x3 instantaneous intensity

Lei Xia

- CRV readout system potential is pretty much explored/exhausted in mu2e
  - Readout limitations will stay ~ the same for mu2e II, unless entire system is re-designed
  - The very high rate channels (<2%): rely on detector change to bring down the rate
  - The high rate channels (~10%): can (further) reduce fraction of input channels AND combine with some detector change to deal with the rate
  - Other channels (~90%): will likely to be fine with increased rate

- Possible detector changes(?)
  - Better shielding
  - Finer segmentation
  - Different detector technology
  - …

Change of duty factor to 90%

Lei Xia

- NO 'off spill' time will be available for 'on-spill' data transmission
  - Effective time to deal with on-spill data: (1.7μs * 100) ~ 170μs
  - 170μs translates to ~46hits/FEB/μbunch for the busiest FEB
  - Compares to: FPGA event builder handles <13 hits/μbunch (without data compression) or < 26 hits/μbunch (with data compression) → translates to 52 – 104 hits/FEB/μbunch
  - Clearly, the data rate out of FEB will be the bottle neck under 90% duty cycle
    - Need a factor of ~x2
- Finding factor of ~2
  - ADC value compression, pre-fetch, etc. can bring incremental improvements, but won't be anywhere close to x2
  - Need to find the x2 somewhere else
    - Would 1/200 trigger faction feasible?
    - Pair high rate inputs with low rate inputs on the same FEB? (cross module?)
    - Any other ideas?
- What about 'off-spill' running? Are we going to have enough off-spill data with 90% duty factor?

RPC technology for CRV?

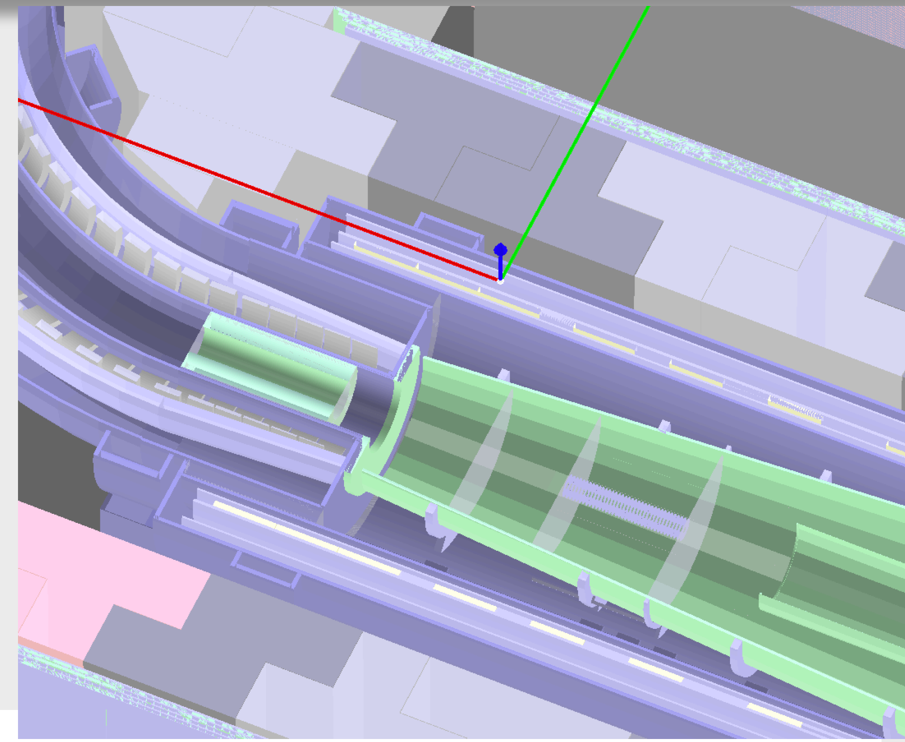
Lei Xia

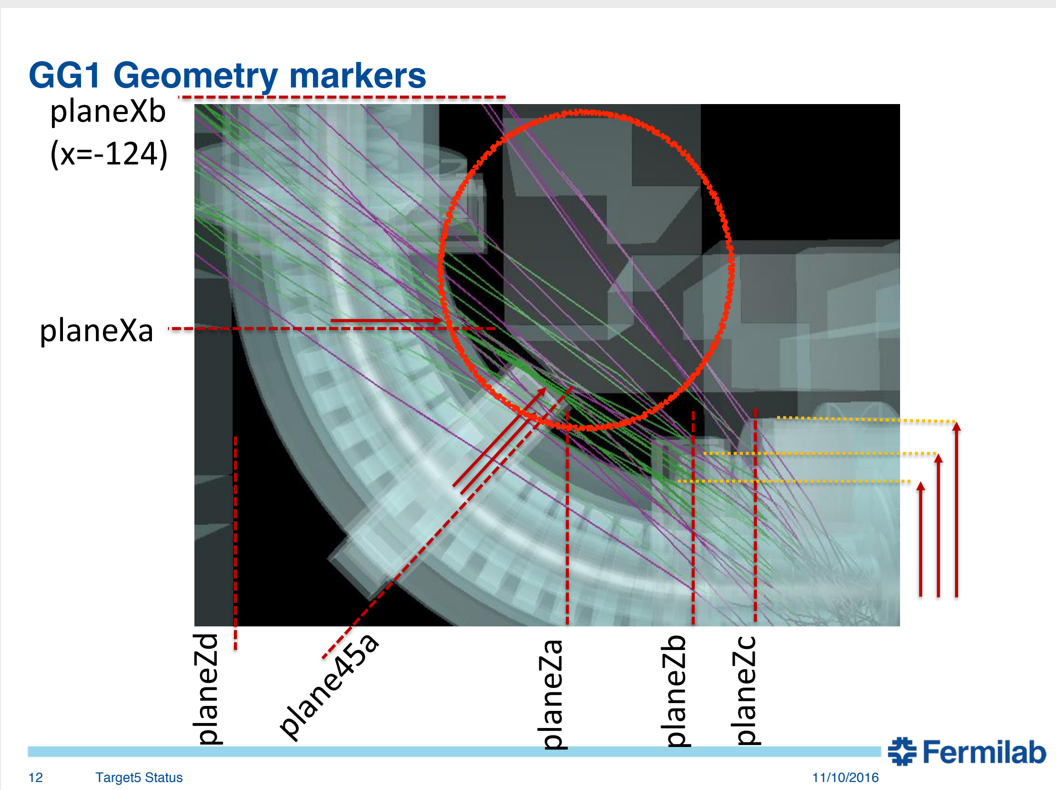
- Reason to consider RPC for high rate region
  - Easy to have arbitrary readout segmentation: smaller readout cell → lower readout rate → less accidental coincidence → less fake rate/dead time
  - Less sensitive to neutral particles (neutron and gamma): eliminate a large portion of background (G4 should give a reasonable estimate on detection efficiency)
  - Signal is compatible with current CRV readout
  - Single gap efficiency of ~90% can be easily achieved/maintained
    - Two gap/layer for higher efficiency and redundancy

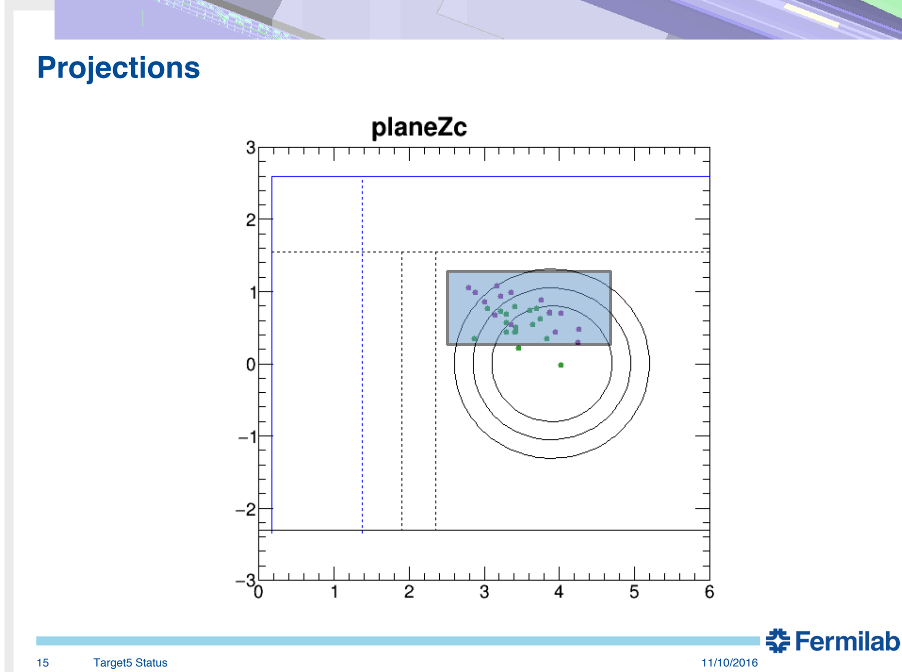
- Potential concerns
  - Additional gas/HV system
  - Some care needed in operation
  - Hard limit on signal rate is likely (better no unexpected…)
  - Noise rate related to electrode material choice, construction technique, and maybe also depends on operation history and integrated charge

Reducing irreducible: Muons

- CR background entering through TS hole is a significant (>0.2) background at Mu2e-II
- We currently reduce this background with passive absorbers and pitch angle cuts
- We can consider:
  - Shielding
  - Active veto around the stopping target

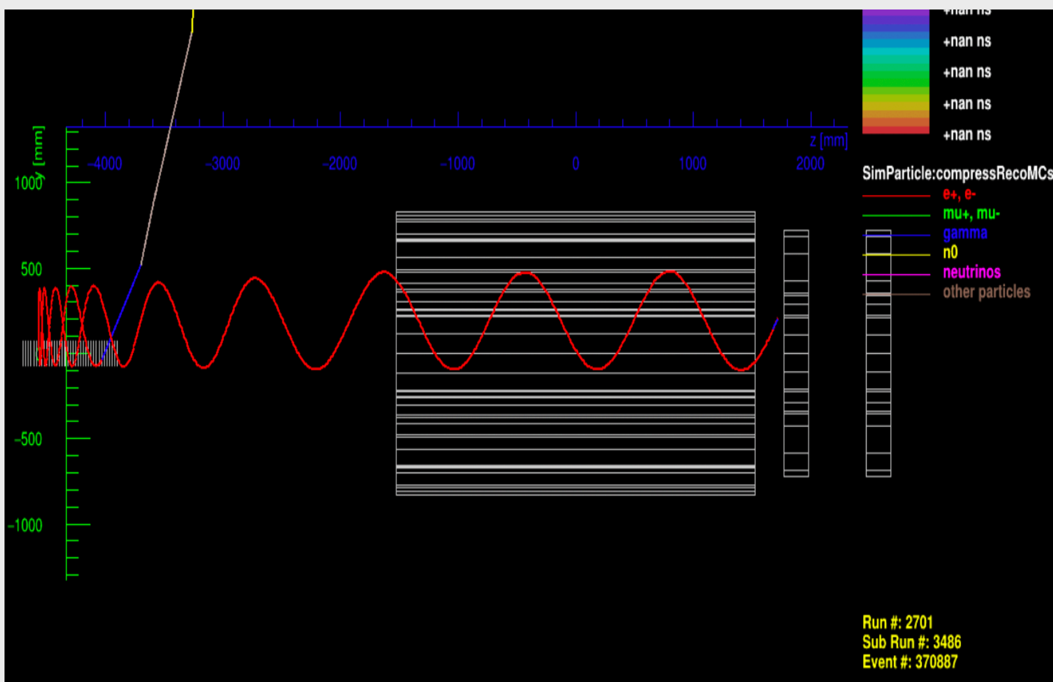


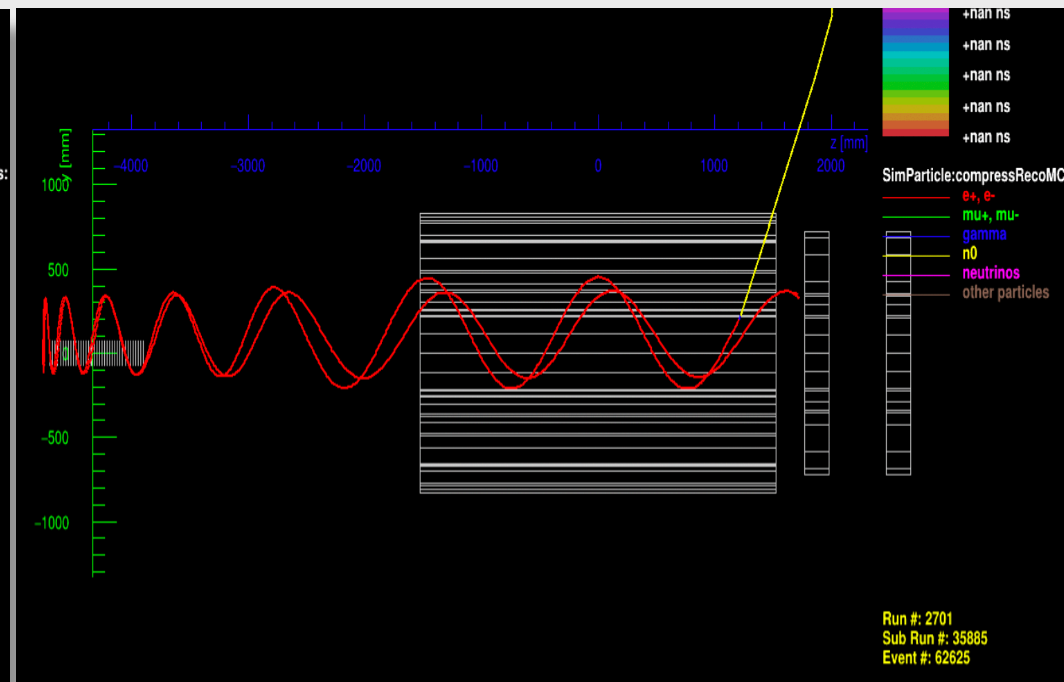




Reducing irreducible: Neutrals

- Cosmic ray background induced by neutrons is not going to be negligible as well
  - The latest estimate suggest 0.007 background events per 1M seconds
  - Mu2e-II will run for ~25M seconds, resulting in 0.175 background induced by neutrals
- We can potentially suppress this background with
  - Shielding
  - Active veto



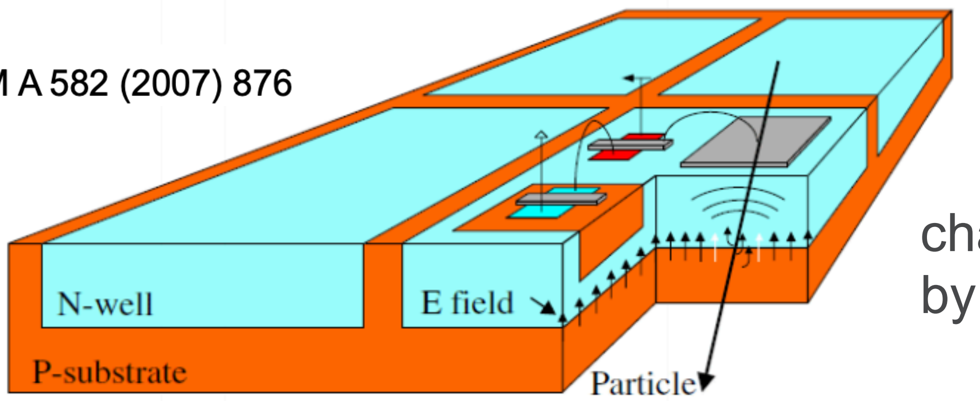


Simon Corrodi

"MUPIX"-STYLE PIXEL

HV-MAPS: High Voltage Monolithic Active Pixel Sensors *High Voltage CMOS*

I.Peric, et al., NIM A 582 (2007) 876



charge collection by drift

they are **fast**
they are **thin**
- no interconnects like hybrid designs
- depletion of O(10um), can be thinned down (~50um)

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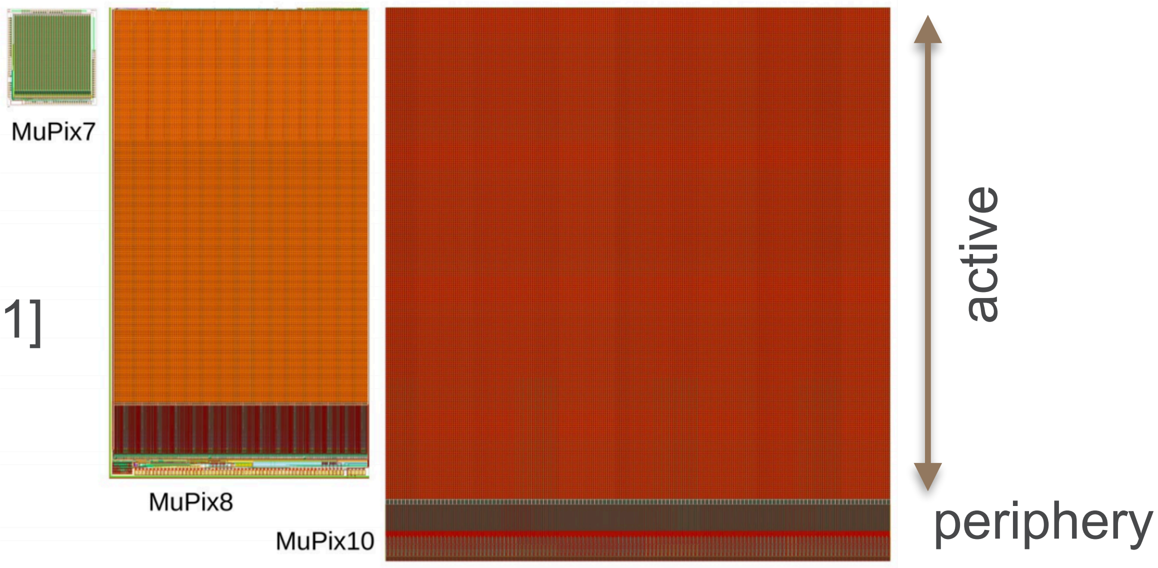
THE MUPIX SENSOR



[1]

MuPix:
- 20.66 x 23.18mm size,
  20.48 x 20.00 mm active
- pixels 80 x 80 um
- thinned 50um
- time resolution < 20ns

MuPix prototypes: [1] mu3e TDR

Output: pixel address, timestamp, [ToT]

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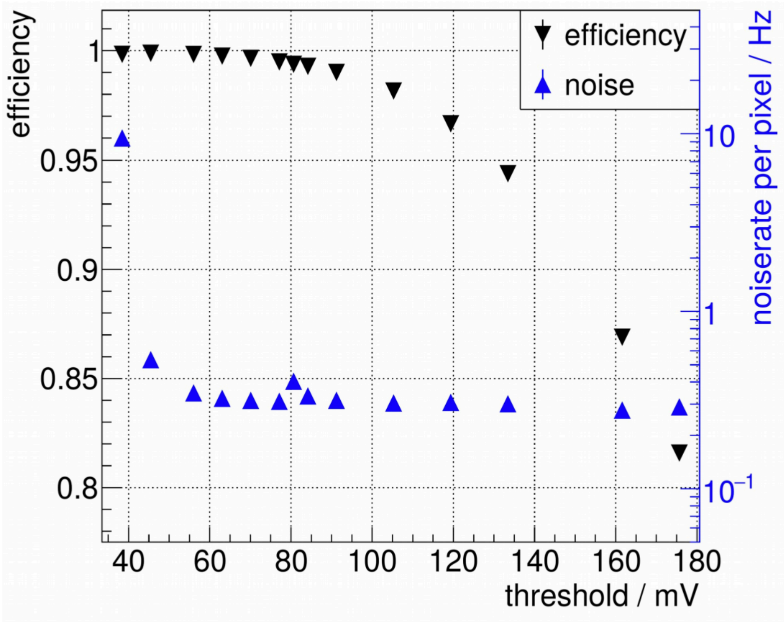
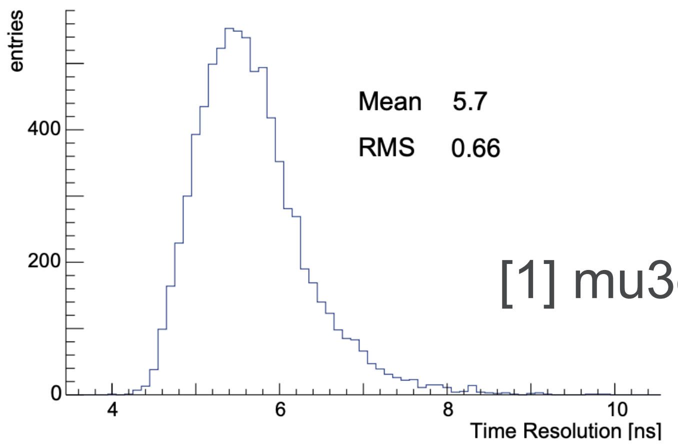
THE MUPIX SENSOR

High efficiency, very low noise



MuPix8, 80 Ωcm substrate, 62 um,
4 GeV electrons at 0deg, operated at -60V.
Note: MuPix10 200 Ωcm

Time Resolution ~8ns



[1] mu3e TDR

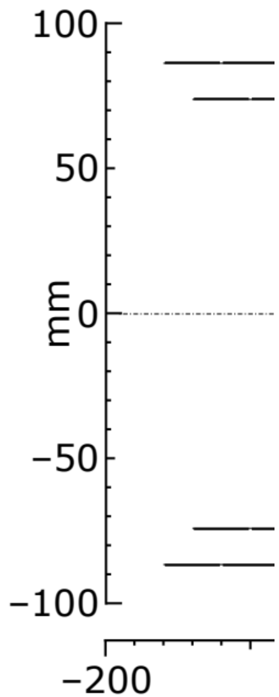
MuPix8: Including time-walk corrections from ToT.

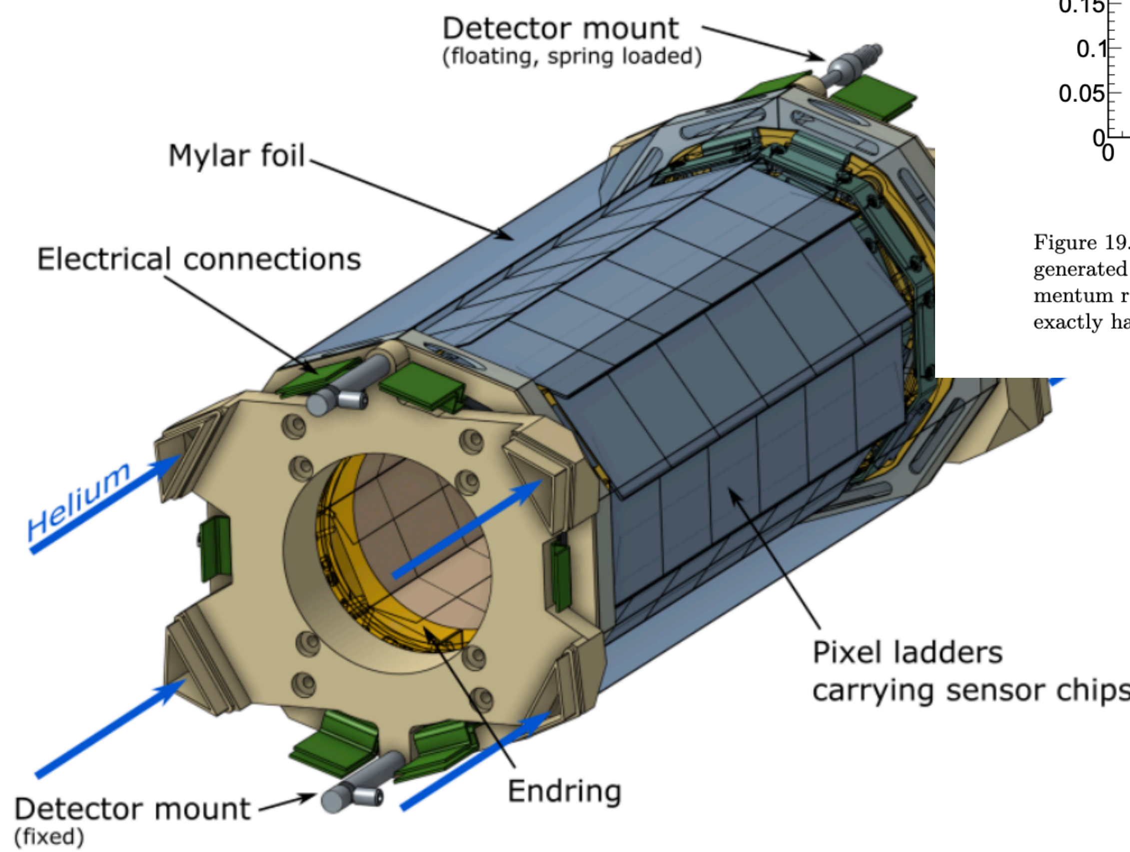
MuPix8 showed significant crosstalk from the long lines. This is expected to be solved in MuPix10.

THE MU3E TRACKER

How Thin? X/X0 = 0.115% per layer

The sensor





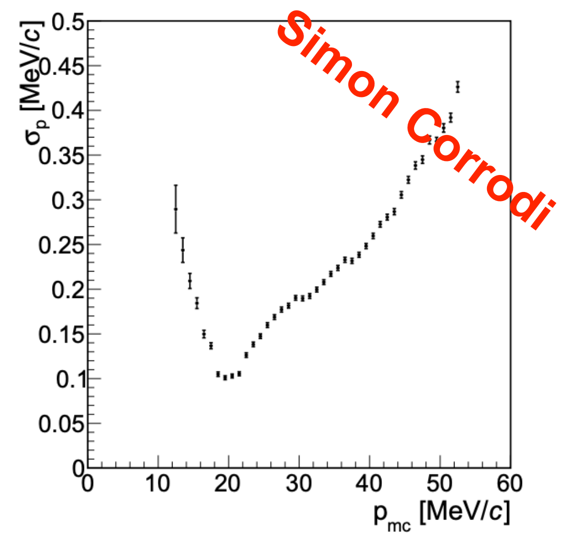
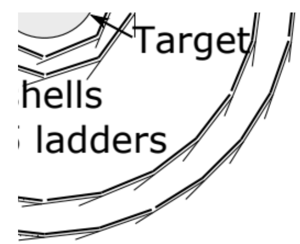


Figure 19.3: Momentum resolution σ_p as a function of the generated momentum p_{mc} of 6-hit long tracks. The momentum resolution has a minimum for tracks that traverse exactly half a circle outside the outermost pixel layer.



[1] TDR

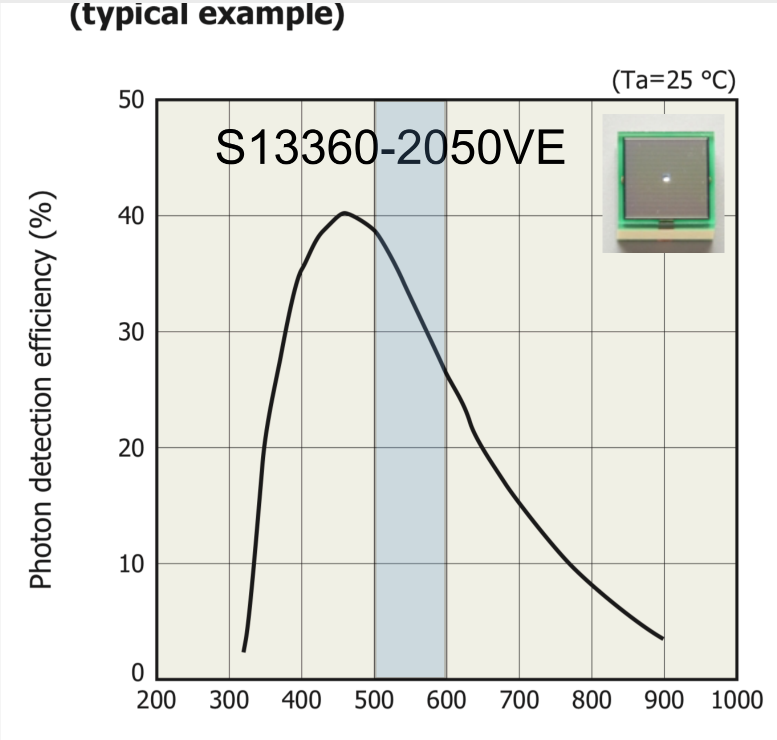
Expected background with current CRV

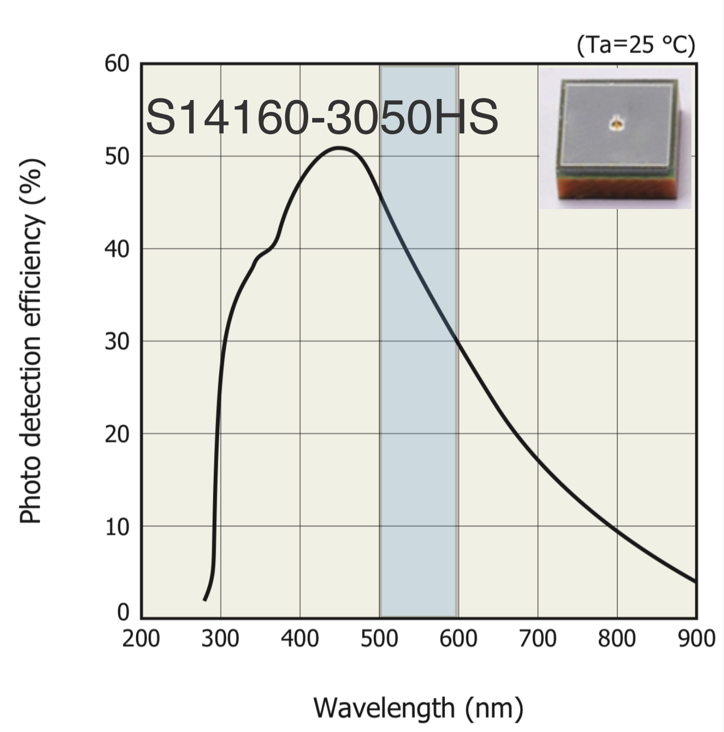
- The total cosmic ray background is ~2 events at Mu2e-II
  - Assuming 30% safety on the light yield
- We can either improve the light yield or address the degradation

	Live veto s			Year 1				Year 2				Year 3		
Run 1	2.45E+07		1	2	Beam type		1	2	Beam type		1	2	Beam type	
				40	Weeks			40	Weeks			40	Weeks	
				90%	Efficiency			90%	Efficiency			90%	Efficiency	
		Run		1.52E+07	Run time (s)			1.52E+07	Run time (s)			1.52E+07	Run time (s)	
		1		8.17E+06	Veto time (s)			8.17E+06	Veto time (s)			8.17E+06	Veto time (s)	
		Total		24	PE yield			22	PE yield			20	PE yield	
Sector	Unscaled Bkgnd	nonvetoed Bkgnd	PE thr.	Scaled Bkgnd	Ineff.	Non Vetoed Bkgnd	PE thr.	Scaled Bkgnd	Ineff.	Non Vetoed Bkgnd	PE thr.	Scaled Bkgnd	Ineff.	Non Vetoed Bkgnd
TS-U	0.5	0.01	10	0.4	0.0070	0.0	10	0.4	0.0117	0.0	10	0.4	0.0197	0.0
TS-D	2.6	0.00	10	2.1	0.0002	0.0	10	2.1	0.0003	0.0	10	2.1	0.0006	0.0
T-U	228.2	0.77	10	186.5	0.0004	0.1	10	186.5	0.0011	0.2	10	186.5	0.0027	0.5
	0.0	0.00	10	0.0	0.0004	0.0	10	0.0	0.0011	0.0	10	0.0	0.0027	0.0
	3.9	0.01	10	3.2	0.0004	0.0	10	3.2	0.0011	0.0	10	3.2	0.0027	0.0
T-D	126.6	0.39	10	103.5	0.0005	0.1	10	103.5	0.0010	0.1	10	103.5	0.0022	0.2
	96.2	0.30	10	78.6	0.0005	0.0	10	78.6	0.0010	0.1	10	78.6	0.0022	0.2
	10.6	0.03	10	8.7	0.0005	0.0	10	8.7	0.0010	0.0	10	8.7	0.0022	0.0
T-Ext	0.1	0.02	10	0.1	0.0520	0.0	10	0.1	0.0529	0.0	10	0.1	0.0538	0.0
L	0.0	0.00	10	0.0	0.0000	0.0	10	0.0	0.0001	0.0	10	0.0	0.0003	0.0
	30.2	0.01	10	24.7	0.0000	0.0	10	24.7	0.0001	0.0	10	24.7	0.0003	0.0
	26.3	0.01	10	21.5	0.0000	0.0	10	21.5	0.0001	0.0	10	21.5	0.0003	0.0
R	27.5	0.01	10	22.5	0.0000	0.0	10	22.5	0.0001	0.0	10	22.5	0.0002	0.0
	36.5	0.01	10	29.9	0.0000	0.0	10	29.9	0.0001	0.0	10	29.9	0.0002	0.0
	30.8	0.01	10	25.2	0.0000	0.0	10	25.2	0.0001	0.0	10	25.2	0.0002	0.0
U	0.1	0.03	10	0.1	0.1105	0.0	10	0.1	0.1556	0.0	10	0.1	0.2123	0.0
D	0.5	0.05	10	0.4	0.0265	0.0	10	0.4	0.0426	0.0	10	0.4	0.0680	0.0
Cryo	1.2	0.00	10	1.0	0.0010	0.0	10	1.0	0.0010	0.0	10	1.0	0.0010	0.0
TS hole	0.09	0.22		0.1	1.0000	0.1		0.1	1.0000	0.1		0.1	1.0000	0.1
	621.9			508.3		0.2		507.3		0.5		507.3		1.0
	Total					0.3				0.5				1.1
	1.7	**1.7**												
	1.9	**1.9**												

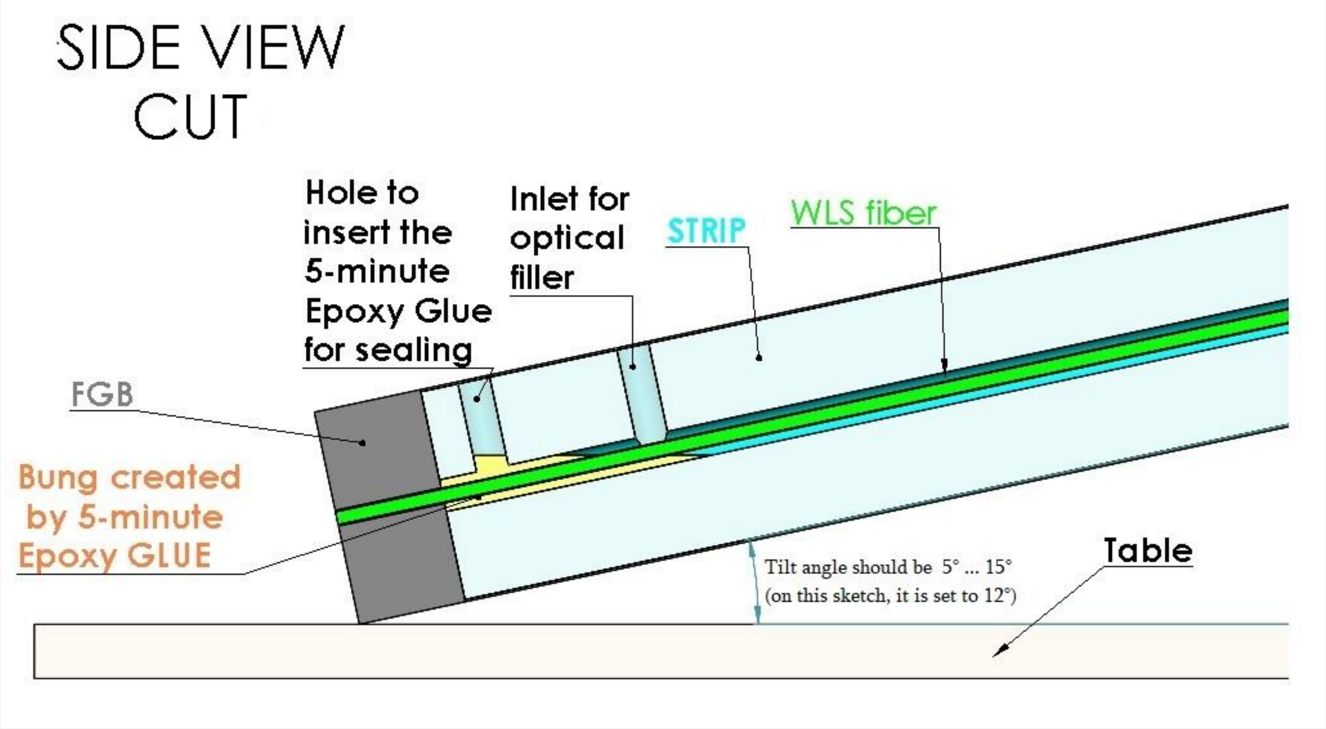
SiPM with improved PDE

- Light yield is improved by 24% by switching from 1.4 to 1.8 mm fiber
- SiPM technology has advanced since the CRV was designed
- We can consider SiPMs with:
  - PDE peaked in green-yellow spectrum
  - Enhanced (20%) PDE overall



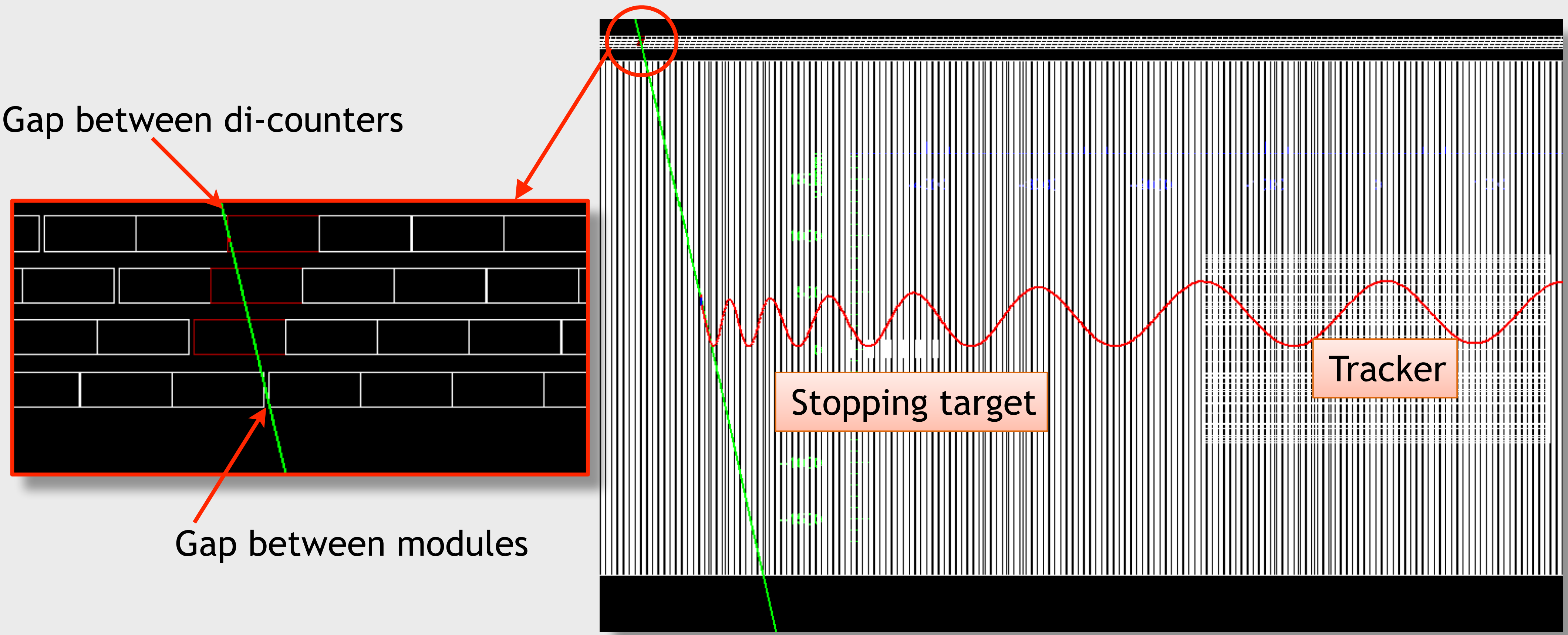


- Light collection can be improved by 40%, if fiber channels are filled with silicone resin
- Concern: silicone resin might leak damaging read-out
- Dubna team has been investigating an improved procedure to pot fibers
  - Fill the counter end with epoxy to enhance the seal at FGB
- **We need to find resources to finalize this procedure**



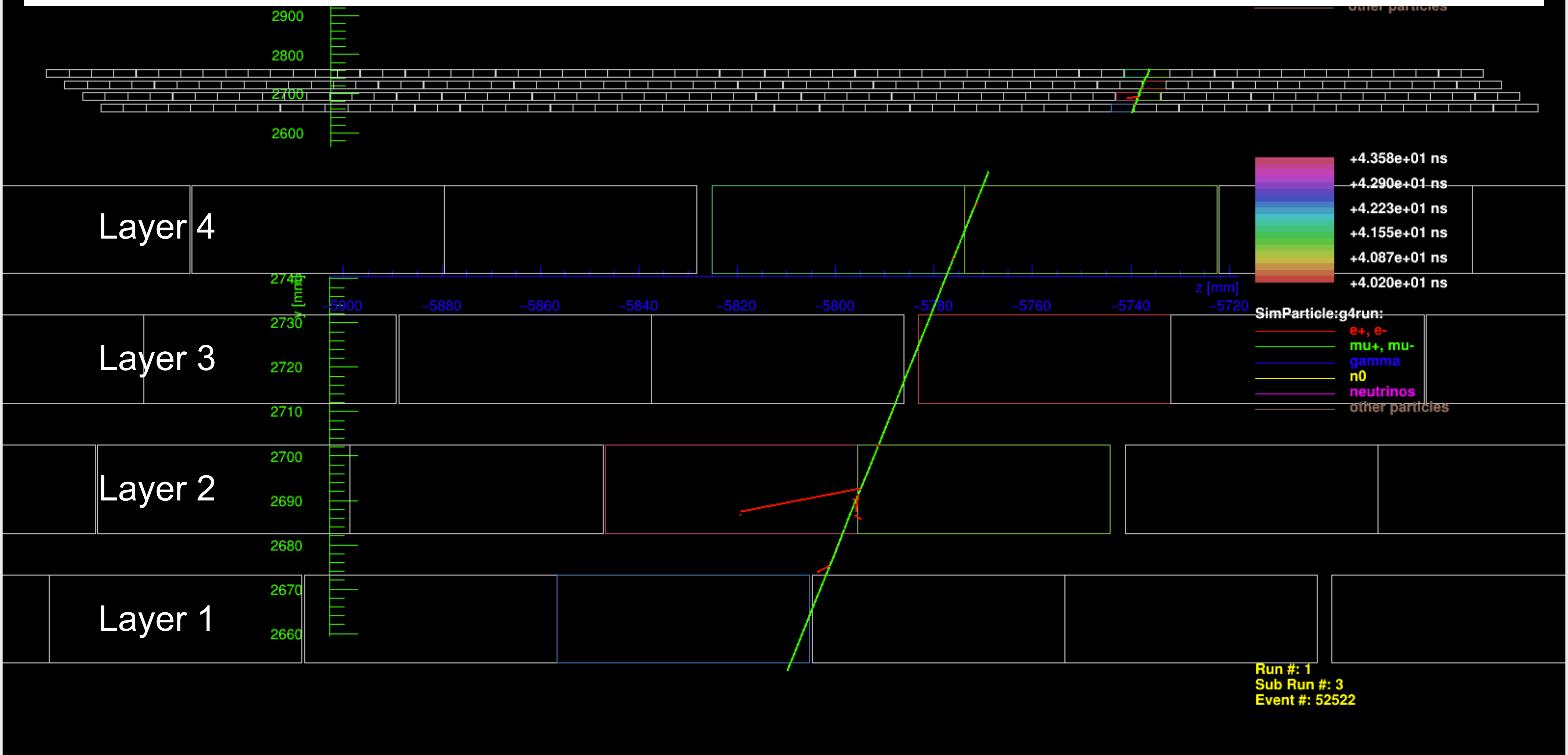
Sources of CRV inefficiencies

- The CRV efficiency is adversely impacted by the gaps between scintillating counters
- The current CRV design partially addresses impact from gaps by staggering CRV layers



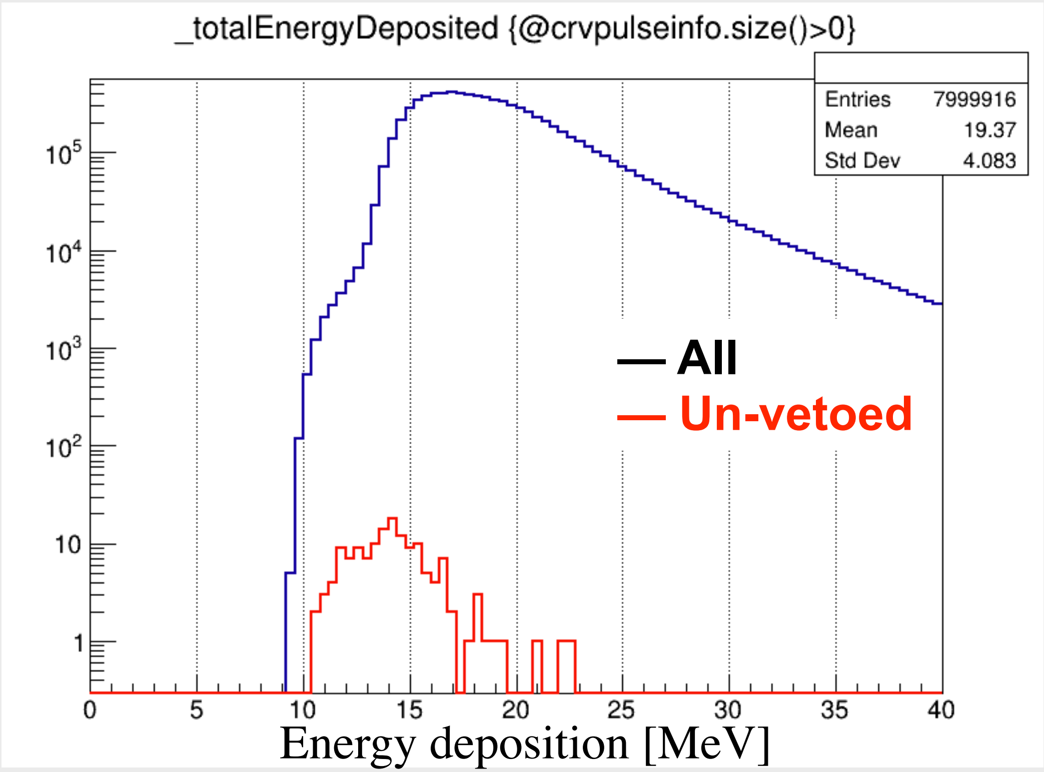
Test stand simulation

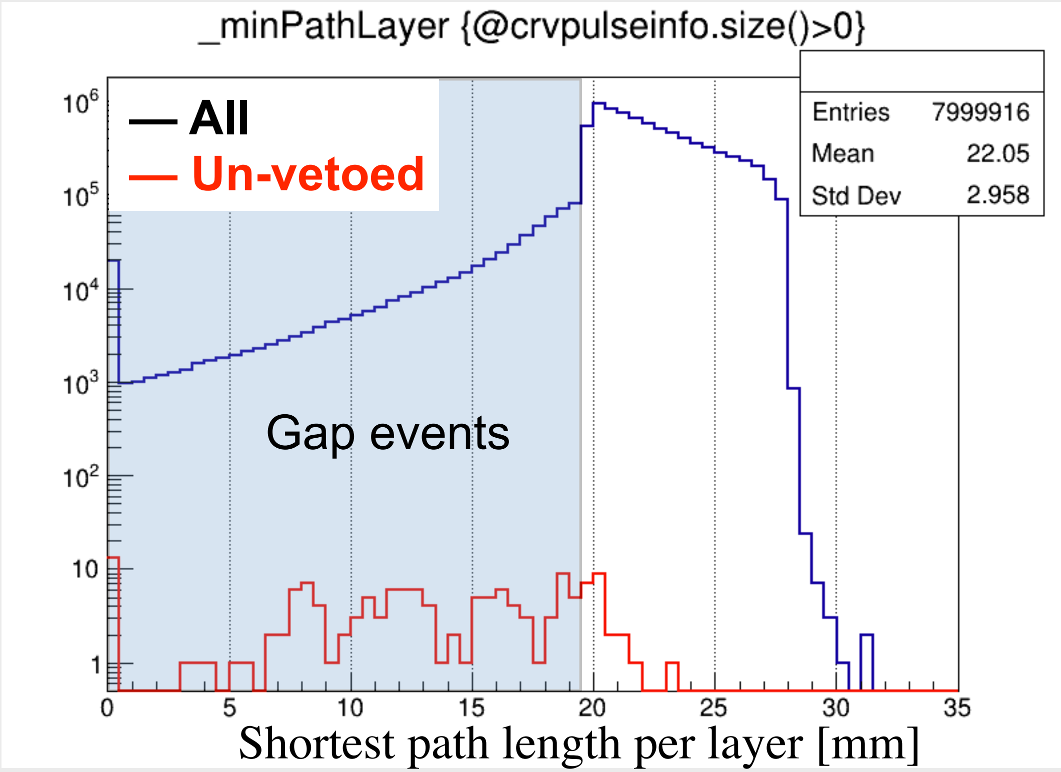
- We have recently simulated the response of 4 CRV modules
- The simulated light yield is 42 PE/cm
- High (20/cm) PE thresholds were assumed



Energy position and path light

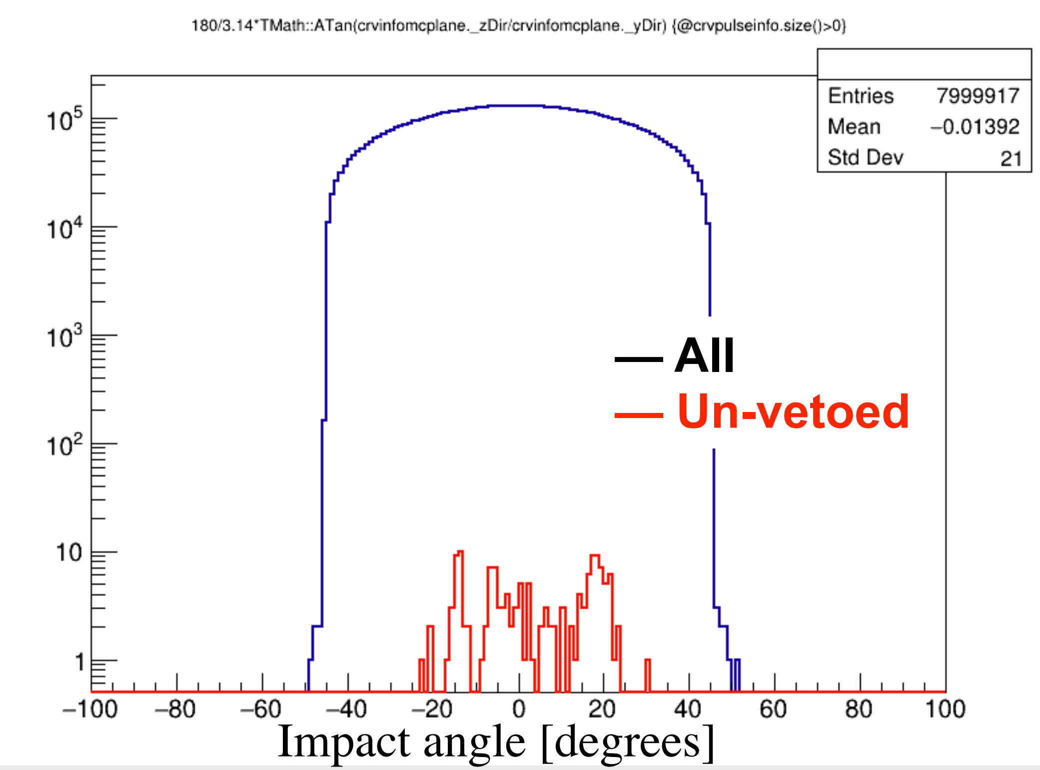
- Events fails veto due to the combination of:
  - Low light yield
  - Impact from gaps
- Un-vetoed events deposit lower energy than a typical muon
- Counter thickness is ~20 mm
  - Shorter path length suggests a muon traversing a module through a gap

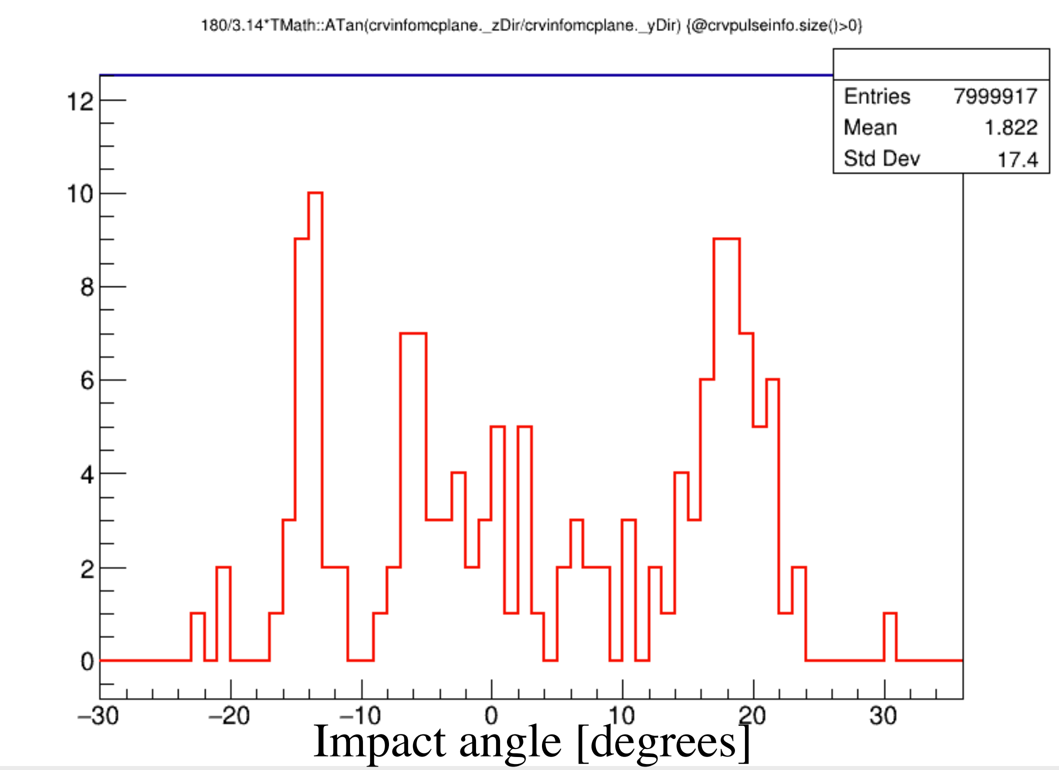




Angular distribution

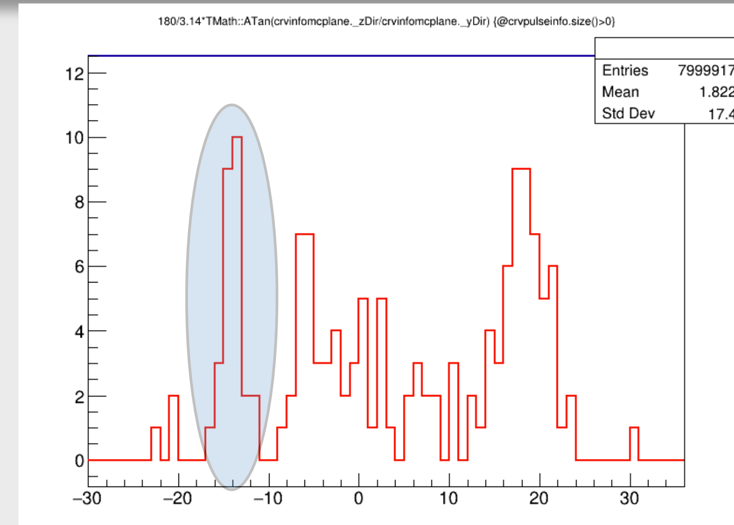
- Angular distribution of un-vetoed vetoed has the structure
- Muons entering at -15, 0, and 18 degrees have higher chance of escaping the detection
- This structure becomes less pronounced if the light yield is lower and the inefficiency is dominated PE statistics
- In order to reach high efficiency

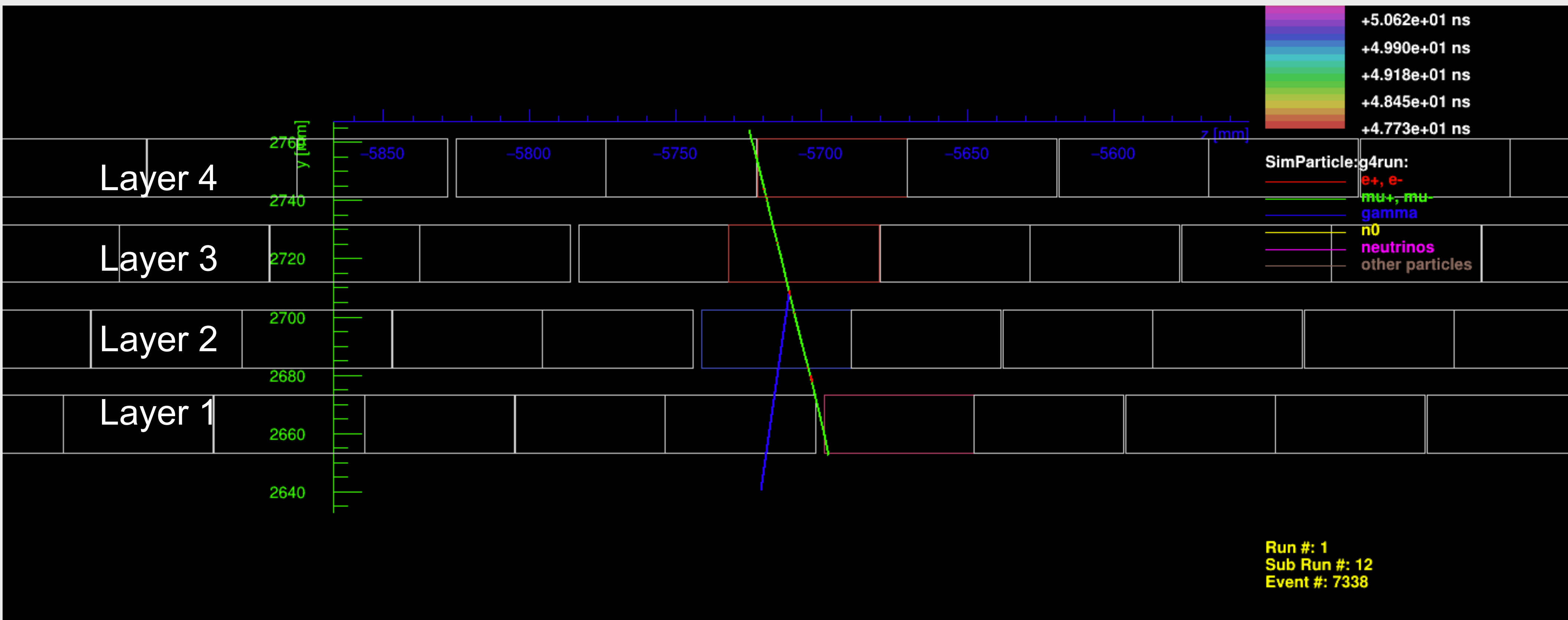




Sources of CRV inefficiencies

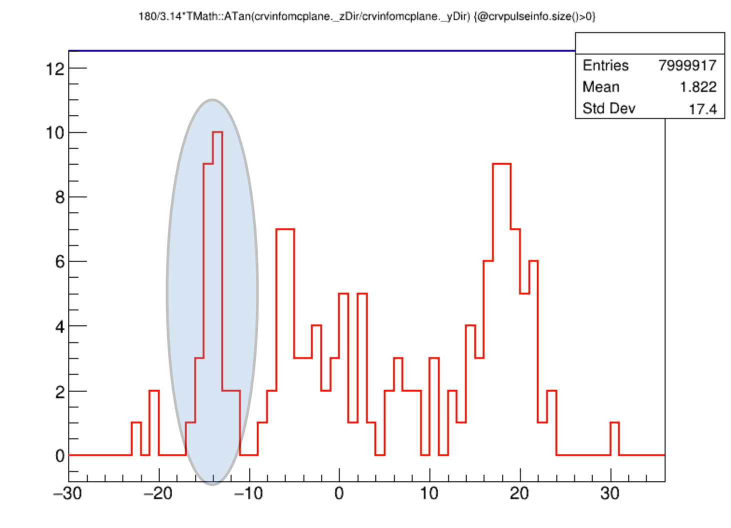
- Total energy deposited: 12.3 MeV
- Min path length per layer: 7.9 mm
- Angle: -14.2

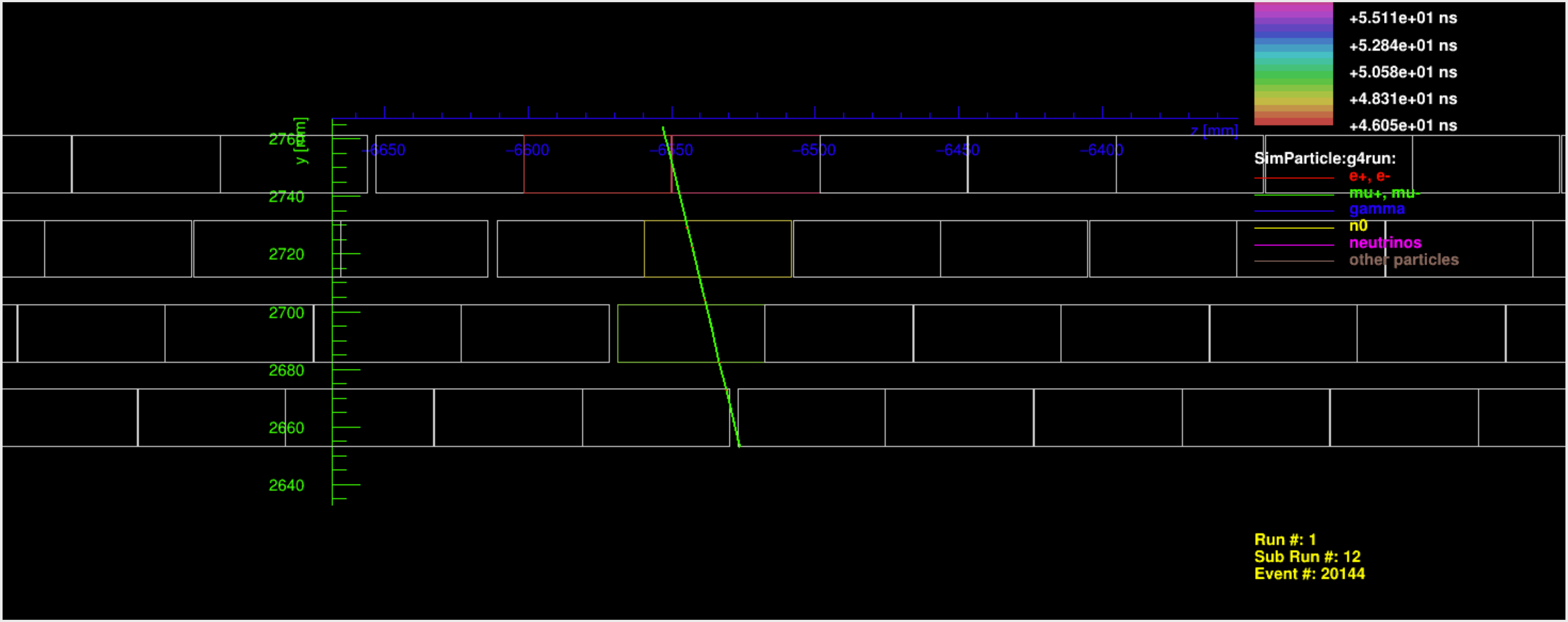




Sources of CRV inefficiencies

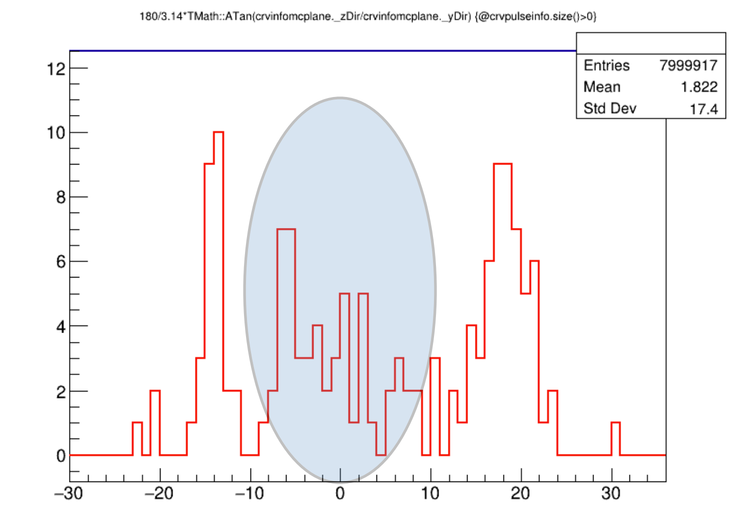
- Total energy deposited: 11.6 MeV
- Min path length per layer: 7.5 mm
- Angle: -13.6

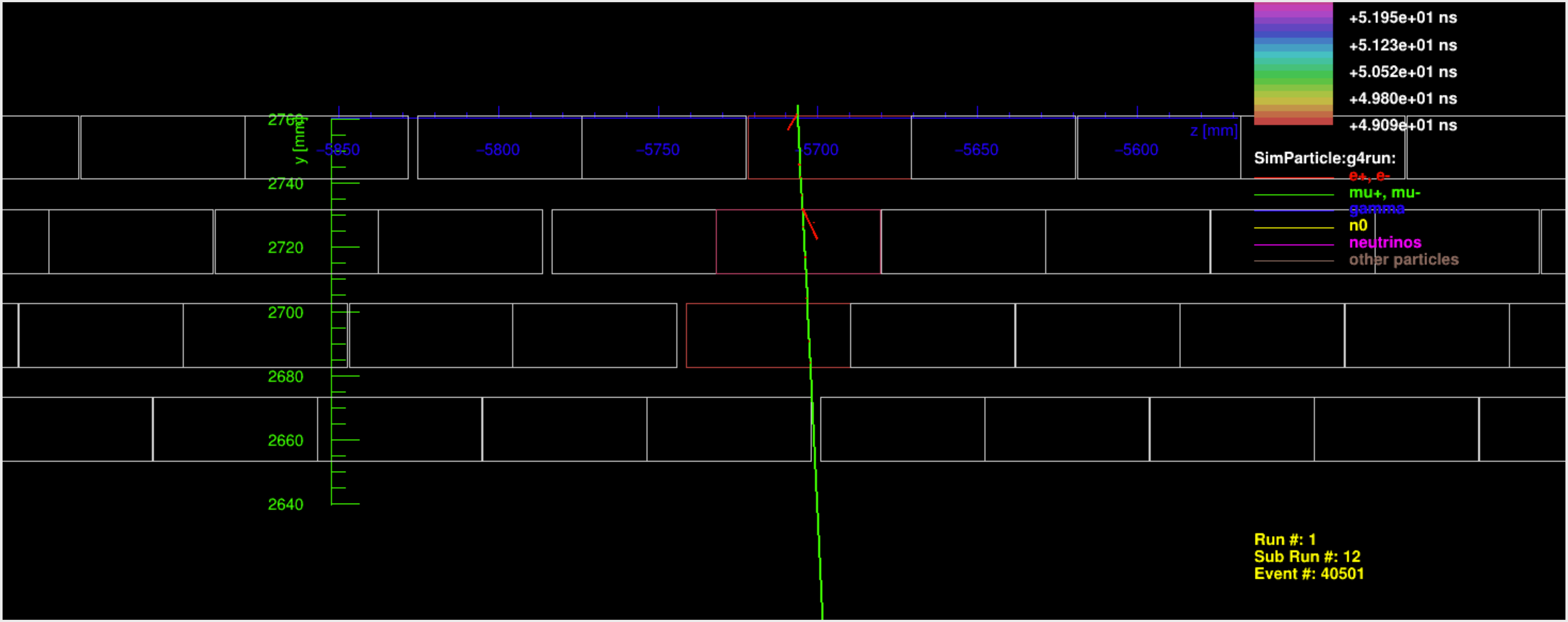




Sources of CRV inefficiencies

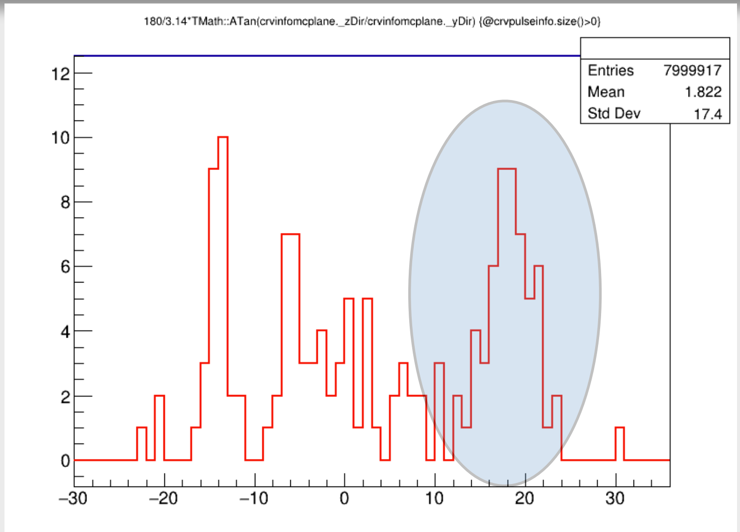
- Total energy deposited: 16.8 MeV
- Min path length per layer: 0 mm
- Angle: -3.2

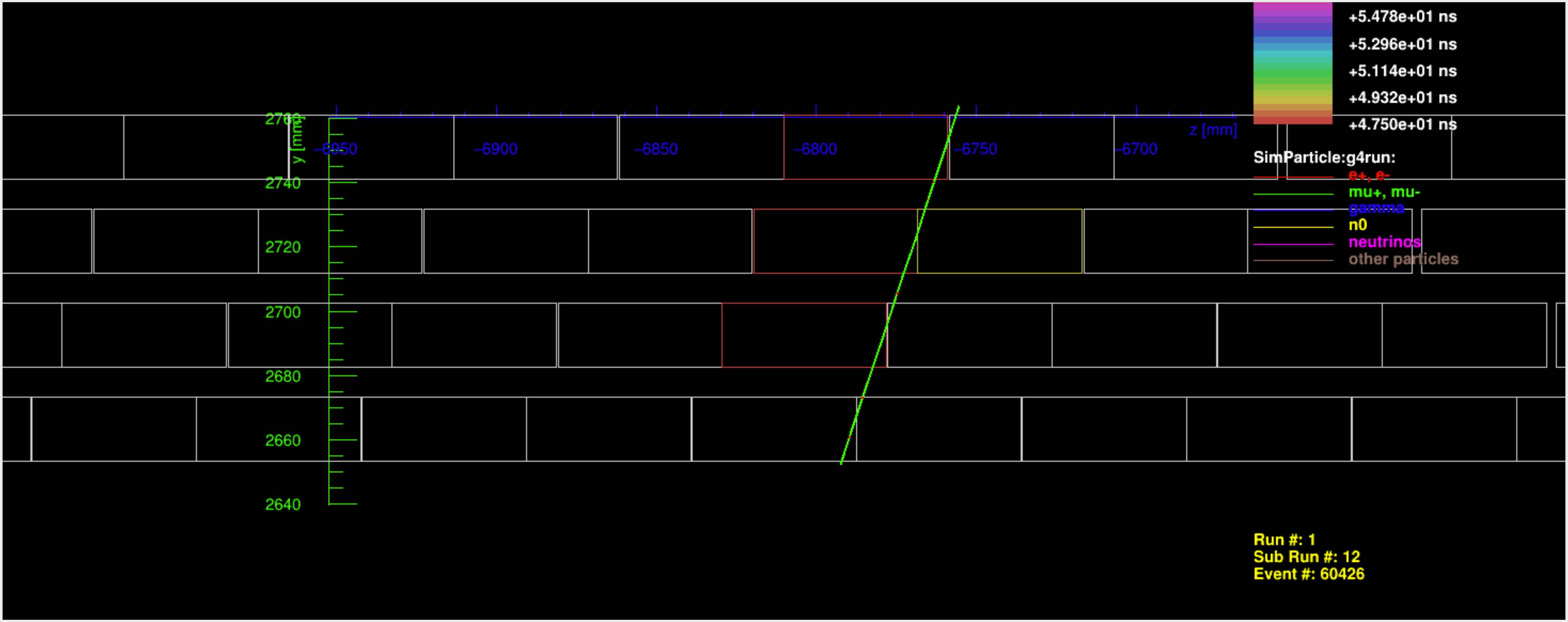




Sources of CRV inefficiencies

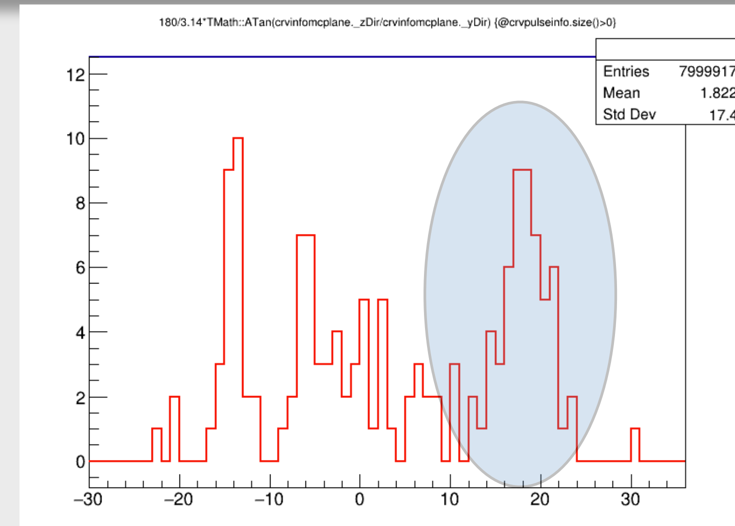
- Total energy deposited: 14.3 MeV
- Min path length per layer: 19.5 mm
- Angle: 18.4

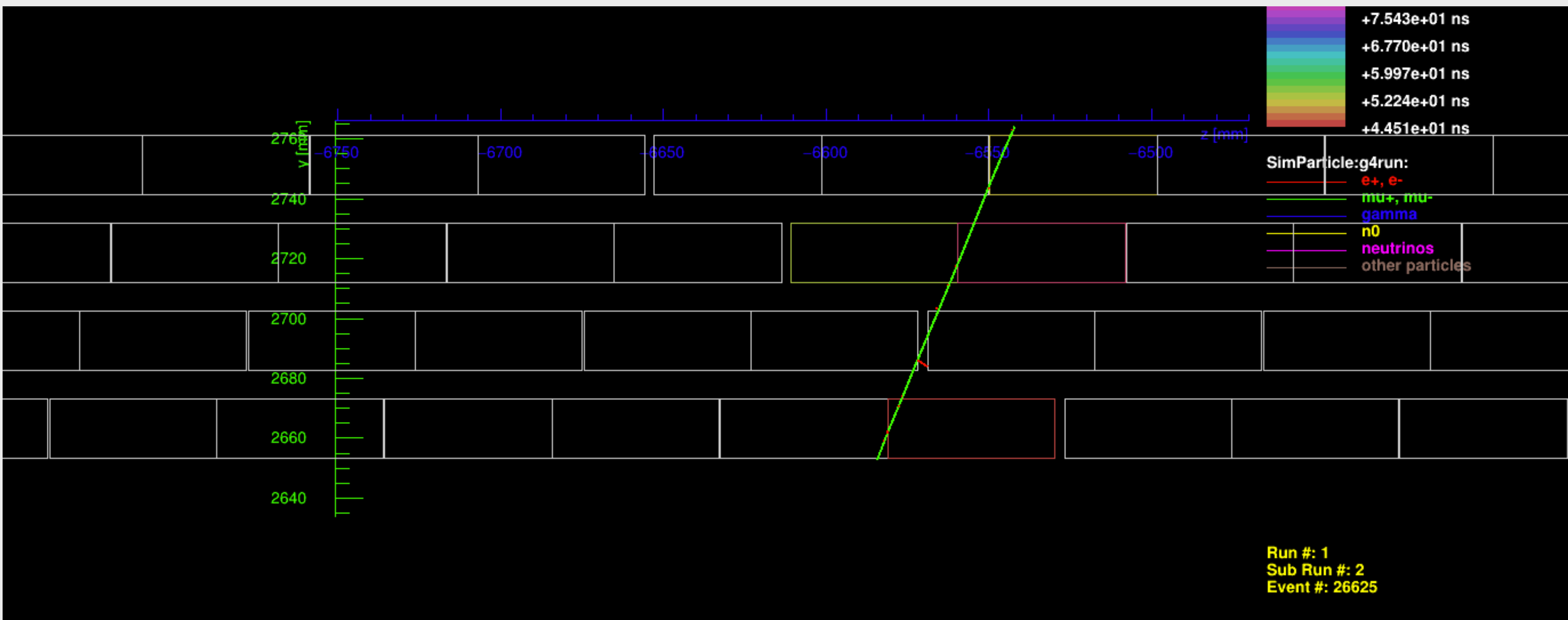




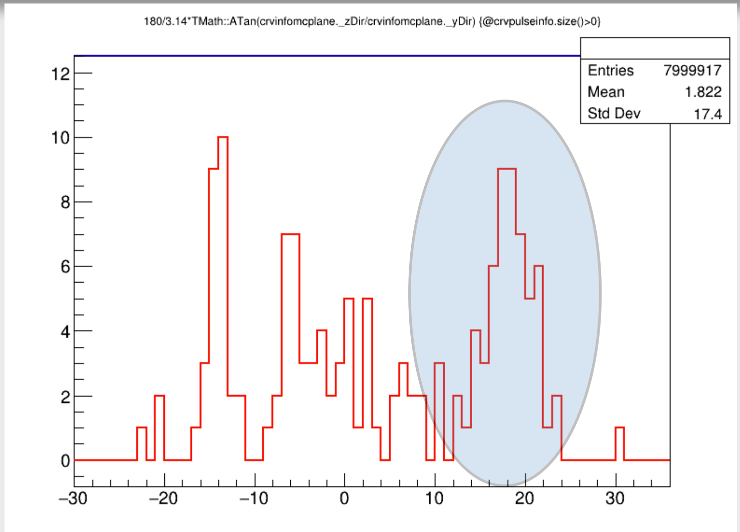
Sources of CRV inefficiencies

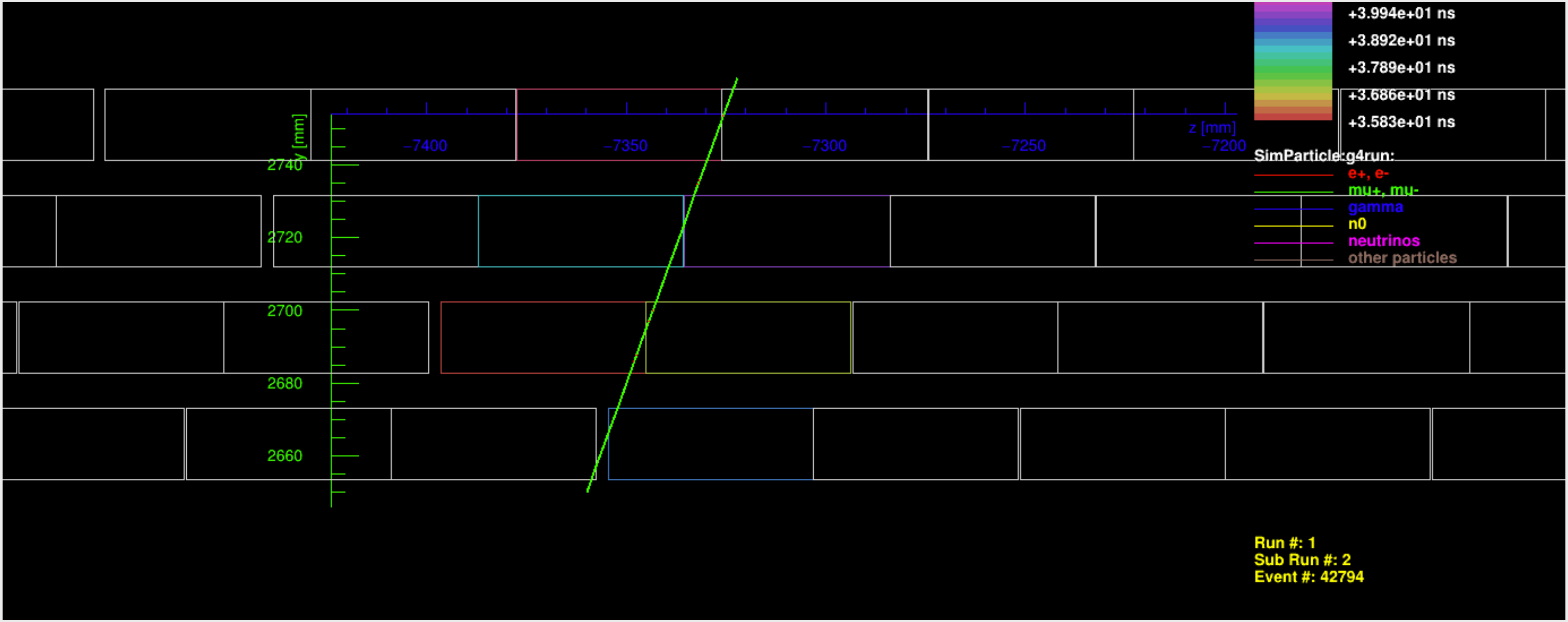
- Total energy deposited: 13.4 MeV
- Min path length per layer: 12.8 mm
- Angle: 20.9





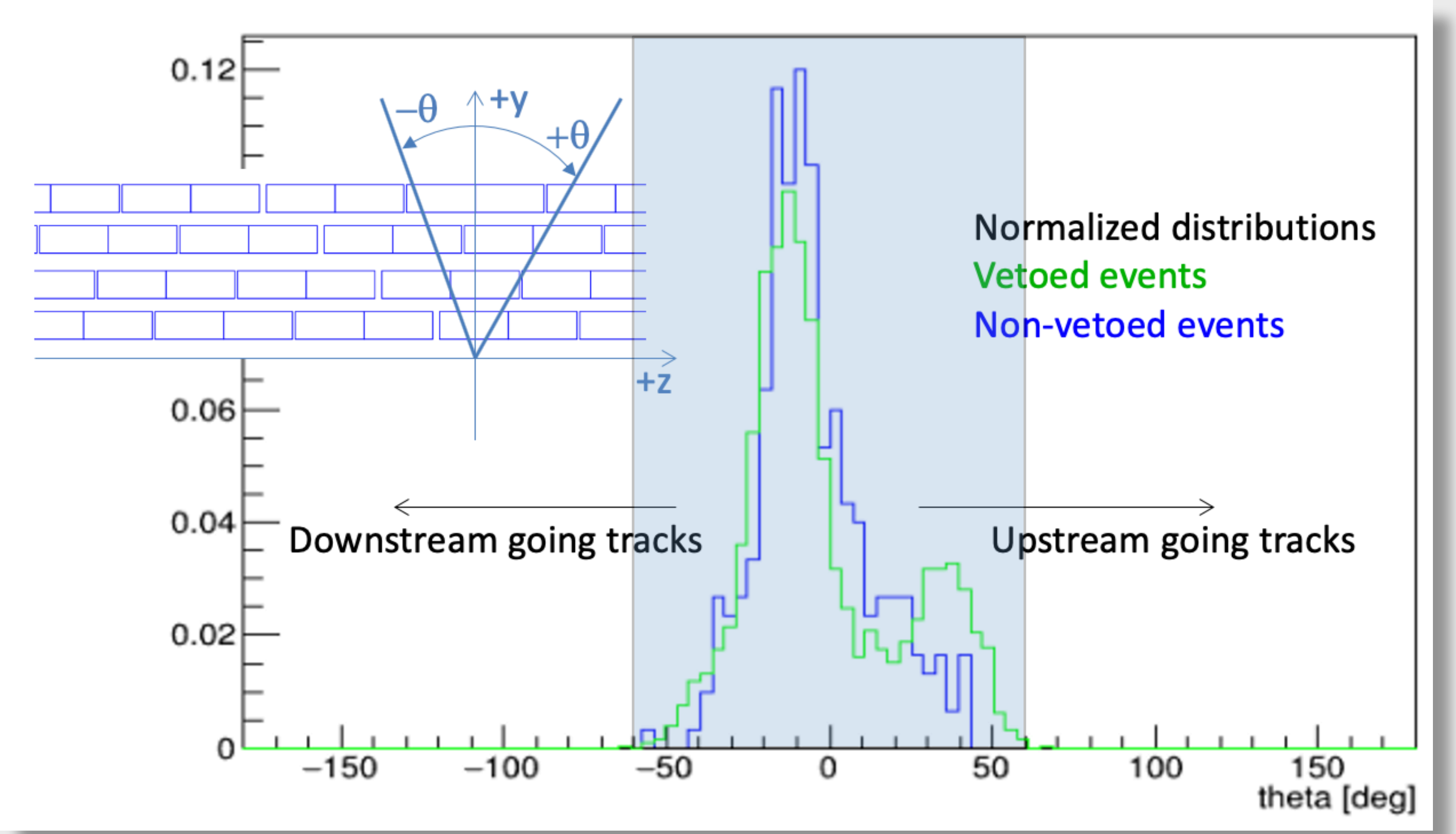
- Total energy deposited: 12.7 MeV
- Min path length per layer: 11.1 mm
- Angle: 18.5





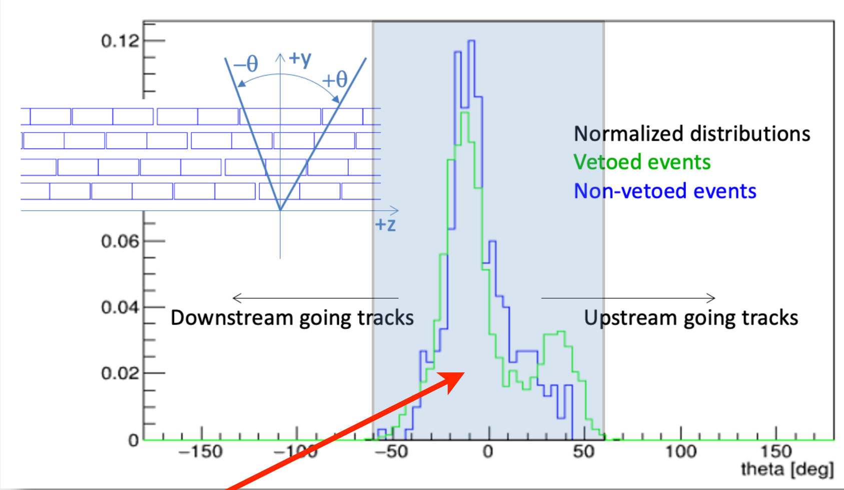
Cosmic ray angles of incidence

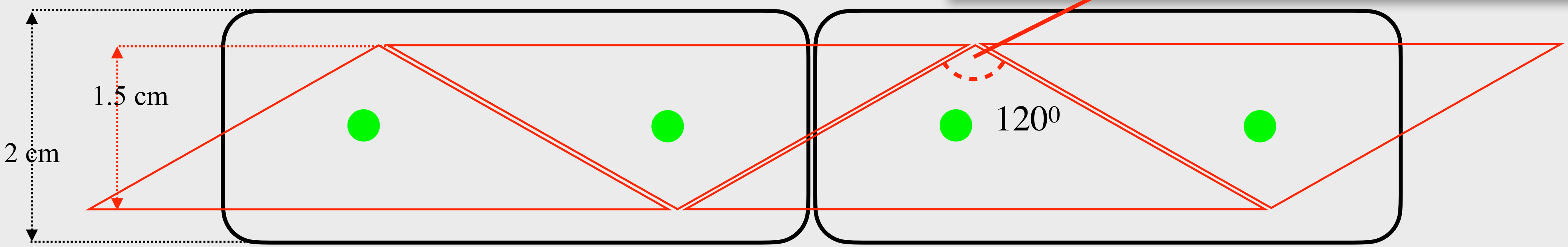
- The dominant fraction of the background inducing CR muons impact CRV at an angle <60^0
- Reminder: this simulations corresponds to the last year of Mu2e operations with low (19 PE/cm) light yield



Proposed counter design

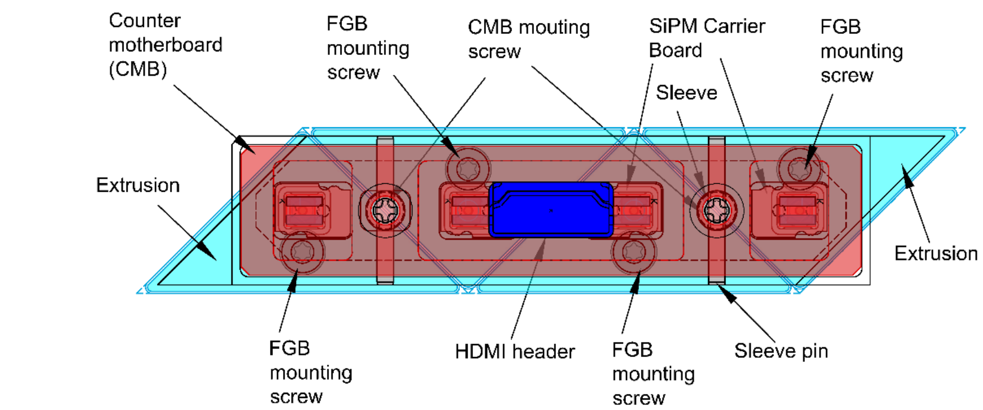
- An impact from gaps can be reduced in triangular-shaped counter design
- Benefits of proposed design:
  - Improved efficiency due to reduced gaps
  - Lower dead-time: improved (x3) positional resolution due to finer granularity and charge-sharing
  - Lower (~x2) per-channel rate
  - Lower (?) aging rate due to smaller profile
  - Simplified design of future modules





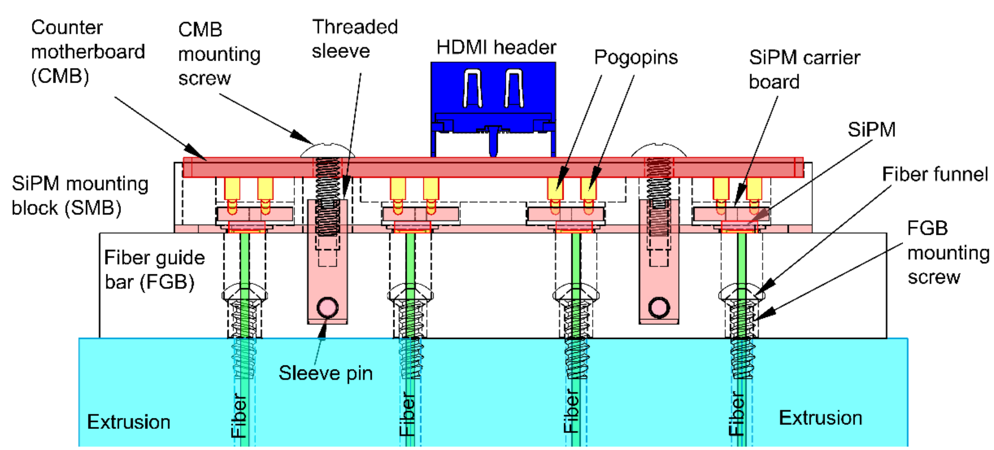
Assembled Quadcounter Manifold

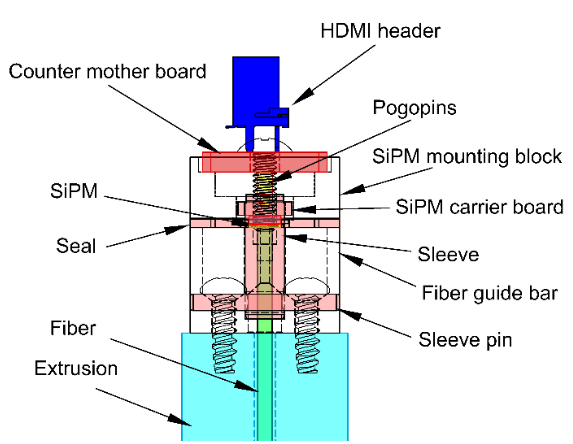
Craig Dukes



Bill of Materials:

	Item	No.	Manufacturer	Serial No.
1.	Fiber Guide Bar (FGB)	1	Krammes	Internal design
2.	SiPM Mounting Block (SMB)	1	Krammes	Internal design
3.	Seal (40 durometer Poron; $\frac{1}{16}$" - 1.5875 mm)	2	Metro Gasket	Custom design
4.	Sleeve	2	Krammes	Internal design
5.	Pin (M2x16 stainless)	2	McMaster-Carr	91585A231
6.	SiPM Carrier Board (SCB)	4	Hamamatsu	
7.	Extrusions	2	Fermilab NiCADD	
8.	Counter Motherboard (CMB)	1	Fermilab electronics	
9.	FGB mounting screws (Torx #4 self-tapping, 3/8" long)	4	McMaster-Carr	99512A216
10.	CMB mounting screws (Phillips 4-40, 3/8" long)	2	McMaster-Carr	91770A108
11.	Gasket [$\frac{1}{4}$" (6.35 mm) wide; $\frac{1}{8}$" (3.175 mm) thick]	1	Metro Gasket	Poron 4701-50-20062





Version History:
1.0 Rectangular design
2.0 Trapezoidal design

Notes:
1. Symmetric fiber guide bar.
2. CMB can be rotated to reverse orientation of HDMI header.
3. Header carrier board not shown.
4. Seal shown compressed.
5. Distance between CMB bottom and SCB top: 3.63 mm [0.147"]. Range should be: 3.1 to 4.5 mm.
6. SiPM: Hamamatsu S13360-2050-VE.
7. Seal glued to SiPM mounting block bottom.
8. HDMI header position approximate.

Mu2e-II Cosmic Ray Veto

University of Virginia
Frontier Physics Group
University of Virginia
Department of Physics
382 McCormick Rd.
Charlottesville, VA 22904, USA
craigdukes@virginia.edu

Quadcounter Readout Manifold: Assembly

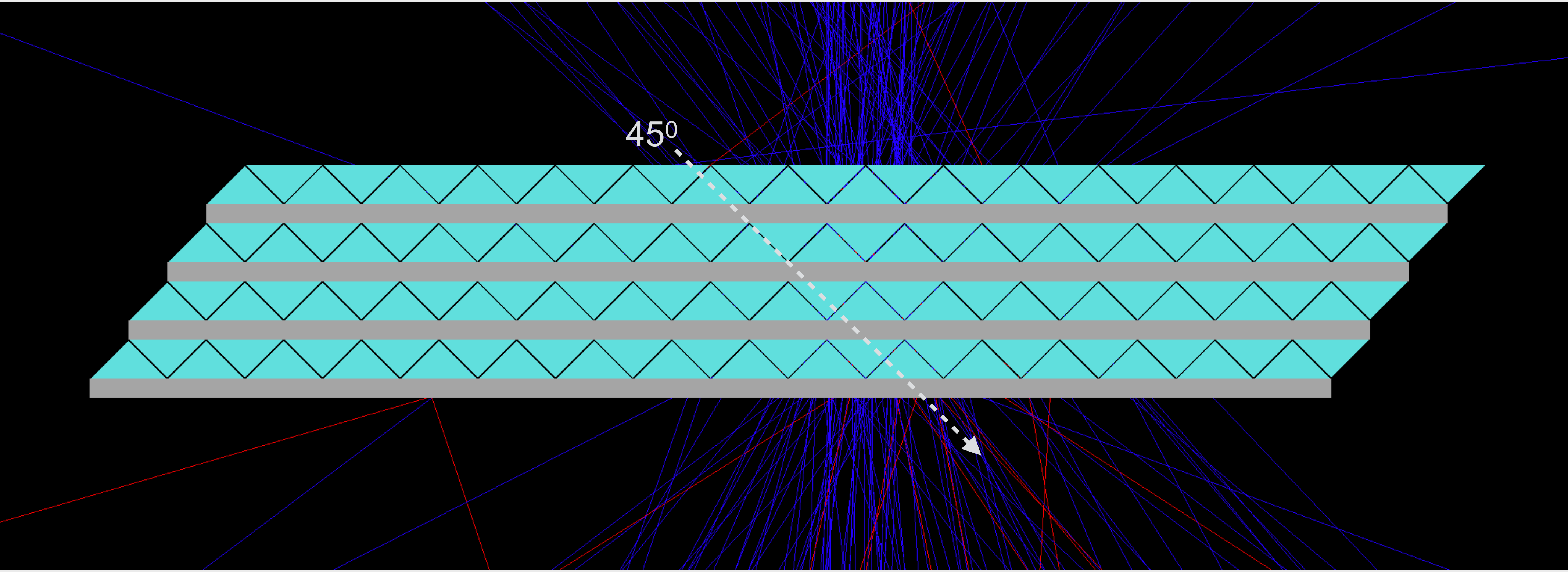
Drawn by: E. Craig Dukes	Version 1: Trapezoidal design	
File: Mu2e-II_CRV_quadcounter_v1.0.dwg		
Name: Mu2e-II_CRV_Quadcounter_v1.0_Readout_Manifold_Assembly	Units: mm [inch]	Scale: 2:1
Date: September 20, 2020		Drawing #: 1
Revised:		
Note:		

CRV-II prototype

- Seek resources to build the CRV prototype for Mu2e-II
- The module will feature:
  - Enhanced detection efficiency through:
    - Improved counter design
    - Develop potting fibers procedure to boost the light yield
  - Aging studies of the prototype
  - Measurement of the positional resolution through charged shared algorithm
  - The prototypes can be later installed at Mu2e-I
    - Study its' performance in the noisy environment for Mu2e-II
    - Enhance and validate the CRV performance at Mu2e-I

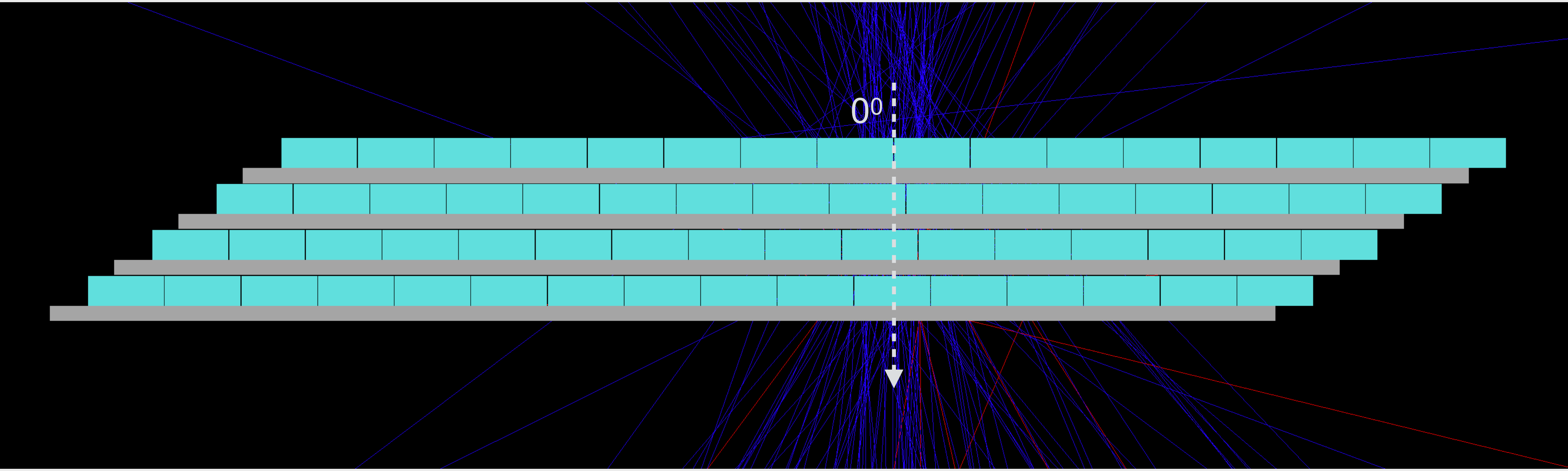
Triangular counters simulation

- Implemented CRV module design in g4bl
- We can study CRV module performance based on the energy deposition
  - Use g4bl sims to estimate the relative improvement to rectangular counter design
- Ideally, we implement triangular counter design in Offline, but it's a major task
- The module design consists of rectangular aluminum absorbers. **No machining is required.**



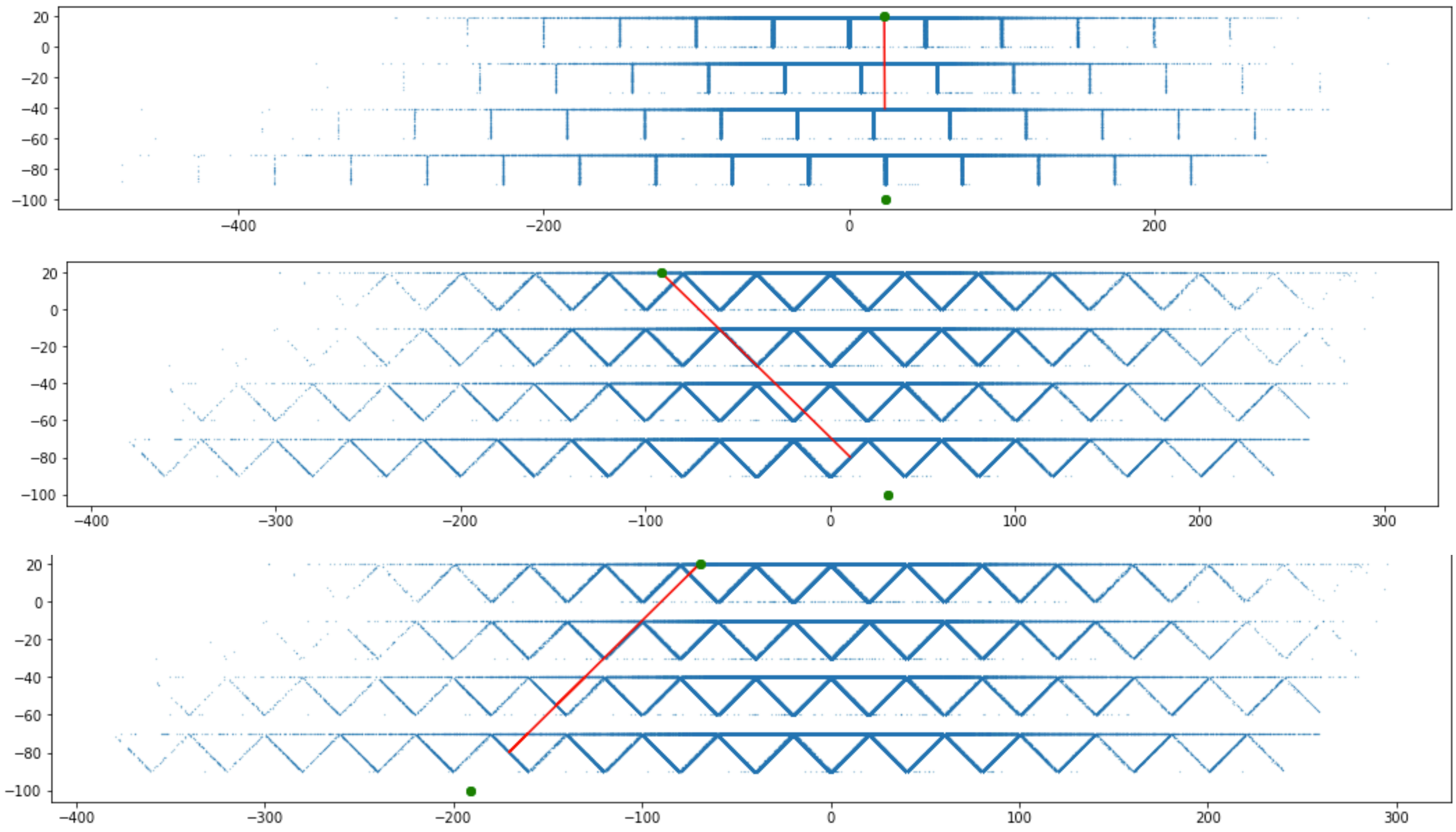
Rectangular counters simulation

- Similarly, implemented present CRV module design in g4bl
- At this moment I have only modeled a single model
- The gap between counters is assumed to be 1 mm
  - Production modules will have 3/1/0.5 mm gaps between modules/di-counters and counters respectively
  - I will refine the geometry details in the future
- Reminder: aluminum absorbers are machined to allow modules interleaving

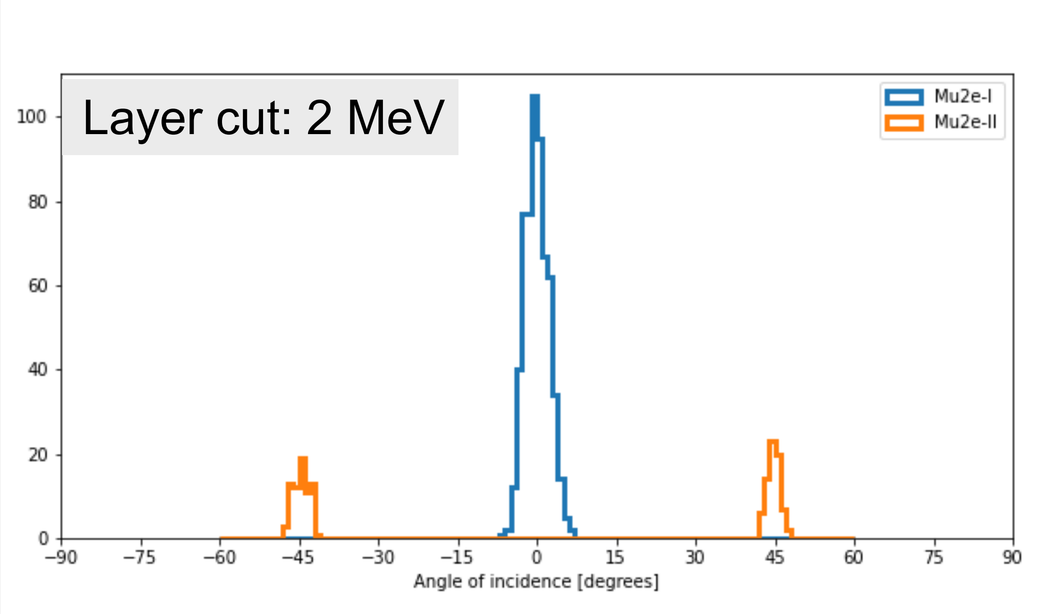


Low energy deposition events

- Select events with less than 0.5 MeV energy deposition in one of the layers

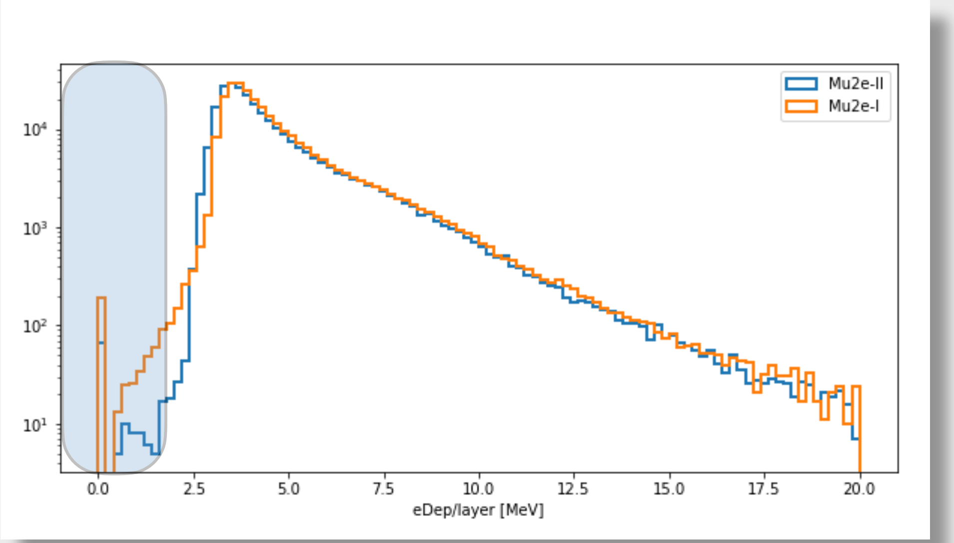


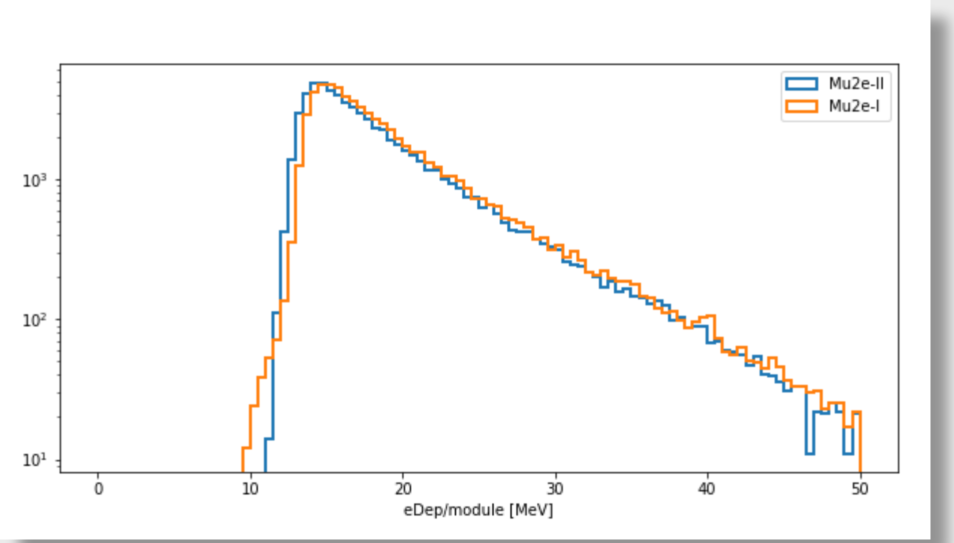
- In this analysis, I discard counters with less than 0.5 MeV deposition
  - This mimics a zero-suppression threshold
  - I will later convert deposited energy into PE using Poisson statistics
- At Mu2e-I, muons escaping a detection in a single layer traverse the CRV module vertically
- At Mu2e-II, the impact angle is at 45^0 - the opening angle of triangular counters



Energy deposition in CRV modules

- Mu2e-I modules show significantly lower per layer energy deposition
  - Bulk of cosmic ray flux enters vertically hitting one of the gaps. When it happens CRV veto relies on **all** 3 remaining layers to satisfy the coincidence.
  - Vertical going muons travel have shorter path length and therefore deposit lower amount of energy
- At Mu2e-II, cosmic muons traveling at 45^0 can escape one of the layers, but…
  - The cosmic muon flux is significantly reduced at 45^0
  - Mu2e is less sensitive to muons impacting at > 45^0
  - Muons entering at 45^0 will deposit (40%) higher energy in remaining 3 layers
- At Mu2e-II, total energy deposition per module is lower: effect of more gaps and finer granularity. Muons clipping counter edges are discarded
  - We need finer granularity to reduce the channel rates and dead-time. Triangular counter are more advantageous than rectangular counter of a similar granularity



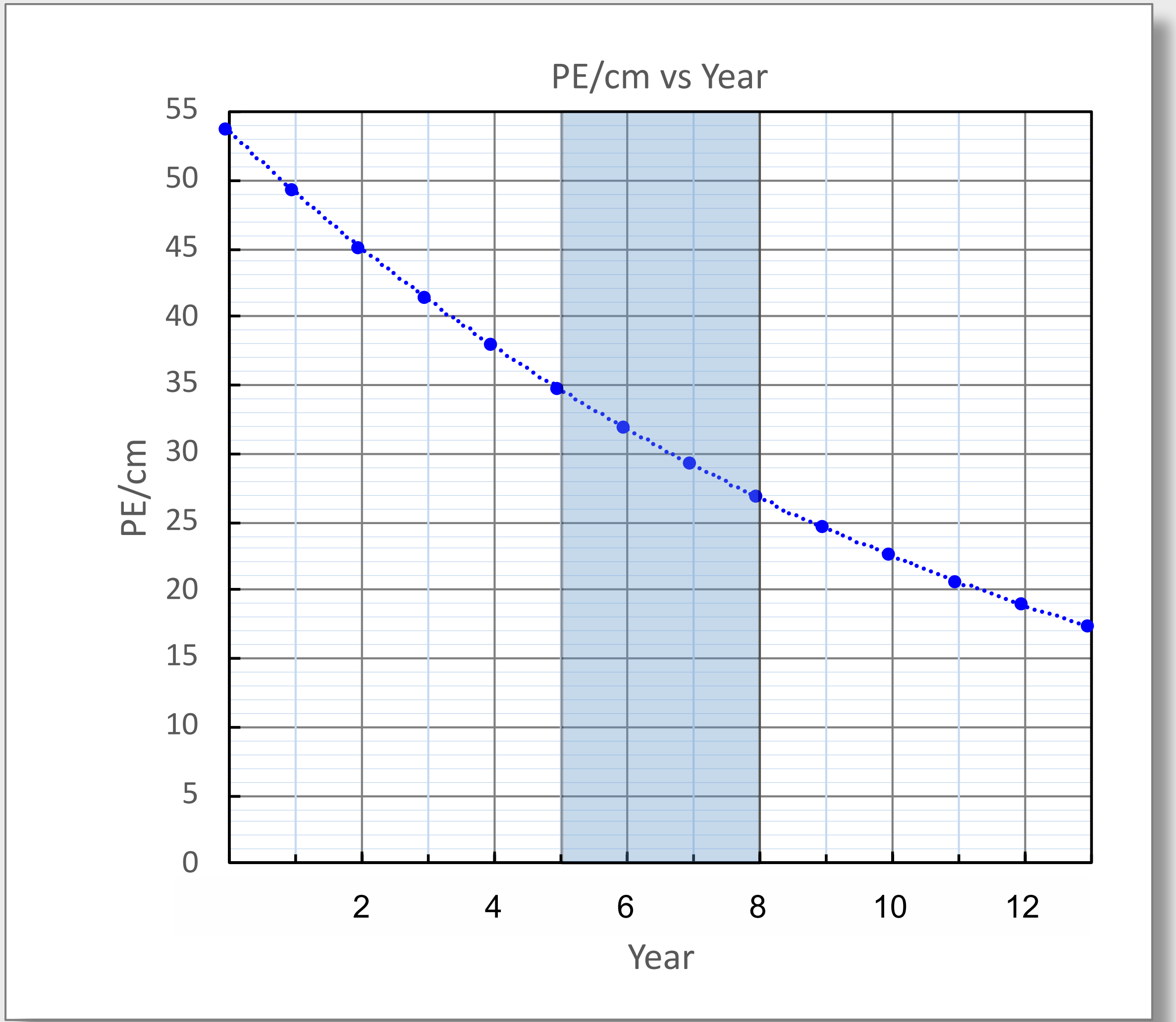


Summary

- The CRV operations at Mu2e-II are challenging, but feasible
- Current CRV detector can't be reused:
  - Detector degradation
  - High noise rate
- Finer granular CRV can be explored
  - Triangular shaped design seems promising
- Light output can be enhanced by using higher PDE SiPMs, thicker fibers, potting fiber channels
- Most critical CRV regions can be enhanced with additional layers
- Shielding needs to be enhanced to suppress: (a) read-out noise and (b) background induced by cosmic neutrons and TS-opening muons
- Other detector technologies can be explored for 'hot' regions and suppress cosmic background sneaking through.

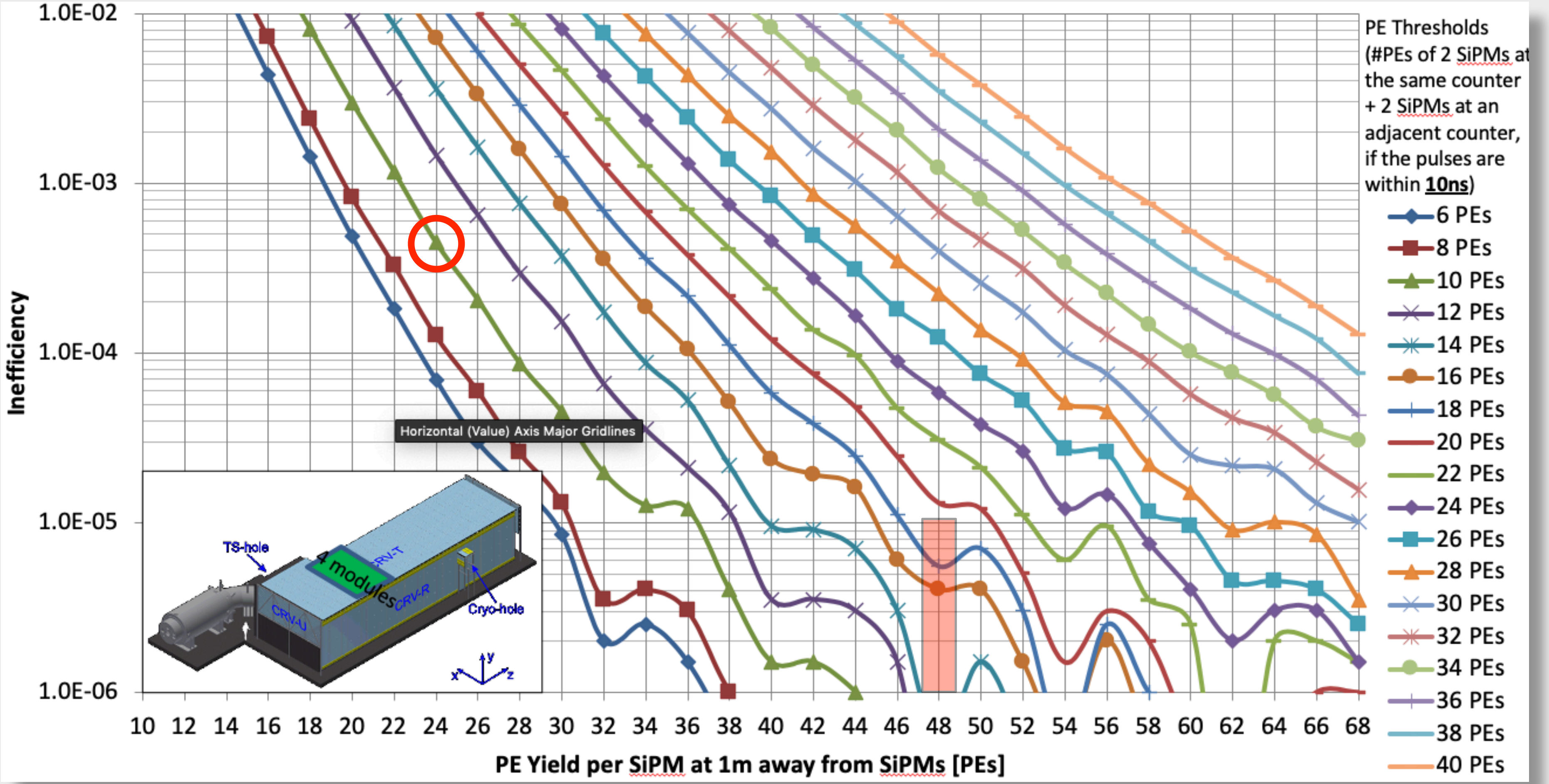
Backup

- Let's assume Mu2e-II starts taking data after 5 years extrusions are fabricated
- Expected light will degrade from 35 to 27 PE/cm



CRV efficiency vs light yield

- The CRV detection efficiency improves by a couple orders of magnitude, if we improve the light yield by a factor of 2
  - This would veto muons impacting CRV to a negligible fraction
- The dominant background contribution (~0.3 events) will be induced by TS-opening events



Cosmic ray background at Mu2e-II

- Assume the CRV performance of the current detector achieved in 2025
- Cosmic background at Mu2e-II will be >2 events

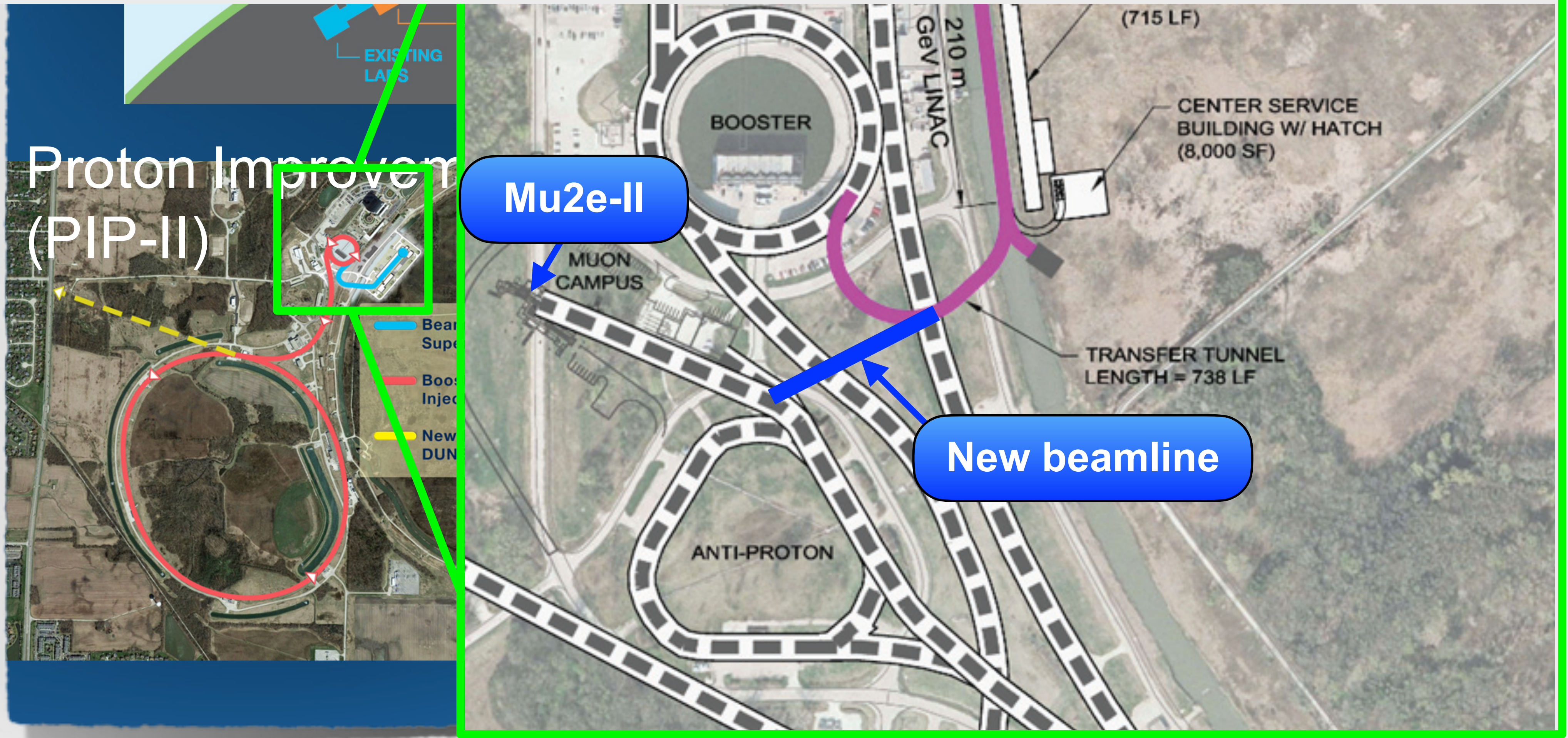
Category	Source	Events (Al)	Events (Ti)
Intrinsic	μ decay in orbit	0.26	1.19
	Radiative μ capture	<0.01	<0.01
Late Arriving	Radiative π capture	0.04	0.05
	Beam electrons	<0.01	<0.01
	μ decay in flight	<0.01	<0.01
	π decay in flight	<0.01	<0.01
Miscellaneous	Anti-proton induced	--	--
	Cosmic ray induced	0.16	0.16
Total Background:		**0.46**	**1.40**

Table 1: Estimated background yields for the Mu2e-II experiment assuming an aluminum (Al) or a titanium (Ti) stopping target. These studies were performed for a proton beam energy of 1 GeV. The total uncertainty is about 20%. Reproduced from arXiv:1307.1168. Note that, unlike in the case of aluminum, the titanium analysis has not yet been rigorously optimized.

Mu2e-II

PIP-II @ Mu2e-II

- PIP-II designed to deliver 800 MeV H- beam to the Booster
  - Capable of running in CW mode with 2 mA average current at 1.6 MW
  - Beam chopper can provide 8 pulses over 50 ns
- Mu2e-II will get a beam at upstream end of transfer line to Booster
  - Need to build a beamline to deliver beam to M4 enclosure



Mu2e-II white paper and workshops

- Mu2e-II is a natural extension of Mu2e
- White Paper arXiv:1307.1168
  - Estimated backgrounds at Mu2e-II rates, using current simulation framework
- Mu2e-II workshops in:
  - IF Workshop (ANL, 04/2013)
  - Snowmass (UM, 08/2013)
  - Mu2e (FNAL, 02/2016)
  - Mu2e II Workshop (ANL, 12/2017)
  - Mu2e-II Workshop (NWU, 08/2018)

arXiv:1307.1168[hep-ex]

Feasibility Study for a Next-Generation Mu2e Experiment

K. Knoepfel[3], V. Pronskikh[3], R. Bernstein[3], D.N. Brown[5], R. Coleman[3], C.E. Dukes[7], R. Ehrlich[7], M.J. Frank[7], D. Glenzinski[3], R.C. Group[3,7], D. Hedin[6], D. Hitlin[2], M. Lamm[3], J. Miller[1], S. Miscetti[4], N. Mokhov[3], A. Mukherjee[3], V. Nagaslaev[3], Y. Oksuzian[7], T. Page[3], R.E. Ray[3], V.L. Rusu[3], R. Wagner[3], and S. Werkema[3]

[1] *Boston University, Boston, Massachusetts 02215, USA*
[2] *California Institute of Technology, Pasadena, California 91125, USA*
[3] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[4] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[5] *Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[6] *Northern Illinois University, DeKalb, Illinois 60115, USA*
[7] *University of Virginia, Charlottesville, Virginia 22906, USA*

Submitted as part of the APS Division of Particles and Fields Community Summer Study

(dated: September 27, 2013)

We explore the feasibility of a next-generation Mu2e experiment that uses Project-X beams to achieve a sensitivity approximately a factor ten better than the currently planned Mu2e facility.

Expression of Interest

Expression of Interest for Evolution of the Mu2e Experiment†

F. Abusalma[23], D. Ambrose[23], A. Artikov[7], R. Bernstein[8], G.C. Blazey[27], C. Bloise[9], S. Boi[33], T. Bolton[14], J. Bono[8], R. Bonventre[16], D. Bowring[8], D. Brown[16], D. Brown[20], K. Byrum[1], M. Campbell[22], J.-F. Caron[12], F. Cervelli[30], D. Chokheli[7], K. Ciampa[23], R. Ciolini[30], R. Coleman[8], D. Cronin-Hennessy[23], R. Culbertson[8], M.A. Cummings[25], A. Daniel[12], Y. Davydov[7], S. Demers[35], D. Denisov[8], S. Denisov[13], S. Di Falco[30], E. Diociaiuti[9], R. Djilkibaev[24], S. Donati[30], R. Donghia[9], G. Drake[1], E.C. Dukes[33], B. Echenard[5], A. Edmonds[16], R. Ehrlich[33], V. Evdokimov[13], P. Fabbricatore[10], A. Ferrari[11], M. Frank[32], A. Gaponenko[8], C. Gatto[26], Z. Giorgio[17], S. Giovannella[9], V. Giusti[30], H. Glass[8], D. Glenzinski[8], L. Goodenough[1], C. Group[33], F. Happacher[9], L. Harkness-Brennan[19], D. Hedin[27], K. Heller[23], D. Hitlin[5], A. Hocker[8], R. Hooper[18], G. Horton-Smith[14], C. Hu[5], P.Q. Hung[33], E. Hungerford[12], M. Jenkins[32], M. Jones[31], M. Kargiantoulakis[8], K. S. Khaw[34], B. Kiburg[8], Y. Kolomensky[3,16], J. Kozminski[18], R. Kutschke[8], M. Lancaster[15], D. Lin[5], I. Logashenko[29], V. Lombardo[8], A. Luca[8], G. Lukicov[15], K. Lynch[6], M. Martini[21], A. Mazzacane[8], J. Miller[2], S. Miscetti[9], L. Morescalchi[30], J. Mott[2], S. E. Mueller[11], P. Murat[8], V. Nagaslaev[8], D. Neuffer[8], Y. Oksuzian[33], D. Pasciuto[30], E. Pedreschi[30], G. Pezzullo[35], A. Pla-Dalmau[8], B. Pollack[28], A. Popov[13], J. Popp[6], F. Porter[5], E. Prebys[4], V. Pronskikh[8], D. Pushka[8], J. Quirk[2], G. Rakness[8], R. Ray[8], M. Ricci[21], M. Röhrken[5], V. Rusu[8], A. Saputi[9], I. Sarra[21], M. Schmitt[28], F. Spinella[30], D. Stratakis[8], T. Strauss[8], R. Talaga[1], V. Tereshchenko[7], N. Tran[2], R. Tschirhart[8], Z. Usubov[7], M. Velasco[28], R. Wagner[1], Y. Wang[2], S. Werkema[8], J. Whitmore[8], P. Winter[1], L. Xia[1], L. Zhang[5], R.-Y. Zhu[5], V. Zutshi[27], R. Zwaska[8]

06 February 2018

arXiv:1802.02599

Abstract

We propose an evolution of the Mu2e experiment, called Mu2e-II, that would leverage advances in detector technology and utilize the increased proton intensity provided by the Fermilab PIP-II upgrade to improve the sensitivity for neutrinoless muon-to-electron conversion by one order of magnitude beyond the Mu2e experiment, providing the deepest probe of charged lepton flavor violation in the foreseeable future. Mu2e-II will use as much of the Mu2e infrastructure as possible, providing, where required, improvements to the Mu2e apparatus to accommodate the increased beam intensity and cope with the accompanying increase in backgrounds.

- Submitted Expression of Interest in 2018
- 130 signatures, 36 institutions
- Positive feedback from Fermilab Physics Advisory Committee: "The PAC endorses the Mu2e-II request of dedicated R&D funding and encourages them to engage the Laboratory and funding agencies into identifying the required resources"

Backgrounds at Mu2e-II

- Mu2e-II assumes 3 years of running
- Total muon stopped muons: $6 \cdot 10^{18}$
- Single event sensitivity: $3 \cdot 10^{-18}$
  - Total background needs to be kept <1 event

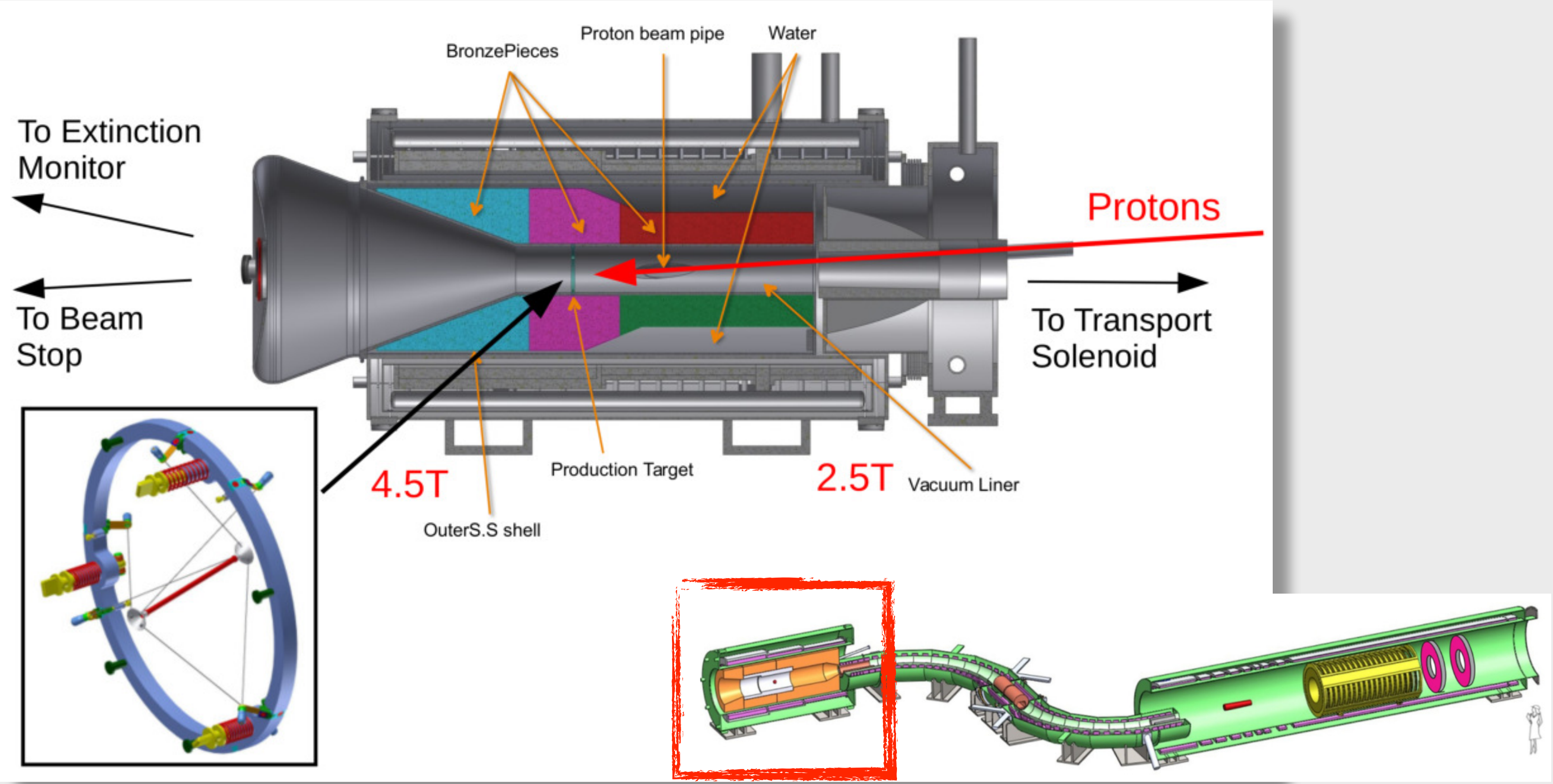
Dominant Background Sources

arXiv:1802.02599

Category	Source	Mu2e	Mu2e-II	Assumption
Intrinsic	μ decay in orbit	0.144	0.26	Improved tracker resolution and thinner ST
Late Arriving	Radiative π capture	0.02	0.04	Extinction $<10^{-11}$
Miscellaneous	Anti-protons	0.04	0	Beam energy below $\overline{p}$ threshold
	Cosmic rays	0.21	0.16	Improved veto efficiency with 3x live-time

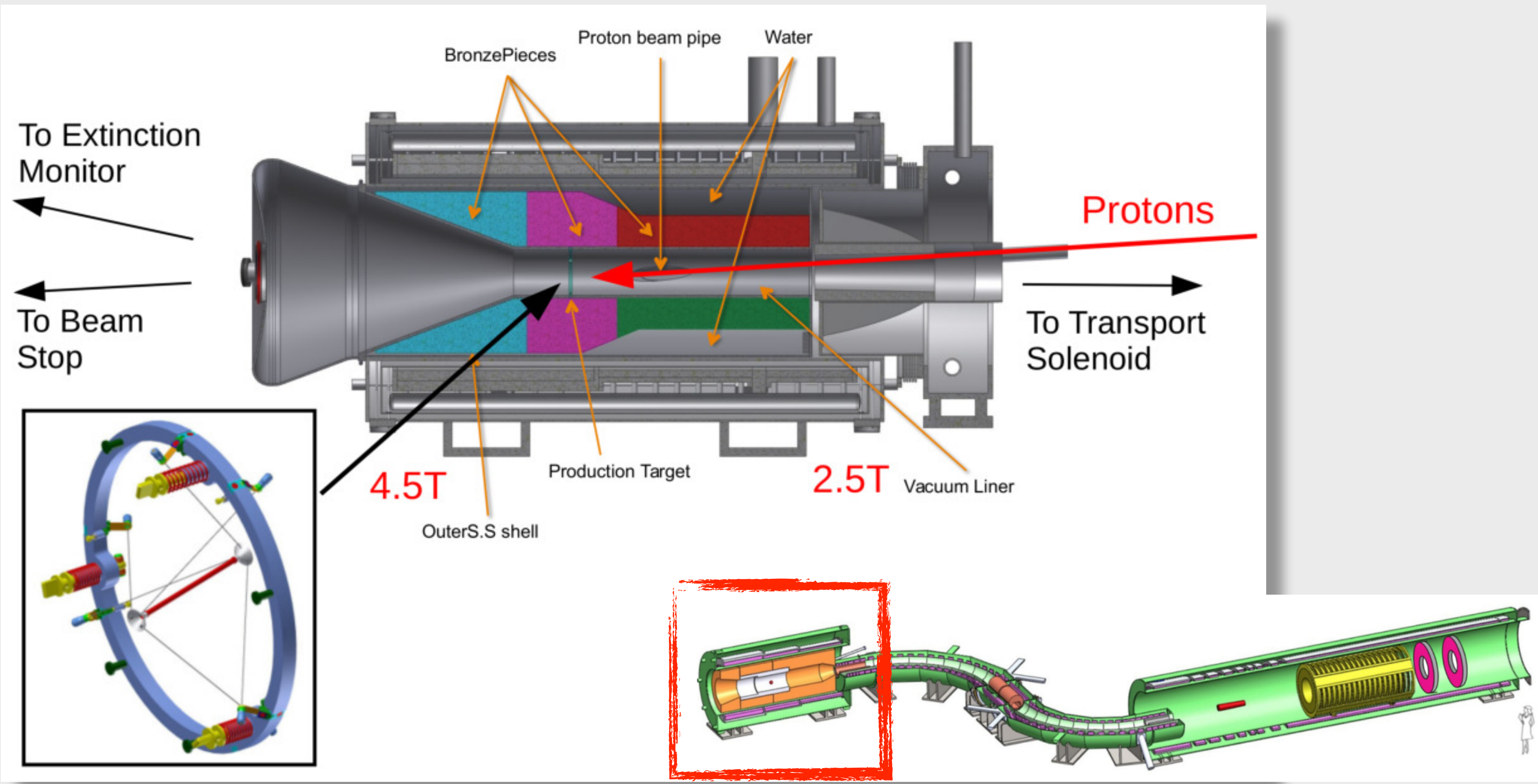
Beam production and transport

- Need to tolerate x10 beam more power
  - Power density and radiation damage imposes challenges
- Target station:
  - Active cooling (water or helium), liquid target and/or rasterizing the beam on the target face



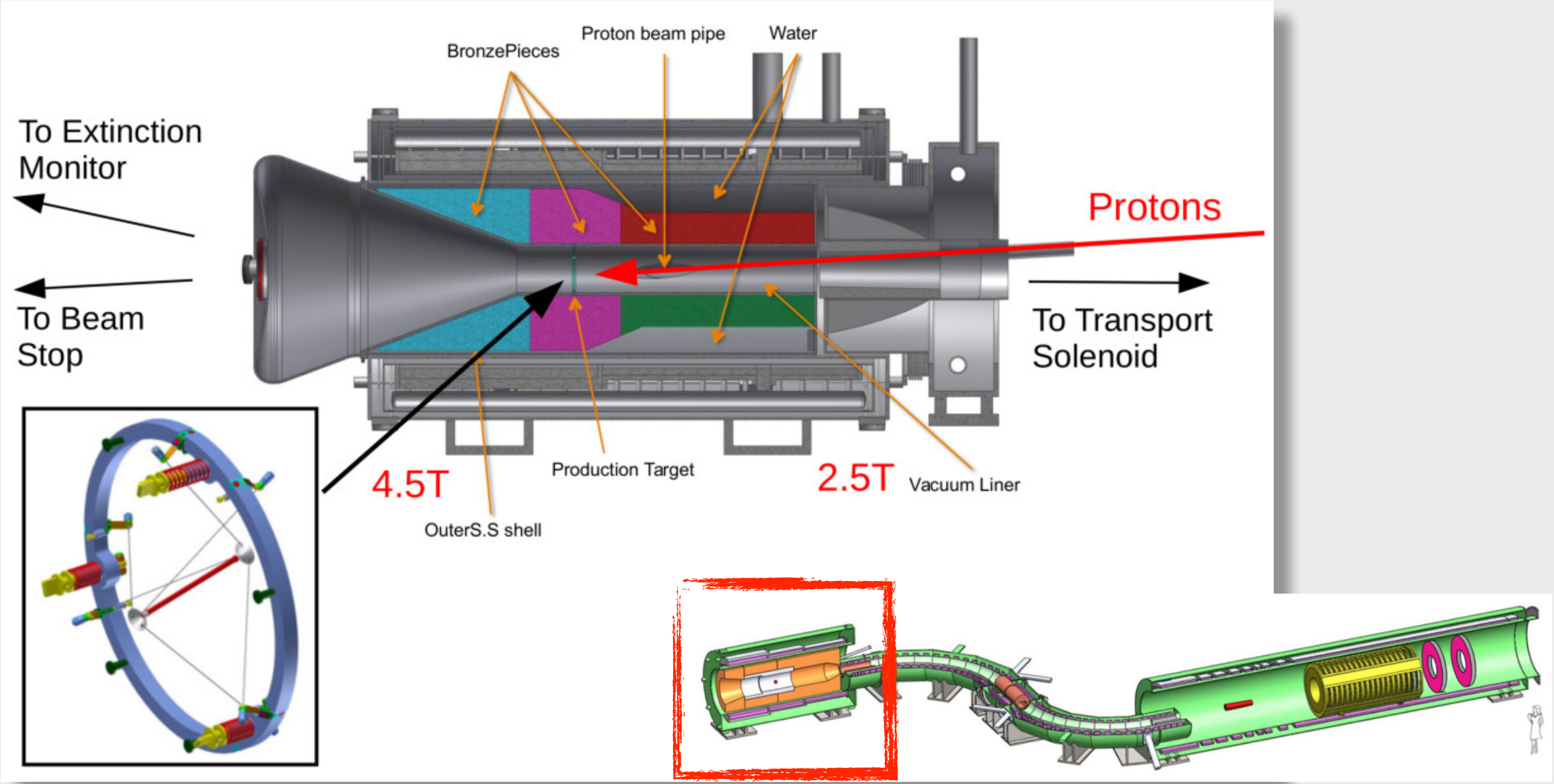
Beam production and transport

- PS Solenoid: radiation damage and heat load in super-conducting coils
  - Simulations indicate that change of Heat Radiation Shield from brass to tungsten may be adequate
- Remote target handling
- Radiation safety (overburden)



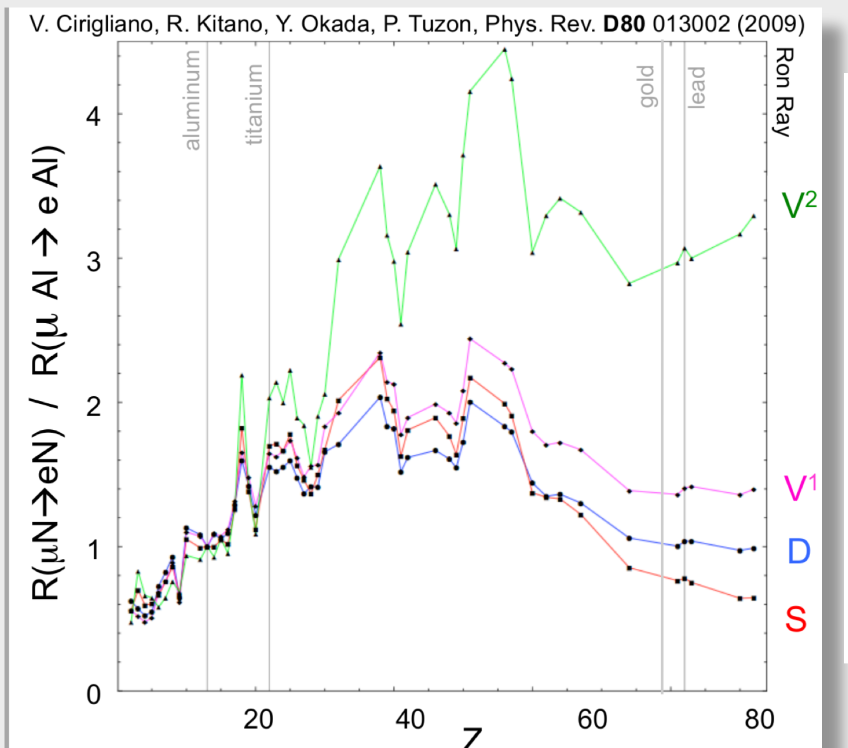
Beam production and transport

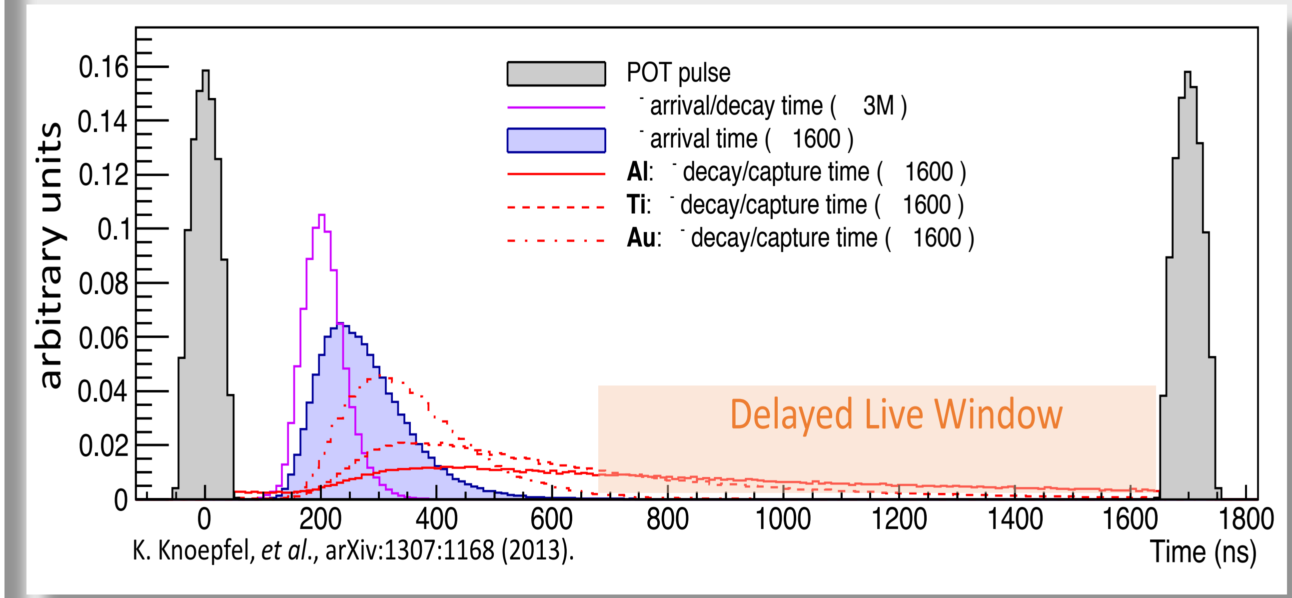
- Aiming the beam on target: 0.8 GeV (Mu2e-II) vs 8 GeV (Mu2e)
  - Studies suggest that Mu2e-II off-axis beam injection may address the aiming issue
  - Impacts the position of beam dump and extinction monitor position



Stopping target

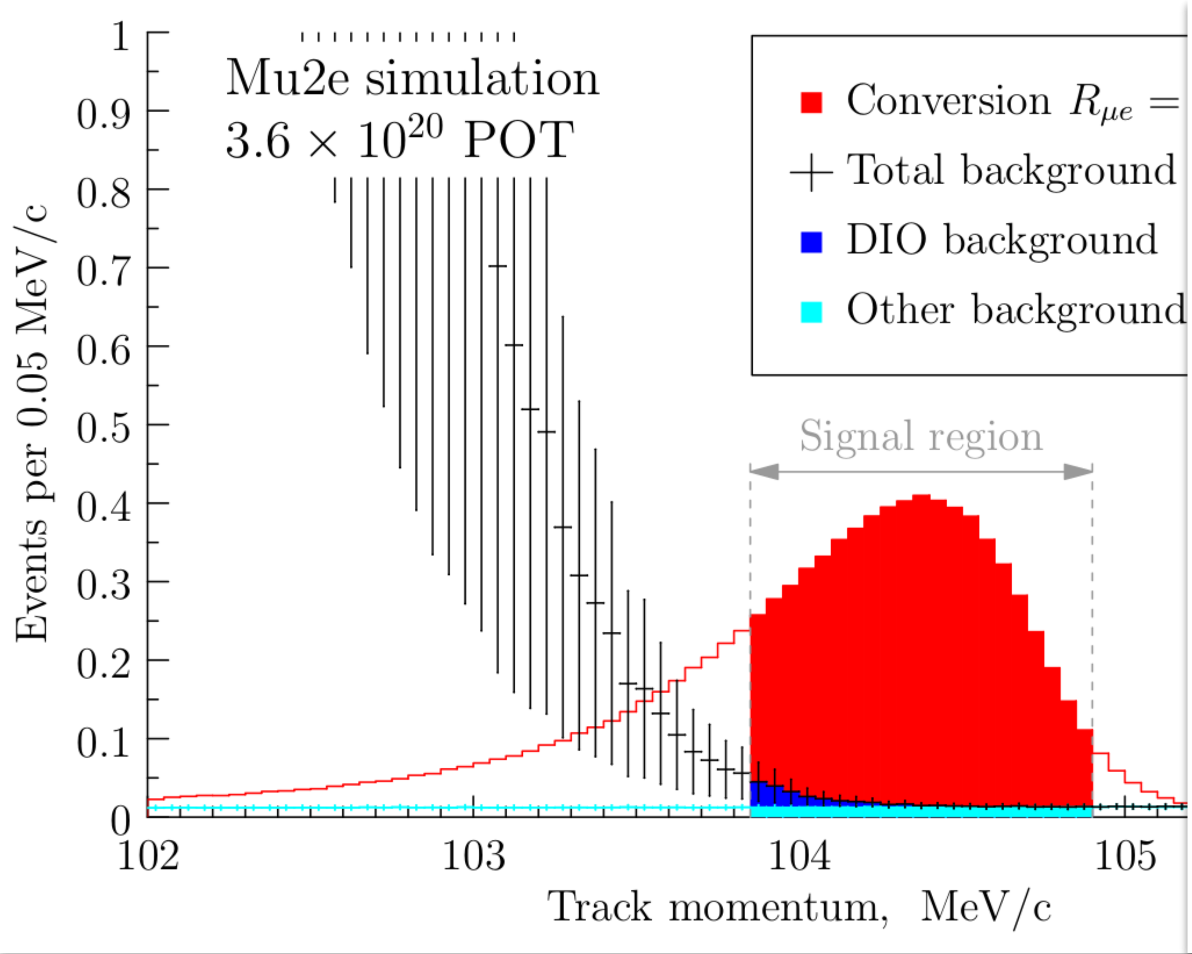
- Mu2e-II will need thinner stopping target, to improve momentum resolution and suppress Decay In Orbit (DIO) background
- If the signal is observed, will change stopping target to probe underlying NP operator
  - Aluminum & Titanium stopping targets investigated
- Will adjust the micro-bunch length period to accommodate the muon lifetime on Titanium: 329 ns

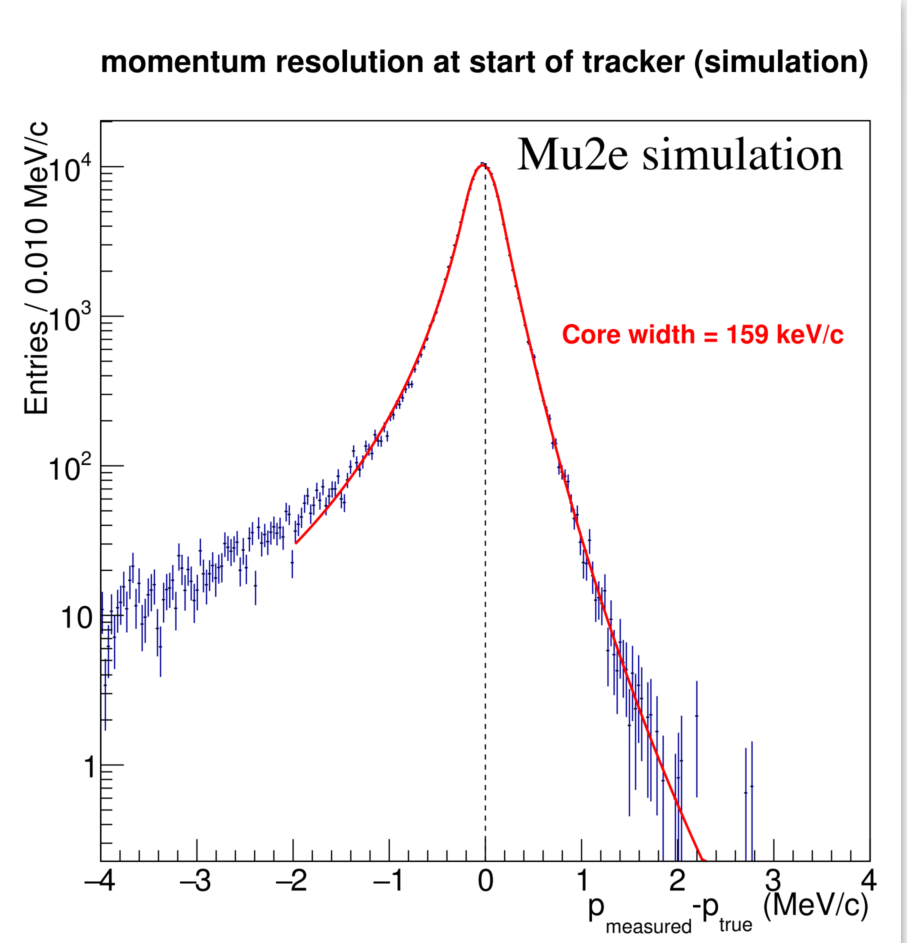




Tracker

- Mu2e tracker features <200 KeV momentum resolution to suppress DIO background
- DIO scales with the number of stopped muon
- Expected DIO background at Mu2e: 0.14 events





Tracker

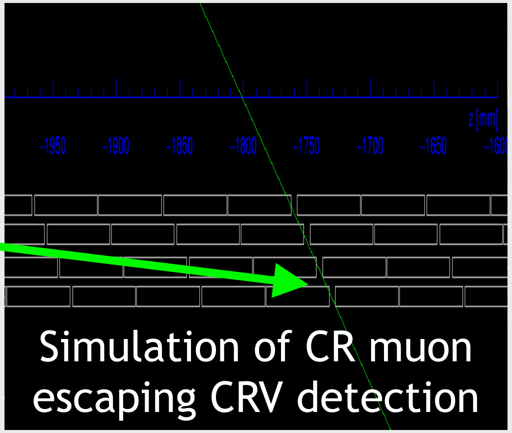
- Mu2e tracker features <200 KeV momentum resolution to suppress DIO background
- DIO scales with the number of stopped muon
- Expected DIO background at Mu2e: 0.14 events
- DIO background would increase 10x at Mu2e-II, linear to the number of stopped muons
- Improve momentum resolution to suppress DIO to 0.26 events by reducing tracker straws thickness: $15\ \mu m \rightarrow 8\ \mu m$
  - Additional R&D is required to address challenges with: vacuum tightness, long term stability and large scale production
- Radiation levels would likely exceed the safety factor
  - Expected 3 Mrad will damage some commercial off-the-shelf tracker components
  - Consider using application-specific integrated circuit electronics to handle the radiation levels in the Mu2e-II environment
- Investigate other detector alternatives

Calorimeter

- Calorimeter is used for PID and cosmic ray suppression
- Fast timing is used to seed tracking and provide a fast trigger
- The radiation doses and rates at Mu2e-II are high for CsI crystals used at Mu2e
- R&D choice has been investigated:
  - BaF_2 is an excellent upgrade choice, if slow visible scintillation component is suppressed
  - Suppress the slow scintillation component by doping BaF_2 with Yttrium
  - Develop photosensor sensitive to the UV component only
    - SiPM with an external filter
    - UV-sensitive photocathodes
    - Solar-blind MCP

Proposed counter design

- The CRV efficiency is adversely impacted by the gaps between scintillating counters and CRV modules
- The dominant fraction (>99%) of the background inducing CR muons impact CRV at an angle $<60^0$



Simulation of CR muon escaping CRV detection

- Benefits of proposed design:
  - Improved efficiency due to smaller effective gaps
  - Improved (x3) positional resolution due to finer granularity and charge-sharing
  - Lower (~x2) per-channel rate
  - Lower (?) aging rate due to smaller profile
  - Simplified design of future modules