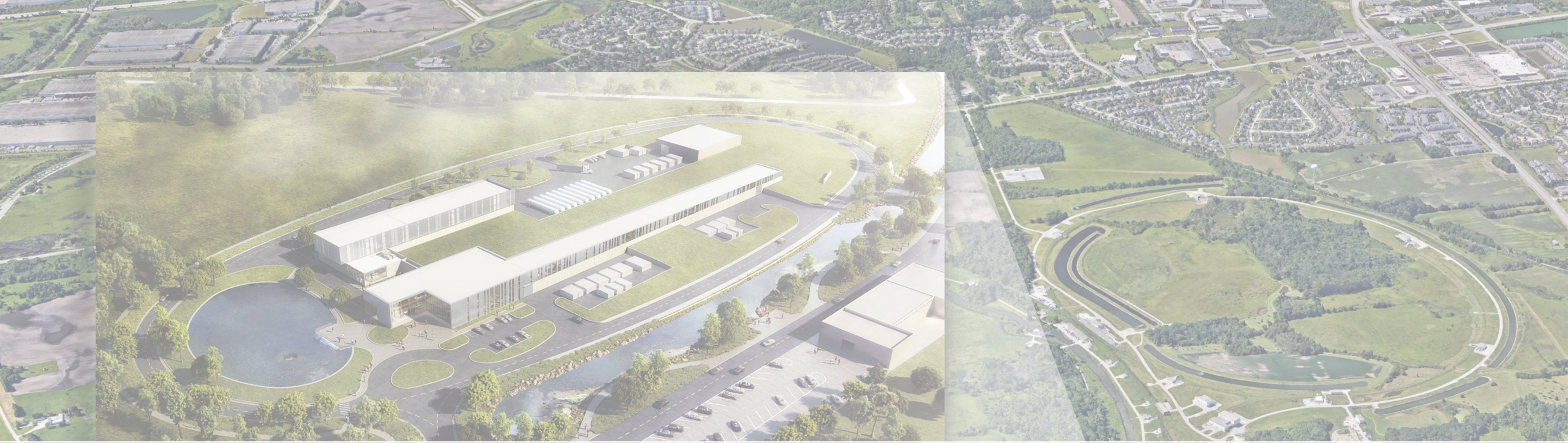


The Advanced Muon Facility at Fermilab

By Sophie Charlotte Middleton

(Caltech)

ACE Science Workshop

14-15th June 2023

What is the Advanced Muon Facility?

Advanced Muon Facility (AMF)

- is a propose FNAL-based multi-purpose muon facility;
- would provide world's most intense muon beam to enable muon science at unprecedented sensitivity;
- experiments at AMF will provide discovery potential orders-of-magnitude beyond current experiments;
- AMF is a great opportunity to maximize the physics potential of ACE, and the proposed 2GeV spigot, to do cutting edge research.

- AMF is in the early stages of design, but the Snowmass study[1] and recent workshop[2] provide starting points for this talk. I recommend looking over them if you are interested in getting involved.
- AMF would come online in the 2040s (technically driven) but R&D needed now to make it a reality.

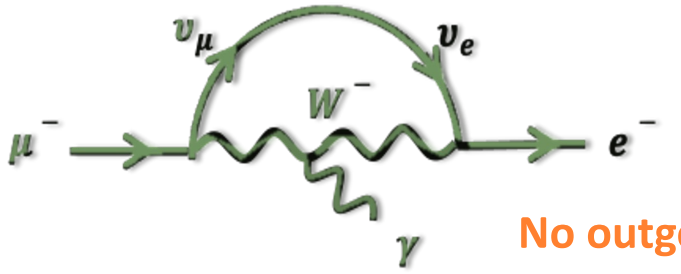
Useful resources:

[1] Snowmass White Paper: arXiv: 2203.08278 [hep-ex]

[2] Agenda of recent workshop: https://indico.fnal.gov/event/57834/timetable/?view=standard → Proceedings soon!

Charged Lepton Flavor Violation (CLFV)

- Neutrino oscillations = Neutral Lepton Flavor Violation
- The minimal extension of the Standard Model, including masses of neutrinos, allows for CLFV at loop level, mediated by W bosons.



No outgoing neutrinos!

- Rates heavily suppressed by GIM suppression and are far below any conceivable experiment could measure:

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2$$

$$B(\mu \to e\gamma) \sim \vartheta(10^{-54})$$

using best-fit values for neutrino data ($m_{\nu j}$ for the neutrino mass and U_{ij} for the element of the PMNS matrix).

If observed in any experiment this would be an unambiguous sign of physics beyond the Standard Model (BSM).

Current Experimental Searches for CLFV

- **There is an on-going global program searching for muon CLFV. Experiments will take data this decade!**
- Muons are a unique, powerful probe thanks to the availability of very intense beams and their relatively long lifetime.
- To elucidate the mechanism responsible for any CLFV – must look at relative rates (if any) in different muon channels.

Mode	Current Upper Limit (at 90% CL)	Projected Limit (at 90% CL)	Upcoming Experiment/s
$\mu^+ \rightarrow e^+\gamma$	**4.2 x 10^{-13}**	**4 x 10^{-14}**	**MEG II**
$\mu^+ \rightarrow e^+e^+e^-$	**~10^{-12}**	**10^{-15} ~ 10^{-16}**	**Mu3e**
$\mu^- N \rightarrow e^- N$	**7 x 10^{-13}**	**10^{-15}** **10^{-17}**	**COMET Phase-I** **Mu2e/COMET Phase-II**

- Synergies with tau CLFV at and Higgs LFV searches at colliders. Need to explore the entire CLFV-sector (analogies with neutrino searches).

Complementarity amongst channels

- All three channels are sensitive to many new physics models → discovery sensitivity across the board.
- Relative Rates however will be model dependent and can be used to elucidate the underlying physics.

Different seesaw models given very different predicted rates of CLFV.

Measuring CLFV can help us understand neutrinos.

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{BR(\mu\to eee)}{BR(\mu\to e\gamma)}$	$\frac{CR(\mu N\to eN)}{BR(\mu\to e\gamma)}$
MSSM	Loop	Loop	$\approx 6 \times 10^{-3}$	$10^{-3} - 10^{-2}$
Type-I seesaw	Loop*	Loop*	$3 \times 10^{-3} - 0.3$	0.1–10
Type-II seesaw	Tree	Loop	$(0.1 - 3) \times 10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$
LFV Higgs	Loop†	Loop*†	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	0.05 – 0.5	2 – 20

arXiv:1709.00294v2 [hep-ph]

from L. Calibbi and G. Signorelli, Riv. Nuovo Cimento, 41 (2018) 71

- **Having all three at one facility would give us unprecedented access to new physics.**
- **AMF would be that facility, placing FNAL at the forefront of the final frontier of flavor physics – CLFV.**

Possibilities

Outcomes of current era of CLFV searches

Signal in Mu2e and/or MEG-II and/or Mu3e

- Nice papers, exciting times!

- AMF makes further measurements.

- Elucidate nature of physics and flavor structure by comparing rates in different channels.

No signals

- AMF pushes higher effective mass scale, opening other BSM scenarios.

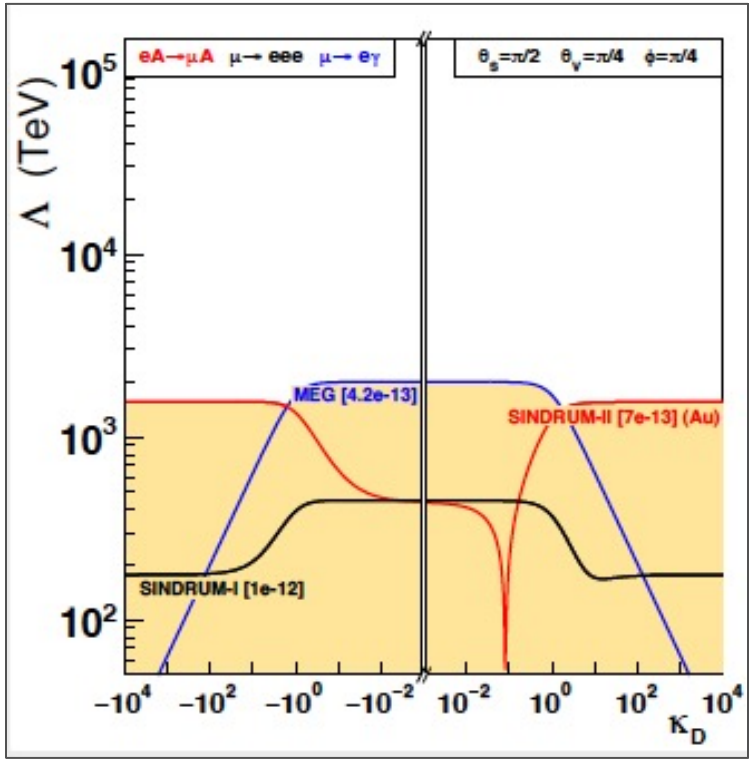
- Some models excluded or heavily constrained.

What's next??? - a multi-purpose FNAL based facility (the Advanced Muon Facility) would be ideal for going beyond and unlocking even more possible new physics in multiple channels!

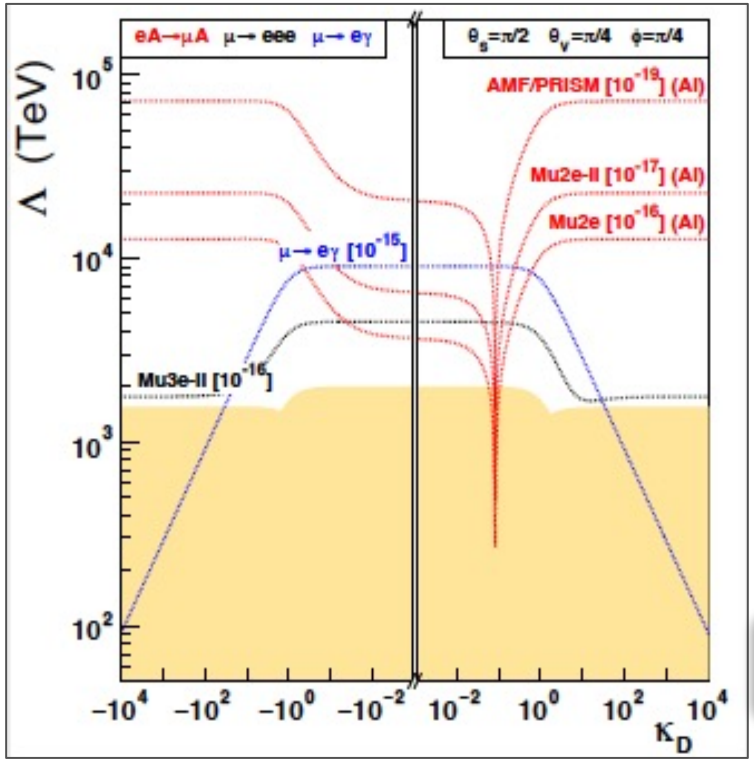
Physics Reach

$$\delta\mathcal{L} = \frac{1}{\Lambda_{LFV}^2}\Big[C_D(m_\mu \bar{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_Re) + C_{VR}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Re) + C_{VL}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight} + C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big] \quad (2.1)$$

Current Limits



Upcoming & Proposed Projections



Parameterize coefficient space with spherical coordinates *lets you express constraints on all three processes simultaneously.*

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

$$\kappa_D = \text{cotan}(\theta_D - \pi/2)$$

where angle θ_D, parametrizes relative magnitude of dipole and four-fermion coefficients.

High magnitude κ_D= contact-like, closer to zero is dipole-like

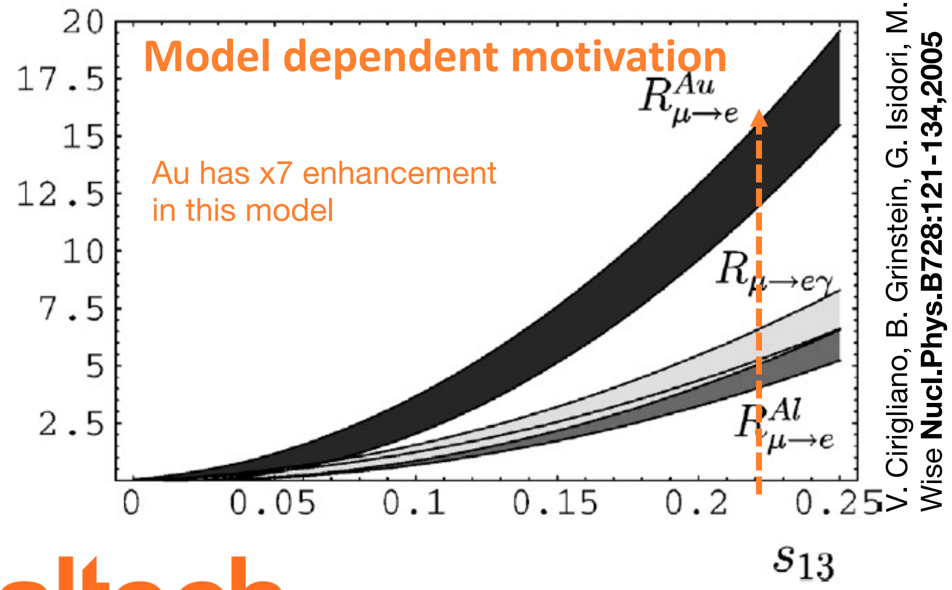
$N\mu^- \rightarrow Ne^-$: Complementarity in Target Materials

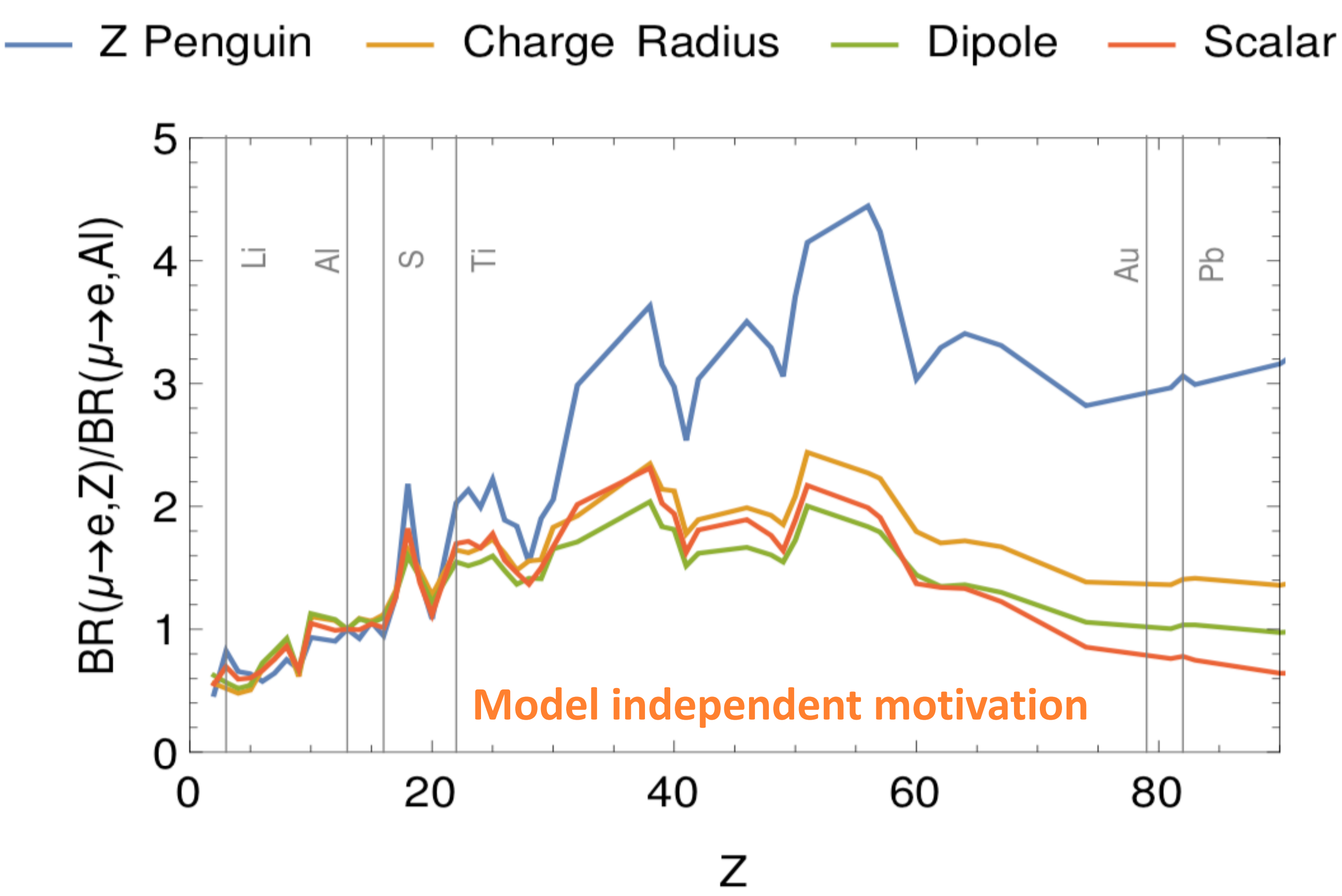
Kitano et al 2002: arXiv:hep-ph/0203110v4

$$\mathrm{BR}(\mu \to e) \propto |DC_{DL} + S^p C^p_{S,L} + V^p C^p_{V,R} + S^n C^n_{S,L} + V^n C^n_{V,R}|^2 + (L \leftrightarrow R)$$

Overlap with nucleus probes form factors and reveals the nature of the interaction.

→ can elucidate type of physics through looking at relative conversion rates.





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The Advanced Muon Facility (AMF): Physics Reach

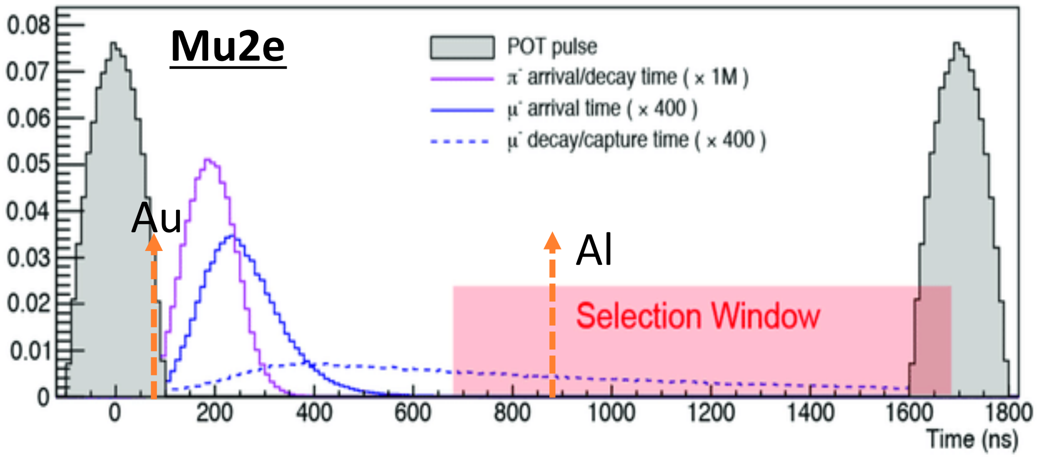
The goals of AMF would be to provide a multi-purpose μ^- and μ^+ facility for CLFV searches with unprecedented physics reach to multiple new physics scenarios:

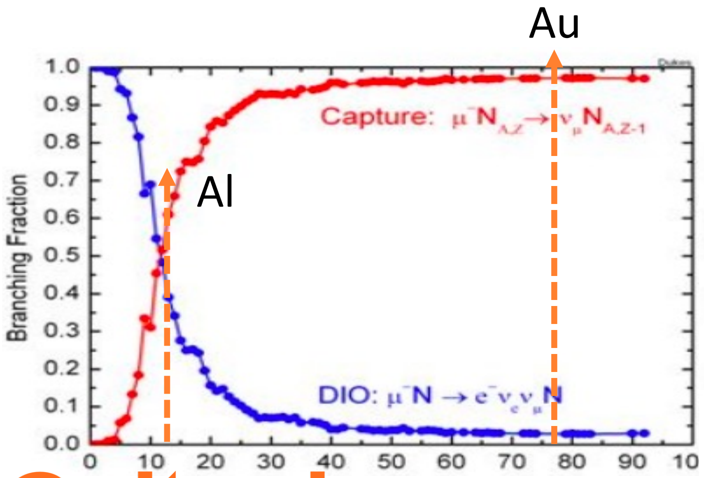
- very intense μ^-beam would enable $\boldsymbol{N\mu^- \rightarrow Ne^-}$ on high Z **(100-1000 x Mu2e)**
- very intense μ^+beam, enable $\mu^+ \rightarrow e^+\gamma$ and $\mu^+ \rightarrow e^+e^+e^-$ with:
  - $\boldsymbol{\mu \rightarrow e\gamma}$: **(x 100 MEG-II)**
  - $\boldsymbol{\mu \rightarrow eee}$: **(x 100 Mu3e-I)**
    - Need new design concept for $\boldsymbol{\mu \rightarrow e\gamma}$ to overcome backgrounds.
  - Need a design concept for simultaneous deliver of μ^+ and μ^-.
- **Muonium - anti-muonium oscillations (x100 existing limits to $\boldsymbol{10^{-5}\, G_F}$)**
- Could do anything else with large muon flux (e.g. muon spin SR experiments)

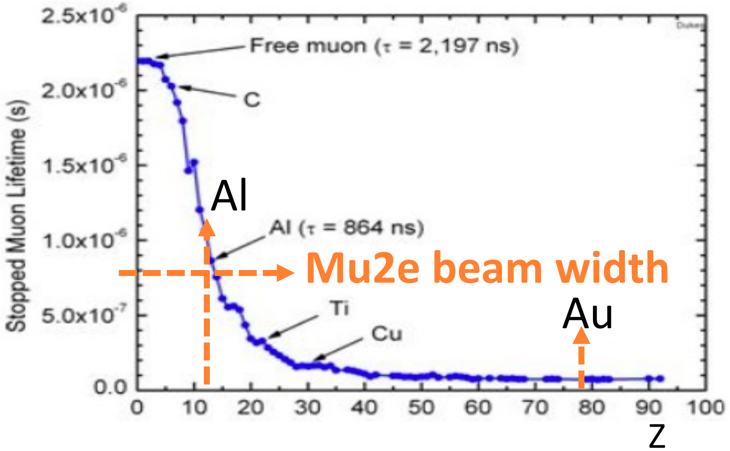
$N\mu^- \rightarrow Ne^-$: Limitations of Current Approach

1. In Mu2e only about 40% of incoming muons stop in the target. These are predominantly those with momentum < 40 MeV/c.
2. Mu2e uses “delayed live-gate” to effectively eliminate pion backgrounds:
   - A high Z target is advantageous:
     - Gold has benefit of larger splitting in conversion rate (compared to Al) for different CLFV operators.
     - Higher Z nuclei have less decay background and shorter mean lifetime.
   - **But** mean muonic lifetime in gold is ~ 70 ns → too short for Mu2e pulsed beam.

Mu2e beam pulse is 250 ns FWHM.







Nucleus	Mean Lifetime [ns]	Decay:Capture [%]	Conversion Electron Energy [MeV]
Al(13, 27)	864	39:61	104.96
Au(79,~197)	73	3:97	95.56

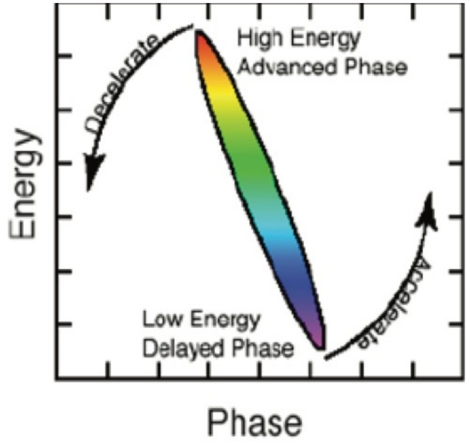
Decay is a key background, to distinguish from signal we need excellent momentum resolution

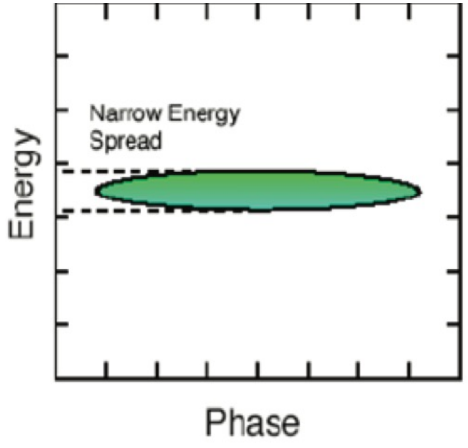
PRISM Concept

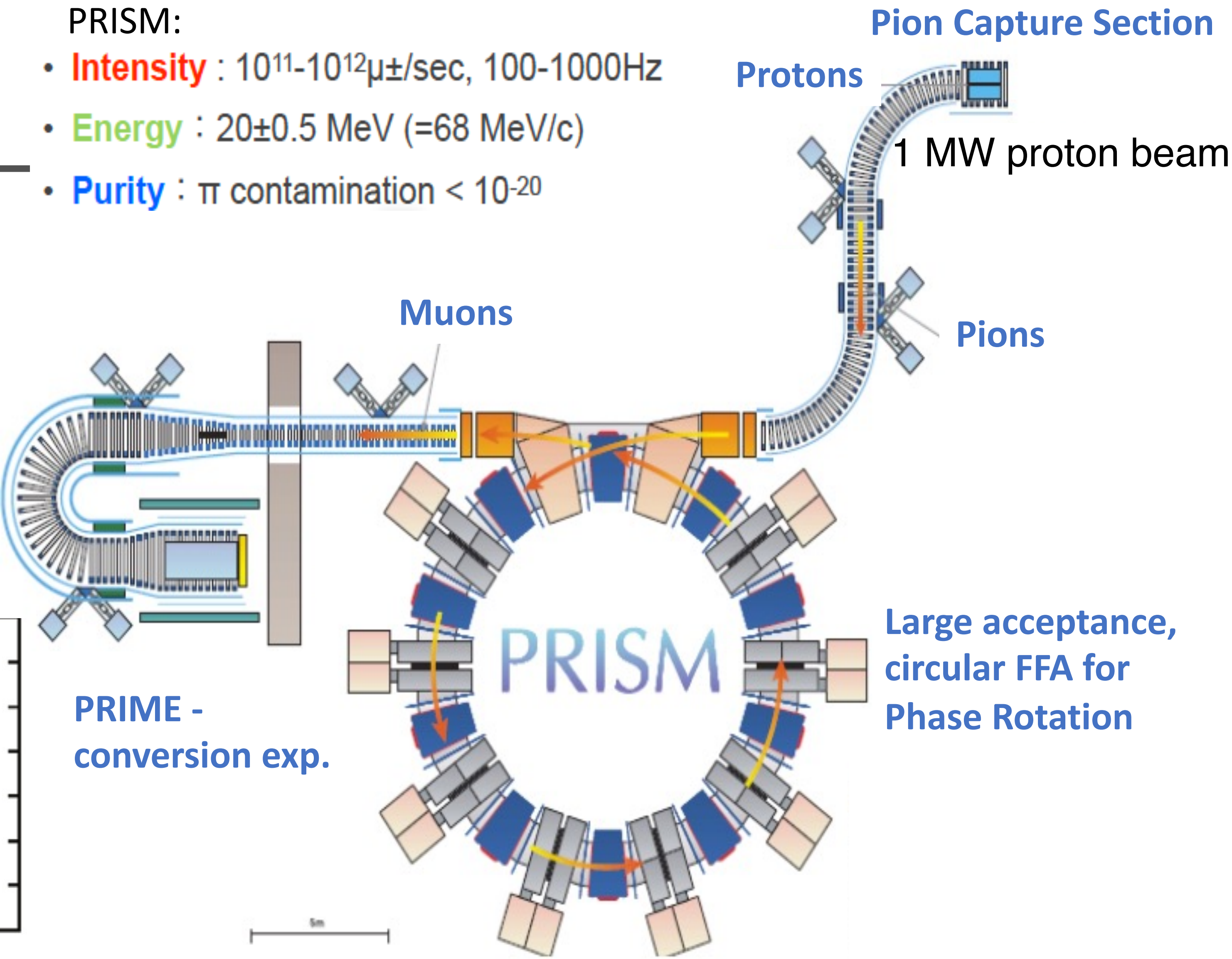
PRISM:

- **Intensity** : 10^{11}-10^{12} $\mu\pm$/sec, 100-1000Hz
- **Energy** : 20±0.5 MeV (=68 MeV/c)
- **Purity** : π contamination < 10^{-20}

- Fixed Field Alternating Gradient (FFA):
  - produces **monochromatic muon bunch**;
  - provides **phase-rotation:** energy resolution of the bunch can be improved by the sacrifice of resolution in time.
- Proof of principle 6 cell machine took data in 2010.







Nuclear Physics B - Proceedings Supplements
Volume 149, Dec. 2005, Pages 376-378

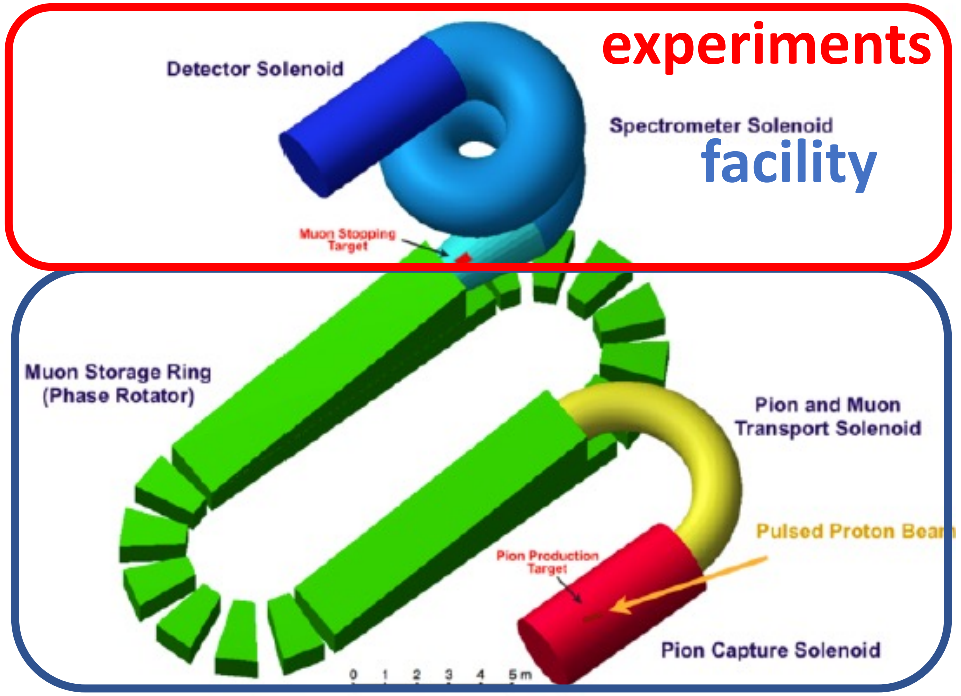
Novel Approach: use an FFA

- AMF aims to utilize a Fixed Field Alternating (FFA) gradient synchrotron to provide:
  1. **Monoenergetic beam with central momentum 20-40MeV/c:**
     - Optimal for decay experiments, $\mu^+ \rightarrow e^+\gamma$ & $\mu^+ \rightarrow e^+e^+e^-$.
     - Means can stop in thinner target for conversion experiments $N\mu^- \rightarrow Ne^-$, this reduces straggling effects and improves momentum resolution on outgoing signal electrons.
  2. **Pure Muon beam:**
     - Avoids need for “delayed live-gate” as pion and beam backgrounds eliminated.
     - Can extract muons from FFA slowly, no longer sit in beam pulse.
     - Gold and Lead are possible target materials → both provide discrimination in Lorentz structure of new physics!

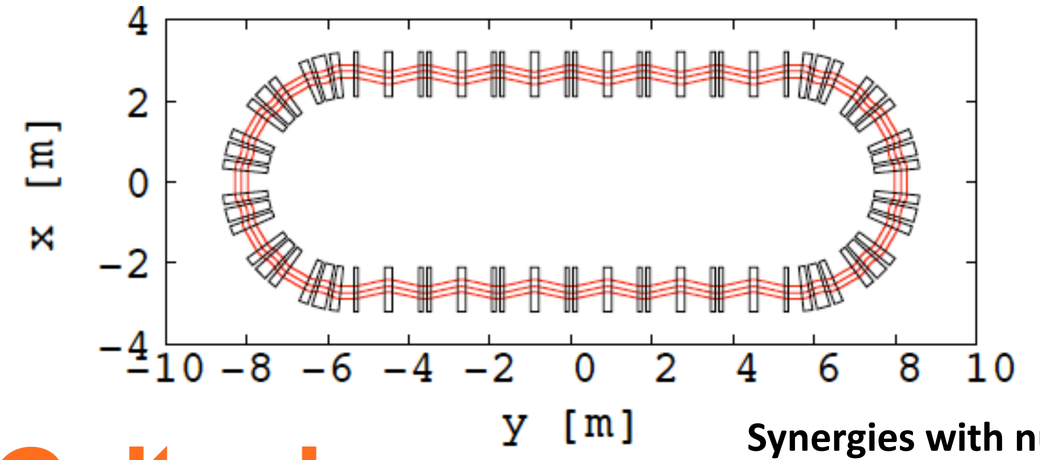
AMF: Racetrack FFA

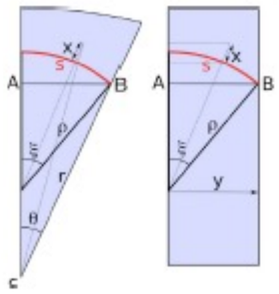
- If we circulate μ^- and μ^+ in the same facility we enable all CLFV searches:
  - might need a racetrack for separate injection/extraction systems.
  - extra space makes injection and extraction easier.
- Consists of:
  - Cells in straight sections with zero net bending;
  - Circular FFA cells in the compact arcs.
- Can accommodate lower momentum muons:
  - Central momentum 20 - 40MeV/c .
  - Ideal for decay and conversion experiments!

Racetrack FFA: J. B. Lagrange et al, Proc. PAC09, FRF5PFP002, Vancouver, Canada, 2009



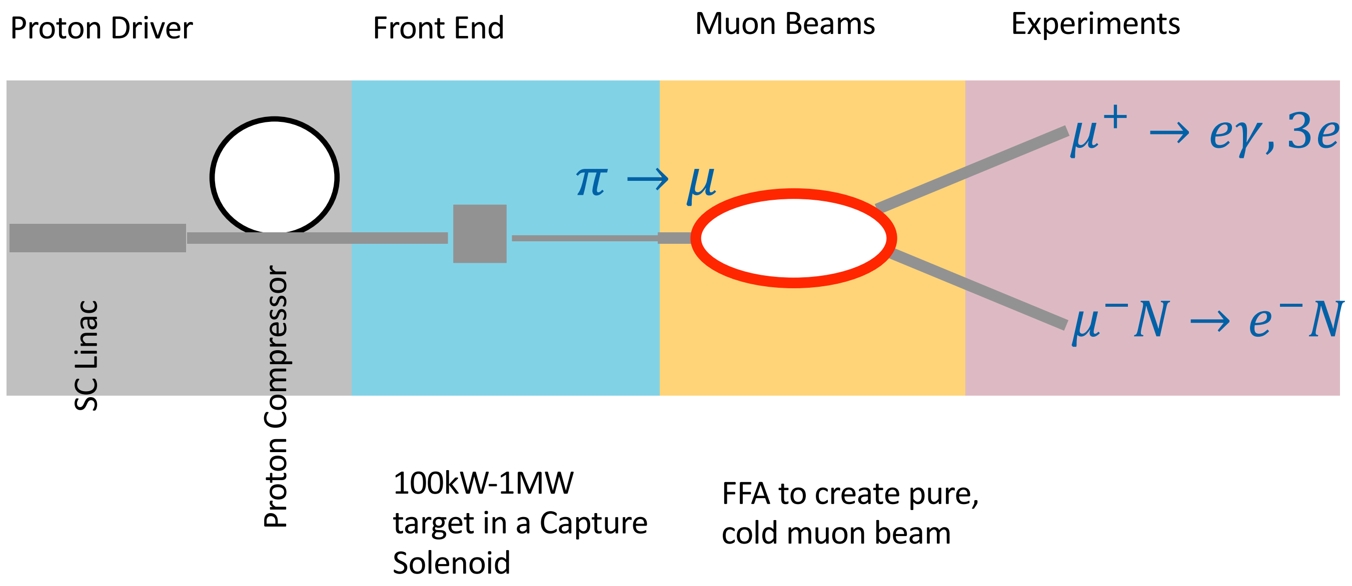
cartoon of possible layout (with conversion exp.)





Synergies with nuSTORM proposal.

AMF: Cartoon Overview



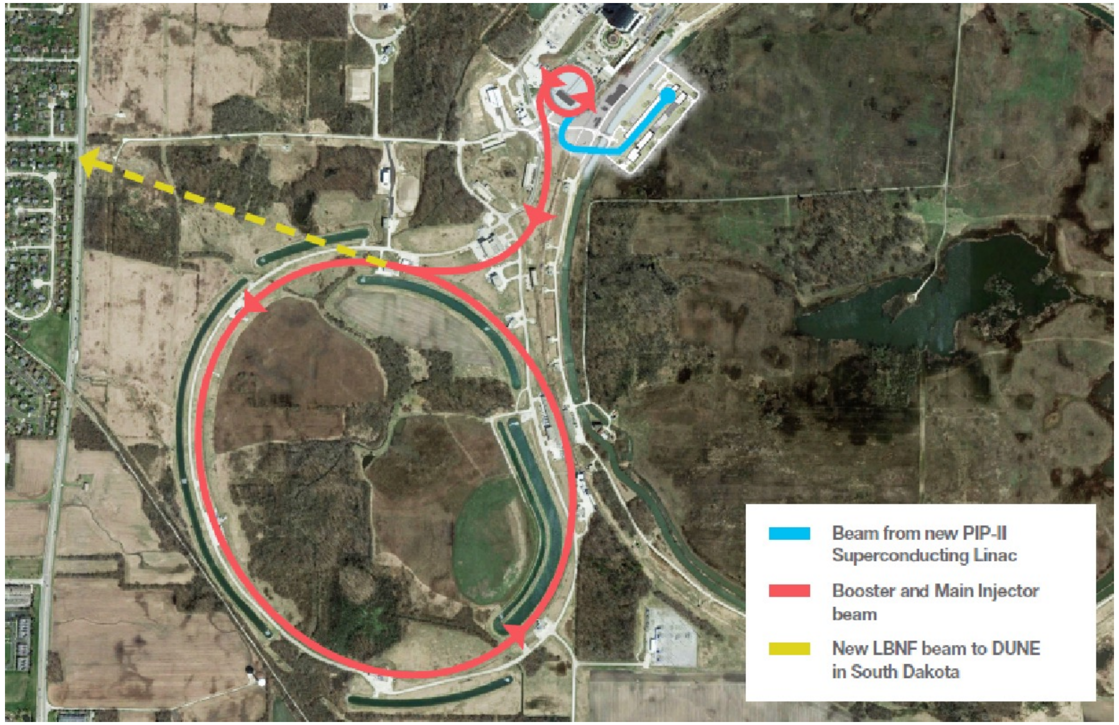
Looks familiar!

Obvious R&D overlaps with Muon Collider (targetry at 1MW, need for compressor/rebunching).

But, no cooling required at AMF.

Accelerator Complex in PIP-II/LBNF Era

- PIP-II Superconducting RF (SRF) Linac will provide beam for injection into existing Booster at 800 MeV.
- Booster cycle time is increased to 20 Hz.
- Proton flux at 8 GeV increases x2: 1.2 MW from Main Injector



The Accelerator Complex Evolution (ACE) is about further improvements on top of this, including:

- Increased power;
- Increased reliability;
- Increased flexibility.

Accelerator Complex Evolution (ACE)

- ACE will extend SRF Linac to higher energy or construct new Rapid Cycling Synchrotron

- Aim is to Provide
  - 2.4 MW to LBNF (x2 improvement);
  - 120 GeV beam for other experiments.

- Also, some potential new science "spigots"
  - 2 GeV Continuous Wave (CW) → *ideal for our muon CLFV Program at AMF!!*
  - 2 GeV Pulsed (~1 MW)
  - 8 GeV Pulsed (~1 MW)

- ***For AMF we would like a beam energy in the 2 GeV range.***

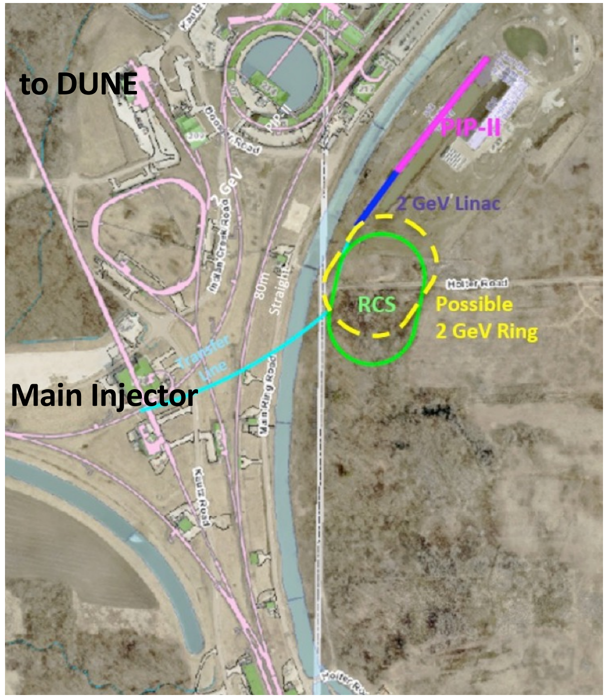
See P5 talk from S. Valishev, https://indico.fnal.gov/event/58272/

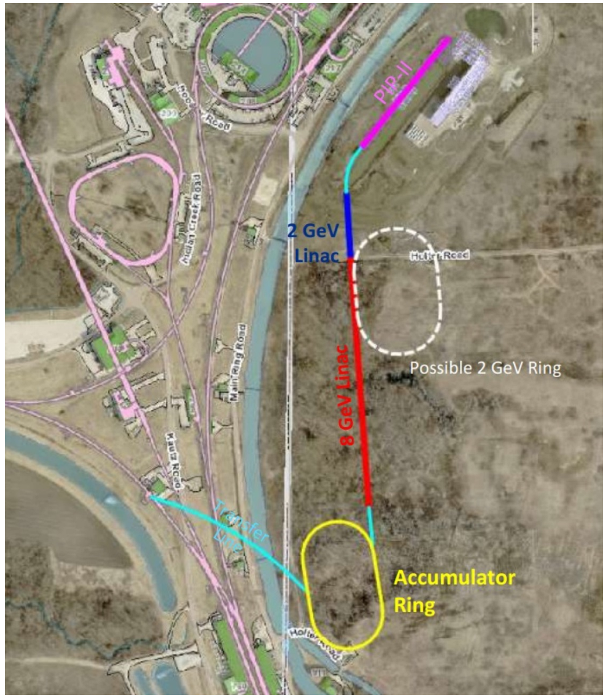
What do ACE Options mean for AMF?

How does AMF fit with ACE options?:

1. PIP-II 2 GeV linac→ rapid cycling synchrotron up to 8 GeV → to Main Injector
   - Potential for 2 GeV ring.
2. PIP-II 2 GeV linac → 8 GeV linac → accumulator ring to store beam → to Main Injector and the 2 GeV ring could provide a muon program.
   - There are several options and tradeoffs.

- **In either scenario a 2GeV ring is possible → should build a future muon program (AMF) in either!**





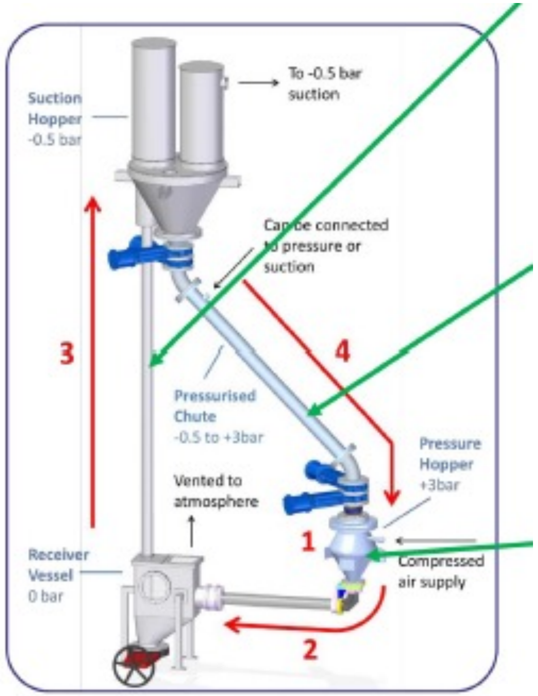
Targetry: 1MW Targeting

- Mu2e uses a cooled tungsten rod target with a 8GeV, 8kW beam.
- AMF has a much more intense environment: ~1GeV, 1MW beam.
  - We will need to re-think our production target design!

- Previous designs for similar complex envisioned a liquid target:
  - **MERIT experiment (possible proof of principle?)**:
    - Liquid mercury - (not an option due to environmental issues);
    - Rep. rates only about 70 Hz, limited by disruption of the jet.

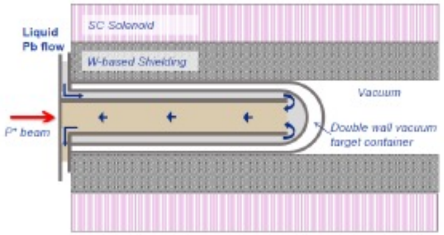
Recent Results from the MERIT Experiment
https://aip.scitation.org/doi/pdf/10.1063/1.3399332

Fluidized Tungsten

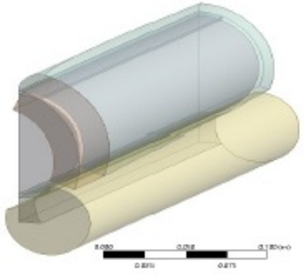


- Mu2e-II: rotating carbon spheres on conveyor (100kW, 800MeV).
- Muon collider at MW: fluidized tungsten, other possibilities…

- **R&D required to design target for the AMF target!**
  - **Exciting synergies with muon collider R&D here.**



Liquid Lead Flow



Lead Curtain

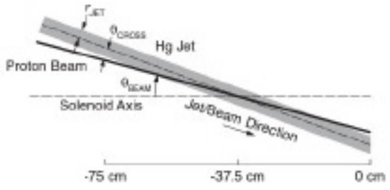


FIG. 3. The mercury jet target geometry. The proton beam and mercury jet cross at $z = -37.5$ cm.

Liquid jet

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$N\mu^- \rightarrow Ne^-$ Conversion Experiment

AMF will be home to multiple CLFV searches: $N\mu^- \rightarrow Ne^-, \mu^+ \rightarrow e^+\gamma$ & $\mu^+ \rightarrow e^+e^+e^-$.

$N\mu^- \rightarrow Ne^-$ will have some technical challenges:

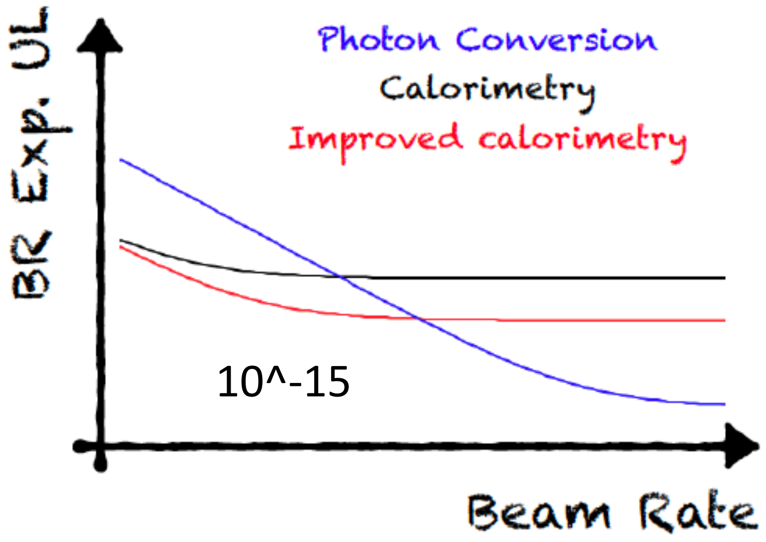
- **Detectors design requires R&D, two main focus points:**
  - **Tracker design: Improving momentum resolution on signal:**
    - Already some benefits to AMF:
      - High Z target: smaller decay fraction (3% in Au compared to 39% in Al)
      - Low central momentum of 20-40MeV/c : thinner target can stop beam → less straggling
    - **Need to rethink detector design - a Mu2e-style straw tube tracker isn't ideal.**
  - **Keeping backgrounds < 1 event:**
    - Need to understand design of active cosmic ray veto.

- **Detector Solenoid also requires some thought and R&D:**
  - The main issue with the detector will be resolution and occupancy. At 100 Hz rep rate, you have a very large number of stopping muons, producing a large number of high-momentum DIOs → detector need to handle this.

Decay Experiments

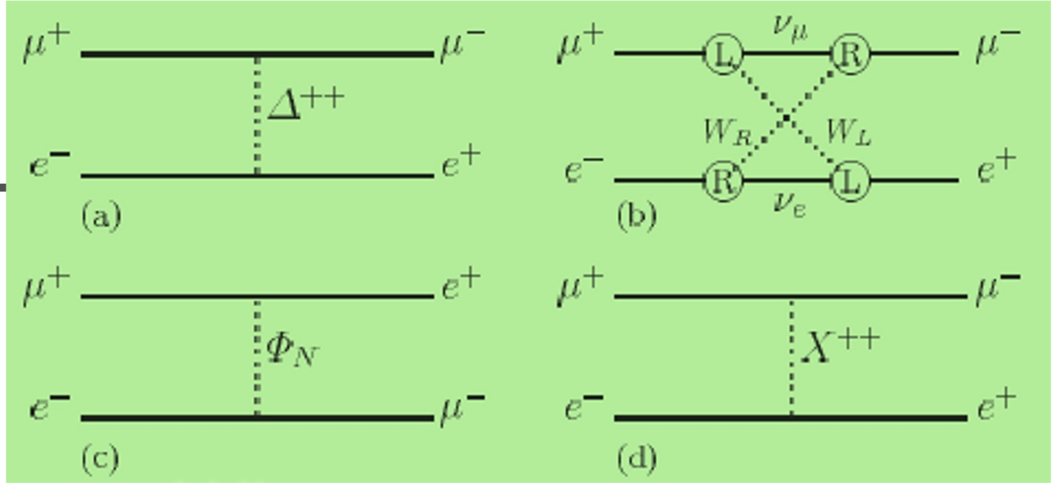
AMF will be home to multiple CLFV searches: $\mu^+ \rightarrow e^+\gamma$ & $\mu^+ \rightarrow e^+e^+e^-$.

- **These experiments require a lower momentum beam which is also advantageous for the conversion experiment.**
  - μ^+ of ~ 30 MeV from pions at rest creating a surface muon beam;
  - $\mu^+ \rightarrow e^+\gamma$: accidental backgrounds come from multiple muon decays and resolution limits → we want as continuous a beam as possible (needs thought)
  - $\mu^+ \rightarrow e^+e^+e^-$: additional backgrounds from radiative muon decay.
- **Detector needs redesigning for $\mu^+ \rightarrow e^+\gamma$.**
  - Pair spectrometer with active converter, All silicon detector, Gaseous detector, Calorimeter with high performance scintillator …
  - To do better than MEG-II we need a new detector concept – exciting R&D! (see F. Renga talk from workshop)



Muonium Oscillations

- **Double CLFV.**
- **Limit set by MACS at PSI: *P*(MM̄) ≤ 8.3 × 10^{-11} (90% C.L.)**



$\mu^+ e^- \leftrightarrow \mu^- e^+$

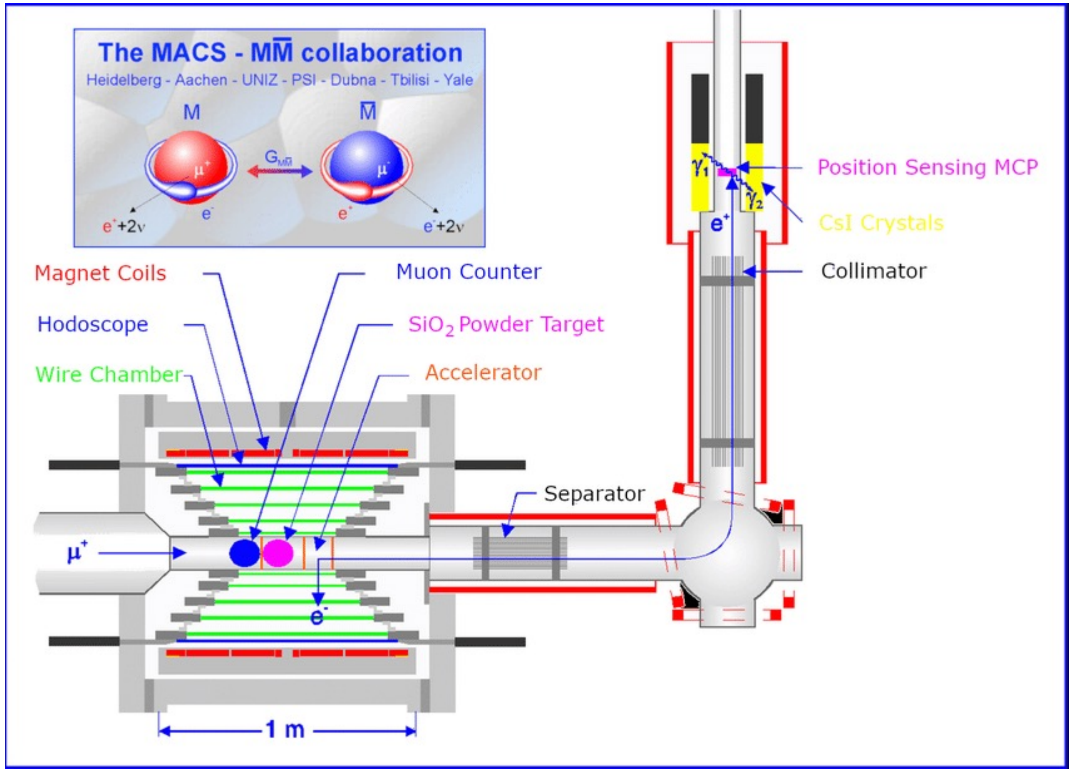
- Lots of new physics: Leptoquarks, doubly charged Higgs, Heavy Majorana neutrinos,...

Signal = μ^- coinciding with an e^+;
Backgrounds = e^+ e^- scattering and rare $\mu^+ \rightarrow e^+ e^+ e^- \nu_e \bar{\nu}_\mu$.

At AMF:

- Both backgrounds can be suppressed with a pulsed beam and waiting out the muon lifetime;
- can make up the muon flux at a hotter beam, which did not exist at the time of MACS;
- An improvement of x100 should be achievable at AMF.

Design of experiment still needs to be finalized!



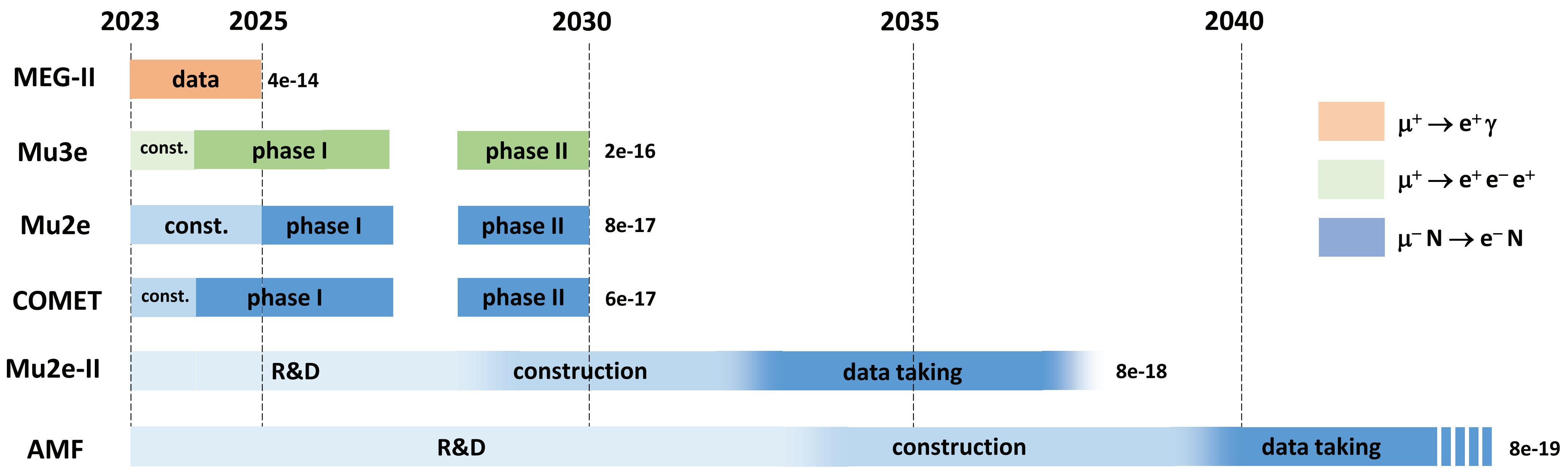
Summary

- AMF is a proposed new facility that would deliver the most intense muon beams in the world. It is a logical extension of the current CLFV muon program.
- R&D program is needed to start now to design a concept and ensure its realization in a timely manner.
- Program could be realized after the completion of Mu2e and operate with LBNF.
- Synergies with other R&D, such as the muon collider and a DM program at FNAL.
- A great opportunity to maximize the physics potential of ACE, and the proposed 2GeV spigot, to do cutting edge research.
- AMF would open a new era in muon physics, and place Fermilab at its center it will enable any science needing high intensity muon beams, this is more than just CLFV experiments.

Thank you for listening!

Any Questions?

Time-line



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Questions

- How does the experiment make use of the ACE beam?
  - Uses 2 GeV Spigot (CW) and Pulsed for muonium-antimuonium oscillations

- Is the experiment uniquely enabled by the ACE upgrades?
  - Having a higher energy (1-3 GeV vs 800 MeV) has some benefits. The Booster Replacement is *not* necessary. The 2 GeV accumulator ring be designed to be the compressor ring required for AMF.

- Can this experiments be performed elsewhere?
  - It is possible that J-PARC could use their RCS and MR but much of what is proposed for AMF would have to be built there. PSI only has a beam at 51 MHz. Although PSI's target is at 1 MW, only about a percent at most is available for the HEP program, so it could do the decay experiments (albeit not as the statistical power of FNAL) but not the conversion experiment.

- What particular accelerator components or capabilities are necessary?
  - compressor for rebunching PIP-II protons, production solenoid and pion production target, FFA for muons that can deliver pulses for conv or "continuous" for decay experiments, then injection/extraction components.

Questions

- What proton energies are needed?
  - 800 MeV to a few GeV

- What proton quantities are needed?
  - $\mathcal{O}(10^{26})$ (SES of 10^{-20} x 10% detector acceptance x $10^{-3}\mu/p$ x 1% transfer efficiencies)

- What time structure is needed? (bunch length, train structure)
  - depends on where you are in the chain. The PIP-II proton source works as a start.

- Can the experiment be performed with 800 MeV protons from PIP-II?
  - Yes. 2-3 GeV is better but this is partly dependent on the Production Solenoid magnetic field. AMF wants to stay below antiproton threshold at 5 GeV if possible.

Questions

- With these sets of parameters, what can be used from Mu2e-II or AMF as R&D for the Muon Collider?

  - Production Solenoid
    - how much are the production solenoid designs similar?
    - what can we learn about targeting?
    - what can we learn about protecting a superconductor
    - are the superconductors for both the same?
  - FFA
    - is there common technology for phase rotation?
    - is a racetrack FFA acceptable for both?
  - Compressor Ring

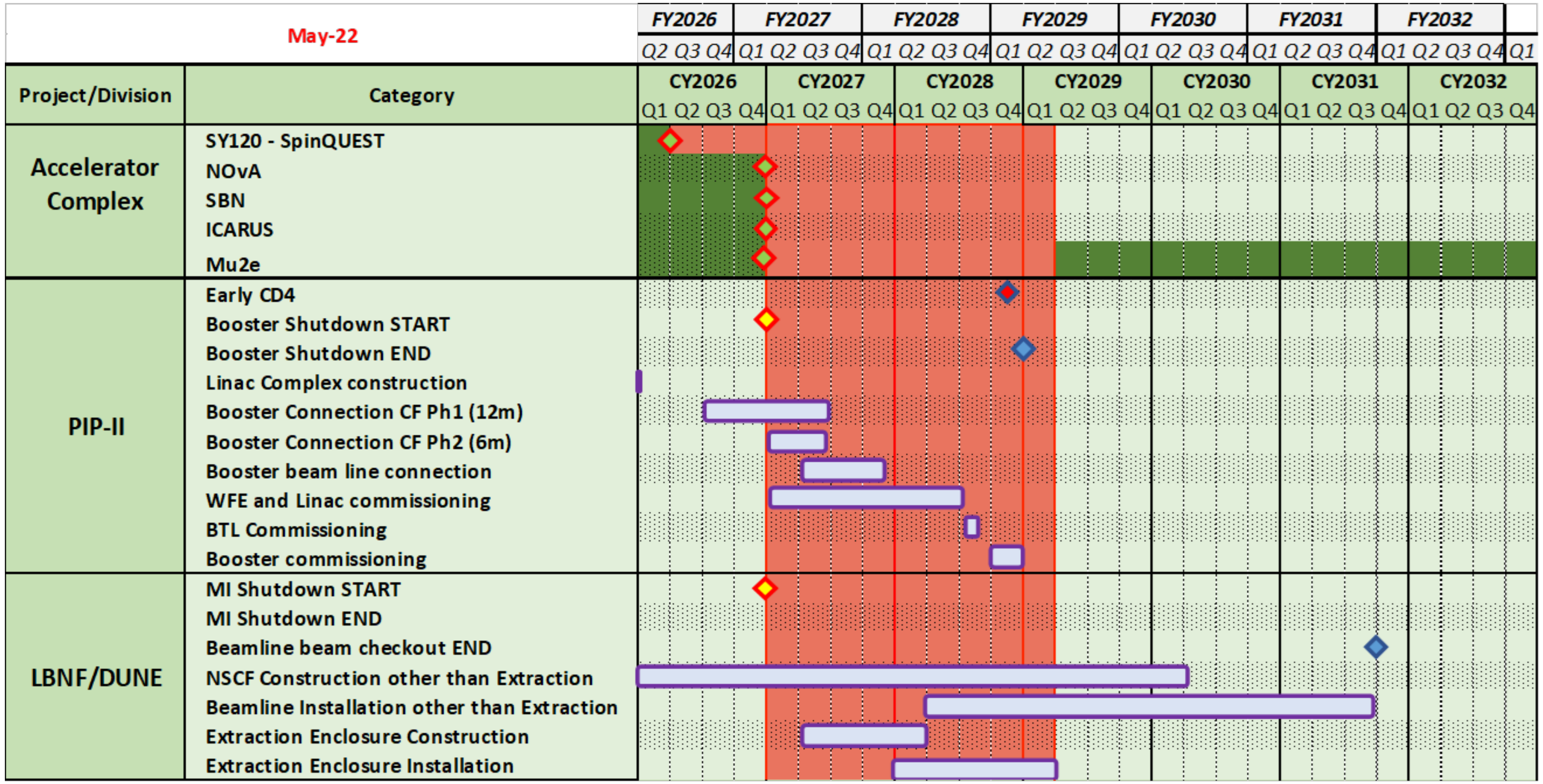
Additional Slides

A few more details…

Main R&D Efforts

- **Production Target:** 1MW Protons in Solenoid – overlaps with Muon collider
- **Compressor:** Understanding requirements of this machine and overlaps with DM program
- **FFA studies:** Need simulation studies and detailed design of the FFA, and understanding of how to inject and extract both charges of muon.
- **Experimental design:**
  - **Conversion experiment:**
    - Understanding requirements of detectors and detector solenoid.
    - Understanding muon stopping target options.
  - **Decay experiments:**
    - Several aspects of re-design already been discussed at PSI.
  - **Other experiments:**
    - Design of experiments such as those for muonium – anti-muonium oscillations.

When Might This Happen?



1st Phase: LBNF/DUNE at 1.2 MW starting in Calendar Year 2027

- **exploring options to take 8 kW to Mu2e starting in CY 2029 until finished; small loss to DUNE during its startup**

2nd Phase: about 10 years after start (> 2040), which is not so far from now!

Random ideas for futuristic μ -> e γ searches

- Active targetry
  - μ/e separation
  - very thin
- Target + detector in vacuum
  - containing the Bragg peak would not be needed anymore (—> thinner target and compensate with more intensity)
  - multiple target option
  - could next-generation straw tubes be a good option for tracking also in μ -> e γ? Too much supporting material? What about silicon detectors (cooling)?
- What about spreading muon stops over a very large surface?
- Stored vs. stopped muons?
- μ -> e γ + μ -> 3e
  - possible in a detector with 2π acceptance in φ
  - give up the low-energy cut of the MEG spectrometer —> higher rate tolerance needed, should be not a problem in a Mu3e-like design

See talk by F. Renga from Muon Workshop

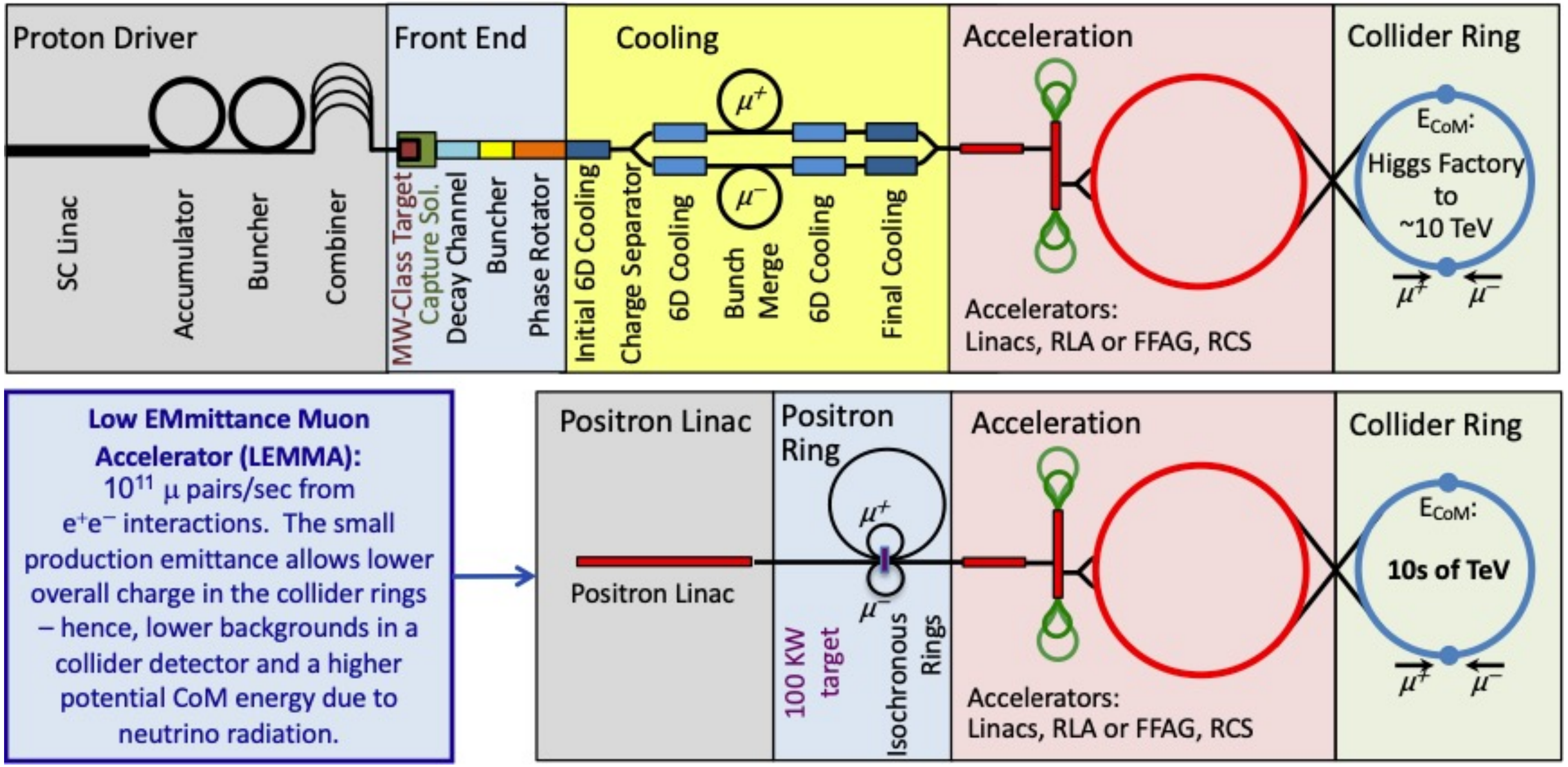
Synergies with Muon Collider R&D?

Parameter	Muon Collider (need to define which one)	AMF
Proton beam energy	8-16 GeV	800 Mev-2 GeV and a compressor ring to re-bunch PIP-II.
Proton beam power	1-4 MW	100kW - 1 MW
Rep Rate (~8Gev beam on target)	5-20 Hz	~20 nsec 2GeV POT
Pulse intensity	40-120 e12 in few 1-3 ns bunches	4e12 ppp in 250 nsec FWHM bunches. Not a critical value, could be shorter but not longer
Production Solenoid Field and Rad levels	20 T; rad levels need to be looked up	5T; rad levels not calculated and require simulations
Muon Frontend		
Muon Cooling Needed? How?	Yes, ionization cooling	no
Muon Acceleration Needed, How?	Yes, early linacs to 60 GeV+ RLA, RCS or FFA…	FFA central momentum 20-30 MeV

Possible synergies:

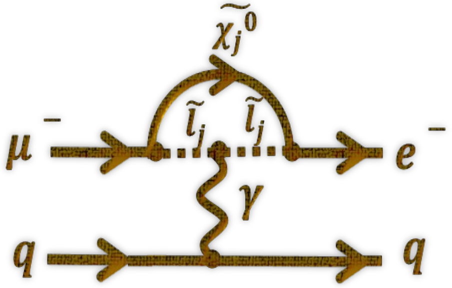
- Targetry : MW protons in solenoid
- Production/capture solenoid designs
- Use of FFAG and compressor (but different specs)

Muon Collider Schematic



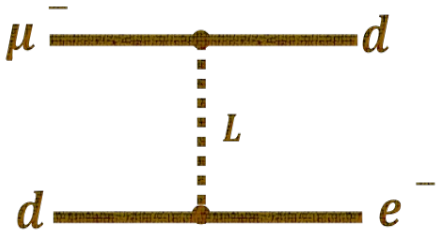
New Physics Scenarios

There are many well-motivated BSM theories which invoke muon CLFV at rates close to current experimental limits i.e. $BF < 10^{-13}$:



SUSY
e.g. L. Calibbi *et al.,* JHEP 1211, 40 (2012).

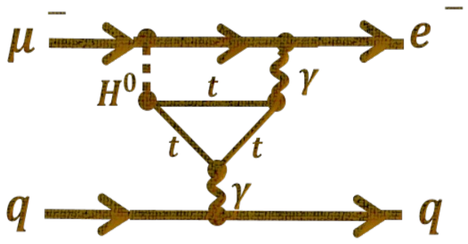
Scalar Leptoquarks
J.M. Arnold *et al.*, Phys. Rev D 88, 035009 (2013).



Muon CLFV channel offer indirect searches for new physics, with sensitivity to lots of models. Even a null result would have big implications!

See-saw models
Nuclear Physics B (Proc. Suppl.) 248–250 (2014) 13–19

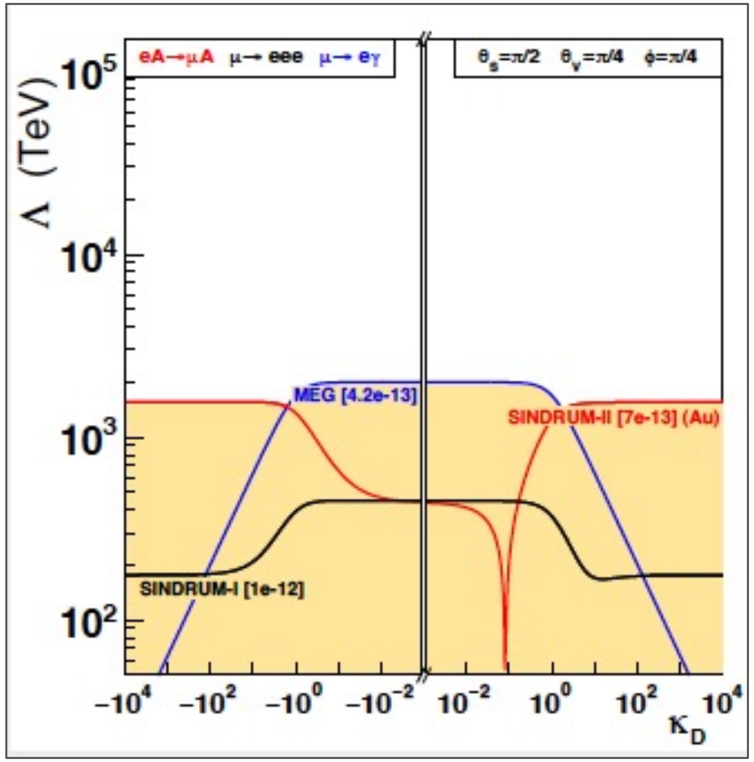
2 Higgs Doublets
C.-H. Lee *et al.*, Phys. ReV D 88, 093010 (2013).



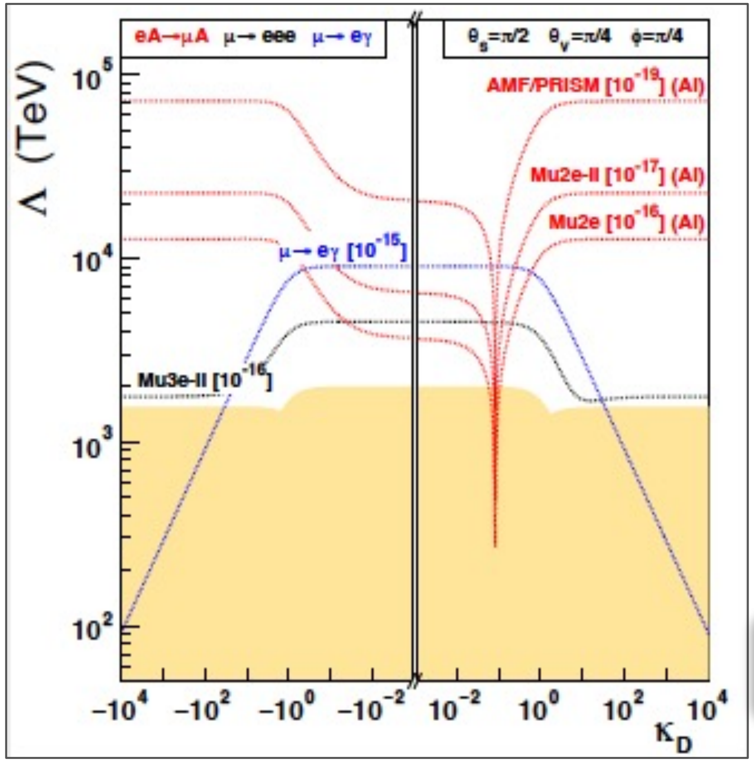
Physics Reach

$$\delta\mathcal{L} = \frac{1}{\Lambda_{LFV}^2}\Big[C_D(m_\mu \bar{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_Re)$$
$$+C_{VR}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Re)$$
$$+C_{VL}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight}$$
$$+C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big] \qquad (2.1)$$

Current Limits



Upcoming & Proposed Projections



High magnitude κ_D= contact-like, closer to zero is dipole-like

Parameterize coefficient space with spherical coordinates *lets you express constraints on all three processes simultaneously.*

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

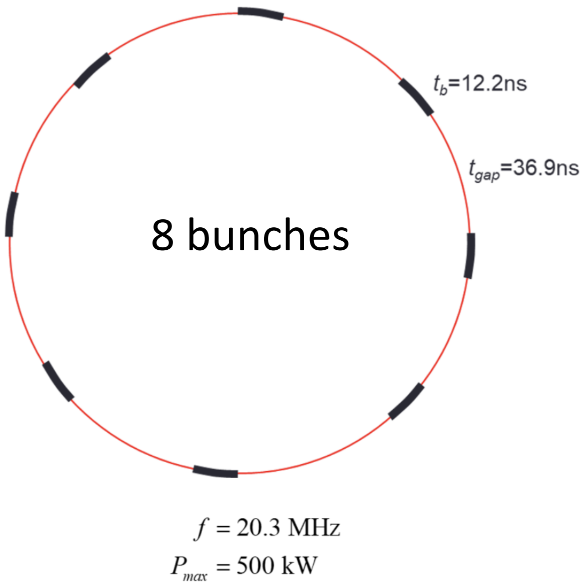
$$\kappa_D = \text{cotan}(\theta_D - \pi/2)$$

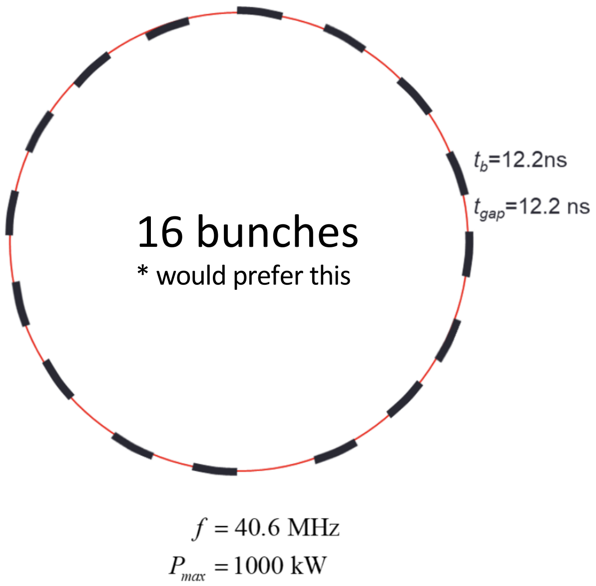
where angle θ_D , parametrizes relative magnitude of dipole and four-fermion coefficients.

AMF: 100m Compressor Scenarios

$$|\Delta\nu_{sc}| = \frac{B n_b N_b r_0}{2\pi\beta\gamma^2\epsilon_N} < \quad \sim 0.2$$

- **Number of bunches** (n_b)
- **Particles per bunch** (N_b)
- **Maximum space charge tune shift** ($|\Delta\nu_{sc}|$)
- **Relativistic βγ factors**
- **Transverse emittance (prop to beam-size squared)** (ϵ_N)





See talk by Eric Prebys for more details.
Also work on going by Jeffrey Eldred on the C-PAR ring

→ Space charge tune shift can be mitigated by keeping the circumference of the ring as small as possible.
But some challenges associated with 1MW, 100m design specifically how to extract/inject at this rate.

Other designs been thought about!

Dark Matter Program

- There are synergies with possible accelerator based dark matter program at FNAL:
  - Compressor ring could be used to re-bunch the PIP-II beam for an accelerator-based dark matter experiment.
  - This experiment needs a higher-intensity, lower repetition rate beam than that envisioned for AMF.
  - Potential operating modes, under the assumption of a 100 m circumference 0.8 GeV ring:

Description	Protons per pulse	Pulse Spacing (ns)	Repetition Rate (Hz)
AMF	7.8×10^{13}	24	100
Dark Matter	6.2×10^{14}	196	100

- ***The construction of a suitable compressor ring would position Fermilab to build a world-class physics program in two significant efforts in the Rare and Precision Frontier.***

$N\mu^- \rightarrow Ne^-$: The Mu2e Experiment

Production Solenoid:

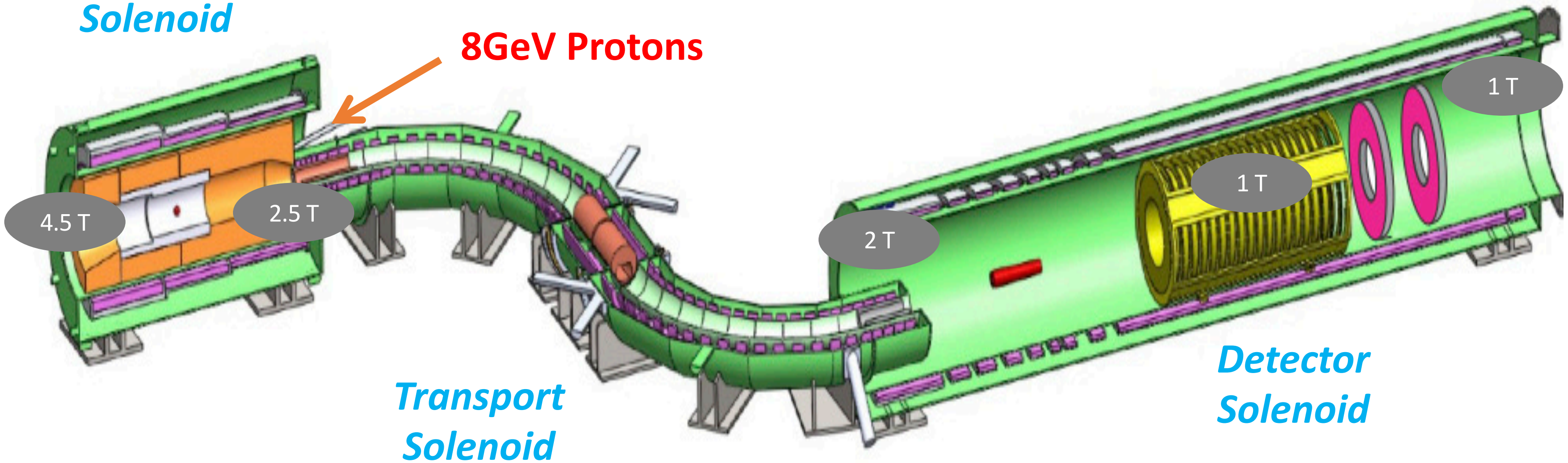
- 8 GeV Protons enter, pions produced, decay to muons.
- Graded magnetic field reflects pions/muons to transport solenoid.

Transport Solenoid:

- "S" shape removes line of sight backgrounds.
- Collimators select low. momentum, negative.

Detector Solenoid:

- Al Stopping Target made of thin foils captures the muons.
- Detectors include straw tube tracker to measure momentum.
- Graded magnetic field reflects backwards going particles.



2026 – 27 Run-I:

- 1.2×10^{-15} 5σ discovery,
- Single-Event-Sensitivity = 2.4×10^{-16}
- U.L : 6.2×10^{-16} (90% C.L.)
  - **1000 x current limit.**
  - **Universe 2023, 9, 54.**

Total (Run-I + Run-II) end-goal:

- Single-Event-Sensitivity = 3×10^{-17}
  - **10000 x current limit.**

$N\mu^- \rightarrow Ne^-$: Removing Backgrounds

Beam delivery and detector systems optimized for high intensity, pure muon beam – must be "background free":

- **Intrinsic :**
  - Scale with number of stopped muons.
- **Late arriving :**
  - Scale with number of late protons/ extinction performance

Type	Source	Mitigation	Yield (for Run-I only)*
Intrinsic	**Decay in Orbit (DIO)**	**Tracker Design/ Resolution**	**0.038 ± 0.002 (stat) $\pm$ 0.001 (sys)**
Beam Backgrounds	**Pion Capture**	**Beam Structure /Extinction**	**(in time) $0.010 \pm 0.002\ (\text{stat})^{+0.001}_{-0.003}$ (sys) (out time) ($1.2 \pm 0.001\ (\text{stat})^{+0.1}_{-0.3}$ (sys)) x 10^{-3}**
Cosmics	**Cosmic Rays**	**Active Veto System**	**0.046 ± 0.010(stat) $\pm$ 0.009 (sys)**

* assumes signal region of 103.6 < p < 104.9 MeV/c and 640 < t < 1650 ns

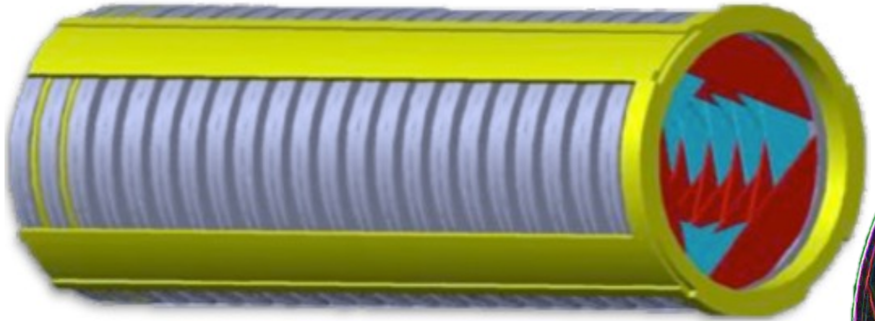
Run-I Sensitivity of Mu2e:
Universe 2023, 9, 54.

$N\mu^- \rightarrow Ne^-$: Removing Backgrounds

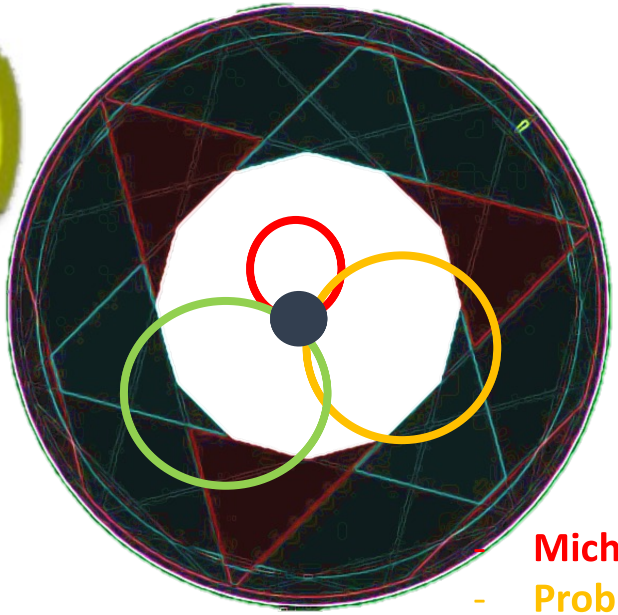
- **Intrinsic :**
  - Scale with number of stopped muons.

Type	Source	Mitigation	Yield (for Run-I only)*
Intrinsic	**Decay in Orbit (DIO)**	**Tracker Design/ Resolution**	**0.038 ± 0.002 (stat) $\pm$ 0.01 (sys)**

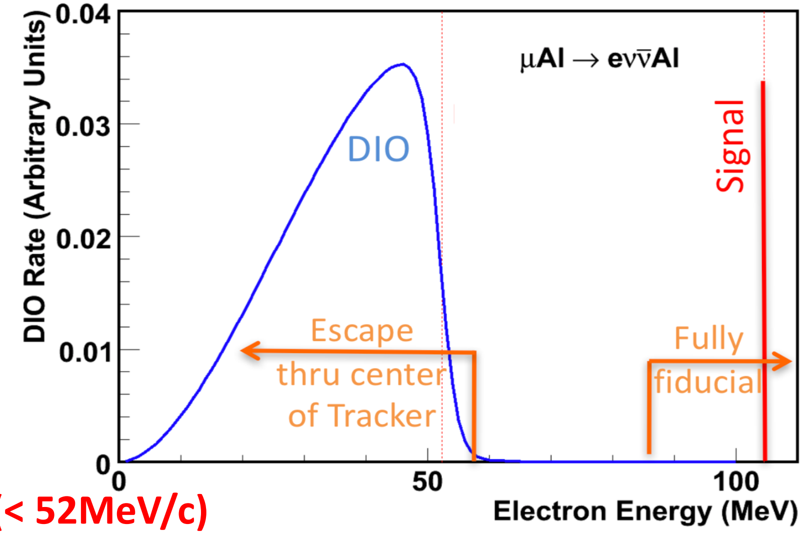
- Annular tracker: Removes > 97% of DIO.
- Low mass design, momentum resolution removes the rest.



Thin straws, arranged in planes



- **Michel Electron (< 52MeV/c)**
- **Problematic Tail (>100MeV/c)**
- **Signal (105MeV/c)**

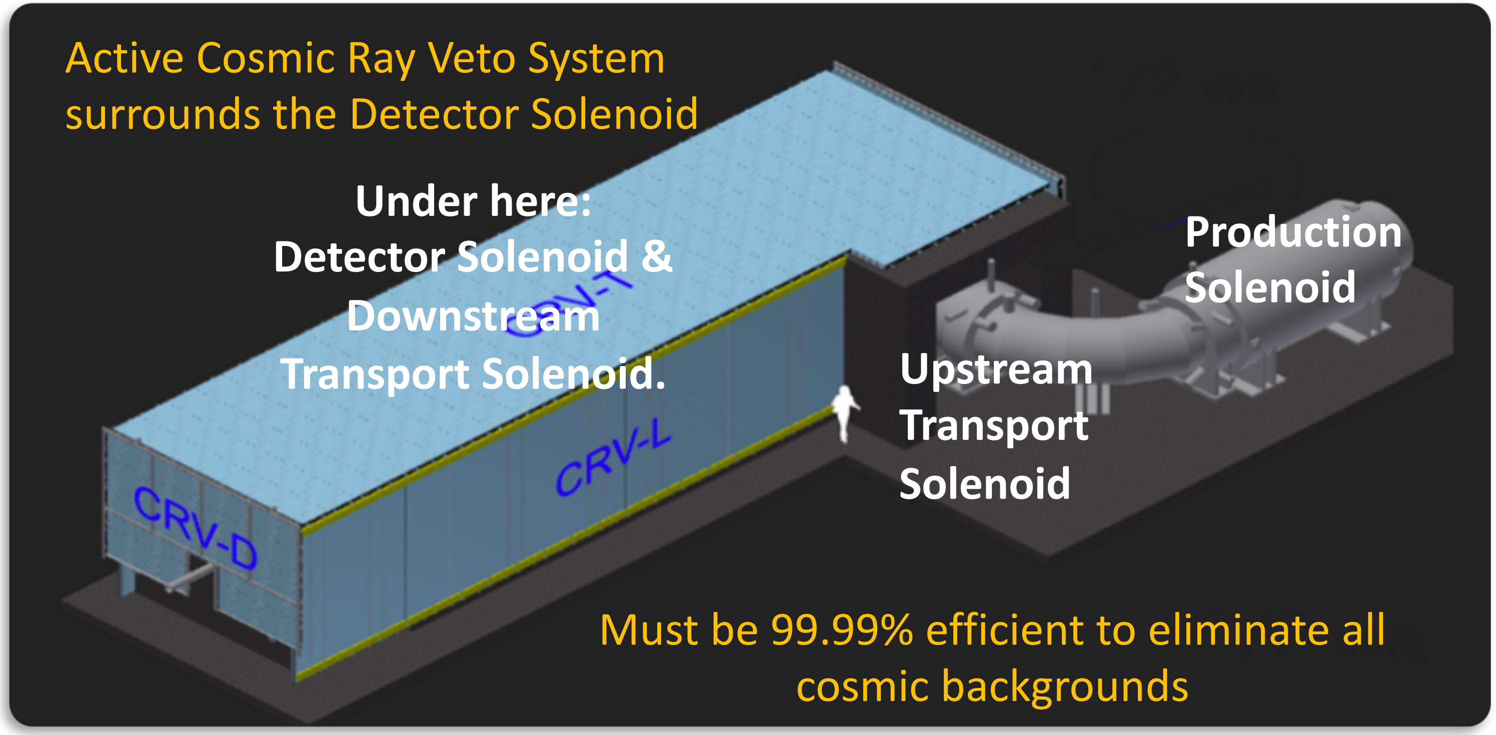


Run-I Sensitivity of Mu2e:
Universe 2023, 9, 54.

$N\mu^- \rightarrow Ne^-$: Removing Backgrounds

Type	Source	Mitigation	Yield (for Run-I only)*
Cosmic	Cosmic Rays	Active Veto System	0.046 ± 0.010(stat) ± 0.009 (sys)

Passive shielding plus an active Cosmic Ray Veto system is key to eliminating cosmic backgrounds.

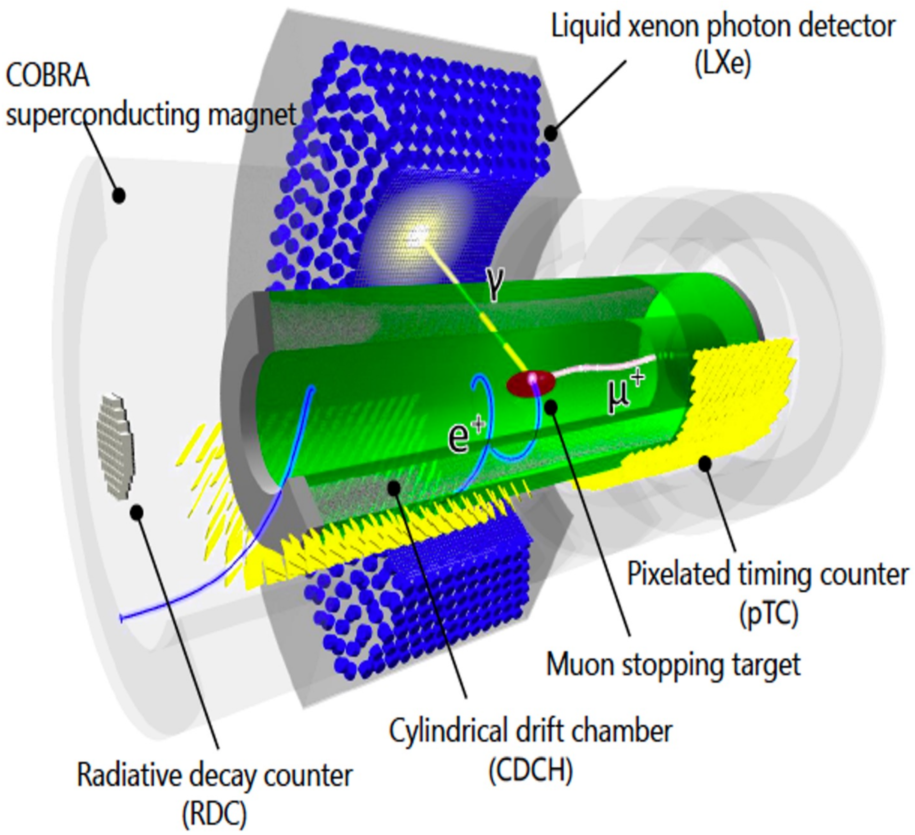


$\mu^+ \to e^+\gamma$: The MEG-II Experiment

Universe 2021, 7, 466

Design:

- Based at PSI, beam delivers 1 x 10^8 μ^+/s.
- μ^+ stopped on thin plastic target - decay at rest to exploit the two-body kinematics.
- Target located at the center of a magnetic spectrometer used to track the candidate positron.
- LXe photon detector measures the timing, energy and the conversion position of the photon.



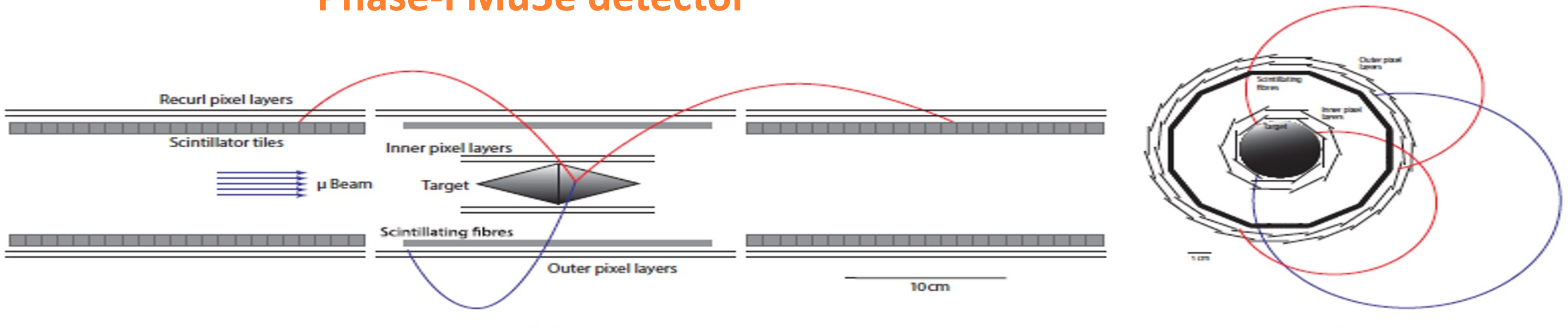
Two sources of background:

- **Irreducible:** Radiative muon decay $\mu^+ \to e^+\nu\bar{\nu}\gamma$.
- **Coincidental:** Ordinary muon decay $\mu^+ \to e^+ \nu\bar{\nu}$.

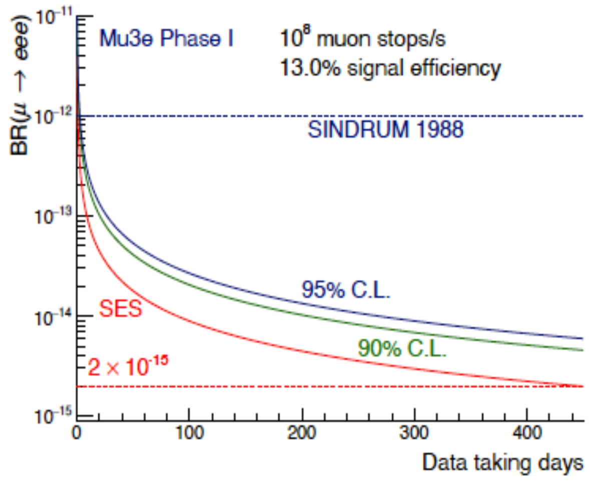
- **Status:**
  - First engineering run with the full detectors completed.
  - Taking physics data soon, so expect a new measurement soon.

$\mu^+ \rightarrow e^+e^+e^-$: The Mu3e Experiment

Phase-I Mu3e detector



(a) (b)



- High tracker occupancy requires excellent timing to select hits belonging to the same track.
- Hollow double cone target made of thin aluminum: large target area spreads out decay vertices and reduces accidental backgrounds.
- Rest of detector geometry is optimized for momentum resolution:
  1. **Low material budget minimizes multiple scattering**.
  2. **Sub-ns timing resolution**: 4 layers of HVMAPS silicon pixel sensors thinned to 50 μm, and scintillating fibre and tile detectors.

$N\mu^- \rightarrow Ne^-$ Tracker Design Options

- **Tracker must have good momentum resolution (< 200keV/c in Mu2e) to distinguish decay backgrounds from conversions.**
- **"Pure muon beam":** still need to handle DIO, cosmics and secondary particles produced from muon captures. High Z target helps here too.
- **"Cold beam":** use thinner stopping target to stop muons to reduce energy loss in target material - improves momentum resolutions.

	Straw tube tracker	Multi-wire proportional chamber	Gas Electron Multiplier (GEM)	New Tech.
pros	• Highly segmented; • Good intrinsic mom. Resolution; • Same as Mu2e.	• Low mass – He?; • One large gas volume; • Easy to make; • Plenty of experience.	• Easy to construct; • Variable geometry; • One large gas volume.	See "Novel sensors for Particle Tracking" Snowmass contribution arXiv:2202.11828.
cons	• Many small gas volumes and surface → leaks; • Hard to manufacture.	• Less segmented than straw design.	• Limited experience on hand; • Intrinsic mass (?)	• R&D required.