Mu2e-II presentation to FNAL Physics Advisory Committee

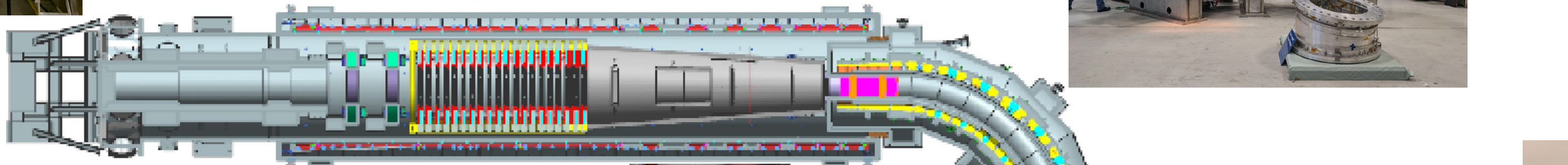
Frank Porter

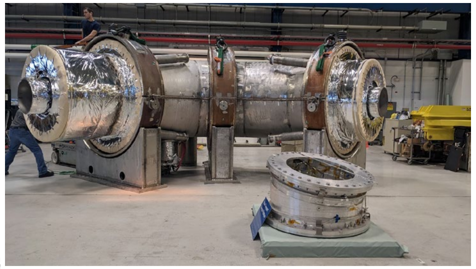
June 7, 2023

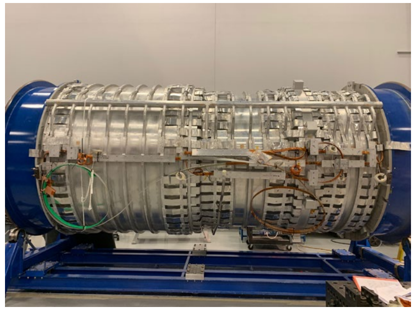
The PAC is asked to review the physics case for the Mu2e II experiment and the foreseen R&D needs

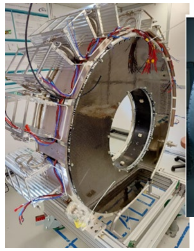
The physics case for Mu2e-II is as the evolution of Mu2e: Improve sensitivity x10 to look for/study new physics using the charged lepton flavor (CLFV) violating process $\mu \to e$ conversion on Al or complementary targets

Mu2e(-II) Experiment Layout

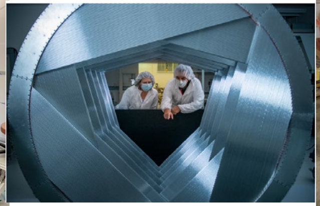








calorimeter



tracker

Stopping target

Surrounded by shielding and Cosmic ray veto counters

Mu2e-II upgrades in
- Muon production
- Detector
- Stopping target

production target

Snowmass paper

arXiv 2203:07569

109 authors

5 theorists

34 institutions

6 countries

Large overlap with Mu2e collaboration

Heavily featured in Snowmass CLFV report arXiv 2209:00142

Also

RPF report arXiv 2210.04765

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

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Snowmass21 Mu2e-II LOIs

- Beam delivery for Mu2e-II
- Calorimeter
- Cosmic Ray Veto
- Production target
- Stopping target monitor
- Theory
- Tracker
- Trigger/DAQ, 2 level, FPGA, scheme A
- Trigger/DAQ, 2 level, FPGA, scheme B
- Trigger/DAQ, 2 level, GPU
- Trigger/DAQ, software trigger

What we measure

$$R_{\mu e} \equiv \frac{\Gamma(\mu^- N(A,Z) \to e^- N(A,Z))}{\Gamma(\mu^- N(A,Z) \to \text{capture})}$$

- Ratio of muon to electron conversion to muon capture in a nucleus
  - Nucleus is Al for Mu2e
- On aluminum $R_{\mu e} \sim 10^{-52}$ in standard model
- Best current limits (SINDRUM II, 90% CL): 4×10^{-12}(Ti); 7×10^{-13}(Au)

PhyLettB 317 (1993)631; EurPhyJ C47 (2006)337

- Mu2e expects SES (single event sensitivity) on Al of 3×10^{-17} [90% CL upper limit 6×10^{-17}]
- Mu2e-II improves on Mu2e by at least an order of magnitude

Mu2e-II provides a natural follow-on to Mu2e, keeping the CLFV physics program active at FNAL until the next-generation Advanced Muon Facility (AMF) is ready

Charged Lepton Flavor Violation (CLFV) is sensitive to New Physics

Standard model rate (GIM-)suppressed by small neutrino masses

"Background free!"

$$\mathrm{BF} \sim \sum_{i<j} \left(\frac{m_{\nu_i}^2 - m_{\nu_j}^2}{M_W^2} \right)^2$$

Many new physics (NP) models are within experimental reach

Sensitive to NP mass scales much higher than direct searches

Potentially closely connected with $(g\text{-}2)_\mu$, DM

Sensitive to many heavy NP scenarios (EFT Lagrangian):

- Loops
  - Supersymmetry
  - Heavy neutrinos
  - Extended Higgs
- Trees
  - Compositeness
  - Leptoquarks
  - New heavy bosons, anomalous couplings

Also sensitive to light NP:

- Axion/ALP/majoron/familon/Z'

e.g., (far from complete!!!)

Arnold et al., PRD **88** (2013) 035009

Bernstein&Cooper, Phy.Rep. **532** (2013)27

Calibbi&Signorelli, Riv.Nuovo.Cim. **41** (2018)71

Cei&Nicolo, Adv.HEP **2014** (2014)282915

Cirigliano et al, PRD **80** (2009)013002

Davidson&Echenard, arXiv:2204.00564

De Gouvea&Vogel, Prog.Part.Nucl.Phy. **71** (2013)75

Heeck, PRD **95** (2017)015022

Kuno&Okada, Rev.Mod.Phy. **73** (2001)151

Lindner et al., Phy.Rep. **731** (2018)1

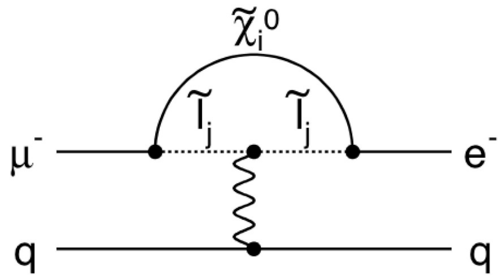
Marciano et al., Ann.Rev.Nuc.Part.Sci. **58** (2008)315

Science Motivation

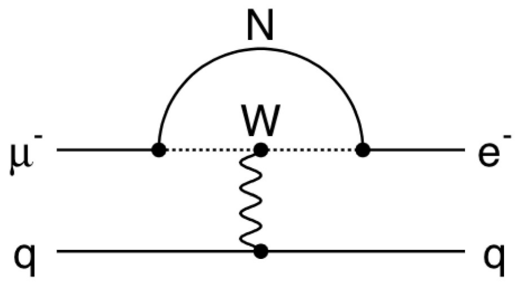
- Direct $\mu \rightarrow e$ conversion is the "Golden Channel" of CLFV
  - Sensitive to broad array of New Physics models

Mu2e comparable To $\mu \rightarrow e\gamma$

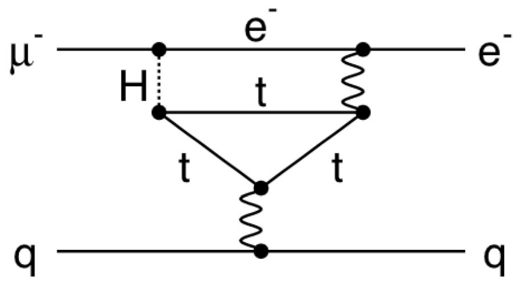
Loops



Supersymmetry



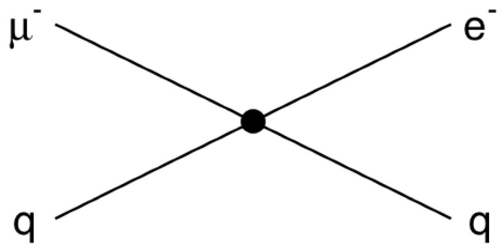
Heavy Neutrinos



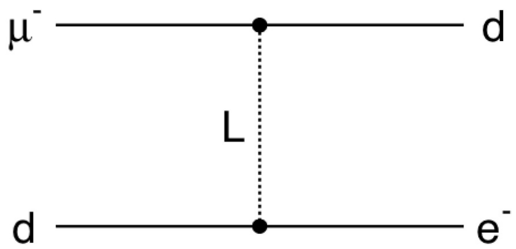
Extended higgs models

Mu2e much more sensitive vs $\mu \rightarrow e\gamma$

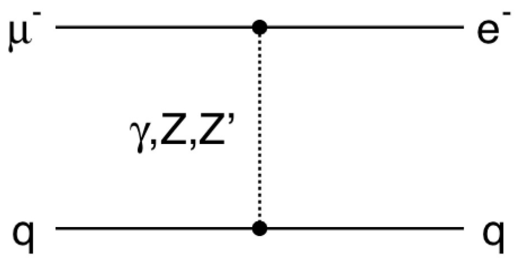
Contact Terms



Compositeness



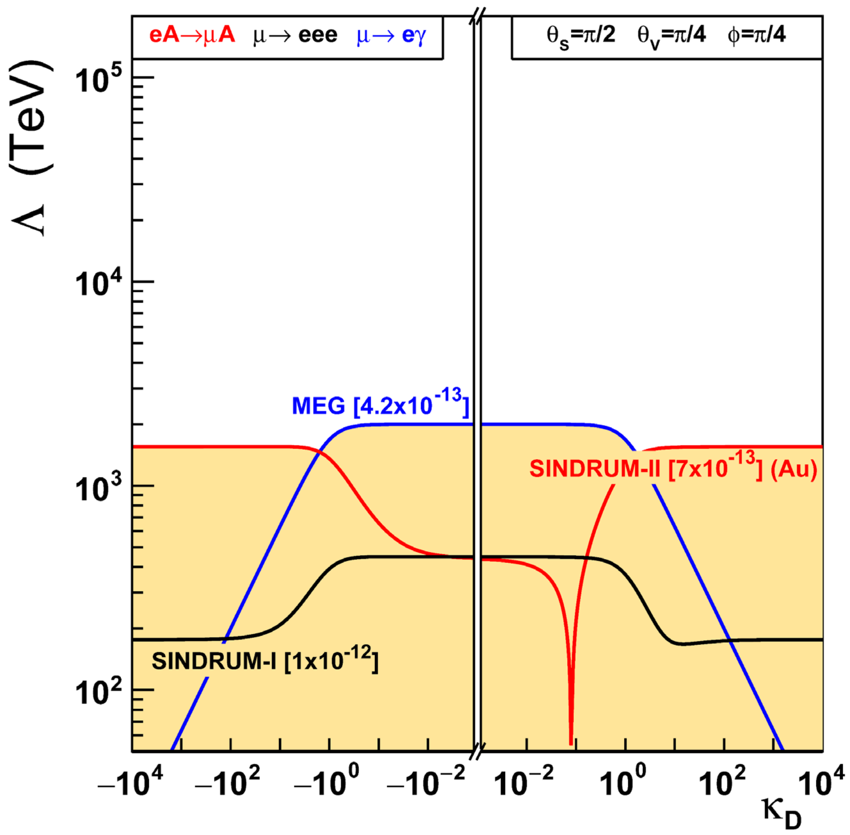
Leptoquarks



New Heavy Bosons / Anomalous Couplings

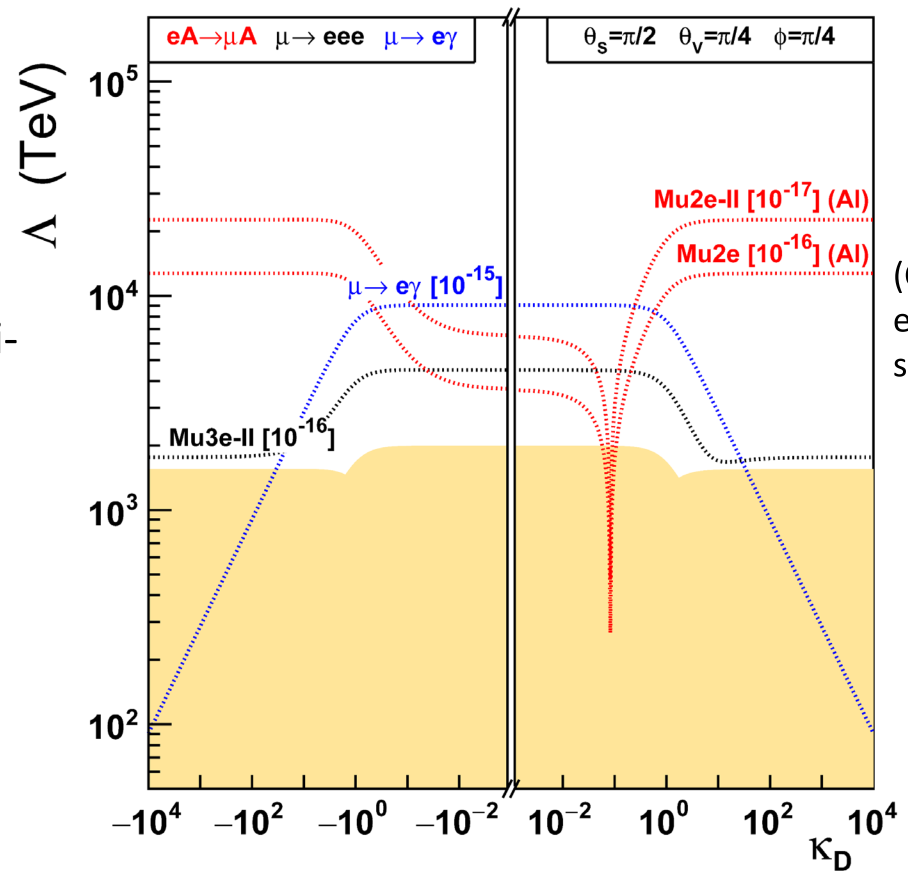
Conversion is sensitive to new physics at very high mass scales

Current exclusion region



(slice of multi-dimensional parameter space)

Future sensitivity



(COMET-II sensitivity expected to be similar to Mu2e)

$$\kappa_D \equiv \cot\left(\theta - \frac{\pi}{2}\right)$$

$|\kappa_D| \ll 1$ dipole operator dominates

$|\kappa_D| \gg 1$ 4-fermion operators dominate

S.Davidson, B.Echenard, et al., Snowmass21 Report of the CLFV topical group RF5

Factor of 10 on $R_{\mu e} \Rightarrow$ factor of ~2 in mass reach. Exploring BSM masses above any current/foreseen collider.

Conversion is sensitive to variety of new physics

(examples from Mu2e-II Snowmass paper)

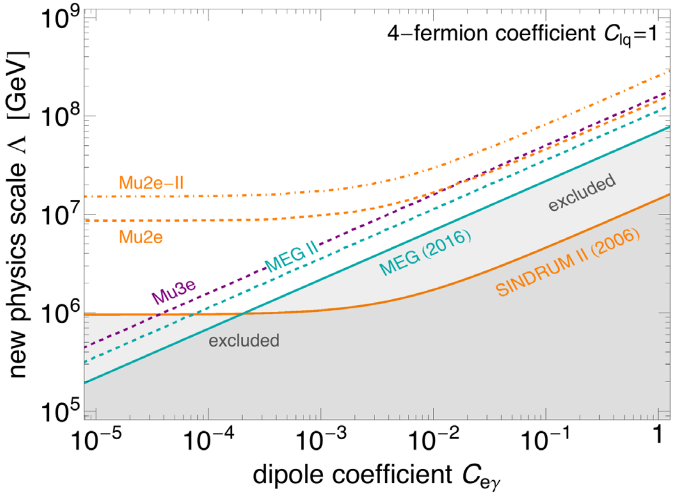


FIG. 1. Current and future 90% CL bounds from $\mu \to e\gamma$ [46, 47] (cyan lines), $\mu \to eee$ [48] (purple line) and $\mu \to e$ conversion (orange lines) on the effective CLFV operators $\frac{C_{e\gamma}}{\Lambda^2}\langle H\rangle \bar{e}_L \sigma^{\mu\nu}\mu_R F_{\mu\nu} + \frac{C_{\ell q}}{\Lambda^2}(\bar{e}_L \gamma^\mu \mu_L)(\overline{Q}\gamma_\mu Q)$, where $Q = (u_L, d_L)^T$ and $\langle H\rangle \simeq 174\,\text{GeV}$ is the vacuum expectation value of the Higgs field. The limits are displayed as functions of the new-physics scale Λ and the Wilson coefficient of the dipole operator $C_{e\gamma}$, while the coefficient of the 4-fermion operator is set to $C_{\ell q} = 1$.

Mu2e-II approximately doubles mass reach

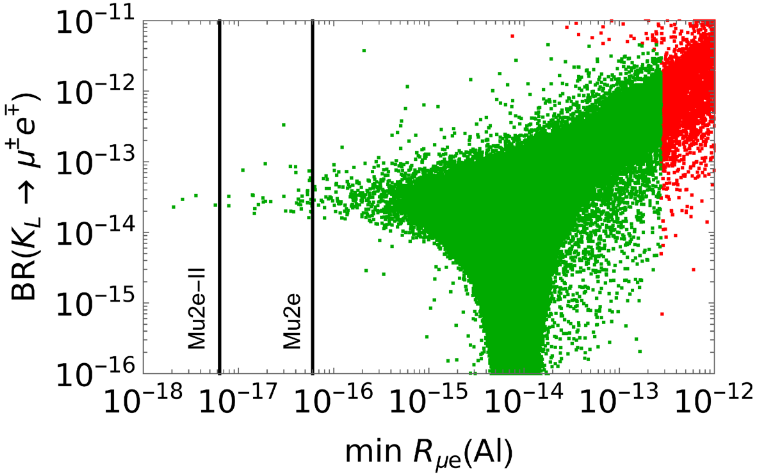


FIG. 2. CLFV predictions in the Pati–Salam model of Ref. [45] that explains neutrino masses together with the neutral-current B-meson anomalies. Red points are excluded, green points are currently allowed. The vertical lines denote the 90% C.L. reach of Mu2e and Mu2e-II.

Leptoquarks

Model from Heeck&Teresi, 1808.07492

Mu2e-II extends reach to nearly completely cover allowed region

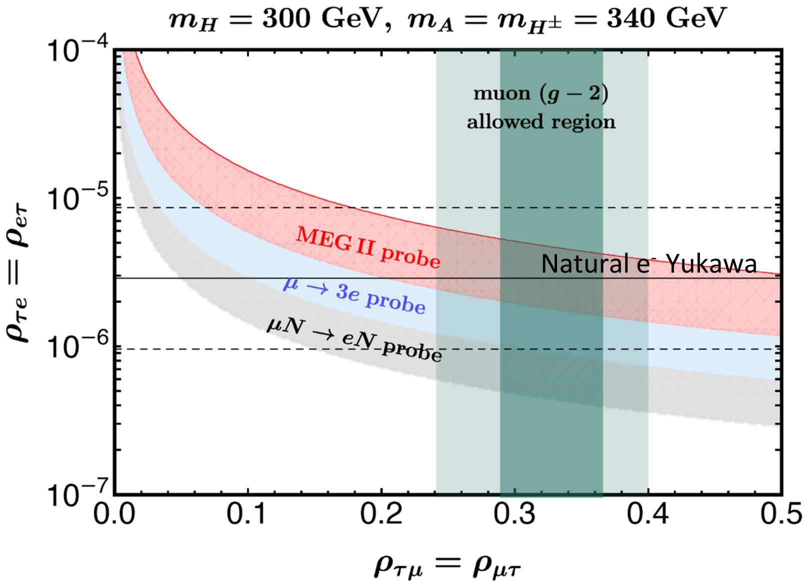


FIG. 3. Bounds on the CLFV couplings of the extra Higgs fields in a two-Higgs-doublet model able to explain the $(g-2)_\mu$ anomaly. Taken from Ref. [64].

Two-Higgs-doublet addressing $(g\text{-}2)_\mu$

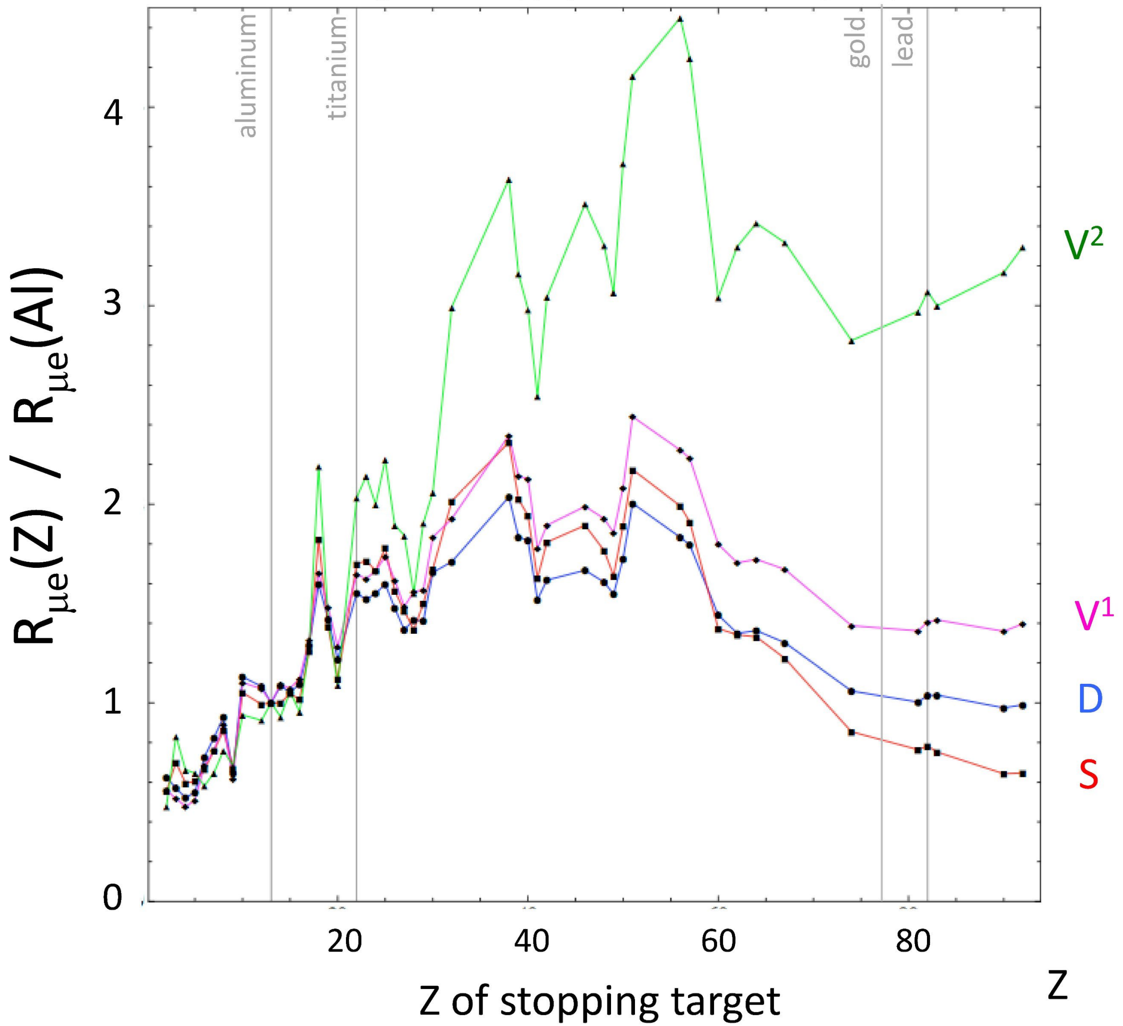
Mu2e-II sensitivity ~10^{-17} (gray band)

Model from Hou&Kumar, 2107.14114

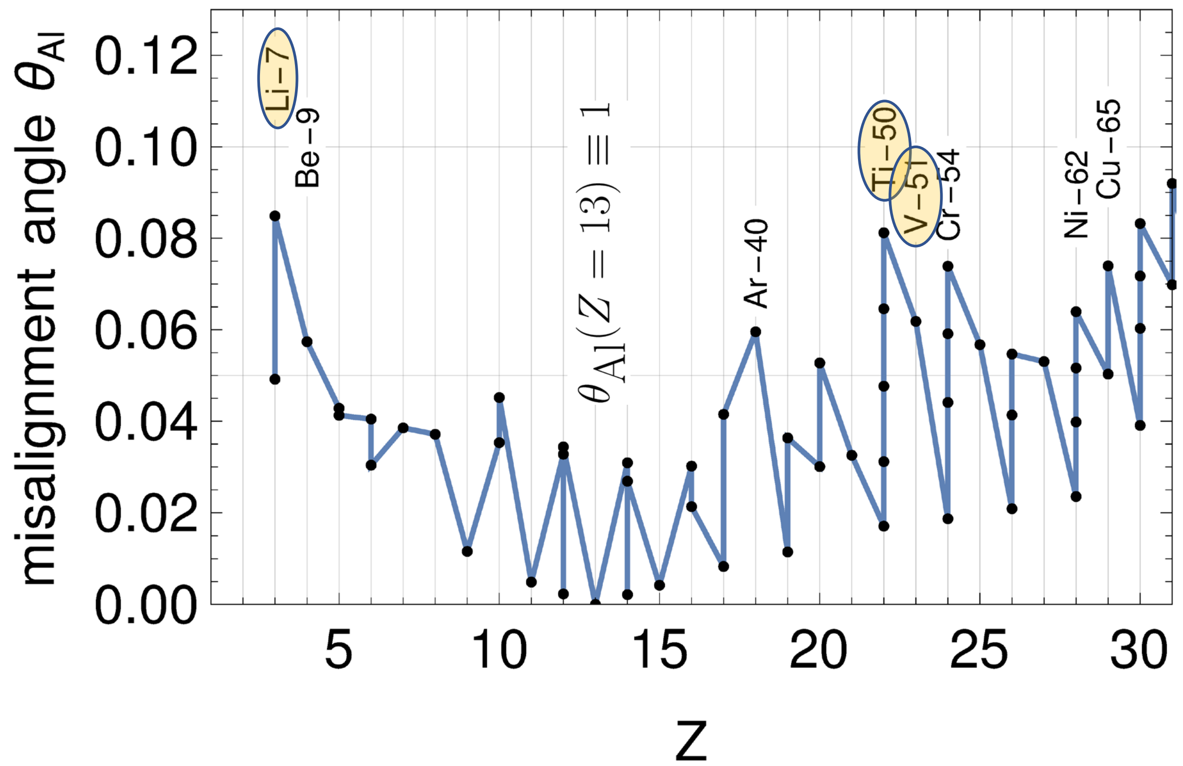
ρ_{ij} are flavor changing neutral couplings

Conversion rate depends on nucleus in different ways for different new physics

V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)



J.Heeck et al., 2203.00702



Overlap integrals:

$$\theta_{\rm Al} \equiv \arccos\left(\frac{\mathbf{v}\cdot\mathbf{v}_{\rm Al}}{|\mathbf{v}||\mathbf{v}_{\rm Al}|}\right) \qquad \mathbf{v} \equiv \left(\frac{D}{4}, V^{(p)}, S^{(p)}, V^{(n)}, S^{(n)}\right)$$

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]

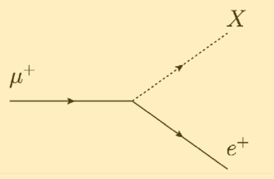
Needs further study, potential for gains similar as $\mu^- \to e^-$ conversion (RMC background, Ti target)

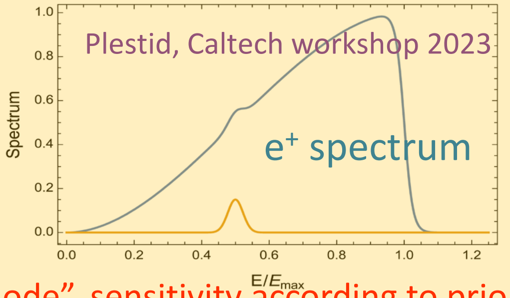
e.g., Geib et al., PL **B764** (2017)157
Berryman et al., PRD **95** (2017)115010
Lee&MacKenzie, 2110.07093

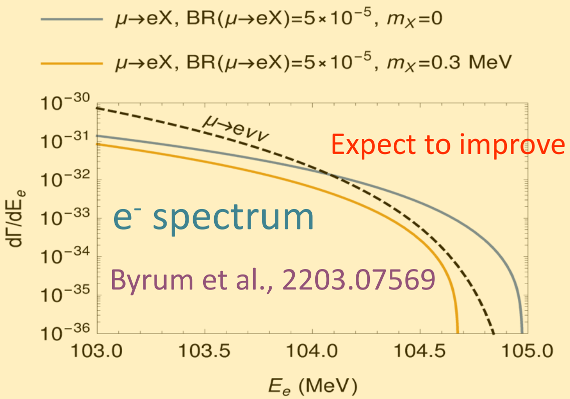
New light boson in $\mu^\pm[N(A,Z)] \to e^\pm X[N(A,Z)]$

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







Expect to improve as $\sqrt{N_\mu}$

"calibration mode", sensitivity according to priority

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

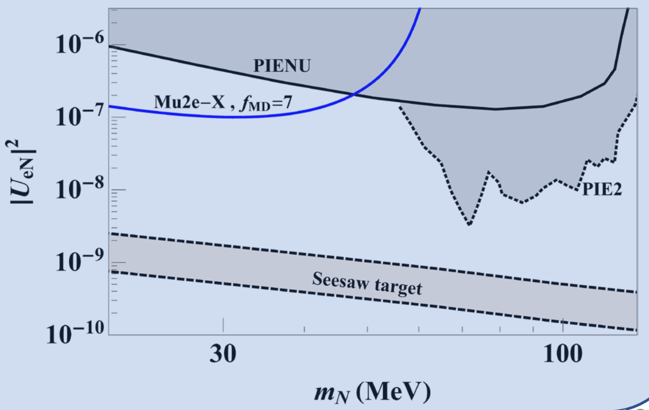
Possible dark matter "portal"

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)



Rationale for Mu2e-II

Scenario I: Mu2e may find a signal in aluminum

- There exists new physics, what is it?
  - Mu2e-II becomes extremely important!!
  - Measure other targets to study physical source

Scenario II: Mu2e may not find a signal in aluminum

- Repeat measurement pushing reach further

Mu2e-II provides continued CLFV physics in gap between Mu2e and potential AMF

- Also provides “R&D” for AMF

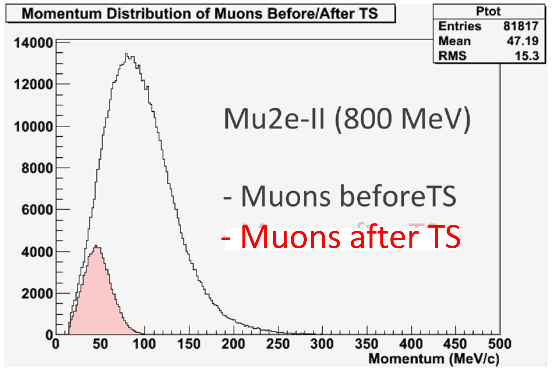
Can build on Mu2e

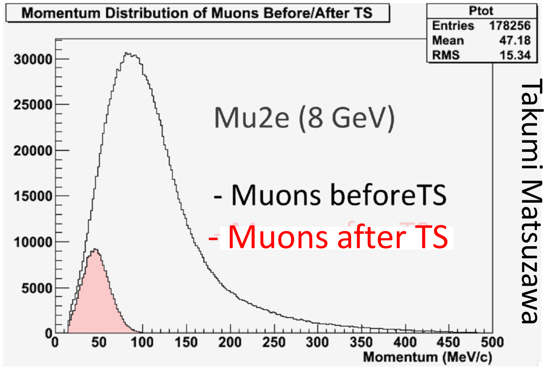
- PIP-II is enabler; Mu2e provides starting point
- Substantial investment in Mu2e (not just $!)
- Many things can be re-used

Beam energy

PIP-II provides 800 MeV protons

- Similar stopping rate as 8 GeV
- About 30% smaller DPA* in solenoid for same power of 8 GeV
- No pbars

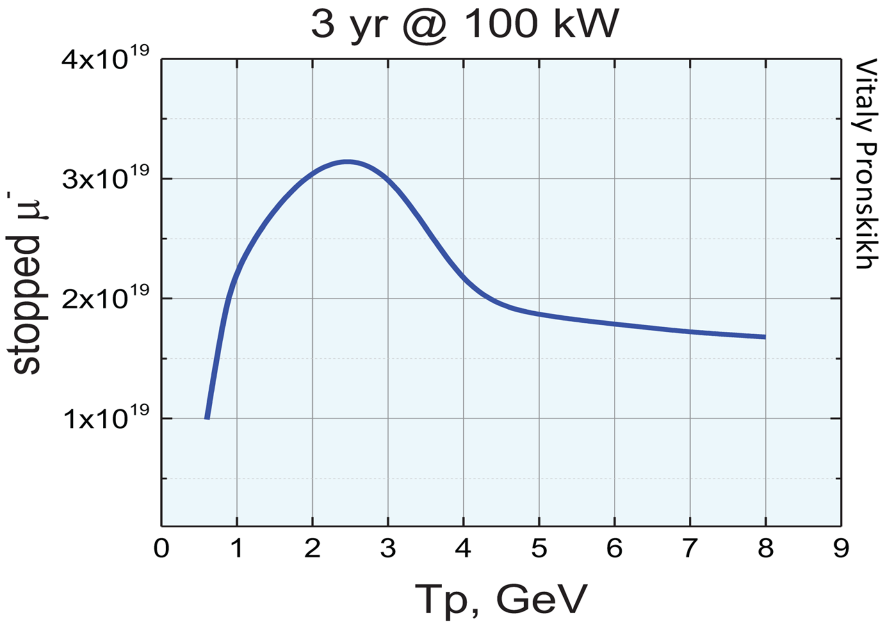




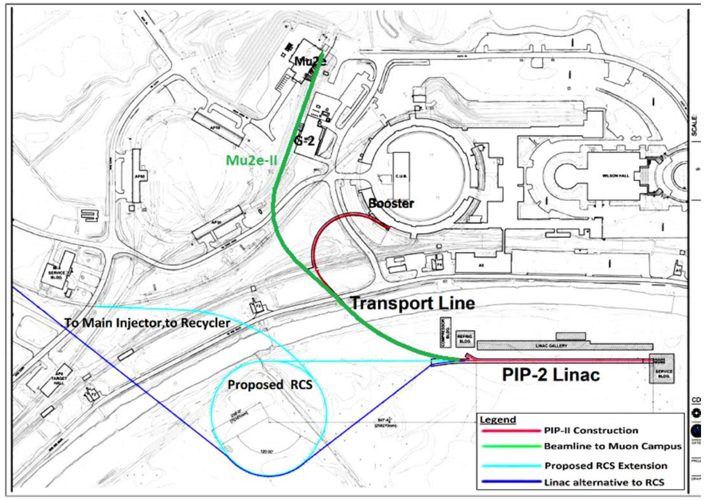
*DPA = Displacements Per Atom

2 GeV upgrade of PIP-II is of interest

- Maximum stopped μ per beam power
- Better beam geometry!!
- Still no pbars



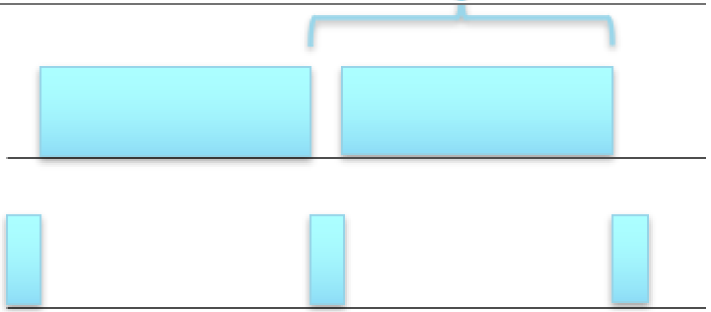
Possible Implementation at PIP-II



Period 50 ms

Muon Campus @ 20Hz

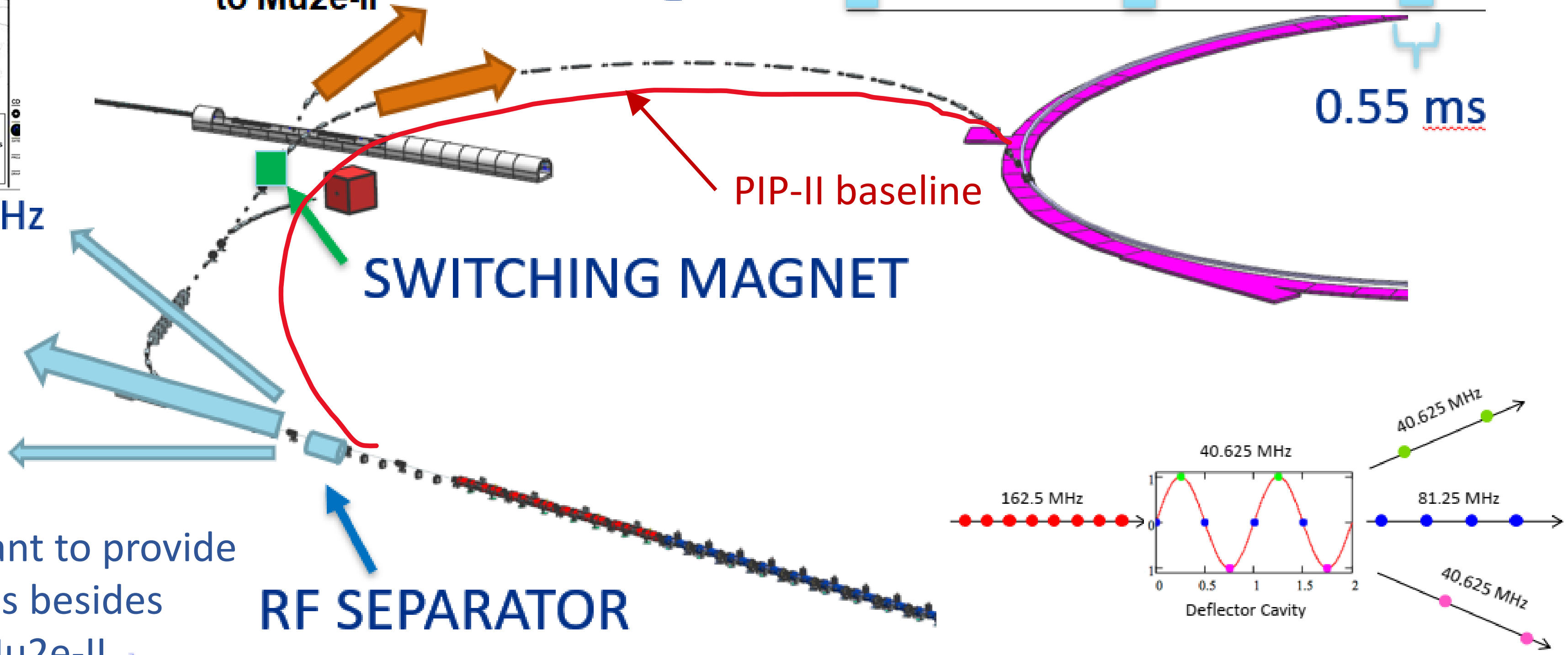
Booster @ 20Hz



0.55 ms

to Mu2e-II

PIP-II baseline



SWITCHING MAGNET

1.5e8 H- @ 40.125 MHz

1.5e8 H- @ 80.25 MHz

1.5e8 H- @ 40.125 MHz

RF SEPARATOR

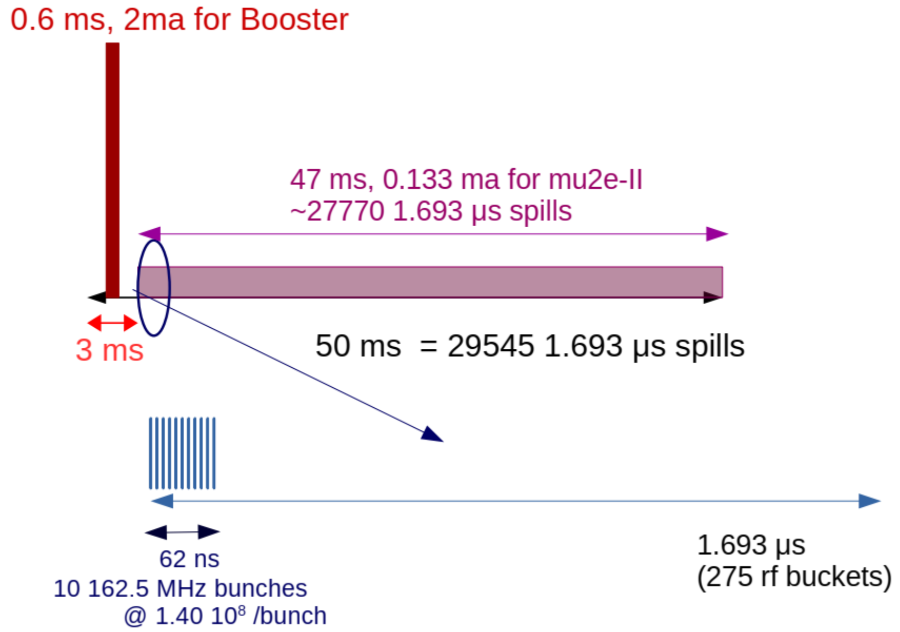
Likely will want to provide for beamlines besides DUNE and Mu2e-II

Time structure

Mu2e: Beam for 380 – 35 = 345 ms every 1400 ms

~200 ns proton pulse separated by 1695 ns

345/1400 ~ 25% use of time



Mu2e-II: Beam for 47 ms every 50 ms

~62 ns proton pulses separated by 1693 ns

47/50 ~ 94% use of time

Beam intensity also much more stable
(no resonant extraction)

Technical Challenges for Mu2e-II

PIP-II solves the first technical challenge, getting enough muons!
Will need some changes/improvements to Mu2e because:

- Power on target is greater (100 kW vs 8 kW)
  - PIP-II is capable of much more
- Beam energy is different (800 MeV vs 8 GeV)
- Rate is higher than Mu2e
- Livetime is also higher
- Must discriminate further against background

Where this presents challenges for Mu2e $\rightarrow$ Mu2e-II:

- Higher power target, passive cooling insufficient
- Higher power, radiation in production solenoid, Mu2e configuration can't handle it
- Different beam energy means different trajectory in production solenoid
- Better resolution to discriminate against DIO background $\Rightarrow$ new tracker (needed anyway)
- Higher rates $\Rightarrow$ partial (or complete) new calorimeter
- Higher livetime, better cosmic background suppression $\Rightarrow$ new CRV
- Higher rates, radiation $\Rightarrow$ improved shielding

R&D!

Some current Mu2e-II R&D

Current R&D

- Tracking LDRD until March 2023
  - Low mass straws, prototype
- Target LDRD (total $385k) until March 2023
  - ~$80k left, frozen, had planned for completion of prototype 2
- Solar-blind SiPMs for fast BaF_2 component (Caltech, some private funds, formerly also JPL&DOE funds)
- Low level unfunded activity (including INFN)

Discussing synergistic R&D with Muon Collider on production target and production solenoid

- Mu2e-II looks like a (target/solenoid) prototype to the muon collider

R&D (future)

Mu2e running experience will be an integral component of R&D

- Feeds into design
- Feeds into R&D questions and activities

Estimate ($10M or $13M) for R&D prior to project funding

- Also anticipate INFN funded R&D (after completion of Mu2e construction)
- Other foreign collaboration from Germany, UK, (Russia)…

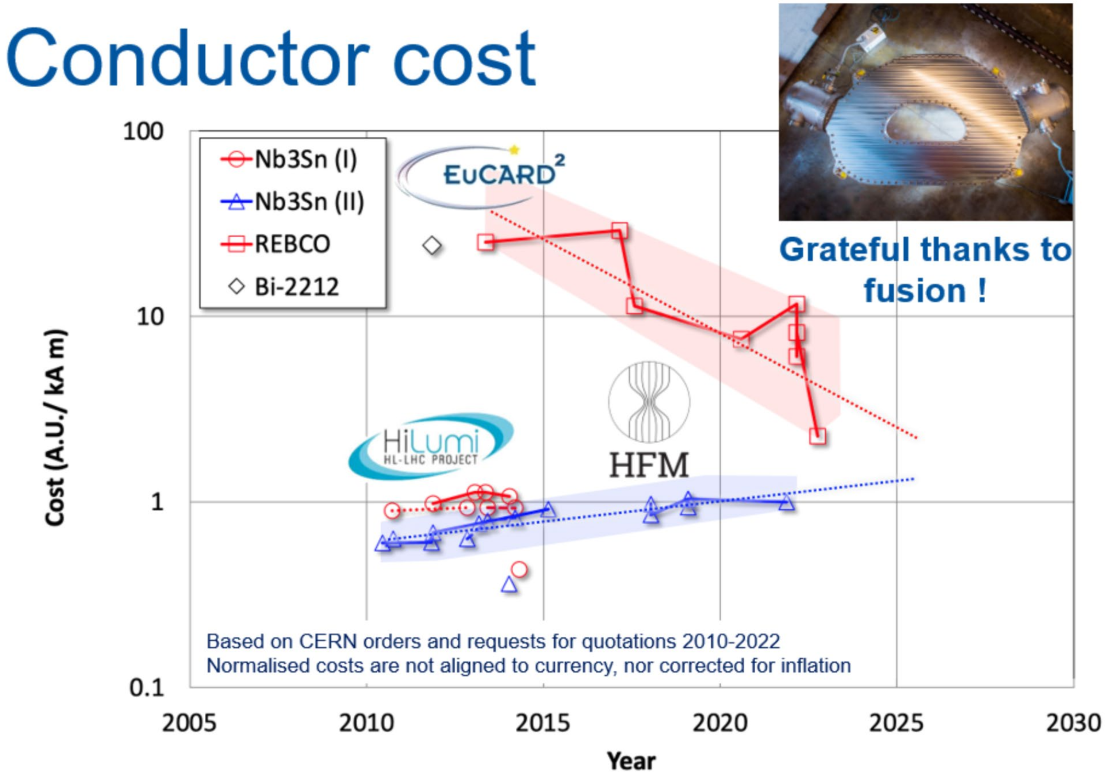
Synergistic R&D with Muon Collider on production target and production solenoid

Mu2e-II R&D is also R&D for AMF

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!

Cost estimate, R&D
(prior to CD-0)

Description	Cost estimate (k$)
Project management	0
Conventional Construction	0
Solenoids (possible additional $3M if chose HTS)	3500
Target	2000
Muon beamline	1000
Tracker	1600
Calorimeter (assumes INFN as with Mu2e)	700
CRV	790
TDAQ	730

TOTAL $10,320k

INFN not included; PIP-II R&D not included

Mu2e-II Summary

- CLFV is a sensitive probe for new physics
  - Mass reach much higher than direct methods
  - $\mu \rightarrow$ e conversion is sensitive to many new physics scenarios
- Mu2e-II will improve CLFV SES by at least an order of magnitude over Mu2e
  - Enabled by PIP-II
  - Different targets, depending on physics needs
- Re-use as much of Mu2e as possible
- Higher power and greater live time imply some changes needed
- R&D required to address technological challenges
- Many of the same challenges faced by AMF; Mu2e-II R&D also helps AMF

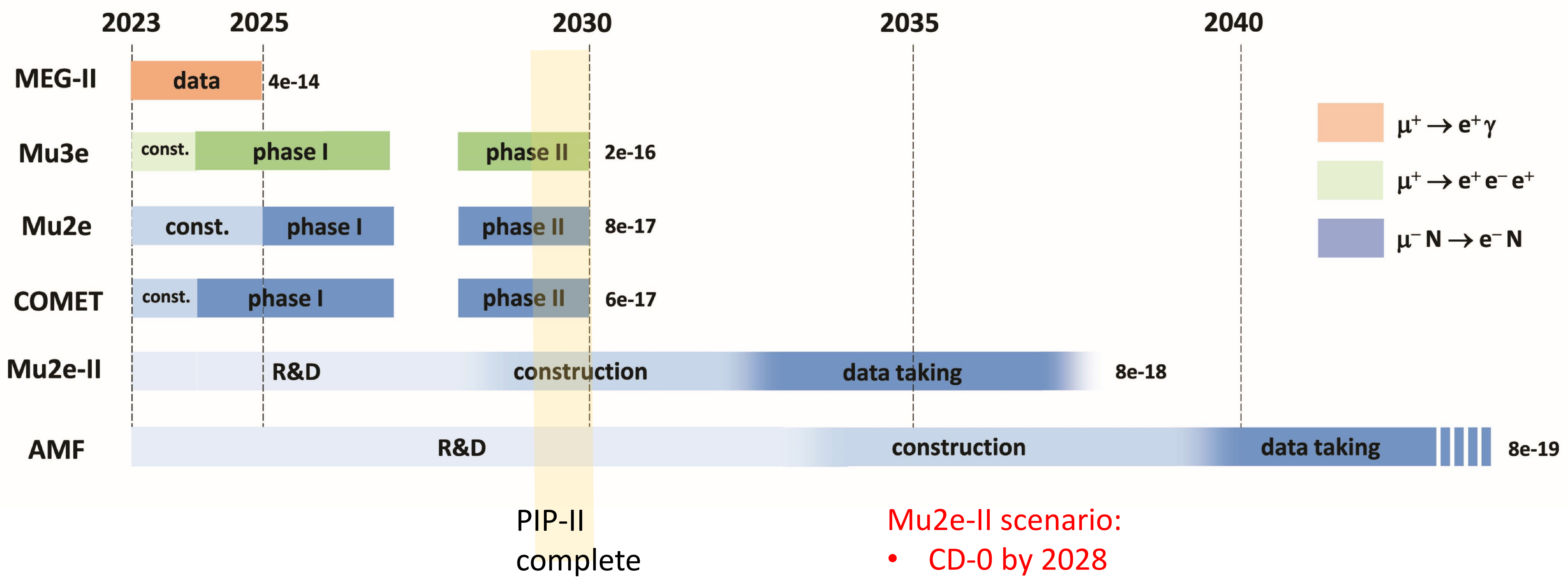
Mu2e-II provides a natural follow-on to Mu2e, keeping the CLFV physics program active at FNAL until the next-generation AMF is ready

Additional Material

Schedule comments

- Mu2e-II schedule shifts with Mu2e
- But some Mu2e-II construction can begin before end of Mu2e data taking
- Radiation issues near production solenoid
  - Floor/wall concrete contact doses ~50-500 mrem/hr after 1 week of cooling after 365 d exposure (target not removed)
  - Need a period of cooling before can do work there
- Next step: Build on Snowmass document to develop a scientific proposal including more refined cost estimates
  - Will need participation from accelerator, technical divisions

CLFV Schedule
(based on Snowmass RPF summary)



Mu2e-II scenario:

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

Summary of Mu2e and Mu2e-II sensitivity

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}

from 2203:07569

Carbon ball production target
Mu2e Al stopping target
8 μm straw chamber, no gold
BaF_2 calorimeter
Mu2e trigger&reconstruction
Mu2e IPA
4.5×10^{22} POT

Other targets:

- Li: SES ~ 10^{-17}
  - Muon lifetime long, capture rate small
  - Density small
  - 400 foils
- V: SES ~ 10^{-18}
  - Large capture rate than Al

Project Costs

Project cost estimate \$119M (current dollars)

- First attempt at bottom-up estimation
  - Input includes Mu2e total cost (\$304M)
  - Large benefit from re-use of Mu2e components as well as from very large uncosted Mu2e work
- Additional contribution anticipated from INFN
  - As with Mu2e
  - Possibly others (Germany, UK also participating in Mu2e-II)
- Production target separated out
  - High power targets are of broader interest (e.g., muon collider, AMF). Benefits go beyond Mu2e-II
- Required PIP-II upgrades (Neuffer, Caltech workshop)
  - PIP-II switch to CW operation (new Medium-Energy Beam Transport chopper) (~10M\$?)
  - Beamline to Mu2e-II, including switching, H- stripping (<25-50M\$)
  - Likely to benefit other efforts besides Mu2e-II

Cost estimate, project

Description	Mu2e (Actual)	Mu2e-II Cost estimate (M$)
Project management	31.8	12
Accelerator*	36.4	0
Conventional Construction	18.8	0
Solenoids	129.6	35
Production Target*	13	13
Muon beamline	25.1	10
Tracker	23.7	22
Calorimeter ((same as Mu2e), assumes INFN as with Mu2e)	6.8	6
CRV (same as Mu2e)	11.4	8
TDAQ (same as Mu2e)	7.3	7
Inflation and COVID corrections to current year dollars for Mu2e-II	-	16
TOTAL	304	119

*Mu2e accelerator included $13M for the production target; this has been separated out; PIP-II upgrades, beamline est. $40M

Muon g-2 and new physics scale

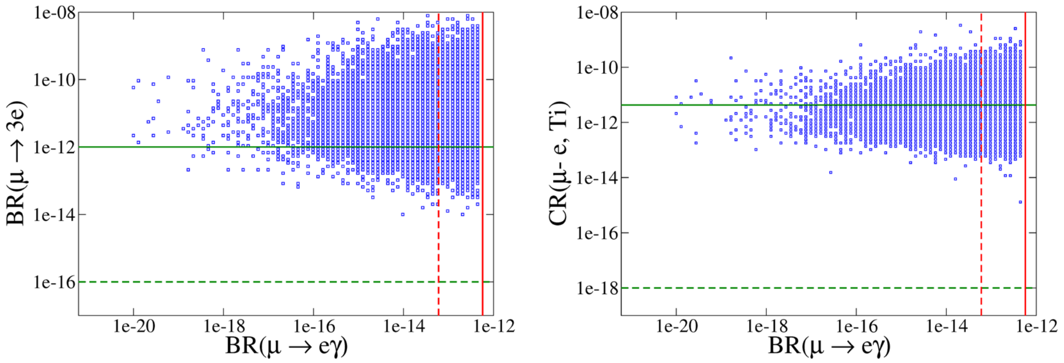
- Interpret muon g-2 anomaly as new physics
- EFT
- Investigate energy scale for unitarity violation
- This scale sets a bound on where new physics can be expected
- Result is new physics < 1000 TeV
- Specific scenarios have lower bounds, e.g., renormalizable scalar Yukawa theories
  - Tensor tree-level operators: $M_{on\text{-}shell} \lesssim 130$ TeV
  - Dipole one-loop level operators: $M_{on\text{-}shell} \lesssim 180$ TeV

Allwicher et al., 2105.13981

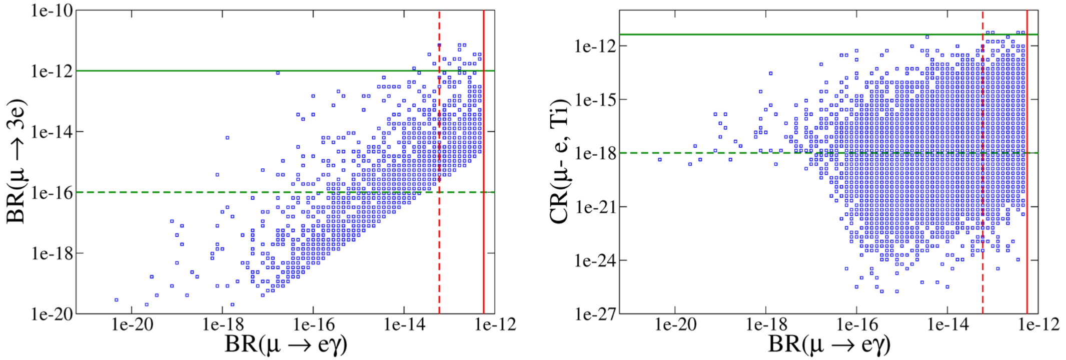
Scotogenic model: DM and LFV

- Accounts simultaneously for:
  - Neutrino Masses
  - Dark Matter
- TeV scale
- 3 singlet fermions (N_1, N_2, N_3) plus scalar $SU(2)_L$ doublet (η)
- New particles odd, SM even under new Z_2 symmetry
- N_1 or η could be DM

DM via N_1 - N_1 annihilation



DM via N_1 - η coannihilation



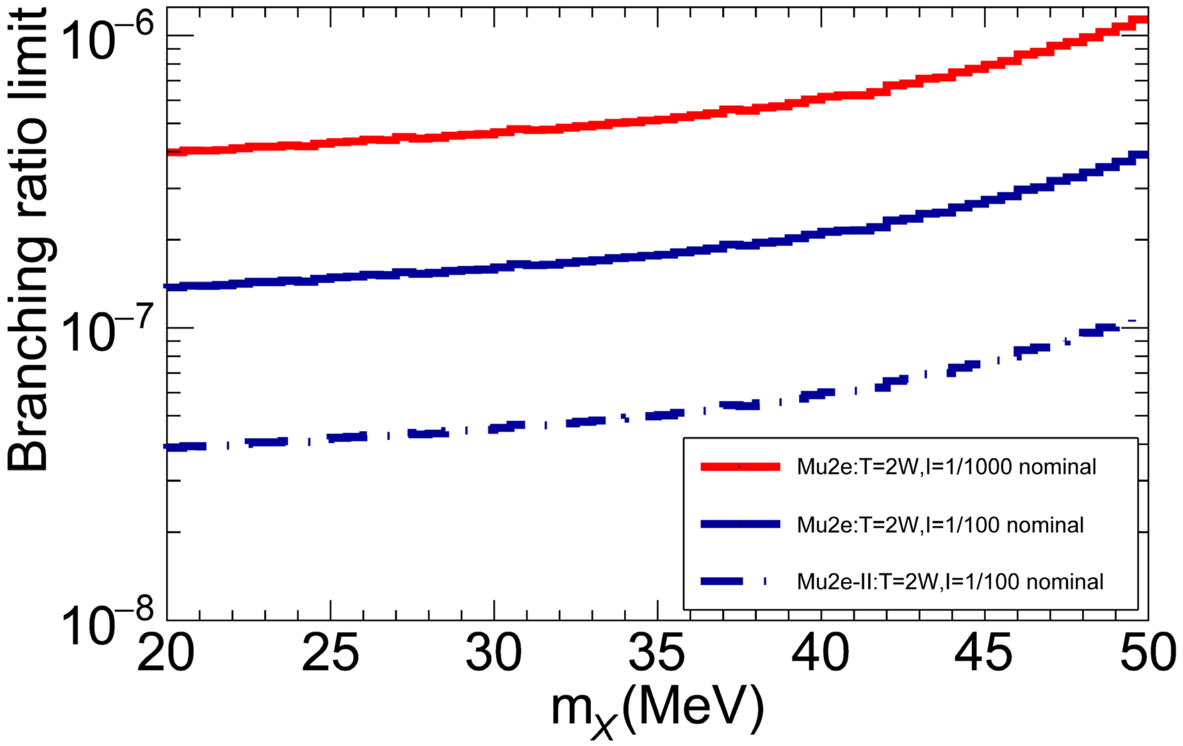
Solid lines: current bounds
Dashed lines: future sensitivities

Vicente&Yaguna, 1412.2545

$\mu^+ N \rightarrow e^+ X N$

- X could be, e.g., a familon, associated with breaking family symmetry
- Best limits from TRIUMF, e.g., < 9×10^{-6} for $3<M_X<87$ (TWIST 2015)
- Select μ^+ by rotating collimator
- P < 53 MeV, so reduce B field
- Reduce beam intensity to not saturate detector

Assume
- 50% B field
- Beam intensity 1/1000 or 1/100 nominal
- Handle 10x Mu2e flux

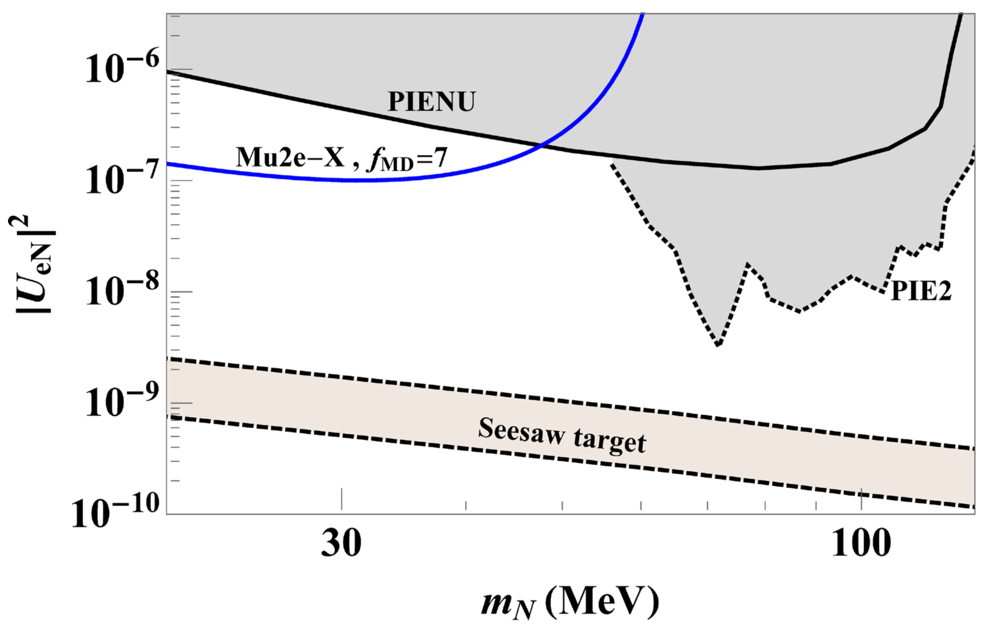


(Shihua Huang)

Heavy neutral lepton

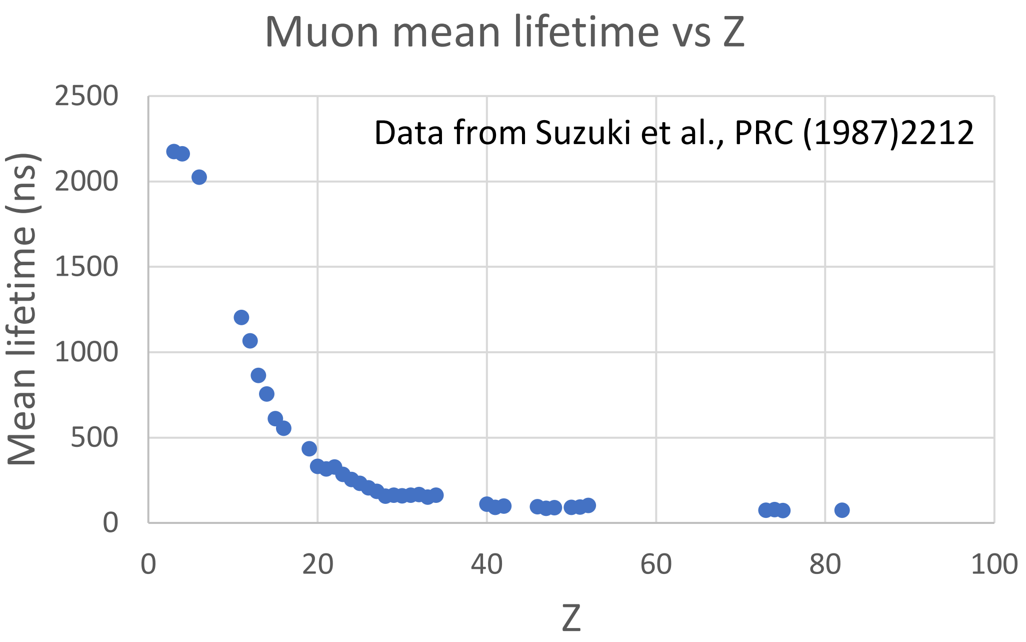
- In $\pi^+ \to e^+X$
- Using "calibration mode" ($\pi^+ \to e^+\nu_e$)
  - 76% B field (removes Michel electrons)
  - Reduced beam intensity
  - Sign select positive particles
  - Degrader (factor 7 sensitivity improvement)
    - Reduce muon decay in flight
    - Increase stopped pions

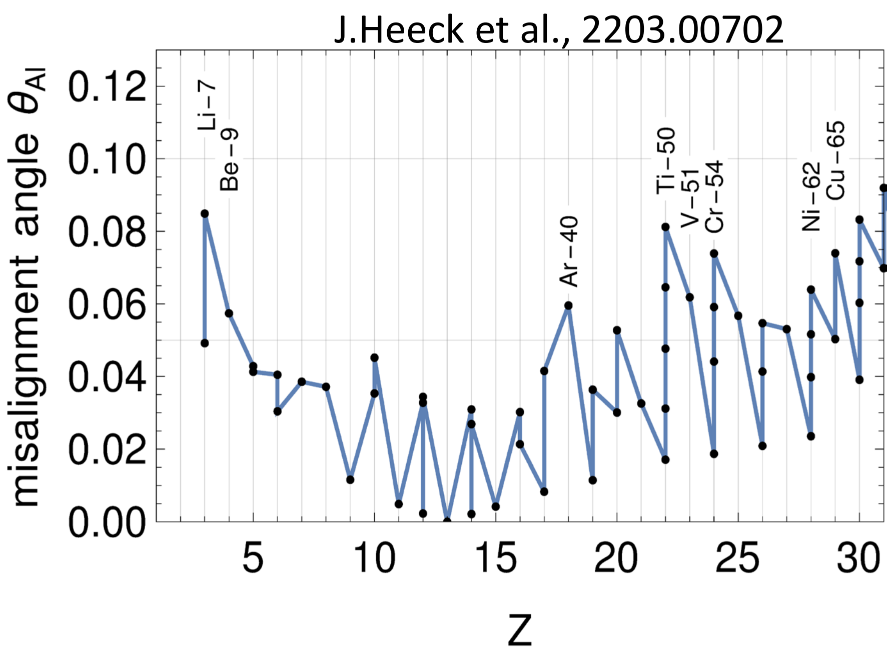
Plestid, Caltech workshop

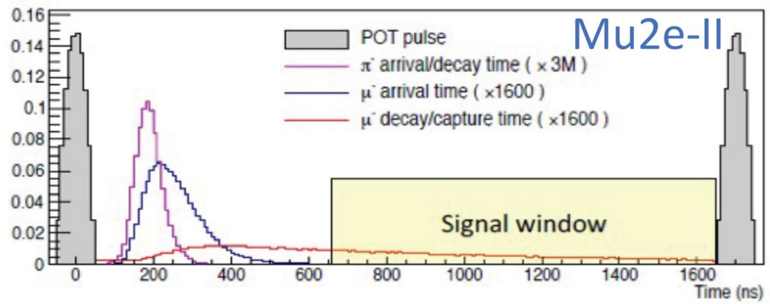


Lifetime vs Z

- Muon lifetime depends on Z
- Mu2e(-II) setup problematic if lifetime too short
  - We rely on time gap to eliminate "prompt" backgrounds
- Restrict to targets with Z < 25 so that $\tau > 250$ ns
- To get most complementarity with Al, consider Li-7, V-51 [Ti-50 has low natural abundance]

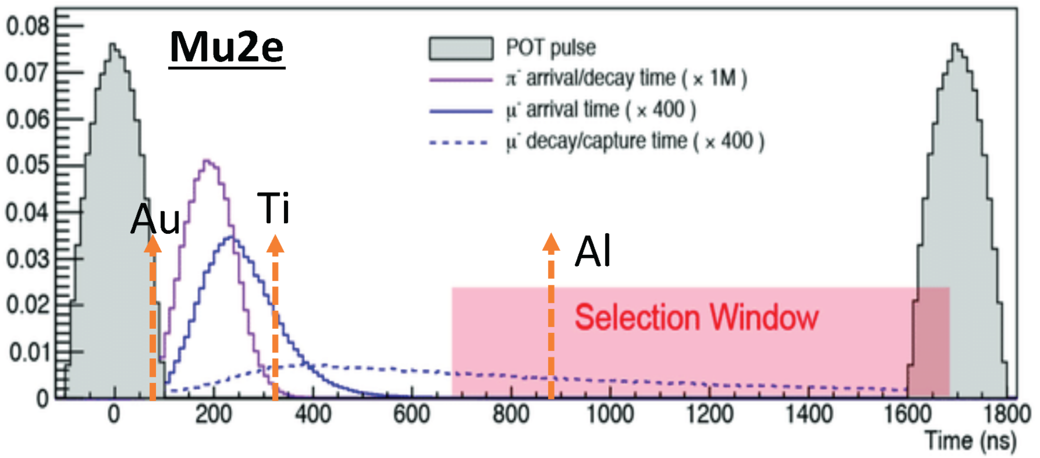




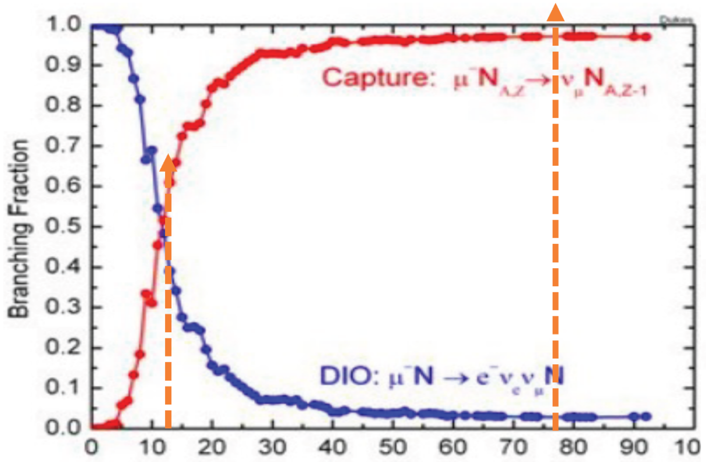


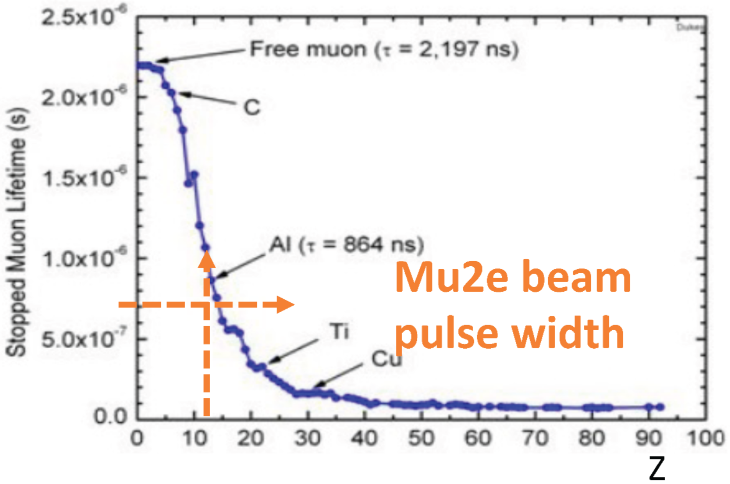
$N\mu^- \to Ne^-$: Limitations of Current Approach

- In Mu2e we uses “delayed live-gate” to effectively eliminate pion backgrounds:
  - Mu2e chose an Al target, mean lifetime of muonic Al is 864 ns, Mu2e beam pulse is 250 ns FWHM.
  - To elucidate new physics a high Z target is advantageous:
    - Gold or lead have benefit of larger splitting in conversion rate (compared to Al) for different CLFV operators.
    - But mean muonic lifetime in gold is ~ 70 ns, too short for Mu2e.
    - Less DIO and shorter mean lifetime.
- Reconstructed momentum resolution of 200keV/c is not enough to reject DIO electrons at these rates < 10^{-18}.

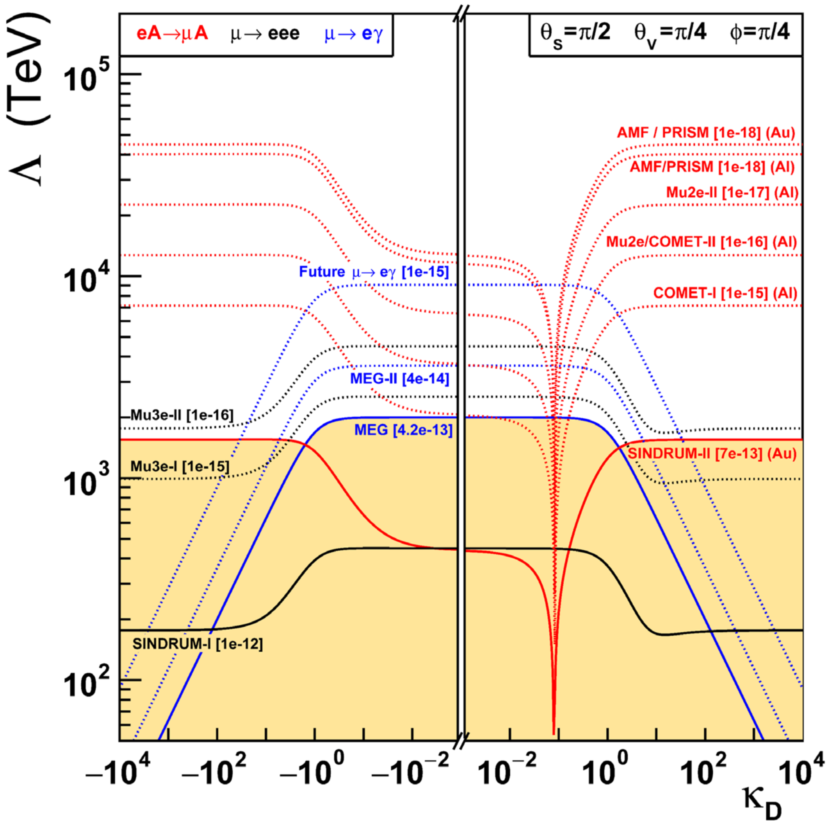


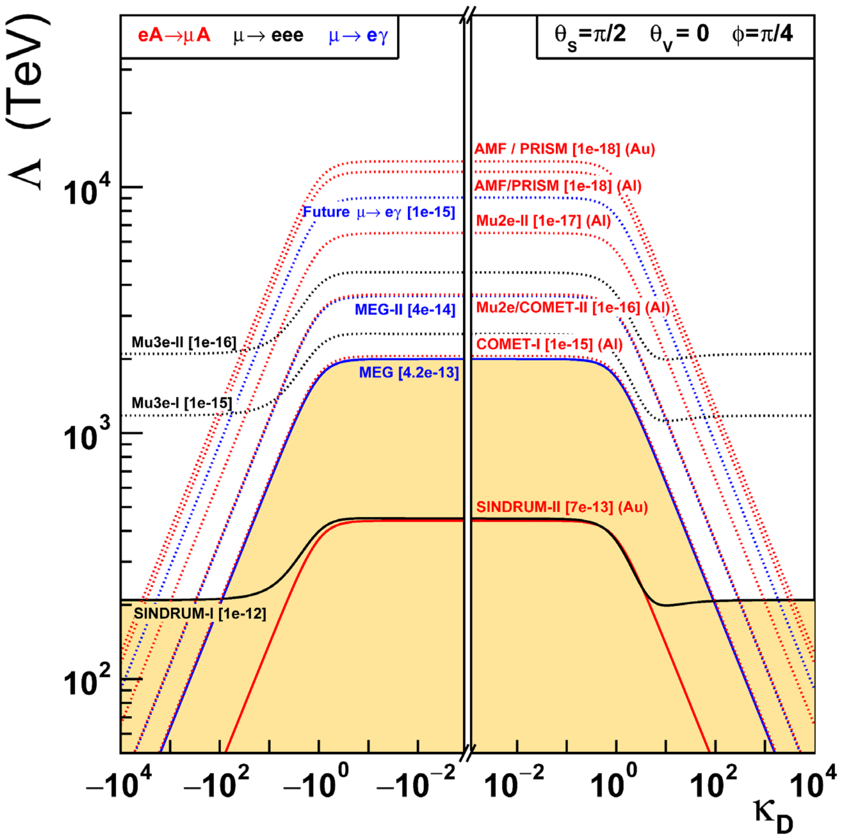
Nucleus	Mean Lifetime [ns]	Conversion Electron Energy [MeV]
Al(13, 27)	864	104.96
Ti(22,~48)	328	104.18
Au(79,~197)	73	95.56





Conversion is sensitive to new physics at very high mass scales





$$\kappa_D \equiv \cot\left(\theta - \frac{\pi}{2}\right)$$

$|\kappa_D| \ll 1$ dipole operator dominates

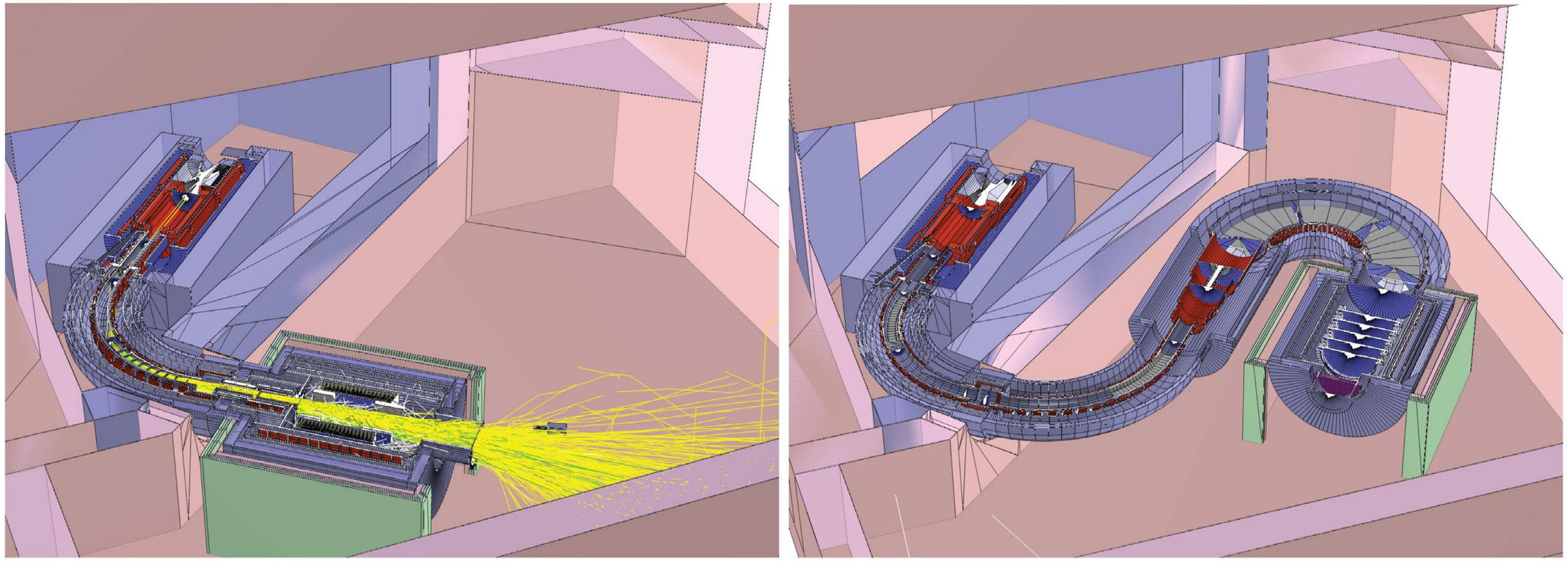
$|\kappa_D| \gg 1$ 4-fermion operators dominate

S.Davidson, B.Echenard, et al., Snowmass21 Report of the CLFV topical group RF5

COMET at J-PARC

8 GeV protons (same as Mu2e)

Jansen et al., EPJ Web of Conferences **282**, 01014 (2023)
Lee et al., arXiv:2203.07089



COMET Snowmass LOI, https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-100.pdf

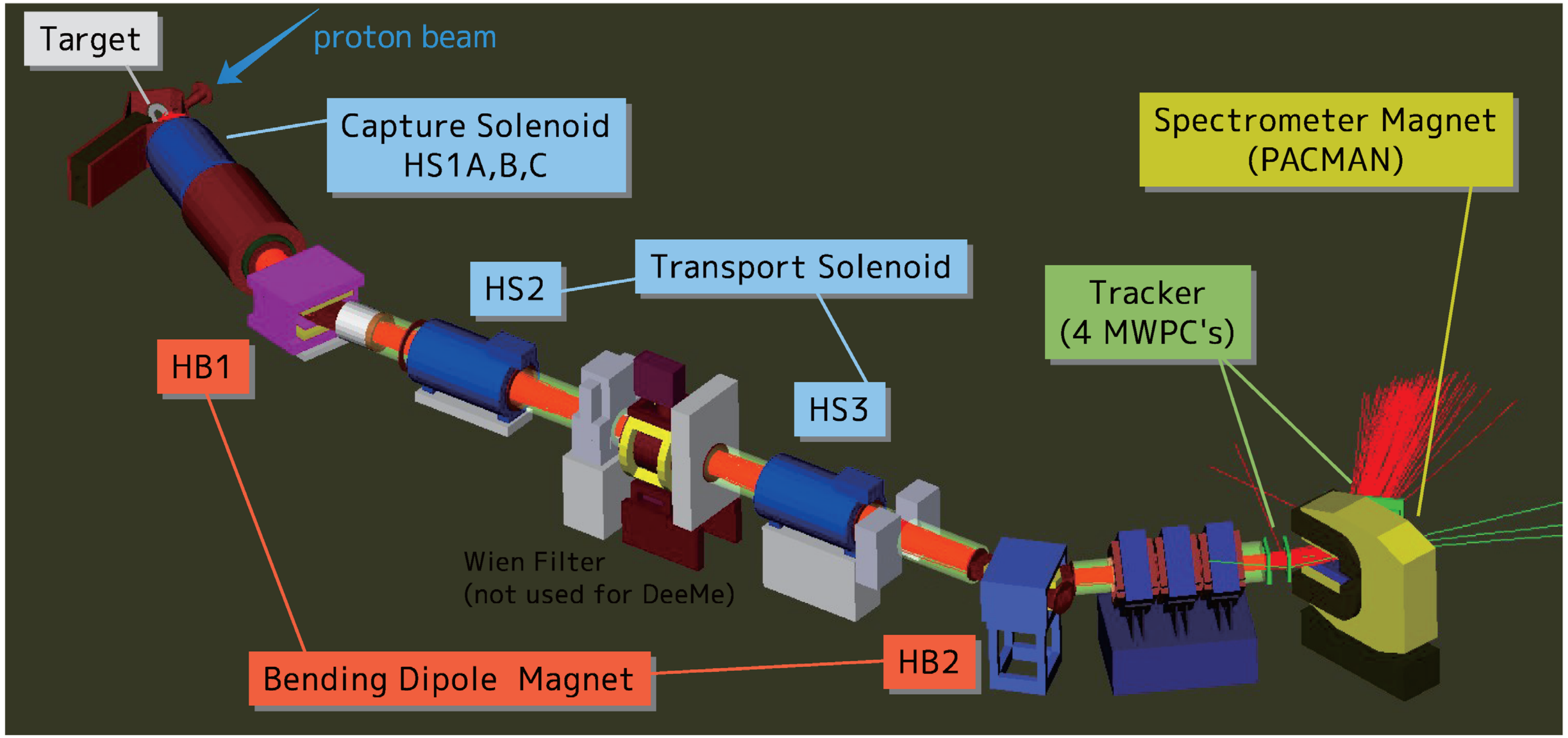
Phase I
- Graphite production target
- 3.2 kW beam
- SES ~ 3x10^{-15}

Phase II
- Tungsten production target
- 56 kW beam
- SES ~ 3x10^{-17}

DeeMe at J-PARC

- 3 GeV protons, carbon production/stopping target
- SES ~ 10^{-13}
- Data planned in 2023

Teshima, arXiv:1911.07143
Lee et al., arXiv:2203.07089

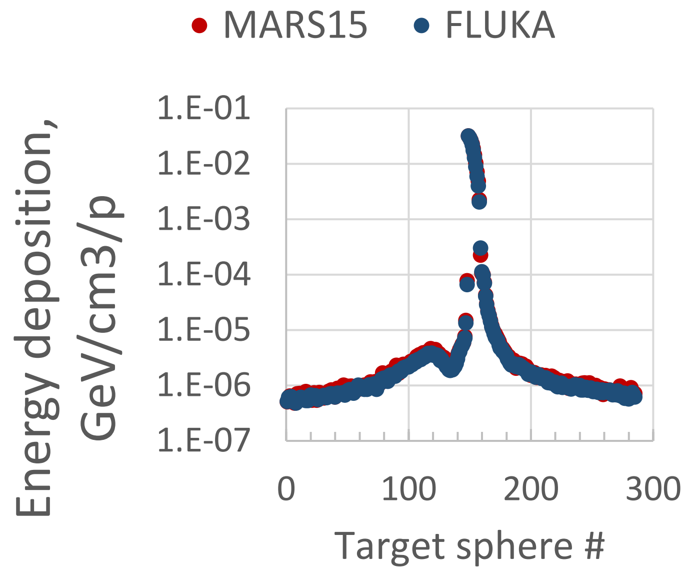


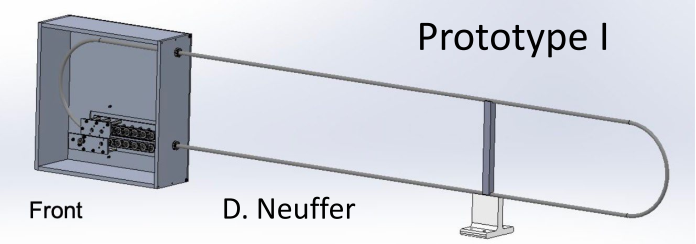
High power target LDRD R&D

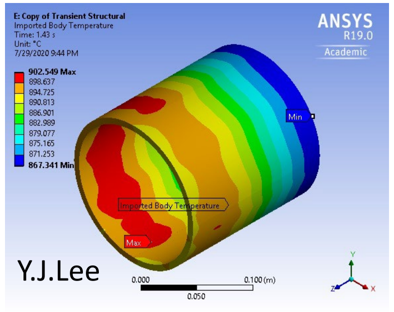
- Beam power 100 kW (800 MeV p) vs Mu2e 8 kW (8 GeV p)
- Stationary target with passive cooling not an option
  - But ongoing Mu2e R&D (planning beam test) helps!
- Considered 3 approaches
  - Conveyor with W/WC or C/SiC selected for prototyping
- Study radiation, pressure profile, thermal profile, stopped muon efficiency
- Hoping to collaborate with ORNL

In discussions with Muon Collider on synergistic R&D on production target and production solenoid

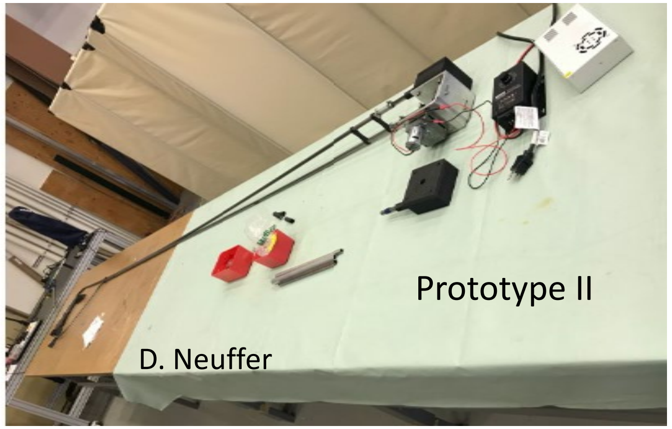
  - Mu2e-II looks like a prototype to the muon collider
  - Also to proposed Advanced Muon Facility







Hollow cylinder
903 C, 8.3 Mpa
15 cm OD, 6.3 mm wall,
16 cm long



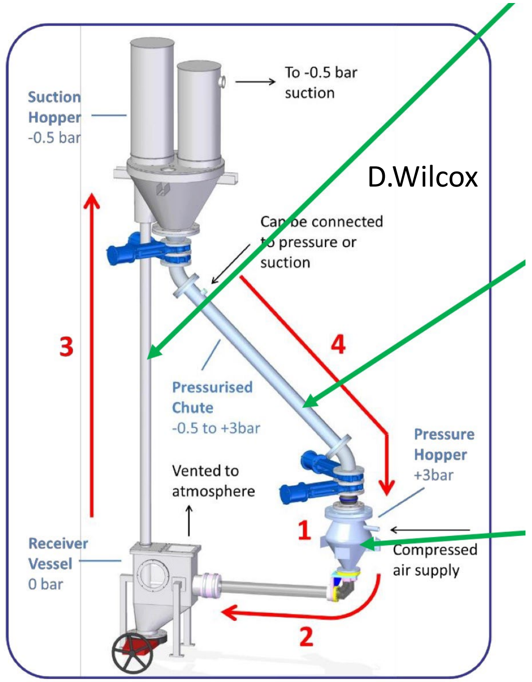
High power target LDRD R&D (future)

- (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

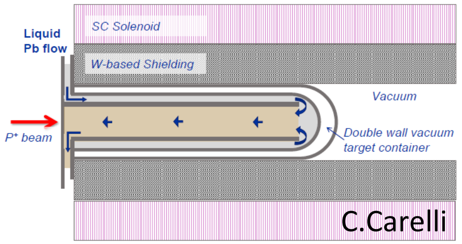
Estimate $2M

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

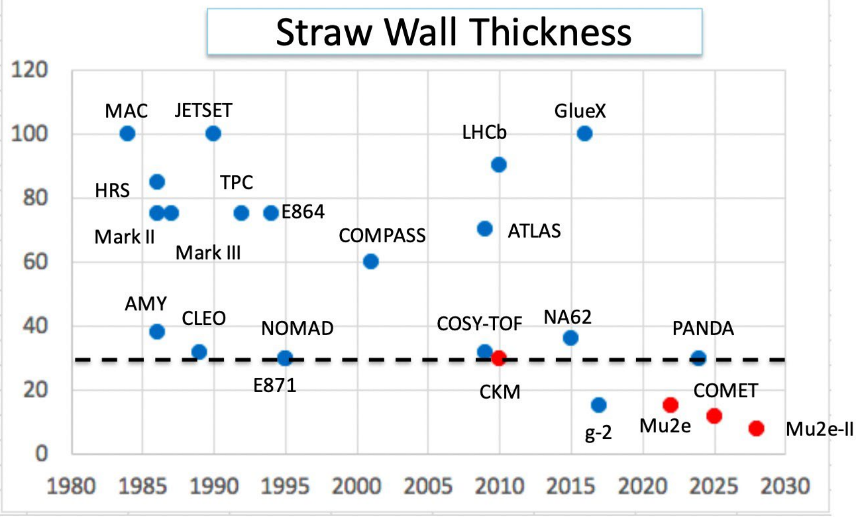


Liquid heavy metal concept

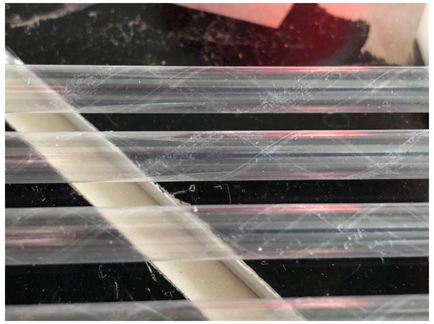
Tracker LDRD R&D

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?

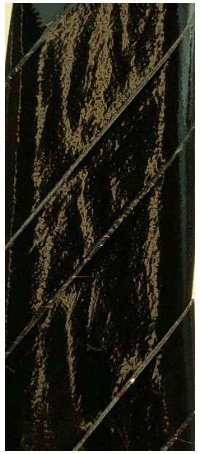


B. Casey, LDRD talk



8 m Mylar straws using spiral winding

8 μ straws with terminations



Gold/aluminum alloy Formation (mu2e straw)

Straw Tracker R&D (future)

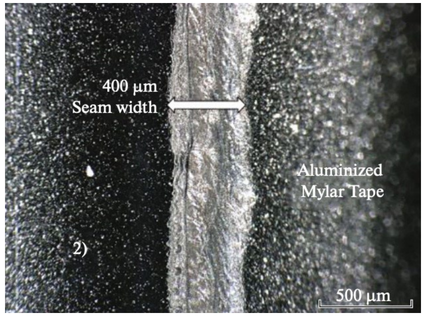
Continuing R&D needed (estimate $2M prior to project start)

- Straw vendors
- Straw handling
- Straw terminations
- Wire alignment
- Metallization (low mass)
- Gas mixture and gas flow
- Leaks
- Use of 3D printing (tolerances, rad hardness?)

Other straw options

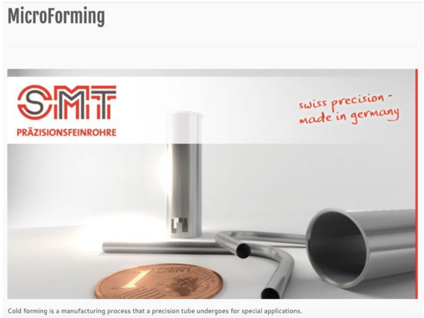
- NA62/COMET 12 μ ultrasound welded
- Microform Al extrusion 2 μ

- Mu2e tracker was very difficult
  - Lengthy R&D, continuing into production
- Mu2e-II tracker will be just as difficult
  - But benefit considerably from Mu2e



DOI: 10.1134/S1547477122020108

COMET 12 μ ultrasound welded



Microform extrusion

15 hr exposure, sparky Mu2e panel

Possible tracker R&D profile

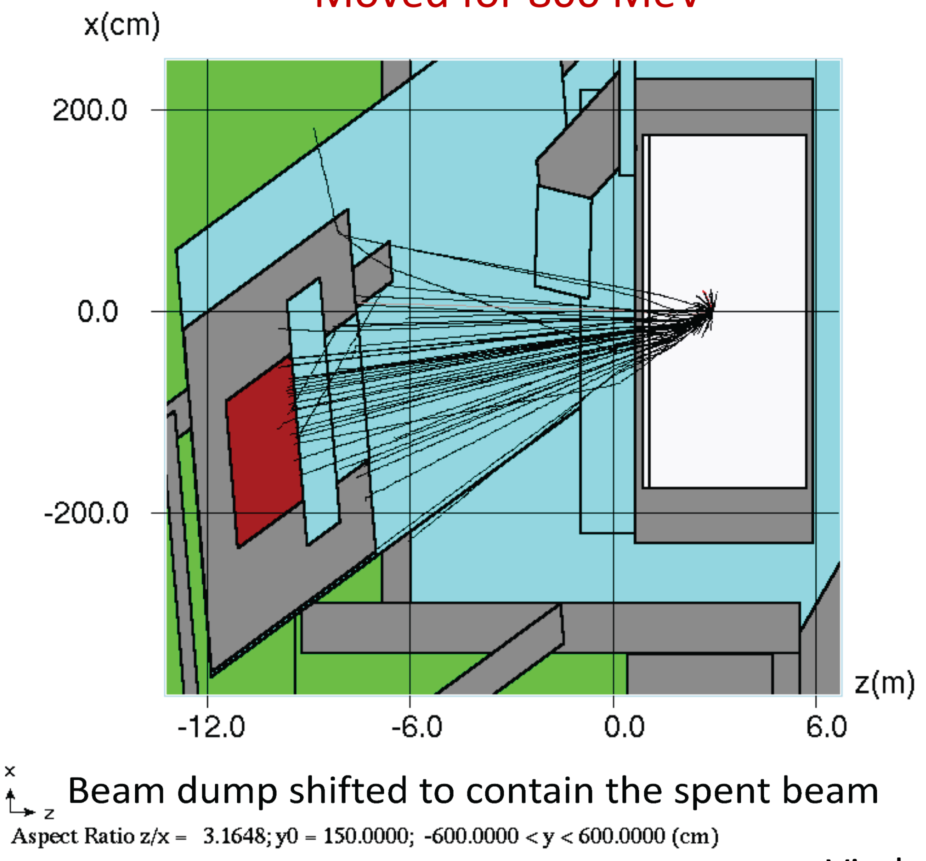
FTE	postdoc	ap phys	senior	eng	tech	M&S ($K)	
FY26	0.25	0.25	0.1	0	0	10	
FY27	0.5	0.25	0.1	0.1	0.1	50	
FY28	0.5	0.25	0.2	0.2	0.2	100	
FY29	0.5	0.25	0.2	0.3	0.3	200	
sum	1.75	1	0.6	0.6	0.6	360	
Burdened							
FY26	43.75	62.5	40	0	0	12	158.25
FY27	87.5	62.5	40	50	17.5	60	317.5
FY28	87.5	62.5	80	100	35	120	485
FY29	87.5	62.5	80	150	52.5	240	672.5
sum	306.25	250	240	300	105	432	1633.25

Brendan Casey

Beam dump move

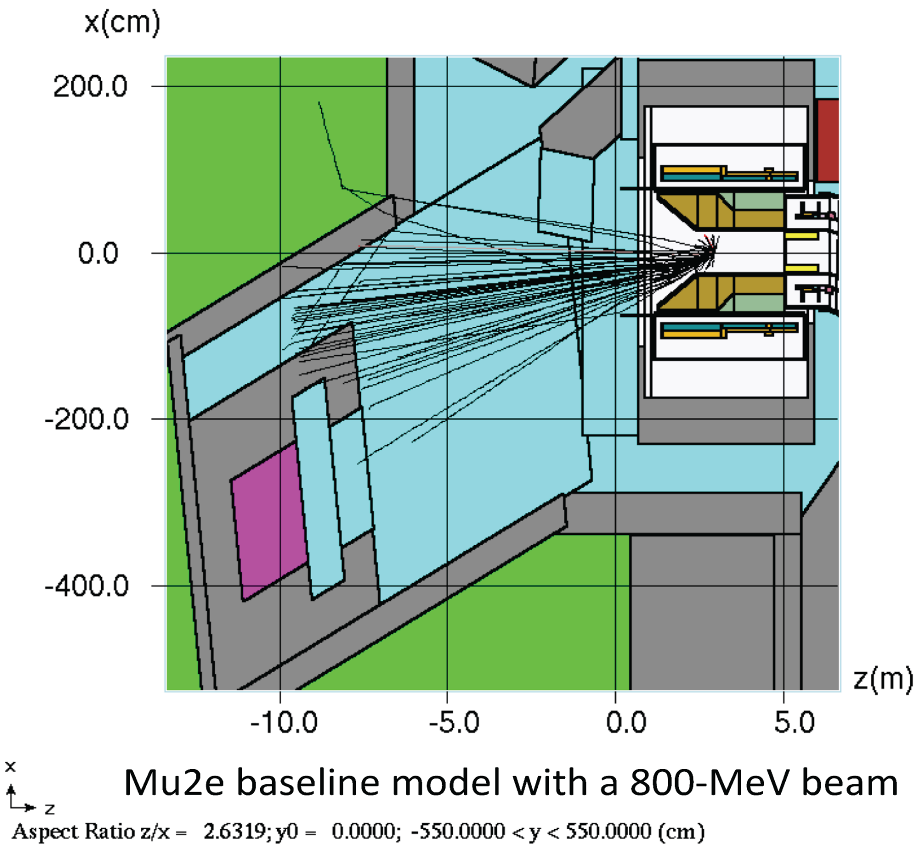
If only beam energy changes, beam dump must be moved

Moved for 800 MeV



Beam dump shifted to contain the spent beam

Mu2e (8 GeV) position

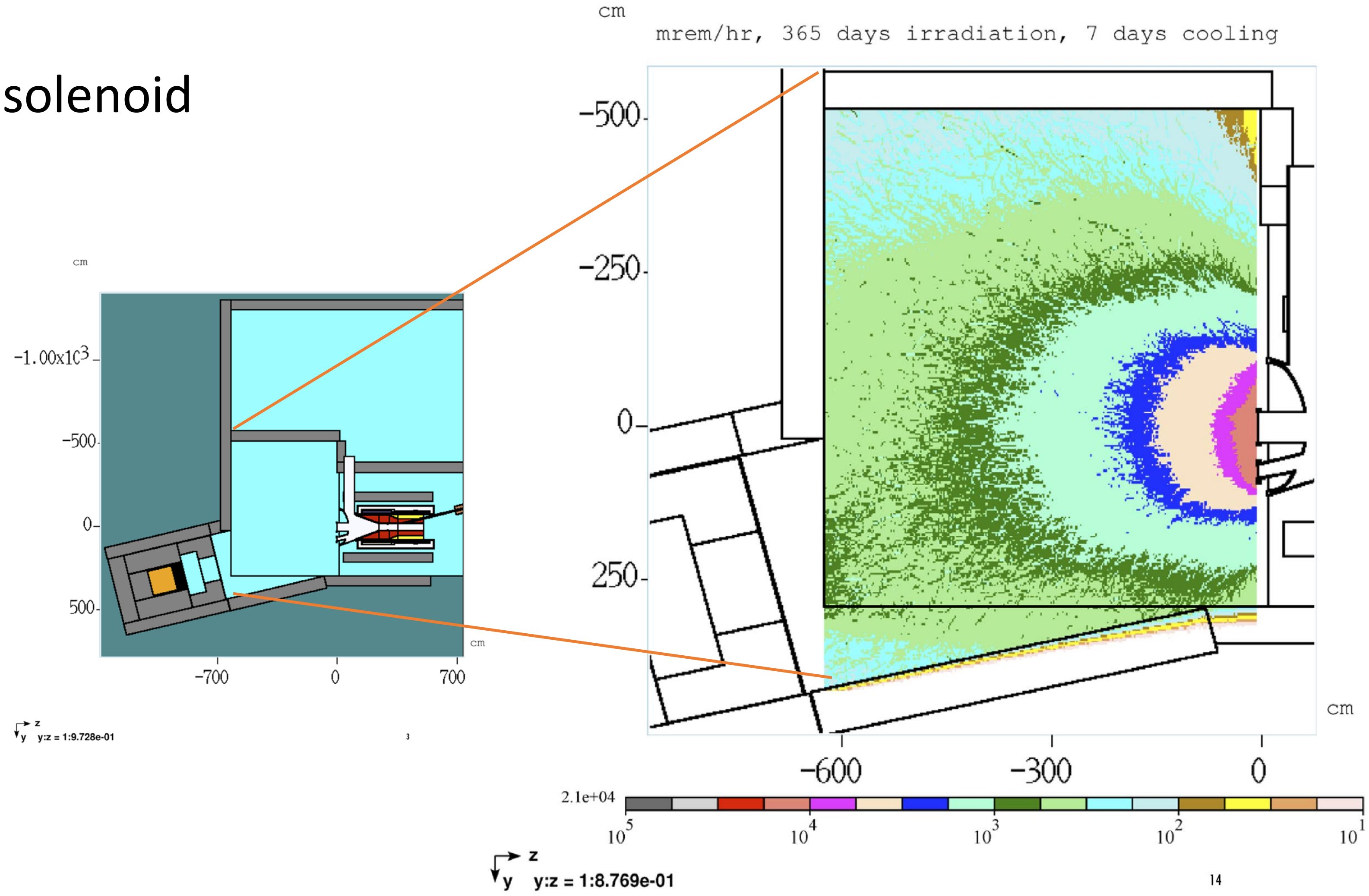


Mu2e baseline model with a 800-MeV beam

Vitaly Pronskikh

Residual dose at production solenoid

- 365 days irradiation
- 8 GeV
- 8 kW
- after 1 week cooldown
- mid-plane of PS



DocDB-5629 (Leveling)
See also:
https://www.sciencedirect.com/science/article/abs/pii/S0168900217309415 (FermiCORD paper)

Hottest point in this region: 21 rem/hr

Mu2e-II Run Parameters

Parameter list on public Wiki:
https://mu2eiiwiki.fnal.gov/wiki/Learn_about_Mu2e-II

Follow Mu2e assumptions, 3rd year
(DocDB-26289, "Mu2e staging options")
Note that this implies 1.5×10^7 s/yr for CE data
Hence 4 years for total run time of 6×10^7 s

Parameter	Value	Units	Value	Units
Accelerator beam	40	week/yr	2.4×10^7	s/yr
Accelerator up time	90	%	2.2×10^7	s/yr
Calibration, background studies, other special runs	30	% of delivered beam	6.5×10^6	s/yr
Mu2e efficiency	100	%		
CE data	70	% of delivered beam	1.5×10^7	s/yr

Mu2e-II Snowmass21 Committee

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Mu2e-II Working Groups

Mu2e-II working groups	Convenors
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Sensitivity estimate (includes simulation, stopping target) mu2e-ii-sensitivity@listserv.fnal.gov	Lisa Goodenough Sophie Middleton Yuri Oksuzian
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Vadim Kashikhin, FNAL

Kevin Lynch, CUNY

James Popp, CUNY

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Radiation simulation and mitigation

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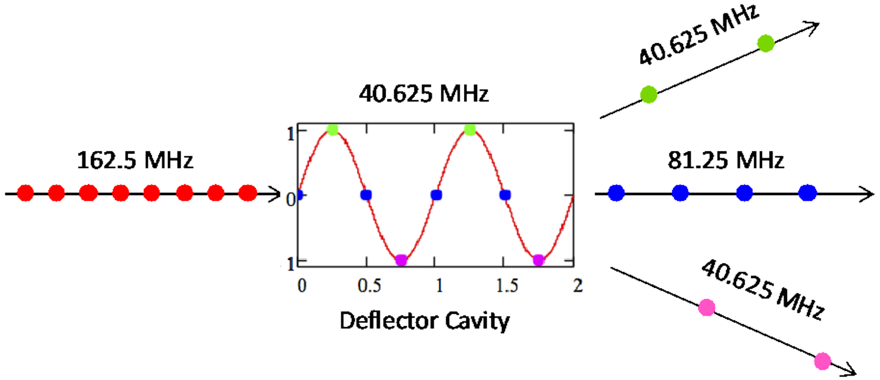
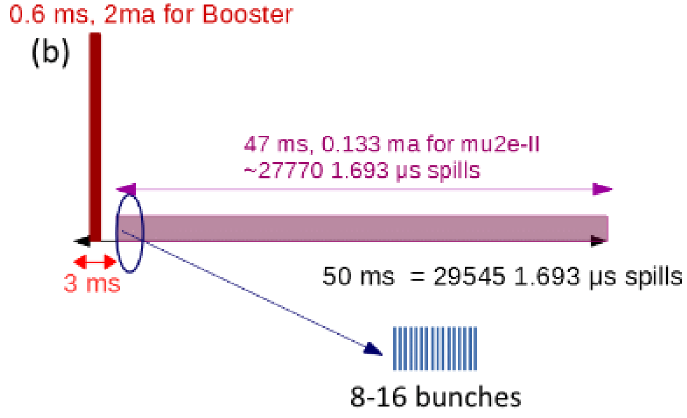
Mu2e-II beam nomenclature

- Follow accelerator group usage
- Beam delivery is different than Mu2e

Quantity	Name
Beam in one PIP-II RF bucket (162.5 MHz)	Bunch
PIP-II pulse (20 Hz/0.55 ms)	Pulse (but see below)*
Mu2e-II repetition (e.g., 1693 ns)	Spill (also pulse, but see above)**
Set of bunches in one spill (e.g., 8)	Burst (also pulse, but see above)**

*One PIP-II pulse is about 27770 Mu2e-II spills; suggest saying “PIP-II pulse” to avoid confusion.
**”Pulse” may be used when distinction is not important





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