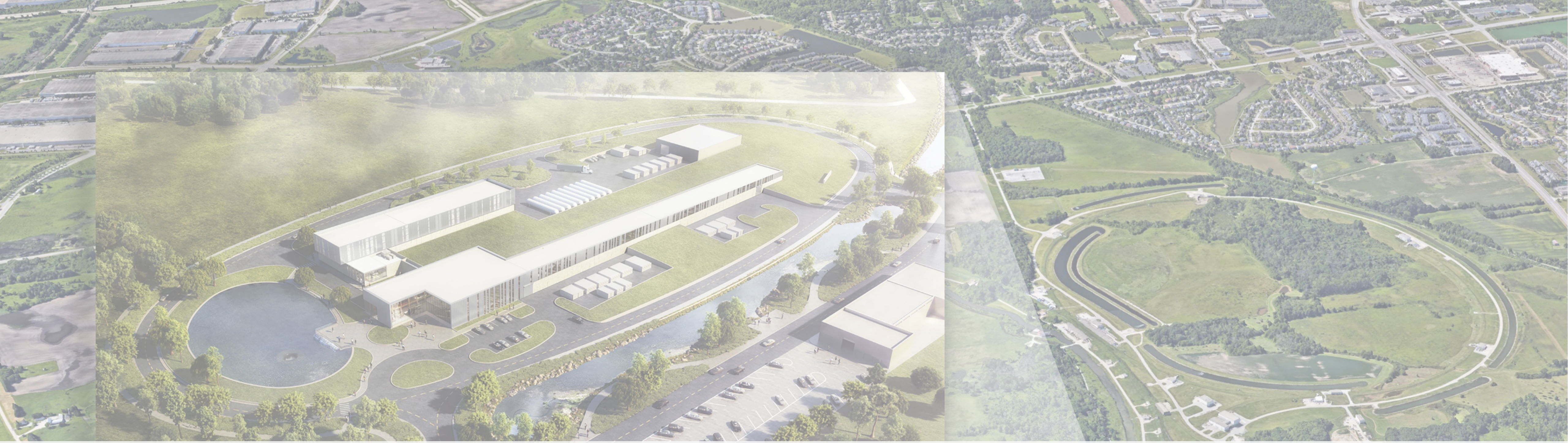


The Advanced Muon Facility at Fermilab

By Sophie Charlotte Middleton

(Caltech)

Looking Ahead of Snowmass Series

25th May 2023

What is the Advanced Muon Facility?

Advanced Muon Facility (AMF)

- is a propose FNAL-based multi-purpose muon facility;
- would provide the most intense muon beam to enable experiments and muon science with unprecedented sensitivity;
- experiment at AMF will provide limits/discovery potential orders-of-magnitude beyond current experiments;
- will utilize PIP-II and Booster Replacement program.

- AMF is in the early stages of design, but 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]

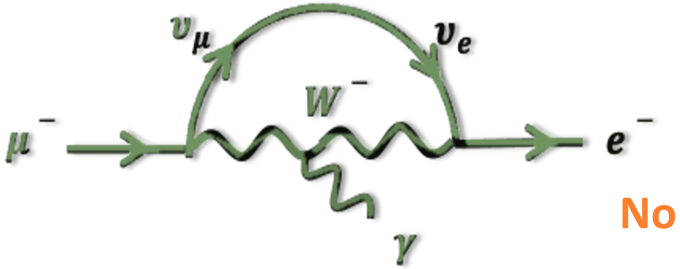
[2] Agenda of recent workshop: https://indico.fnal.gov/event/57834/timetable/?view=standard → Proceedings soon!

Introduction

Current Muon Projects & Physics Motivations for CLFV

Charged Lepton Flavor Violation (CLFV)

- 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:

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

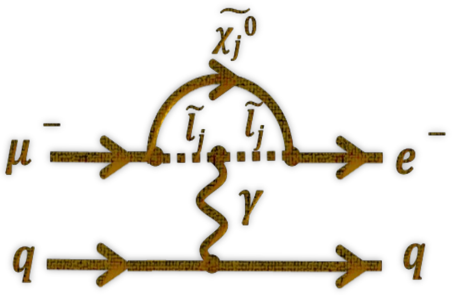
$$\boldsymbol{B(\mu \to e\gamma) \sim \vartheta(10^{-54})}$$

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).

New Physics Scenarios

There are many well-motivated BSM theories which invoke for example muon conversions mediated by (pseudo) scalar, (axial) vector, or tensor currents at rates close to current experimental limits i.e. $B \approx 10^{-15} - 10^{-17}$:

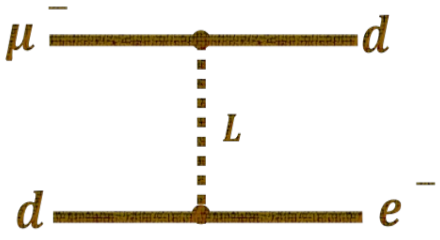


SUSY

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

Scalar Leptoquarks

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

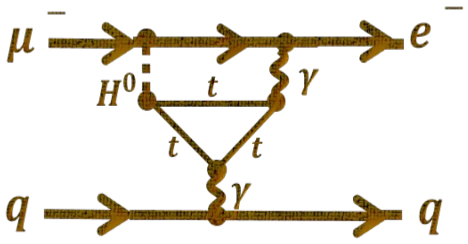


See-saw models

Nuclear Physics B (Proc. Suppl.) 248–250 (2014) 13–19

2 Higgs Doublets

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



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

Current Experimental Searches for CLFV

- **There is an on-going global program searching for CLFV. Many experiments will take data this decade!**
- Muons are a very 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.

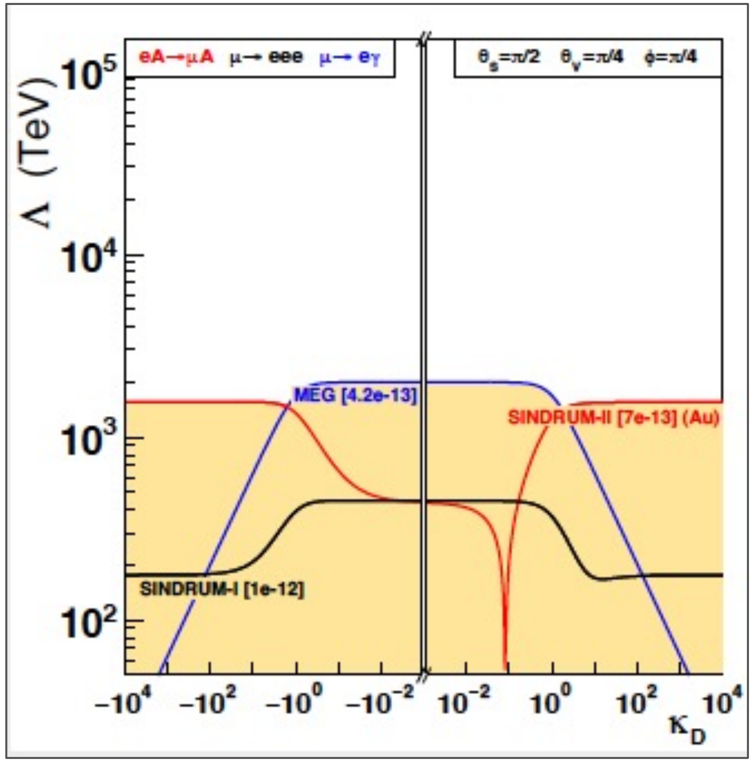
Mode	Current Upper Limit (at 90% CL)	Projected Limit (at 90% CL)	Upcoming Experiment/s
$\mu^+ \rightarrow e^+\gamma$	**4.2×10^{-13}**	**4×10^{-14}**	**MEG II**
$\mu^+ \rightarrow e^+e^+e^-$	**$\sim 10^{-12}$**	**$10^{-15} \sim 10^{-16}$**	**Mu3e**
$\mu^- N \rightarrow e^- N$	**7×10^{-13}**	**10^{-15}**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

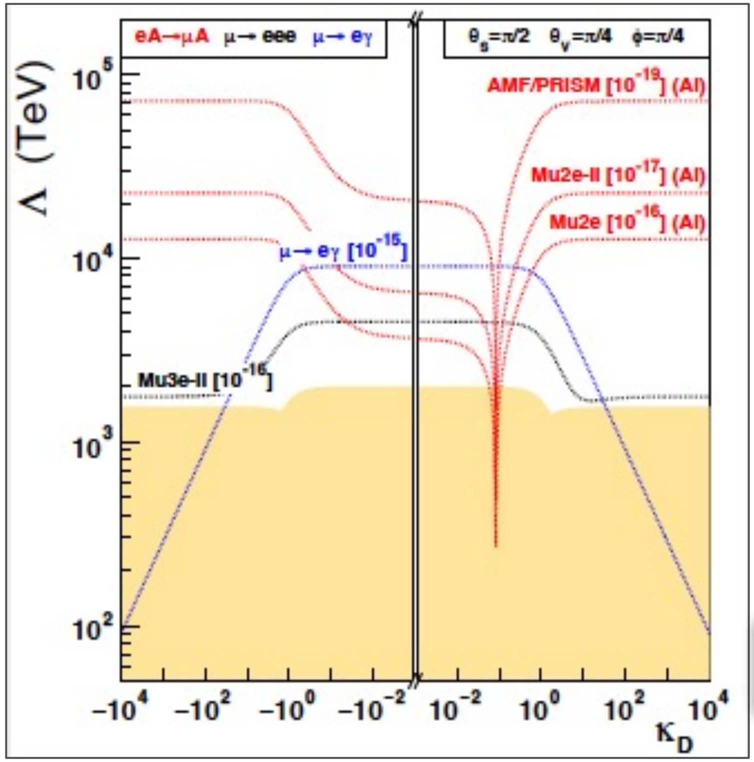
Physics Reach

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

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**

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

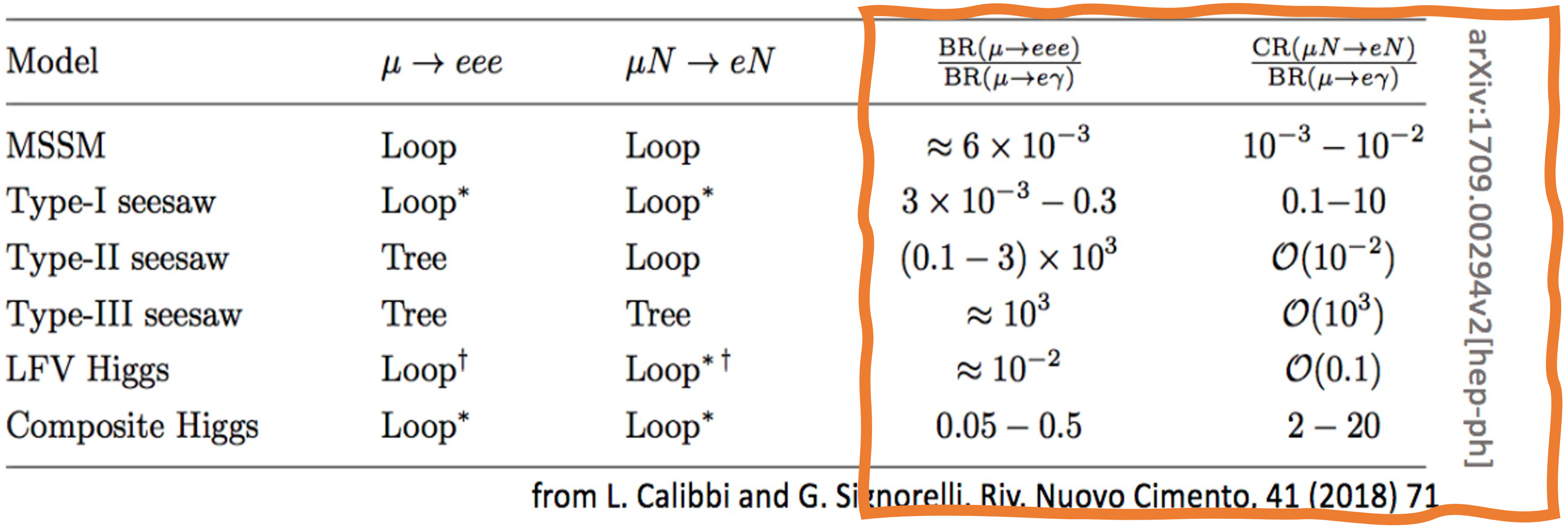
where angle θ_D , parametrizes relative magnitude of dipole and four-fermion coefficients.

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

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 → very different rates of CLFV



Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu \to eee)}{\mathrm{BR}(\mu \to e\gamma)}$	$\frac{\mathrm{CR}(\mu N \to eN)}{\mathrm{BR}(\mu \to e\gamma)}$
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

$N\mu^- \rightarrow Ne^-$: Signal

- The $\mu \rightarrow e$ conversion rate is measured as a ratio to the muon capture rate on the same nucleus:

$$R_{\mu e} = \frac{\Gamma(\mu^- + A(Z,N) \rightarrow e^- + A(Z,N))}{\Gamma(all - captures)}$$

- Low momentum (-) muons are captured in the target atomic orbit and quickly (~fs) cascades to 1s state.
- In aluminum:
  - *39 % Decay :* $\mu + N \rightarrow e + \bar{\upsilon}_e + \upsilon_\mu$ *(Background)*
  - *61 % Capture :* $\mu + N \rightarrow \upsilon_\mu + N'$ *(Normalization)*
  - *< 7 x 10^{-13} Conversion :* $\mu + N \rightarrow e + N$ *(Signal)*
- Signal is monoenergetic electron consistent with:

$\boldsymbol{E_e = m_\mu - E_{recoil} - E_{1S\,B.E}}$, **e.g For Al: E_e = 104.97 MeV.**

  - Nucleus coherently recoils off outgoing electron; it does not break-up!
  - Will be smeared by material effects in detector and stopping target.

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

Production Solenoid:

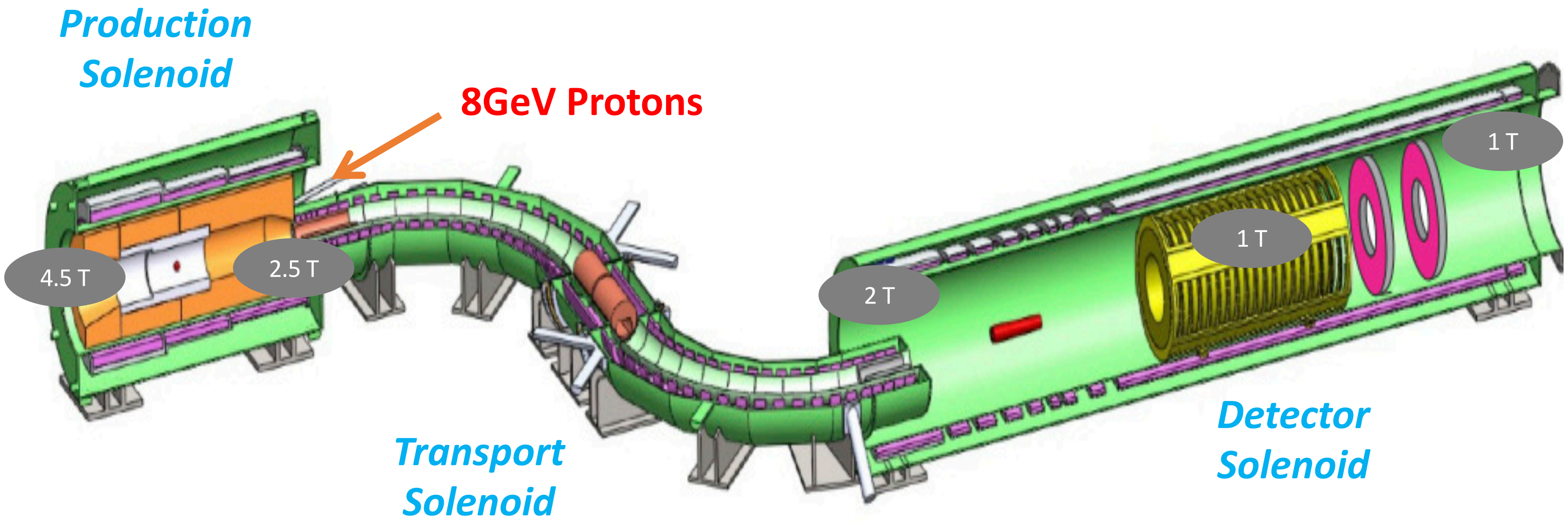
- 8 GeV Protons enter, pions produced, decay to muons.
- Graded magnetic field reflects pions/muons to transport solenoid.

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.**

Caltech

The Advanced Muon Facility at Fermilab – Sophie Middleton – sophie@fnal.gov

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

$N\mu^- \to Ne^-$: 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

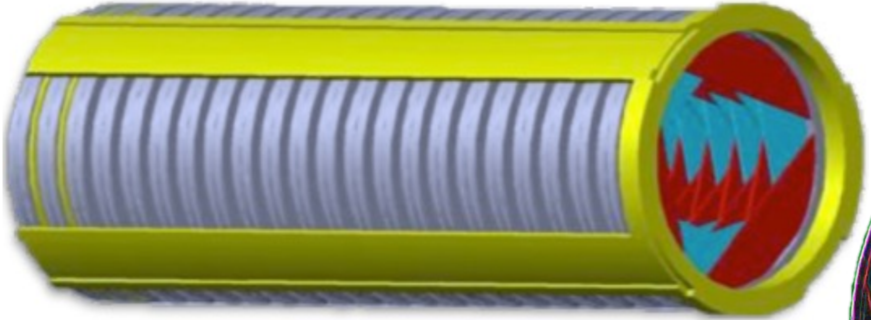
$N\mu^- \rightarrow Ne^-$: Removing Backgrounds

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

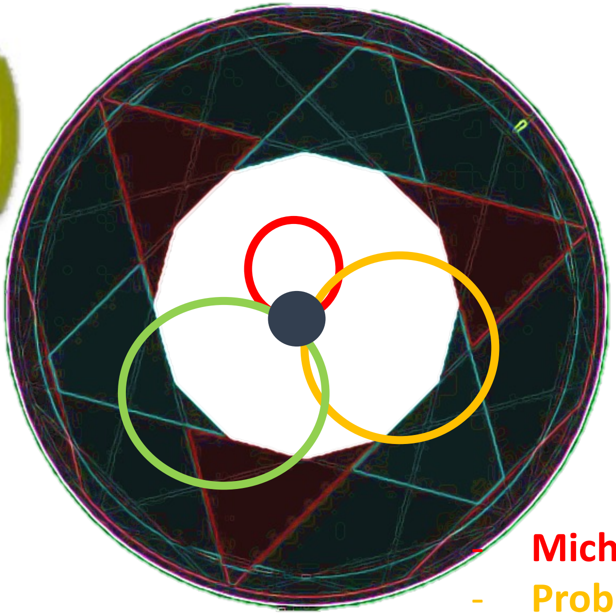
- **Intrinsic :**
  - Scale with number of stopped muons.

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

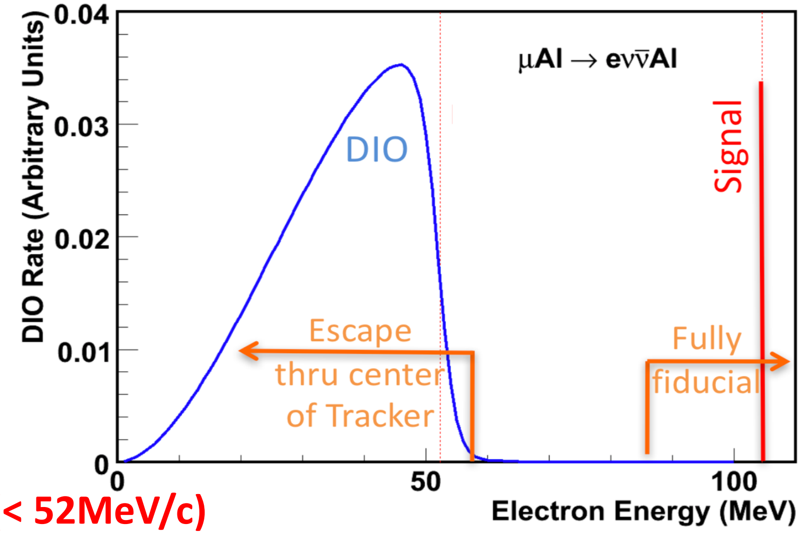
- Annular tracker: Removes > 97% of DIO.
- Low mass design, momentum resolution removes the rest.



Thin straws, arranged in planes



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



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

$N\mu \rightarrow Ne$: Removing Backgrounds

- **Late arriving :**
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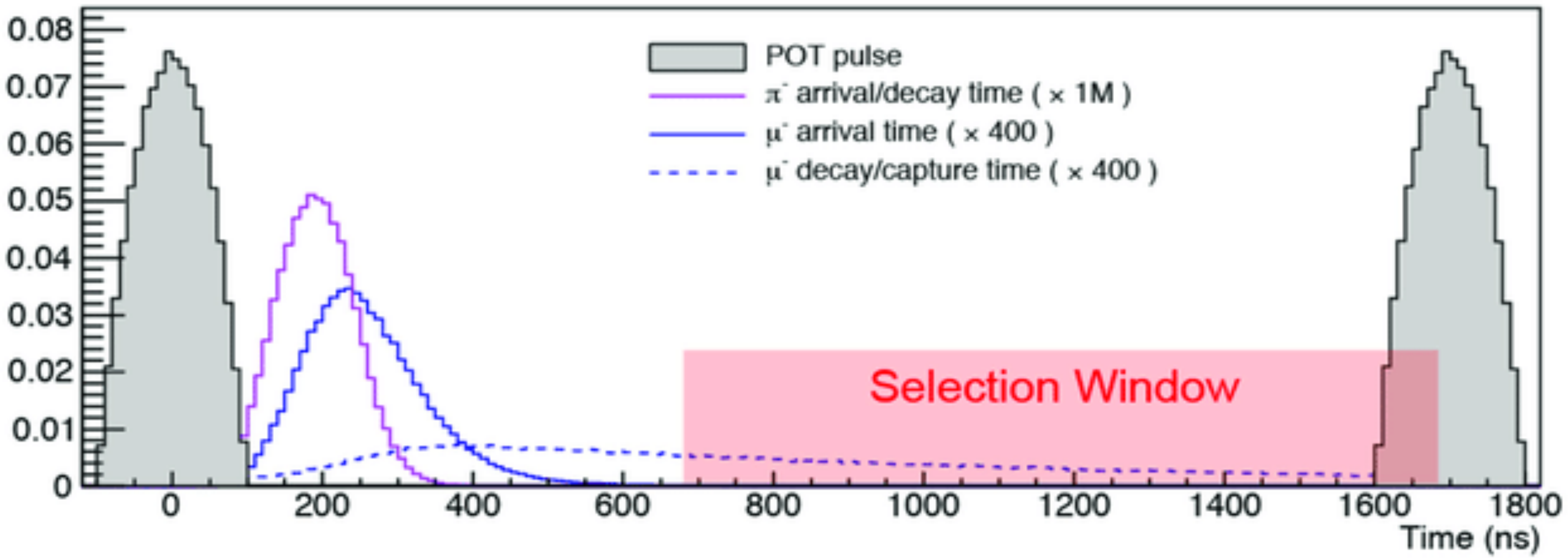
Type	Source	Mitigation	Yield (for Run-I only)*
Beam Backgrounds	**Pion Capture**	**Beam Structure /Extinction**	**(in time) 0.010 $\pm$ 0.002 $(\text{stat})^{+0.001}_{-0.003}$ (sys)** **(out time) (1.2 $\pm$ 0.001 $(\text{stat})^{+0.1}_{-0.3}$ (sys)) x 10^{-3}**

Delayed live-gate helps remove pion and beam backgrounds.



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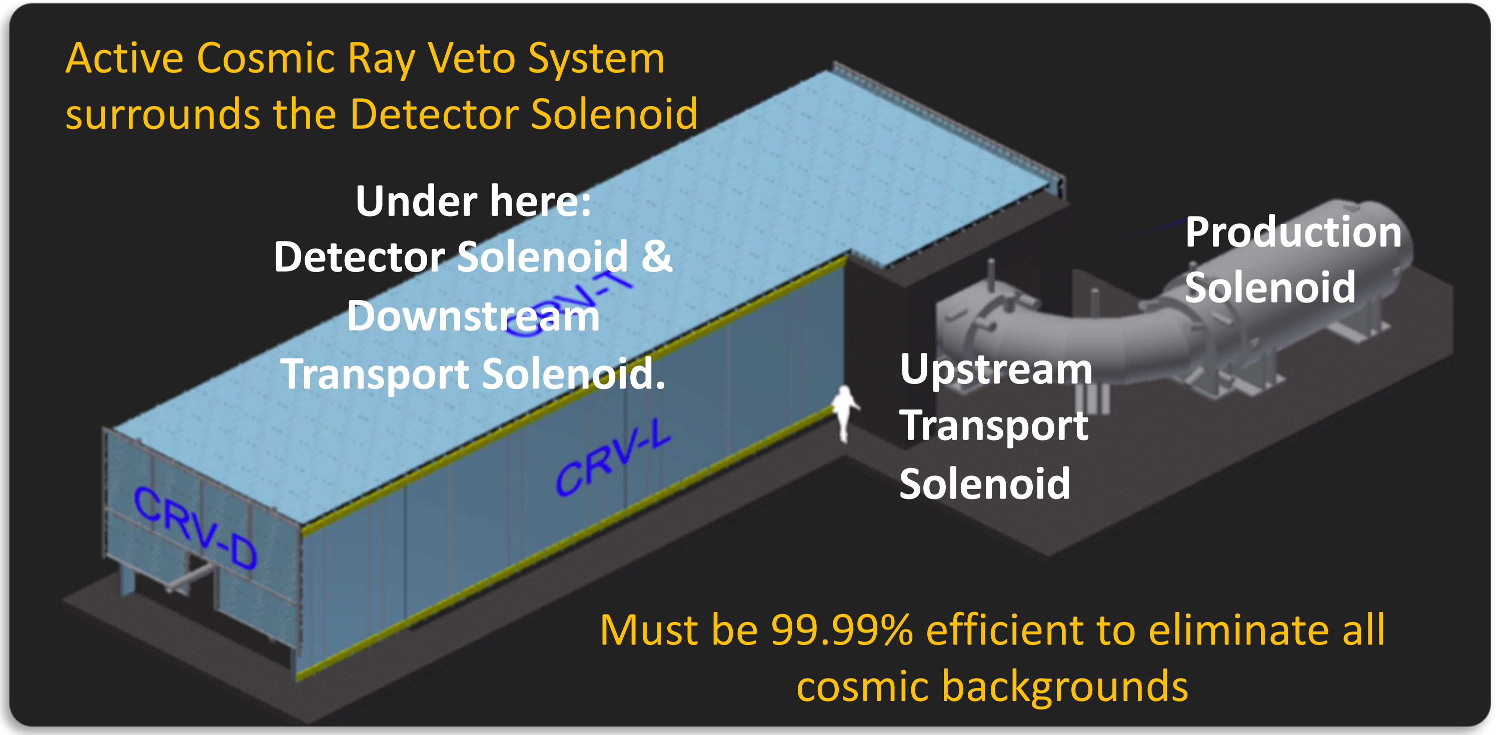
$N\mu^- \rightarrow Ne^-$: Removing Backgrounds

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

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

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



Active Cosmic Ray Veto System surrounds the Detector Solenoid

Must be 99.99% efficient to eliminate all cosmic backgrounds

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

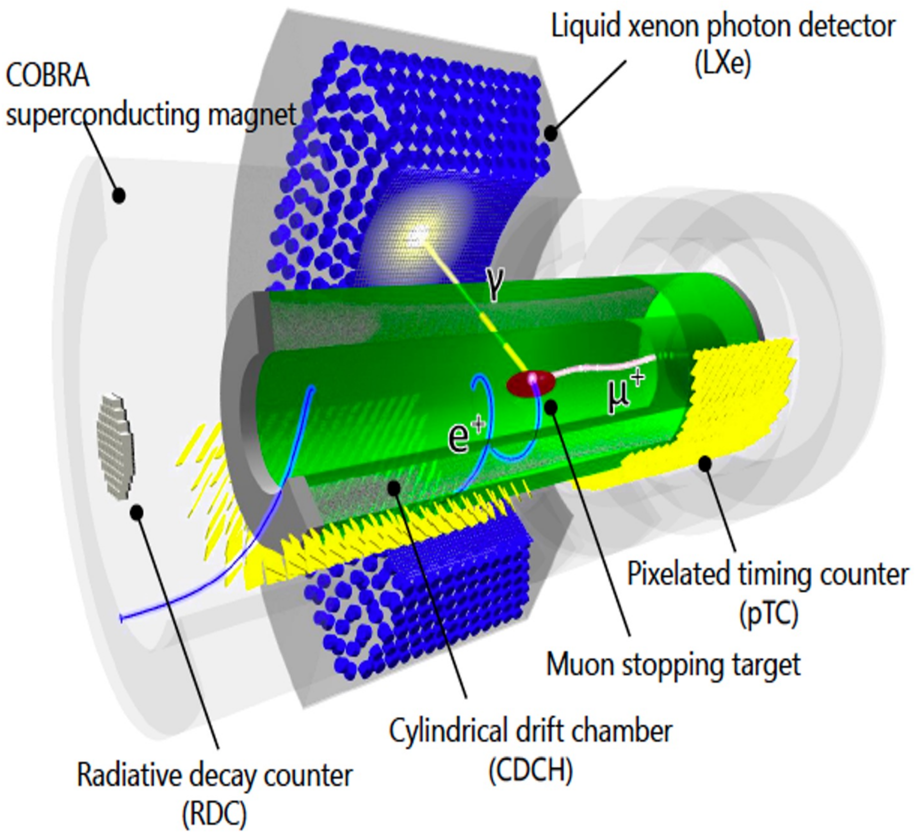
Design:

- 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.

Universe 2021, 7, 466



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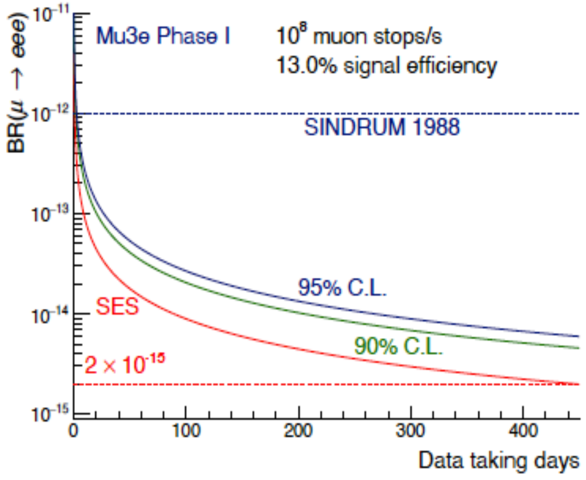
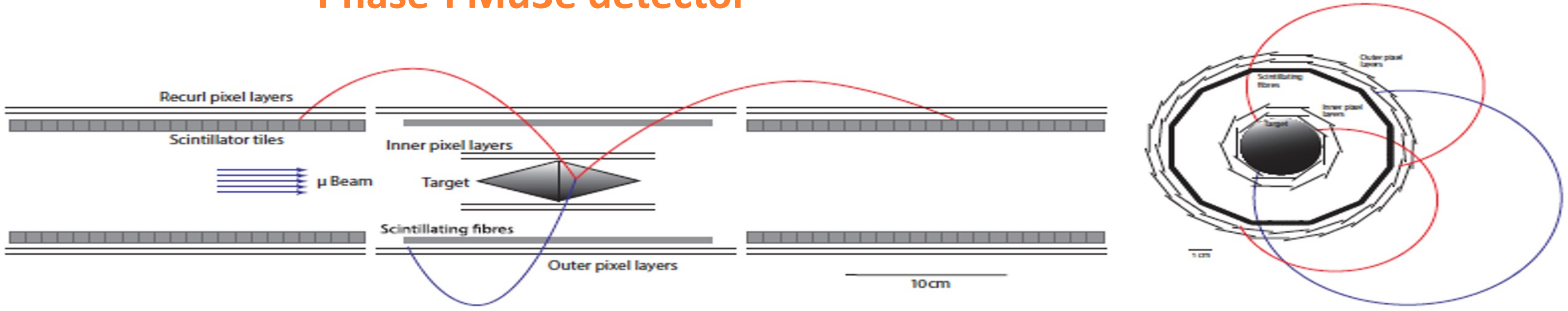
$\boldsymbol{\mu^+ \to e^+ e^+ e^-}$: The Mu3e Experiment



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.

Possibilities

Outcomes of current era of CLFV searches

- ✓ Signal in Mu2e and/or MEG-II and/or Mu3e
  - arXiv Nice papers, exciting times!
  - 
    AMF look at other target (for conversion).
  - 
    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.

<u>What's next???</u> - 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!

The Advanced Muon Facility

A Proposed Multi-purpose Muon Facility at Fermilab

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:

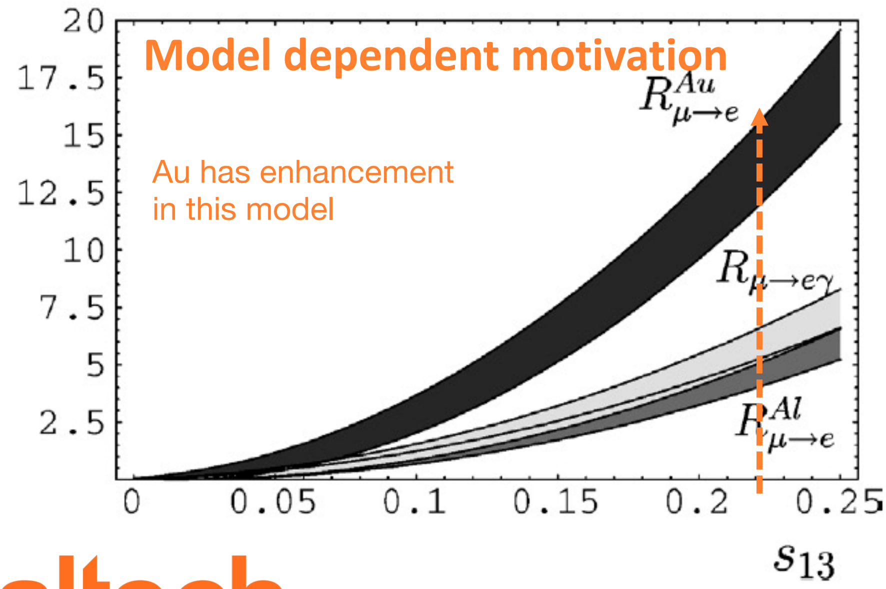
- very intense μ^-beam would enable $\boldsymbol{N\mu^- \rightarrow Ne^-}$ on high Z **(100-1000 x Mu2e)**
- very intense μ^+beam, enable $\mu^+ \rightarrow e^+\gamma$ and $\mu^+ \rightarrow e^+e^+e^-$ with:
  - $\boldsymbol{\mu \rightarrow e\gamma}$: **(x 10 MEG-II)**
  - $\boldsymbol{\mu \rightarrow eee}$: **(x 10 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 $\mathbf{10^{-5}}$ $\boldsymbol{G_F}$)**
- Could do anything else with large muon flux (muSR?)

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

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

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

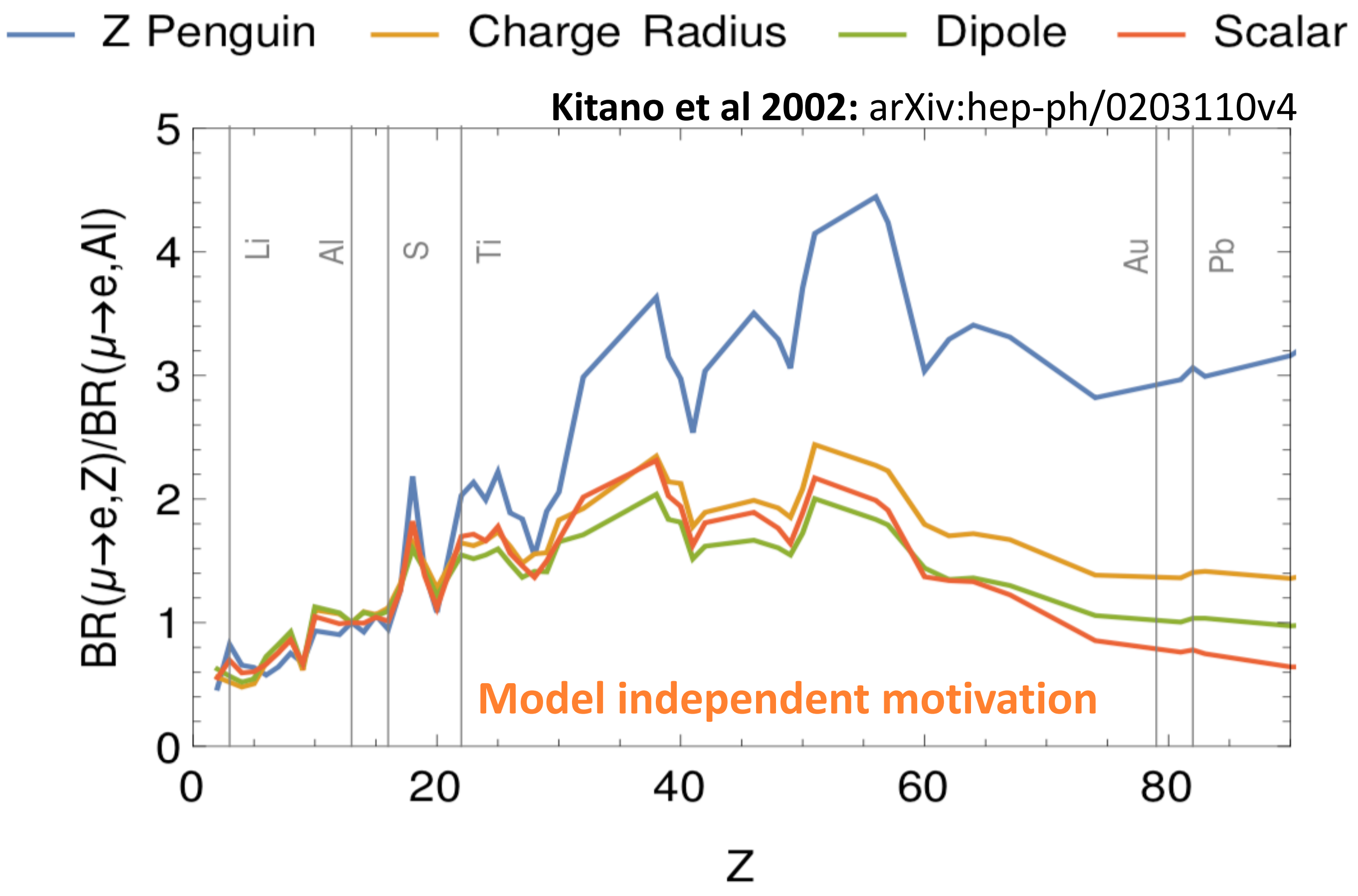
→ can elucidate type of physics through looking at relative conversion rate.



Model dependent motivation

Au has enhancement in this model

V. Cirigliano, B. Grinstein, G. Isidori, M. Wise **Nucl.Phys.B728:121-134,2005**

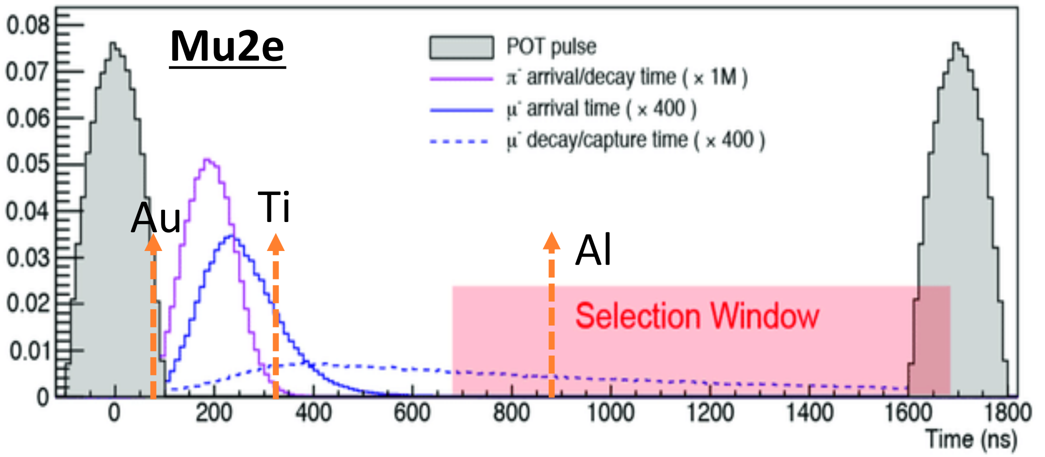


Kitano et al 2002: arXiv:hep-ph/0203110v4

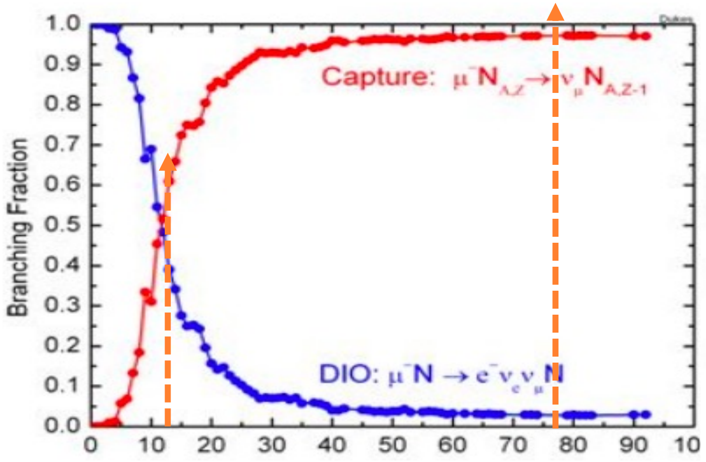
Model independent motivation

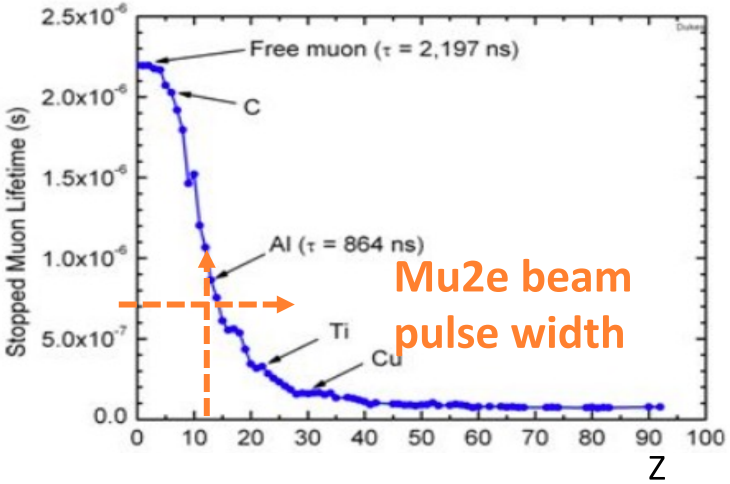
$N\mu^- \rightarrow Ne^-$: Limitations of Current Approach

- 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



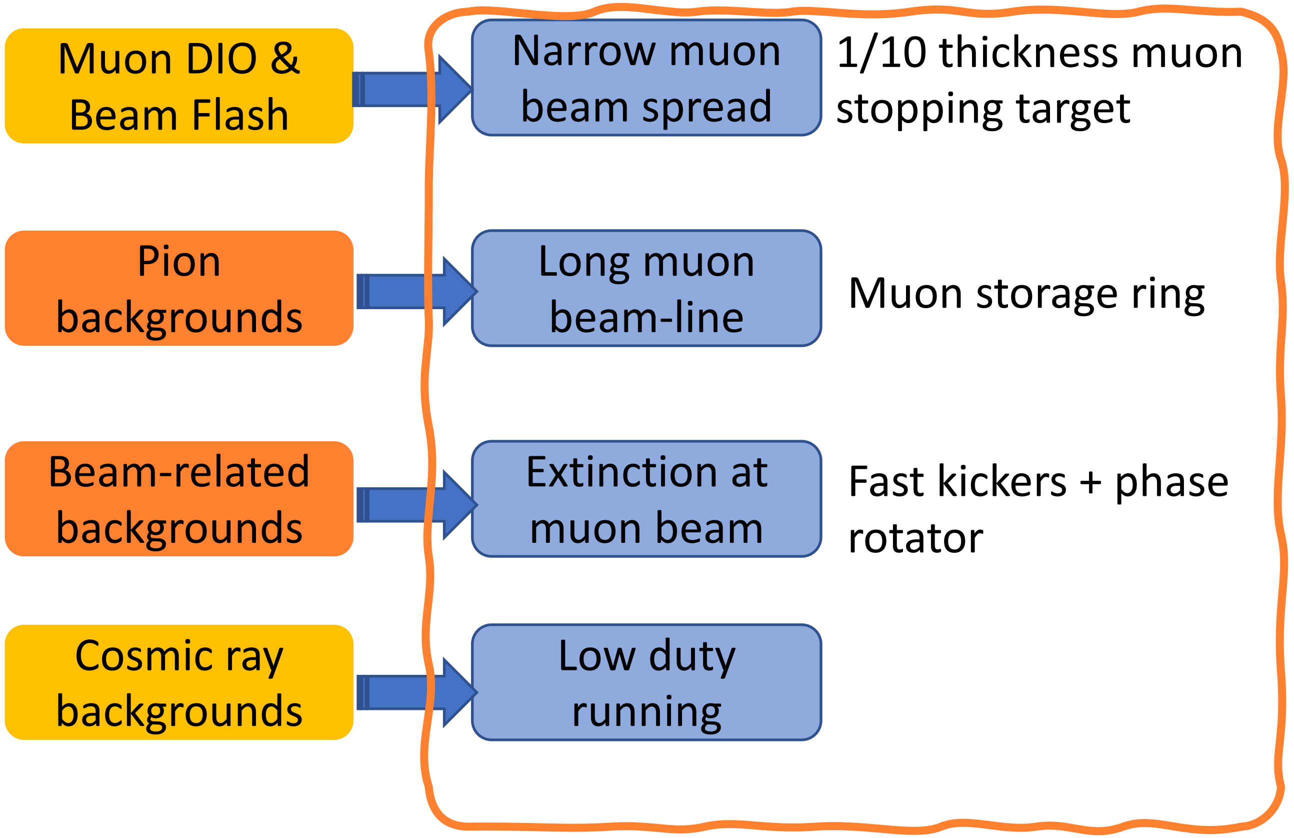


FFA = FIXED FIELD ALTERNATING GRADIENT SYNCHROTRON

Novel Approach: use an FFA

Mono-energetic muon beam

Pure muon beam



Muon DIO & Beam Flash	Narrow muon beam spread	1/10 thickness muon stopping target
Pion backgrounds	Long muon beam-line	Muon storage ring
Beam-related backgrounds	Extinction at muon beam	Fast kickers + phase rotator
Cosmic ray backgrounds	Low duty running	

By adding an FFA Phase Rotator

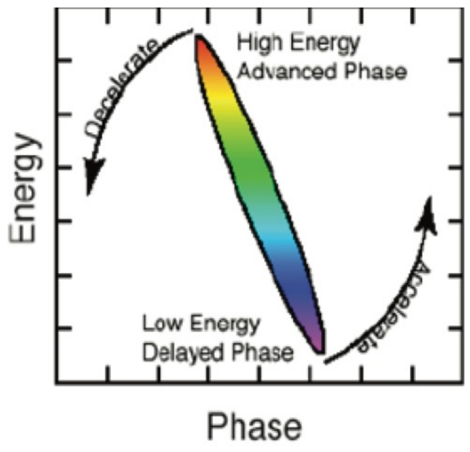
FFA can provide mono-chromatic, pure muon beam!

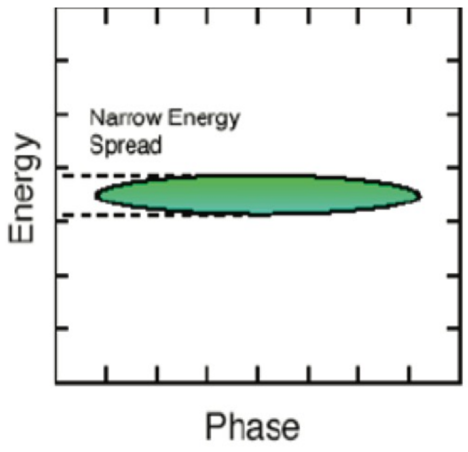
PRISM Concept

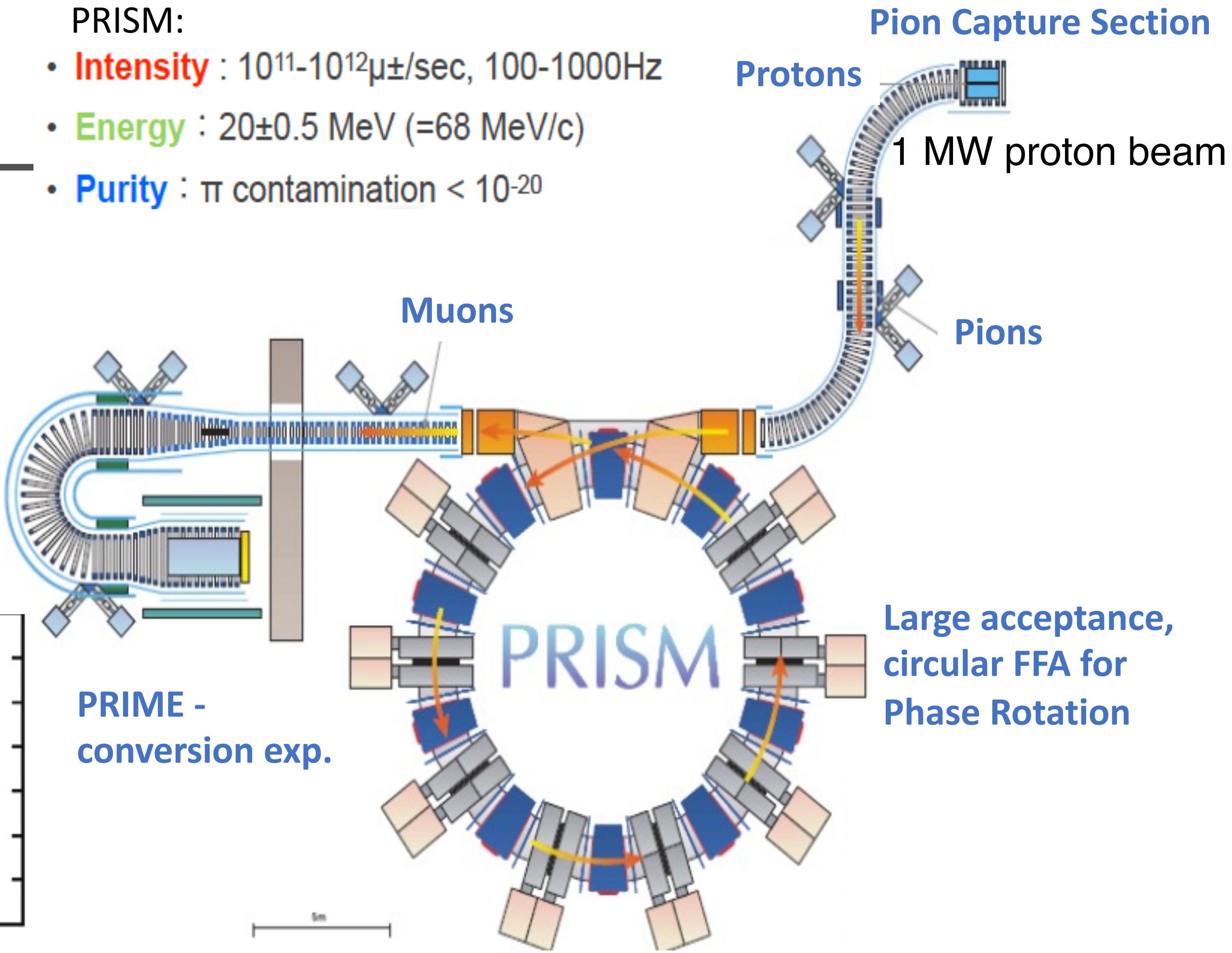
PRISM:

- **Intensity** : 10^{11}-10^{12} μ±/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.






Pion Capture Section

Protons

1 MW proton beam

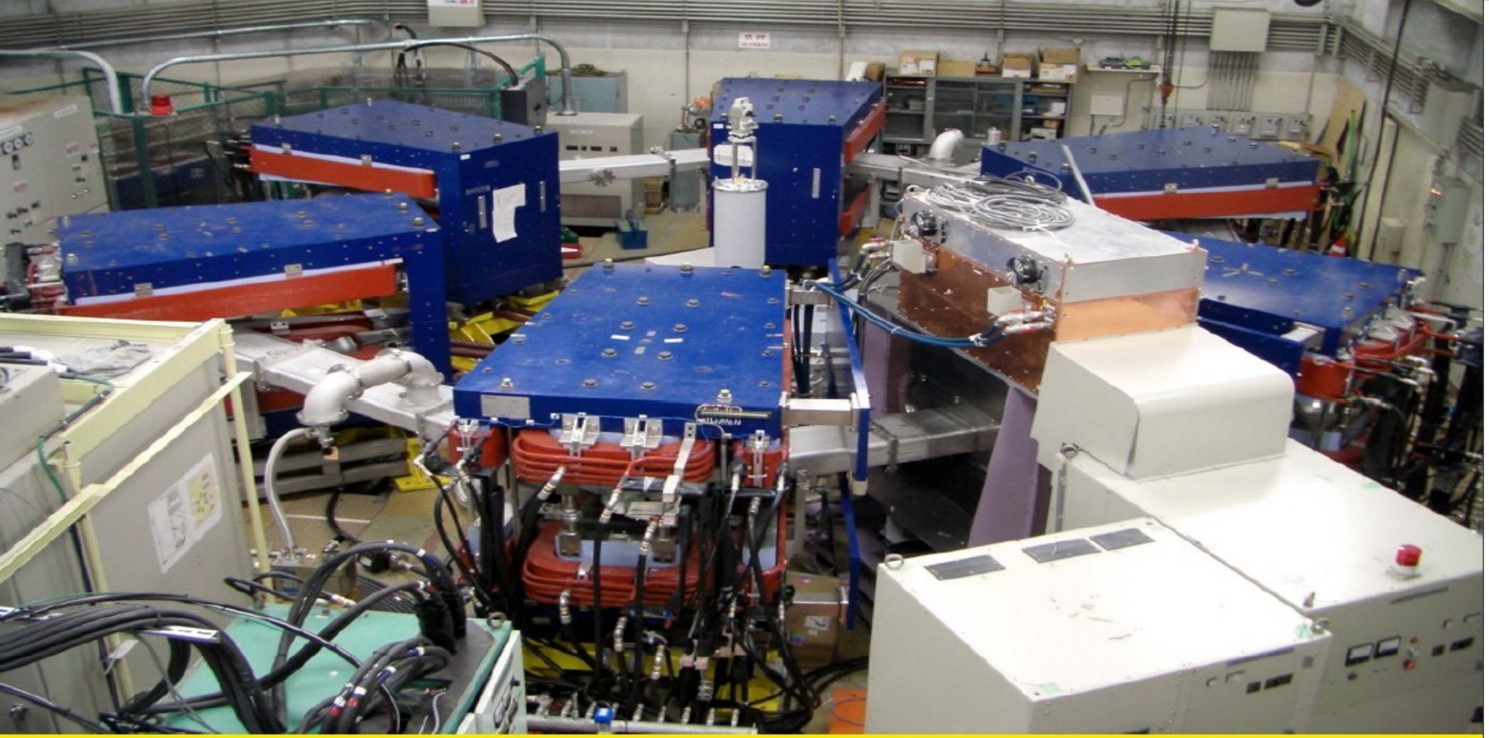
Pions

Muons

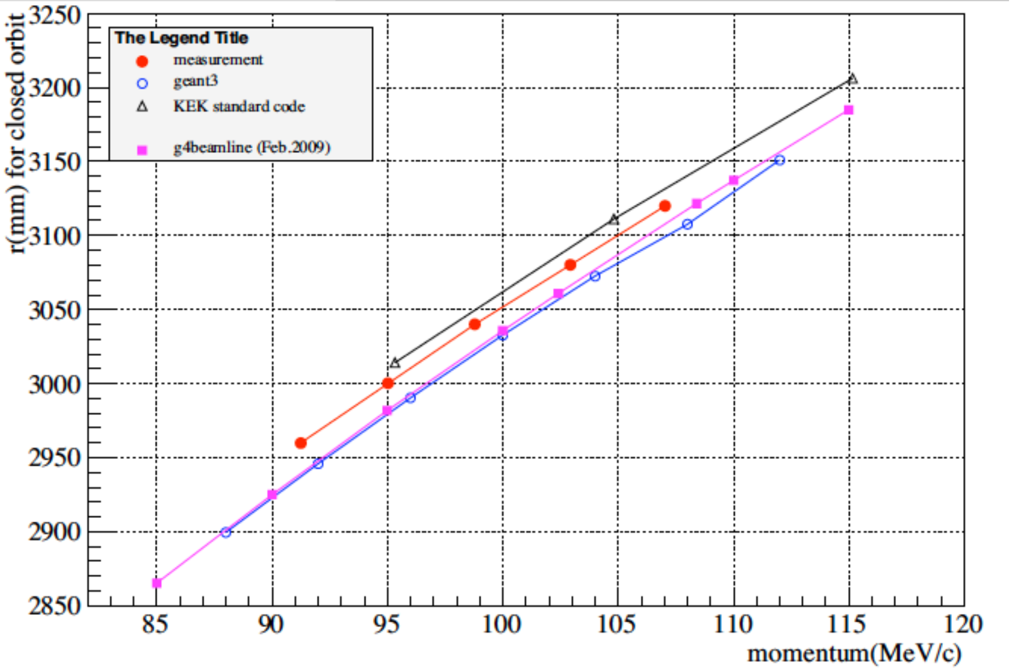
PRIME - conversion exp.

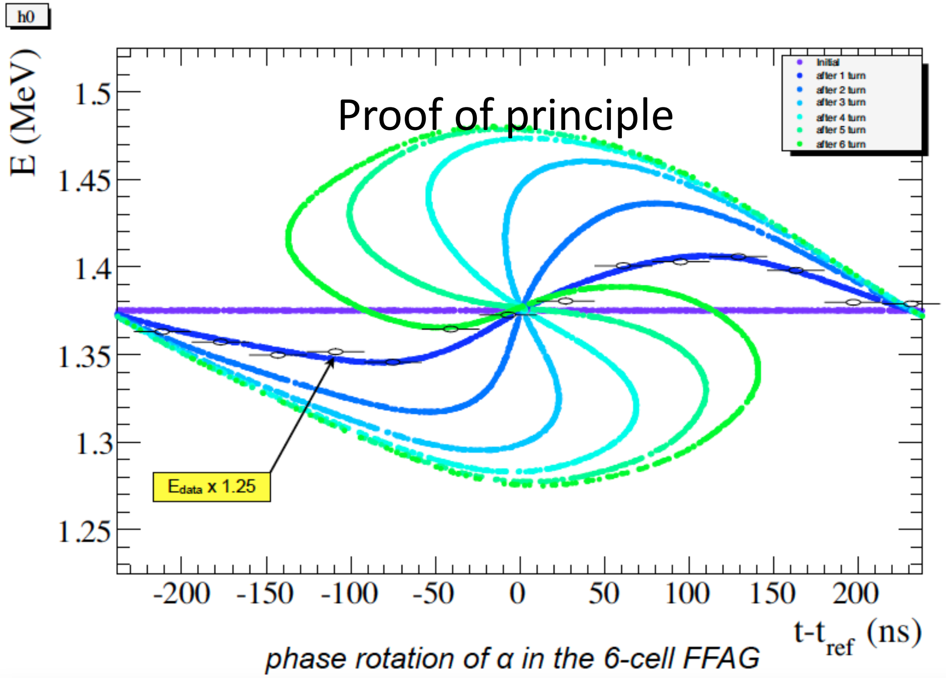
Large acceptance, circular FFA for Phase Rotation

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



6-sector PRISM-FFAG at RCNP, Osaka Univ.





phase rotation of α in the 6-cell FFAG

Initial baseline based on a scaling DFD triplet experimentally verified in prototype:

- Took data in 2009-10
- PRISM-FFAG Magnet x 6, RF x 1
- Beam : α-particles from radioactive isotopes
  - 241Am 5.48MeV(200MeV/c) → degrade to 100MeV/c

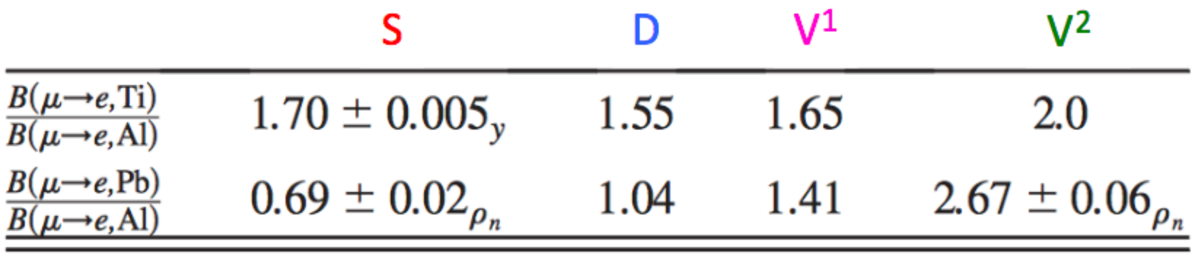
Caltech

AMF: Physics Advantages

- In AMF with the FFA we no longer need to worry about the beam backgrounds.
- Can extract muons from FFA slowly, no longer sit in beam pulse → don't need delayed live-gate!
- Gold and Lead are possible target materials → both provide discrimination in Lorentz structure of new physics!

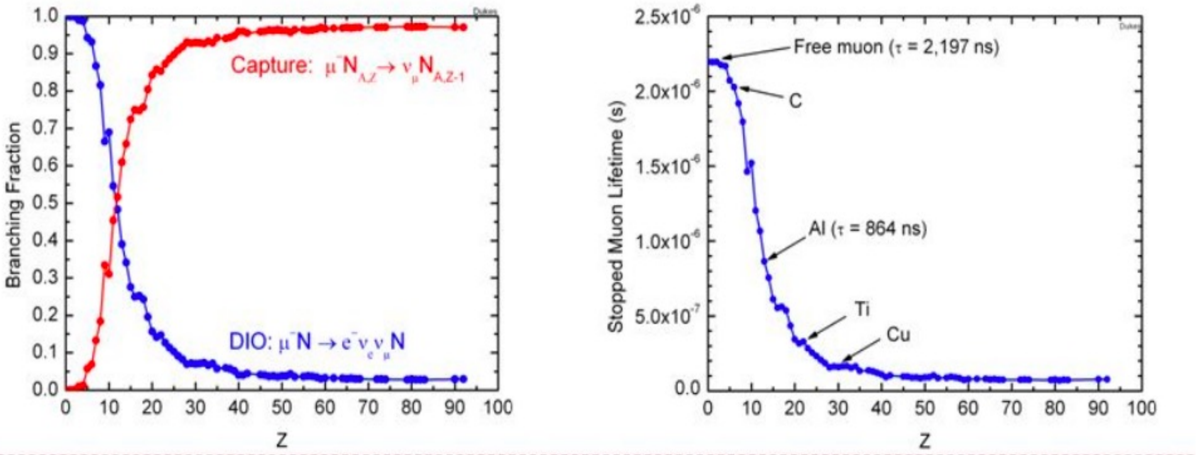
Nucleus	**Mean Lifetime [ns]**	**Conversion Electron Energy [MeV]**
Al(13,27)	864	104.96
Ti(22,~48 (multiple isotopes))	328	104.18
Au(79,~197)	73	95.56

Rates relative to Al for various new physics:



	S	D	V^1	V^2
$\frac{B(\mu\to e,\mathrm{Ti})}{B(\mu\to e,\mathrm{Al})}$	$1.70 \pm 0.005_y$	1.55	1.65	2.0
$\frac{B(\mu\to e,\mathrm{Pb})}{B(\mu\to e,\mathrm{Al})}$	$0.69 \pm 0.02_{\rho_n}$	1.04	1.41	$2.67 \pm 0.06_{\rho_n}$

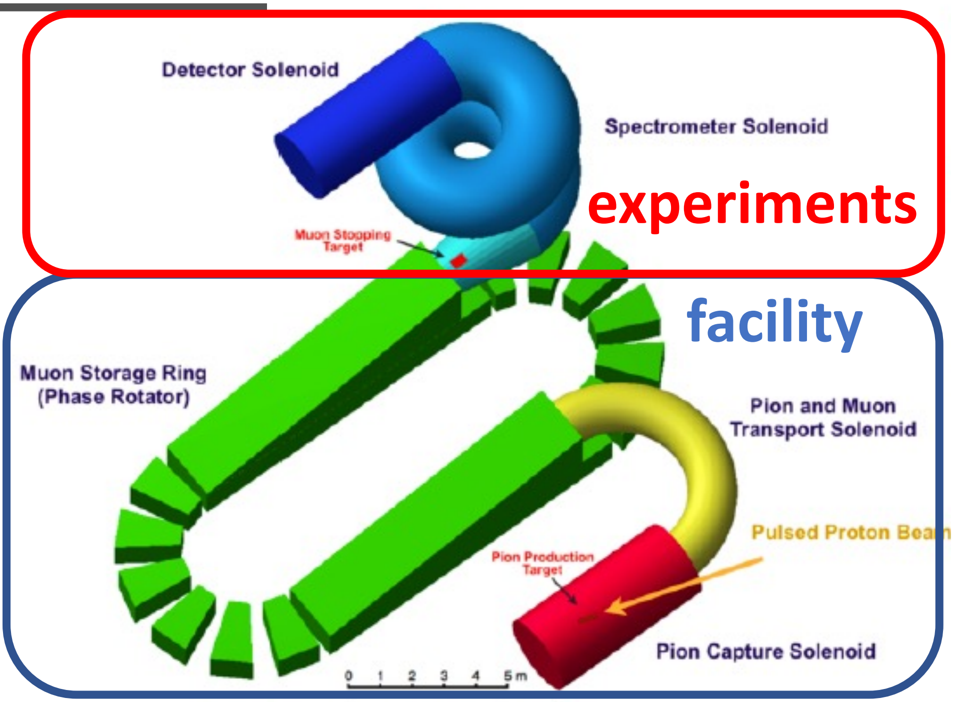
y = nuclear scalar form factor, ρ_n = nuclear neutron density



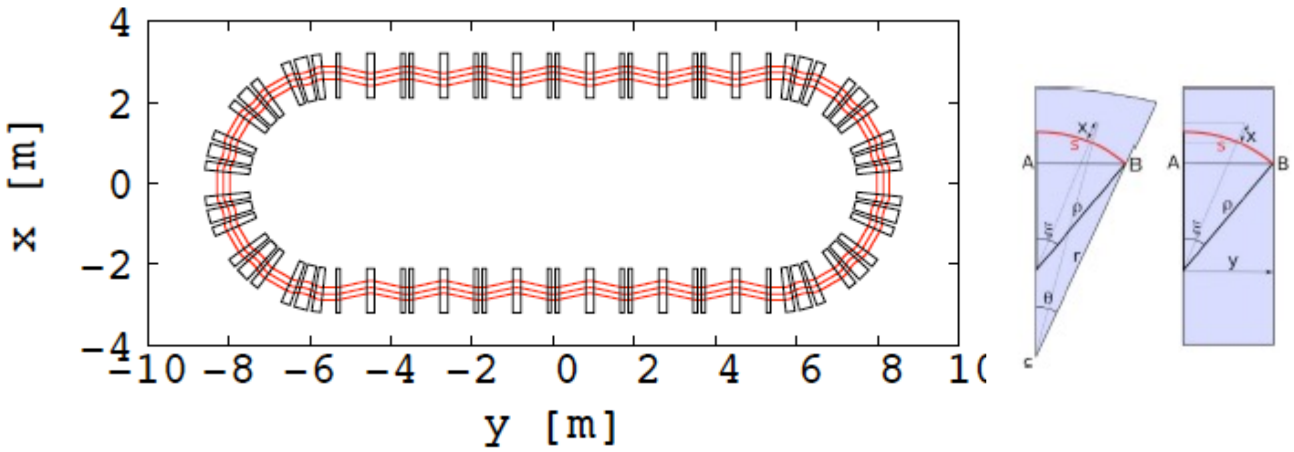
AMF: Racetrack FFA

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

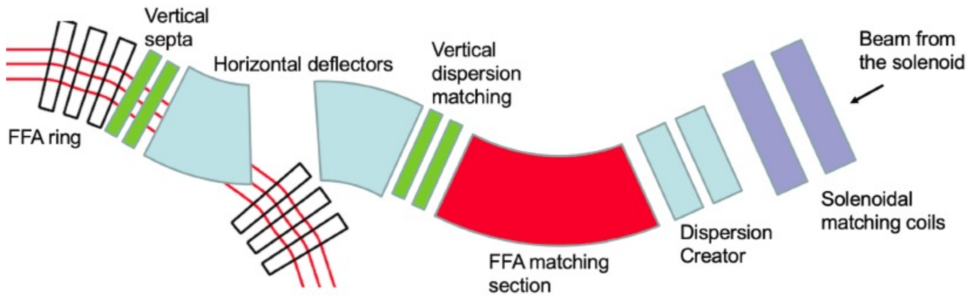
- If we circulate μ^- and μ^+ in the same facility we enable all CLFV searches.
  - need a racetrack for separate injection/extraction systems.
- Cells in straight sections with zero net bending and circular FFA cells in the compact arcs.
- Loses symmetry, but the extra space makes injection and extraction easier.
- **Importantly: can accommodate lower momentum muons**
  - central momentum 20 - 40MeV/c which is << 68MeV/c in PRISM design.



(above) cartoon of possible layout (with conversion experiment)

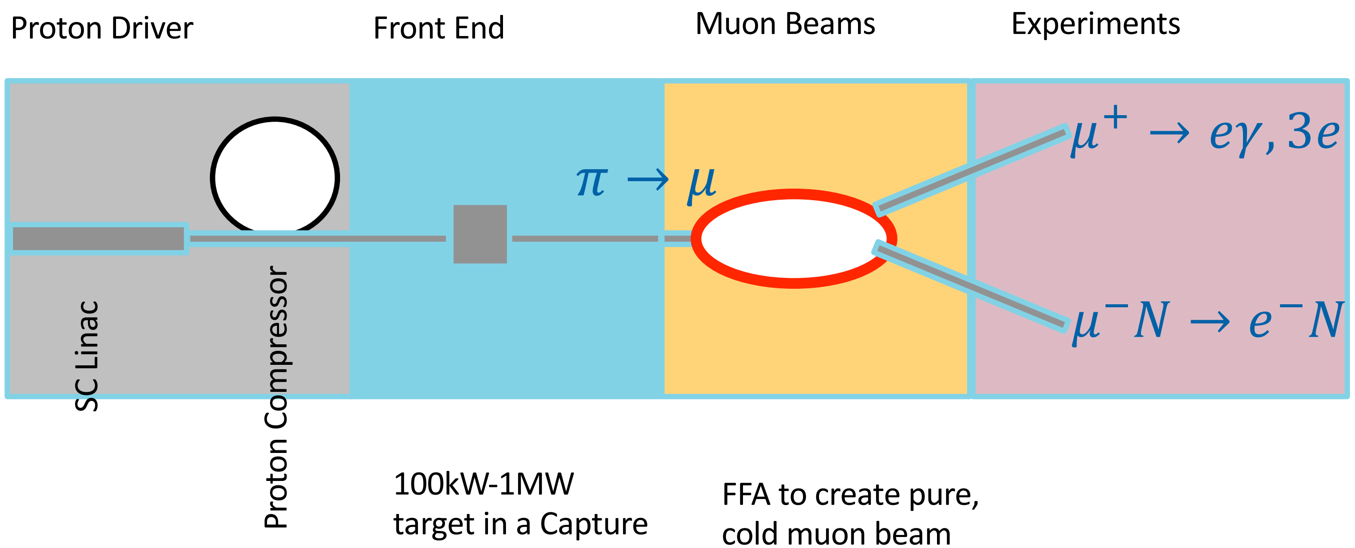


Closed orbits of 55 MeV/c, 68 MeV/c and 82 MeV/c muons



(below) Possible injection scheme

AMF: Cartoon Overview



100kW-1MW
target in a Capture
Solenoid

FFA to create pure,
cold muon beam

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

AMF: Compressor Scenarios

- AMF requires a very short proton pulse, O(10 ns) long at 100-1000 Hz.
- Need a “compressor ring” to accumulate protons and extract them with the requisite bunch structure.
- Required normalized emittance to maintain a maximum tune shift of < 0.2 for rings of 100 or 500 m at 100,500, 1000 kW total beam power. Assuming a 100 Hz extraction rate:

	C = 100 m			C=500 m (PAR)		
Power [kW]	**100**	**500**	**1000**	**100**	**500**	**1000**
$N_b[10^{12}]$	7.8	39.1	78.1	7.8	39.1	78.1
$\varepsilon_N\,[\pi$-mm-mr]	54	268	536	268	1339	2678
Radius ($\beta_\perp$ =20m) [mm]	26	58	83	58	131	185

Number of bunches **Particles per bunch**

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

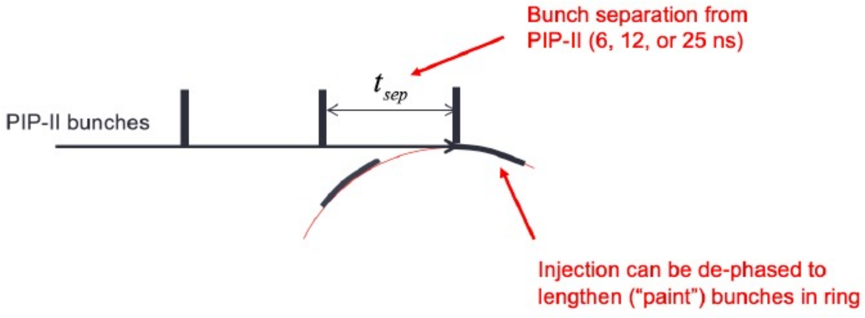
Maximum space charge tune shift **Relativistic βγ factors** **Transverse emittance (prop to beam-size squared)**

A ring with a circumference of 100m, performs x5 better!

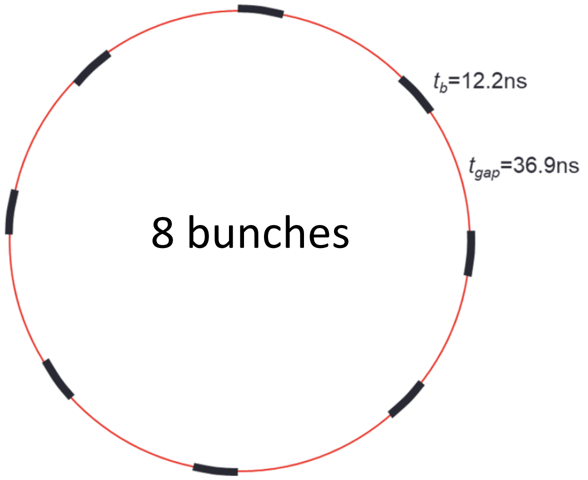
→ Space charge tune shift can be mitigated by keeping the circumference of the ring as small as possible.

AMF: 100m Compressor Scenarios

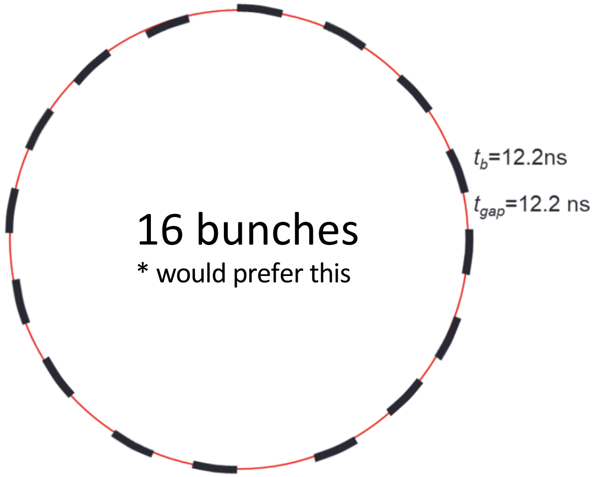
Injection into compressor:



Fill every bucket, every other bucket, or every X buckets.



$f = 20.3$ MHz
$P_{max} = 500$ kW



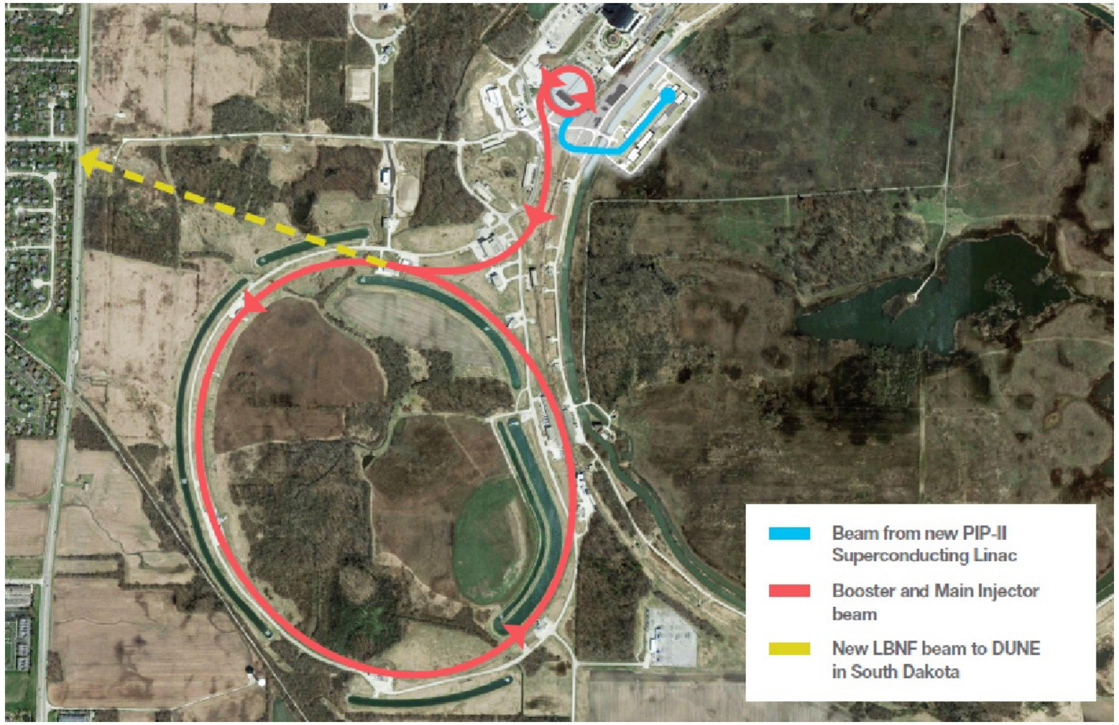
$f = 40.6$ MHz
$P_{max} = 1000$ kW

Extraction: extract each bunch one at a time, using extraction kickers with 10-30ns rise/fall time (should be possible, compare 60ns Booster kickers).

Single-bunch extraction at a rate of 100 Hz (compare SNS 60 Hz).

Accelerator Complex in PIP-II/LBNF Era

- New PIP-II SRF Linac provides beam for injection into existing Booster at 800 MeV instead of current 400 MeV
- Booster cycle time is increased to 20 Hz from 15 Hz
- Proton flux at 8 GeV increases x2: 1.2 MW from Main Injector



Accelerator Complex Evolution (ACE) is about further improvements:

- increasing power
- increasing reliability
- increasing flexibility

Accelerator Complex Evolution (ACE)

- Extend Superconducting RF (SRF) Linac to higher energy or construct new Rapid Cycling Synchrotron

- Provides
  - 2.4 MW to LBNF (x2 improvement)
  - 120 GeV beam for other experiments

- Potential new science "spigots"
  - 2 GeV Continuous Wave (CW) ← *muon CLFV Program?*
  - 2 GeV Pulsed (~1 MW)
  - 8 GeV Pulsed (~1 MW)

- Platform for collider R&D

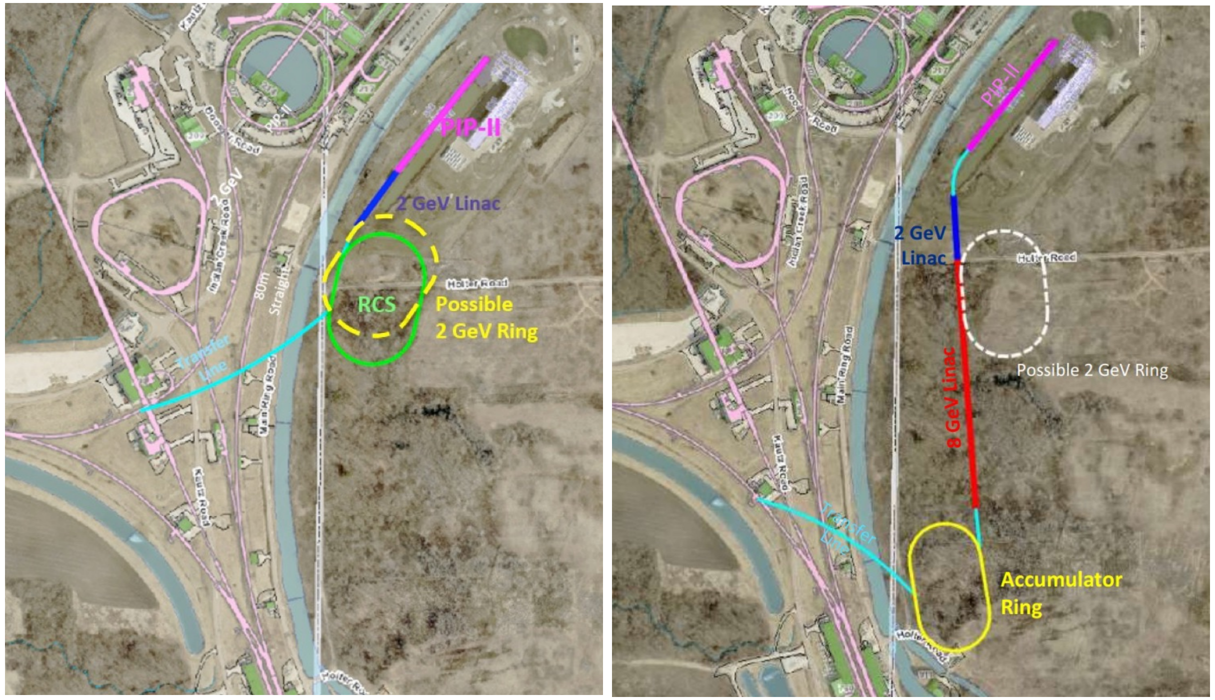
- Front-end of future multi-TeV collider ←*Muon Collider Program*

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

ACE Options

Two Options:

1. PIP-II 2 GeV linac → rapid cycling synchrotron up to 8 GeV → to Main Injector
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.



- Planning is happening now!
    - workshop at FNAL 14-15 June https://indico.fnal.gov/event/59663/
    - **which option is chosen defines any future muon program!**

Targetry: 1MW Targeting

- The environment at the Production Solenoid end will be very different from Mu2e.
  - We will need to re-think our production target design!

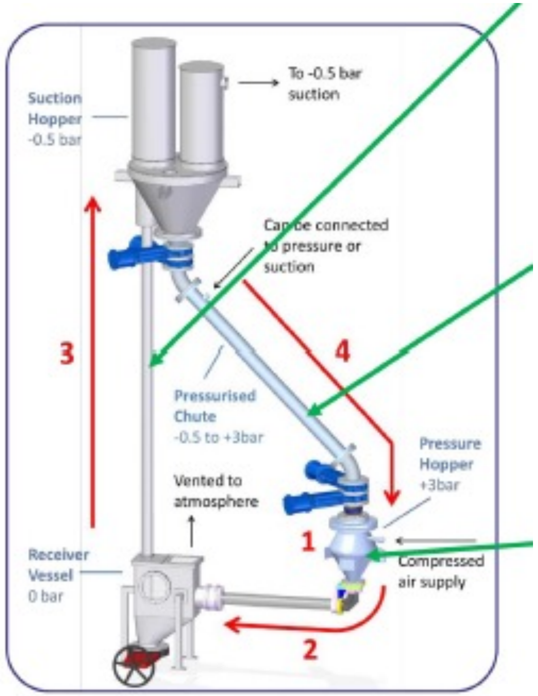
- Previous designs for similar complex envisioned a liquid target:
  - **MERIT experiment (possible proof of principle?)**:
    - Liquid mercury - (not an option due to environmental issues);
    - Rep. rates only about 70 Hz, limited by disruption of the jet.

Recent Results from the MERIT Experiment

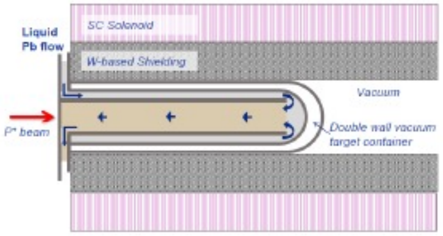
https://aip.scitation.org/doi/pdf/10.1063/1.3399332

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

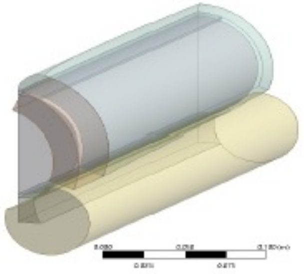
- **R&D required to design target for the AMF target!**
  - **Exciting synergies with muon collider R&D here.**



Fluidized Tungsten



Liquid Lead Flow



Lead Curtain

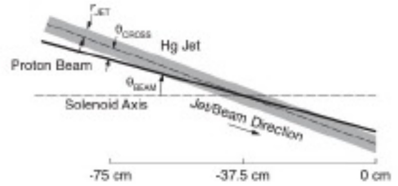


FIG. 3. The mercury jet target geometry. The proton beam and mercury jet cross at $z = -37.5$ cm.

Liquid jet

Caltech

$N\mu^- \rightarrow Ne^-$ 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 a number of technical challenges:

- **Detector 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:**
        - Expect that dominant background will be cosmic rays producing electrons in signal region – we need a Cosmic Ray Veto system x 100-x 1000 better than Mu2e – how do we do this?

- **Detector Solenoid:**
    - Still have activity from muon capture, how does detector survive?
    - **Several ideas being discussed, many detailed simulation studies required to propose a concept.**

$N\mu^- \rightarrow Ne^-$ 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.

Decay Experiments

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

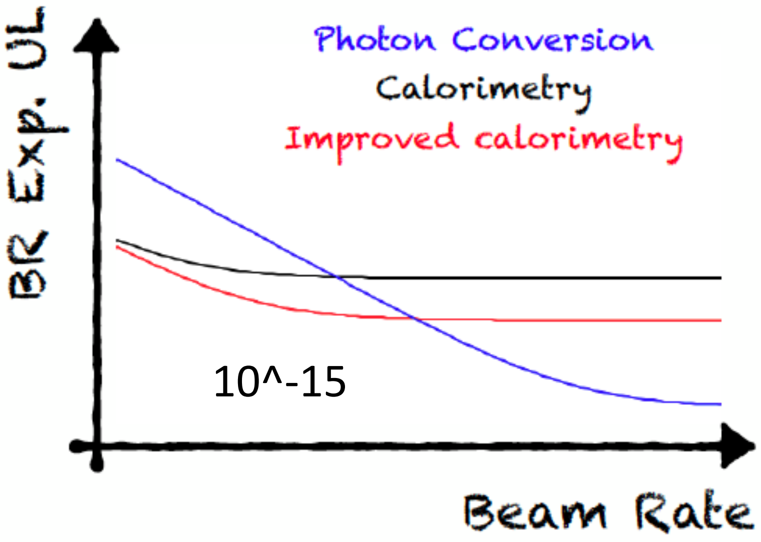
- **These experiments require μ^+:**
  - Get muons from pions, more π^+produced from protons on target than π^-
  - Eliminate muon capture possibility, produces accidental backgrounds
  - Don't have to worry about pion capture backgrounds
    - Latter two cause backgrounds at conversion experiments.

- **These experiments require a lower momentum beam which is also advantageous for the conversion experiment.**
  - $\boldsymbol{\mu}^+$of $\sim$ 30 MeV brought to rest in material creating a surface muon beam;
  - $\mu^+ \to e^+\gamma$: accidental backgrounds come from multiple muon decays and resolution limits → we want as continuous a beam as possible (needs thought)
  - $\mu^+ \to e^+e^+e^-$: additional backgrounds from radiative muon decay.

Decay Experiments

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

- **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)
- Could we do $\mu^+ \rightarrow e^+\gamma$ & $\mu^+ \rightarrow e^+e^+e^-$ in same machine?
- **Need to understand how to accommodate both μ^+ and μ^- :**
  - one question we asked is: can we do both searches with a single facility?
  - the other question is can we produce μ^+ and μ^- beam simultaneously, or do we need to alternate? We're trying to come up with a scheme to allow both beams at the same time.



Muonium Oscillations

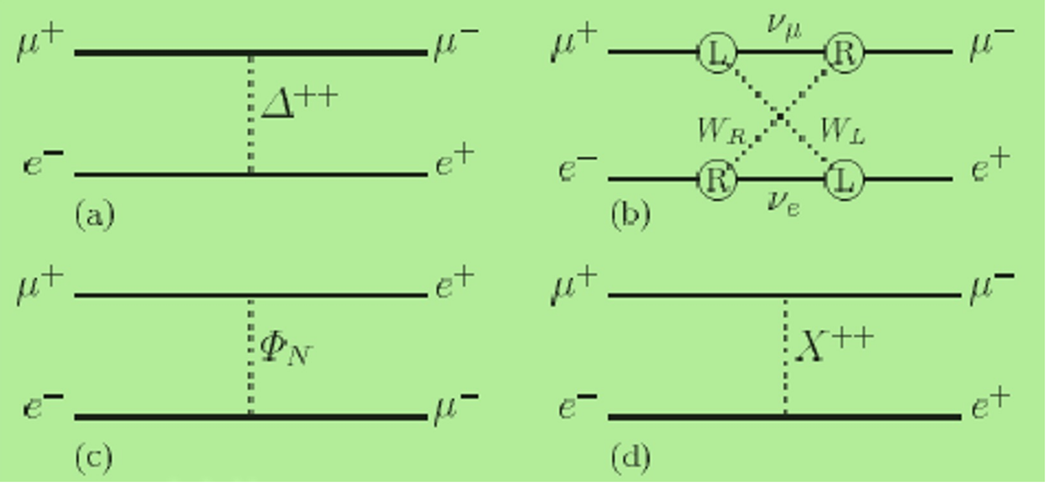
- Once such application is for muonium-antimuonium oscillations.
  - Doubly CLFV-ing.
- **Limit set by MACS at PSI: $P(M\bar{M}) \leq 8.3 \times 10^{-11}$ (90% C.L.) in 0.1 T.**
- MACE proposal: https://arxiv.org/abs/2203.11406

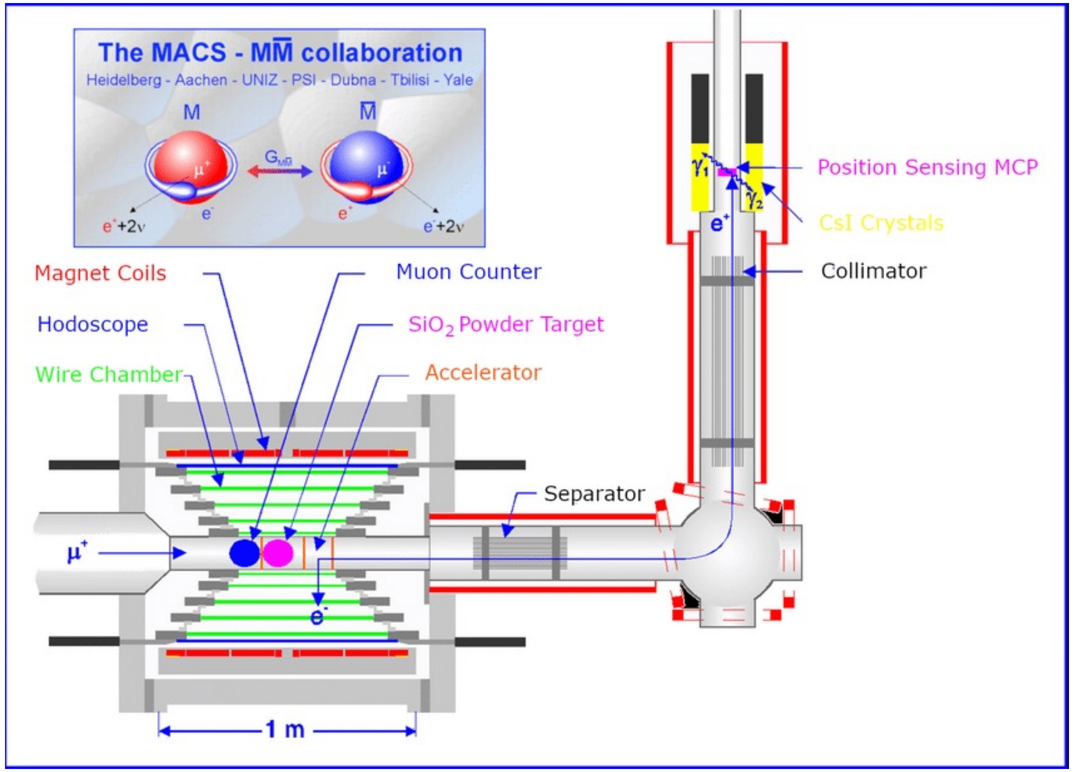
$$\mu^+ e^- \leftrightarrow \mu^- e^+$$

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

Making Muonium:

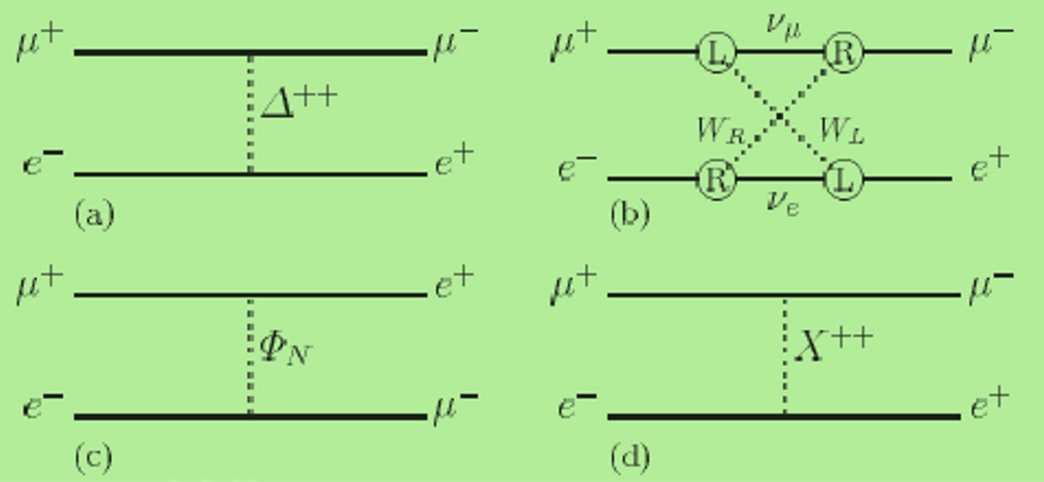
- Need a sub-surface beam - lower momentum distribution than surface beams;
- Smaller straggling and tighter spatial stopping distribution;
- μ^+ stop in SiO_2 powder, a technique invented at TRIUMF, prevents escape.





Muonium Oscillations

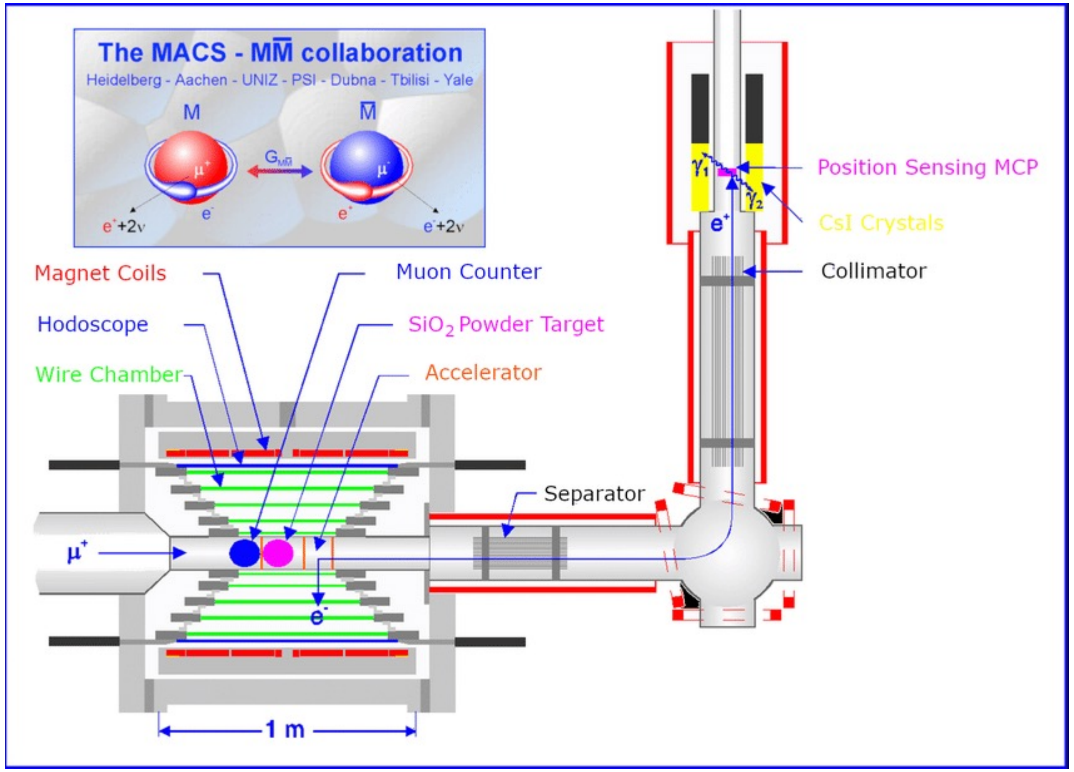
Signal = μ^- coinciding with an e^+;
Backgrounds = $e^+ e^-$ scattering and rare $\mu^+ \rightarrow e^+e^+e^-\nu_e\bar{\nu}_\mu$.



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!



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 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

  - In the case of AMF, the ring is filled with 16 bunches evenly spaced, separated by 24 ns. A kicker fires every 100 Hz removing exactly one of the bunches at a time. The resulting pulse structure is 8×10^{13} protons over 12 ns every 100 Hz.
  - **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.**

Summary

AMF: bringing the future of muon physics to Fermilab

Summary

- AMF is a proposed new facility that would deliver the most intense muon beams in the world. It is well motivated from that perspective, and 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. Can utilize ACE.
- 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.

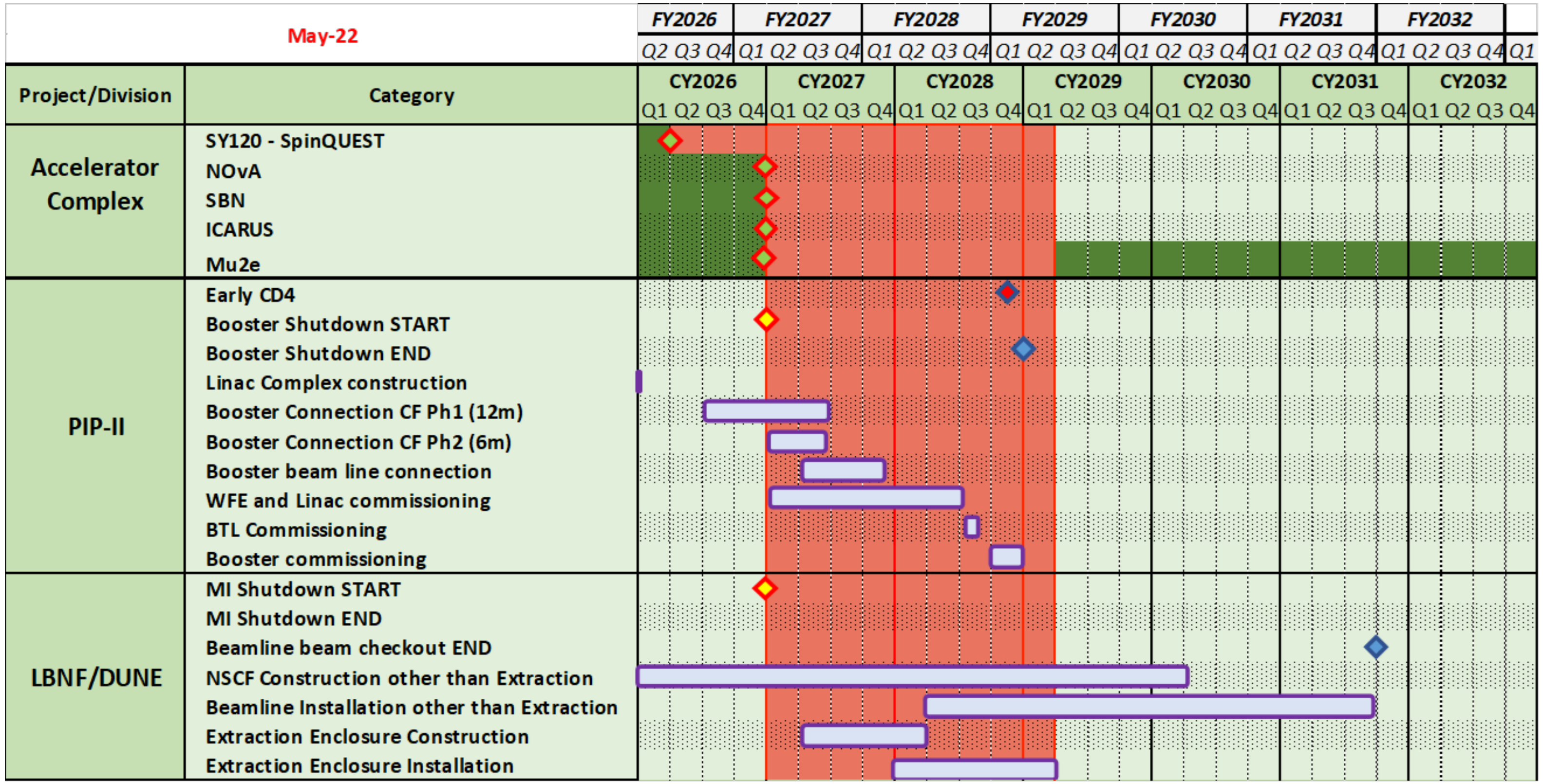
Thank you for listening!

Any Questions?

Additional Slides

A few more details…

When Might This Happen?



May-22

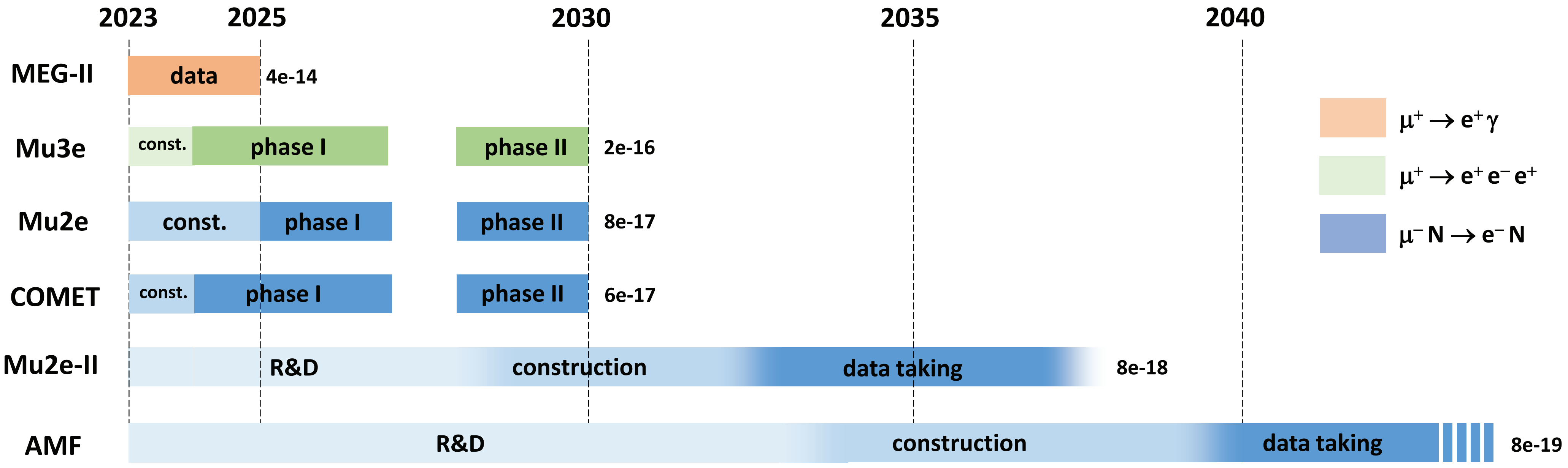
Project/Division	Category
Accelerator Complex	SY120 - SpinQUEST
	NOvA
	SBN
	ICARUS
	Mu2e
PIP-II	Early CD4
	Booster Shutdown START
	Booster Shutdown END
	Linac Complex construction
	Booster Connection CF Ph1 (12m)
	Booster Connection CF Ph2 (6m)
	Booster beam line connection
	WFE and Linac commissioning
	BTL Commissioning
	Booster commissioning
LBNF/DUNE	MI Shutdown START
	MI Shutdown END
	Beamline beam checkout END
	NSCF Construction other than Extraction
	Beamline Installation other than Extraction
	Extraction Enclosure Construction
	Extraction Enclosure Installation

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!

When Might This Happen?



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

🟧 $\mu^+ \to e^+\gamma$

🟩 $\mu^+ \to e^+ e^- e^+$

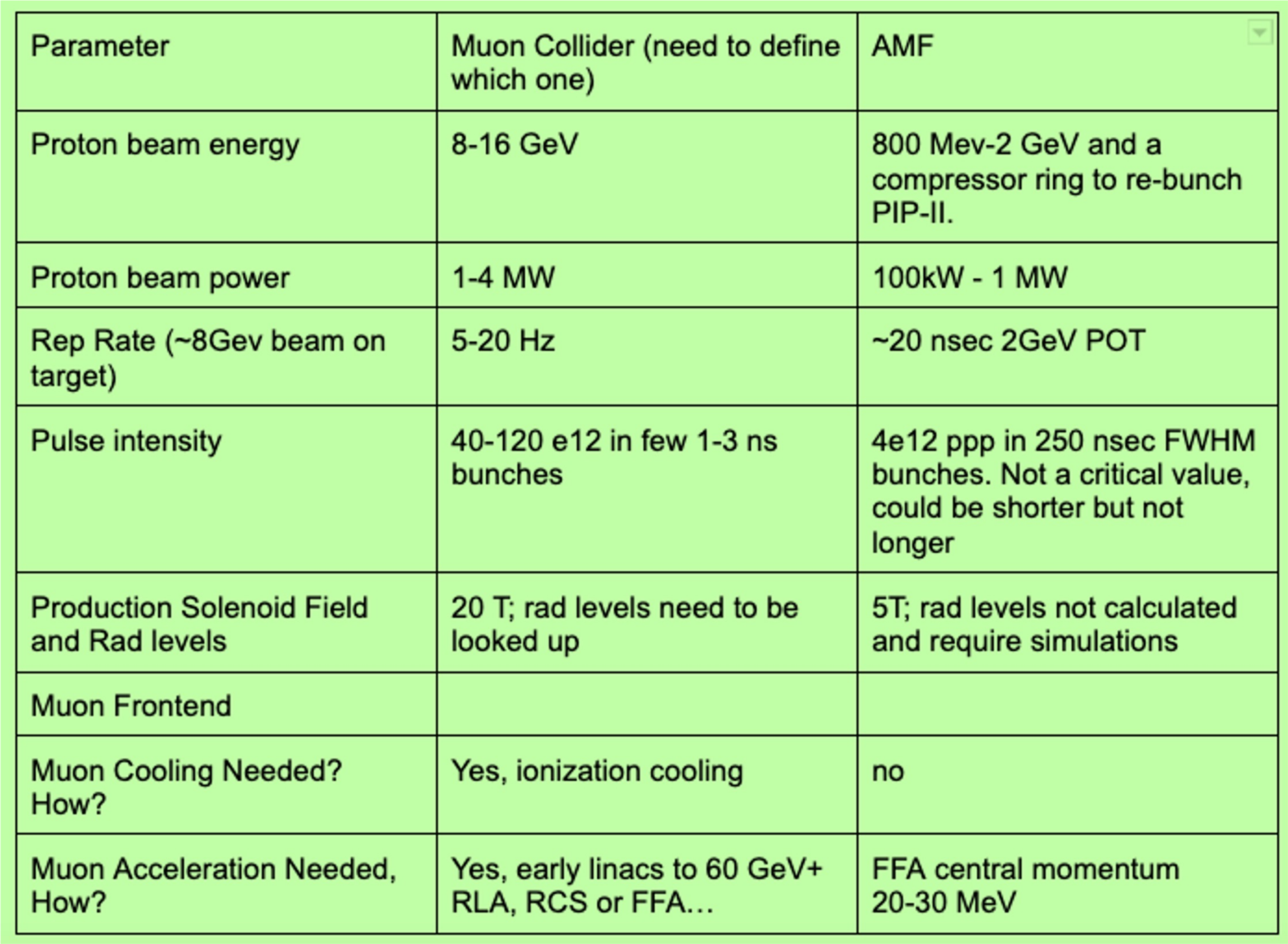
🟦 $\mu^- N \to e^- N$

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?

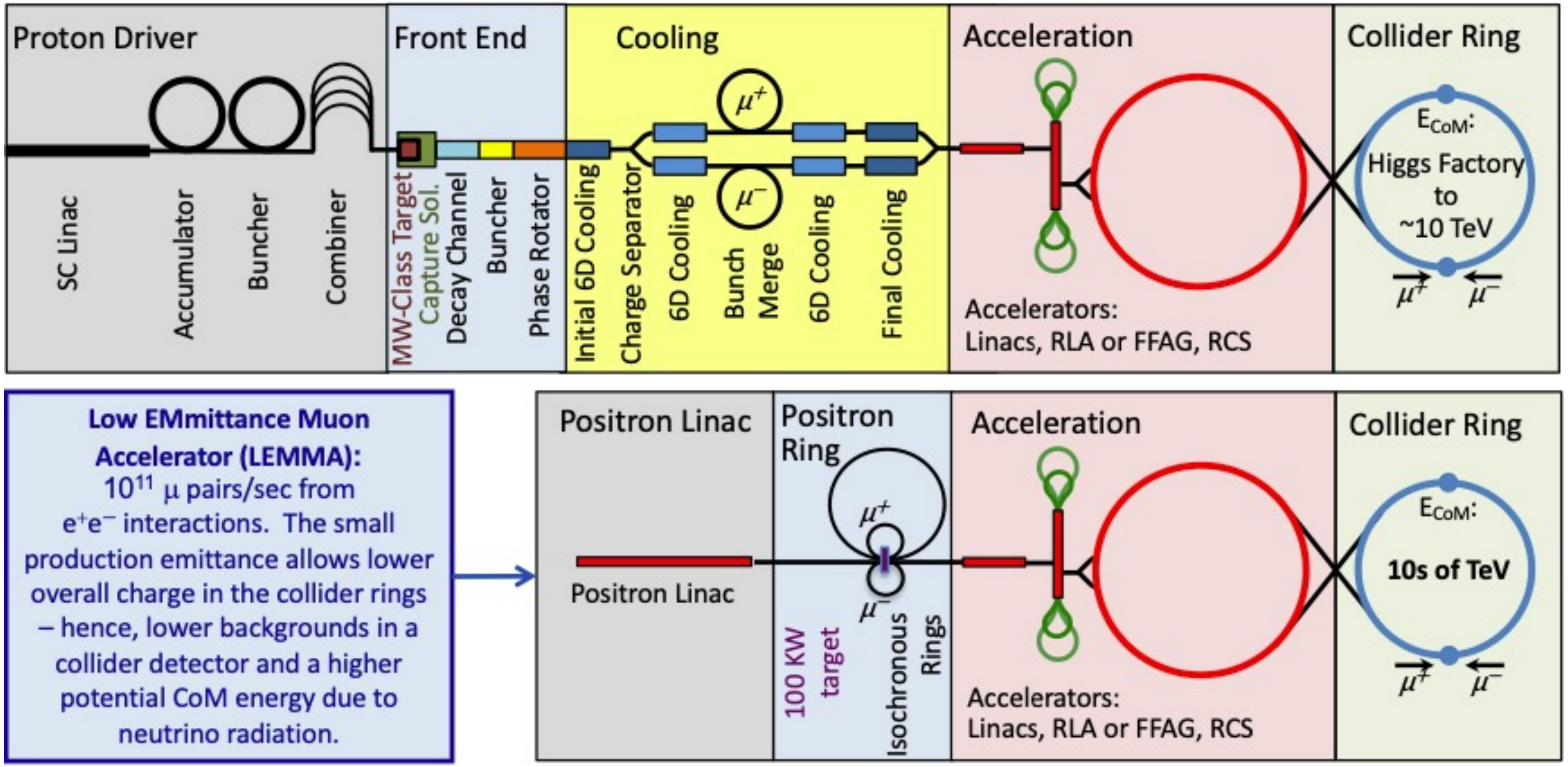


Parameter	Muon Collider (need to define which one)	AMF
Proton beam energy	8-16 GeV	800 Mev-2 GeV and a compressor ring to re-bunch PIP-II.
Proton beam power	1-4 MW	100kW - 1 MW
Rep Rate (~8Gev beam on target)	5-20 Hz	~20 nsec 2GeV POT
Pulse intensity	40-120 e12 in few 1-3 ns bunches	4e12 ppp in 250 nsec 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



Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

Muon Collider Options

- Fermilab ACE program has many overlaps with Muon Collider R&D
- Could provide a path for a Muon Collider front-end
- Again, see ACE workshop

Muon Collider Proton Driver Parameters	
Energy	5-15 GeV
Rep. rate	5-10 Hz
Ave. Beam Power	1-4 MW
Proton structure	1-3 ns bunch with ~10^{14}

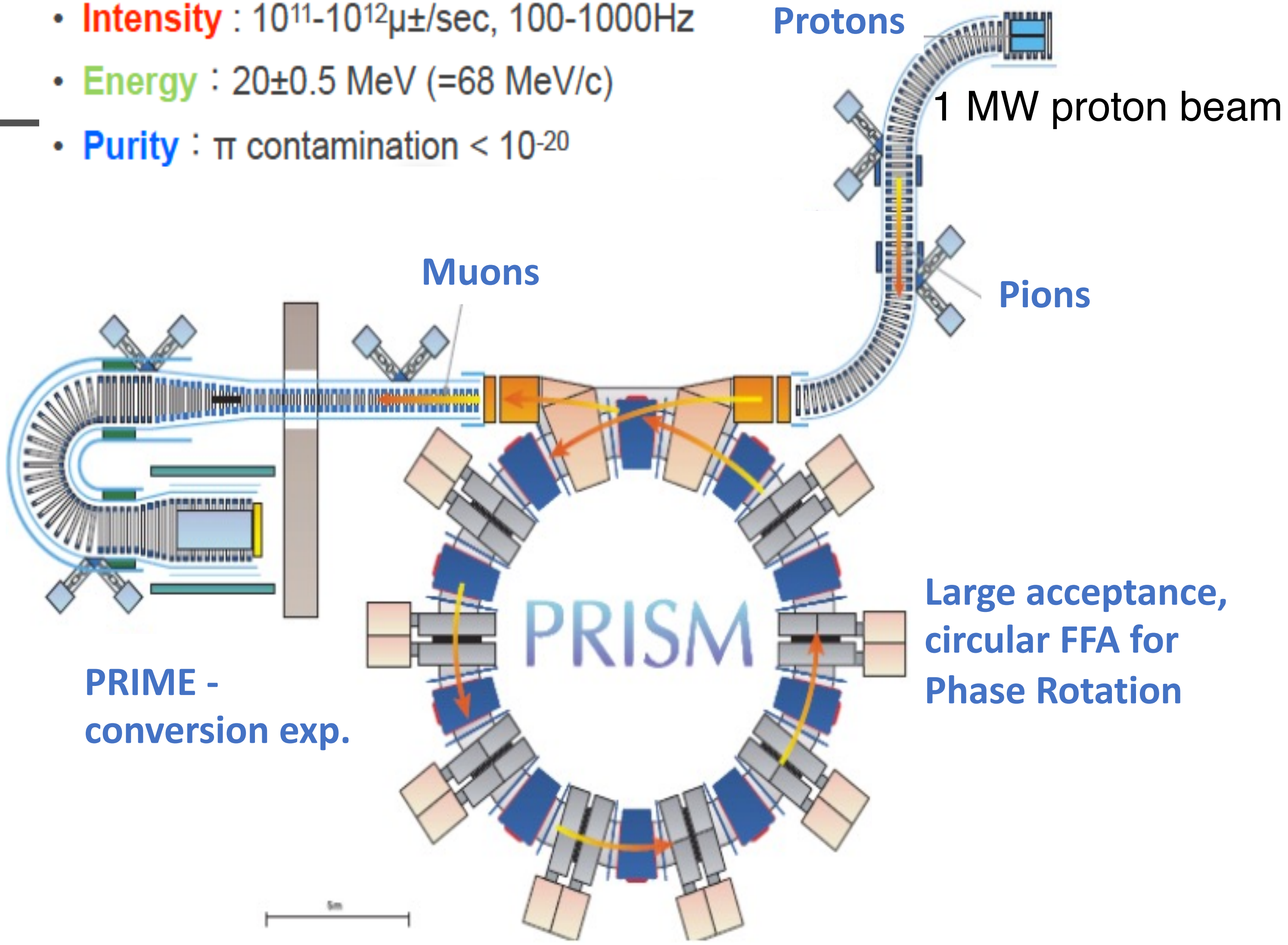
Muon Collider synergies with ACE program

ACE	Target	SRF	Proton Driver
Main injector upgrade	YES		
Booster replacement	YES	YES	YES

PRISM Concept

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

- **Injection:**
  - momentum : 68MeV/c $\pm$20%
  - beam size: 100cm x 30cm
  - time dist.: 40ns(/270ns)
  - kicker fall time < 230ns
- **Extraction:**
  - momentum : 68MeV/c $\pm$ 2%
  - beam size: 70cm x 30cm
  - time dist. : 200ns(/270ns)
  - kicker rise time < 70ns-100ns



Large acceptance, circular FFA for Phase Rotation

PRIME - conversion exp.

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

Mu2e-II

Extending Mu2e into PIP-II era

Motivations

Mu2e-II aims to improve the sensitivity ($R_{\mu e}$)to the neutrinoless conversion of a muon-to an-electron in the field of a nucleus by a further order of magnitude than Mu2e i.e. SES $\sim\vartheta(10^{-18})$

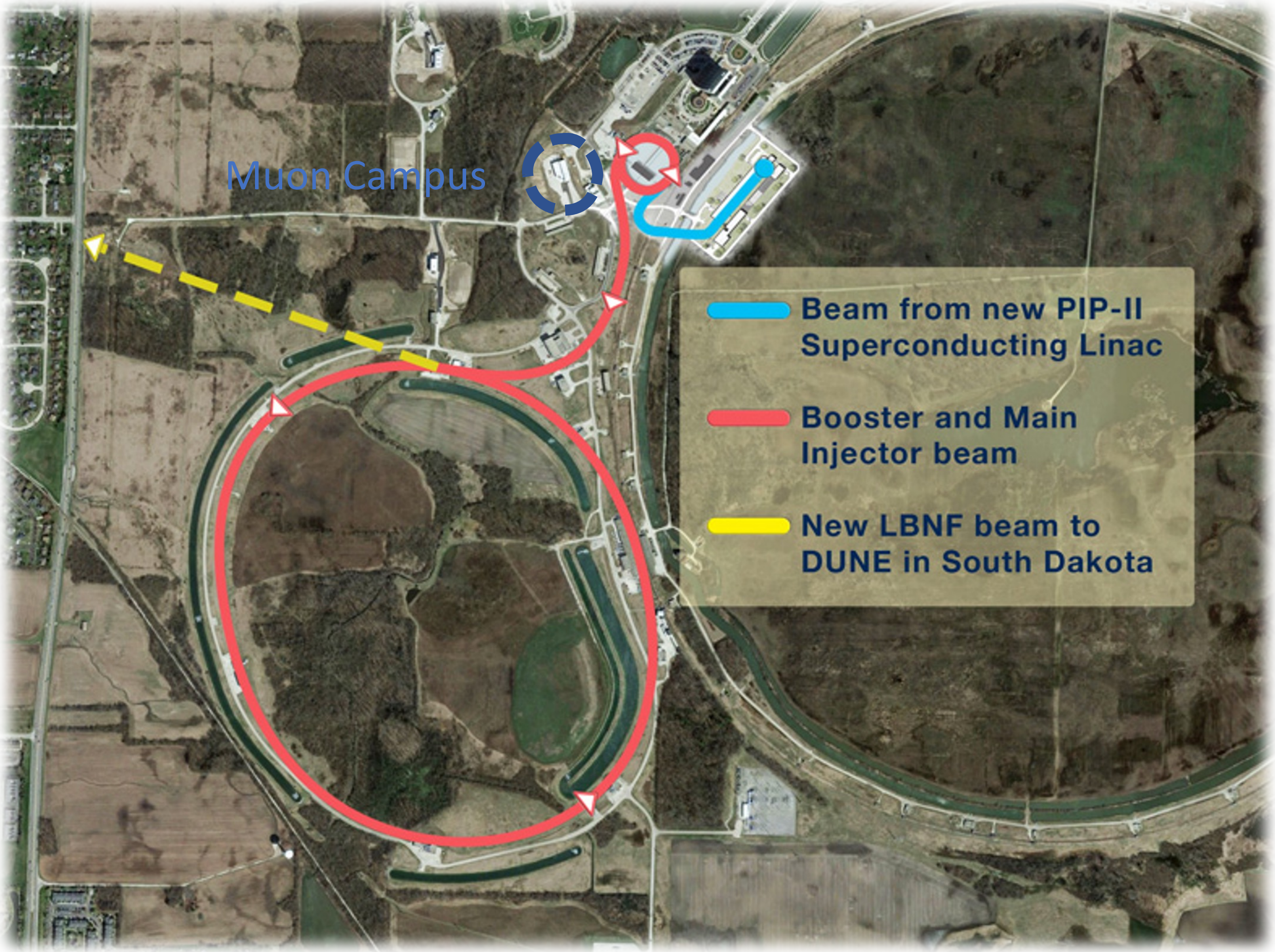
- **There are 2 possible outcomes from Mu2e:**
  1. **Conversion not observed** - motivates pushing to higher mass scales.
  2. **Conversion observed** - motivates more precise measurements with different targets.
- **Either way Mu2e-II is well motivated!**

Mu2e-II would:

- Be based at Fermilab. Will utilize the (nominal) 100kW 800MeV H- beam from Proton Improvement Plan II (PIP-II).
- Start a few years after the end of Mu2e run with an expected 3+1 years of physics running.
- Salvage and refurbish as much of Mu2e infrastructure as possible.
- Upgrade Mu2e components where required to handle higher beam intensity.

The purpose of the Snowmass 2022 study is to formalize ideas, simulate proposed geometries and assess the physics reach with the current design of the geometry.

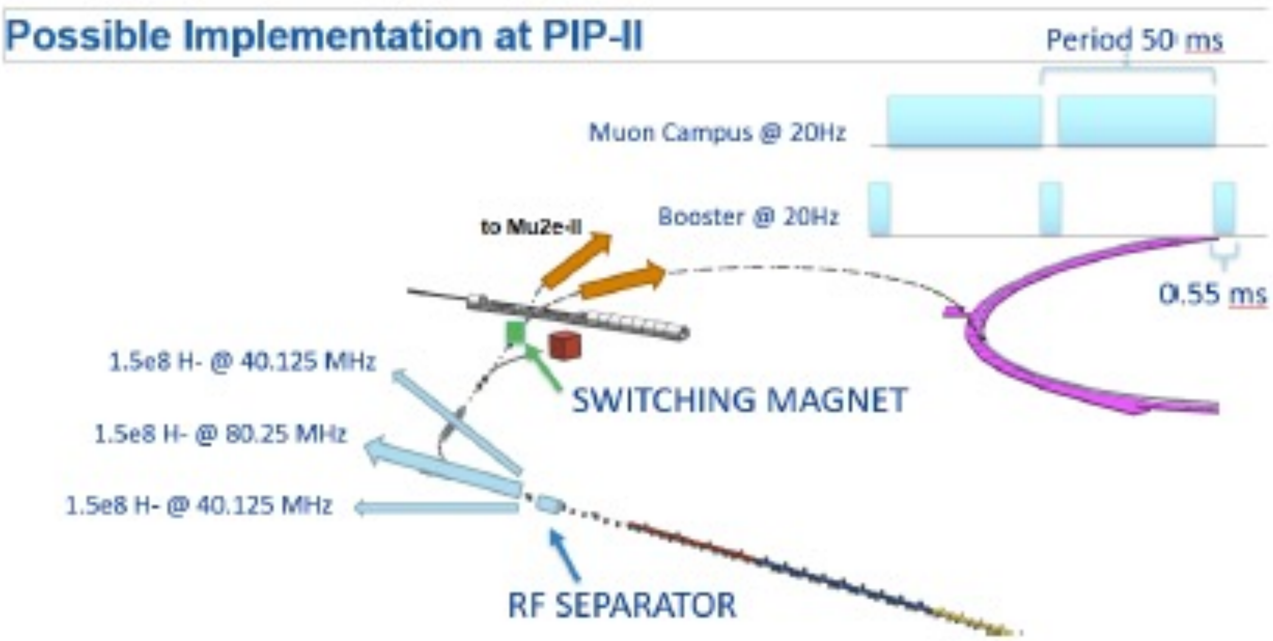
PIP-II

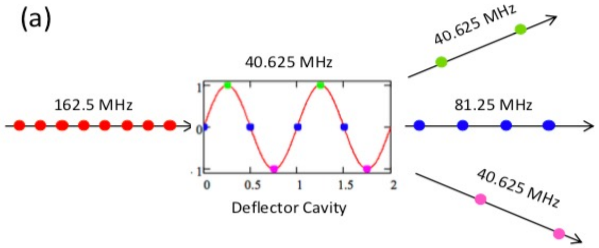


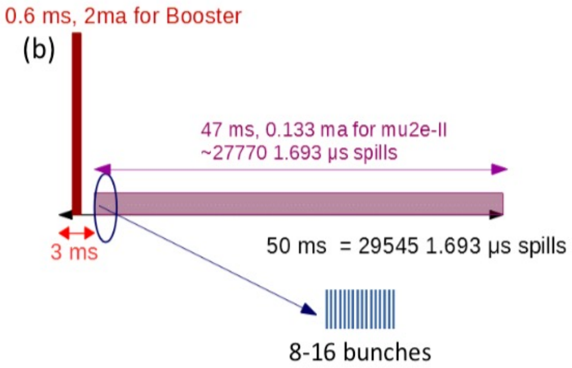
- PIP-II designed to deliver 800 MeV H- beam to the Booster.
- Chopper pattern can produce pattern filled or empty 162.5 MHz buckets
- Maximum current per bucket is ~ 5mA (1.93×10^8 H-)
- Mu2e-II will get a beam at upstream end of transfer line to Booster:
  - Need to build a beamline to deliver beam to M4 enclosure

Mu2e-II Beam Delivery

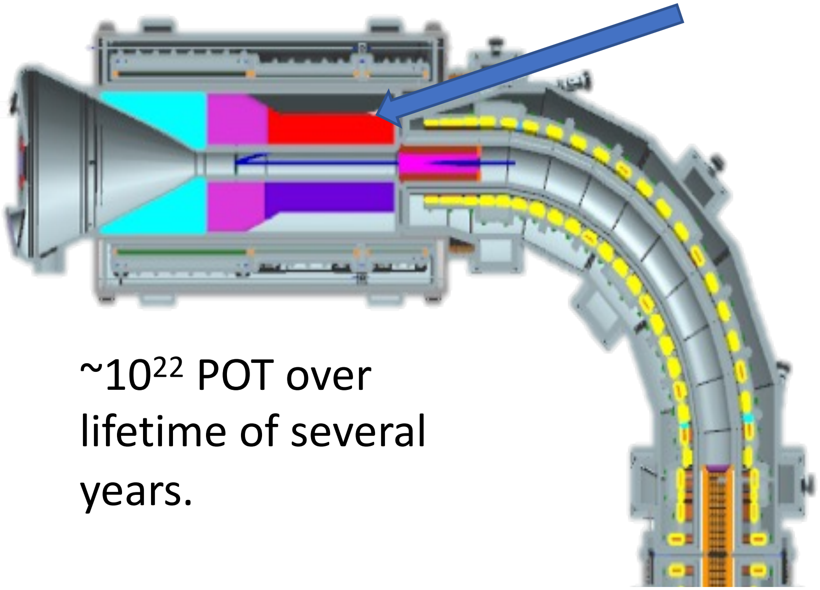
- Proposed beam structure at Mu2e-II (assuming 100 kW):
  - Leading concept for remaining beam involves a 40.625 MHz RF deflector to split the beam into three sub-lines - Mu2e-II will have access to receive bunches at up to 81.25 MHz.
  - Booster requires ~ 3ms out of 50 ms – the rest can be sent to Muon Campus
  - Beam structure like Mu2e – short spill followed by gap to match muon lifetime in the stopping target
- Mu2e-II needs 10 buckets in each spill – pulse will be ~ 62ns – compared to 250 ns as Mu2e
- Can consider running Mu2e-II at even higher beam intensities.







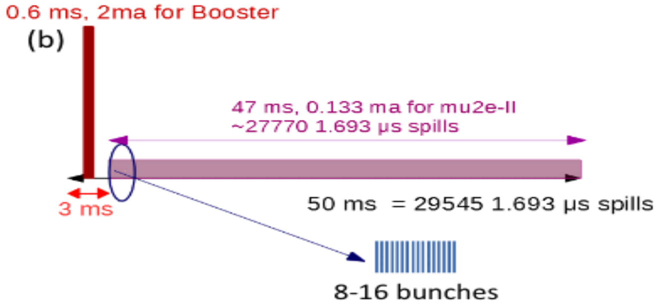
Mu2e-II

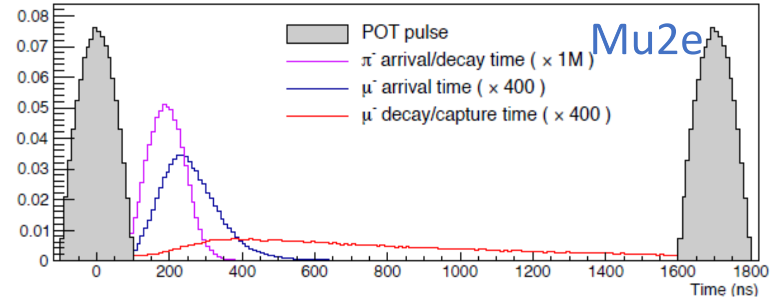


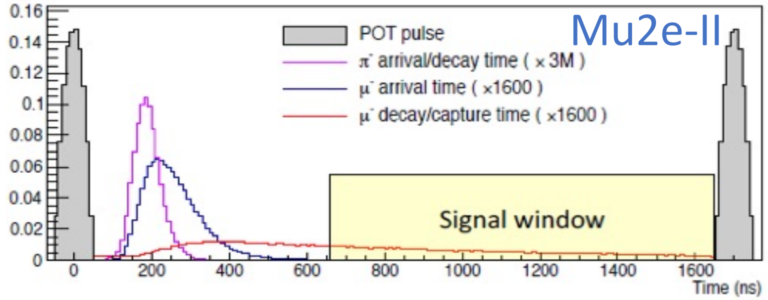
~10^{22} POT over lifetime of several years.

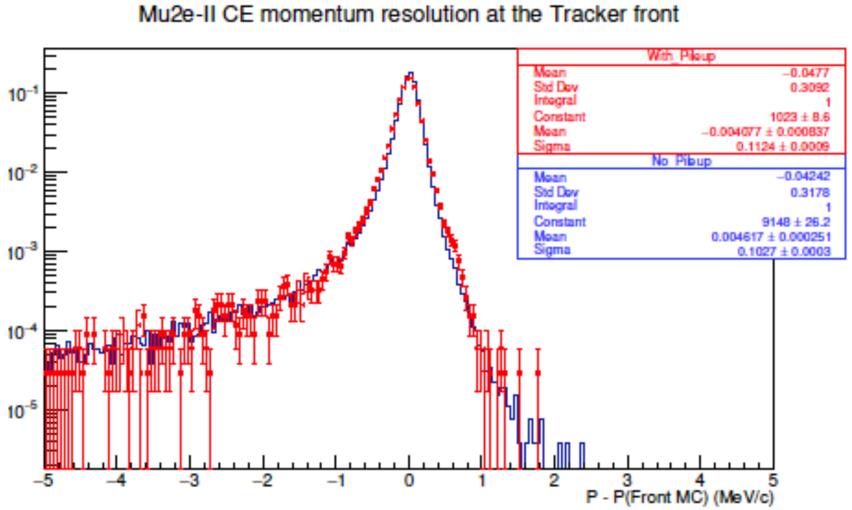
800MeV PIP-II beam means:

- Narrower pulses;
- Less pulse-to-pulse variation;
- Higher intensity;
- Higher duty factor.

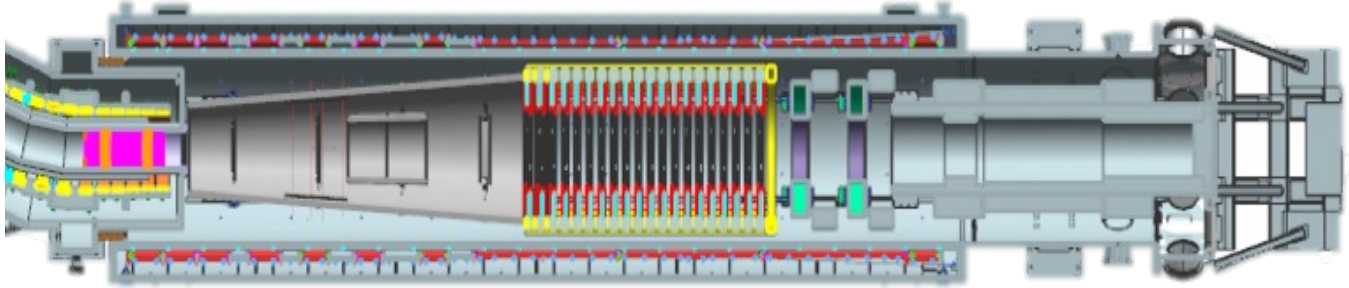








Estimated Stopped Muon rate = 0.00009/POT



Beam Requirements

- PIP-II can deliver these requirements to Mu2e-II

	Mu2e	**Mu2e-II**	**comments**
Source	Slow extracted from Delivery Ring	H- direct from PIP-II Linac	Mu2e-II will need t strip H- ions upstream of the production target
Beam energy [MeV]	8000	800	Optimal beam energy 1-3 GeV
Total POT	3.6×10^{20}	4.5×10^{22}	Approx.
Lifetime [yr]	3	5	
Run Time [sec/yr]	2×10^{7}	2×10^{7}	
Duty factor	25%	>90%	Important for keeping instantaneous rates under control
P pulse width [ns]	250	62	
P pulse spacing [ns]	1695	1700	Assumes Al target
Extinction	1×10^{-10}	1×10^{-11}	Ratio of out:in time protons
Average beam power [kW]	8	100	100kW approx.

Mu2e-II: 2022 Snowmass Contributed Paper

2-year long effort resulted in Snowmass Contributed Paper

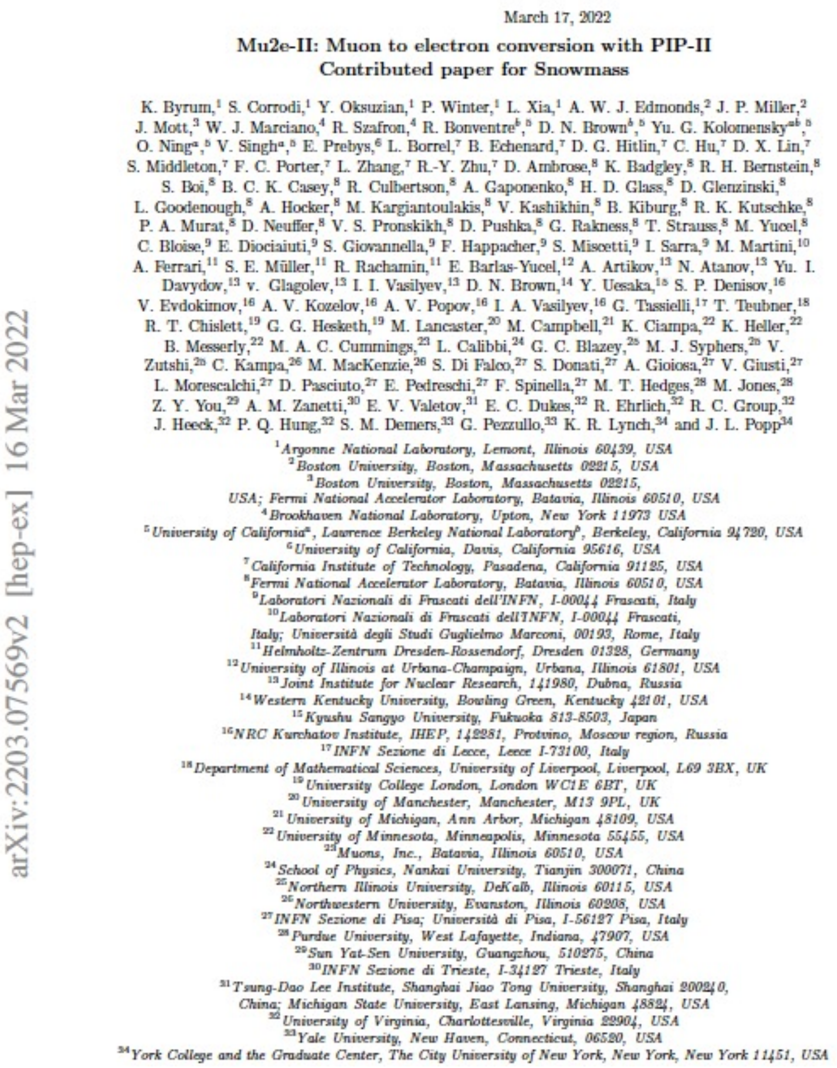
https://arxiv.org/abs/2203.07569

~100 co-signed
34 institutions
6 countries

Assumed:

- POT = 4.5 x 10^{22}
- 5 years of running
- **BaF_2 calorimeter crystals -** same dimensions as CsI
- **Straw tube tracker** - no gold layer and 8 µm straws
- **Carbon production target, conveyor design.**
- No $\bar{p}$ windows in TS.
- Mu2e Al stopping target with foil design.
- Mu2e reconstruction and trigger algorithms.
- Mu2e IPA dimensions.

Background	Mu2e	Mu2e-II (5 years)
Decay in orbit	0.144	0.263
Cosmics	0.209	0.171
Radiative Pion Capture (in-time)	0.009	0.033
Radiative Pion Capture (out-of-time)	0.016	< 0.0057
Radiative Muon Capture	< 0.004	< 0.02
Anti-protons	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}
$R_{\mu e}\ (90\%\ C.L.)$	6.01×10^{-17}	6.39×10^{-18}



arXiv:2203.07569v2 [hep-ex] 16 Mar 2022

March 17, 2022

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

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