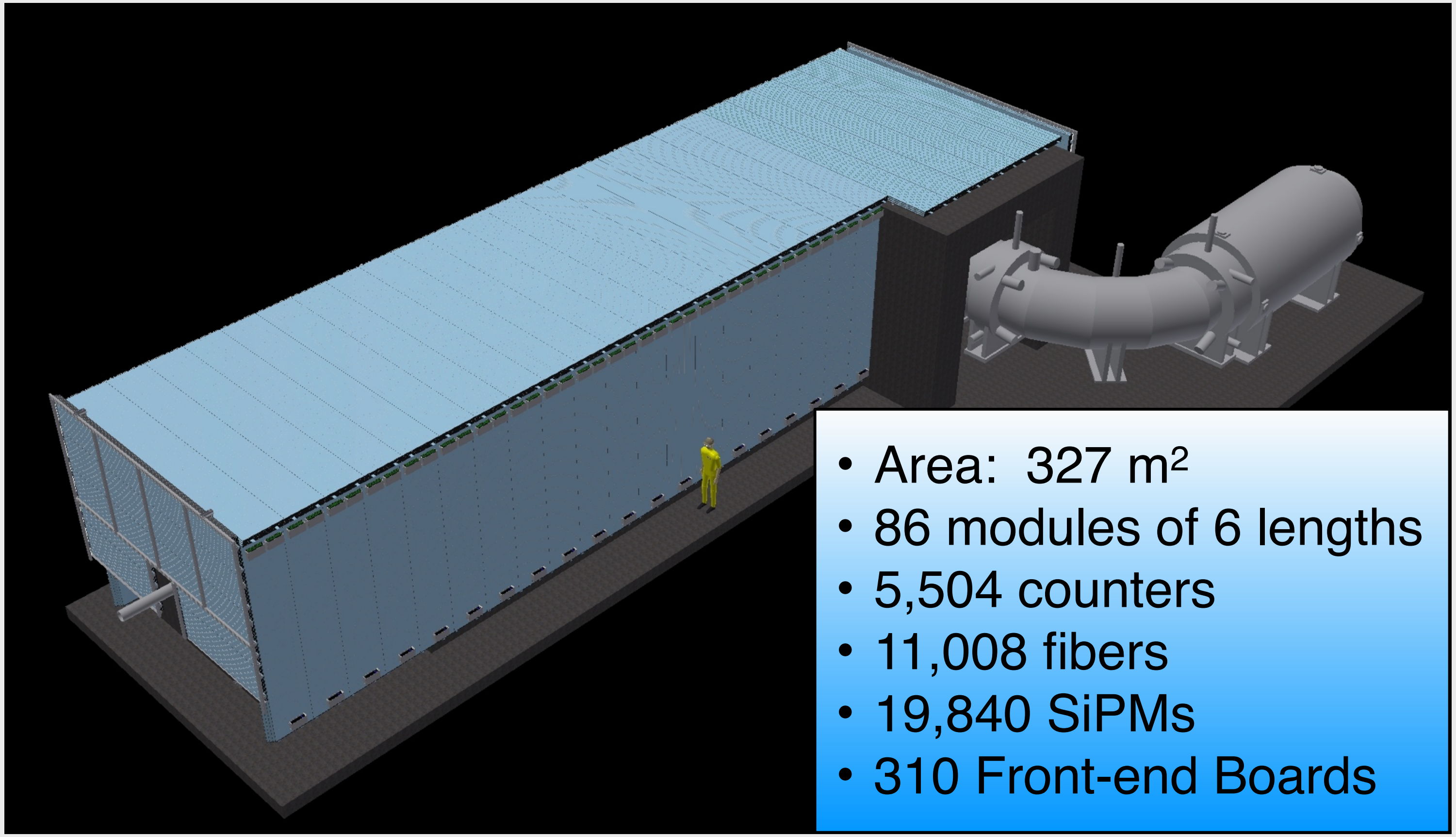
CRV at Mu2e-II

Members and goals

- Conveners: Yuri Oksuzian, Craig Dukes
- Group members: current CRV team members
- Group goals:
  - Submit LOI by the end of August 2020
  - Explore the CRV design(s) that will work at Mu2e-II
  - Submit Snowmass contributed paper by the end July 2021

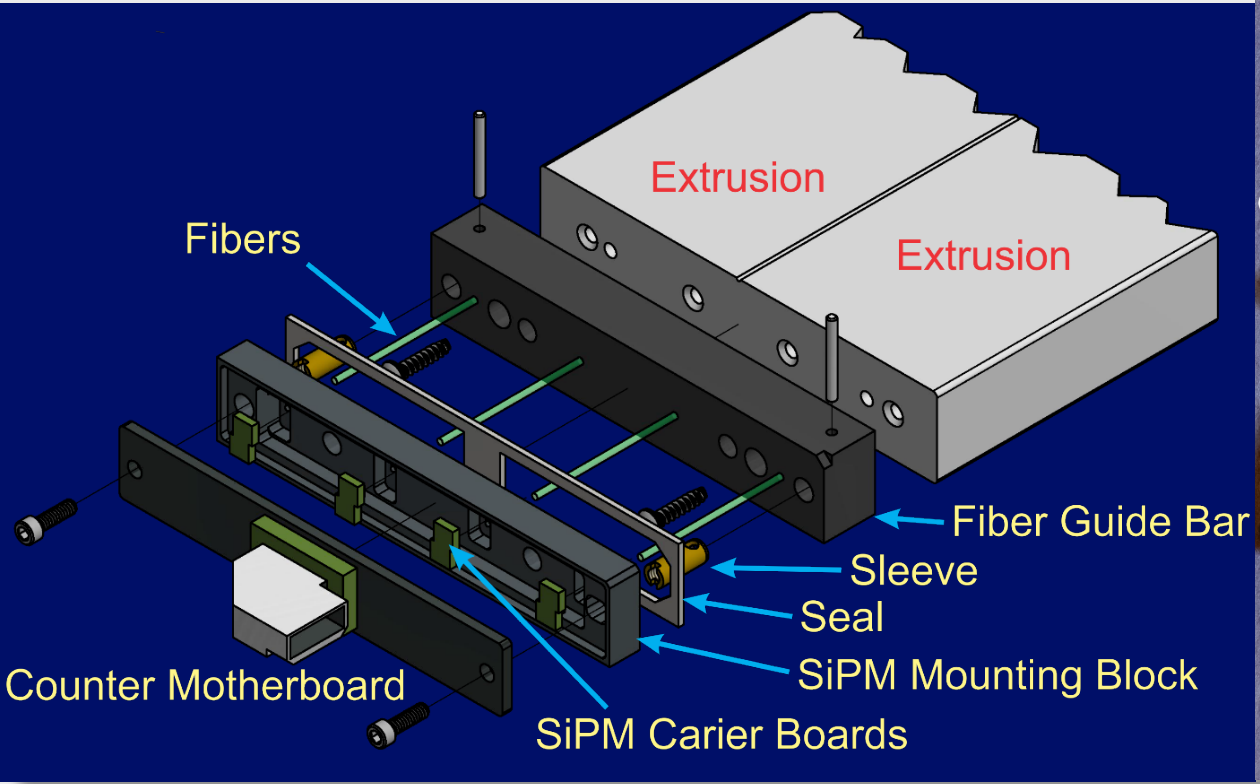
Cosmic Ray Veto

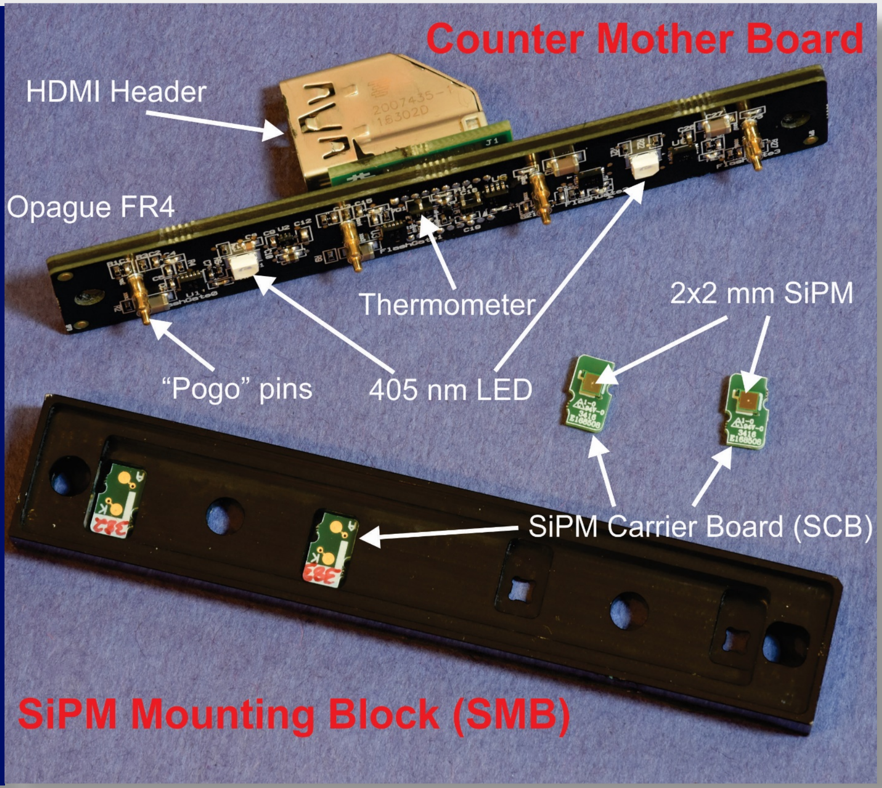
- CRV consists of 4-layer scintillating 5x2 cm^2 counters, read-out through wavelength-shifting fibers by 2x2 mm^2 SiPMs
- Cosmic ray muon detection - hits coincidence in 3/4 (or 4/4) layers localized in time and space
- Veto (offline) 125 ns from a signal window after a coincidence in the CRV



- Area: 327 m^2
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards

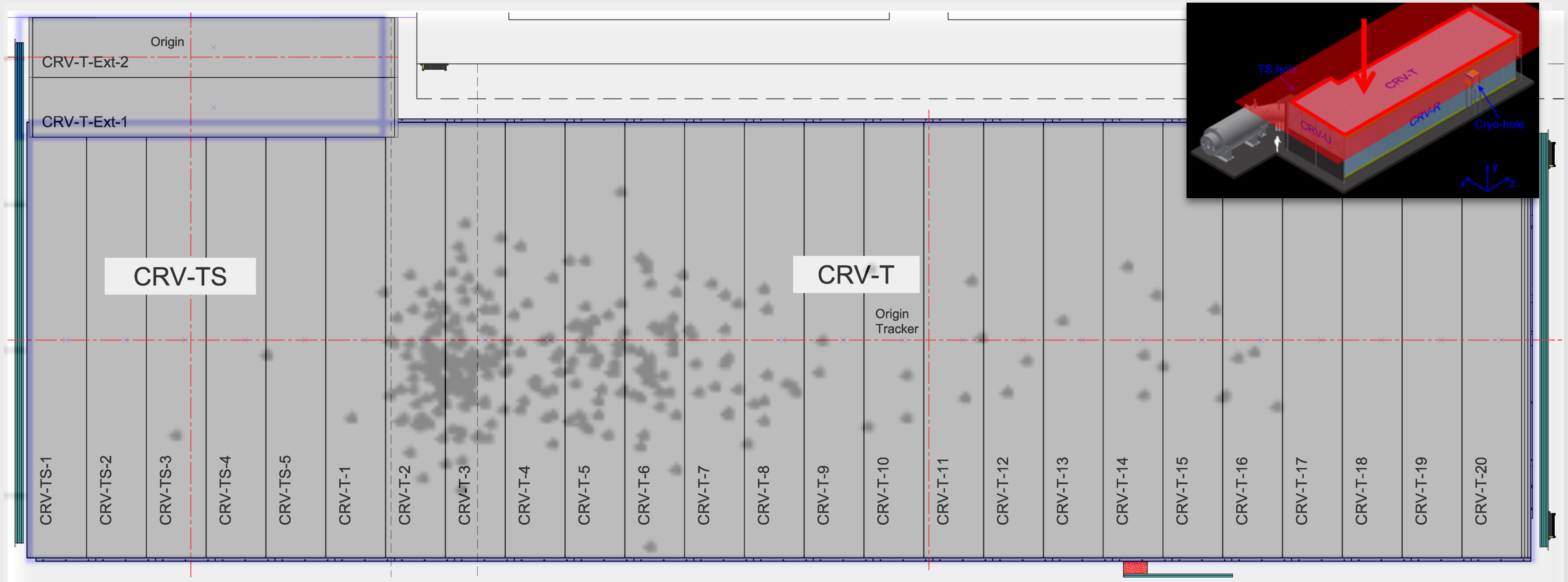
- Counters: extruded PS doped with 1%PPO+0.05%POPOP, coated with TiO_2
  - Glued in pairs to make di-counters
- Each counter has two 1.4 mm wavelength-shifting fibers placed in channels
- Fiber Guide Bar is glued and fly-cut
- Fibers are read out by SiPMs





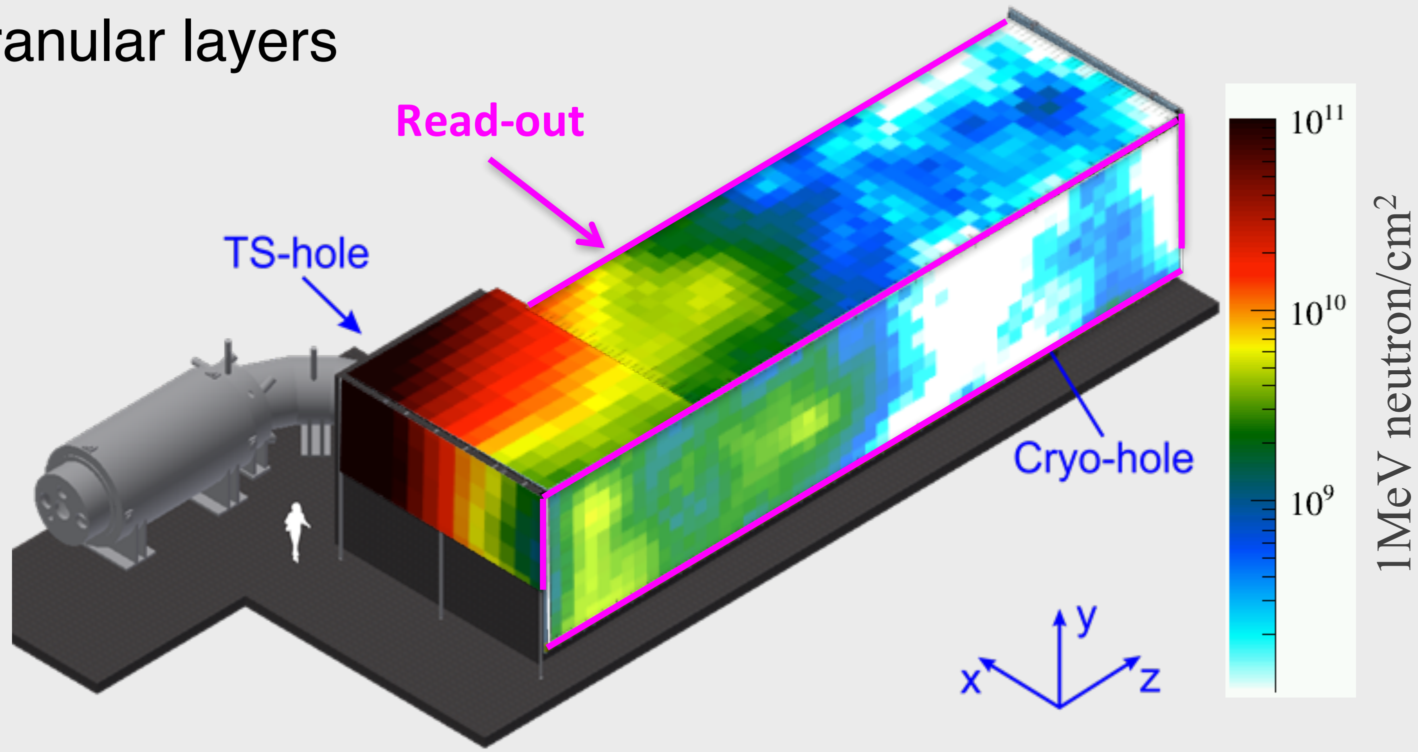
Enhancing CRV performance

- 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



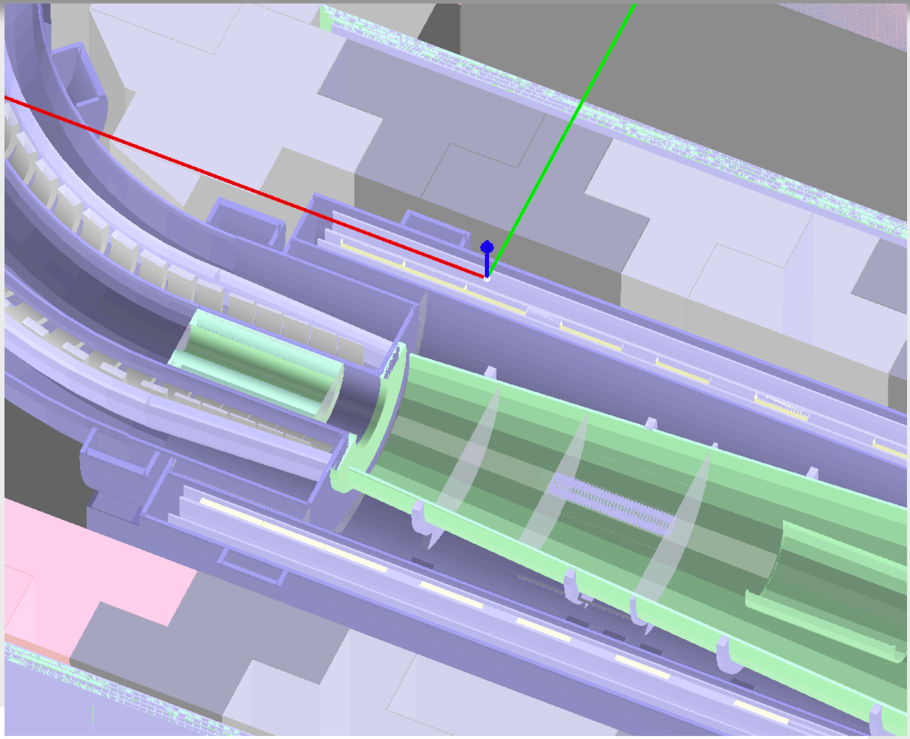
Cosmic Ray Veto

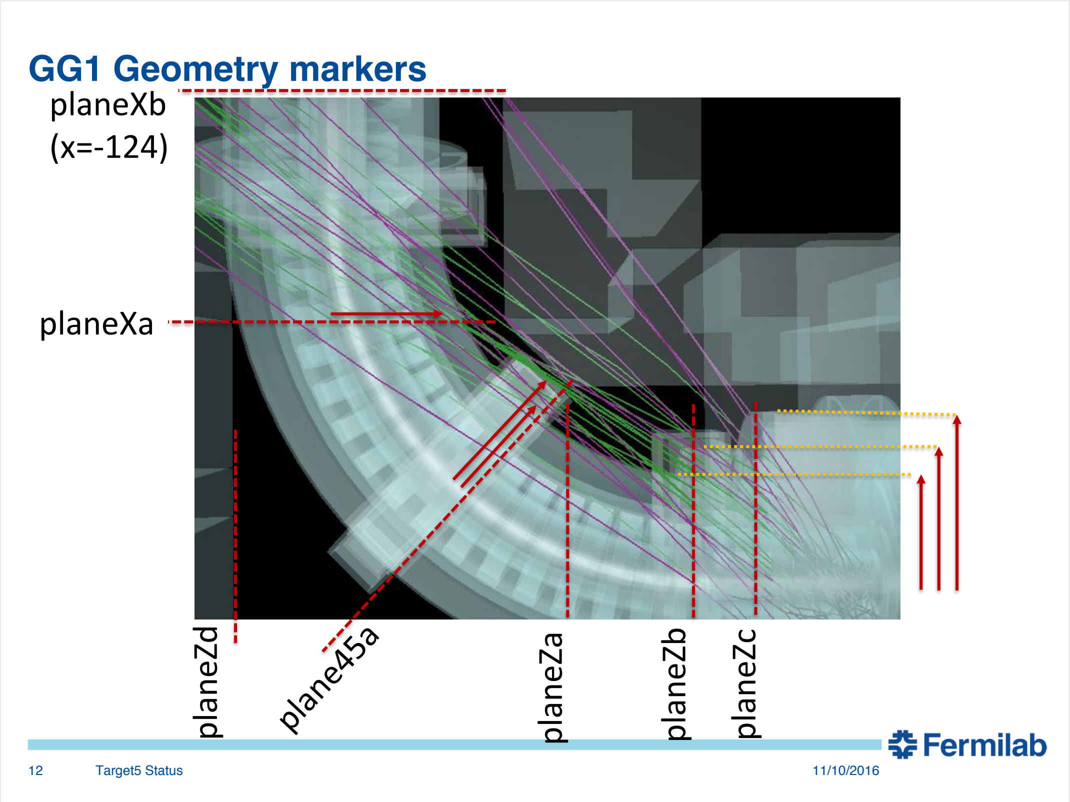
- Higher (x2-3) noise rates impose challenges: higher DAQ rates, rad damage to electronics and induced dead-time by CRV
  - Consider enhanced shielding: tungsten PS and high-Z boron doped concrete
  - Explore other detector technologies to withstand higher rates in ‘hot’ regions
  - Add more fine-granular layers

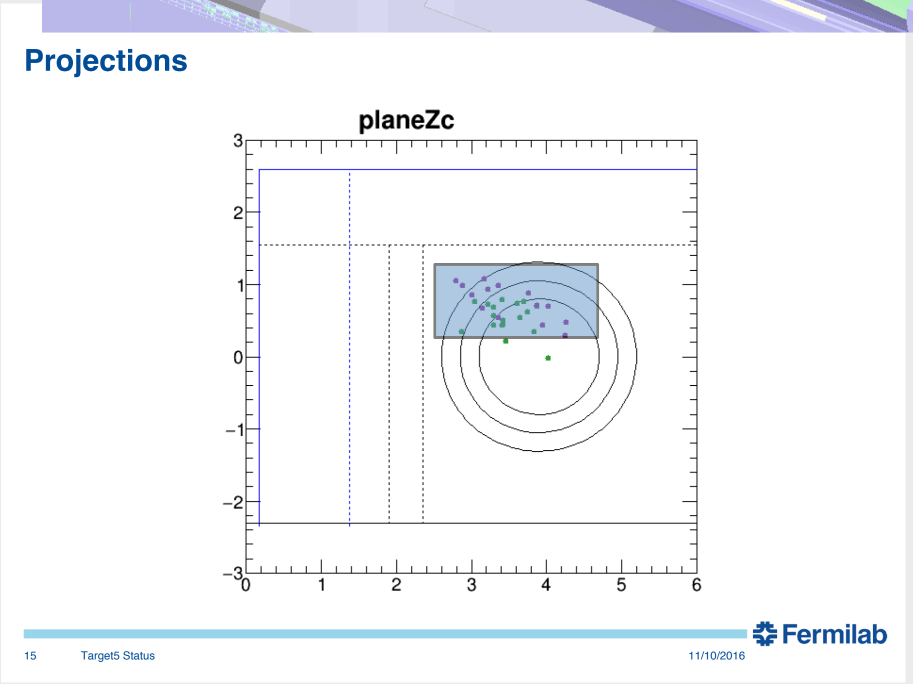


Reducing irreducible

- CR background entering through TS hole is a significant (>0.15) background at Mu2e-II
- We currently reduce this background with passive absorbers
- We can consider:
  - Additional passive absorbers
  - CRV along the beam-line or inside DS

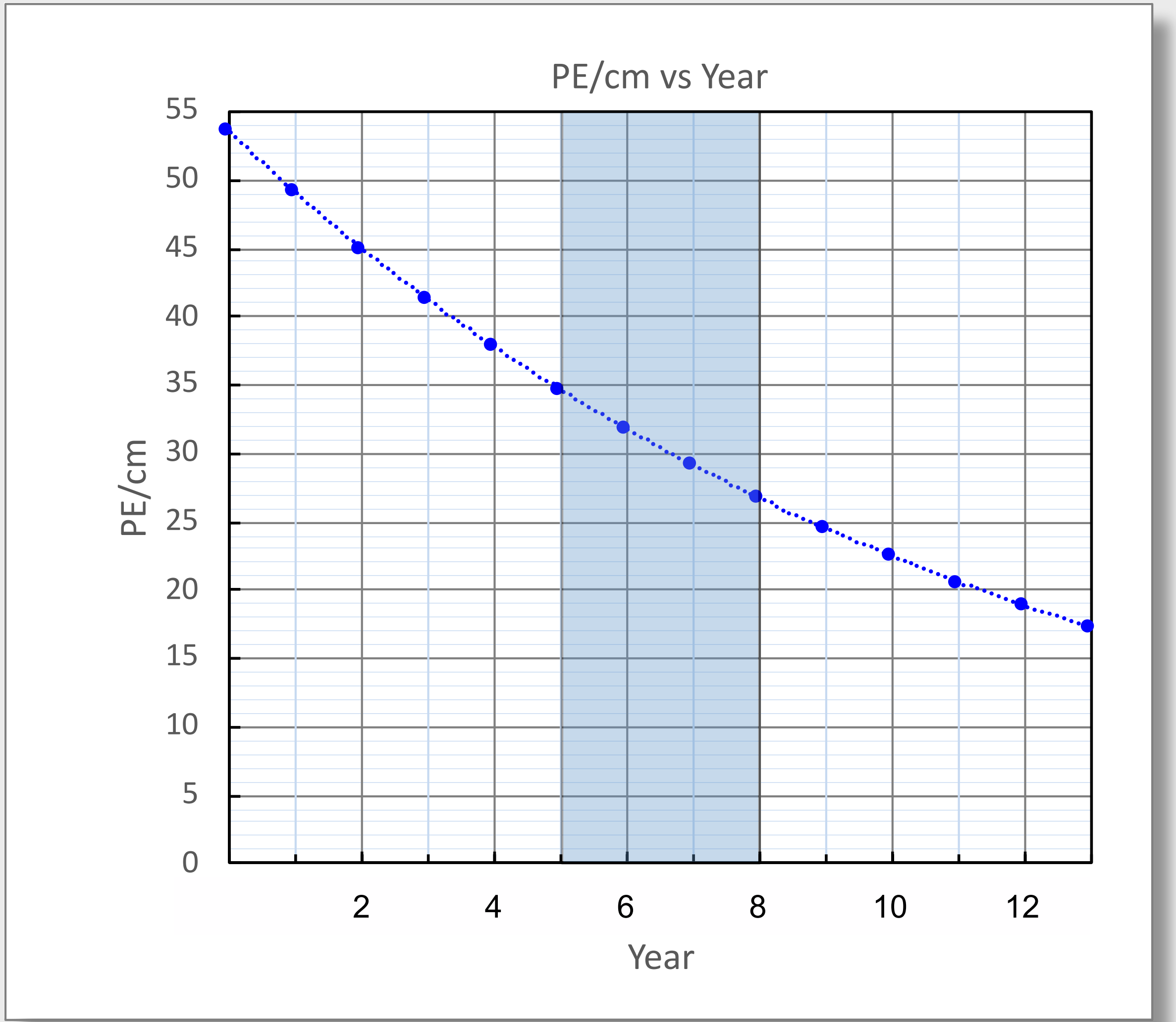






Light yield degradation

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



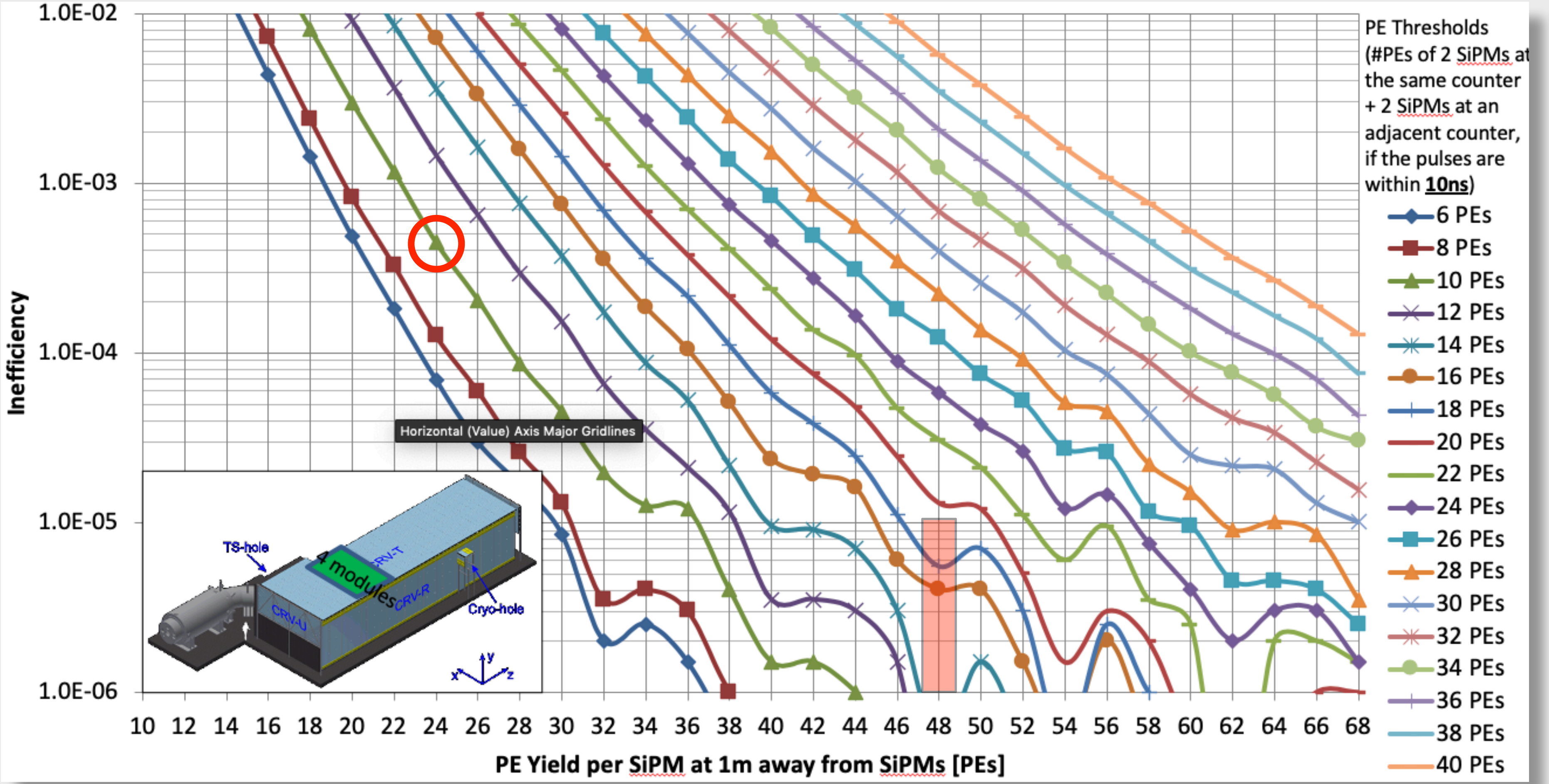
Expected background with current CRV

- 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
Neutrals	0.02	0.04		0.0	1.0000	0.0		0.0	1.0000	0.0		0.0	1.0000	0.0
	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**												

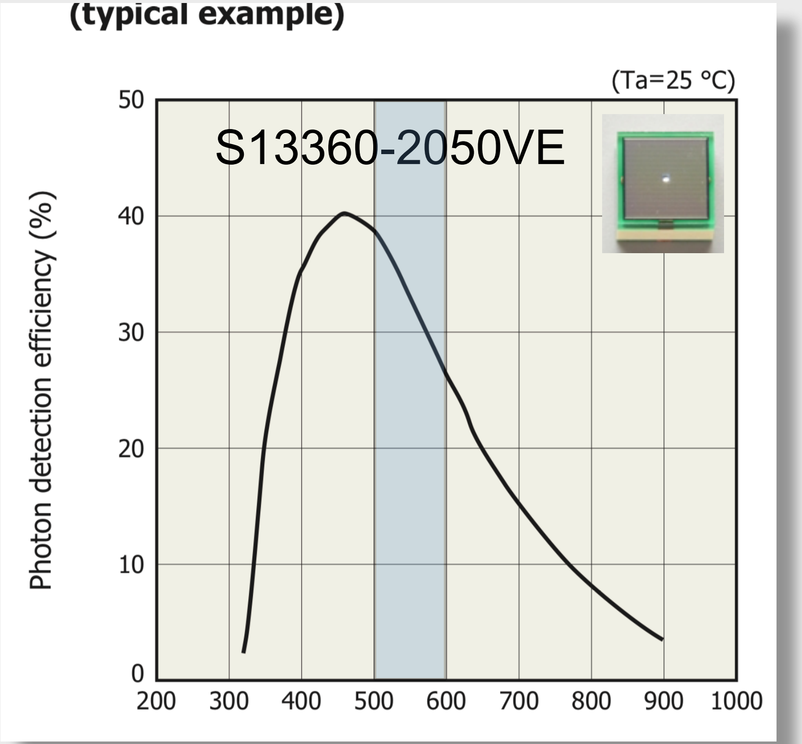
CRV efficiency vs light yield

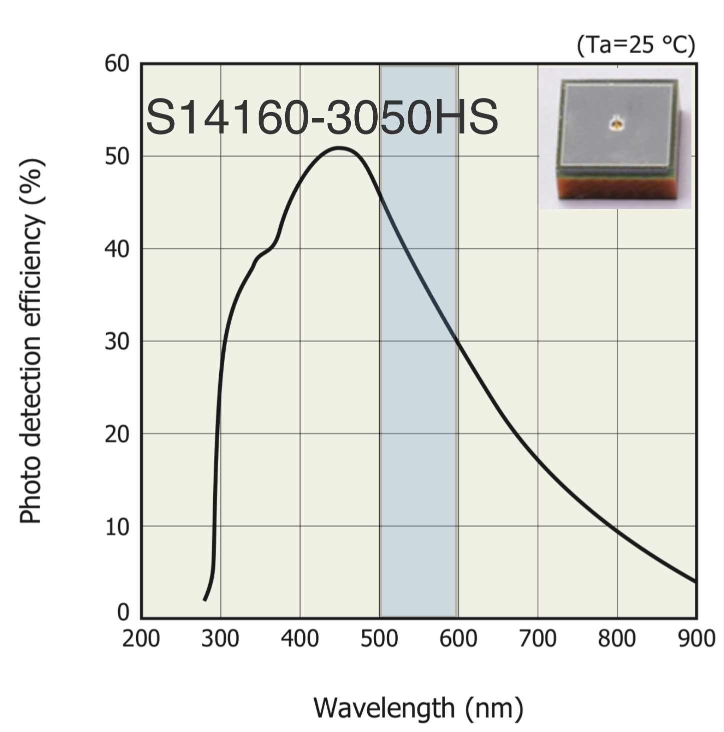
- The CRV detection efficiency improves by a couple orders of magnitude, if we improve the light yield by a factor of 2
  - This would veto muons impacting CRV to a negligible fraction
- The dominant background contribution (~0.3 events) will be induced by TS-opening events



SiPM with improved PDE

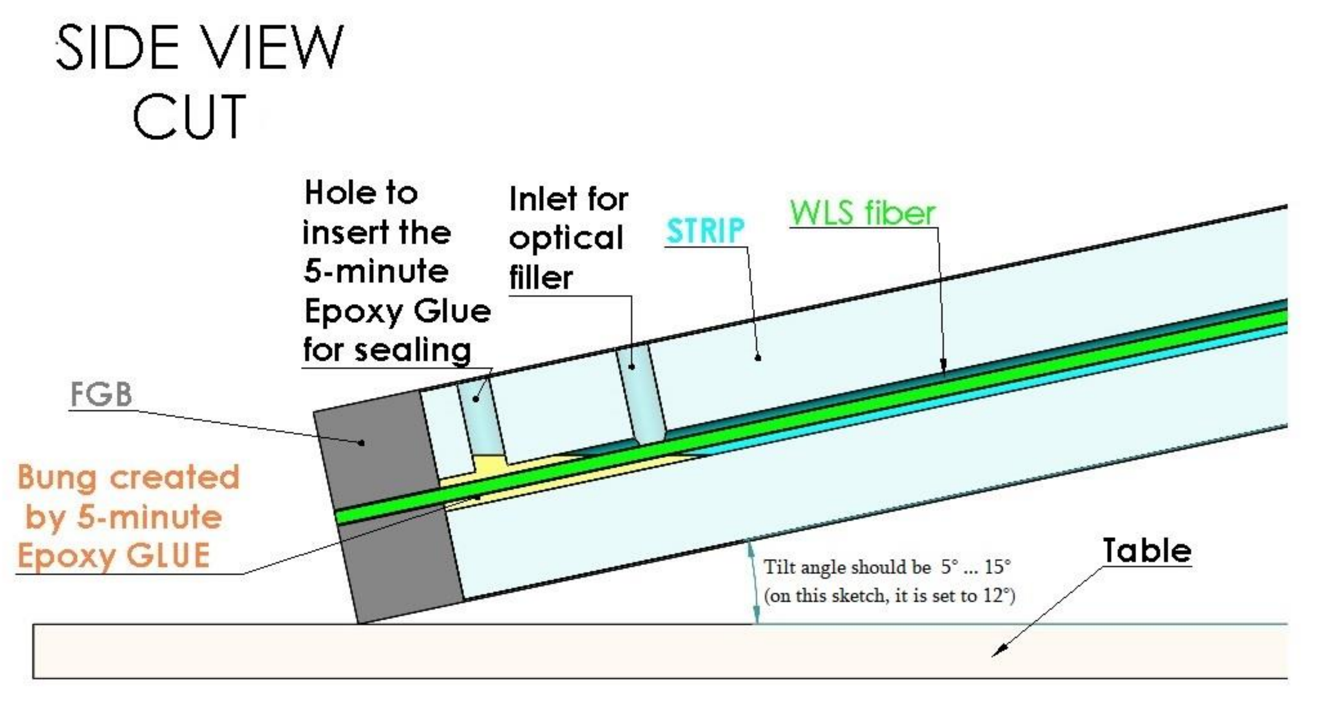
- Light yield is improved by 24% by switching from 1.4 to 1.8 mm fiber
- SiPM technology has advanced since the CRV was designed
- We can consider SiPMs with:
  - PDE peaked in green-yellow spectrum
  - Enhanced (20%) PDE overall





Potting fiber channels

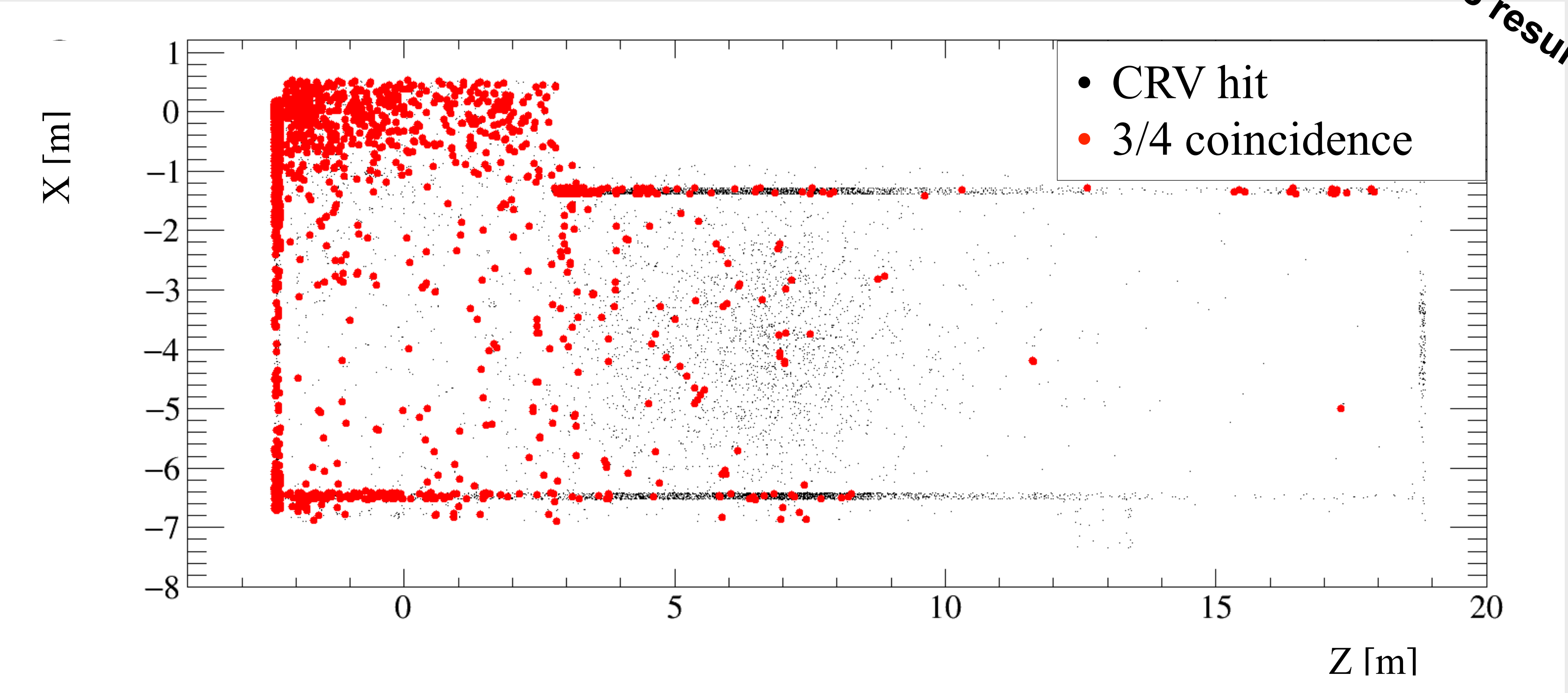
- Light collection can be improved by 40%, if fiber channels are filled with silicone resin
- Concern: silicone resin might leak damaging read-out
- Dubna team has been investigating an improved procedure to pot fibers
  - Fill the counter end with epoxy to enhance the seal at FGB
- Plan to send required material to Dubna to perform the studies



Dead-time at Mu2e II

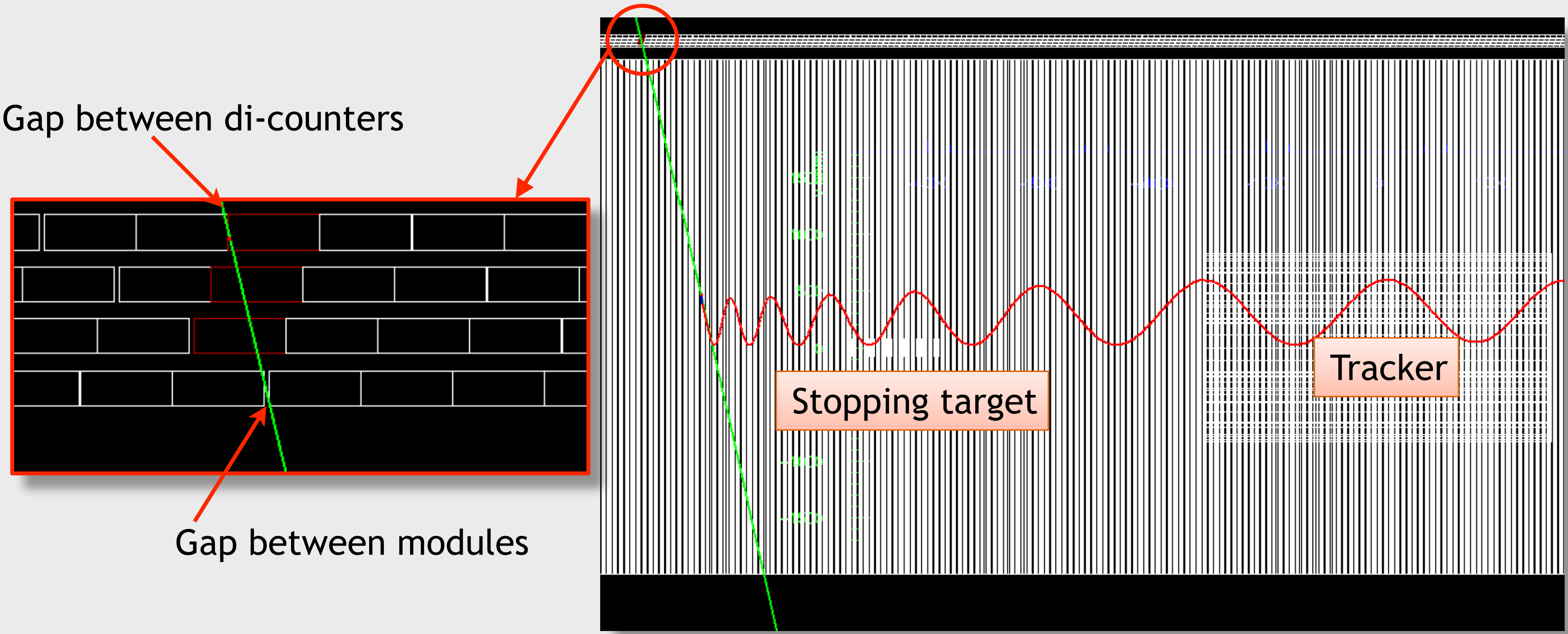
- I simulated 800 MeV protons to estimate the rates and dead-time in CRV
  - The total simulated POT of 10E9 is only sufficient for ~10 ubunches
- The total dead-time > 50%
- Finer granularity detector is required to suppress the dead-time
  1. 2.5x2 cm2 rectangular extrusions
  2. 2.5x1.5 cm2 triangular extrusions

2018 results



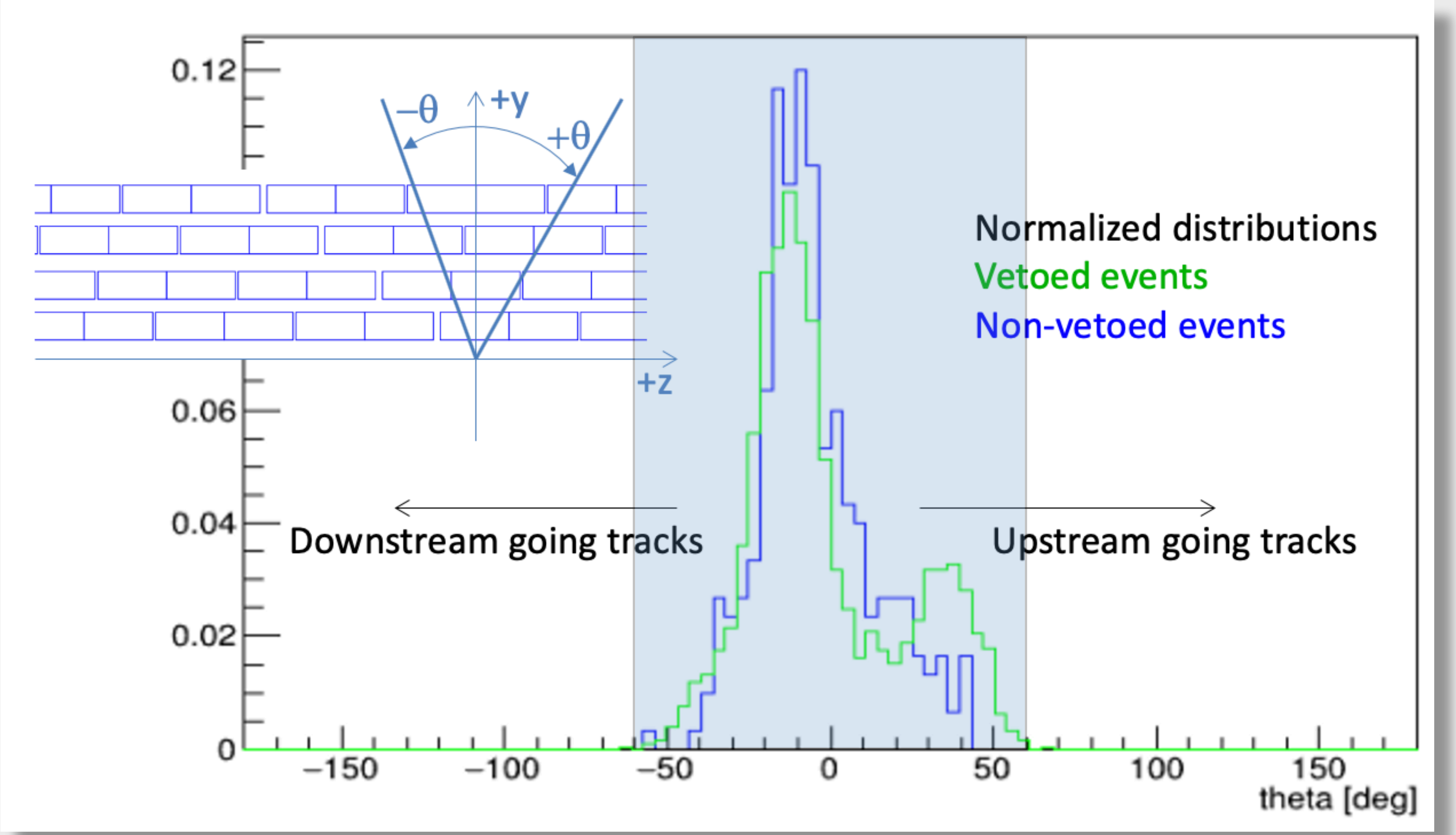
Sources of CRV inefficiencies

- 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



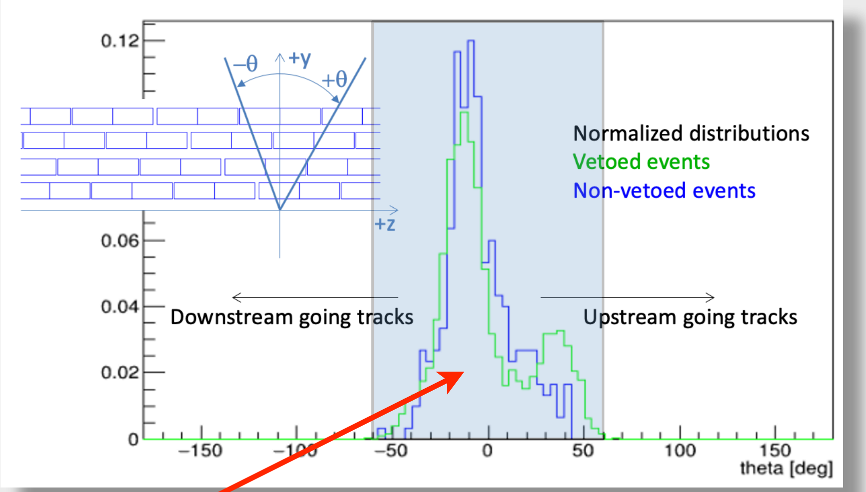
Cosmic ray angles of incidence

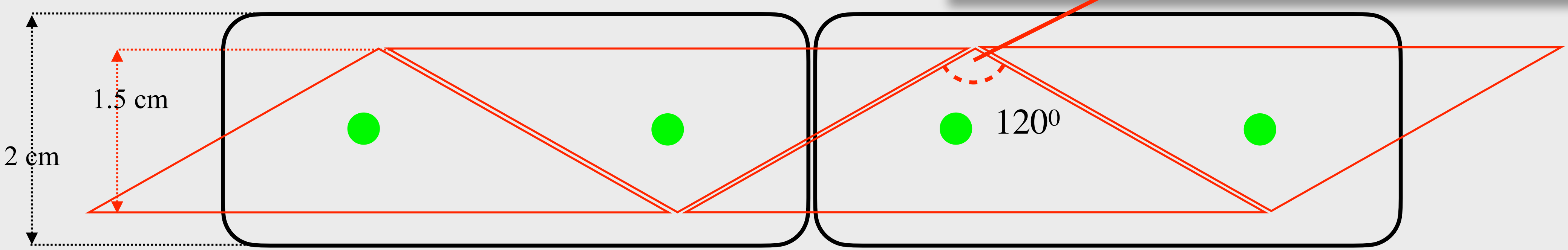
- The dominant fraction of the background inducing CR muons impact CRV at an angle <60^0



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





Options to explore

- Option 1: Current CRV design: 5x2 cm^2 counter profile
  - Advantages: mature design, available simulation tools (MC samples and reco algorithms) to extract background rates
  - Disadvantages: sensitive to gaps, high aging rate, high noise rates
  - Baseline CRV performance
- Option 2: Triangular-shape counter design
  - Advantages: addresses disadvantages from option 1
  - Disadvantages: requires additional R&D resources
  - Enhanced CRV performance
- Option 3: 2.5x2 cm^2 counter profile
  - Advantages: similar to ‘option 1’
  - Disadvantages: more gaps than in ‘option 1’
- Other options: RPC in hot regions

Cosmic ray background simulation

- We can explore the following for the Snowmass process
- Update the CRV and shielding geometry
- Update or reuse light yield lookup tables
- Update the coincidence finder
- Produce a sample of cosmic ray muons to estimate the background at Mu2e-II
- Produce a sample of beam induced neutrons to estimate the rad damage, SiPM noise and dead-time

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 read-out noise
- The background contribution from TS-opening becomes large at Mu2e-II
- The group is just forming
  - Help is welcome

Backup

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

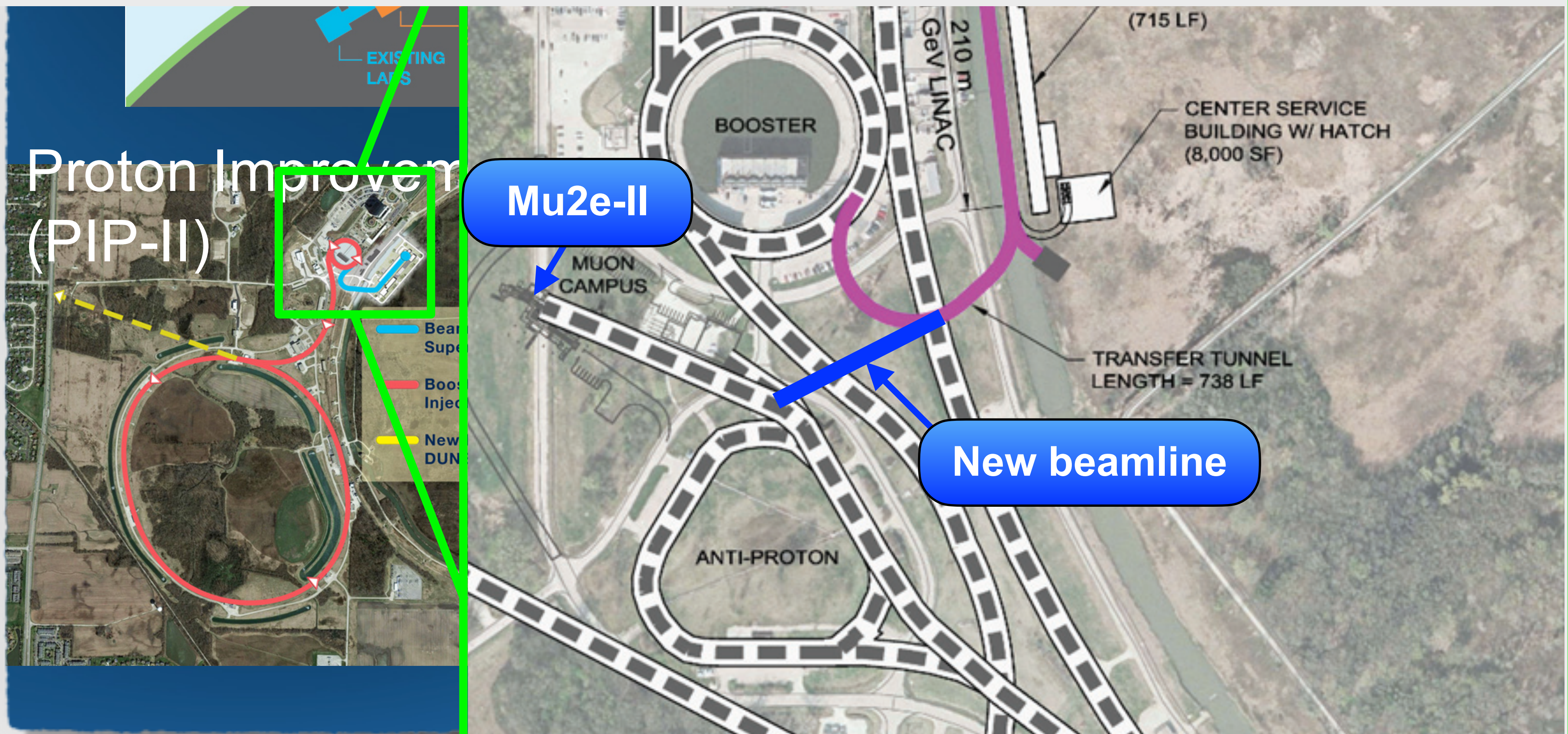
Category	Source	Events (Al)	Events (Ti)
Intrinsic	μ decay in orbit	0.26	1.19
	Radiative μ capture	<0.01	<0.01
Late Arriving	Radiative π capture	0.04	0.05
	Beam electrons	<0.01	<0.01
	μ decay in flight	<0.01	<0.01
	π decay in flight	<0.01	<0.01
Miscellaneous	Anti-proton induced	--	--
	Cosmic ray induced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

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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

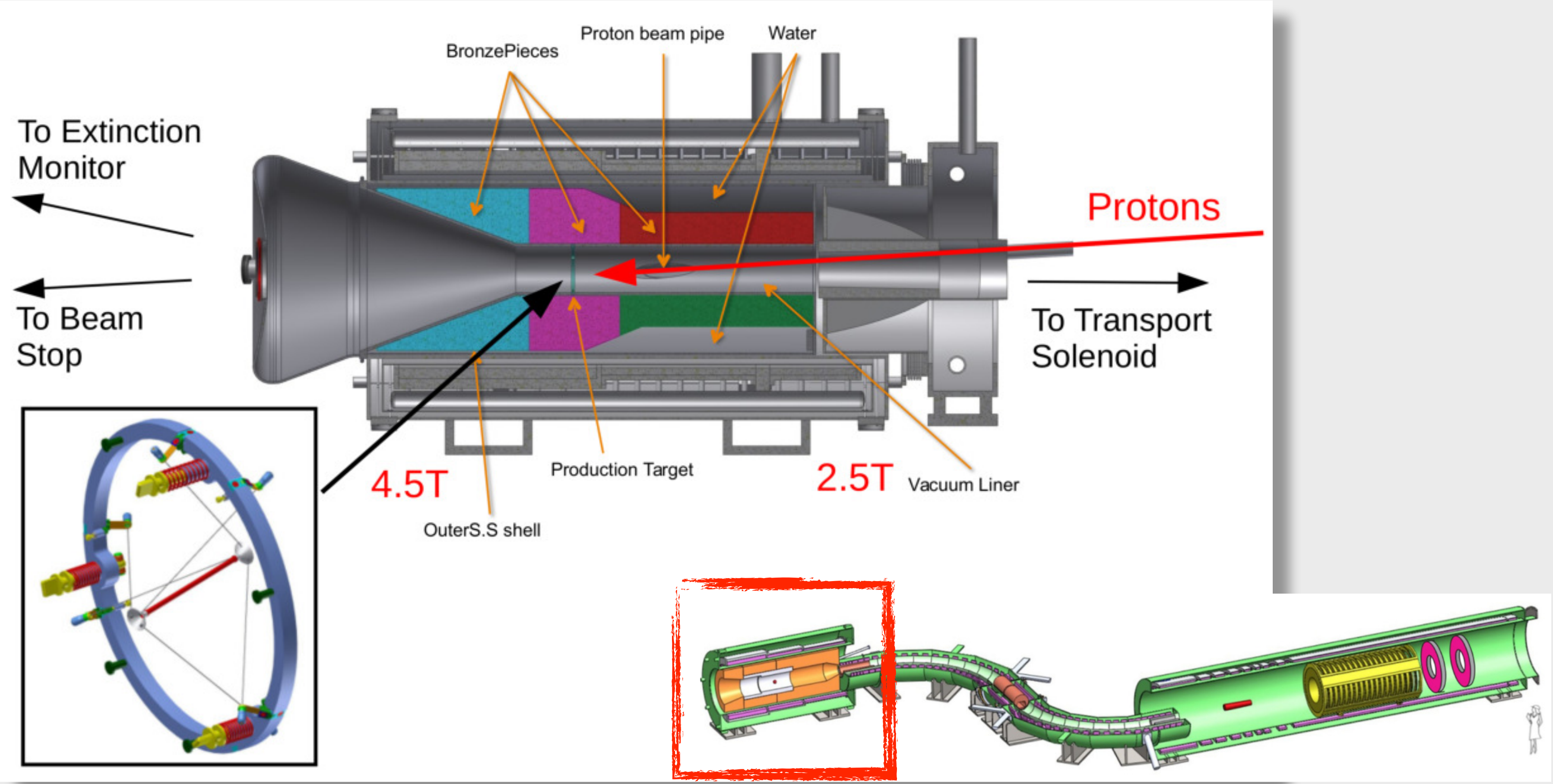
Dominant Background Sources

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

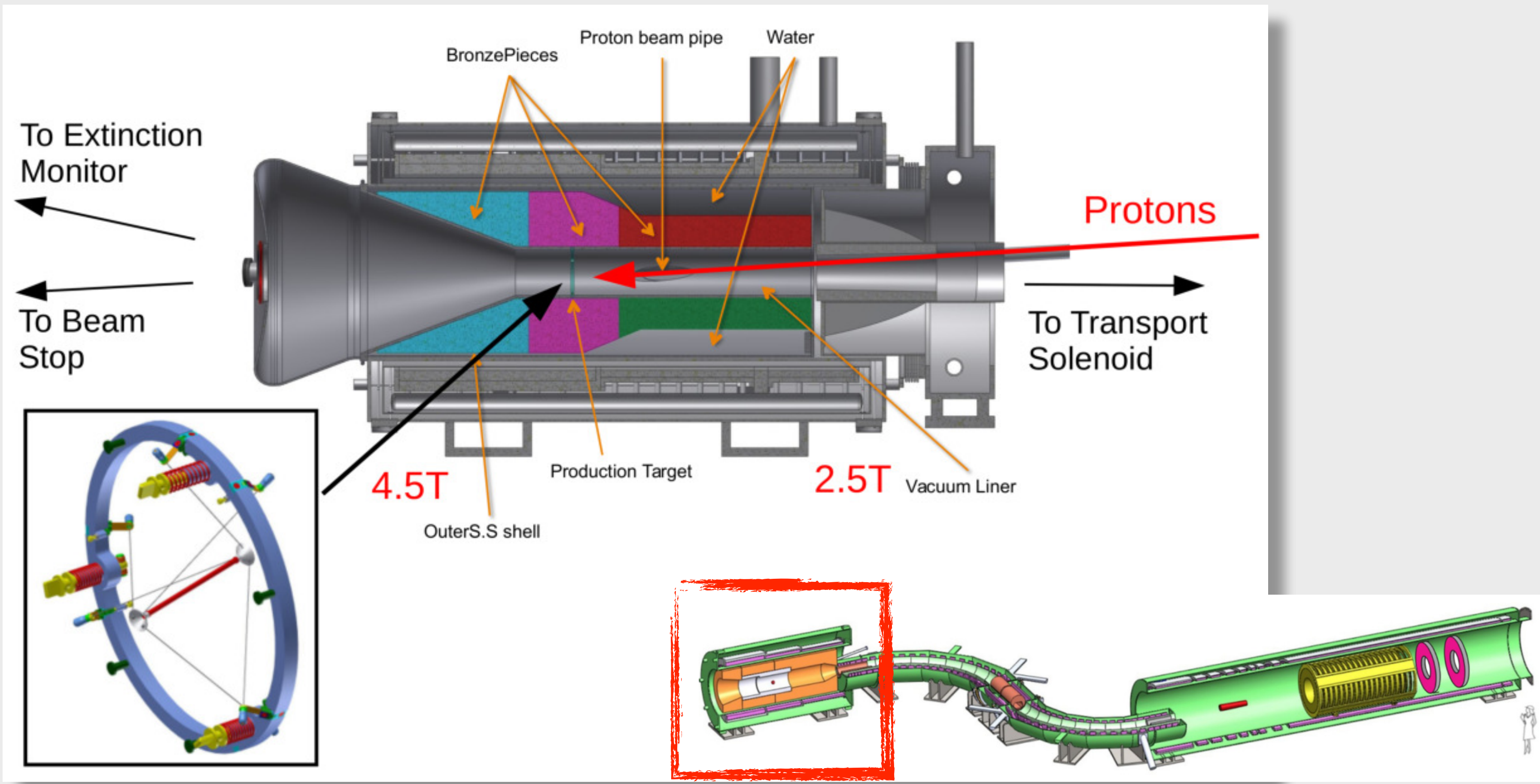
Beam production and transport

- 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



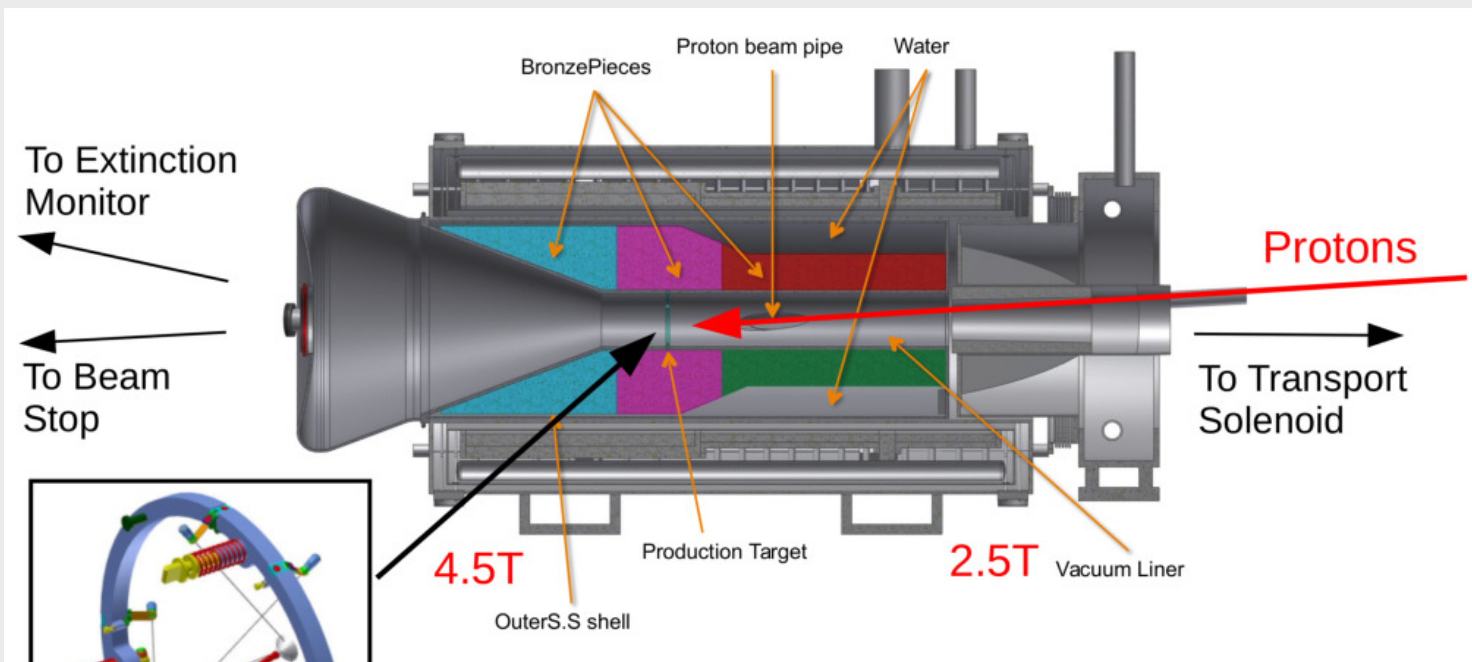
Beam production and transport

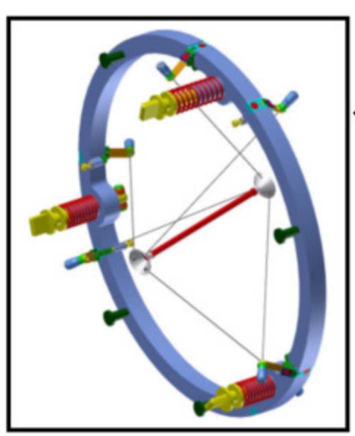
- PS Solenoid: radiation damage and heat load in super-conducting coils
  - Simulations indicate that change of Heat Radiation Shield from brass to tungsten may be adequate
- Remote target handling
- Radiation safety (overburden)

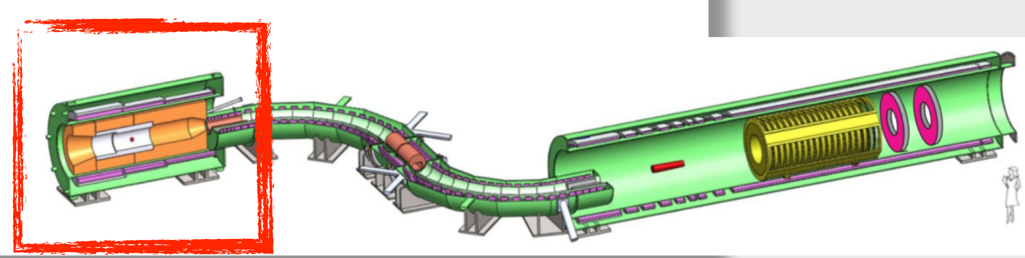


Beam production and transport

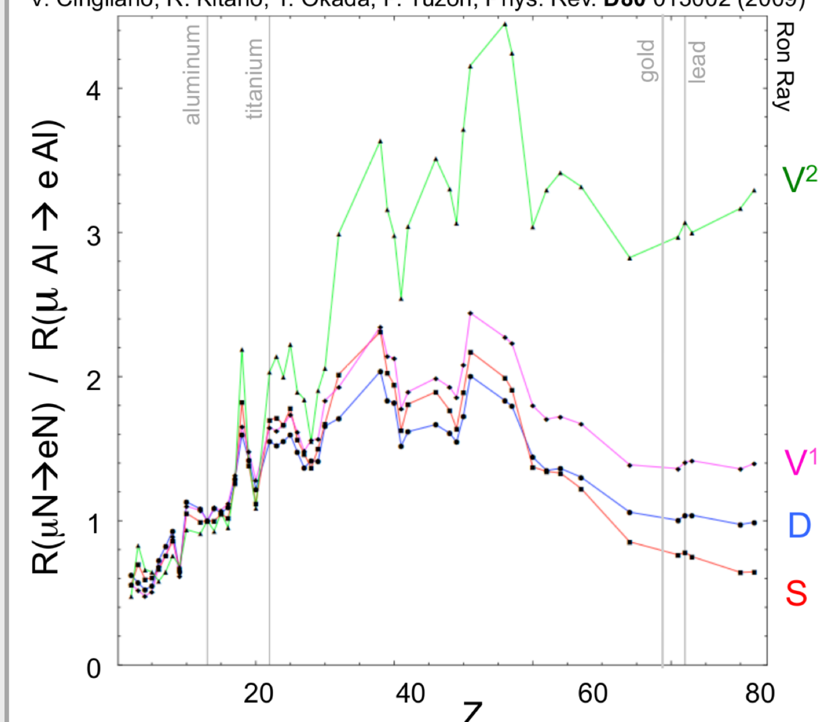
- Aiming the beam on target: 0.8 GeV (Mu2e-II) vs 8 GeV (Mu2e)
  - Studies suggest that Mu2e-II off-axis beam injection may address the aiming issue
  - Impacts the position of beam dump and extinction monitor position



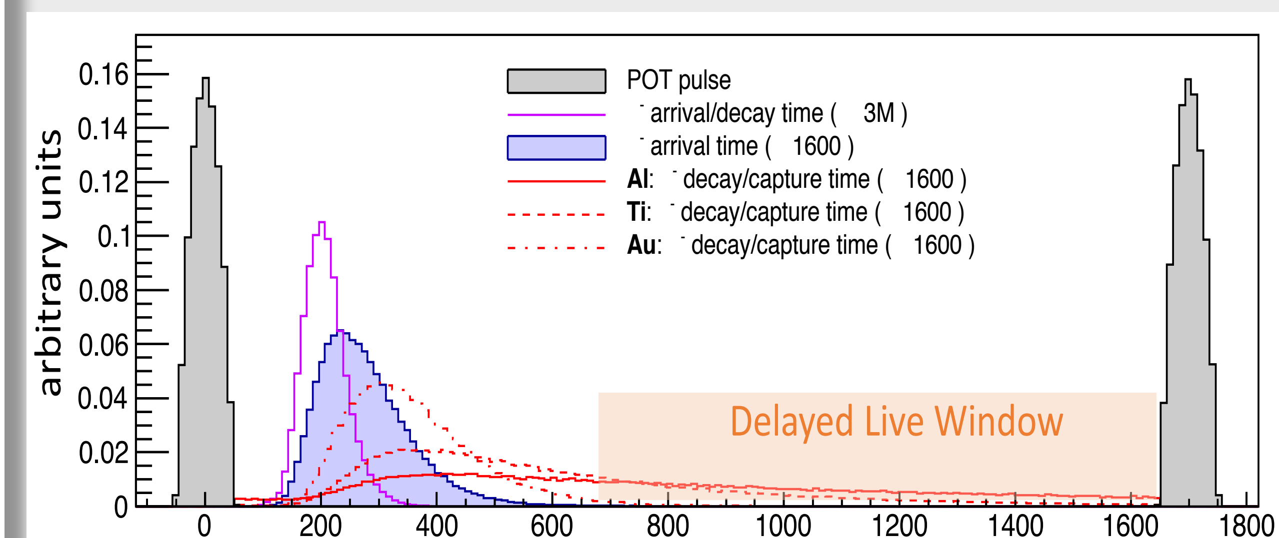




- Mu2e-II will need thinner stopping target, to improve momentum resolution and suppress Decay In Orbit (DIO) background
- If the signal is observed, will change stopping target to probe underlying NP operator
  - Aluminum & Titanium stopping targets investigated
- Will adjust the micro-bunch length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



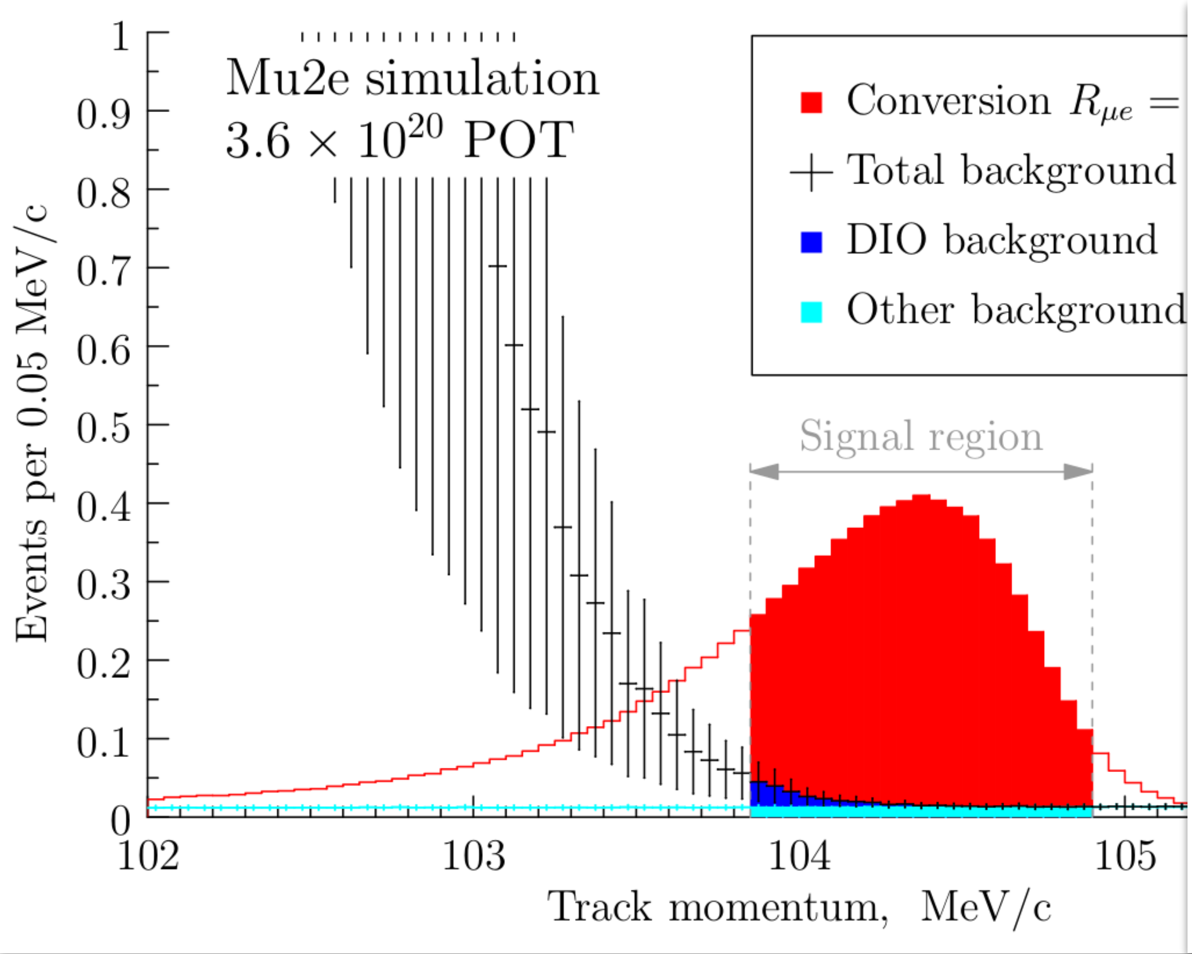
V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon, Phys. Rev. **D80** 013002 (2009)

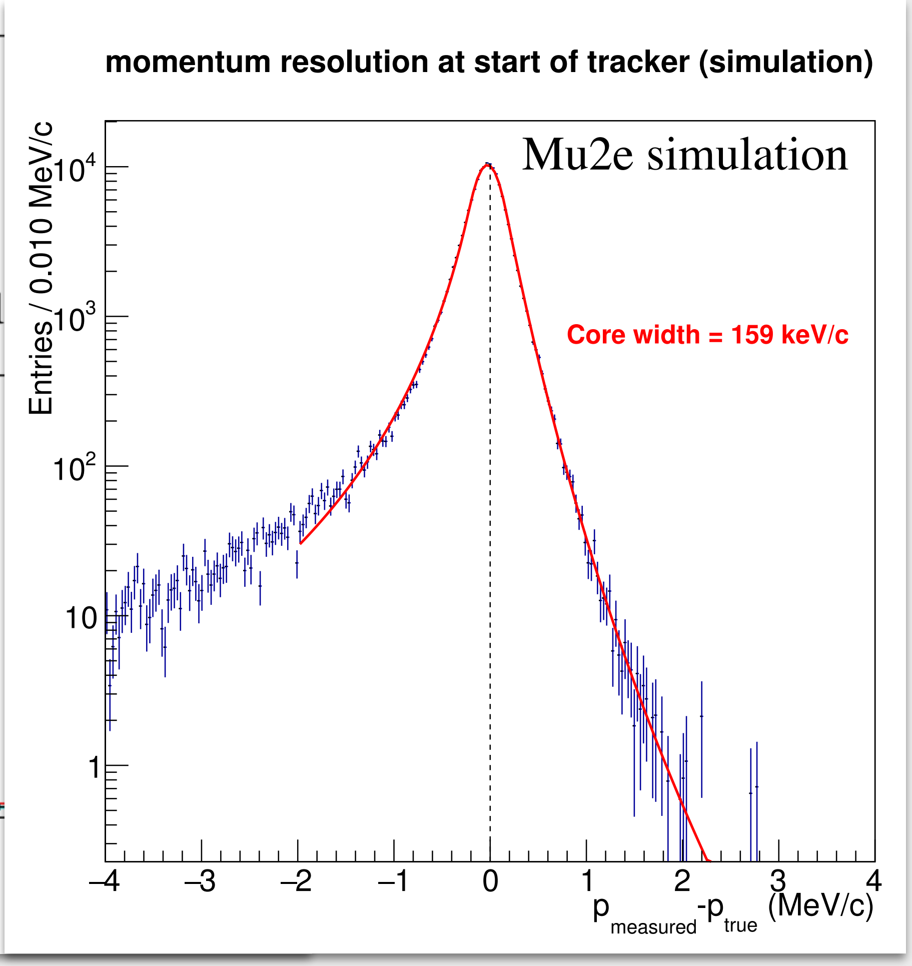


K. Knoepfel, *et al.*, arXiv:1307:1168 (2013).

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

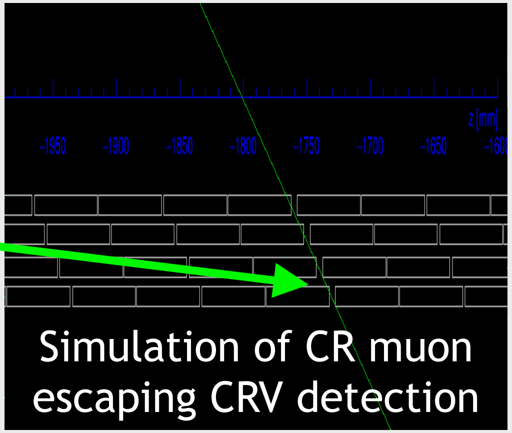
- Mu2e tracker features <200 KeV momentum resolution to suppress DIO background
- DIO scales with the number of stopped muon
- Expected DIO background at Mu2e: 0.14 events
- DIO background would increase 10x at Mu2e-II, linear to the number of stopped muons
- Improve momentum resolution to suppress DIO 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 <60⁰


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