Mu2e-II Experiment at Fermilab

Mete Yucel

Tau Lepton 2023

Interest in Mu2e-II

Snowmass LOI

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

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ArXiv Link

AMF workshop 2023

	Session	Speaker	Location	Time
	PIP-II	*David Neuffer*	*269, Lauristen*	13:30 - 13:45
	Calorimeter	*Ivano Sarra et al.*	*269, Lauristen*	13:45 - 14:00
14:00	**Trigger and DAQ**	*Gianantonio Pezzullo*	*269, Lauristen*	14:00 - 14:15
	Magnets	*Karie Badgley*	*269, Lauristen*	14:15 - 14:30
	Cosmic ray veto (CRV)	*Simon Corrodi*	*269, Lauristen*	14:30 - 14:45
	Production target	*Vitaly Pronskikh*	*269, Lauristen*	14:45 - 15:00
15:00	**Tracking**	*Mete Yucel et al.*	*269, Lauristen*	15:00 - 15:15
	Sensitivity	*Sophie Middleton*	*269, Lauristen*	15:15 - 15:30
	Coffee break		*2nd floor, Lauristen*	15:30 - 16:00
16:00	**AMF - Compressor summary**	*Jeffrey Eldred*	*269, Lauristen*	16:00 - 16:15
	AMF - FFA accelerator summary	*Robert Bernstein*	*269, Lauristen*	16:15 - 16:30
	AMF - Conversion experiment summary	*Cole Kampa et al.*	*269, Lauristen*	16:30 - 16:45
	AMF - Other experiment summary	*Daniel Kaplan*	*269, Lauristen*	16:45 - 17:00
17:00	**AMF - Decay experiments summary**	*Francesco Renga*	*269, Lauristen*	17:00 - 17:15
	Closing workshop remarks	*Bertrand Echenard et al.*	*269, Lauristen*	17:15 - 17:25

ArXiv Link

What is Mu2e-II

- Current experiments searching muon sector of CLFV;

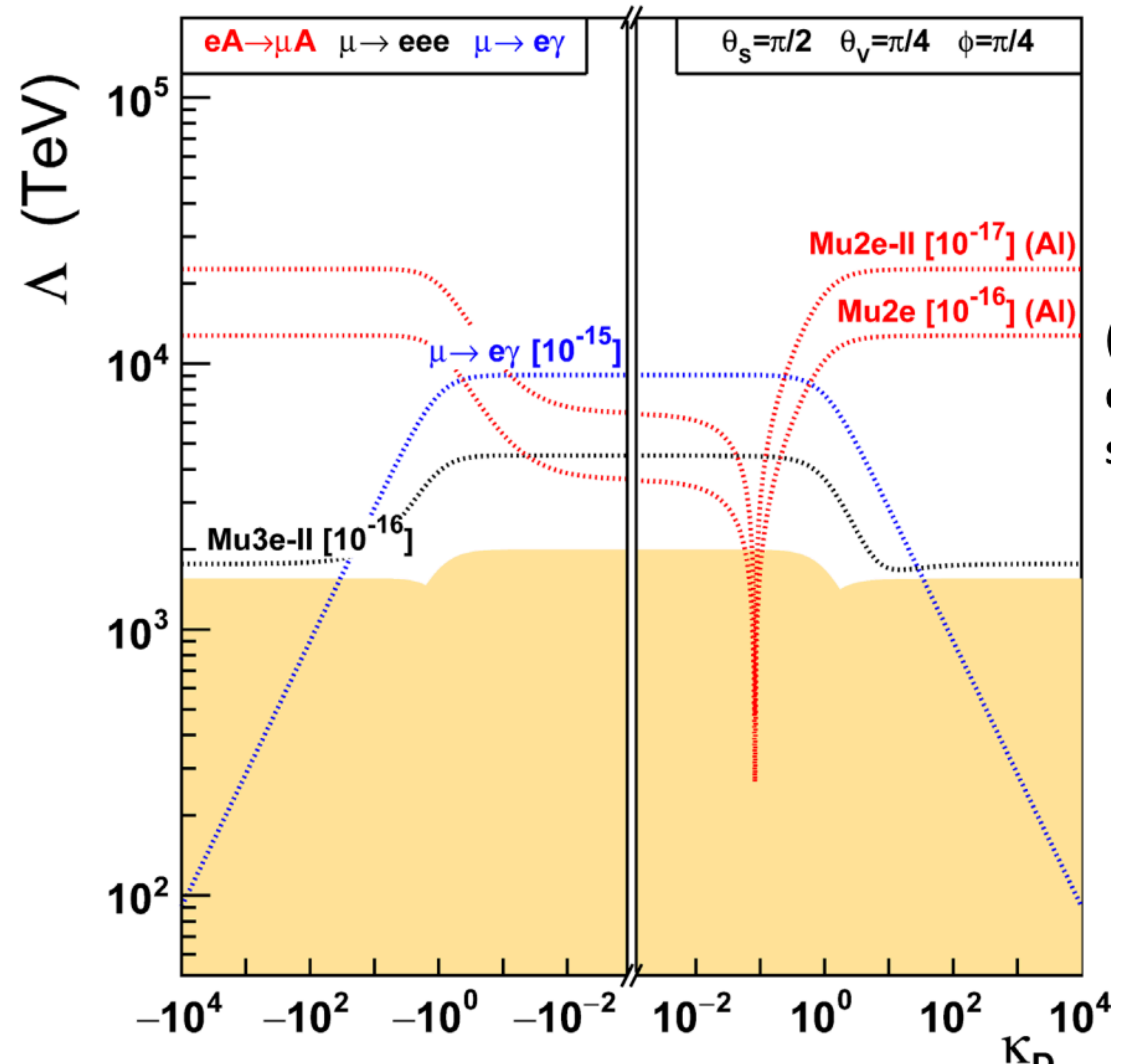
Exp	Institut	Process	Sensitivity
MEG II	PSI	$\mu^{\pm} \to e^{\pm} + \gamma$	4.2×10^{-14}
Mu2e	FNAL	$\mu^{-} + N \to e^{-} + N$	6.0×10^{-17}
COMET	JPARC	$\mu^{-} + N \to e^{-} + N$	$10^{-15} - 10^{-17}$
Mu3e	PSI	$\mu^{\pm} \to e^{\pm} + e^{+} + e^{-}$	$10^{-14} - 10^{-16}$

Increasing Mu2e capability

- Improve sensitivity.
- Probe higher mass scale.

Expanding upon Mu2e goals

- Change targets.
- Focus on excluding/including models.
- $\mu^{-} + N \to e^{+} + N'$
- $\mu \to eX$

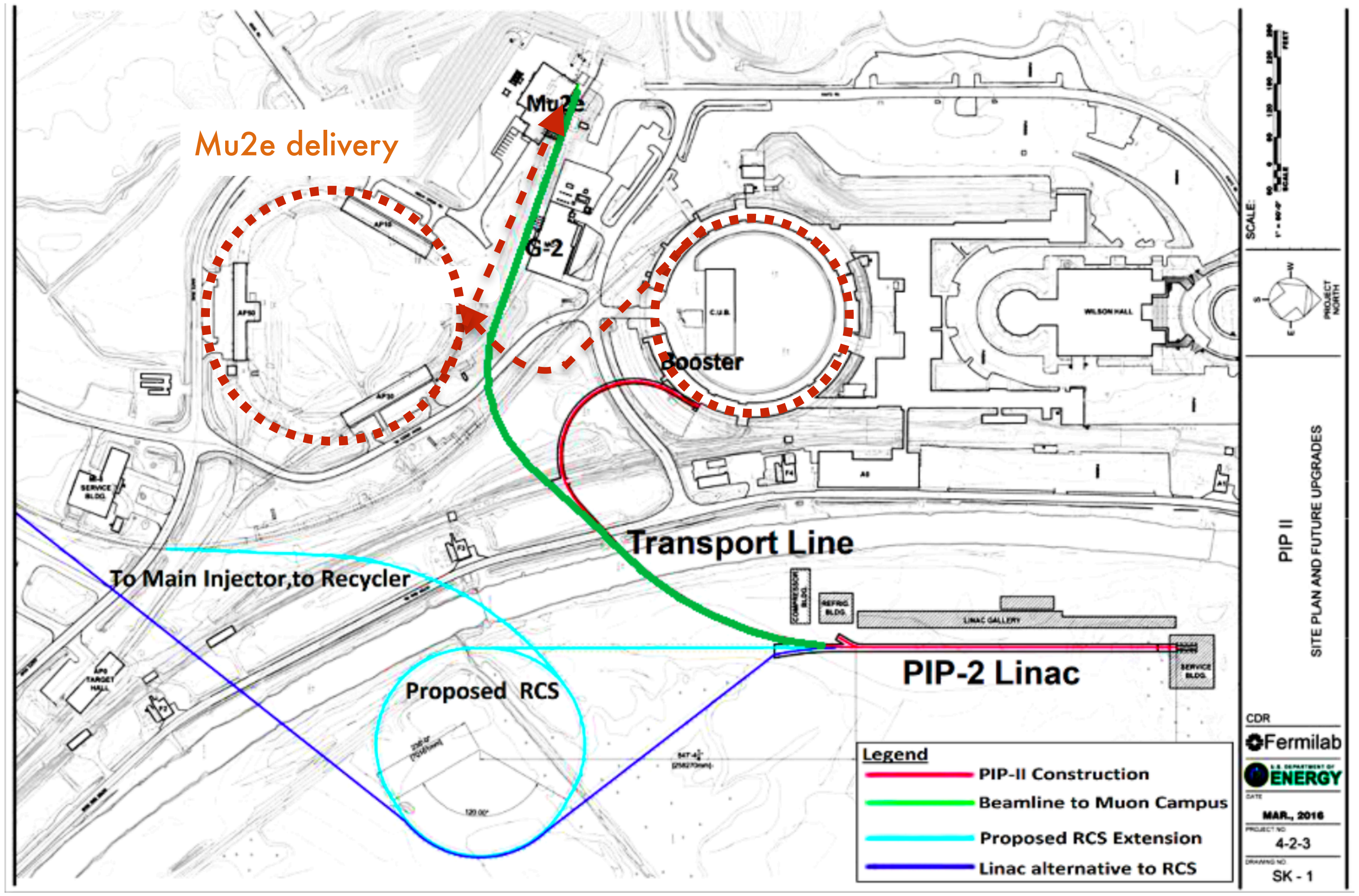


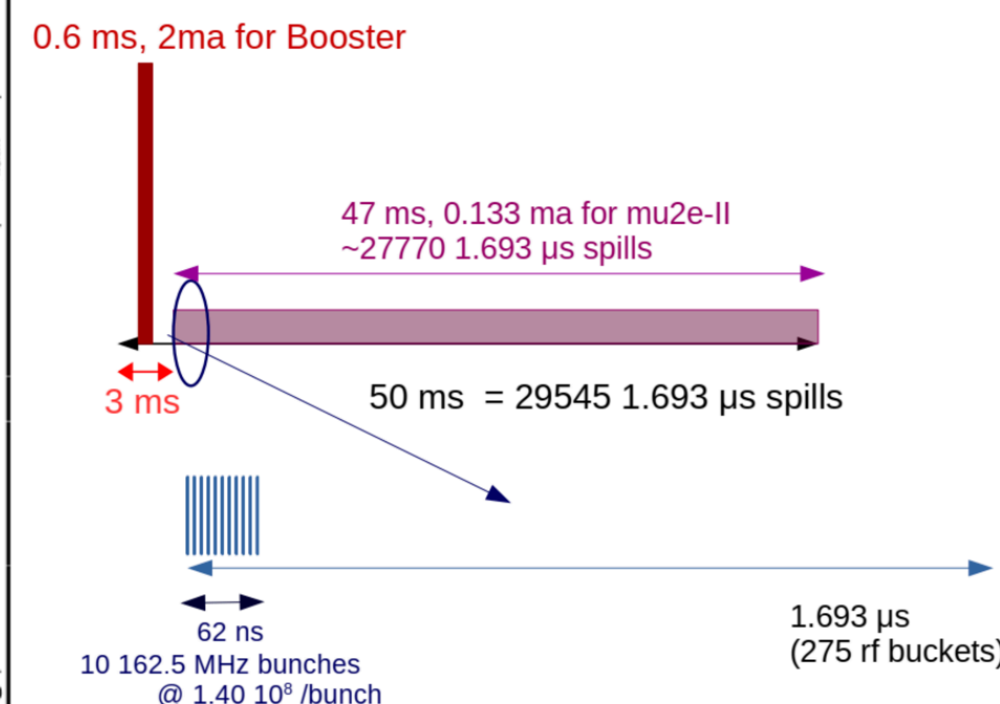
Eur.Phys.J.C 82 (2022) 9, 836

$\kappa_D = \cot an(\theta_D - \pi/2)$

θ_D parametrizes relative Magnitude of dipole and four-fermion coefficients.

PIP-II



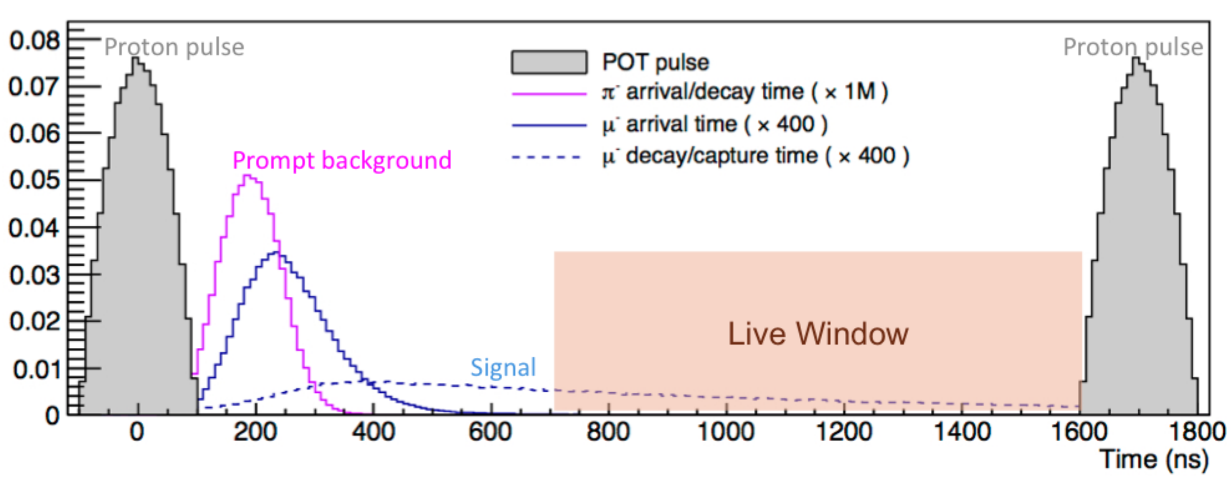


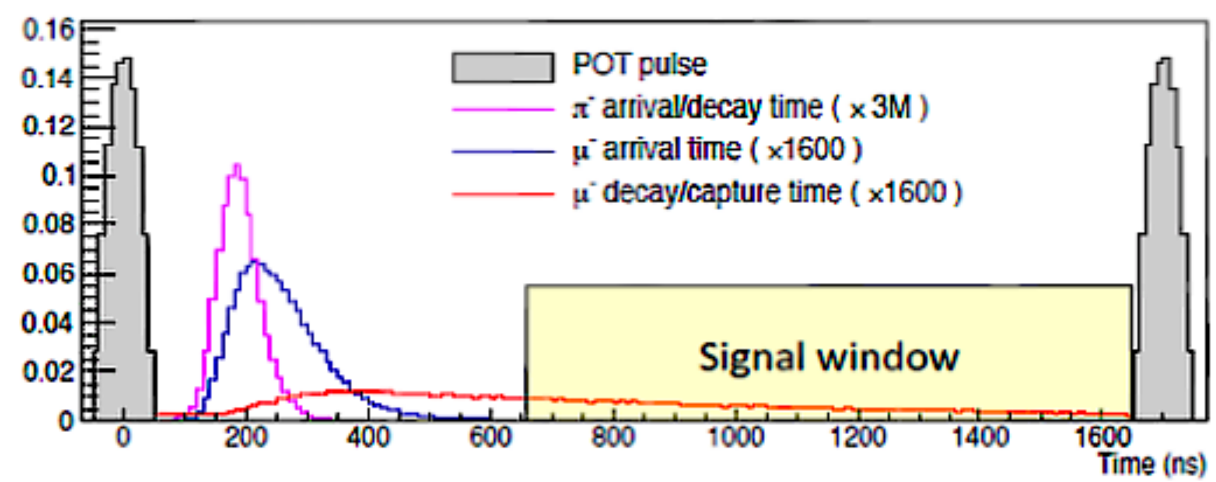
- Mu2e-II beam is delivered using CW of magnetically stripped H^- directly from LINAC instead of slow extracted protons from delivery ring(DR).
- 1.4×10^9 H^- per spill, 62 ns bunch width compared to 250 ns for Mu2e.
- 10^{-11} extinction is required for the beam compared to 10^{-10} for Mu2e.

Mu2e vs Mu2e-II Beam Comparison

Parameter	Mu2e	Mu2e-II
Proton source	Slow extraction from DR	PIP-II Linac
Proton kinetic energy	8 GeV	0.8 GeV
Beam Power for expt.	8 kW	100 kW
Protons/s	6.25×10^{12}	7.8×10^{14}
Pulse Cycle Length	1.693 μs	1.693 μs
Proton rms emittance	2.7	0.25
Proton geometric emittance	0.29	0.16
Proton Energy Spread (σ_E)	20 MeV	0.275 MeV
$\delta p/p$	2.25×10^{-3}	2.2×10^{-4}
Stopped μ per proton	1.59×10^{-3}	9.1×10^{-5}
Stopped μ per cycle		1.2×10^{5}

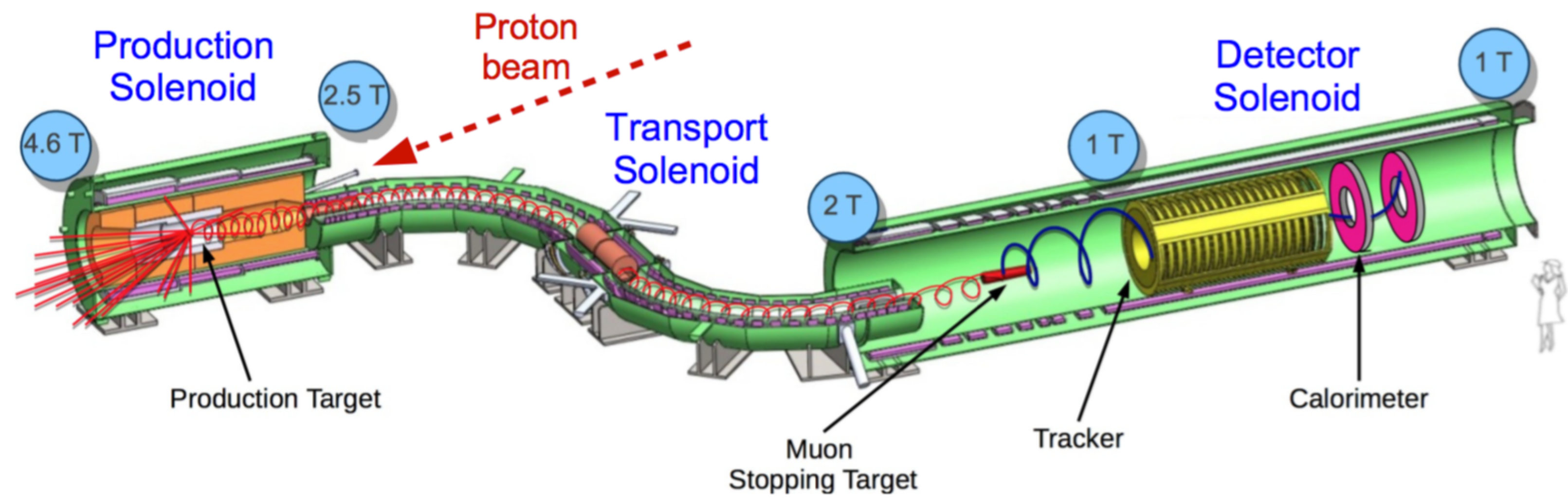
Mu2e → Mu2e-II



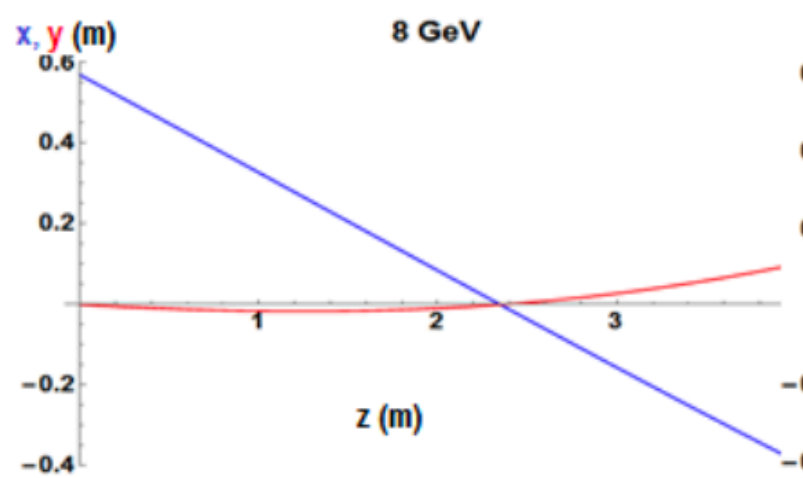


Solenoids

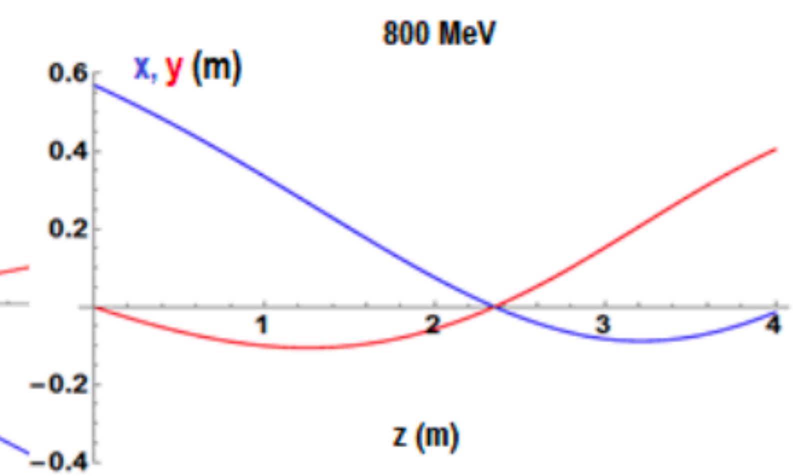
- Production solenoid(PS) needs to change(cold mass) to handle the increased power delivered by PIP-II beam line.
- Lower energy beam is deflected more in vertical direction entering PS.
- Replacing PS cold mass;
  - Superconducting;
    - Cable-in-conduit conductor(CICC).
    - Internally cooled Al cable.
    - High-temperature superconducting(HTS) coils.
  - Resistive;
    - Water cooled resistive Cu coil.
    - LN_2 cooled resistive Cu or Al coil.
- TS may require some modifications.
- DS will be used as is.



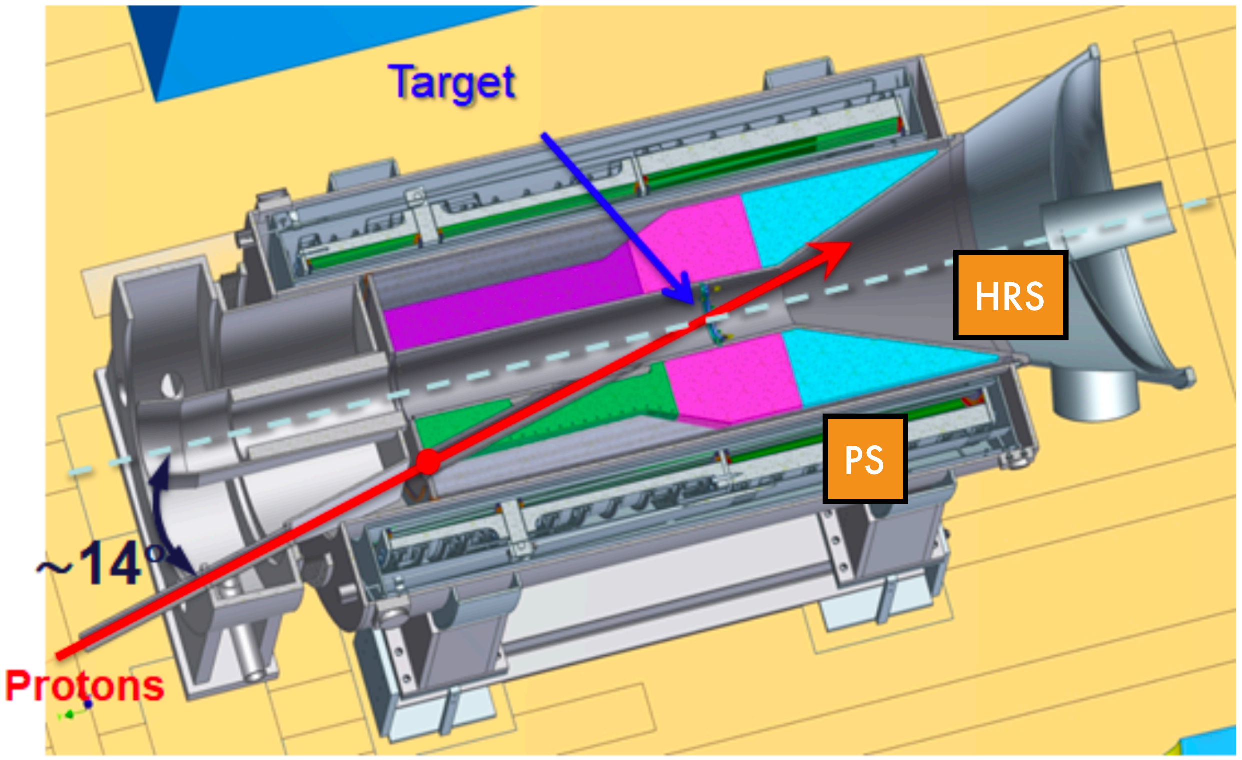
Mu2e

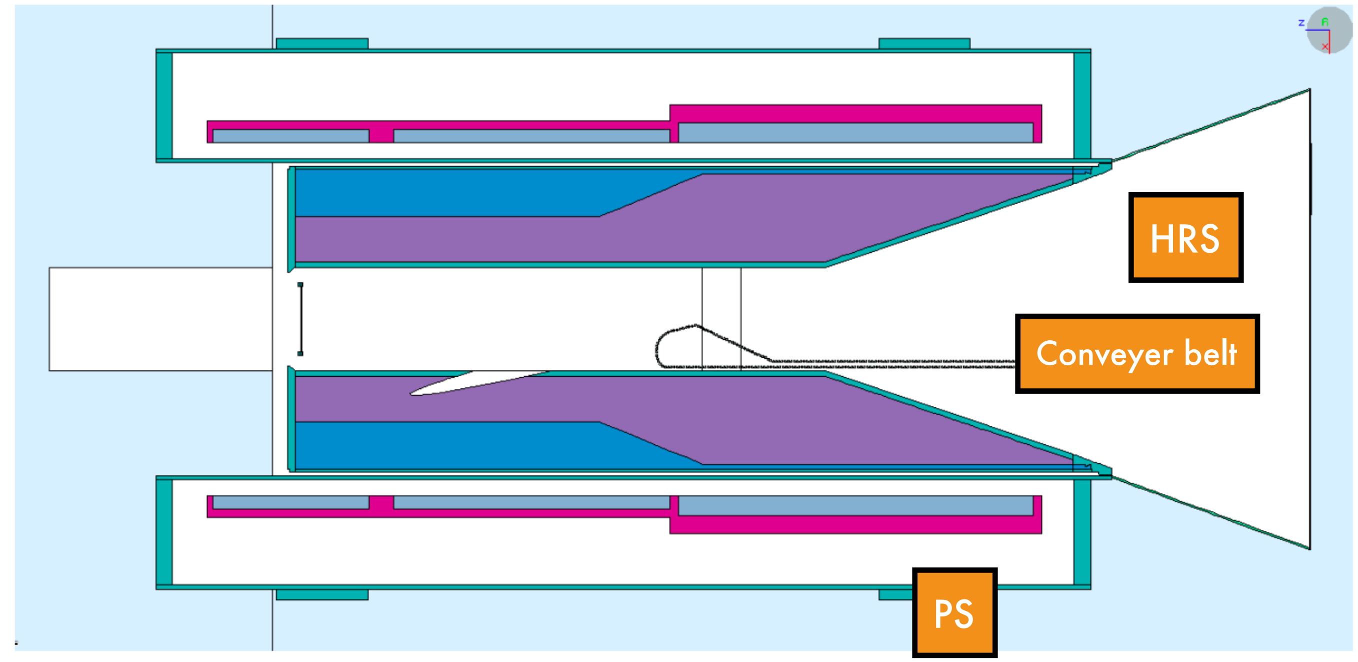


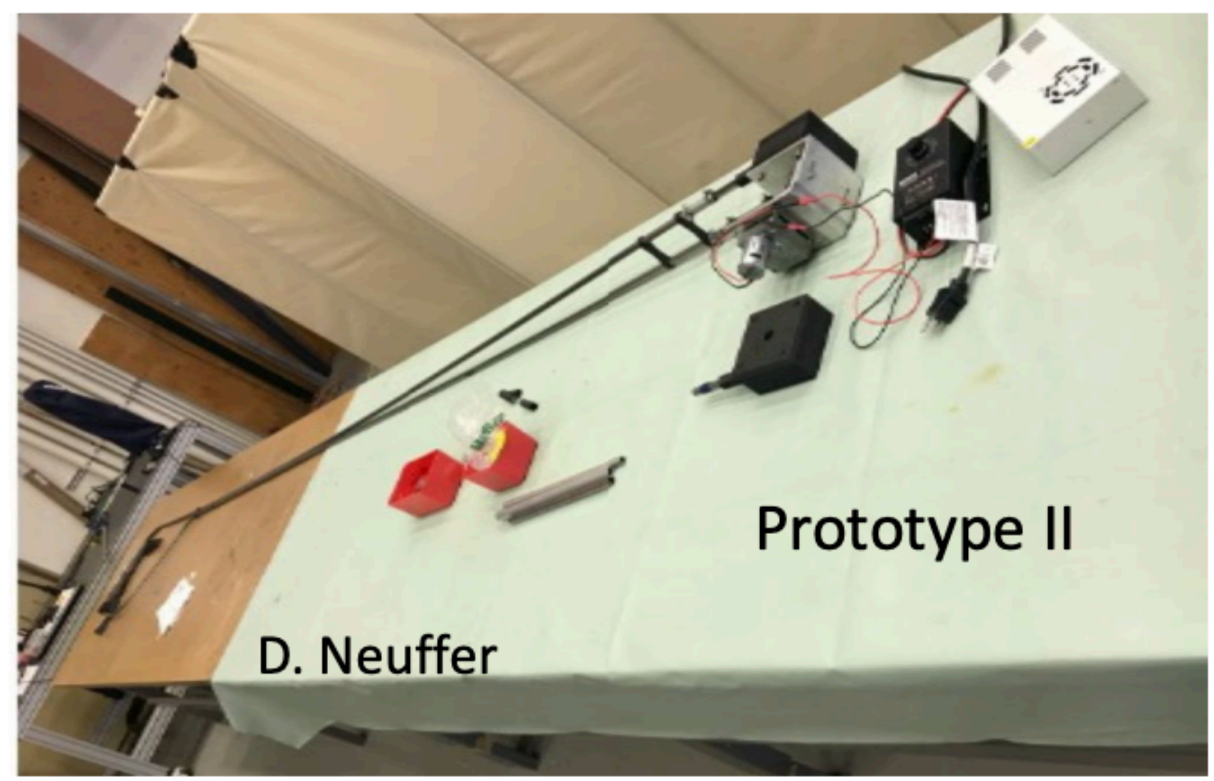
Mu2e-II



Production target



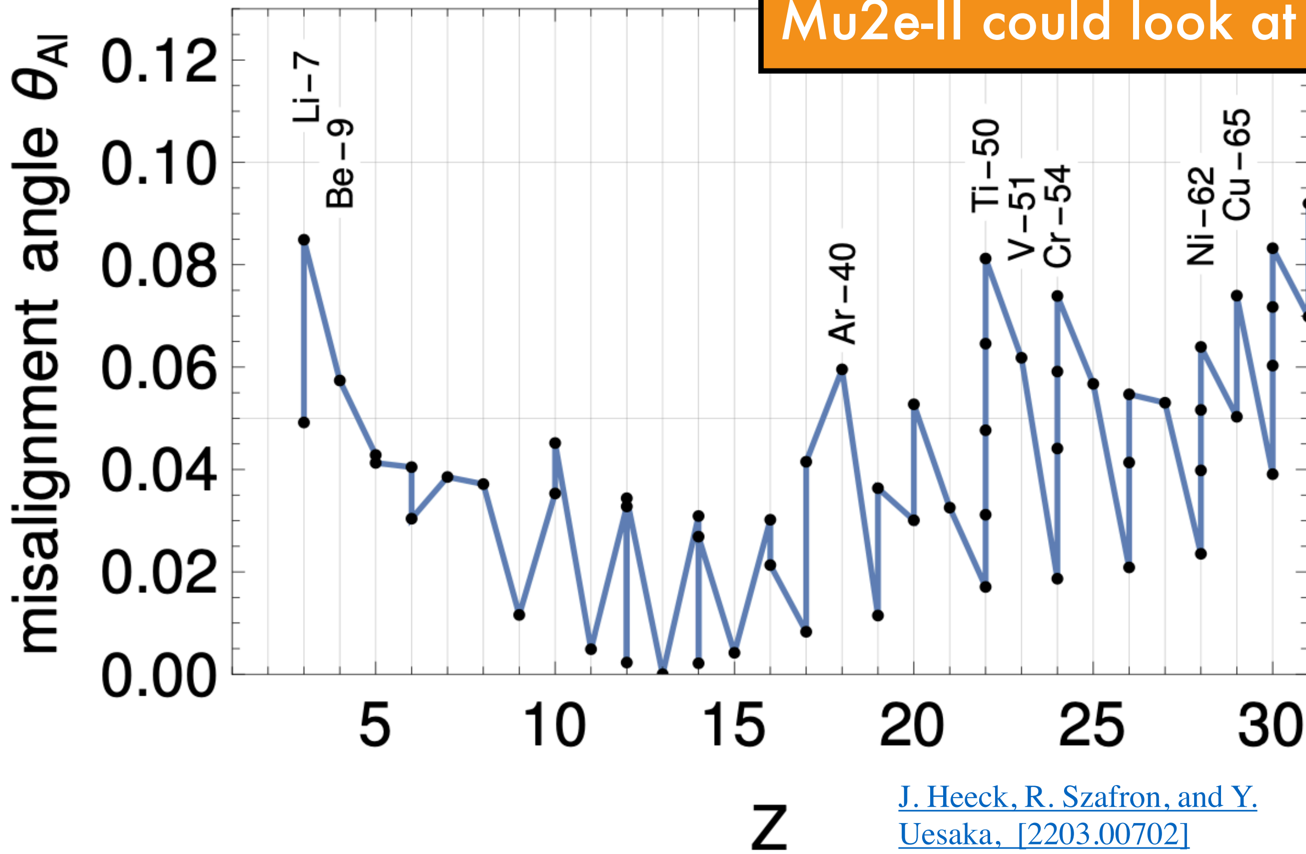




- 100 kW on Mu2e-II target needs active cooling.
  - Carbon or Tungsten spheres on a conveyer belt.
  - Switch from copper to tungsten for HRS.
  - Need in situ monitoring of the target.
- R&D platform for AMF experiments and the Muon Collider.

Potential stopping targets

Mu2e-II could look at different targets!



J. Heeck, R. Szafron, and Y. Uesaka, [2203.00702]

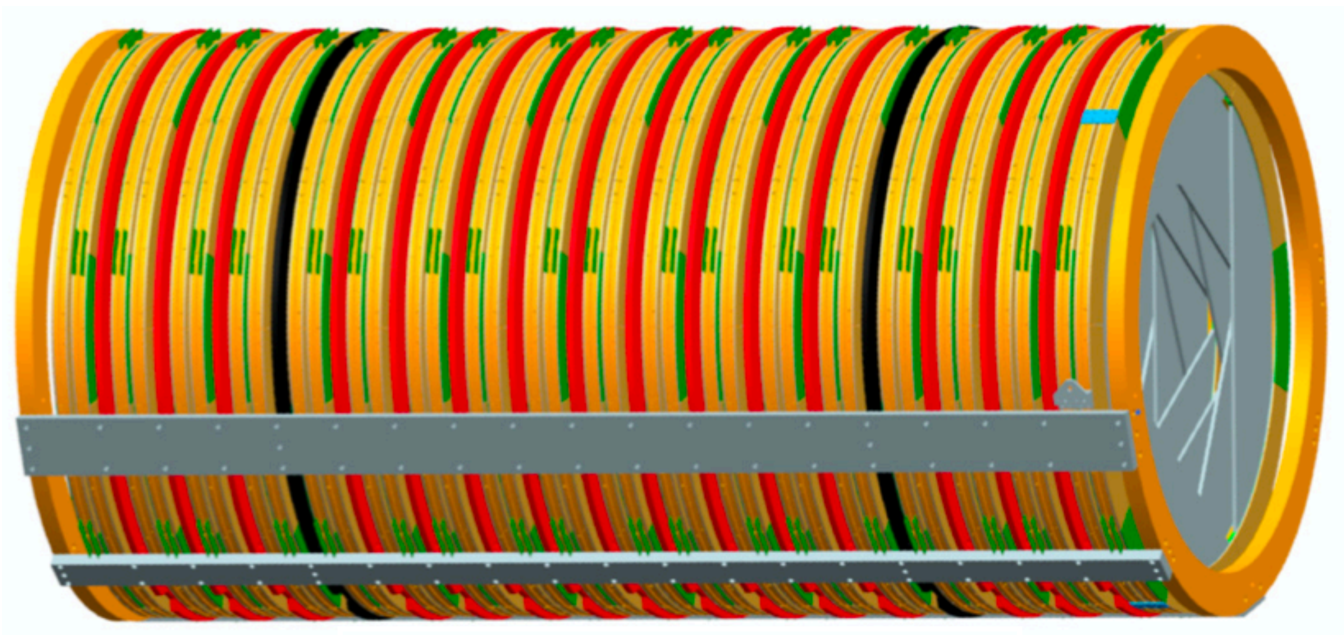
- Misalignment angle probes different Wilson coefficients.
- Preferably, for a complementary study one requires large angle -> heavy Z.
- Need muon lifetime > 250 ns, therefore Z < 25.

Decay In Orbit comparison

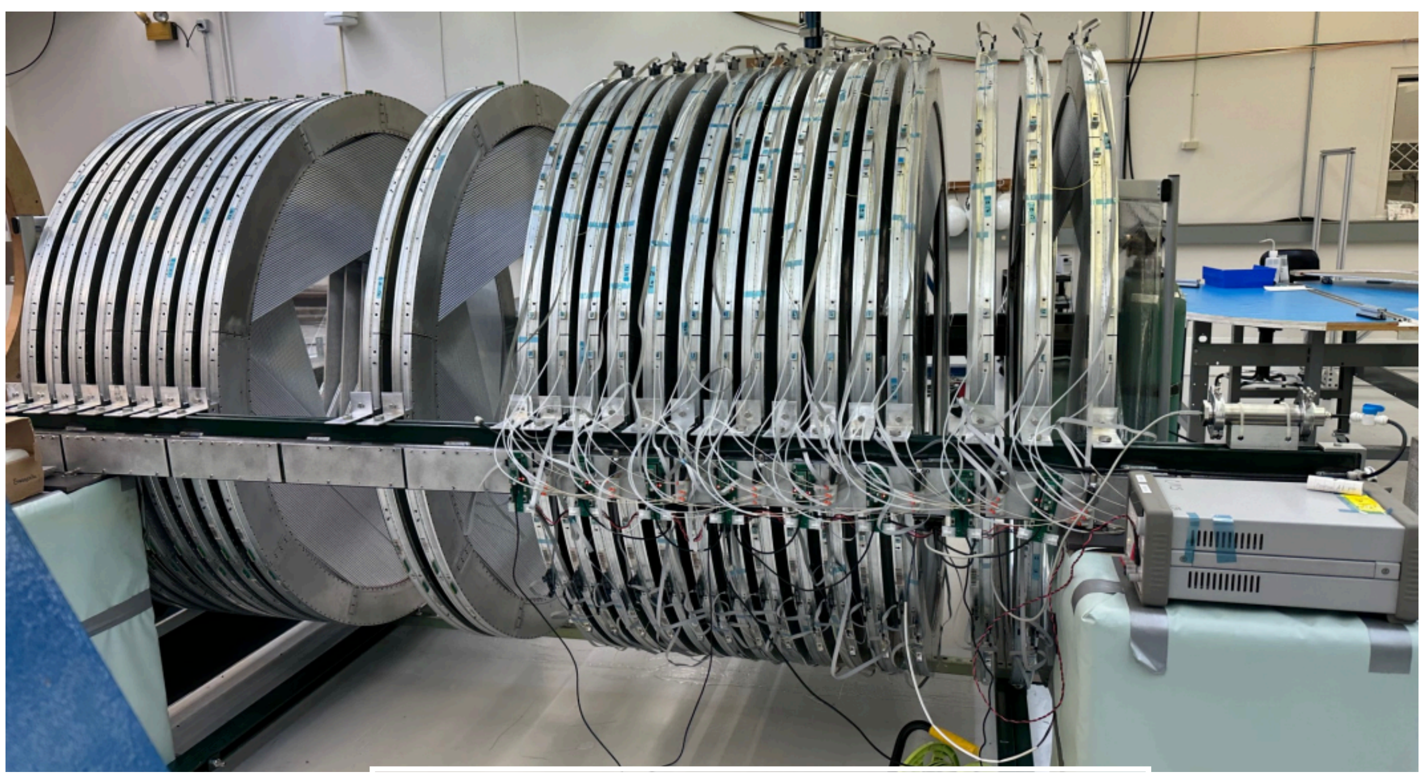
	spin	NA/%	$E_{\text{end}}/\text{MeV}$	B/MeV^{-6}	τ_μ/ns	$\Gamma_{\text{cap}}/s^{-1}$
${}^{6}_{3}\text{Li}$	1	7	104.64	1.3×10^{-19}	2175.3	4680
${}^{7}_{3}\text{Li}$	$\frac{3}{2}$	93	104.78	1.3×10^{-19}	2186.8	2260
${}^{27}_{13}\text{Al}$	$\frac{5}{2}$	100	104.97	8.9×10^{-17}	864	662×10^{3}
${}^{46}_{22}\text{Ti}$	0	8	104.25	5.2×10^{-16}		
${}^{47}_{22}\text{Ti}$	$\frac{5}{2}$	7	104.26	5.3×10^{-16}		
${}^{48}_{22}\text{Ti}$	0	74	104.26	5.3×10^{-16}	329.3	2.59×10^{6}
${}^{49}_{22}\text{Ti}$	$\frac{7}{2}$	5	104.26	5.4×10^{-16}		
${}^{50}_{22}\text{Ti}$	0	5	104.26	5.4×10^{-16}		
${}^{51}_{23}\text{V}$	$\frac{7}{2}$	100	104.15	6.3×10^{-16}	284.5	3.07×10^{6}
${}^{50}_{24}\text{Cr}$	0	4	104.04	7.1×10^{-16}	233.7	3.82×10^{6}
${}^{52}_{24}\text{Cr}$	0	84	104.04	7.2×10^{-16}	256.0	3.45×10^{6}
${}^{53}_{24}\text{Cr}$	$\frac{3}{2}$	10	104.05	7.1×10^{-16}	266.6	3.30×10^{6}
${}^{54}_{24}\text{Cr}$	0	2	104.05	6.9×10^{-16}	284.8	3.06×10^{6}

T. Suzuki, D. F. Measday, and J. P. Roalsvig,
"Total Nuclear Capture Rates for Negative Muons," Phys. Rev. C 35 (1987) 2212.
J. Heeck, R. Szafron, and Y. Uesaka, [2110.14667]

Tracker



Tracker Model - 36 tracker planes

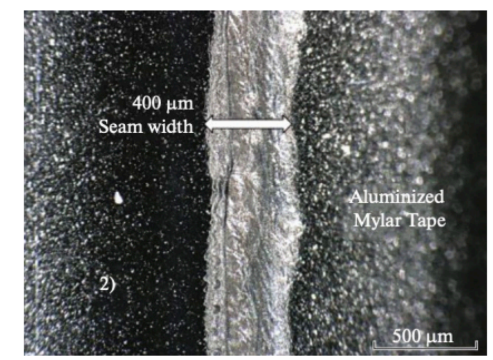


Tracker Planes(24/36) - November 2023

Biggest difference is the reduced straw thickness from 15 μm to 8 μm

	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

- R&D needed for;
  - Straw handling.
  - Module production.
  - Leaks.
- Consider other tech;
  - NA62/COMET 12 μm ultrasound weld.
  - Microform Al extrusion 2 μm



DOI: 10.1134/S1547477122020108

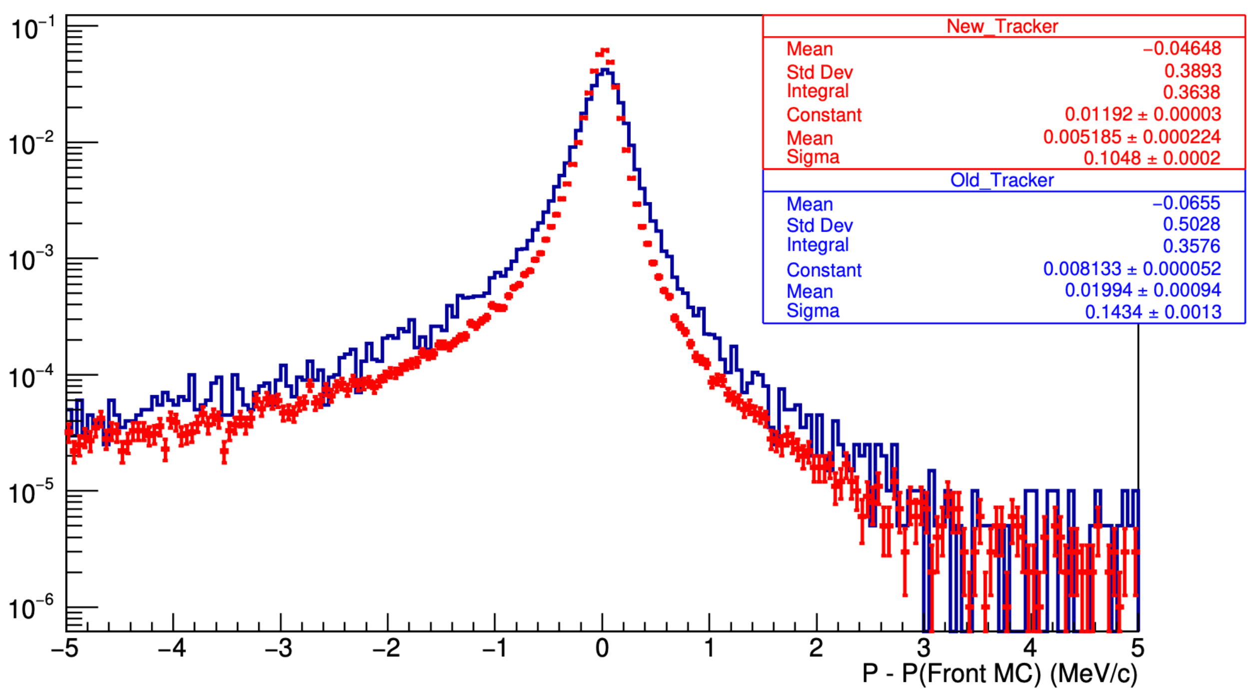
COMET 12 µ ultrasound welded

Microform extrusion

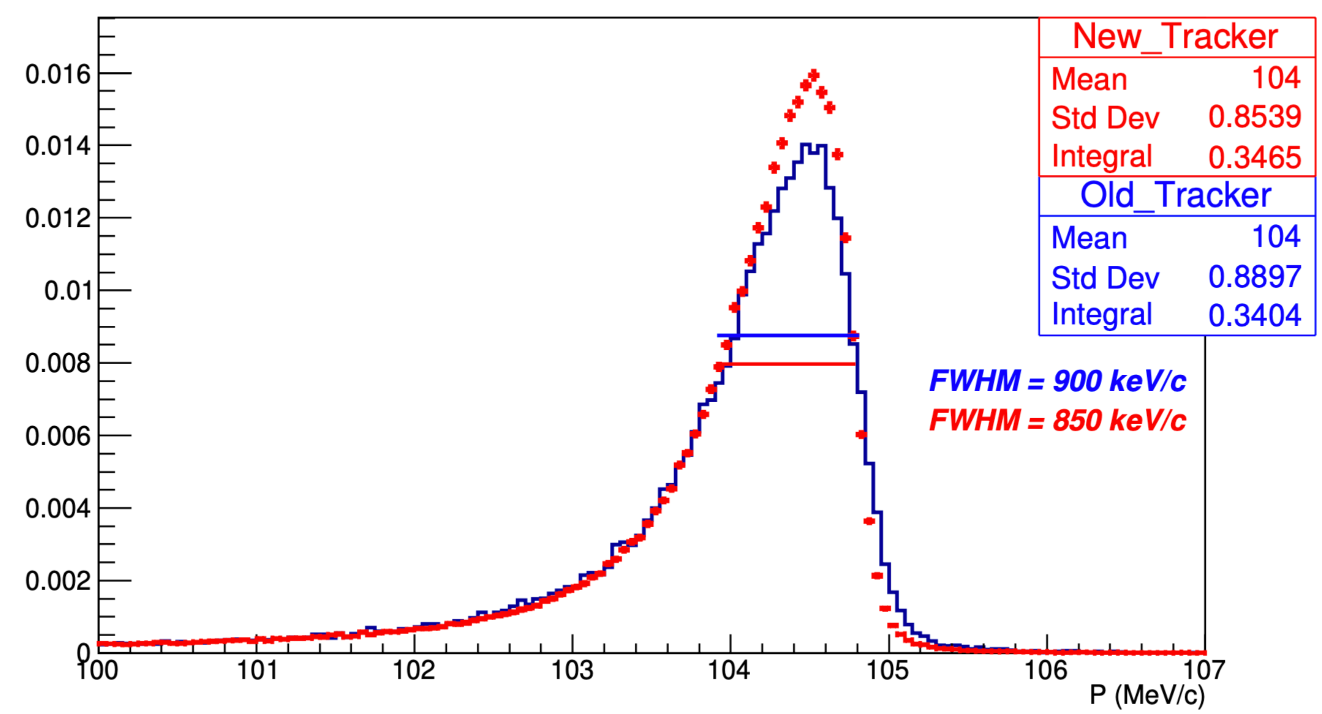
Comparison using thinner straws

15 μm vs 8 μm

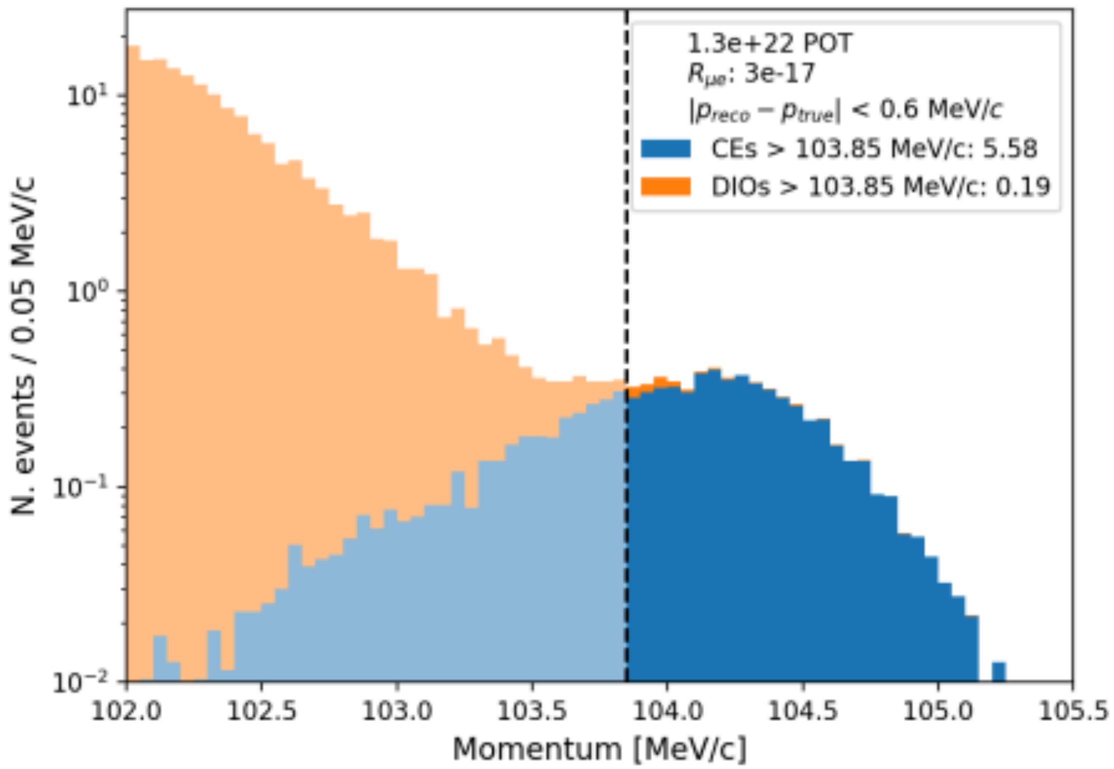
Mu2e-II CE momentum resolution at the Tracker front



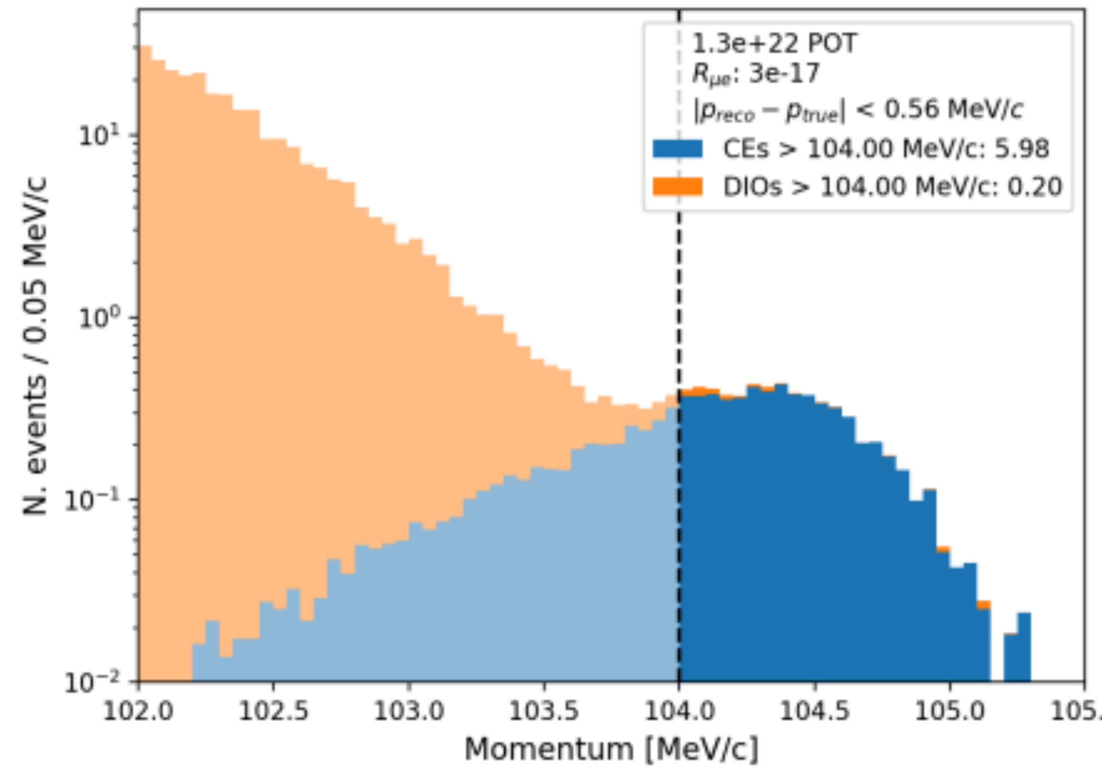
Mu2e-II CE reconstructed momentum



Conversion electron



15 μm straws (Mu2e)

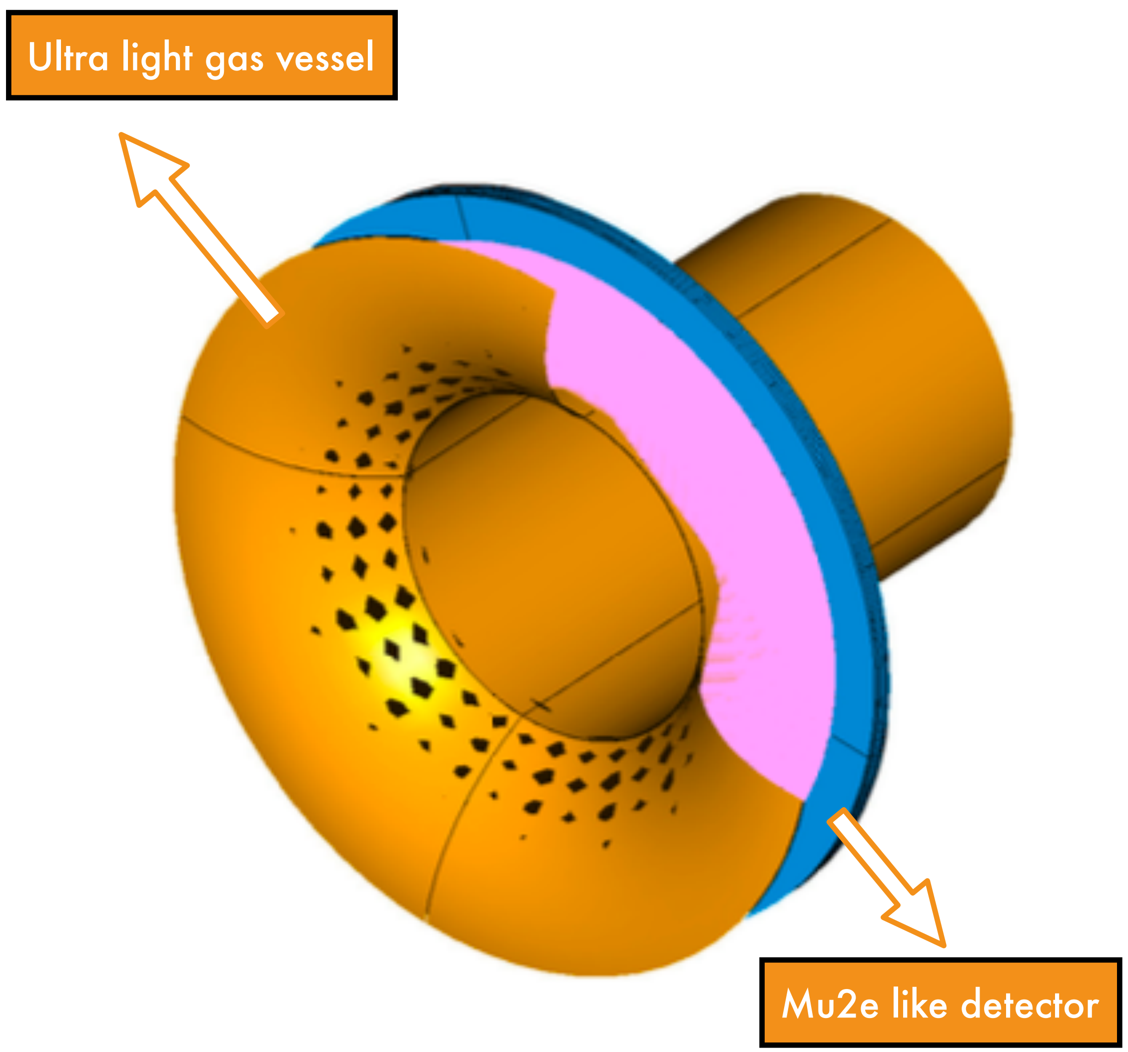


8 μm straws (Mu2e-II)

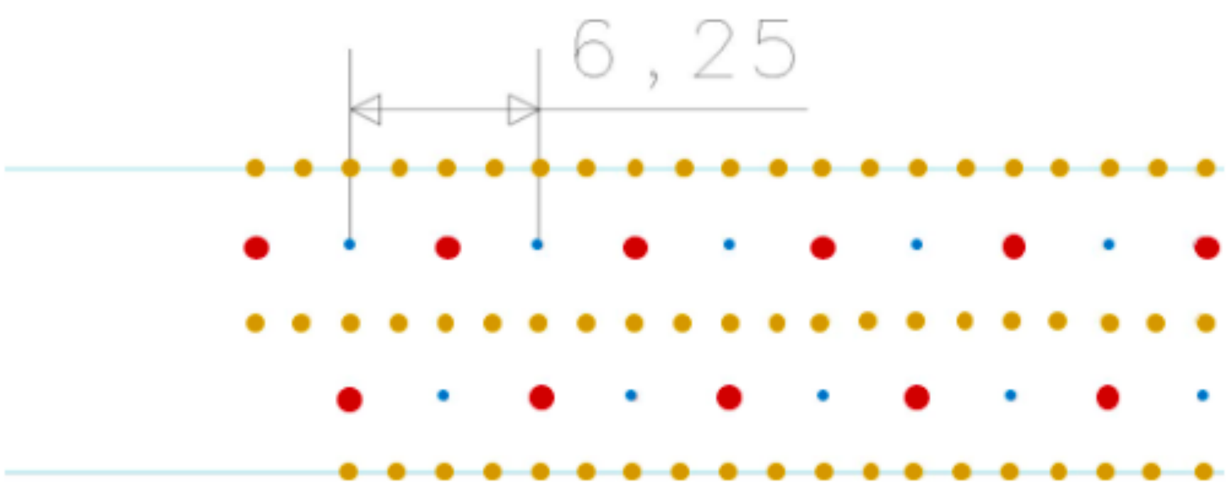
10% improvement on CE efficiency

R&D is needed to improve pattern recognition and track finding

Alternative tracker geometry



Blue is 25 μm W sense wire, **red** is 50 μm Al and **orange** is 40 μm Al field wires. Alternatively 5 μm metaled mylar foils can replace the field layer.

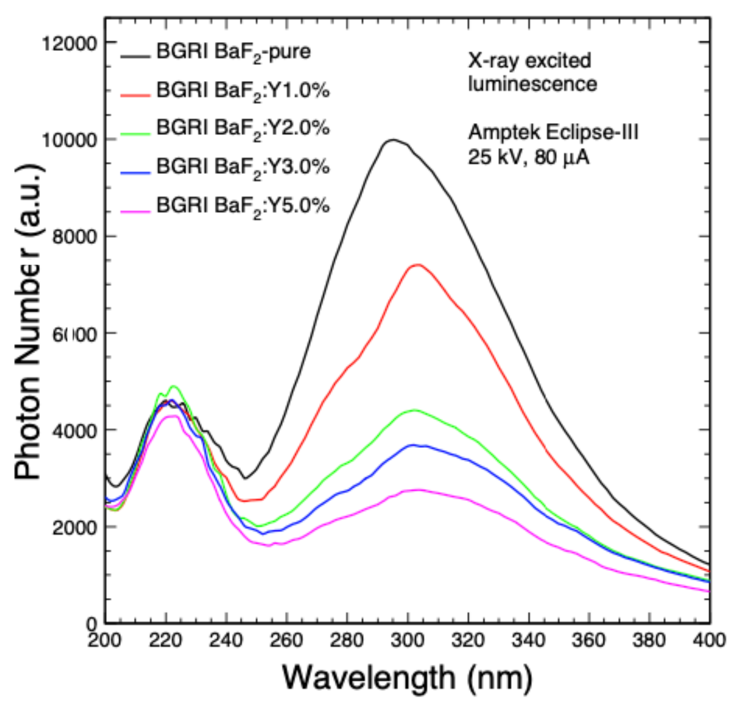


- No glueing is needed as there is no need to eliminate leaks.
- He is needed for the drift gas to minimize multiple scattering.
- However He is $\times 2$ slower than ArCO_2 and will reduces rates.

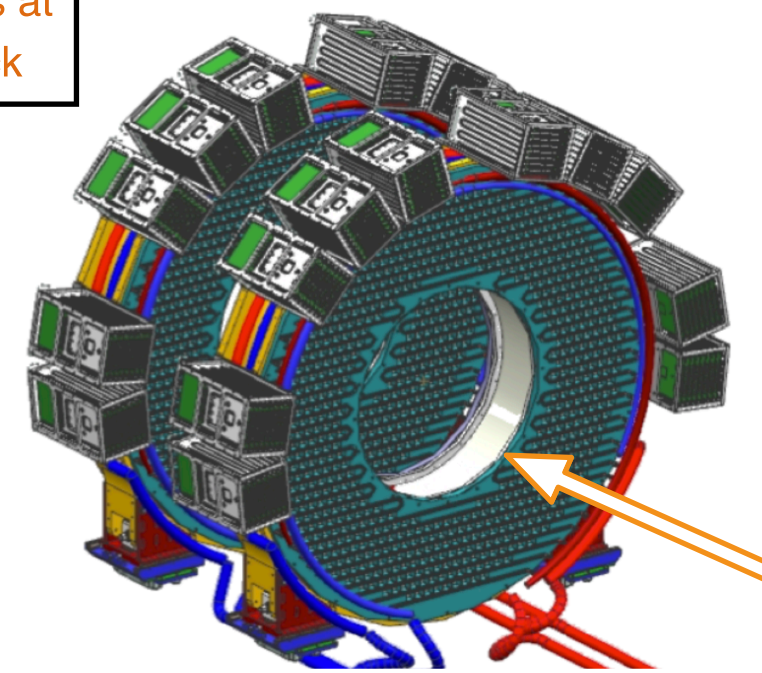
Calorimeter

- Crystal needs to withstand 0.1-1 Mrad;
  - BaF_2 met requirements but long wavelengths must be suppressed.
  - LYSO:Ce also met requirements but is slower(40 ns decay time).
- Photosensors has the same rad requirements;
  - For BaF_2 they must be sensitive to 220 nm fast component and insensitive to 300 nm slow component.
  - AlGaN photocathode works well with BaF_2.
  - R&D is underway to improve radiation hardness of these SiPMs.

BaF2 Crystal Response

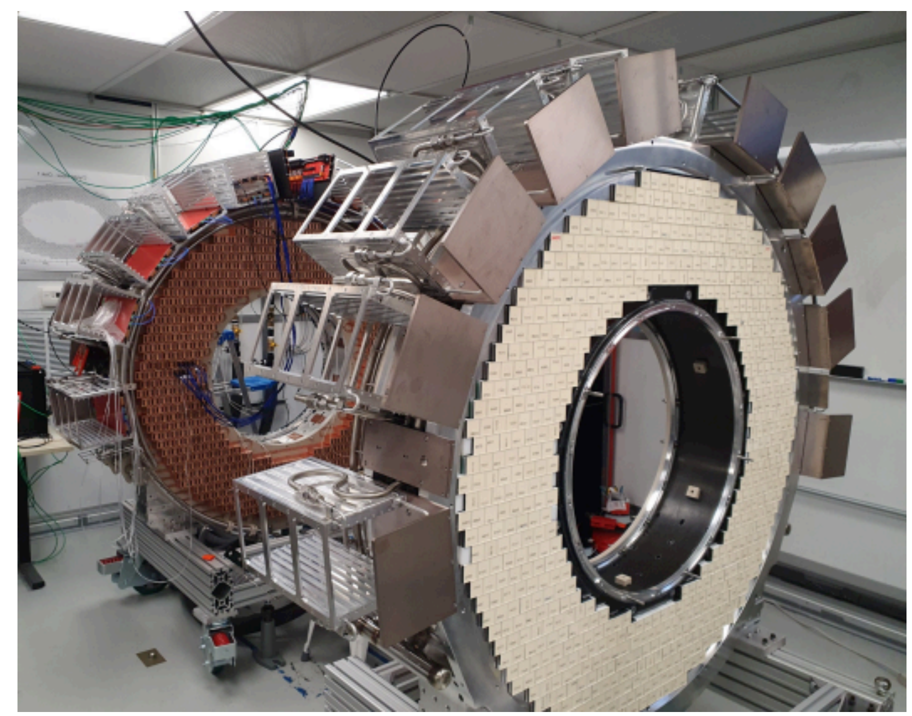


Keep CsI crystals at the back



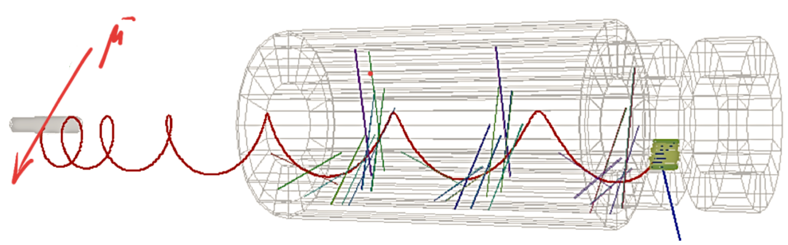
Change only front facing crystals

Beam

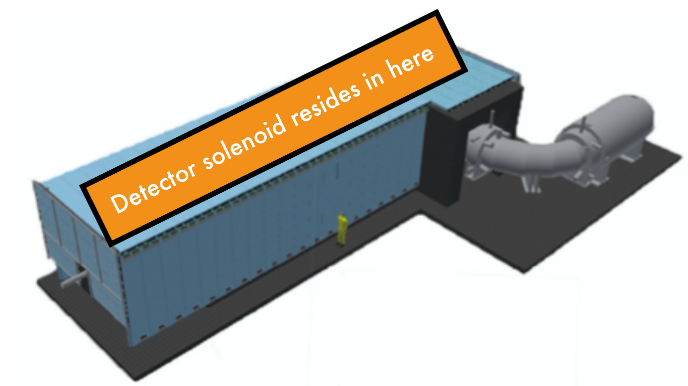


Calo disks - October 2023

Cosmic ray veto



Cosmic background ~= 1 bg event per day.
Covers all DS and part of TS.



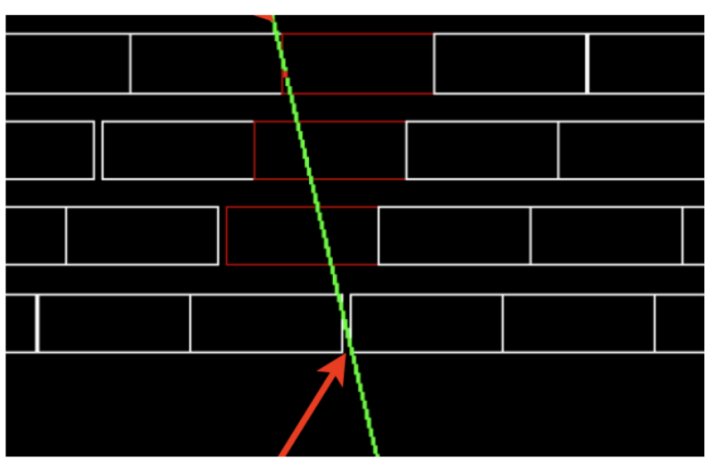
Mu2e → Mu2e-II

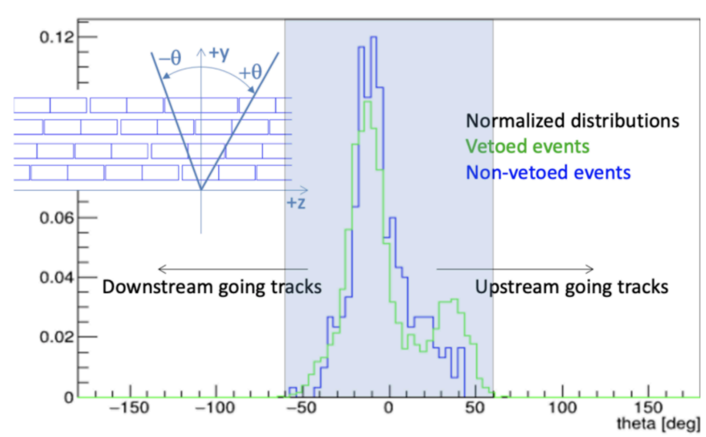
Mu2e

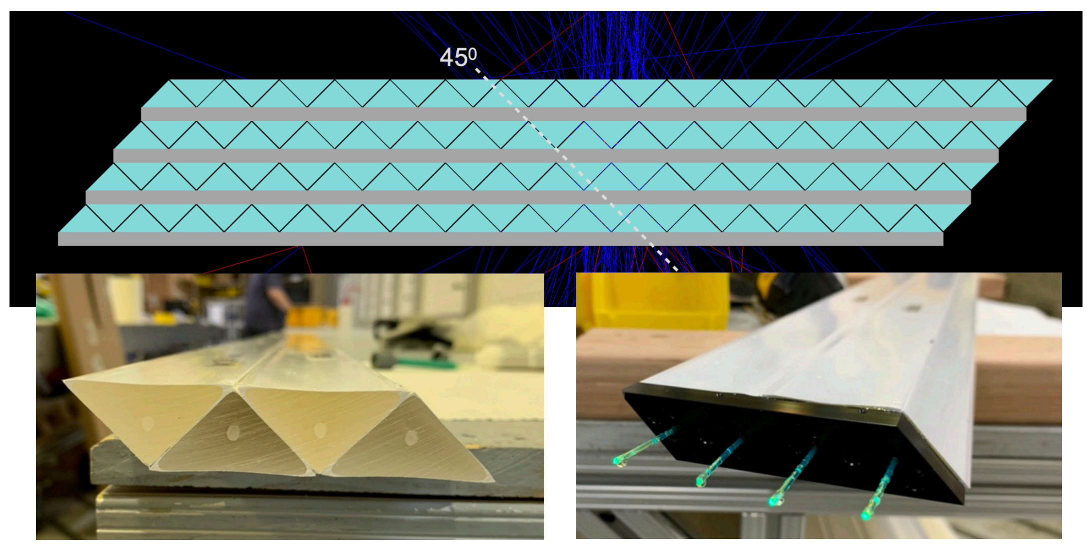
- Polystyrene scintillators coated with TiO2 sandwiched between Al absorbers.
- 4 overlapping layers of scintillators.
  - 3 layer coincidence veto
- Readout through WLS fibers & 2x2 mm^2 SiPMs on both ends.

Mu2e-II

- Improve concrete shielding with Barite and Boron loaded concrete.
- Change geometry to further minimize gaps between scintillators and increase granularity.
- SiPMs with better PDE and potted fibers to increase light yield.

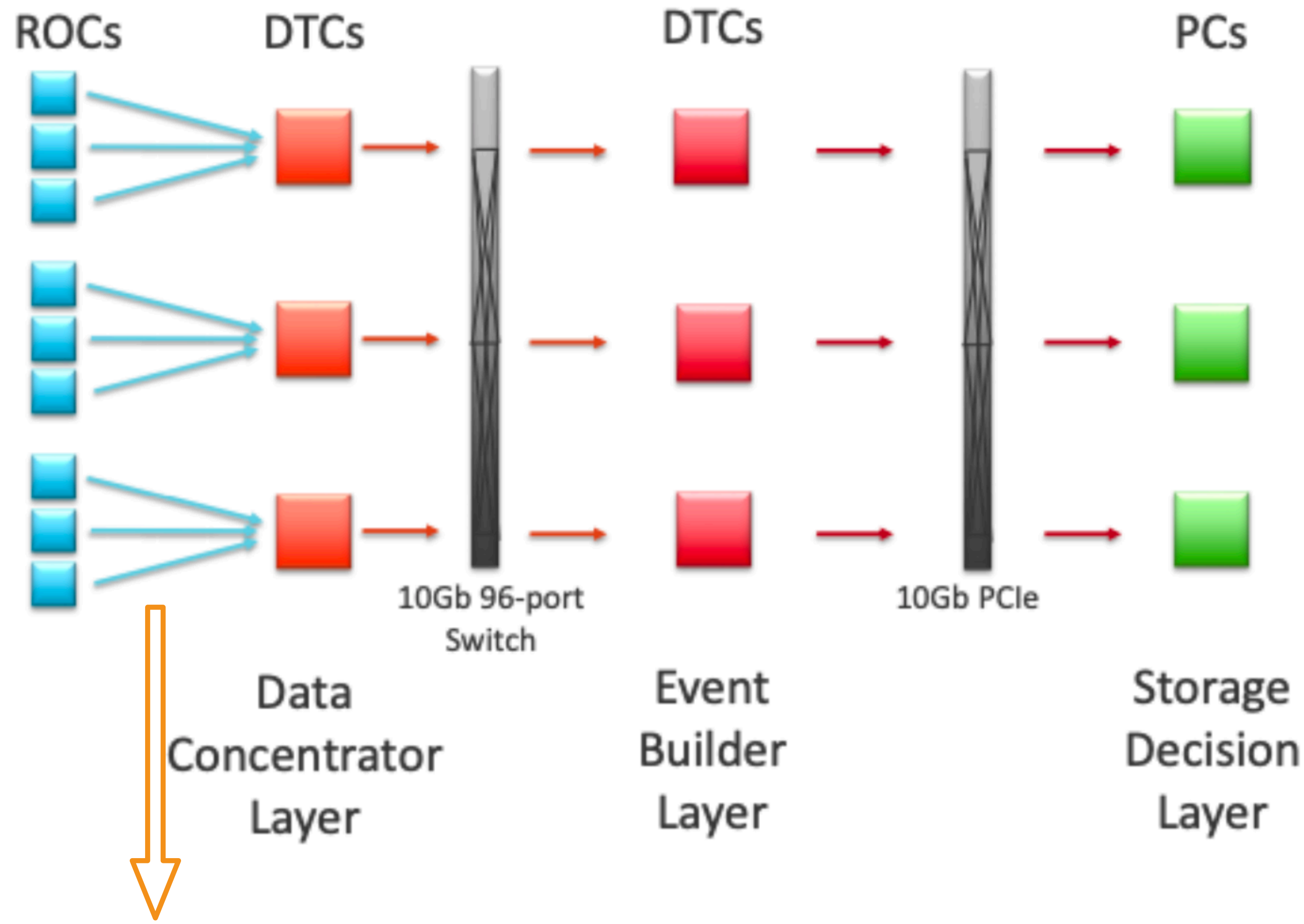






Trigger and Data Acquisition(TDAQ)

- × 6 event size @ 1MB/s.
- Reduced period with no beam.
- × 5 better Mu2e trigger rejection.
- × 10 Rad dose.
- 14 PB/y data.



Track reconstruction;

1. Hit preparation.
2. Pattern recognition.
3. Track fit.

Use FPGA for L1 hardware trigger

Use GPUs for software trigger

Development can start now!

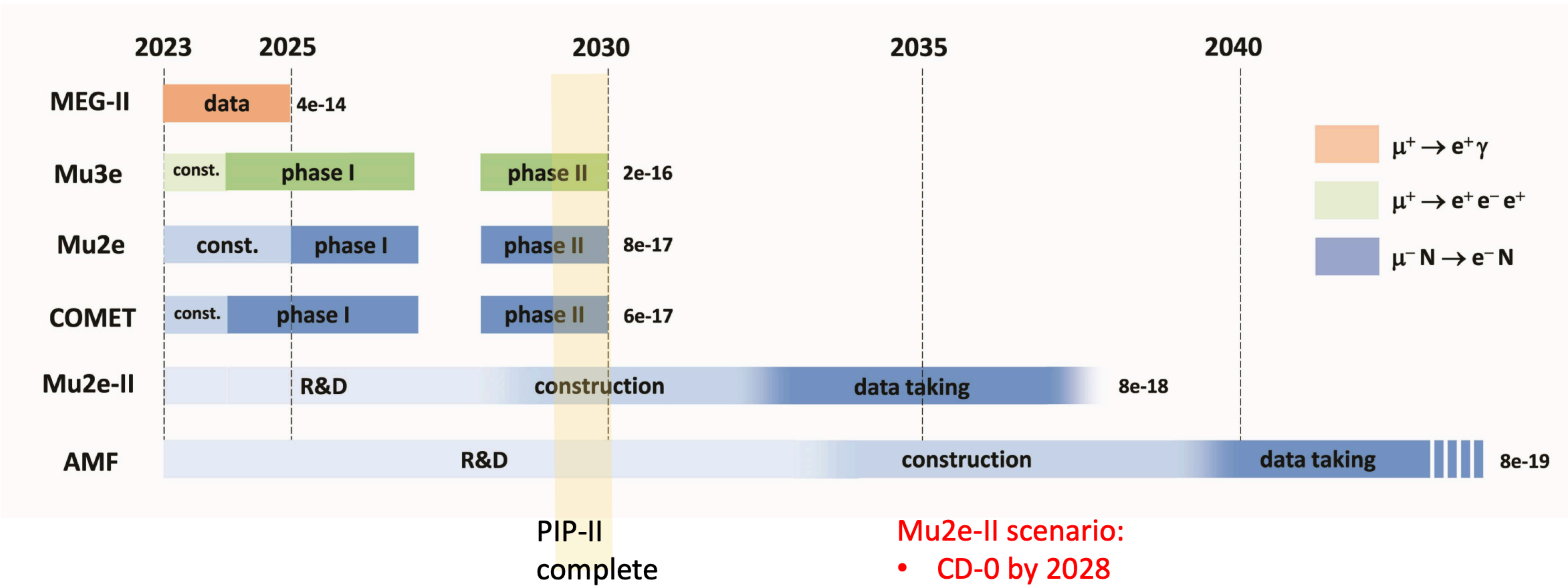
Backgrounds and sensitivity

- Mu2e-II results are for a C production target.
- More R&D and software optimization is needed.
- This estimate is considered to be conservative.

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}

Arxiv link

Schedule Prediction



Mu2e-II scenario:

- CD-0 by 2028
- Construction 2028-2032 (5 years)
- Data 2033-2037… (5… years)

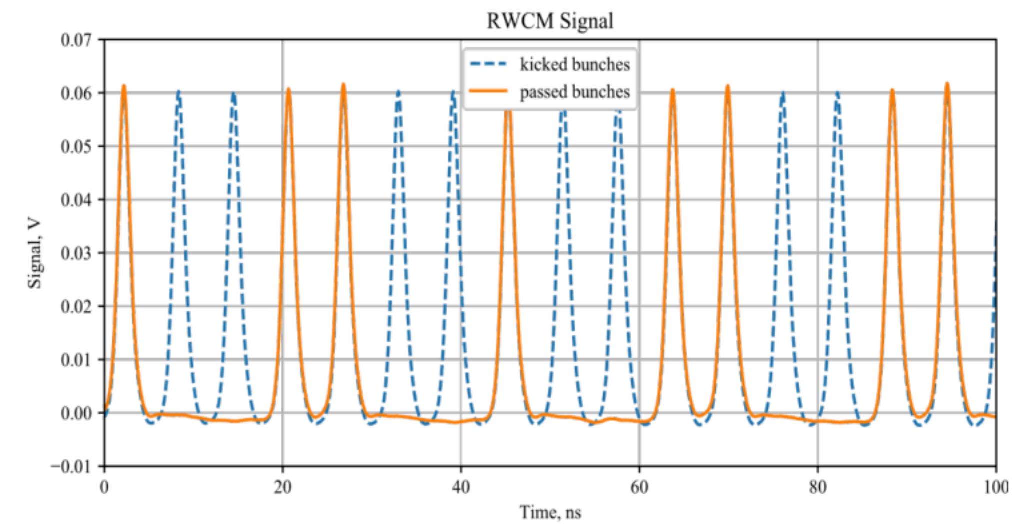
Summary

- Mu2e-II is a worthwhile follow up to Mu2e in all cases with respect to Mu2e result.
- PIP-II will provide a much finer beam allowing Mu2e-II and other muon experiments to flourish.
- However more intense beam brings a harsher environment in terms of radiation. All subsystems will require significant R&D to meet this criteria.
- Mu2e-II offers many challenges and opportunities to work on regardless of the subsystem.

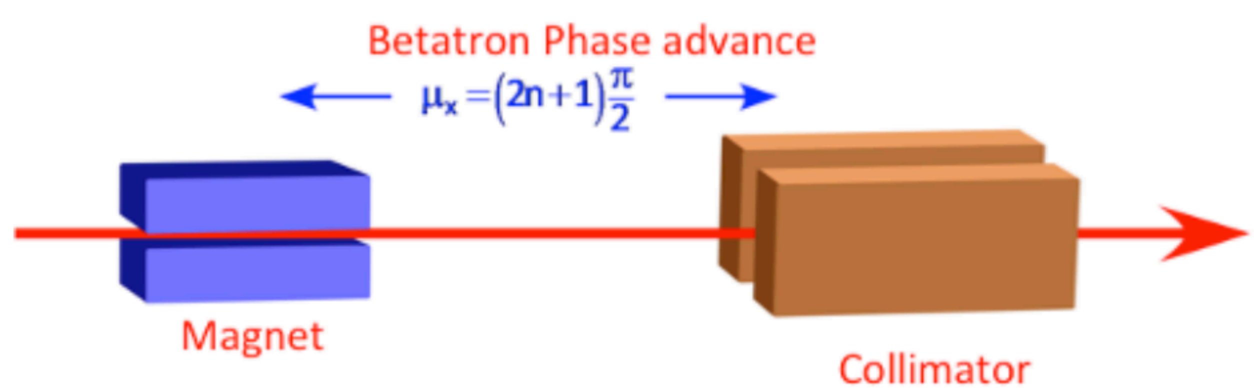
BACKUP

Extinction

- Extinction is measure of out-of-time beam
- Mu2e-II requires extinction < 10^{-11}
  - cf Mu2e requirement < 10^{-10}
- PIP-II specification is 10^{-4}
  - Likely will be better
- Second stage (10^{-9} with safety margin) with resonant dipoles and collimators, modified from Mu2e
  - Lower momentum means larger deflection
  - No beam halo from Mu2e's slow extraction septum
  - Lower momentum means lower punch through at collimator



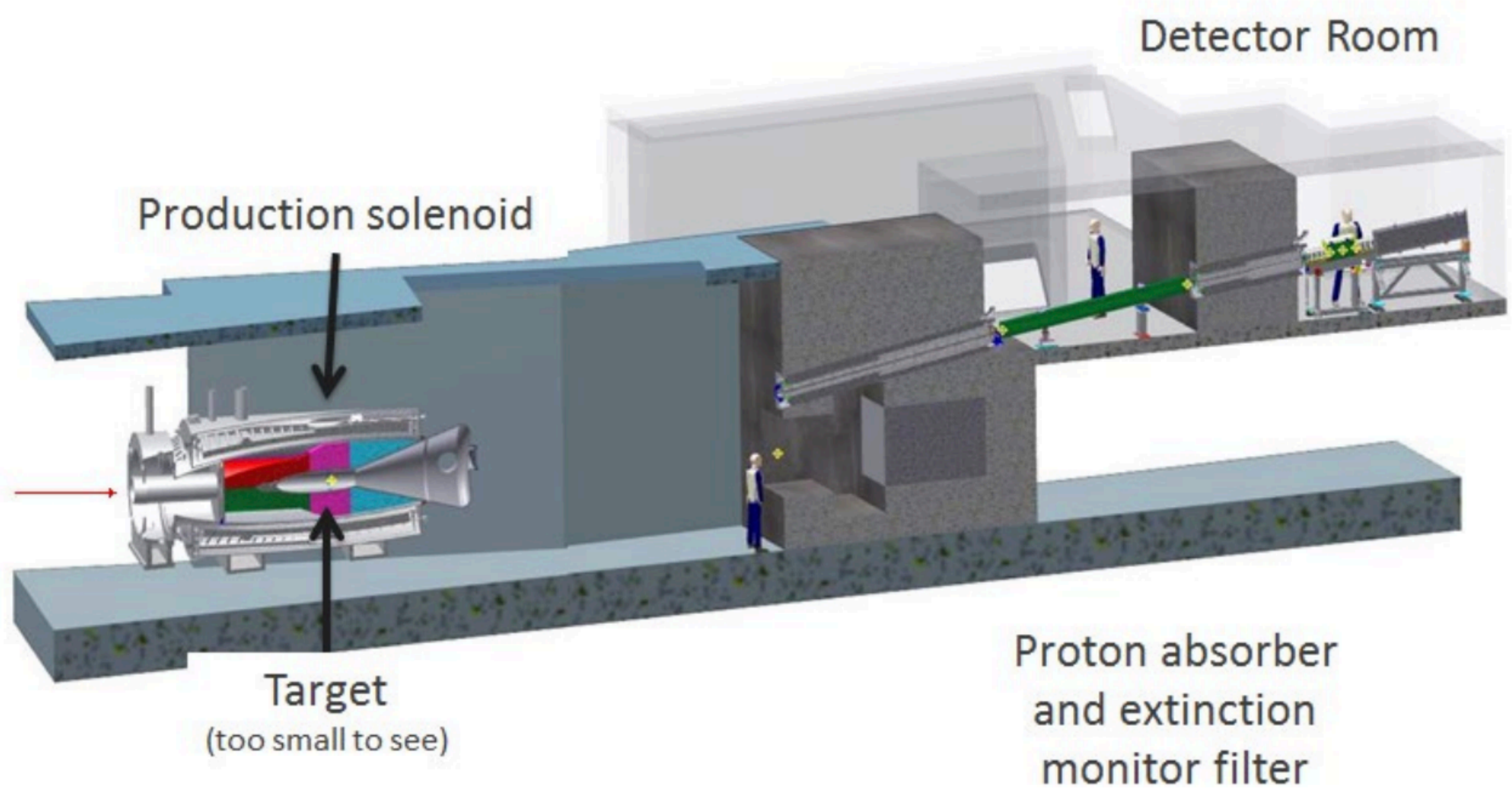
Measured bunch-by-bunch extinction from PIP-II linac



Extinction monitor

Mu2e's extinction monitor is integrated into beam dump shielding

- Sees about one ~4 GeV/c particle per 10^6 protons on target
- Statistical measurement of extinction over several hours
- Monitor adaptable to Mu2e-II (800 MeV beam)
- Acceptance of channel is a challenge since trajectory much different
- Reworking requires R&D



Mu2e Extinction monitor

Radiation

Radiation around production target

- Displacements/atom (DPA) damage to PS coil
  - FOM is ratio of muon stops in stopping target to hottest DPA rate in PS coil
  - For Mu2e-II beam this FOM is close to or better than for Mu2e 8 GeV beam
  - DPA level around 4×10^{-5} DPA/yr
  - Allows to run without annealing for ~1 yr

Beam power may imply different HRS

- W HRS with 25 cm inner bore radius would tolerate 100 kW beam

Radiation at the detector

- Doses ~20 times Mu2e at electronics and equipment alcoves
- Scaling by beam power yields estimated hadron fluxes (E > 30 MeV):
  - 3.7×10^5 h/cm2/yr at rack electronics
  - 750 h/cm^2/yr tracker and calorimeter electronics
- Estimates will be improved, but will require radiation-tolerant electronics

Environmental radiation

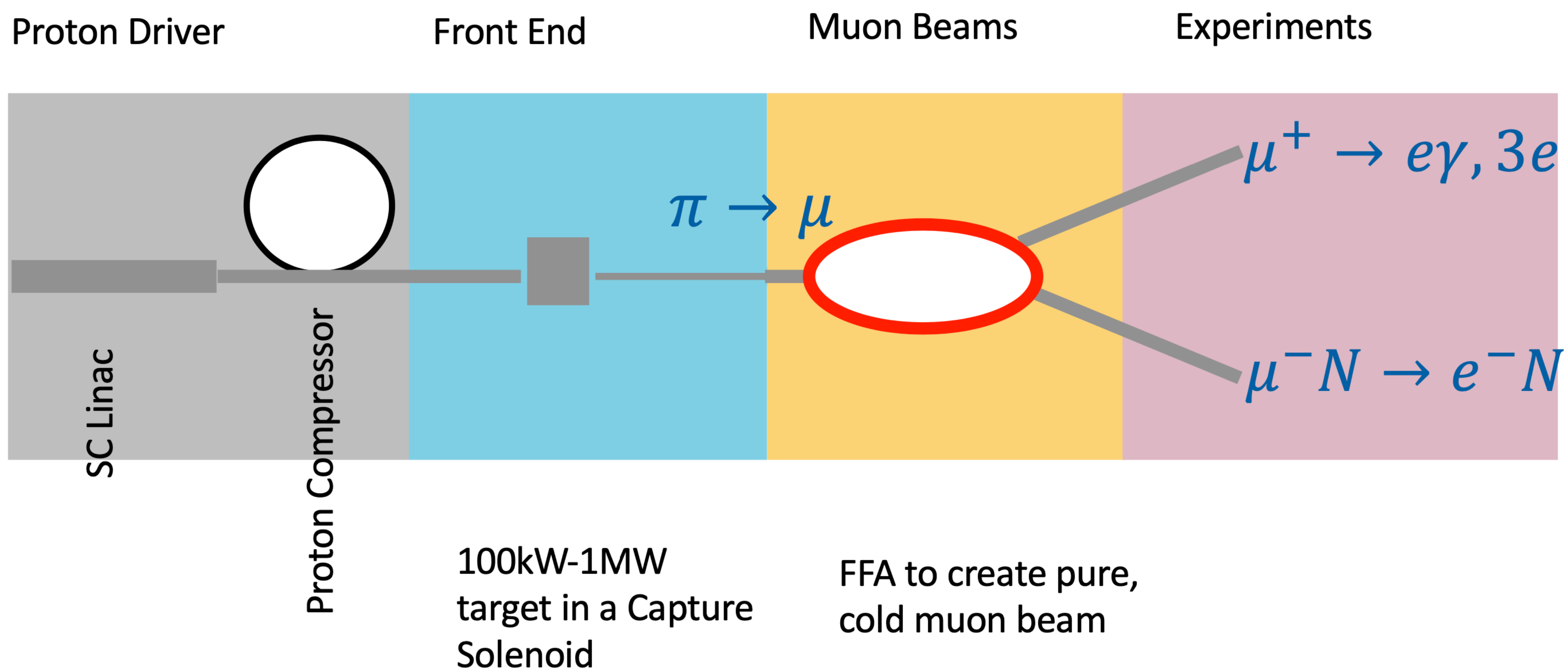
- MARS simulations suggest approximately 20 times Mu2e
- Mitigation to be evaluated, may require, e.g.,
  - Increasing berm
  - Fencing a controlled area

Stopping Target Monitor

Stopping Target Monitor (STM) measures denominator of Rme

- Monitors X-ray and g-ray emission from stopping target during muon capture
- 10% accuracy
- For Al target:
  - 347 keV from 2p to 1s transition, prompt with muon stop
  - 1809 keV from nuclear capture, with 864 ns muon lifetime in Al
  - 844 keV from $^{26}Mg^*$ capture product, lifetime 9.5 minute
- Mu2e uses HPGe detector (excellent resolution) and $LaBr_3$ crystal (high rate, radiation hard) at 34 m from target
- To continue to use in higher rate and higher dose Mu2e-II may:
  - Increase absorber in STM beamline to reduce "beam flash"
  - Use HPGe at low intensity to calibrate $LaBr_3$
  - Move detectors off-axis
  - Replace some calorimeter crystals with $LaBr_3$ or LYSO
  - Create tertiary photon beam and measure that
- Subject of further R&D

AMF concept

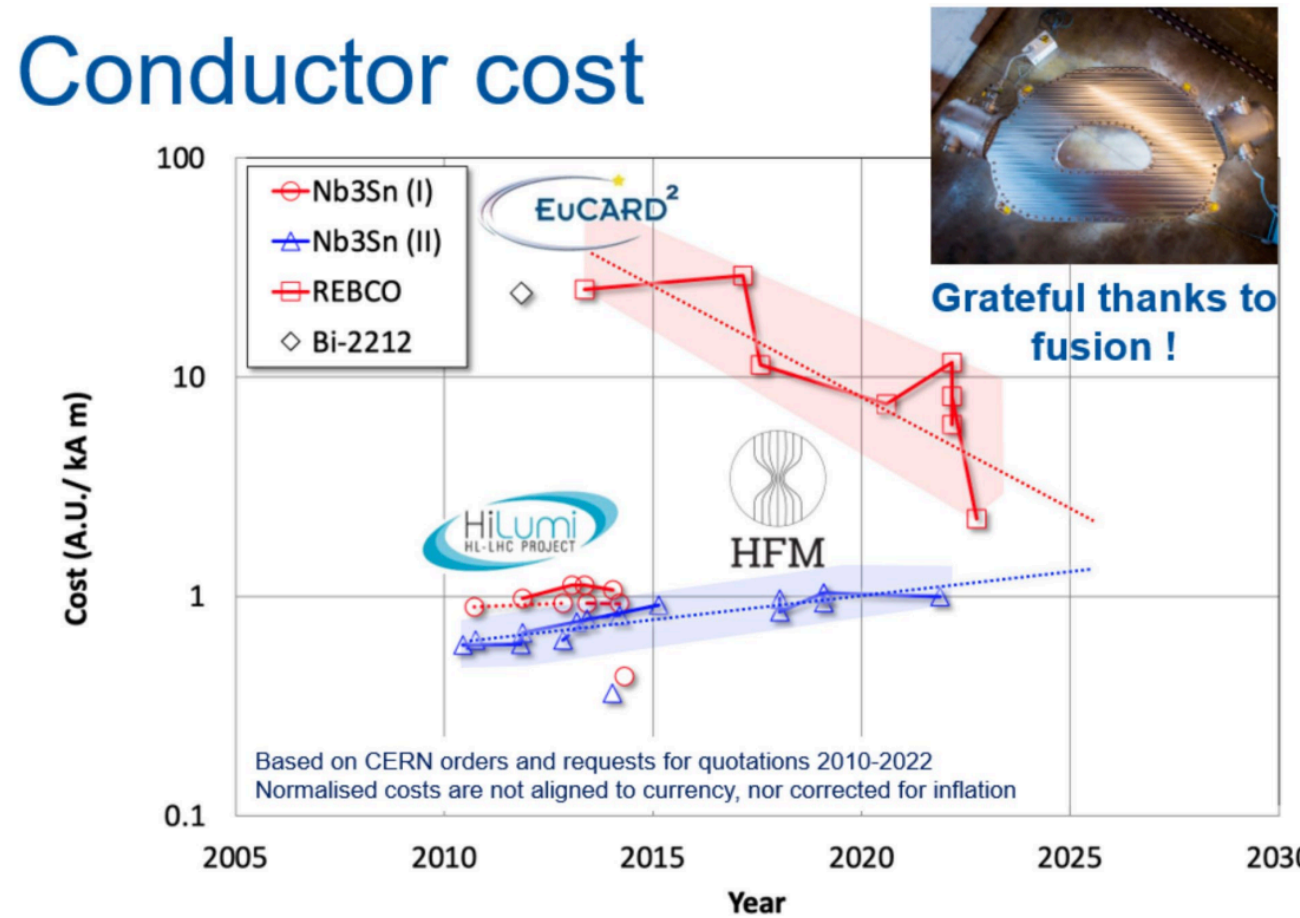


Fermilab

High Temperature Superconductor (HTS)

Thinking about HTS for production solenoid

- Cable more costly than LTS
  - But gap is closing
  - Can operate at higher current density
- R&D will cost more than for LTS
  - Thanks to fusion, already high on learning and availability curves
  - What we learn is of interest to others
  - E.g., muon collider “prototype”, maybe AMF
- Operating cost lower than for LTS
  - Higher temperature operation
  - Gaseous cooling
  - Cryostable (hard to quench)
    - Quench detection harder
- Radiation damage limits similar with LTS
  - HTS conductor (REBCO) can be annealed; Nb3Sn can not



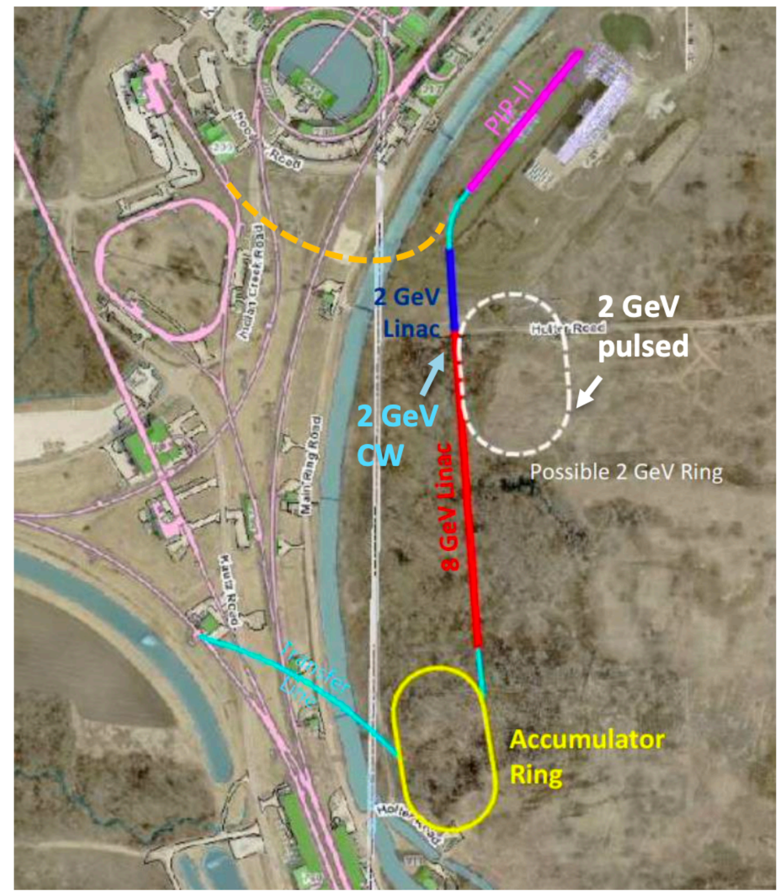
Luca Bottura, Caltech workshop

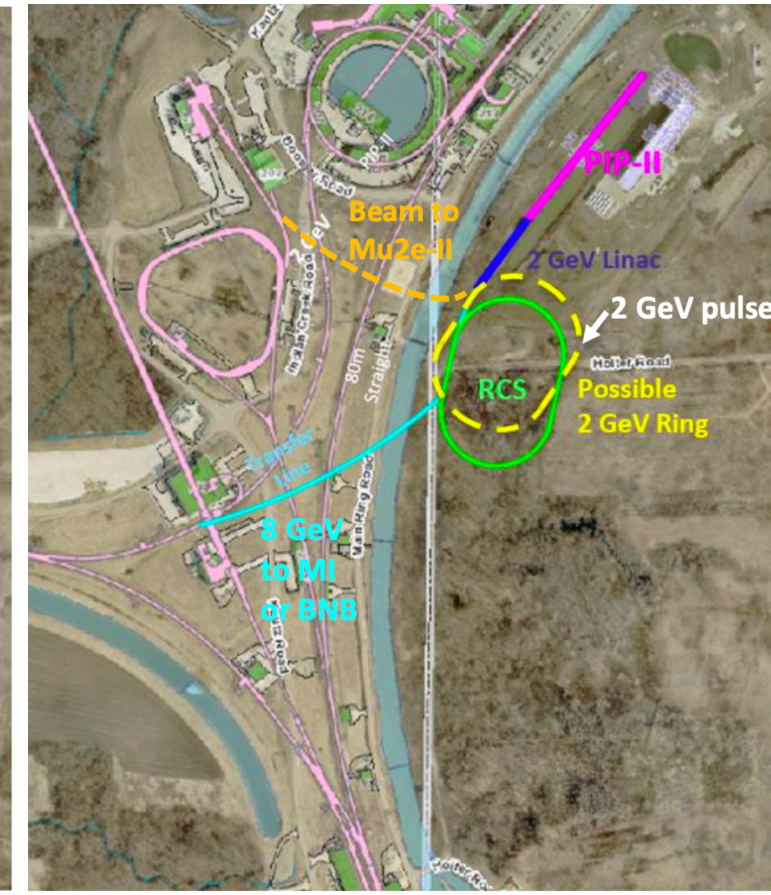
Thanks to Zachary Hartwig and Luca Bottura!

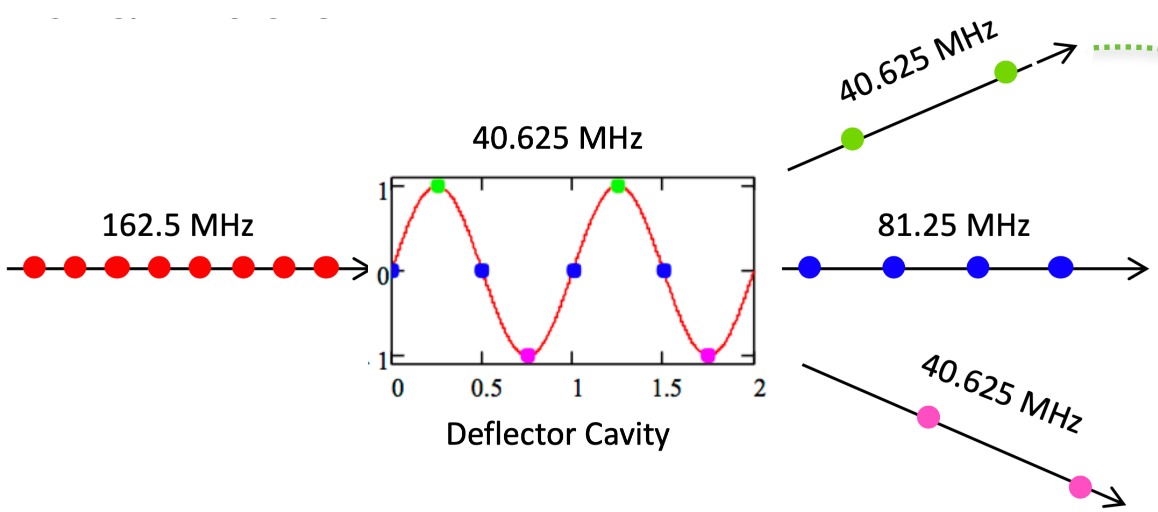
Fermilab

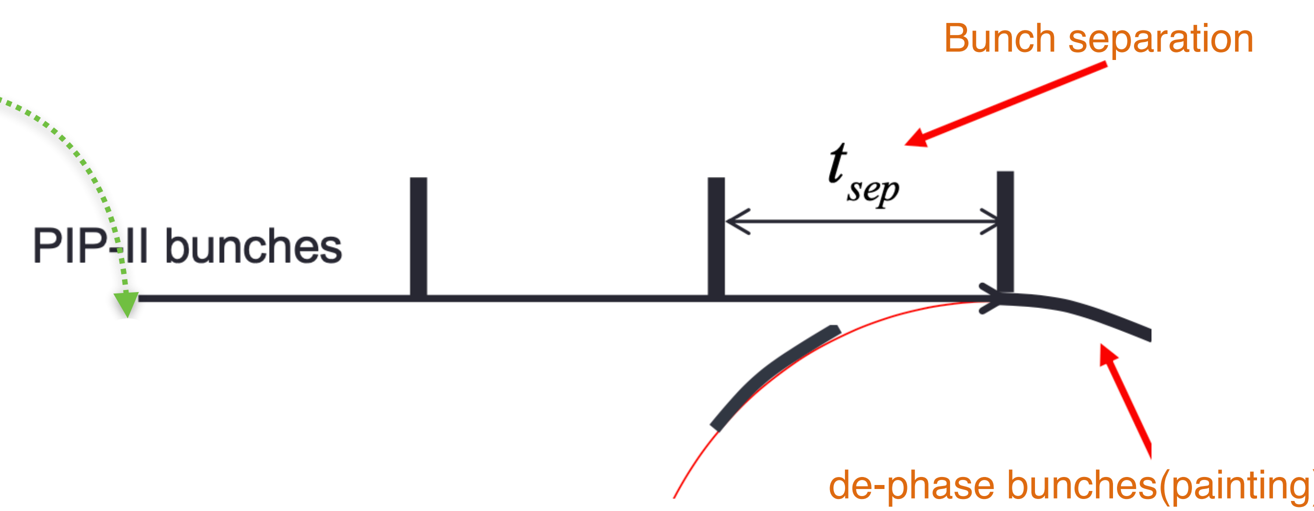
Accelerator Evolution(ACE) formerly known as PIP-III

- Booster replacement.
  - Extend SRF or a new RCS.
  - Supply 8 GeV up to 2.4 MW.
  - New science spigots;
    - 2 GeV continuous wave. What we want !
    - 2 GeV pulsed(~1MW).
    - 8 GeV pulsed(~1MW).
- AMF can work with both options.
  - Needs accumulator ring in both cases.









Mu2e(-II) physics besides $\mu \to e$

$\Delta L=2$ in $\mu^- N \to e^+ N'$

Majorana neutrinos, matter-antimatter asymmetry

Currently <1.2x10-12 [SINDRUM II, on Ti, PLB 422(1998)334]

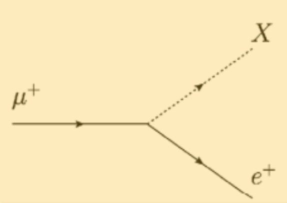
Needs further study, potential for gains similar as $\mu^- \to e^-$ conversion (RMC background, Ti target)

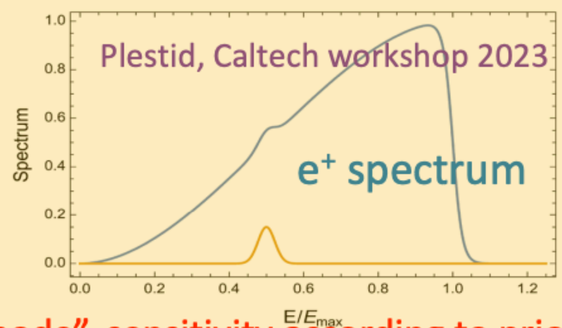
e.g., Geib et al., PL **B764** (2017)157
Berryman et al., PRD **95** (2017)115010
Lee&MacKenzie, 2110.07093

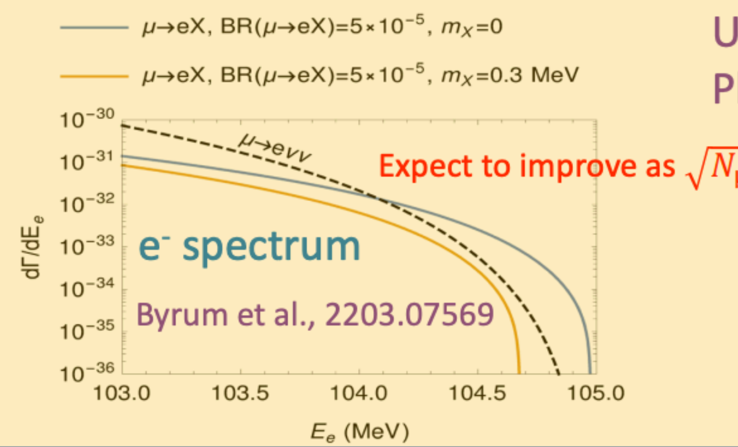
New light boson in $\mu^{\pm}[N(A,Z)] \to e^{\pm}X[N(A,Z)]$

Currently <5.8x10^{-5} [TWIST, 1409.0638]

e.g., Garcia et al., PRD **84** (2011)113020
Uesaka, PRD **102** (2020)095007
Plestid, Caltech workshop 2023







"calibration mode", sensitivity according to priority

"Heavy" (20-50 MeV) neutral lepton in $\pi^+ \to e^+X$ at rest

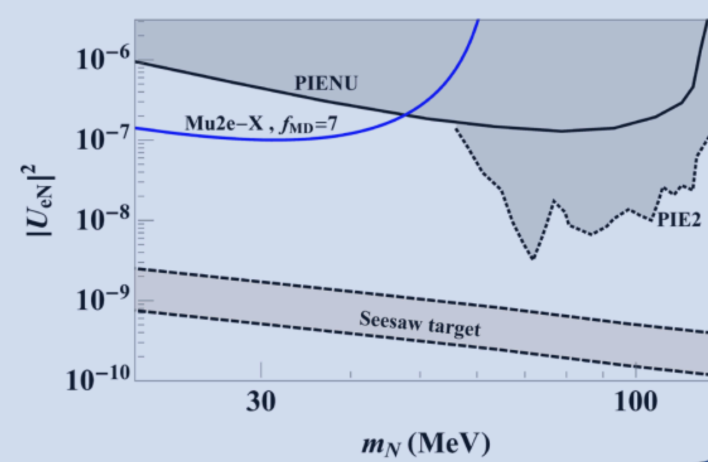
Possible dark matter "portal"

Plestid, Caltech workshop 2023

"calibration mode", plus degrader, sensitivity according to priority

Sensitivity to right-handed neutrinos mixing with e-flavor in "calibration" data with degrader

Plestid, Caltech workshop 2023 (credit S. Huang)



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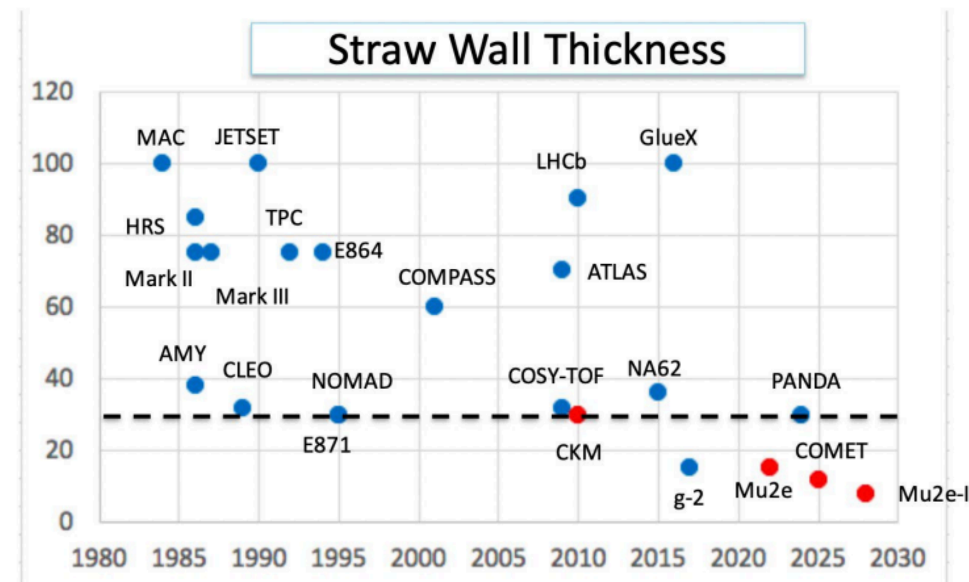
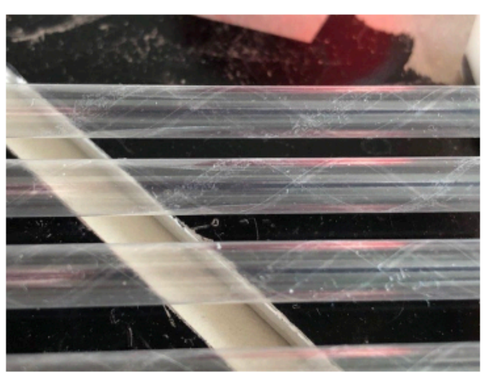
Tracker LDRD R&D

Achieving higher sensitivity requires better resolution

- Discriminate to higher momentum in decay-in-orbit tail
- Tracking LDRD has been extremely useful so far
  - Low mass straws 15 μ Mu2e $\rightarrow$ 8 μ Mu2e-II
- Investigating challenges
  - Collapse under own weight or static forces
  - Keep inflated once terminated
  - Metallization important to lowering leak rate
  - Paper removal, Alloy formation
  - Finding companies willing to make samples
    - 3 μ straws?



B. Casey, LDRD talk



8 m Mylar straws using spiral winding

8 □ straws with terminations

Gold/aluminum alloy Formation (mu2e straw)

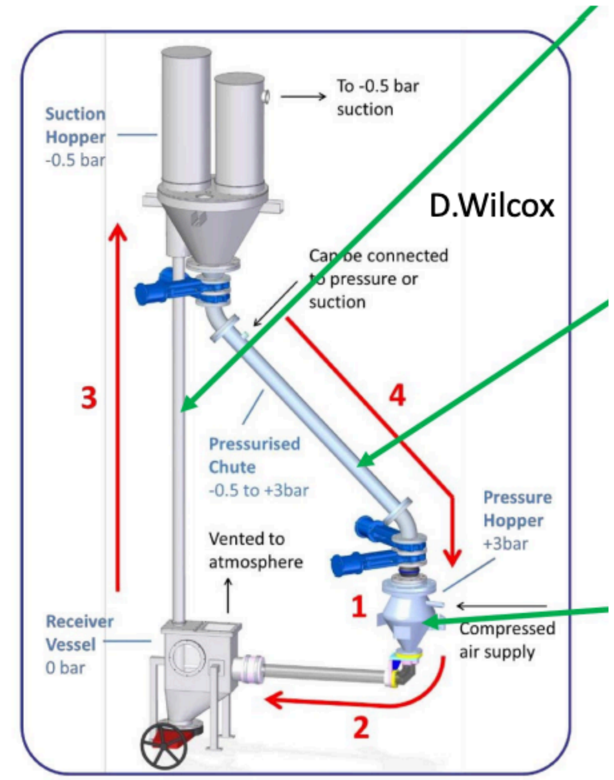
High power target LDRD R&D (future)

- (Continue to) study configurations in simulation
- Additional realism in prototyping
  - (prototype 3 with realistic materials)
- Investigate other options, perhaps jointly with muon collider
  - Fluidized tungsten powder
  - Liquid heavy metal
- Cooling plant, remote handling

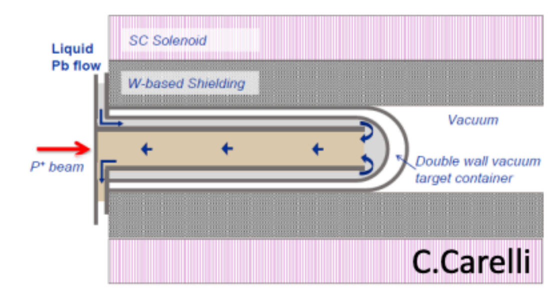
Estimate $2M

Discussion with K.Lynch:

- Good for designs, prototypes, long-term testing
- Likely to need more, but would be good start
- Additional work also may have additional sources (university program, GARD, LDRD for novel ideas, SBIR/STTR, some on FNAL ops, etc)
- Preparing a list of R&D items



Concept for fluidized tungsten target



Liquid heavy metal concept

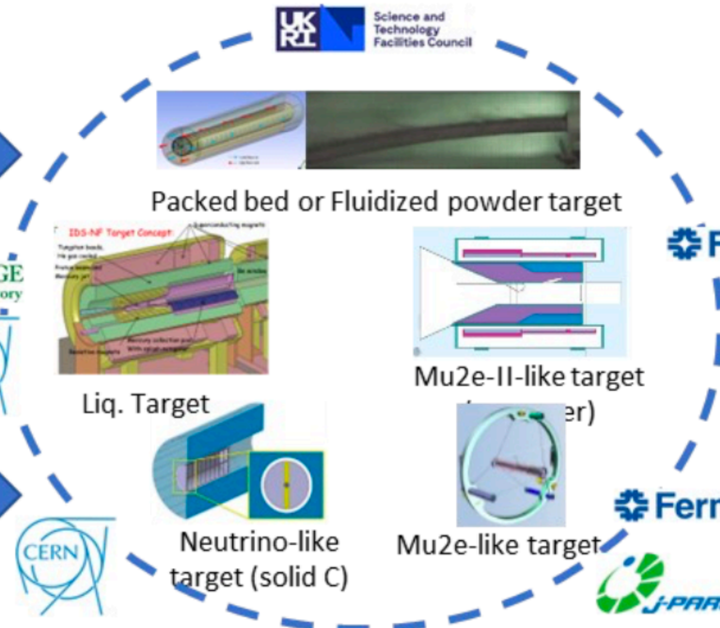
RPF Experiment Targetry – R&D Approach for Muon Collider

DESIGN

- FEA simulations

PHYSICS

- Evaluate physics performance



MATERIAL

- Material Sciences
- Radiation Damage

RaDIATE

R&D Phase up to 2030

Demonstration Phase up to 2040

Selected Target Design → Prototype