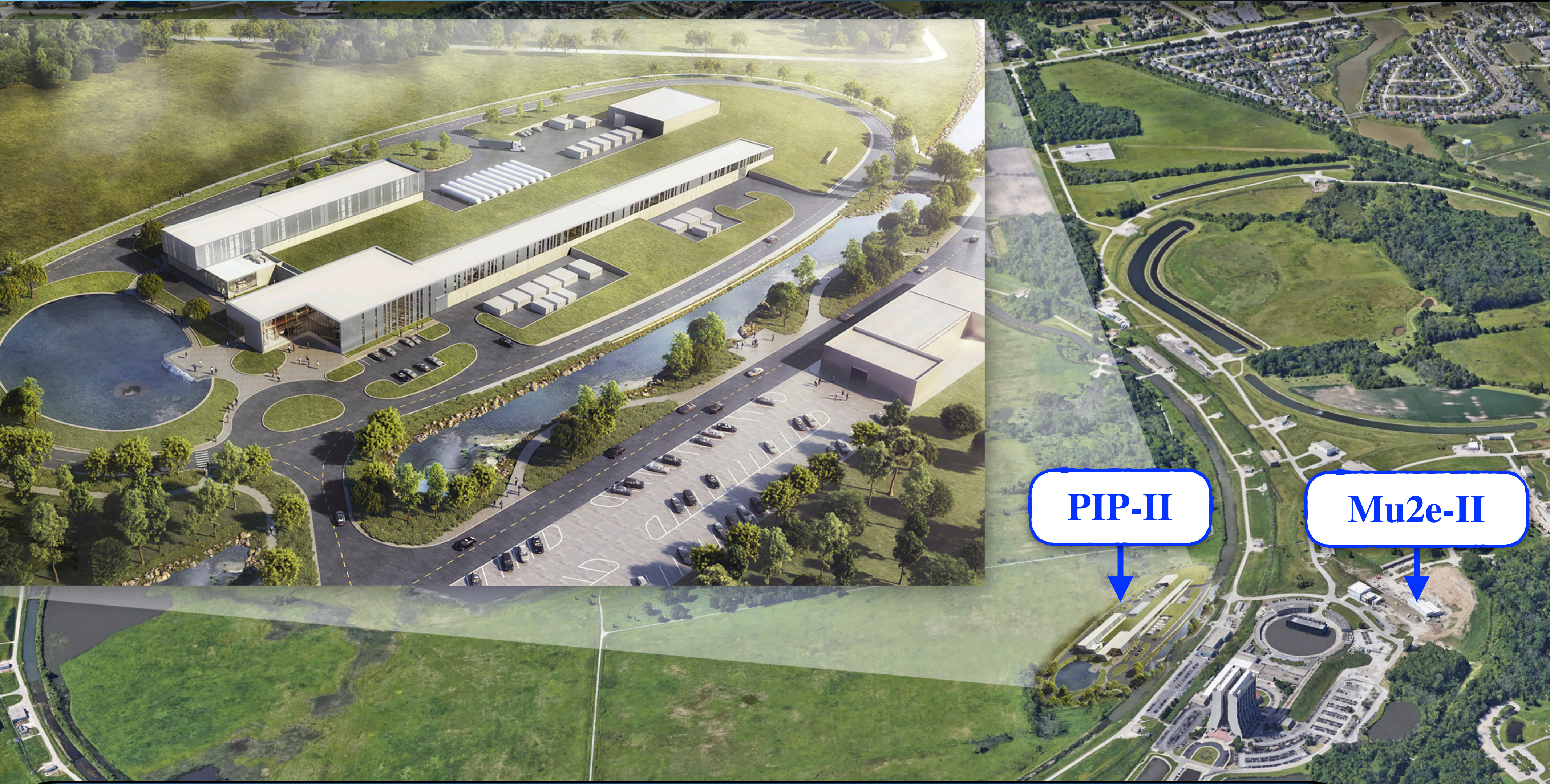


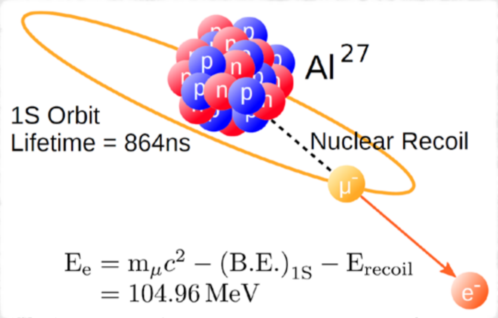
Mu2e-II : next generation muon conversion experiment

Yuri Oksuzian
On behalf of the Mu2e-II working group

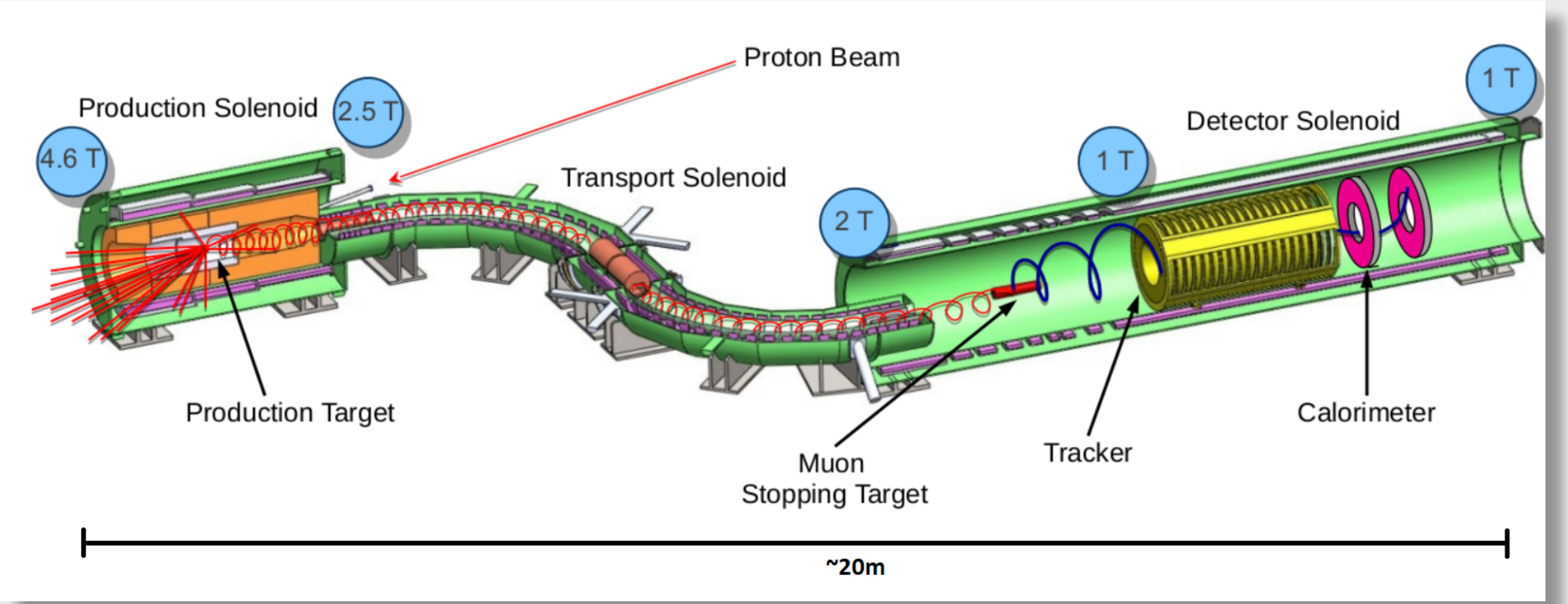
Mu2e

- Mu2e will search for a neutrino-less $\mu^- N \rightarrow e^- N$ conversion on Al
- Improve the current limit on the conversion rate ($R_{\mu e}$) by **four orders** of magnitude:

$$R_{\mu\rightarrow e} = \frac{\Gamma\left(\mu^- + N(Z,A) \rightarrow e^- + N(Z,A)\right)}{\Gamma\left(\mu^- + N(Z,A) \rightarrow \nu_\mu + N(Z-1,A)\right)} < 6\times 10^{-17} \text{ (90\% CL)}$$



- Mu2e will produce and stop 7×10^{18} muons on aluminum foils
  - Searching for ~ 105 MeV electrons originating from the stopping target
  - In SM, $\mu^- N \rightarrow e^- N$ is *practically* forbidden ($R_{\mu e} \sim 10^{-54}$)
- **Signal observation at Mu2e is unambiguous sign of New Physics**



Mu2e-II

- What is Mu2e-II?
  - If approved, Mu2e-II will improve $R_{\mu e}$ sensitivity by $\times 10$ beyond Mu2e limits
  - Refurbish as much of Mu2e infrastructure as possible
  - Upgrade Mu2e components to handle higher beam intensity

- When?
  - Few years after the end of the Mu2e run
  - Expected 5 years of physics run

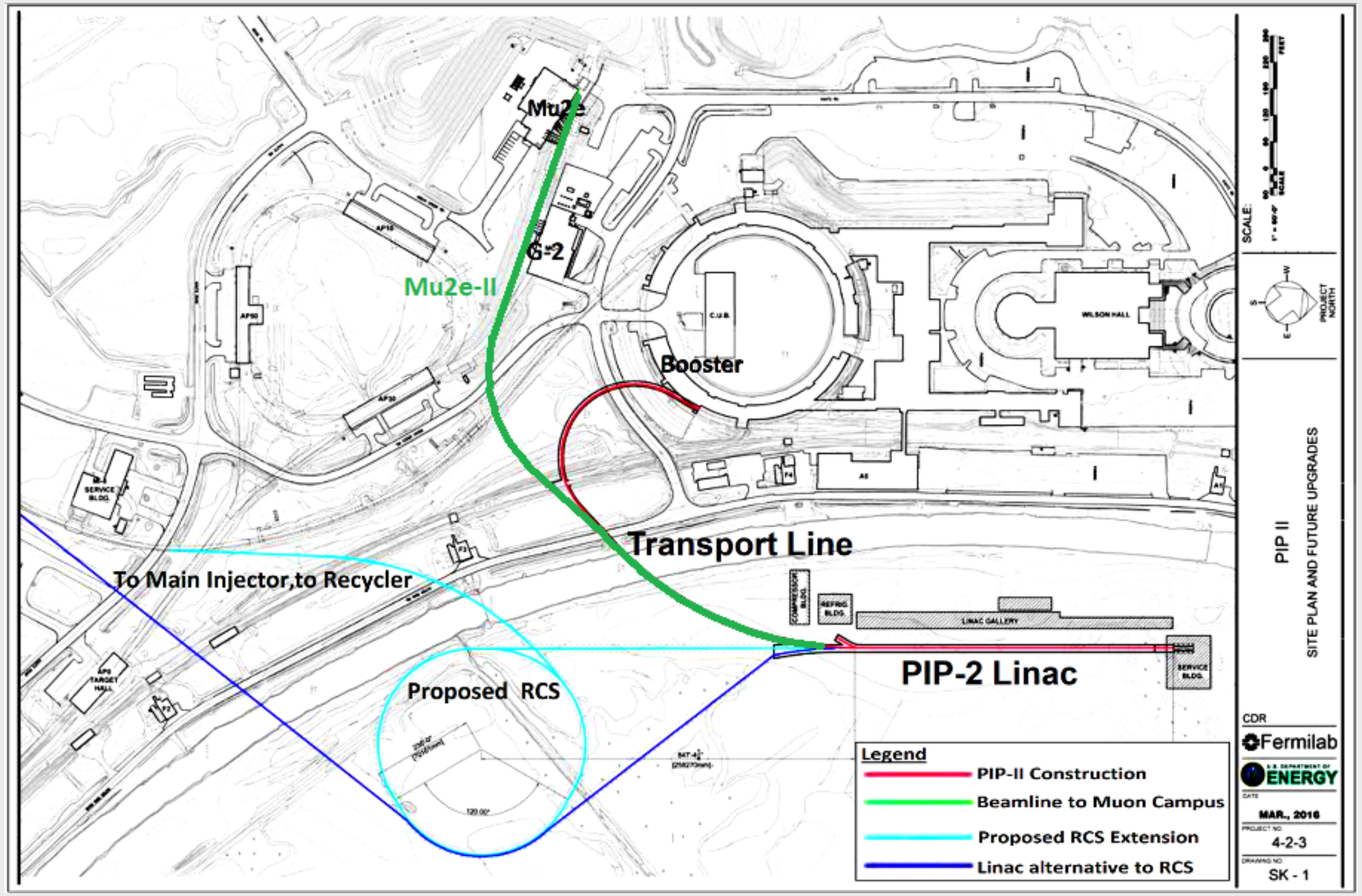
- Where?
  - Mu2e will utilize a 100kW proton beam from PIP-II at Fermilab

PIP-II status

- PIP-II powers DUNE and experiments like Mu2e-II
  - Project completion this decade
- PIP-II delivers design proton power on the LBNF target
  - with >90% beam allocation for other users

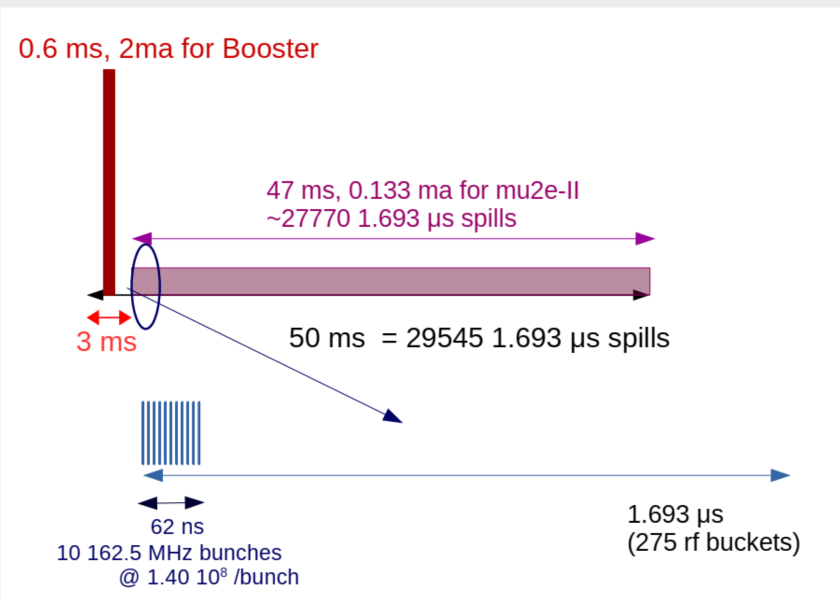
PIP-II @ Mu2e-II

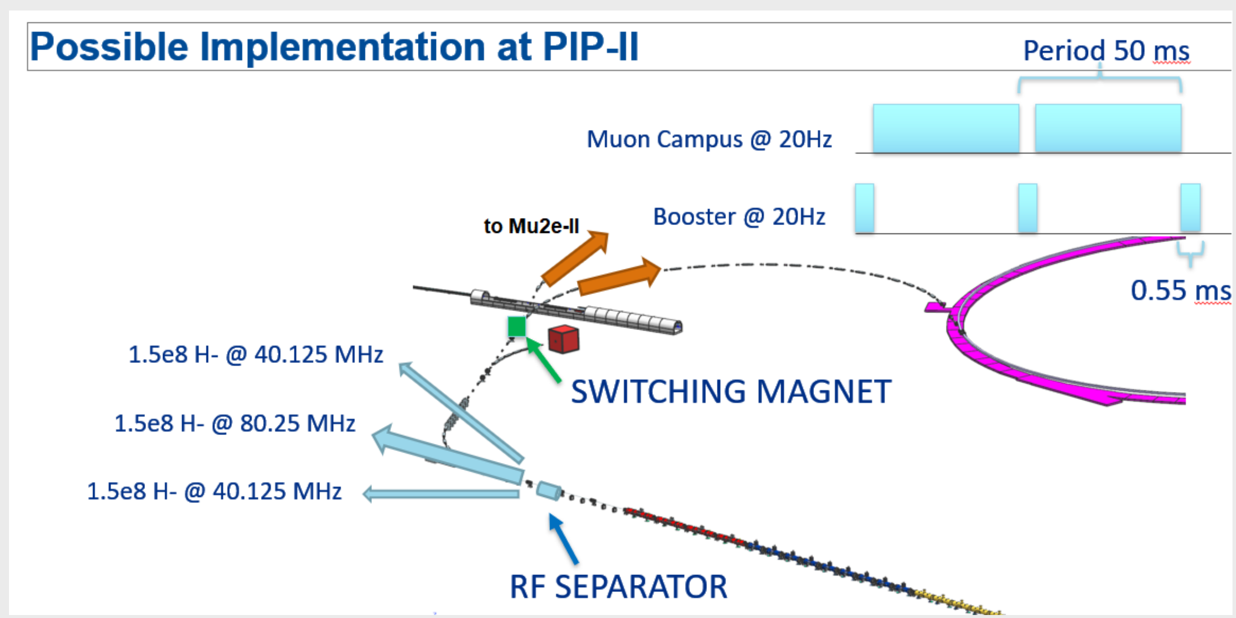
- PIP-II designed to deliver $800\ \text{MeV}\ H^-$ beam to the Booster
  - Chopper system can produce an arbitrary pattern of filled or empty $162.5\ \text{MHz}$ buckets
  - The maximum current $\sim 2mA$
- Mu2e-II will get a beam at upstream end of transfer line to Booster
  - Need to build a beamline to deliver beam to Muon Campus



Mu2e-II beam formation

- Beam structure for Mu2e-II $(100\ \mathrm{kW})$:
  - Injection: intensity is limited to $1.4 \times 10^{8}\ H^{-}$ per bucket
  - Booster requires $\sim 3\ ms$ out of every $50\ ms$. The rest to Muon Campus
  - Mu2e-II needs a short spill followed by a gap to suppress prompt background
- Mu2e-II needs only 10 buckets in each spill
  - beam pulse width is $\sim 62\ ns$ - much narrower than at Mu2e
- Consider running Mu2e-II at even higher beam intensities





Mu2e-II efforts

- Mu2e-II is a natural extension of Mu2e
- Feasibility studies started a decade ago at last Snowmass
  - Since then, we submitted several study papers and held multiple workshops
- We submitted 12 LOI on Mu2e-II subsystems for Snowmass 21

30 Sep 2013

Feasibility Study for a Next-Generation Mu2e Experiment

https://arxiv.org/abs/1307.1168 **2013**

K. Knoepfel[3], V. Pronskikh[3], R. Bernstein[3], D.N. Brown[5], R. Coleman[3], C.E. Dukes[7],

R. Ehrlich[7]

J. Mill

Expression of Interest for Evolution of the Mu2e Experiment†

https://arxiv.org/abs/1802.02599 **2018**

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.

M.A. Cumm

March 17, 2022

Mu2e-II: Muon to electron conversion with PIP-II
Contributed paper for Snowmass

https://arxiv.org/abs/2203.07569 **2022**

K. Byrum,[1] S. Corrodi,[1] Y. Oksuzian,[1] P. Winter,[1] L. Xia,[1] A. W. J. Edmonds,[2] J. P. Miller,[2]
J. Mott,[3] W. J. Marciano,[4] R. Szafron,[4] R. Bonventre[b],[5] D. N. Brown[b],[5] Yu. G. Kolomensky[ab],[5]
O. Ning[a],[5] V. Singh[a],[5] E. Prebys,[6] L. Borrel,[7] B. Echenard,[7] D. G. Hitlin,[7] C. Hu,[7] D. X. Lin,[7]
S. Middleton,[7] F. C. Porter,[7] L. Zhang,[7] R.-Y. Zhu,[7] D. Ambrose,[8] K. Badgley,[8] R. H. Bernstein,[8]
S. Boi,[8] B. C. K. Casey,[8] R. Culbertson,[8] A. Gaponenko,[8] H. D. Glass,[8] D. Glenzinski,[8]

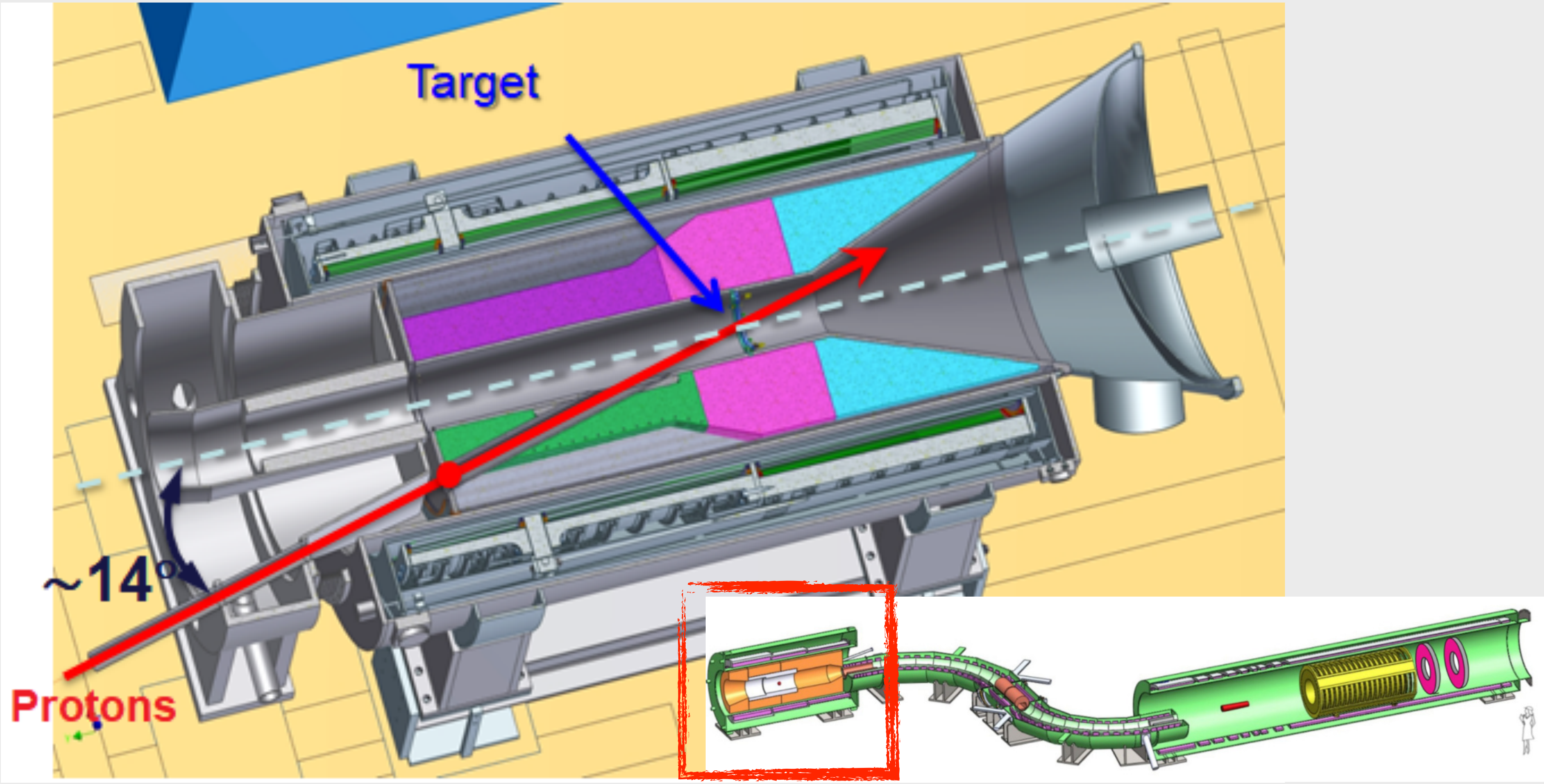
Mu2e-II background and sensitivity

- Mu2e-II assumes 5 years of running and 5.5×10^{19} stopped muons
- Maintaining <1 event total background requires detector and beam enhancements
- Higher beam intensity and improved detectors at Mu2e-II yield an order of magnitude sensitivity improvement beyond Mu2e

Results	Mu2e	Mu2e-II (5-year)	Required improvement
Backgrounds			
Decay In Orbit	0.144	0.263	Improved tracker resolution
Cosmics	0.209	0.171	Improved veto and enhanced shielding
Radiative Pion Capture	0.025	0.033	Improved extinction $< 10^{-11}$
Radiative Muon Capture	< 0.004	< 0.02	
Antiprotons	0.040	0.000	Beam energy below $\overline{p}$ threshold
Others	< 0.004	< 0.017	
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}	
$R_{\mu e}$(90% CL)	6.01×10^{-17}	6.39×10^{-18}	
$R_{\mu e}$(discovery)	1.89×10^{-16}	2.34×10^{-17}	

Beam production and transport

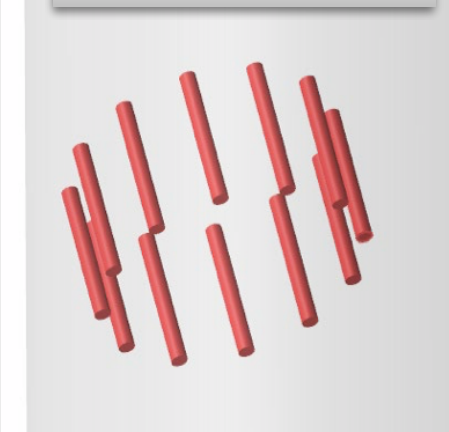
- Mu2e-II requires the ability to withstand ten times the current beam power
  - The existing Mu2e target and superconducting coils might not be capable of handling this increased power
- Exploring alternative designs, including tungsten Heat Radiation Shields to reduce damage to coils



Production target

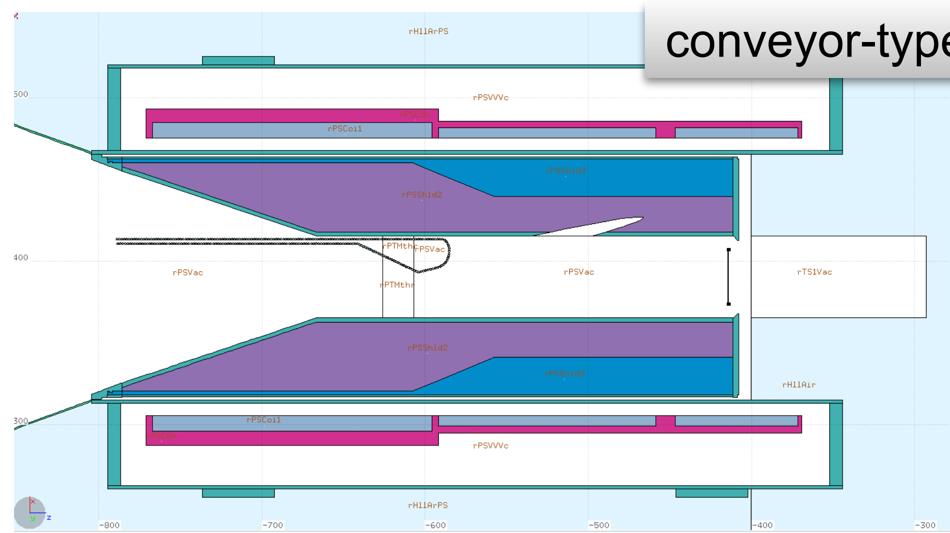
- Fermilab's LDRD project explores production target concepts resilient to Mu2e-II beam intensities: rotating, granular, and conveyor
- Simulations cover muon yield, thermal stress, radiation damage, residual activation, and radiation loads

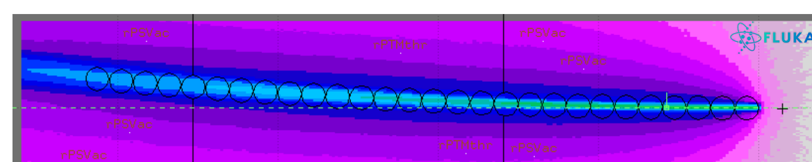
Rotating Elements



Fixed Granular with Gas Cooling

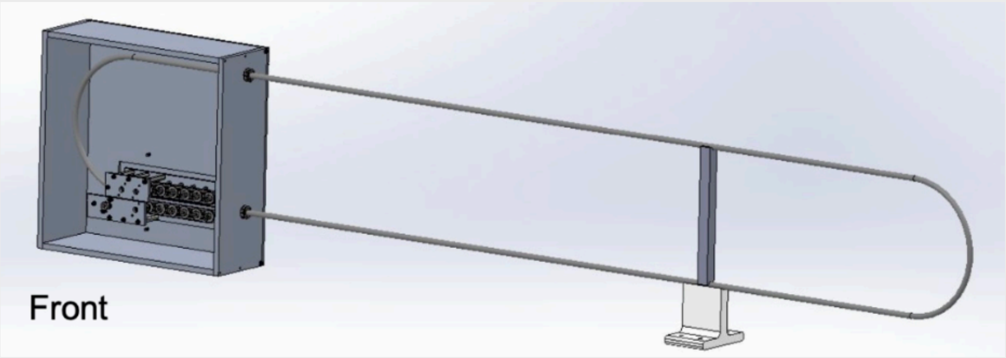
conveyor-type

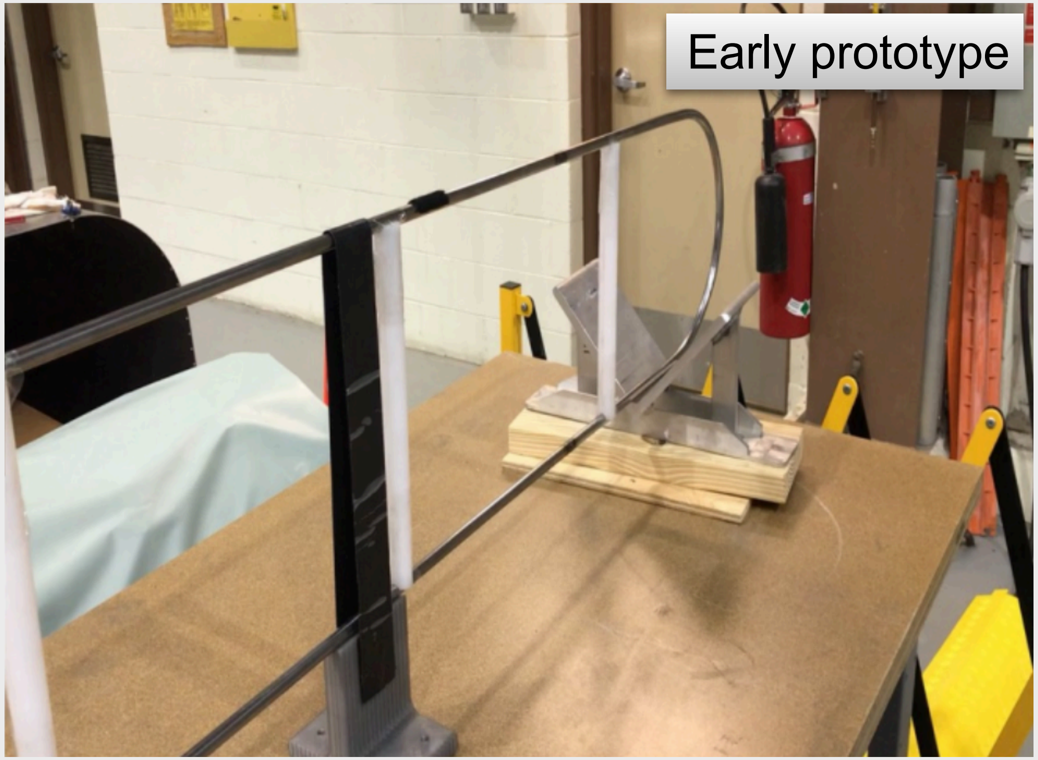




Production target

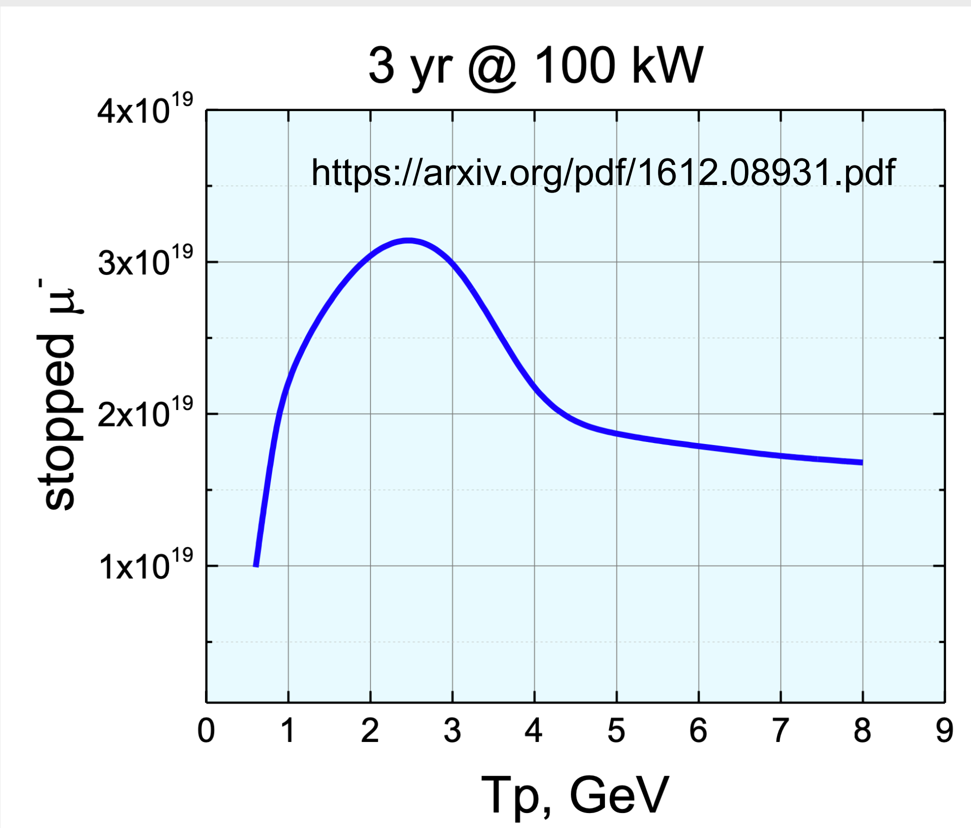
- Mu2e-II sensitivity studies considered carbon spheres for conveyor-type production target
  - We have produced an early prototype
- Alternative designs include
  - Fluidized tungsten powder
  - Liquid heavy metal

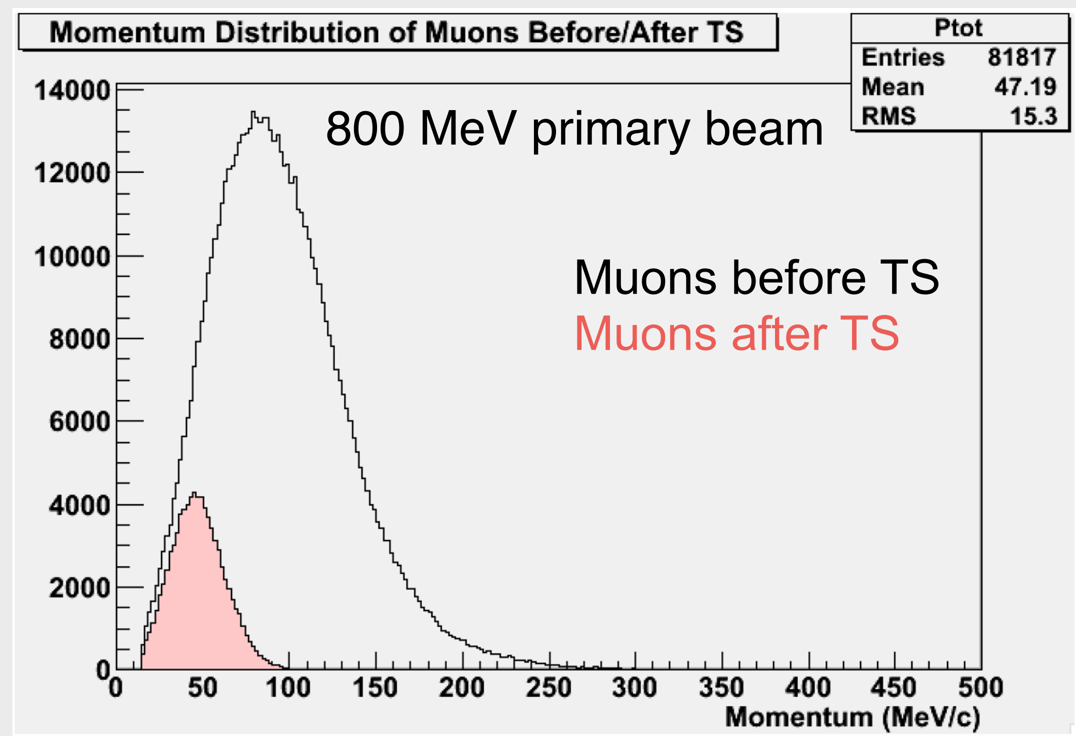




Optimal proton energy

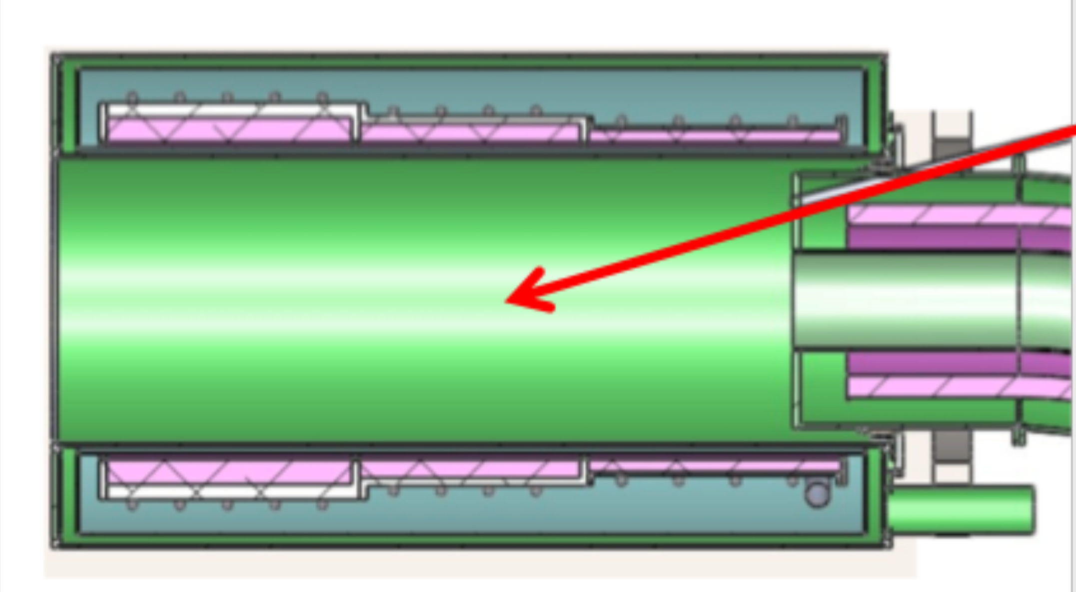
- Plot below: the number of stopped muons as a function of proton energy for a nominal 3 year run with 100 kW of beam power
  - The optimal energy is ~2.5 GeV
- The 2 GeV upgrade of PIP-II is of interest to Mu2e-II
  - No pbar background at either 800 MeV or 2 GeV

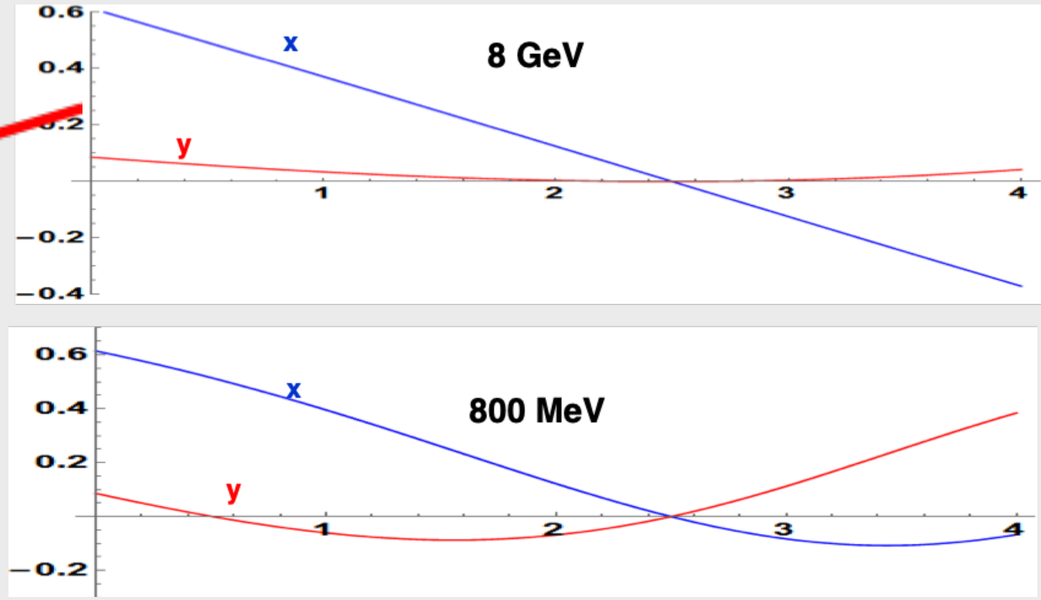




Beam production and transport

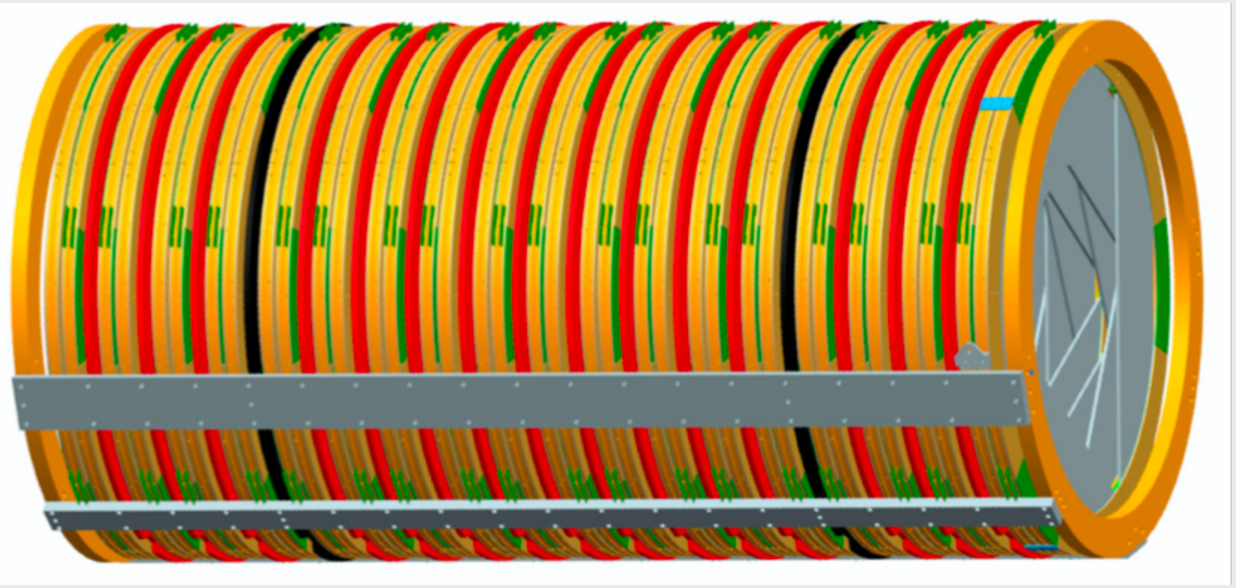
- Beam targeting differs between Mu2e-II (0.8 GeV) and Mu2e (8 GeV)
  - Affecting beam dump and extinction monitor positions
- To hit the target, Mu2e-II must optimize:
  - Vertical and horizontal angles,
  - Production target location
  - Production Solenoid magnetic field
- 2 GeV beam energy will significantly reduce the challenges above





Tracker

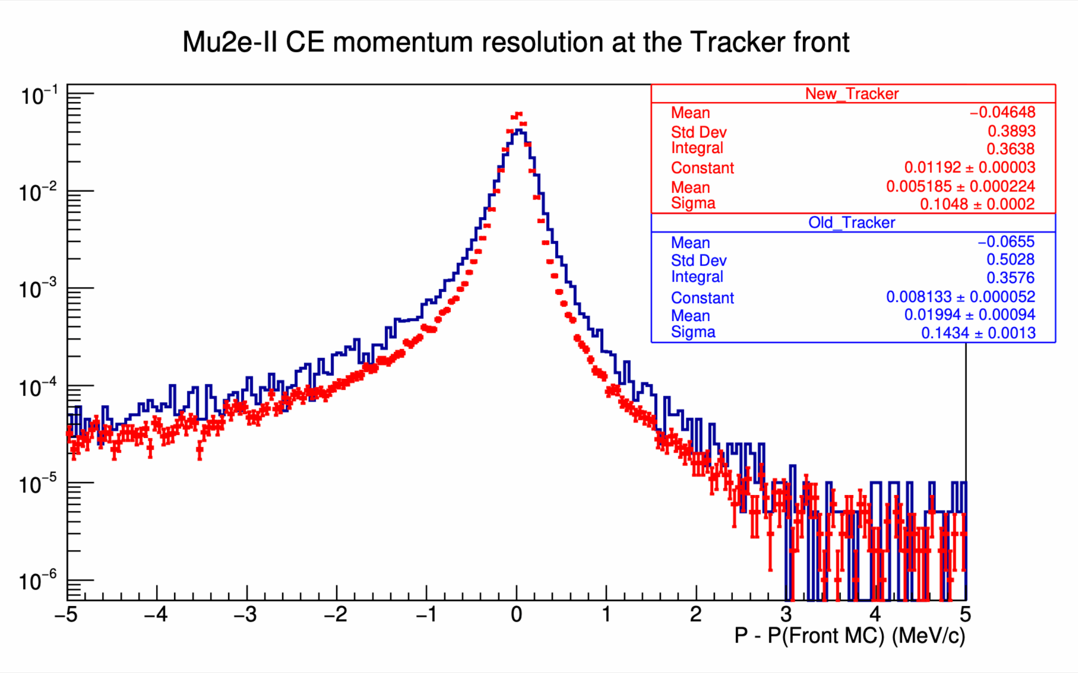
- Mu2e reconstructs conversion electron momentum with the straw tracker
- Expected Decay In Orbit (DIO) background at Mu2e: 0.144 events
  - DIO background would increase 10x at Mu2e-II, proportional to stopped muons
- Plan: enhance momentum resolution by reducing straw thickness: $15\ \mu m \rightarrow 8\ \mu m$
  - Additionally, we narrowed the momentum window $1.05\ MeV \rightarrow 0.85 MeV$ to further suppress DIO



	Mu2e	Mu2e-II
Wall thickness (μm)	18.1	8.2
Al thickness (μm)	0.1	0.2
Au thickness (μm)	0.02	0.0
Linear Density (g/m)	0.35	0.15
Pressure limits (atm)	0–5	0–3
Elastic Limit (gf)	1600	500

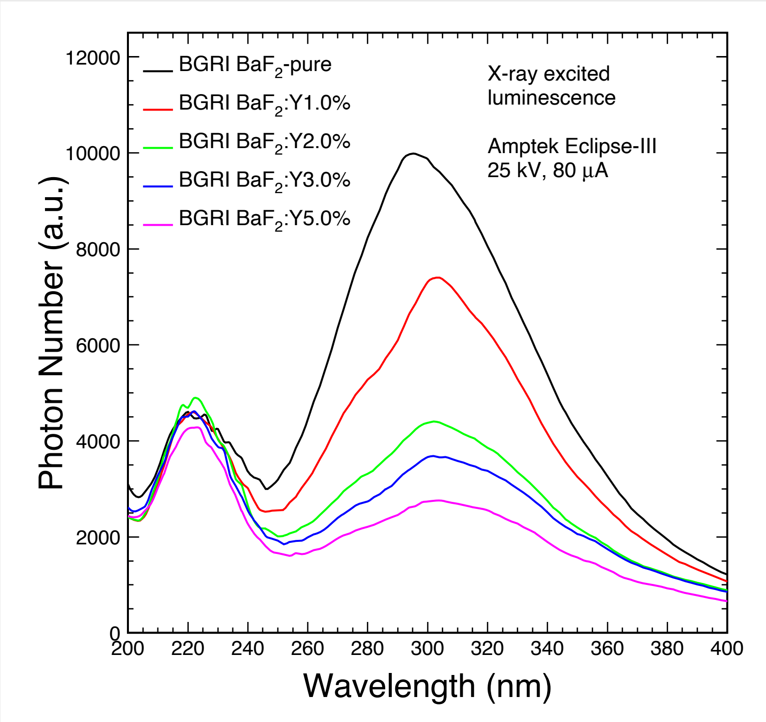
Tracker

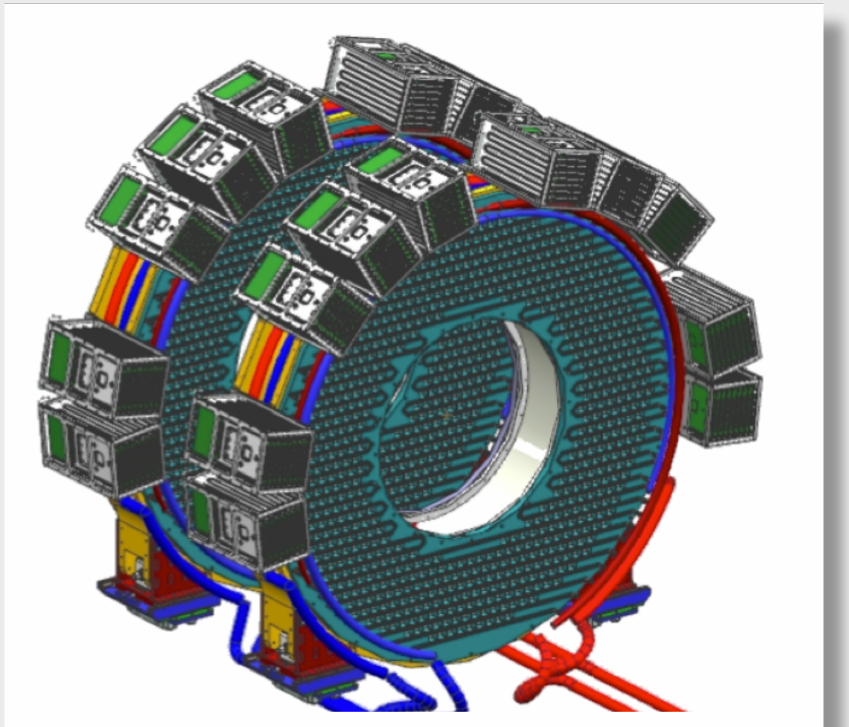
- Thinner straws enhance momentum resolution: $140 \rightarrow 100\ keV$
- Fermilab's LDRD works on challenges in vacuum tightness, long-term stability, and large-scale production
- Radiation levels (3 Mrad) surpass safe limits for electronics
  - Explore application-specific integrated circuit electronics
- Investigate alternative detectors
  - Light gas vessel to alleviate straw leakage requirements
  - All-wire construction, eliminating straws
  - Wires separated by mylar walls



Calorimeter

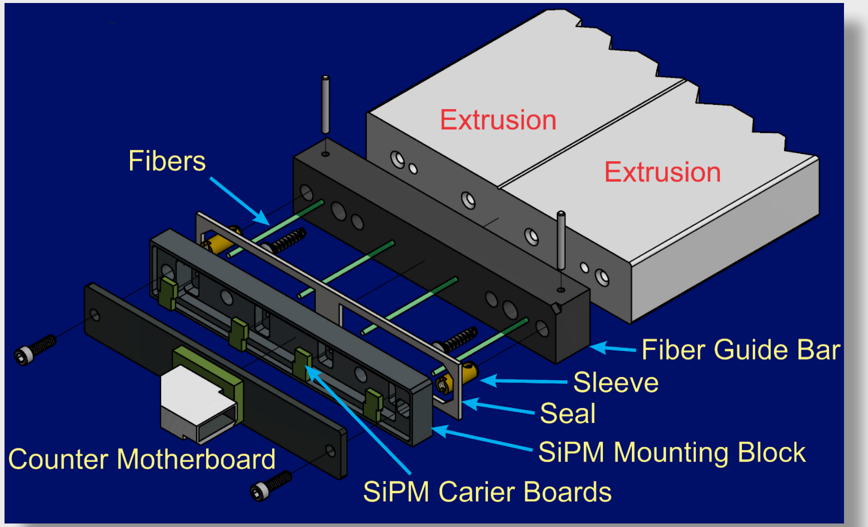
- Mu2e utilizes CsI calorimeter for PID, seed tracking, and fast trigger
- Requirements: $\sigma_E/E < 10\,\%\,@\,100MeV$ and $\sigma_t < 500\ ps\,@\,100MeV$
- CsI cannot withstand rad doses and occupancies at Mu2e-II: $< Mrad,\ 10^{13}\ n_{1MeV-eq}/cm^2$
- BaF_2 is a promising candidate with a rad hardness of < 100 Mrad and a fast UV component
  - Challenge: slow scintillation component
  - Suppress the slow component through doping BaF_2 with (Y)ttrium, (La)nthanum and (Ce)rium
  - Develop solar-blind photosensor: SiPMs with an external filter or UV-sensitive photocathodes
- This R&D is currently unfunded

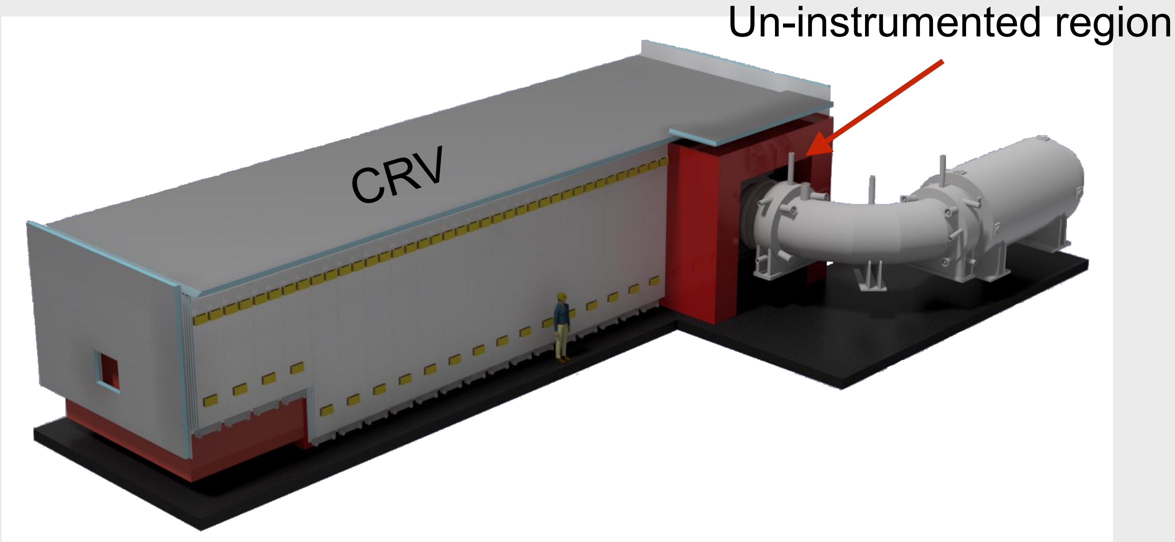




Cosmic Ray Veto (CRV)

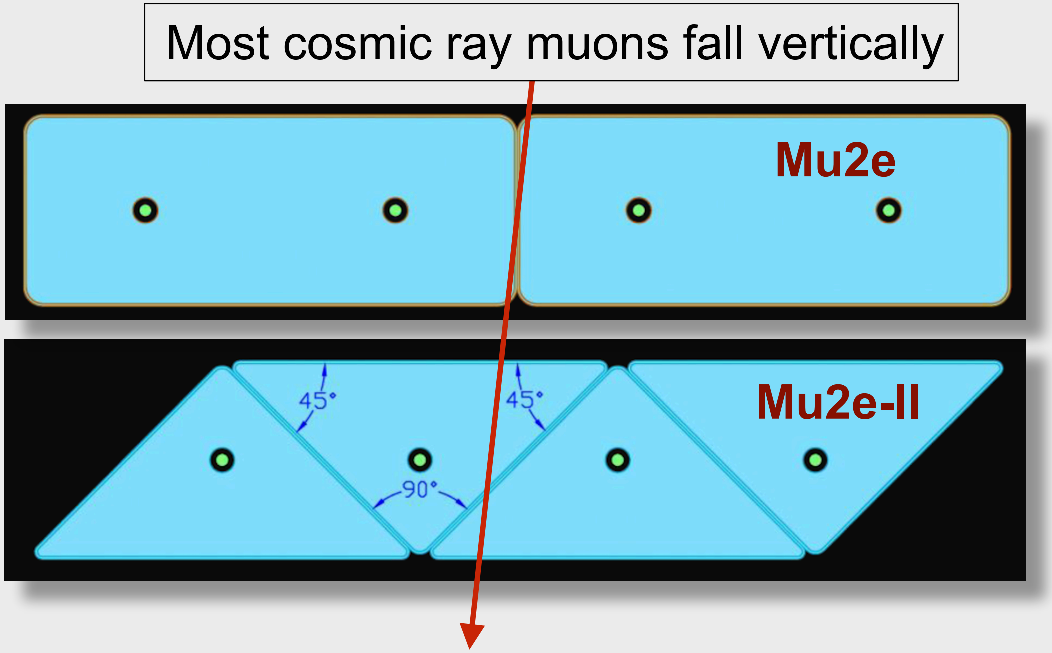
- CRV identifies cosmic ray muons that produce conversion-like backgrounds
- Technology: Four layers of extruded polystyrene scintillator counters with embedded wavelength shifting fibers, read out with SiPM photodetectors
- Expected live-time and hence cosmic ray background is >3x higher at Mu2e-II
  - Use alternative CRV design to enhance the detection efficiency
- Higher (>x3) rad doses: higher DAQ rates, dead-time, rad damage
  - Promising results with enhanced shielding: tungsten PS and boron doped heavy concrete
- Cosmic ray background sources undetectable by CRV:
  - Cosmic ray neutrons is a significant (~0.6) source, if not addressed with enhanced shielding
  - Muons entering through un-instrumented CRV region is small (<0.1), but challenging to suppress contribution

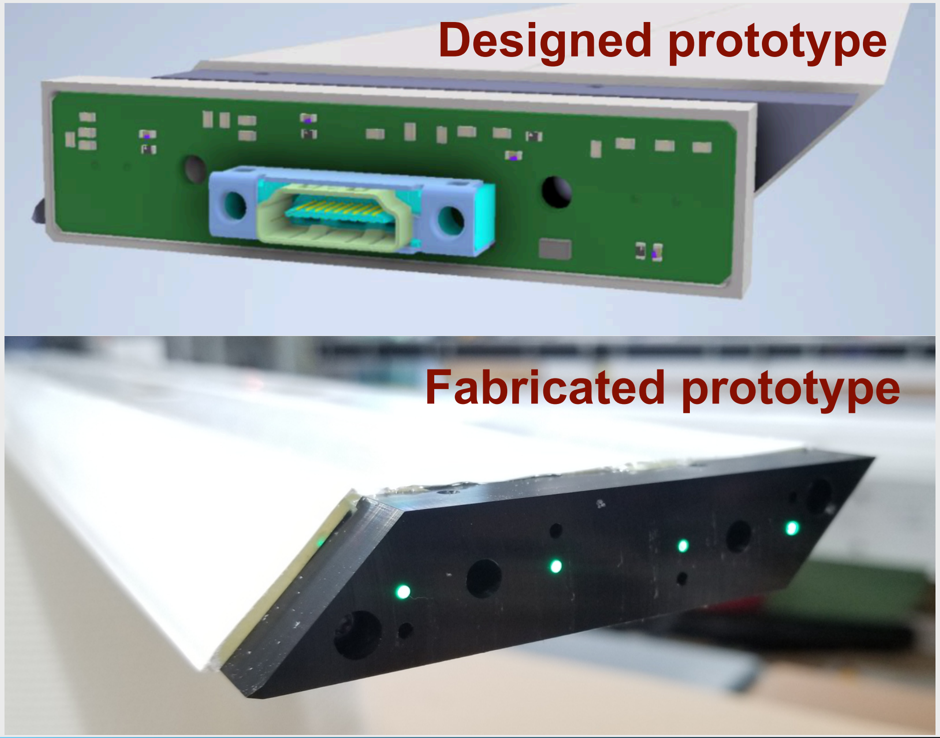




CRV design@Mu2e-II

- Enhanced CRV design using triangular-shaped counters
  - Improved efficiency due to reduced gaps
  - Better (1 mm) positional resolution reduces fake cosmic id, and hence dead-time
  - Lower DAQ rate from beam-induced detector noise
- CRV will be replaced due to aging
  - Enhance the light yield with thicker fiber, improved PDE SiPMs and potting fiber
- A prototype has been designed, fabricated and studies show promising results
- This R&D is currently unfunded





Stopping target

- We have considered stopping target designs alternative to Mu2e
  - However, we found that the current design with 34 Al foils is close to optimal
- If the signal is observed, will change stopping target to probe underlying New Physics operator
  - Titanium (Vanadium) and even Lithium stopping targets will be investigated
- Will adjust the micro-bunch length period to accommodate the muon lifetime of 329 ns on Ti vs 864 ns on Al

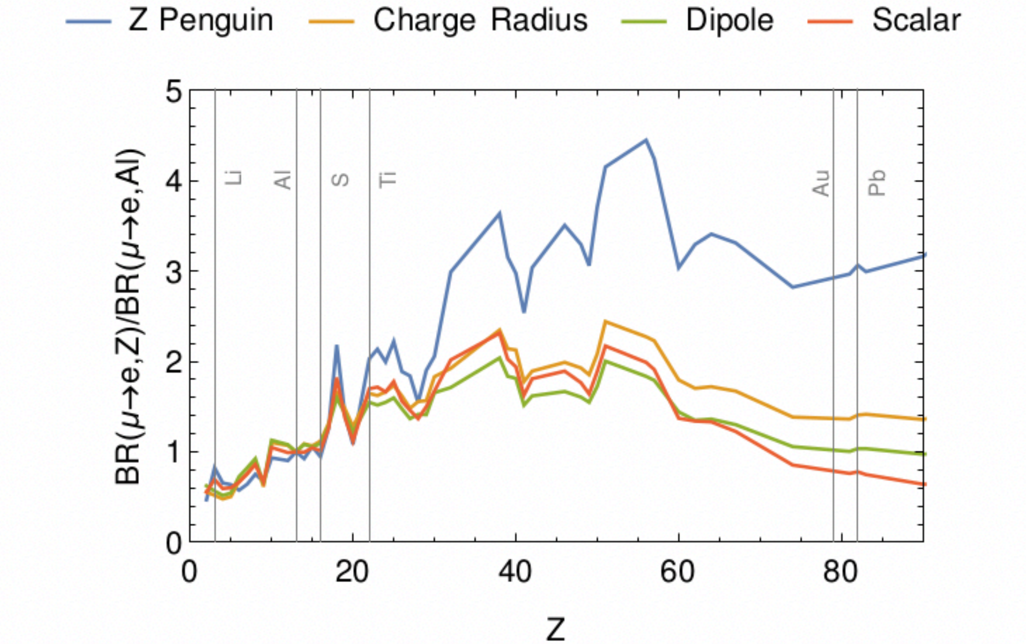
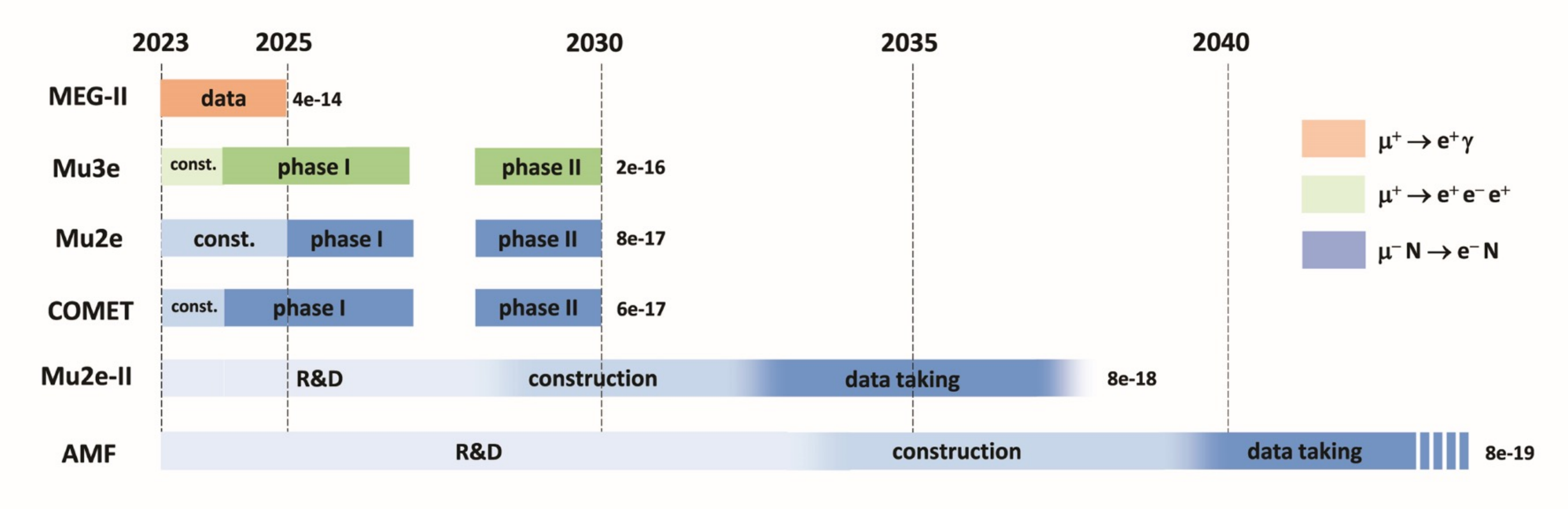


FIG. 1: Z dependence of $\mu \to e$ conversion rates for some example scenarios

CLFV Schedule

- Preliminary Mu2e-II scenario based on Snowmass RPF summary:
  - CD-0 by 2028
  - Construction 2028-2032
  - Data 2033-2037



Summary

- Mu2e-II will advance CLFV with the search in $\mu^- N \rightarrow e^- N$ channel
  - Achieving an order of magnitude improvement in $R_{\mu e}$
- The physics case for Mu2e-II is compelling, independent of the findings from Mu2e
  - If Mu2e observes a signal, Mu2e-II will conduct detailed studies of the underlying physics
  - In the absence of a signal in Mu2e, Mu2e-II will extend the sensitivity reach even further
- Mu2e-II has support from the muon physics community and Fermilab's PAC
- A comprehensive R&D program has been identified for Mu2e-II
  - We can achieve an improvement beyond x10 in sensitivity with additional R&D, higher beam energy, and a production target beyond 100 kW
- Pending approval, Mu2e-II is expected to commence data-taking in the 2030 decade
- Mu2e-II can act as a bridge to AMF
  - Synergistic R&D with Muon Collider on production target and solenoid

Backup slides