Future charged lepton flavor violation muon program

Mete Yucel
Lepton-Photon
Melbourne, July-2023

Advanced Muon Facility(AMF)

- AMF is a proposed muon facility to feed next generation of precision muon experiments.
  - Powered by intense muon beams future Fermilab accelerator projects PIP-II and ACE provide.
  - Hosts multiple CLFV muon experiments that would enable future physics discoveries.
  - R&D bed for leading edge accelerator and detector technology.
- AMF is planned for 2040s and there is strong interest!

Snowmass LOI

A New Charged Lepton Flavor Violation Program at Fermilab

M. Aoki,[1] R. B. Appleby,[2,3] M. Aslaninejad,[4] R. Barlow,[5] R.H. Bernstein,[6] C. Bloise,[7] L. Calibbi,[8] F. Cervelli,[9] R. Culbertson,[6] André Luiz de Gouvêa,[10] S. Di Falco,[9] E. Diociaiuti,[7] S. Donati,[9] R. Donghia,[7] B. Echenard,[11] A. Gaponenko,[6] S. Giovannella,[7] C. Group,[12] F. Happacher,[7] M. T. Hedges,[13] D.G. Hitlin,[11] E. Hungerford,[14] C. Johnstone,[6] D. M. Kaplan,[15] M. Kargiantoulakis,[6] D. J. Kelliher,[16] K. Kirch,[17] A. Knecht,[18] Y. Kuno,[1,19] A. Kurup,[20] J.-B. Lagrange,[16] M. Lancaster,[21] K. Long,[20] A. Luca,[6] K. Lynch,[22] S. Machida,[16] M. Martini,[23,*] S. Middleton,[11] S. Mihara,[24] J. Miller,[25] S. Miscetti,[7] L. Morescalchi,[9] Y. Mori,[26] P. Murat,[6] B. Muratori,[27,3] D. Neuffer,[6] A. Papa,[9] J. Pasternak,[20] E. Pedreschi,[9] G. Pezzullo,[28] T. Planche,[29] F. Porter,[11] E. Prebys,[30] C. R. Prior,[16] V. Pronskikh,[6] R. Ray,[6] F. Renga,[31] C. Rogers,[16] I. Sarra,[7] A. Sato,[1] S. L. Smith,[27,3] F. Spinella,[9] D. Stratakis,[6] M. Syphers,[32] N.M. Truong,[30] S. Tygier,[2,3] Y. Uchida,[20] and M. Yucel[6]

Link to arxiv

AMF workshop 2023

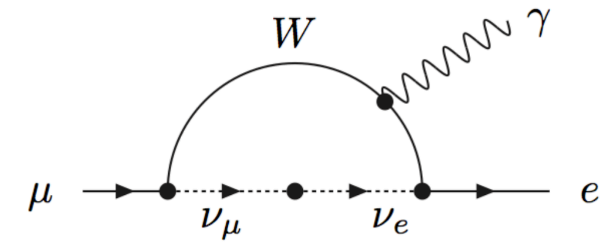
	PIP-II	269, Lauristen	David Neuffer	13:30 - 13:45
	Calorimeter	269, Lauristen	Ivano Sarra et al.	13:45 - 14:00
14:00	Trigger and DAQ	269, Lauristen	Gianantonio Pezzullo	14:00 - 14:15
	Magnets	269, Lauristen	Karie Badgley	14:15 - 14:30
	Cosmic ray veto (CRV)	269, Lauristen	Simon Corrodi	14:30 - 14:45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

Link to indico

CLFV Program

Current experiments searching muon sector of CLFV;

Experiment	.	*Process*	*Sensitivity*
MEG II	*PSI*	$\mu^+ \to e^+ + \gamma$	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*	$\mu^+ \to e^+ + e^+ + e^-$	$10^{-14} - 10^{-16}$
MACE(prpsd.)	*PSI*	$\mu^+ + e^- \to \mu^- + e^+$	$\sim 10^{-15}$



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

Heavily suppressed in SM, perfect for searching new physics !!!

- CLFV is NP!
  - If found we should study models.
- AMF aims to do all three.
  - Different models are sensitive to different channels.
  - In addition muonium-antimuonium experiment is also planned.
- World leading muon program thanks to beam powered by PIP-II and ACE.

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$^{*\,\dagger}$	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05 - 0.5$	$2 - 20$

Lorenzo Calibbi, Giovanni Signorelli.

CLFV Program

Experiment	.	Process	Sensitivity
MEG II	*PSI*	$\mu^+ \rightarrow e^+ + \gamma$	4.2×10^{-14}
Mu2e	*FNAL*	$\mu^- + N \rightarrow e^- + N$	6.0×10^{-17}
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See talks by

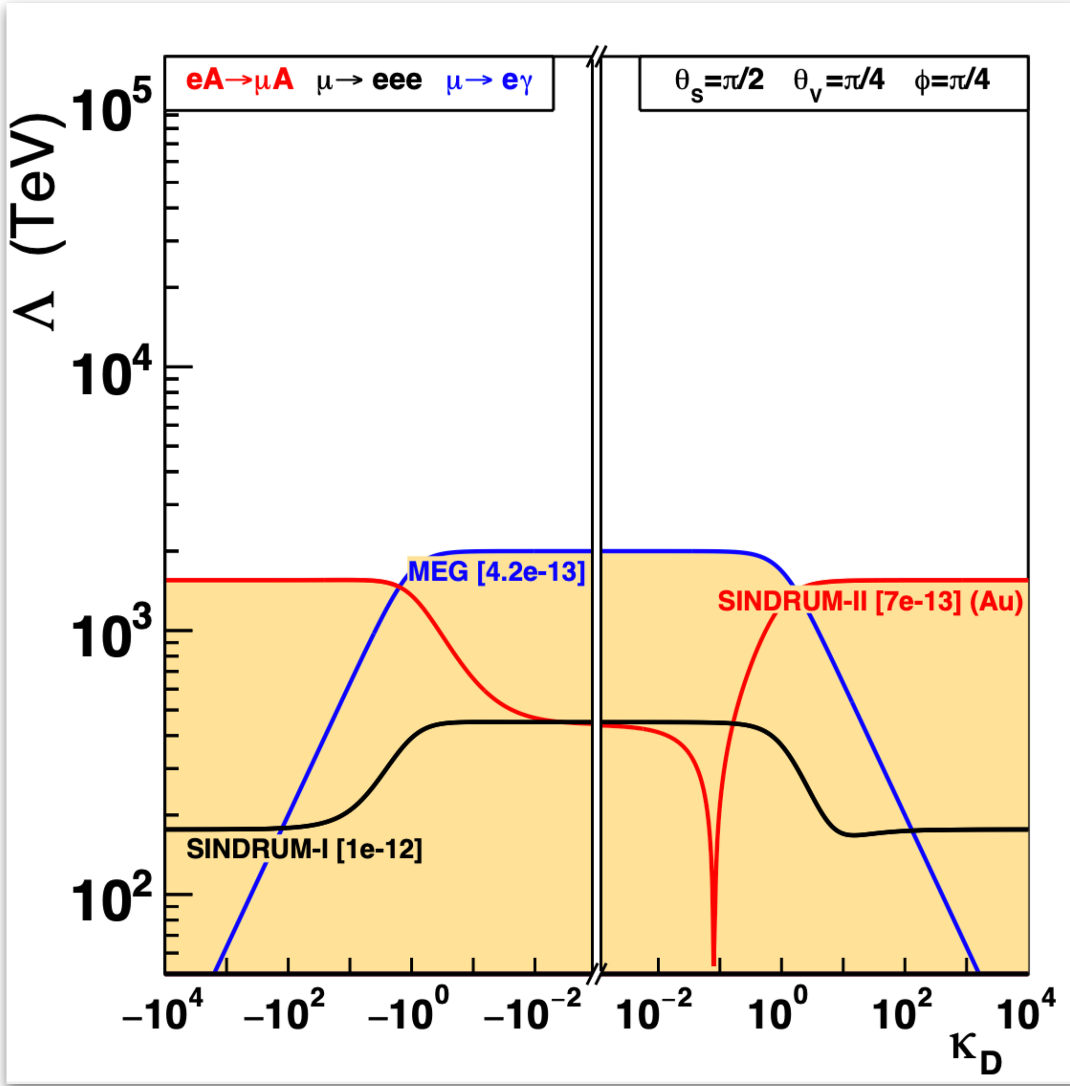
Angela Papa

Kenneth Heller

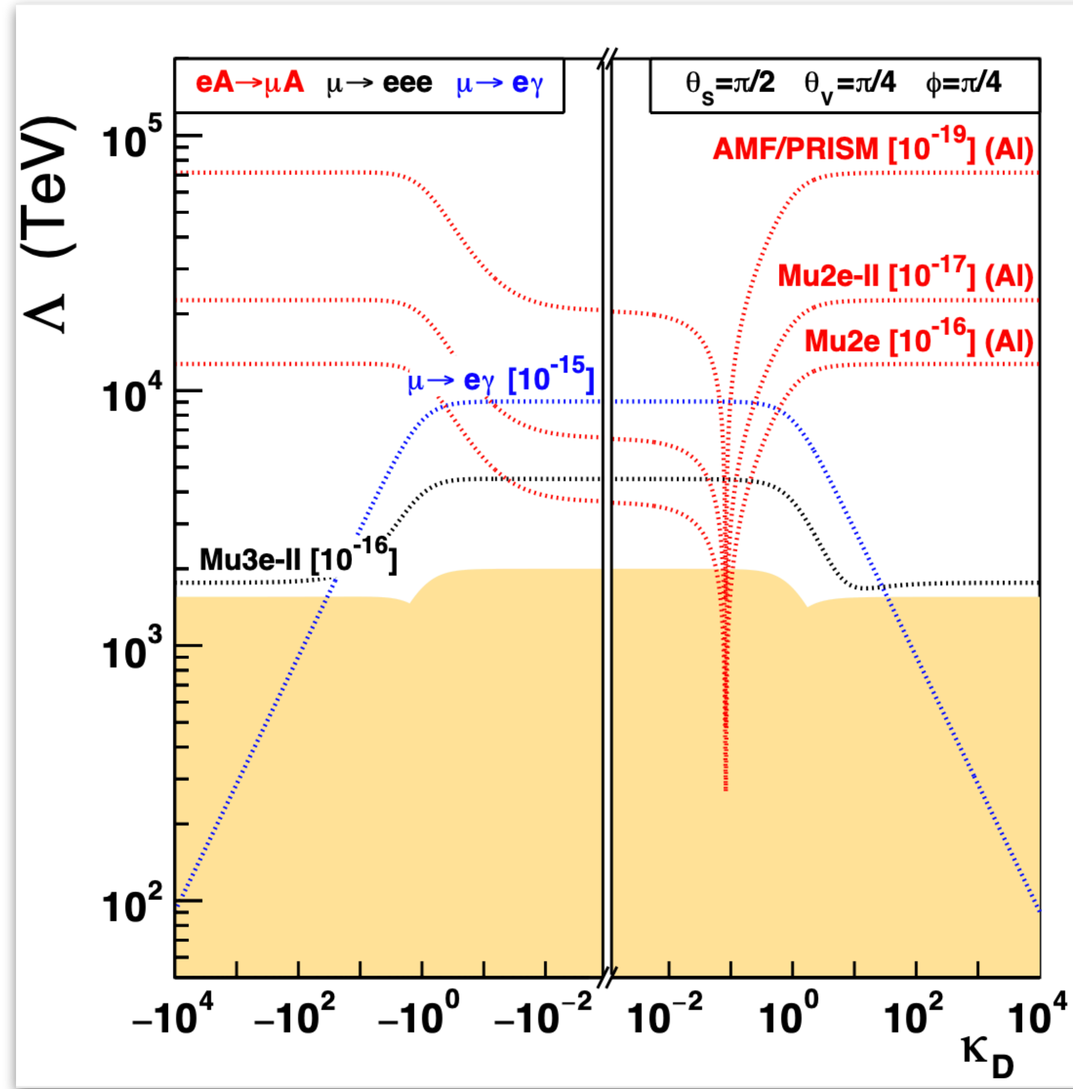
Hajime Nishiguchi

Physics reach

Current Limits



AMF Projections



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

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

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

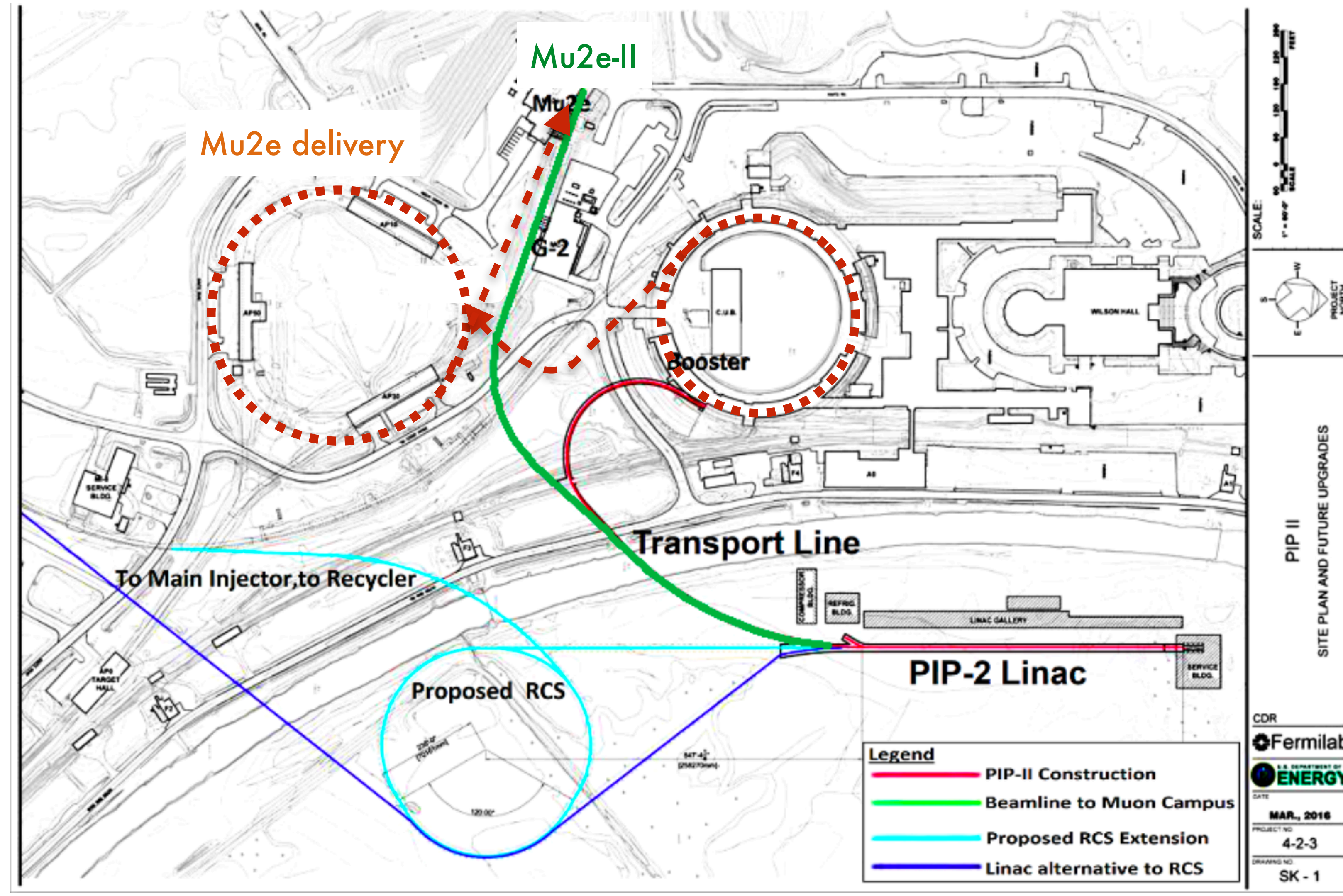
θ_D parametrizes relative Magnitude of dipole and four-fermion coefficients.

Design Goals

- 1MW beam delivery.
- 10 ns pulse length at 100 Hz.
- Have $\times$100-1000 improvement over previous experiments with intense μ^-, μ^+beams and reduced backgrounds.
- Run μ^-, μ^+ at the same time.
- Run decay, conversion and muonium experiments at the same time.

Capitalize on the new beam lines

PIP-II

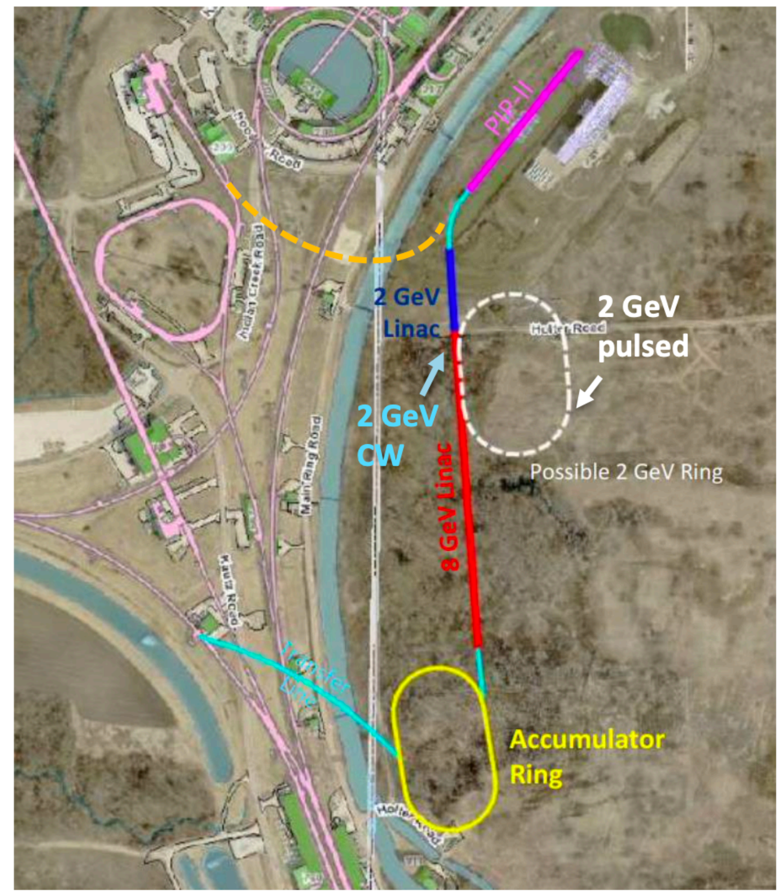


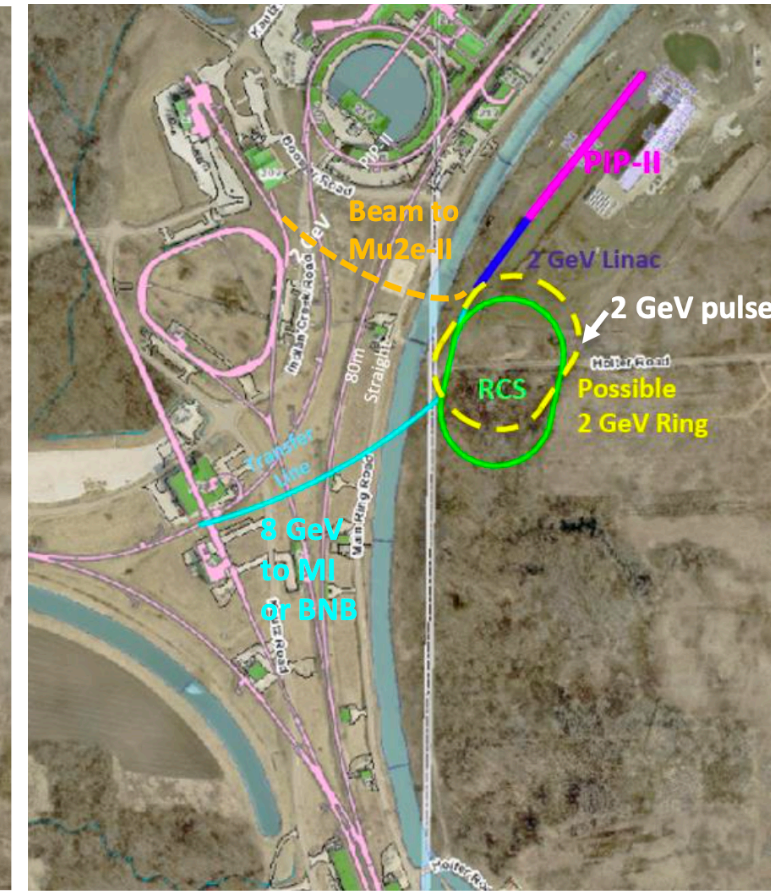
- Proton improvement plan;
  - SRF LINAC producing 800 MeV H^- instead of 400 MeV.
  - Increased proton beam intensity at 8 GeV for 1.2 MW.
  - Increased booster cycle from 15 kHz to 20 kHz.
- Use cases;
  - High energy programs(LBNF/DUNE);
    - 0.55 ms @ 20 Hz into the booster.
    - 1% of the beam is actually used.
  - Rest of the beam;
    - ???
    - We could split the beam and supply different experiments.
    - At first stage PIP-II will feed Mu2e-II.

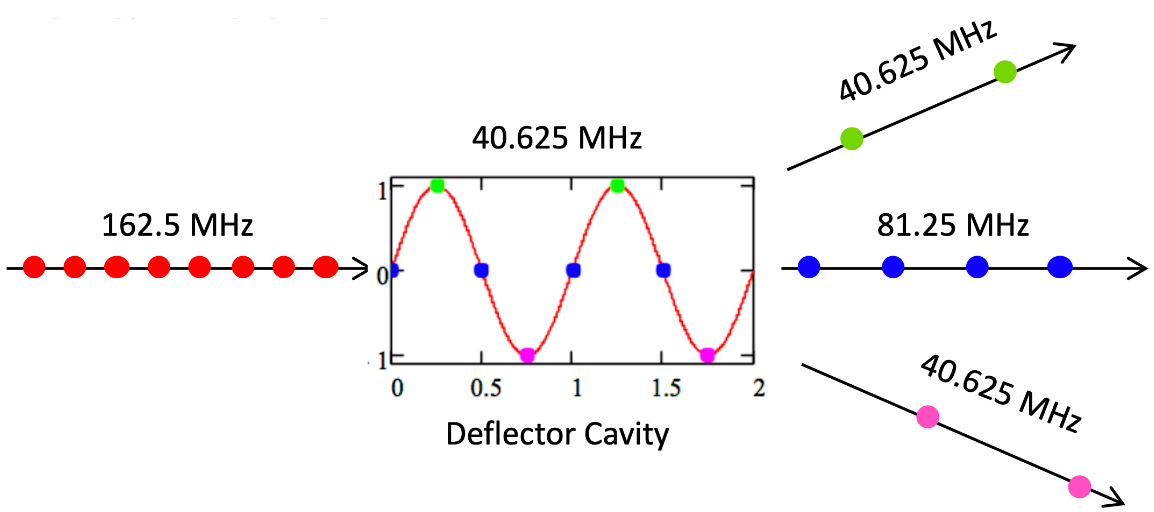
Parameter	Mu2e	Mu2e-II
Proton source	Slow extraction from DR	PIP-II Linac
Proton kinetic energy	8 GeV	0.8 GeV
Beam Power for expt.	8 kW	100 kW
Protons/s	6.25×10^{12}	7.8×10^{14}
Pulse Cycle Length	1.693 μs	1.693 μs
Proton rms emittance	2.7	0.25
Proton geometric emittance	0.29	0.16
Proton Energy Spread (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}

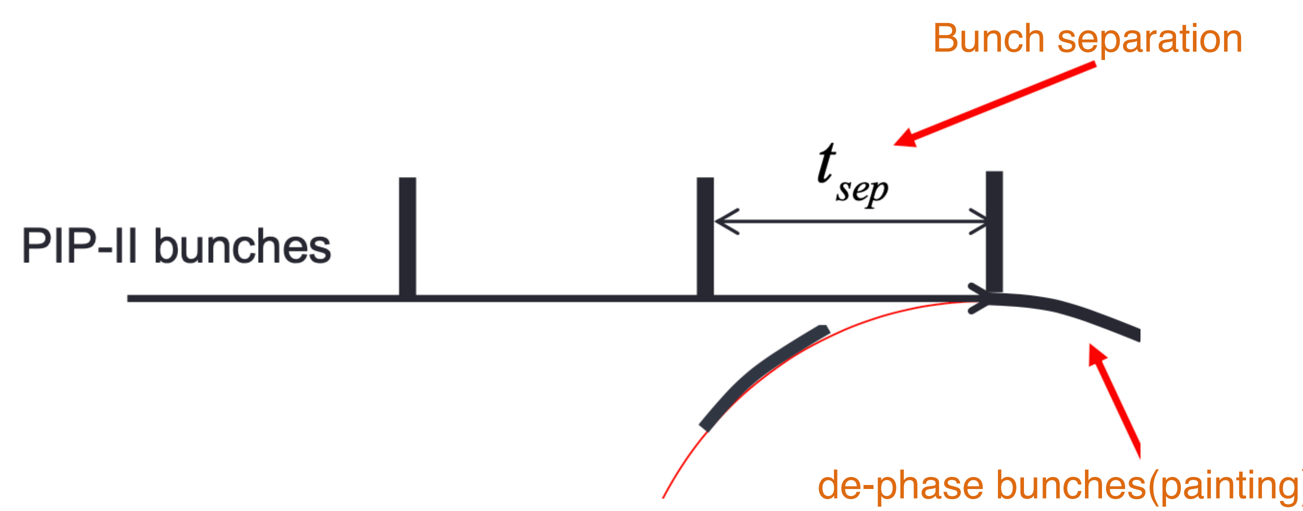
Accelerator Evolution(ACE) formerly known as PIP-III

- 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.



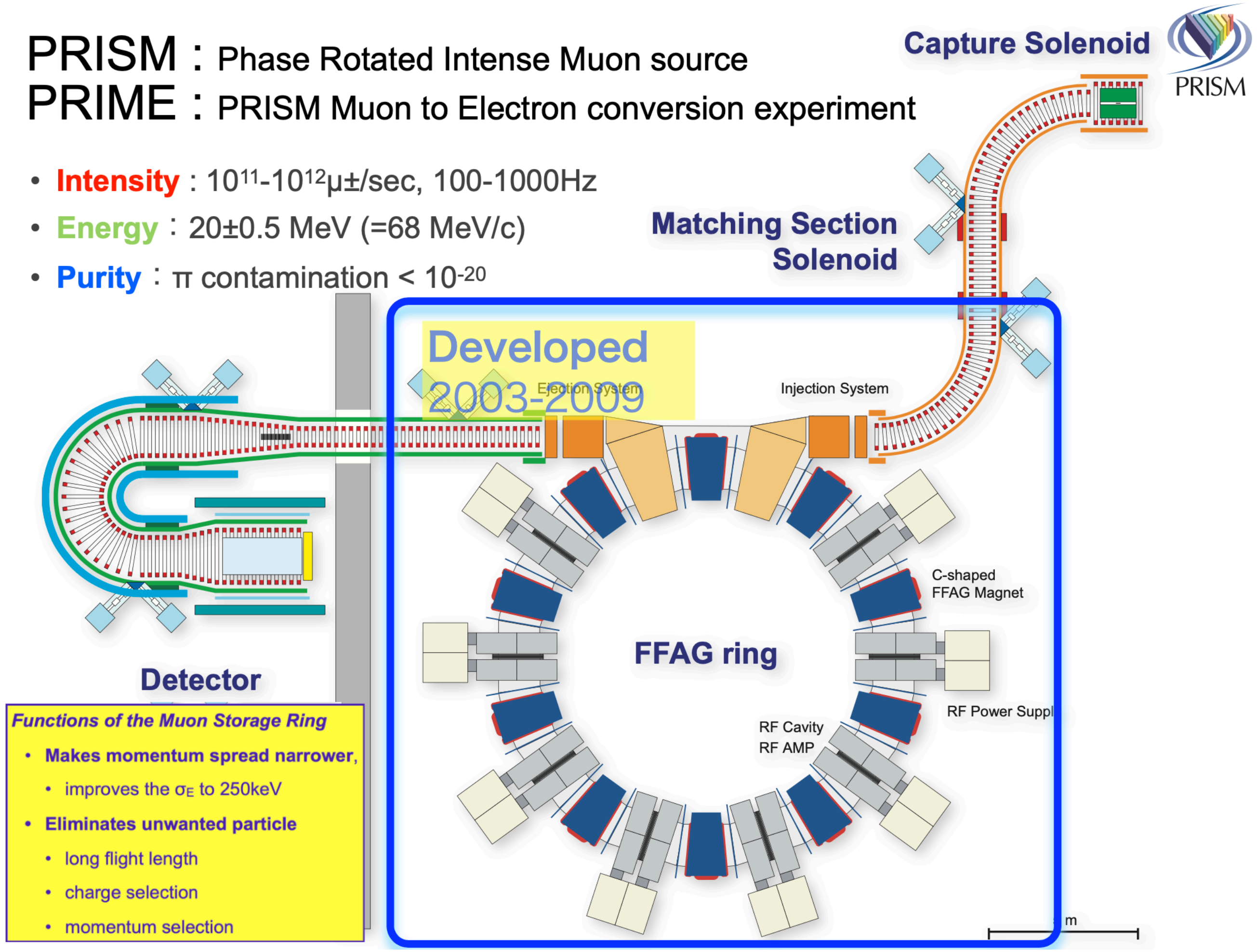




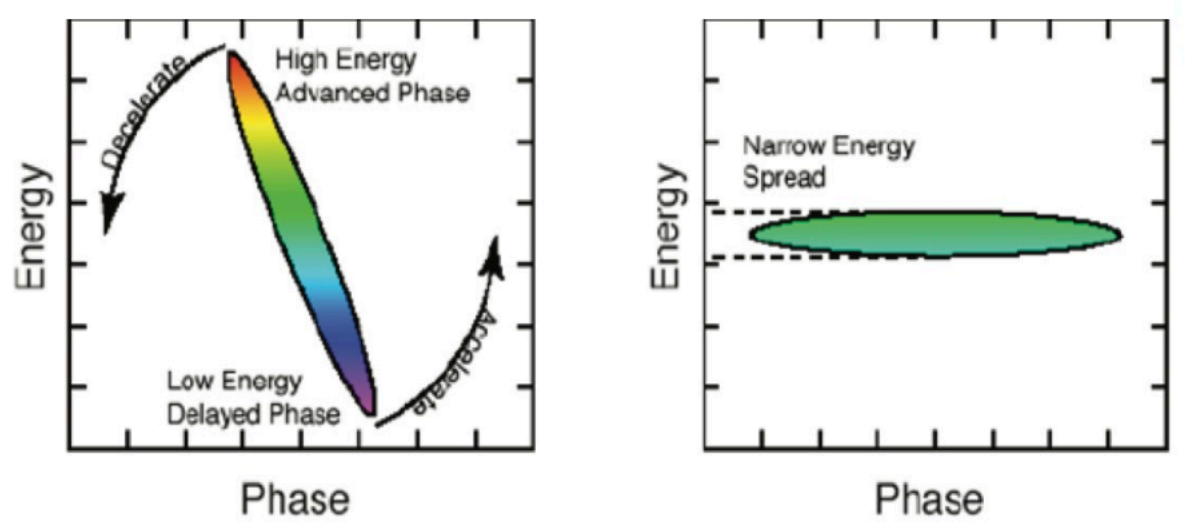


FFA and PRISM

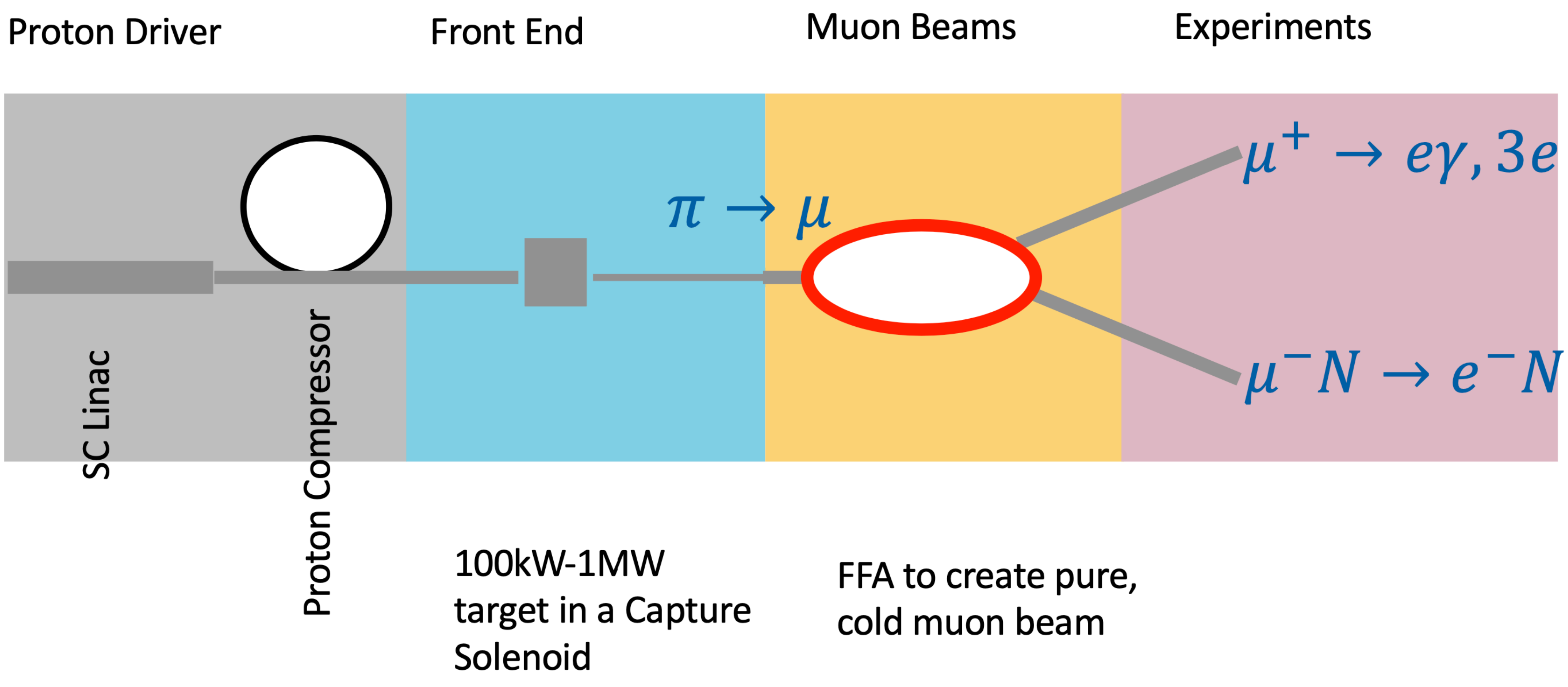
- Fixed Field Alternating Gradient(FFA);
  - Should produce monochromatic muons around 20-40 MeV with varying phase.
  - Acts as a muon storage ring.
  - Eliminates decay background from pions and beam related backgrounds.
    - Allows for high Z stopping targets for conversion experiments.
    - Perfect for decay experiments.
  - Demonstrated at Osaka in 2010.
- Technical challenges;
  - Can't be supplied as is from PIP-II.
  - Need to determine design to feed multiple experiments at the same time.



Akira Sato, AMF Workshop

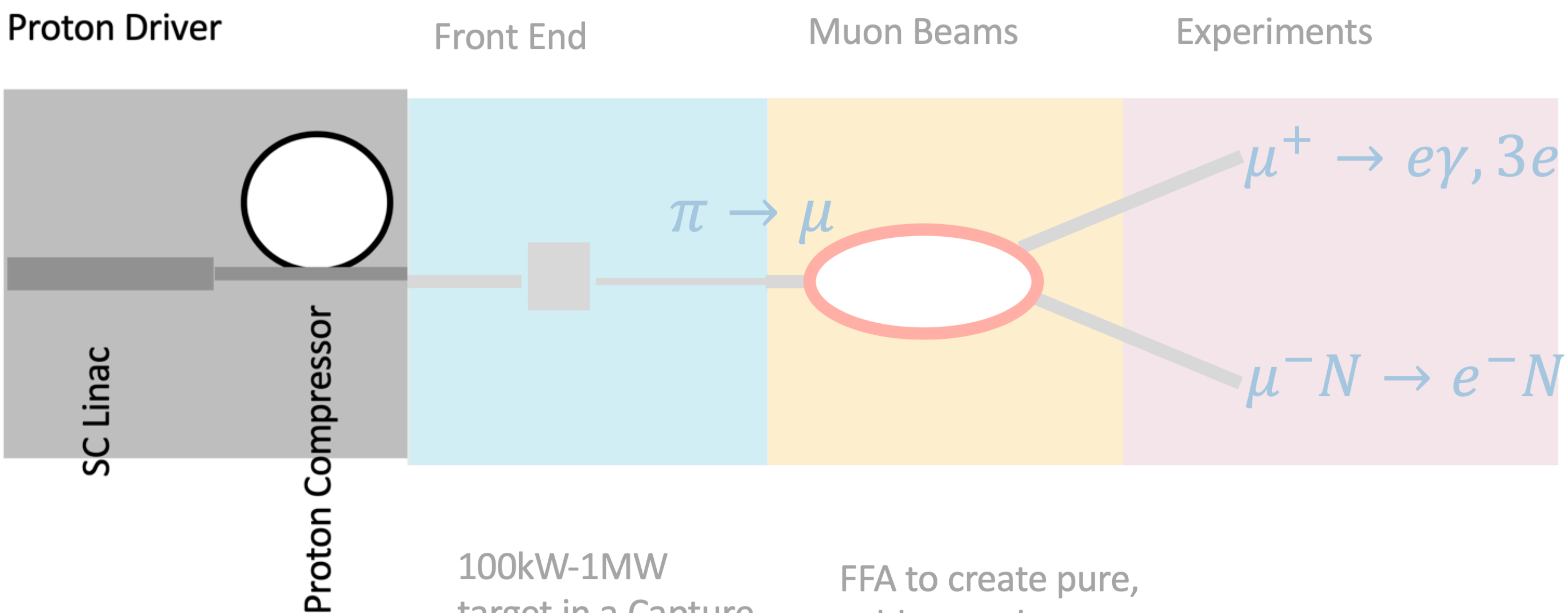


AMF concept

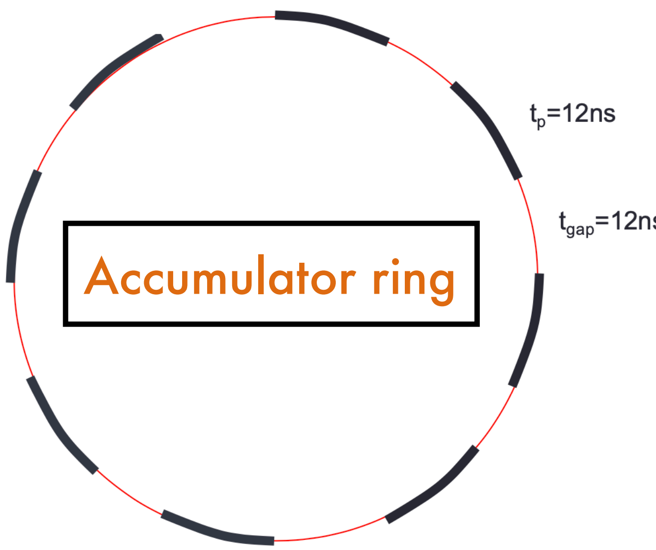


Each step has its own challenges.

AMF concept



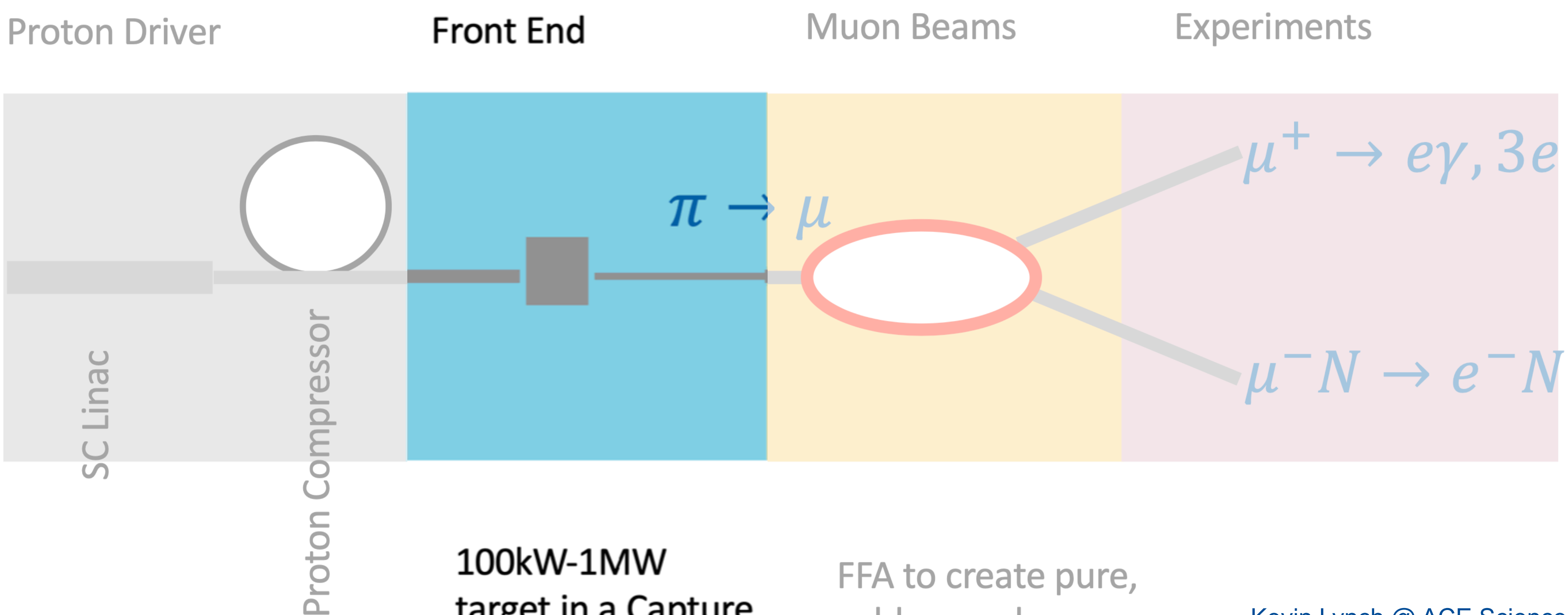
- Accumulator ring is needed before PRISM.
  - PIP-II bunches needs to accumulated.
  - 10^12 protons per bunch is needed vs 2×10^8 from PIP-II Linac
  - 2×10^8 from PIP-II Linac @ 10 ns cycles -> 31 μs is too long.
  - 1MW extraction possible for 10 ns kicker pulse at ~100 Hz.



Extraction is very difficult.

Fermilab

AMF concept

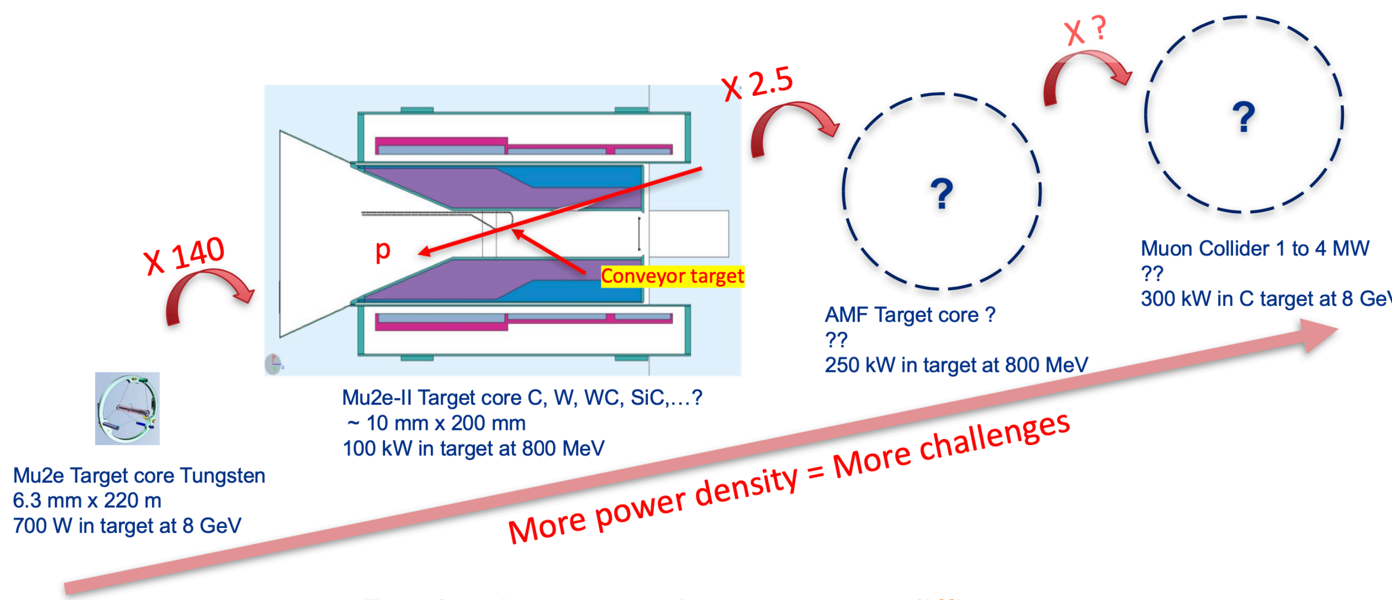


100kW-1MW target in a Capture Solenoid

FFA to create pure, cold muon beam

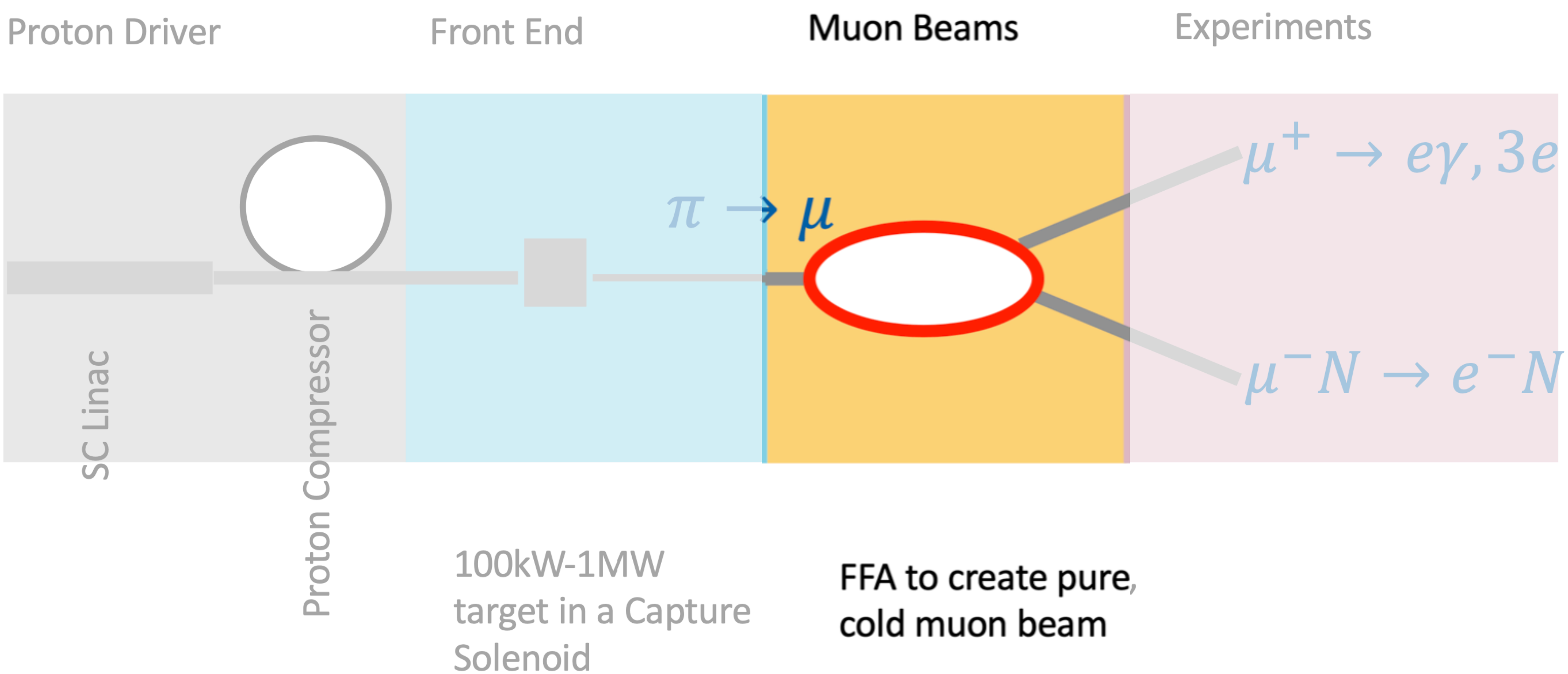
Kevin Lynch @ ACE Science Workshop - HPT R&D

- High power targetry(1MW) is needed.
  - Material studies.
  - Liquid vs fluid targets.
  - Active cooling solutions.
  - All needs to work in a super conducting solenoid.

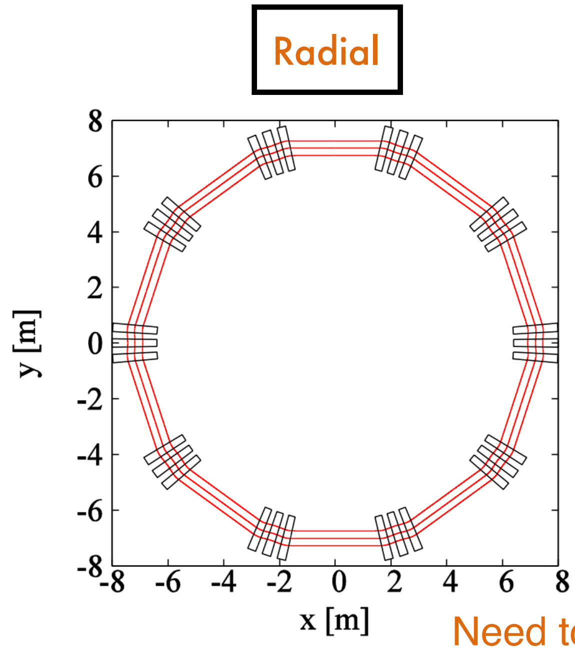


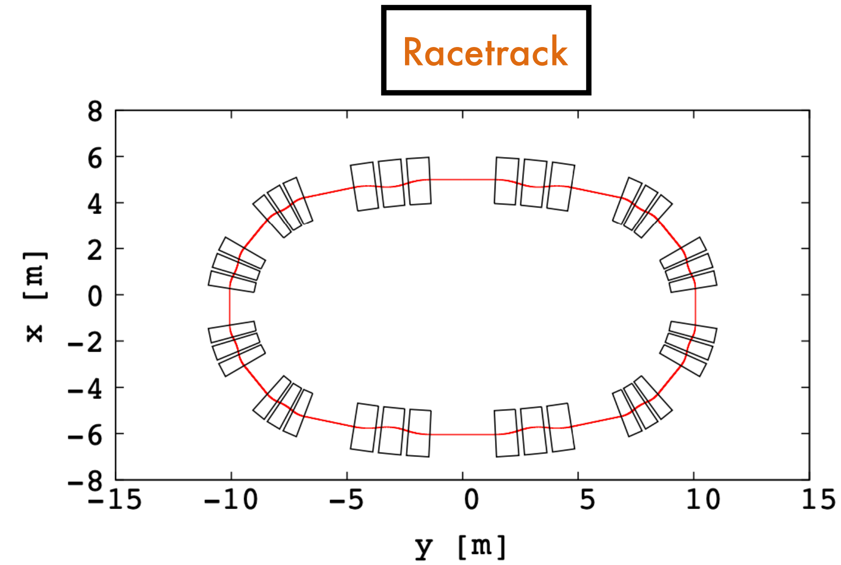
Production target is extremely difficult and never done before.

AMF concept



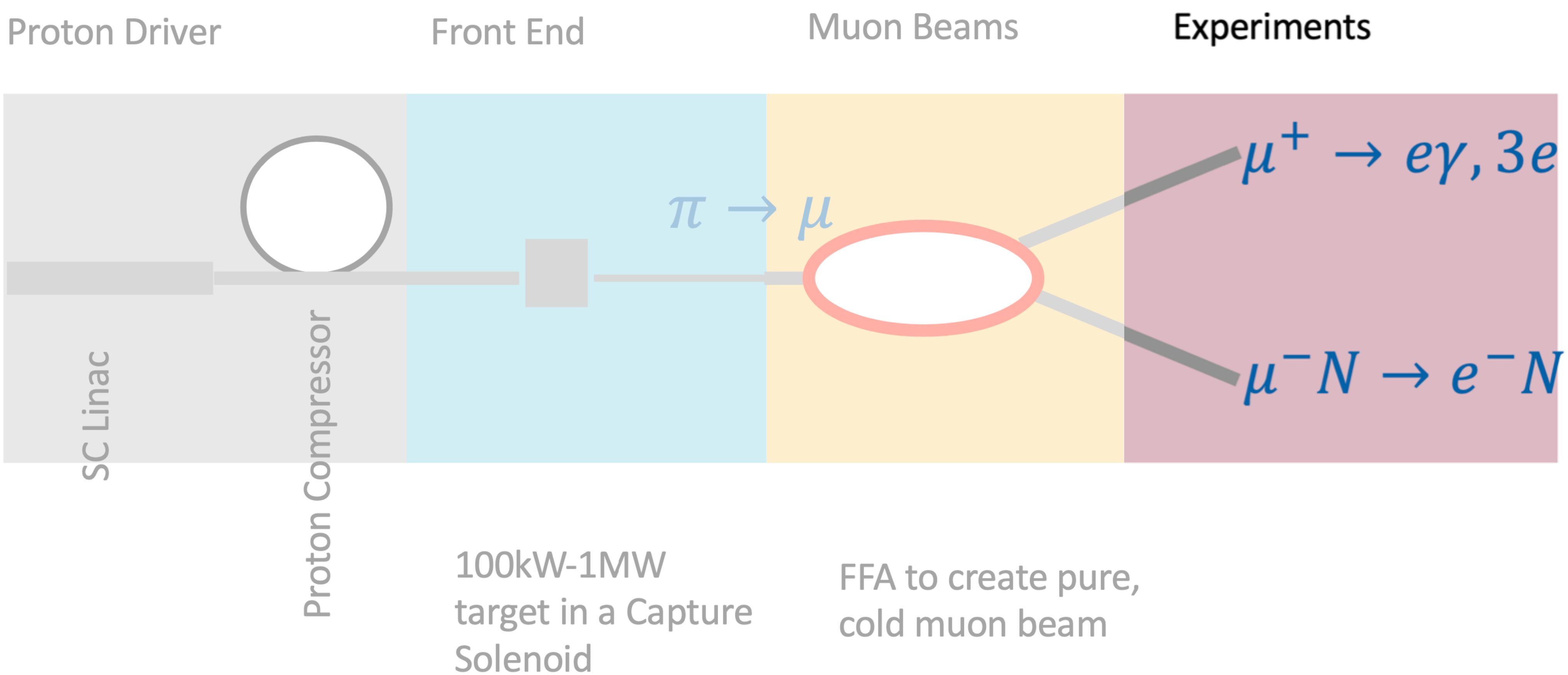
- Different FFA designs;
  - Base radial FDF 10 cell.
  - Egg or racetrack.
- Which one is better for running μ^-, μ^+ at the same time?
- FFA designs are for 68 MeV/c, need to reduce it to 20-30 MeV.





Need to figure out the best design.

AMF concept

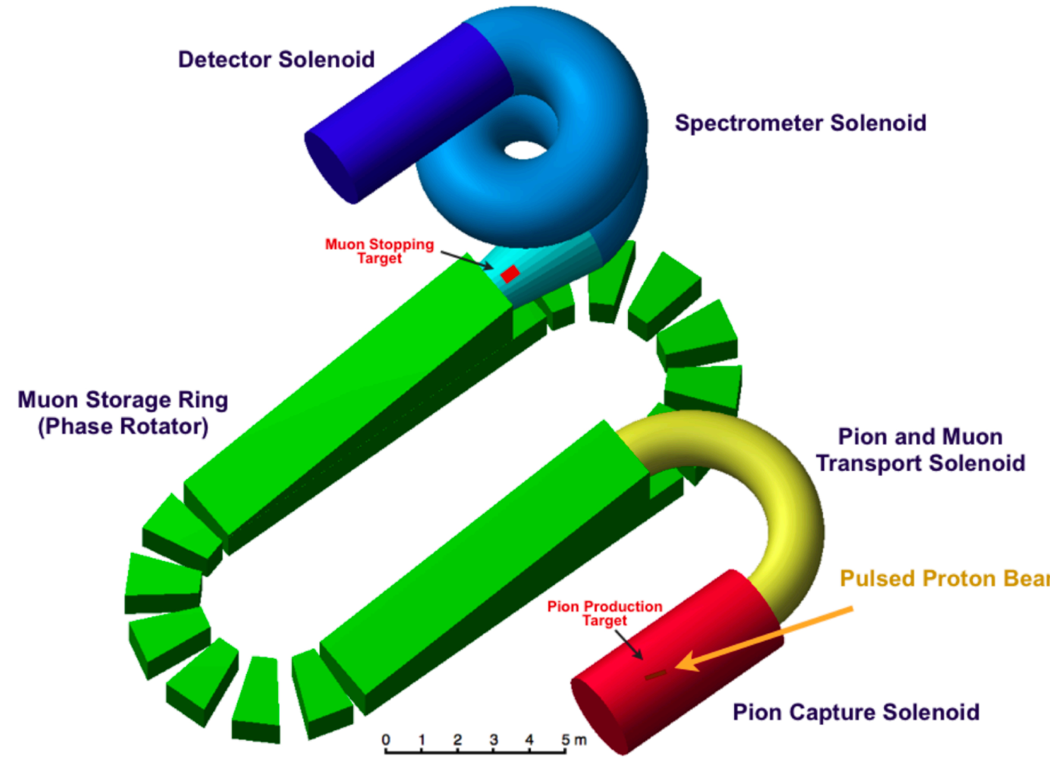


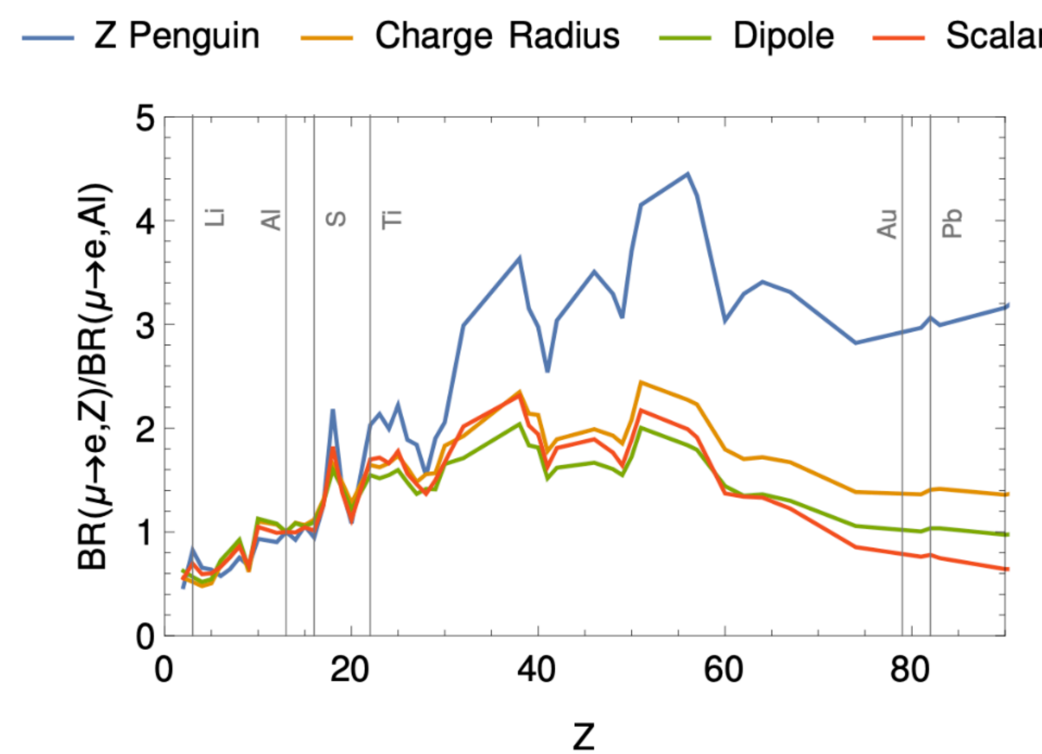
Each experiment needs to be considered on its own terms.

Fermilab

Conversion experiments

- Muon to electron conversion in the vicinity of N;
  - $\mu^- + N \rightarrow e^- + N$
- Backgrounds;
  - Eliminated beam flash.
  - High energy DIO is still there.
  - Cosmic ray veto is the dominant bkg.
- Detectors;
  - Needs to handle increased rates.
  - New tracker design is needed.
- AMF;
  - N → use high Z stopping target.
  - Less decay in high Z, ex. Au 3%, Al 39%).
  - Thinner target due to lower muon energy.
  - Can we run μ^-, μ^+ at the same time?

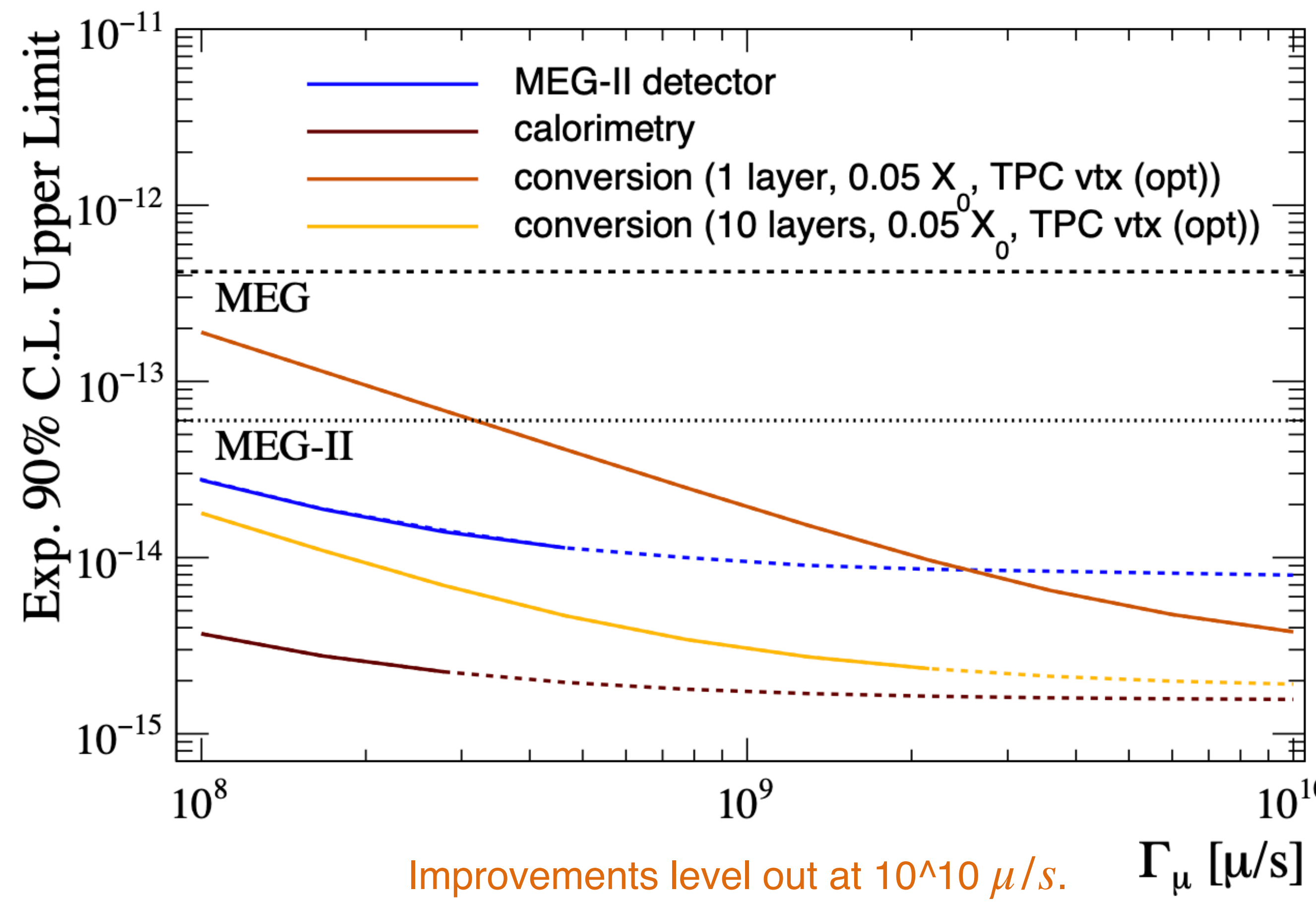




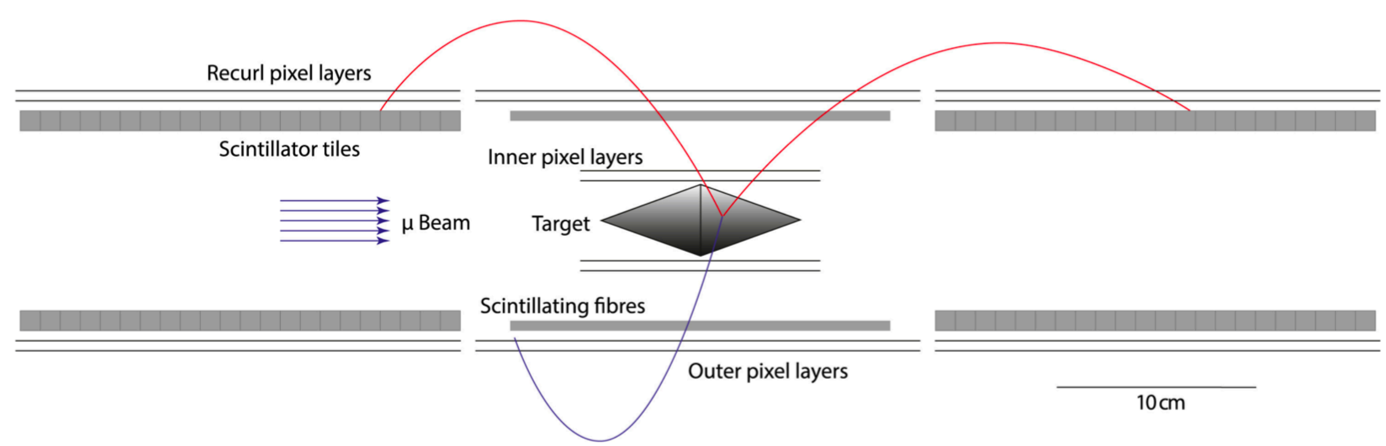
Fermilab

Decay experiments

- Two experiments;
  - $\mu^+ \rightarrow e^+ + \gamma$
  - $\mu^+ \rightarrow e^+ + e^+ + e^-$
- Backgrounds;
  - Accidental decays dominate at high muon stopping rates for $\mu^+ \rightarrow e^+ + \gamma$.
  - Radiative muon decays dominate for $\mu^+ \rightarrow e^+ + e^+ + e^-$.
- Detectors;
  - Need better γ energy resolution(1 MeV), look into new crystals like LaBr3(Ce) for.
  - Need better $e^{\pm}$ resolution, look into drift gas R&D and new Si detectors.
- AMF;
  - Can we combine two experiments?



Improvements level out at 10^10 μ/s.



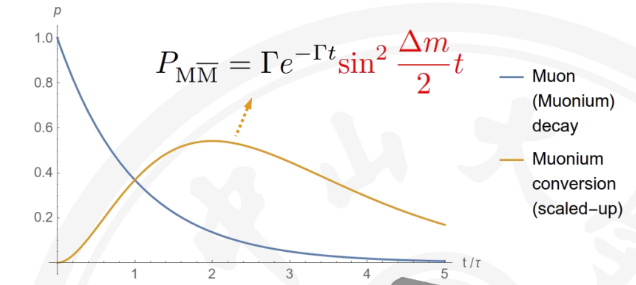
$\mu \rightarrow 3e$ detector

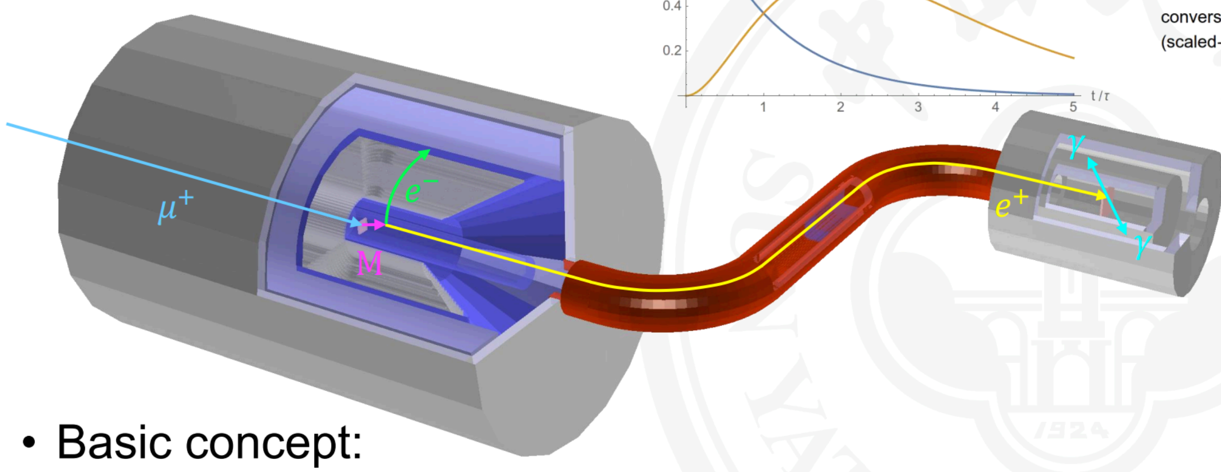
Muonium oscillations

- Muonium to anti-muonium conversion is double the CLFV , $\Delta L = 2$.
  - $\mu^+ + e^- \rightarrow \mu^- + e^+$
- Backgrounds;
  - e^+e^- scattering.
  - $\mu^+ \rightarrow e^+ + e^+ + e^- + \nu_e + \bar{\nu}_\mu$
  - Can be suppressed thanks to pulsed beam.
- Detectors;
  - Silica aerogel target optimized to increase yield or very thin SFHe.
  - Drift chamber detects e^-.
  - MCP and CsI calorimeter for e^+ detection.
- AMF;
  - MACE aims for 10^{-15} sensitivity.
  - $10^8 - 10^{10}$ μ^+ rate is needed for next generation experiment at 10^{-18}sensitivity.

- Signal process:

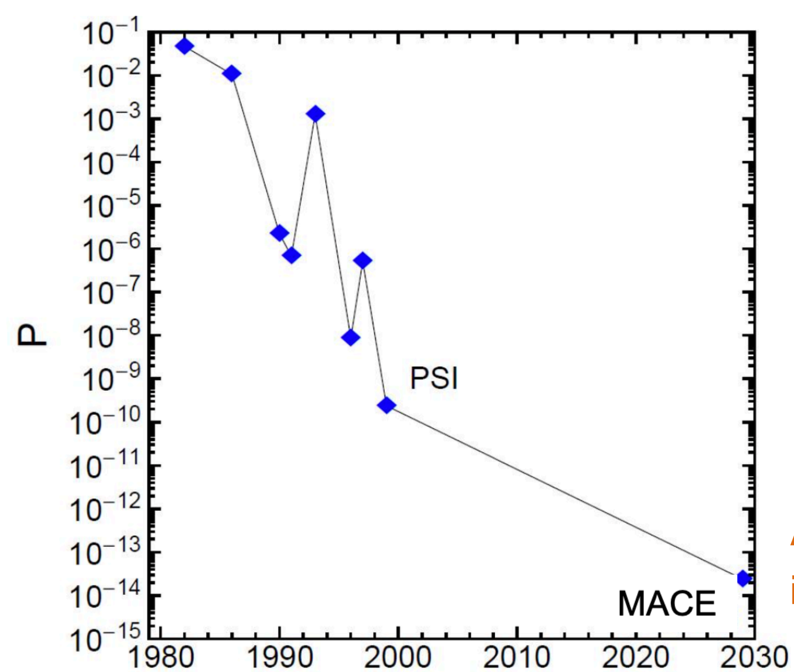
$$\mathrm{M} \rightarrow \bar{\mathrm{M}} \rightarrow e^+ e^- \nu_\mu \bar{\nu}_e$$





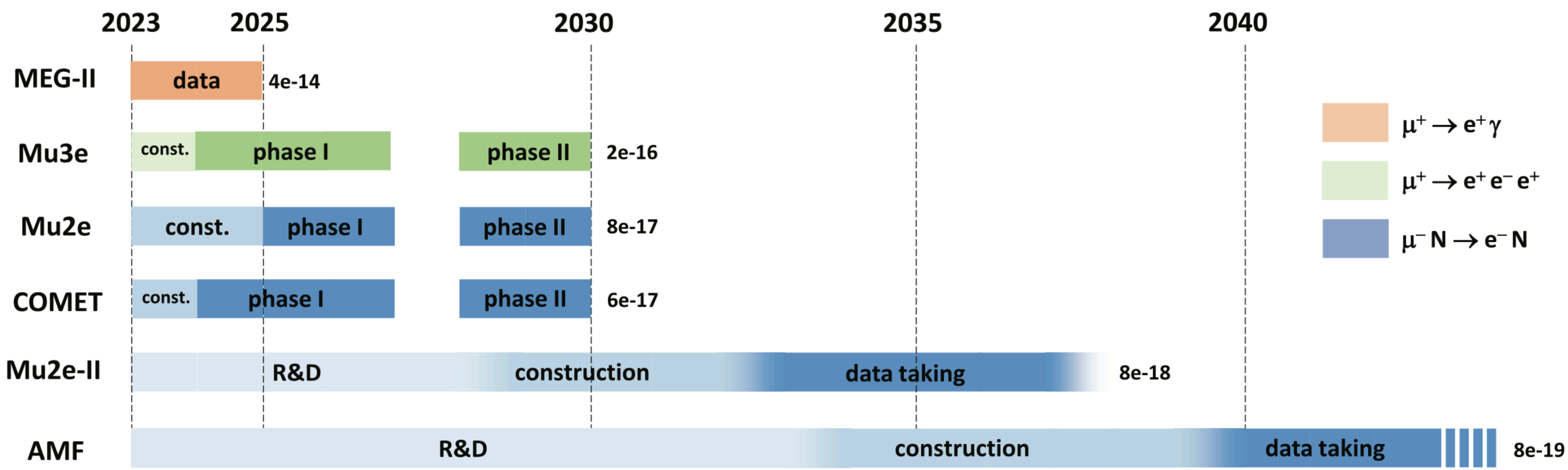
- Basic concept:
  - Coincidence of a Michel e^- and a e^+ from atomic shell:

1. Spectrometer $\bar{\mathrm{M}} \rightarrow \nu\nu e^- e^+$
2. MCP $\bar{\mathrm{M}} \rightarrow \nu\nu e^- e^+$
3. Calorimeter $\bar{\mathrm{M}} \rightarrow \nu\nu e^- e^+, e^+ \xrightarrow{\text{annihilate on MCP}} \gamma\gamma$



AMF provides $\times$ 100 improvement.

Timeline


2023
2025
2030
2035
2040
MEG-II
data
4e-14
Mu3e
const.
phase I
phase II
2e-16
Mu2e
const.
phase I
phase II
8e-17
COMET
const.
phase I
phase II
6e-17
Mu2e-II
R&D
construction
data taking
8e-18
AMF
R&D
construction
data taking
8e-19
$\mu^+ \to e^+ \gamma$
$\mu^+ \to e^+ e^- e^+$
$\mu^- N \to e^- N$

Summary

- Proposed AMF aims to host most major muon CLFV experiments.
- Capitalize on the knowledge and infrastructure developed by the Fermilab muon program.
- Provides $\times 100 - 1000$ sensitivity improvements in the CLFV experiments proposed.
- R&D synergy with the future muon collider.
- Outstanding potential for innovation in detector design and accelerator design.
- R&D needs to start now to deliver on the AMF potential according to the proposed schedule.

BACKUP

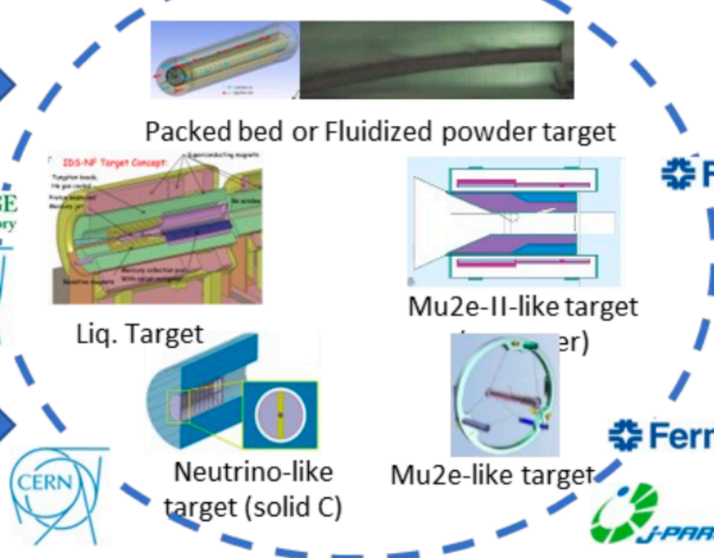
RPF Experiment Targetry – R&D Approach for Muon Collider

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

Kevin Lynch @ ACE Science Workshop - HPT R&D

Stopping target comparison for AMF

Nucleus	$R_{\mu e}(Z) / R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy
Al(13,27)	1	864 nsec	104.96 MeV
Ti(22,~48)	1.7	328 nsec	104.18 MeV
Au(79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV

PRISM parameters

PRISM parameters

Parameter	Value
Target type	solid
Proton beam power	~1 MW
Proton beam energy	~ GeV
Proton bunch duration	~10 ns total
Pion capture field	10 -20 T
Momentum acceptance	±20 %
Reference μ^-momentum	40-68 MeV/c
Harmonic number	1
Minimal acceptance (H/V)	3.8/0.5 π cm rad or more…
RF voltage per turn	3-5.5 MV
RF frequency	3-6 MHz
Final momentum spread	±2%
Repetition rate	100 Hz-1 kHz

J. Pasternak

Would ideally like to lower this.

Induction linac, maybe?

Mu2e and Mu2e-II beam pulse

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
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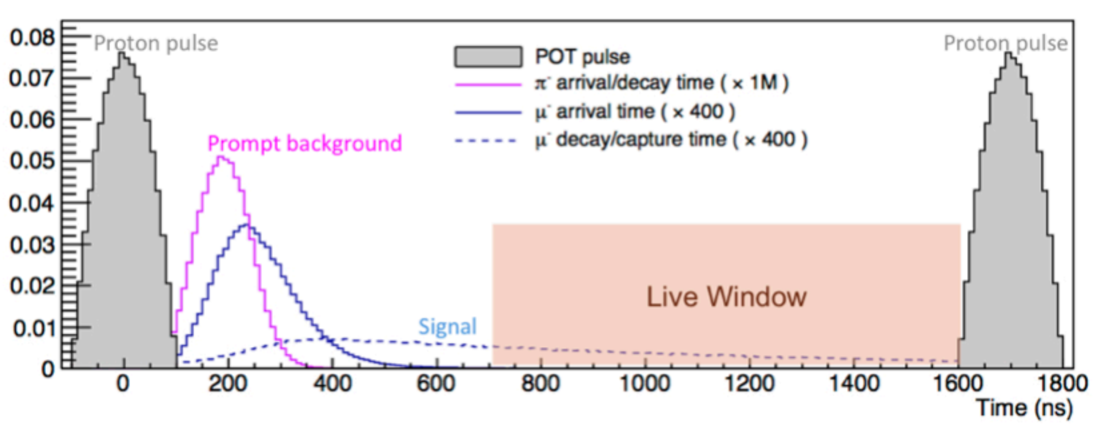
Stopped μ per proton	1.59×10^{-3}	9.1×10^{-5}
Stopped μ per cycle		1.2×10^{5}

Mu2e



Mu2e-II