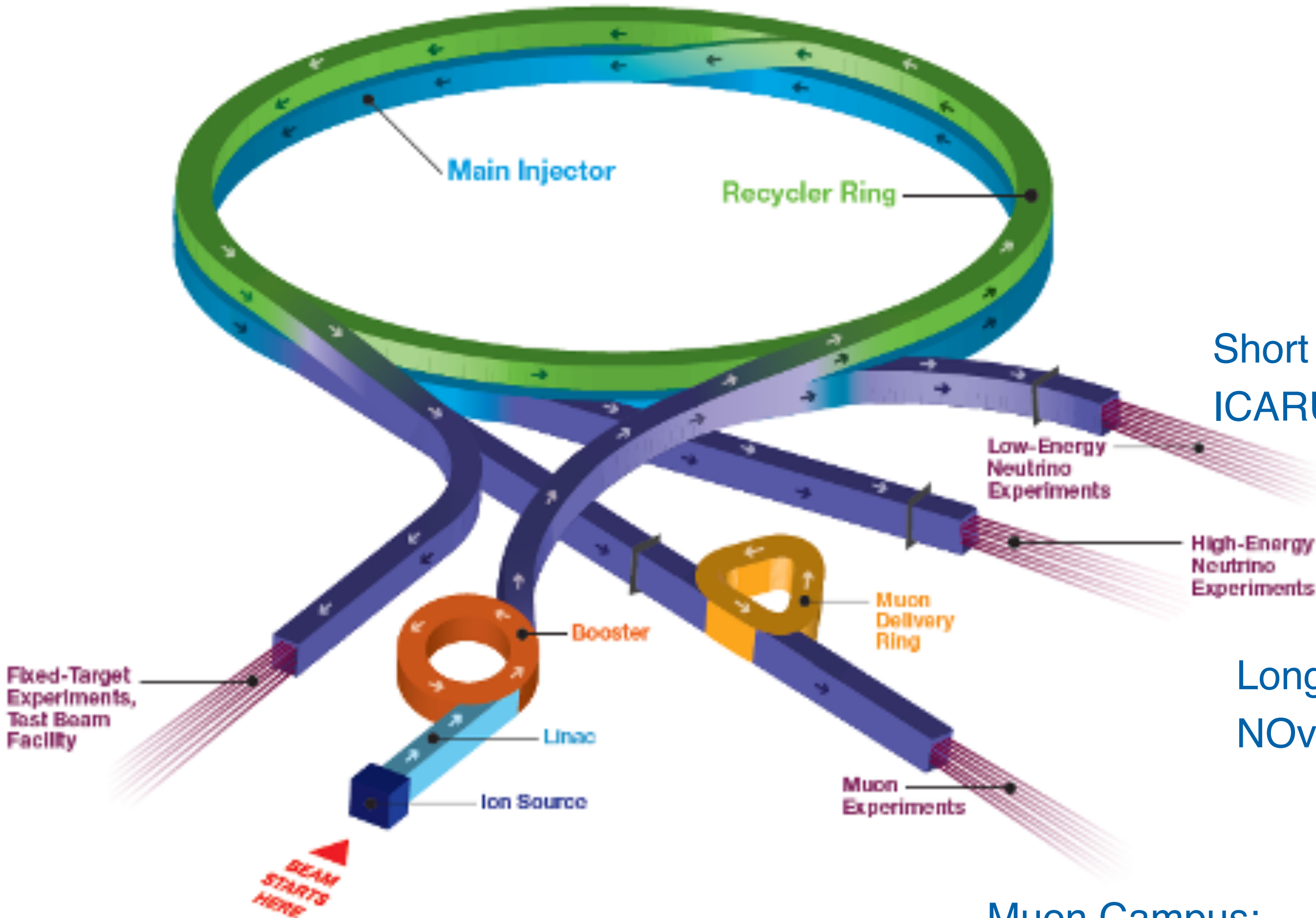
Fermilab Upgrades and a Future Muon Program

Robert Bernstein
Muon4Future, Venice
29 May 2023

Current Accelerator Complex



Short Baseline Neutrino:
ICARUS, ANNIE, SBND

Long Baseline Neutrino:
NOvA

Muon Campus:
g-2 (completes this year)
Mu2e (construction and commissioning)

Plans Relevant for Muon Program:

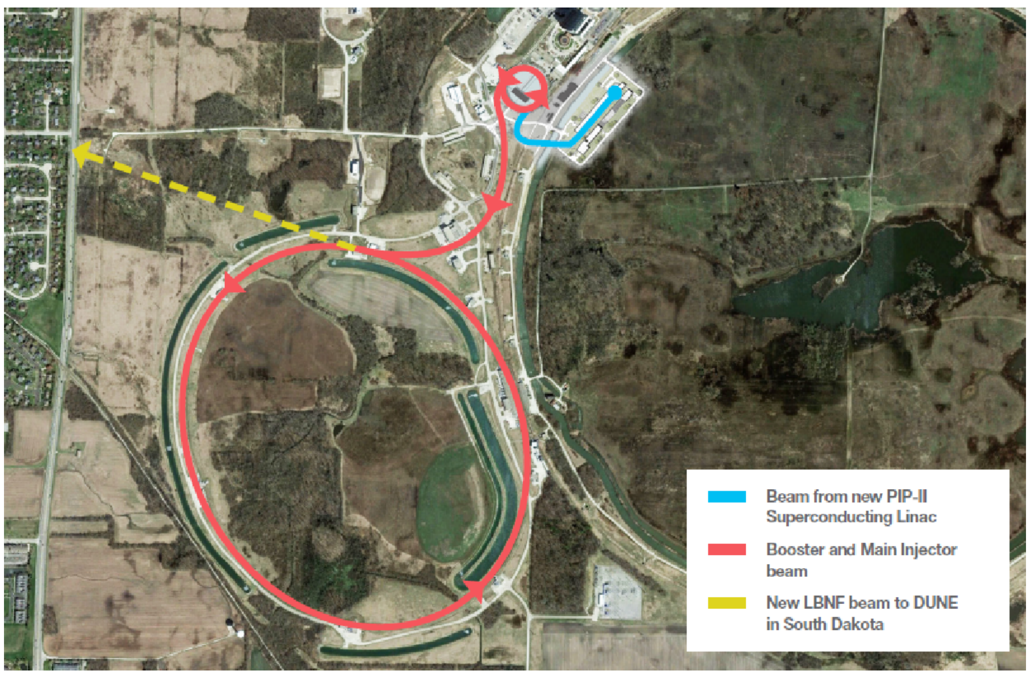
1) **Booster will be replaced**
2) **Muons will come from new PIP-II accelerator**

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 Enhancement (ACE) is about further improvements:

  - increasing power
  - increasing reliability
  - increasing flexibility

Accelerator Complex Enhancement

- 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; focus on this*
  - 2 GeV Pulsed (~1 MW) ← *possible backup but will have to be better understood; might be best for muonium-antimuonium oscillations*
  - 8 GeV Pulsed (~1 MW)

- Platform for collider R&D

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

ACE Options

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

- Looking at three options of each type

- All six ((SRF or RCS)=2 x three options each) require extension of SRF Linac to 2 GeV
  - future plans may go to an even higher energy (will discuss later)

- 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

- *input from muon community is needed!*

Muon Collider Options

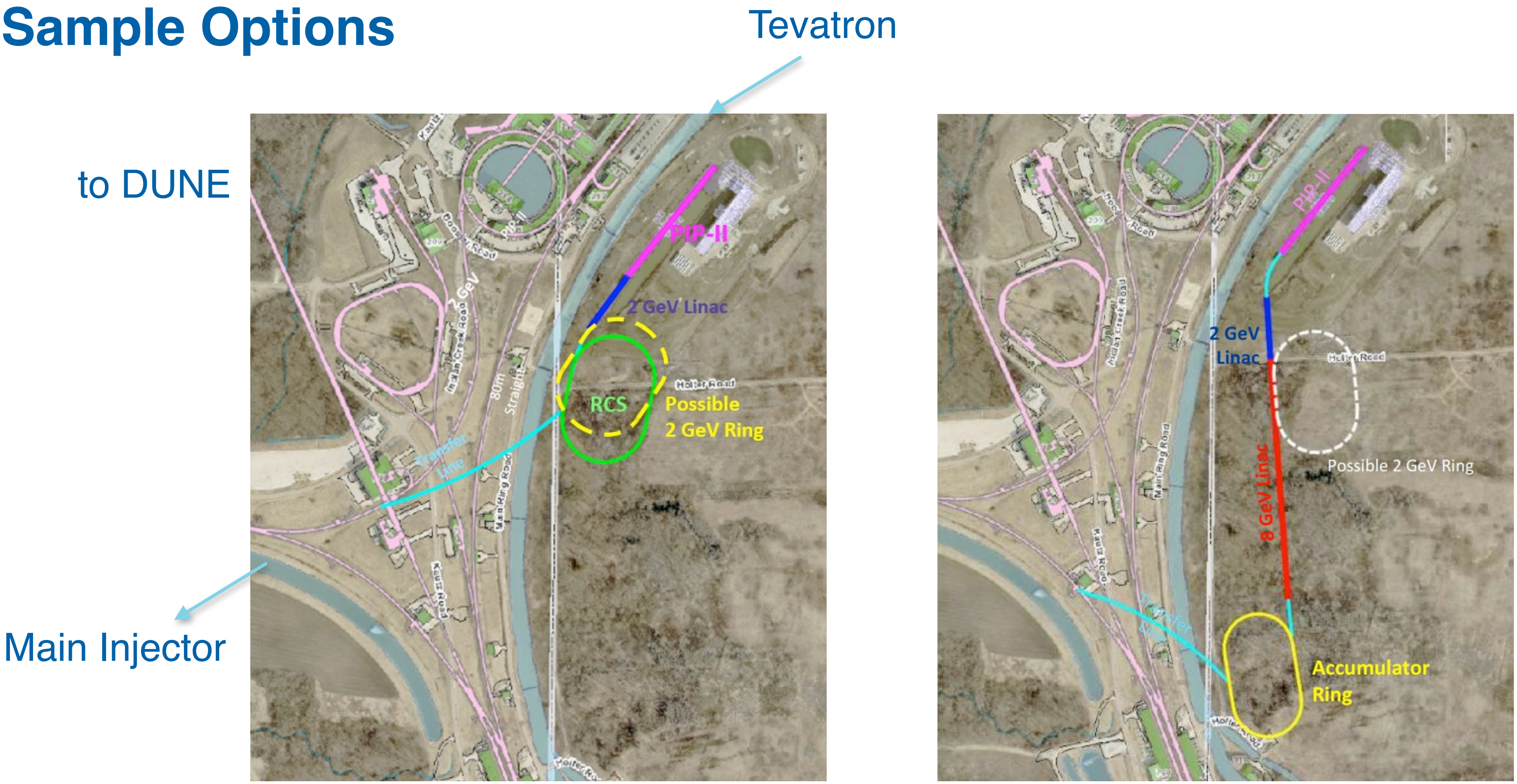
- Fermilab ACE program has many overlaps with Muon Collider R&D
- Could provide a path for a Muon Collider front-end
- Again, see ACE workshop

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

Sample Options

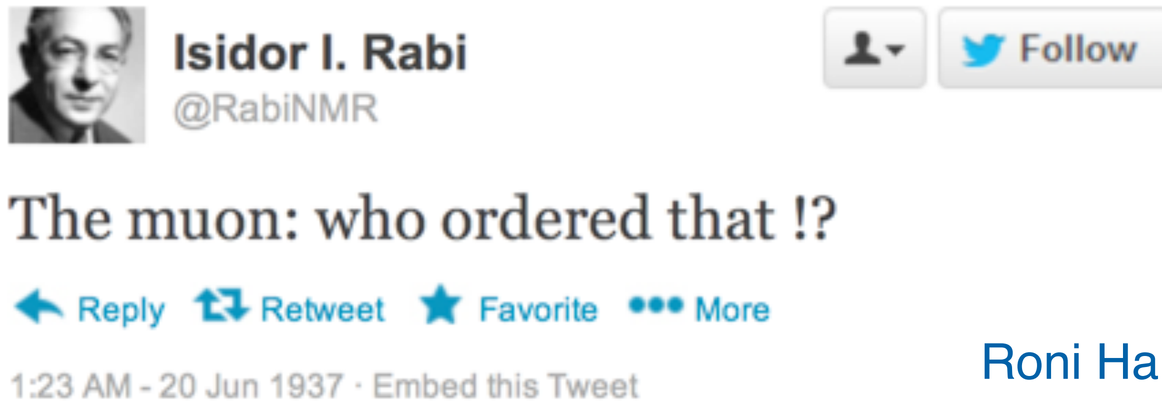


Two Options:

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.

Why Muon Physics at ACE?



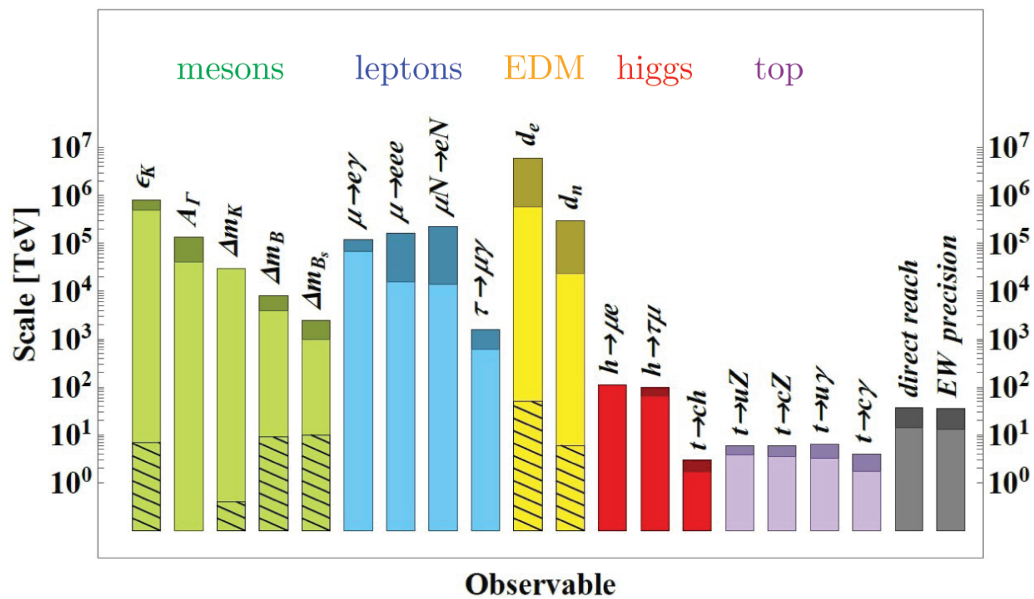
Roni Harnik

- Why are there lepton (or any) flavors?

- Muon Charged Lepton Flavor Violation (CLFV) probes mass scales $\geq 10^5$ TeV

- Can study $\Delta L = 2$ processes such as $\mu^- N \rightarrow e^+ N'$: related to Dirac/ Majorana neutrino mass

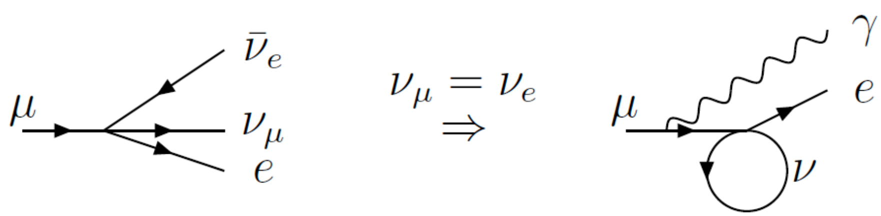
- Muonium-antimuonium oscillations



operator coefficients =1,
Physics Briefing Book, 1910.11775

CLFV, Muons, and Neutrinos

- After the μ was discovered, it was logical to think the μ is just an excited electron:
  - expect BR($\mu \rightarrow e\gamma) \approx 10^{-4}$
  - Unless another ν, in Intermediate Vector Boson Loop, cancels (Feinberg, 1958)
    - ➡ same as GIM mechanism!



[1]Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \rightarrow e + \nu + \bar{\nu}$.

CLFV Muon Processes

like many other indirect studies:
any of these would be an unambiguous signal of new physics; comparing channels pins down the source

- $\mu^+ \to e^+\gamma$
  - most powerful limits, and the best experiments so far: MEG and MEG-II at PSI
  - exploit two-body kinematics to identify a signal
  - proceeds through loops
- $\mu^+ \to 3e$
  - Mu3e experiment at PSI
  - look for $3e$ at muon mass

μ^+ is preferred for the decay experiments, since you can stop the muons in material without nuclear capture

need to produce both $\mu^\pm$

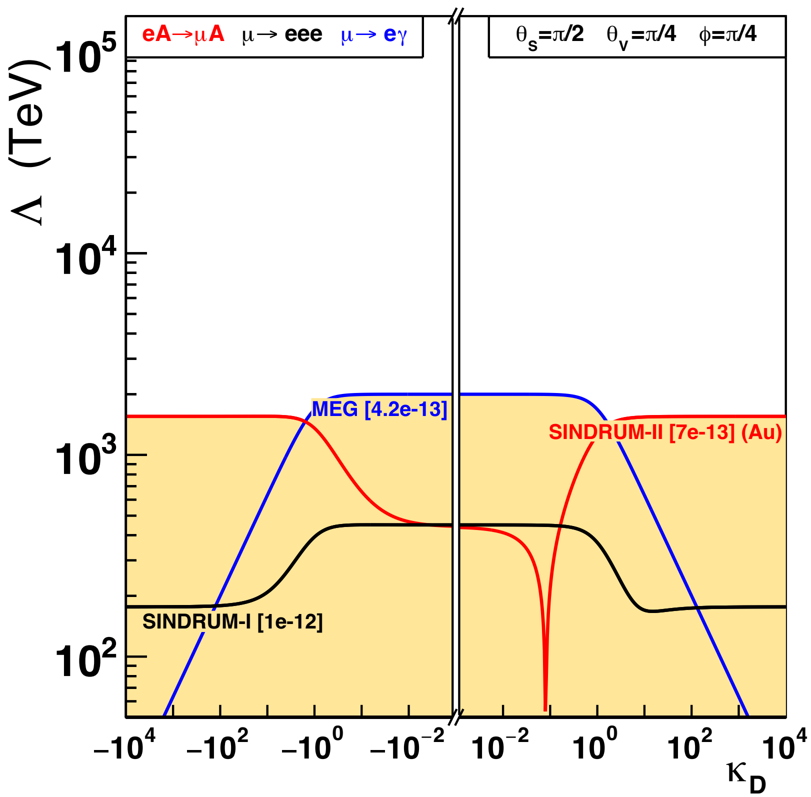
- $\mu^- N \to e^- N$
  - Mu2e, Mu2e-II at FNAL, and COMET at J-PARC
  - signal is a mono-energetic electron at just under the muon mass

μ^- is required for the capture experiments

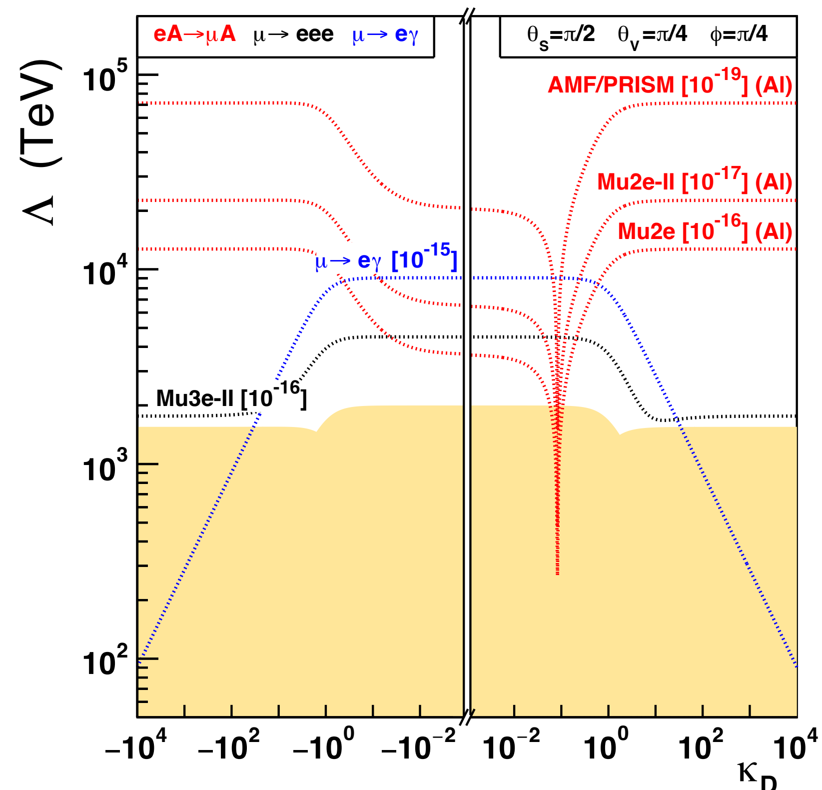
What are the Target Sensitivities for Next-Generation Studies?

S. Davidson and B. Echenard, 2010.00317 [hep-ph]

Today



Future



In an EFT Lagrangian we can define κ_D arising from "loop" vs. "contact" terms; Λ is the new physics mass scale

Goals:

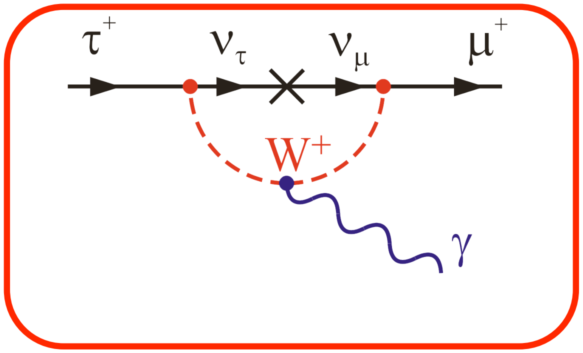
- **improve discovery potential for muon-electron conversion by at least x10 over Mu2e (this is x1000!): mass scales at 10^5 TeV**
- **make corresponding improvements in $\mu \to e\gamma$ and $\mu \to 3e$**

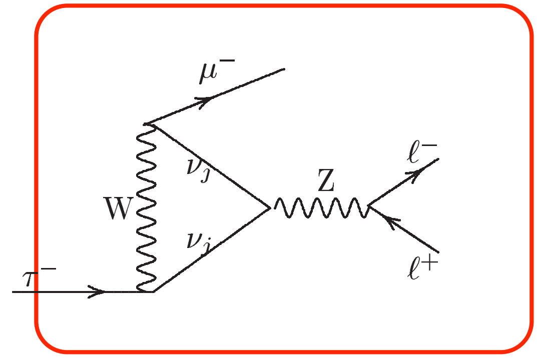
CLFV in τ Decays

- τ sector

τ processes also suppressed in Standard Model but less:

Lee, Shrock
Phys.Rev.D16:1444,1977





Pham, hep-ph/9810484

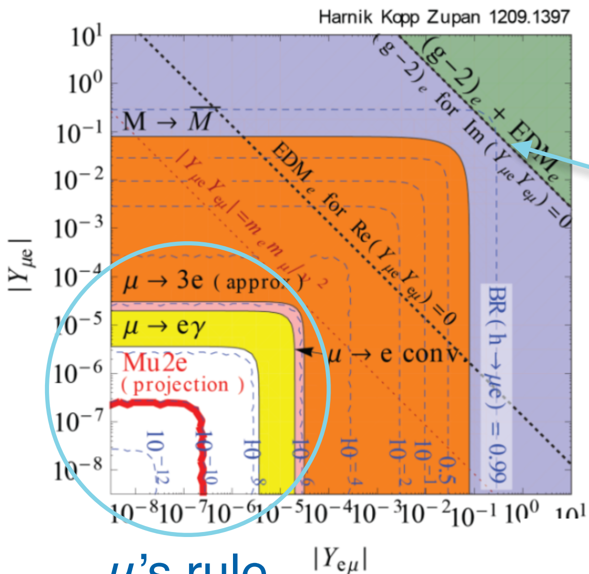
Good News:
Beyond SM rates can be orders of magnitude larger than in associated muon decays

Bad News:
τ's hard to produce:
~10^{10} τ/*yr* vs >10^{11} μ/*sec* in upcoming muon experiments

- Rough analogy to neutrinos: muon CLFV is "θ_{12}" ; anything involving the τ is in the θ_{13} or θ_{23} sector

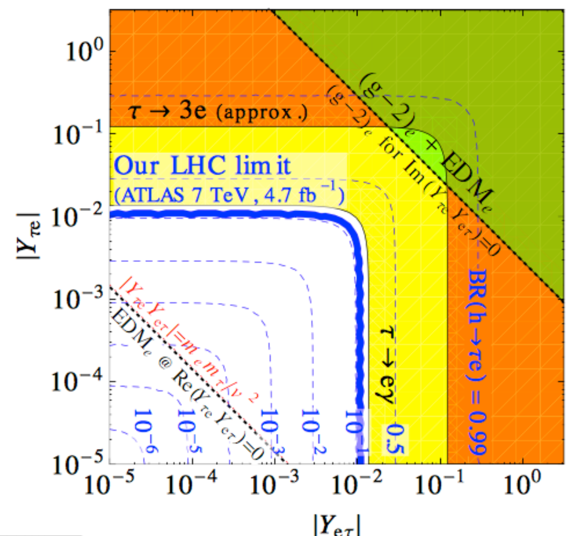
CLFV in Higgs Decays

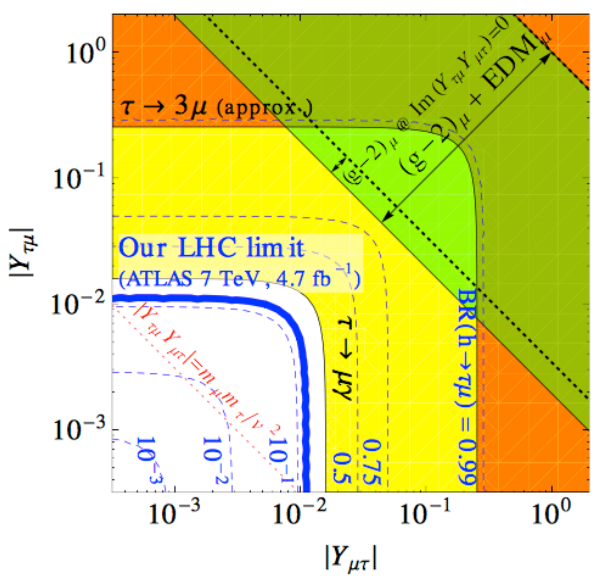
- Muon CLFV dominates in $e - \mu$ sector once again: 7-8 orders of magnitude



collider direct

μ's rule





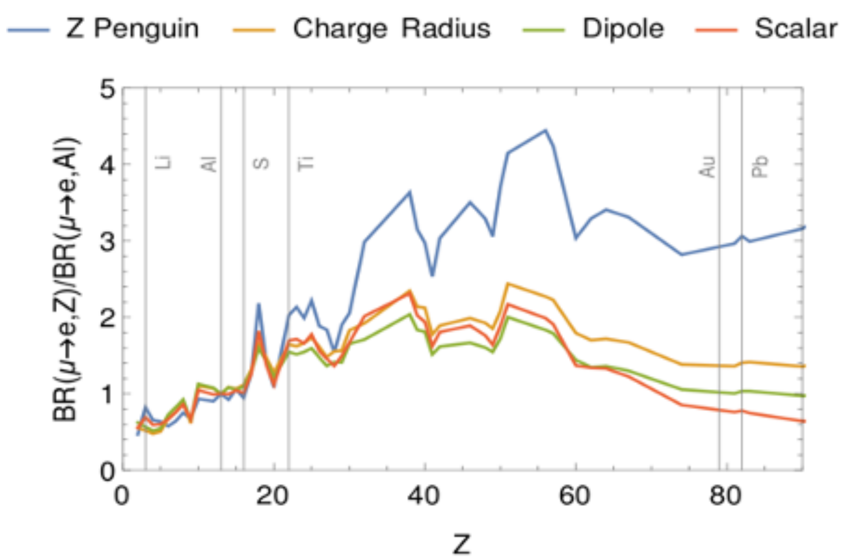
we say nothing in τ processes

High-Z nuclei and CLFV

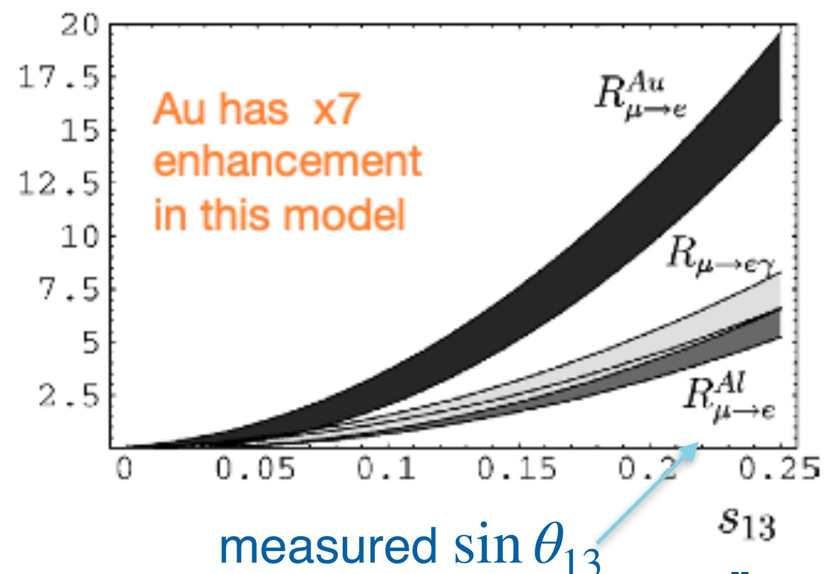
- Muonic lifetime decreases with Z
  - nucleus larger, Bohr orbit smaller; turns over as orbit falls inside nucleus

- *overlap with nucleus probes form factors and reveals the nature of the interaction*

- there's physics at high-Z; and it's related to neutrinos!



Kitano et al. 2002 hep-ph/0203110v4



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

Why do we need AMF?

V. Lobashev, MELC 1992:

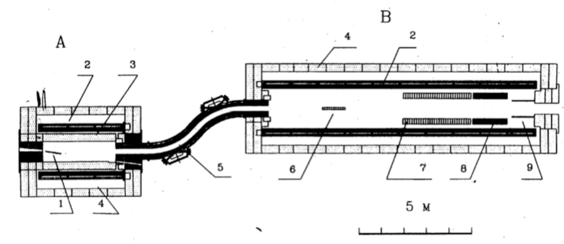
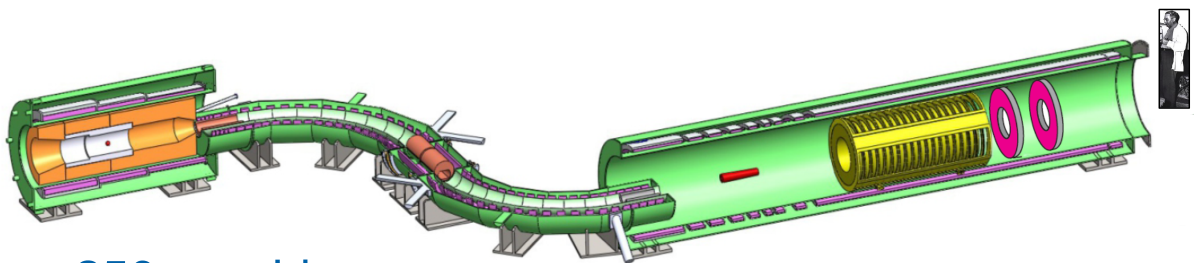
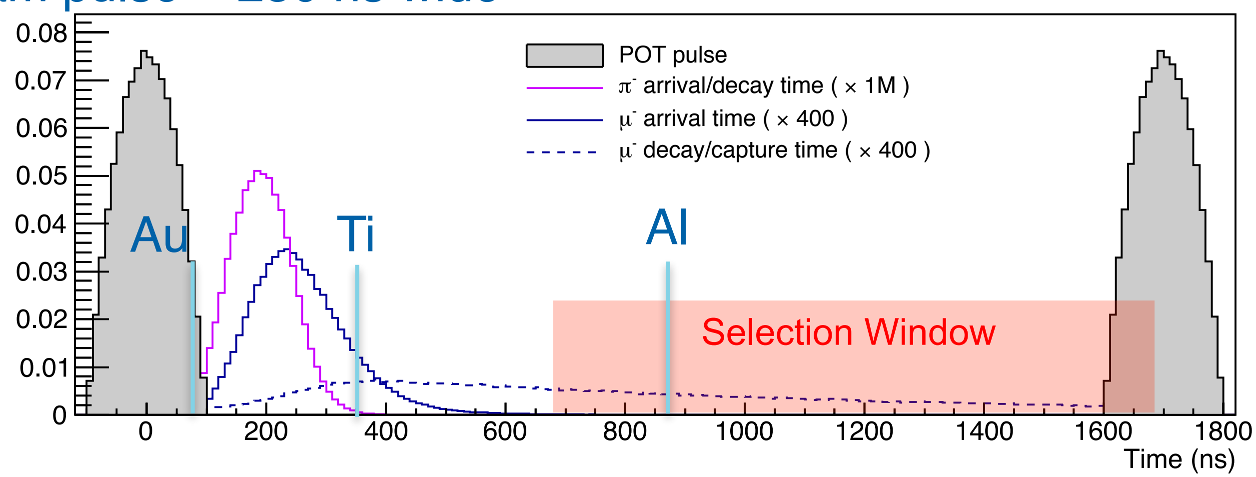


Fig. 1. Set-up MELC: A – meson-production part, B – detector part.
1 – tungsten target of the meson-production part (T_1),
2 – big superconducting solenoids, 3 – protection of the solenoid against radiation,
4 – steel magnetic circuit, 5 – solenoid-collimator,
6 – aluminium-target of the detector part (T_2),
7 – coordinate detector,
8 – total absorption scintillation spectrometer,
9 – protection of the detector against background.

- We want to be able to probe high-Z materials
  - Mu2e and COMET use the “Lobashev Scheme”
    - protons hit a target and make π’s, then $\pi \to \mu\nu$



beam pulse ~ 250 ns wide



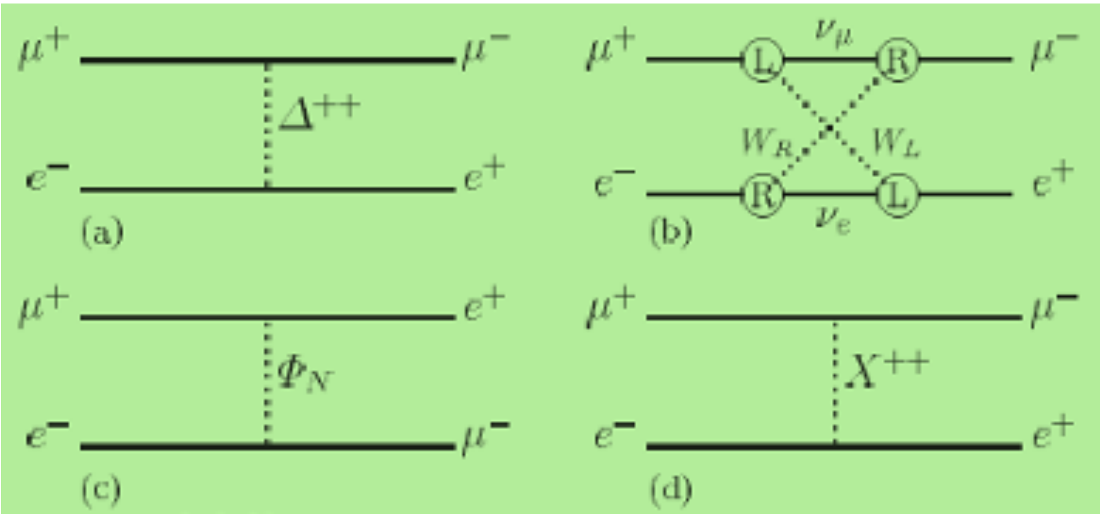
“beam flash” of e^- arising from initial collisions overwhelms detectors

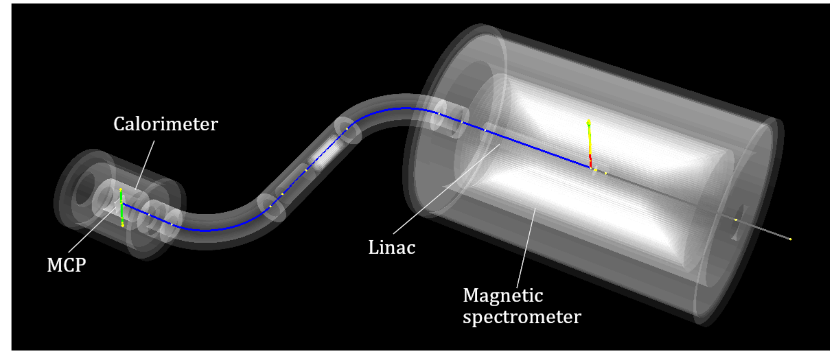
background from surviving π’s: $\pi^- N \to \gamma N', \gamma \to e^+ e^-$ with an electron faking a signal

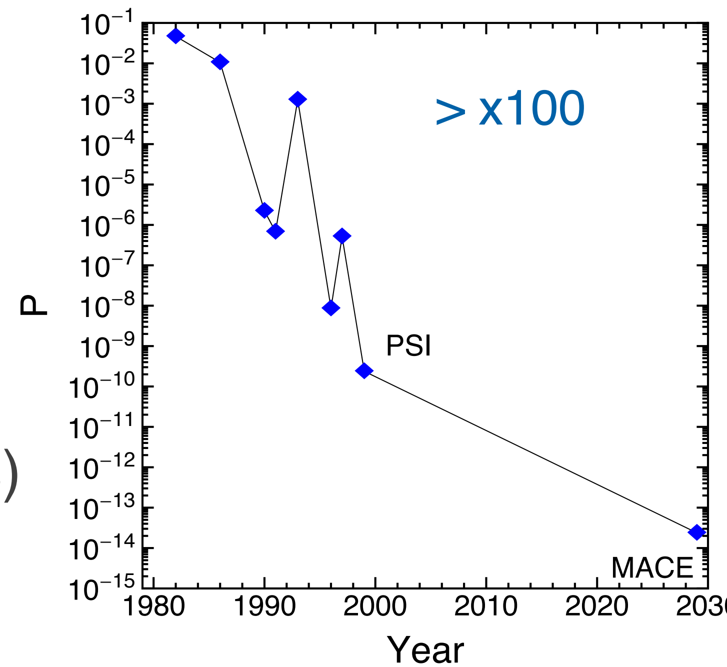
need to wait at least 300-400 ns and have a delayed signal window

Other Muon Physics

- Why stop with CLFV? *doubly CLFV!*
  - muonium-antimuonium oscillations $\mu^- e^+ \leftrightarrow \mu^+ e^-$
    - MACE (2203.11406) proposed in China



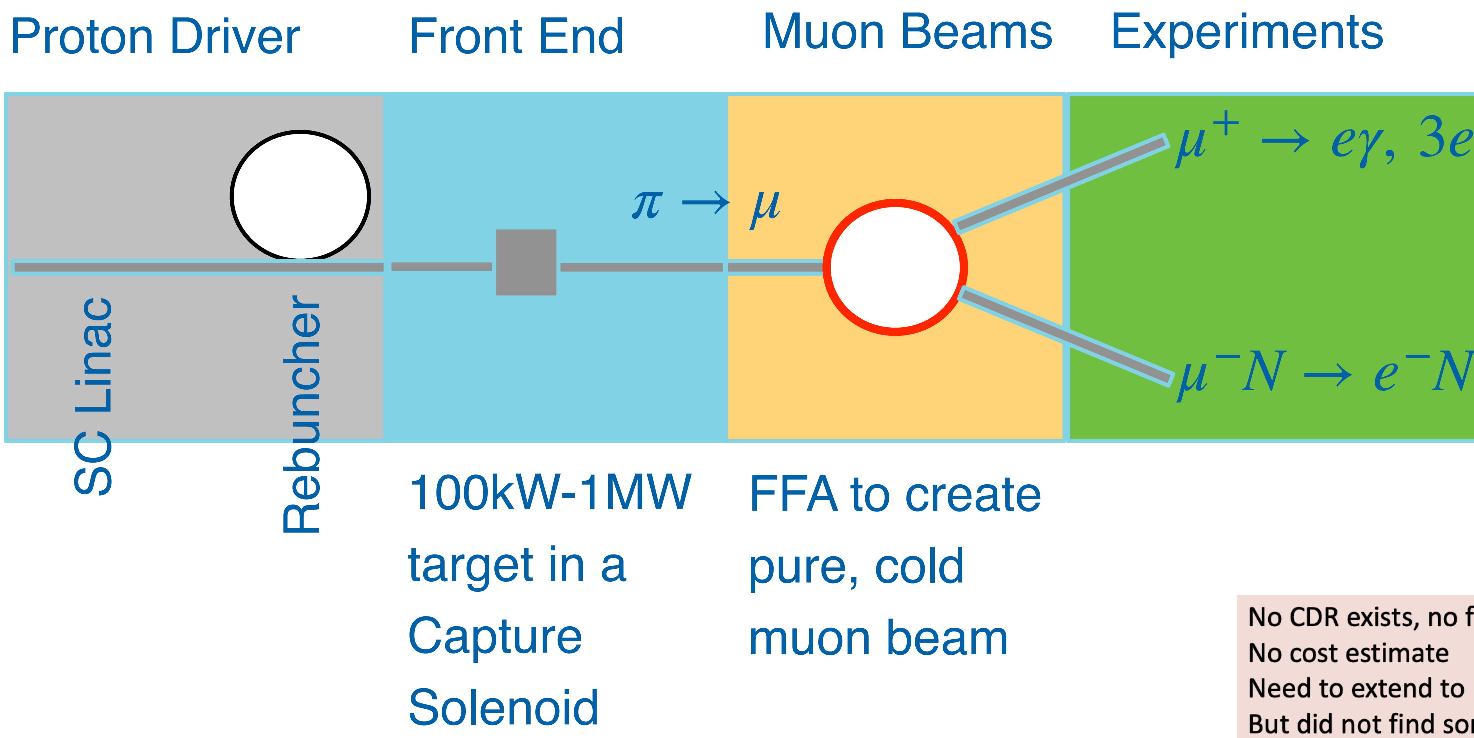




$$P(M_\mu \to \bar{M}_\mu) = \frac{\Gamma(M_\mu \to \bar{f})}{\Gamma(M_\mu \to f)}$$

- $\Delta L = 2$: $\mu^- N \to e^+ N'$ (sensitive to leptoquarks)
  - at Mu2e (simultaneous) or COMET (special run)
  - Black-box theorem: *any $\Delta L = 2$ process implies Majorana neutrino mass*
    J. Schechter and J.W.F. Valle, *Phys. Rev.* **D 25** (1982) 2951

Advanced Muon Facility: Cartoon Overview



No CDR exists, no fully integrated baseline
No cost estimate
Need to extend to higher energies (10+ TeV)
But did not find something that does not work

D. Schulte, https://indico.cern.ch/event/930508/

This should look very familiar to anyone involved in the Muon Collider!

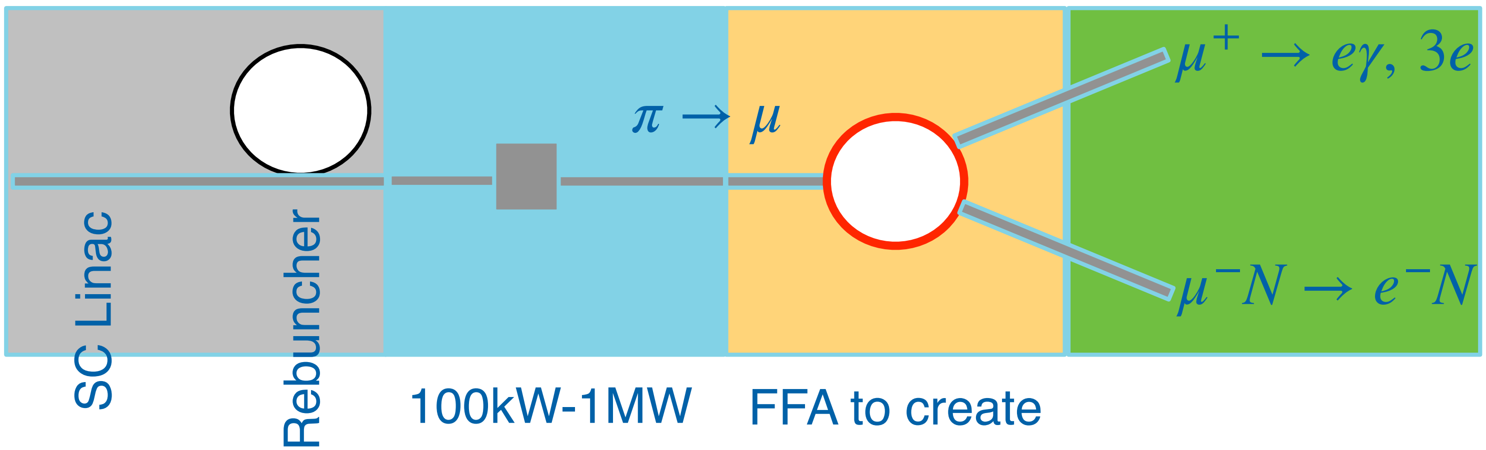
Core ideas from PRISM/PRIME (https://arxiv.org/2203.08278)

We don't need the cooling of the Muon Collider

Let's start at the experiments and work backwards to explain the requirements at each stage

Advanced Muon Facility: Cartoon Overview

Proton Driver | Front End | Muon Beams | Experiments



100kW-1MW target in a Capture Solenoid

FFA to create pure, cold muon beam

No CDR exists, no fully integrated baseline
No cost estimate
[redacted]
But did not find something that does not work

D. Schulte, https://indico.cern.ch/event/930508/

This should look very familiar to anyone involved in the Muon Collider!

Core ideas from PRISM/PRIME (https://arxiv.org/2203.08278)

We don't need the cooling of the Muon Collider

Let's start at the experiments and work backwards to explain the requirements at each stage

What Do the Experiments Want?

see Pezzullo, this conf.

https://arxiv.org/2203.08278

Core Idea from PRISM/PRIME but we are making changes and evolving it in collaboration with PRISM/PRIME physicists

Experiments

$\mu^+ \to e\gamma,\, 3e$

$\mu^- N \to e^- N$

What would we like? (leave out muonium for now)

Pure, cold beams: all muons, nearly mono-energetic so range straggling minimized

1. pure, cold, negative muon beam at ~20-30 MeV/c with pulses separated by hundreds of ns

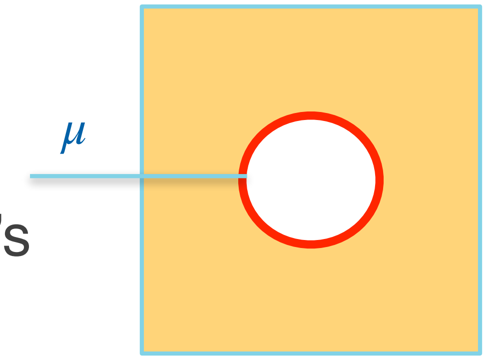
- $\mu^- N \to e^- N$ on Au (Mu2e and COMET-type detectors)

detectors are a separate topic

2. pure, cold, positive muon beam at ~20-30 MeV/c with pulses as continuous as possible.

- $\mu^+ \to e\gamma, e^+e^-e^+$ (MEG-II and Mu3e)
- this facility could provide several orders of magnitude more μ^+ than HiMB

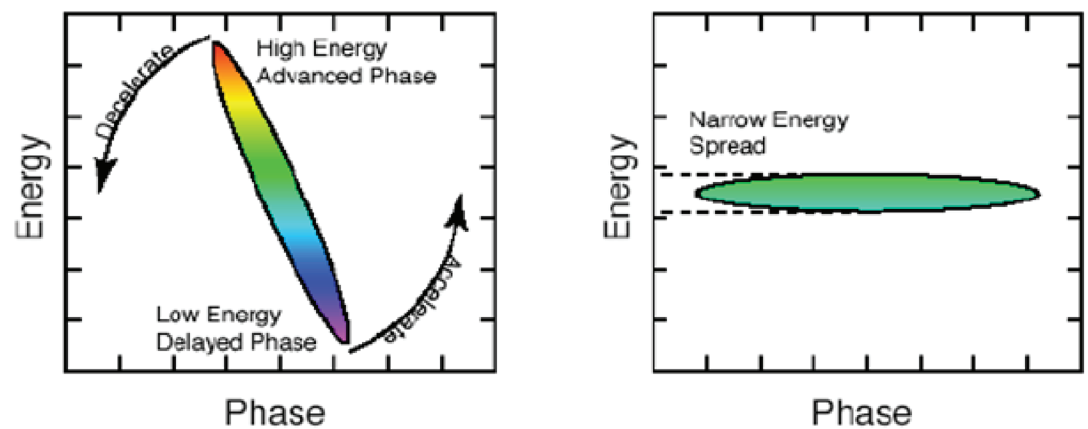
AMF: Making the Final Muon Beam



- Previous stage will give us a beam of π's decaying into μ's
- Want a pure muon beam
- A fixed-field, alternating gradient synchrotron is a natural choice
- Essentially a muon storage ring

FFA to create pure, cold muon beam

- uses RF to phase rotate a pulsed beam to be more evenly spread out in time but nearly mono-energetic



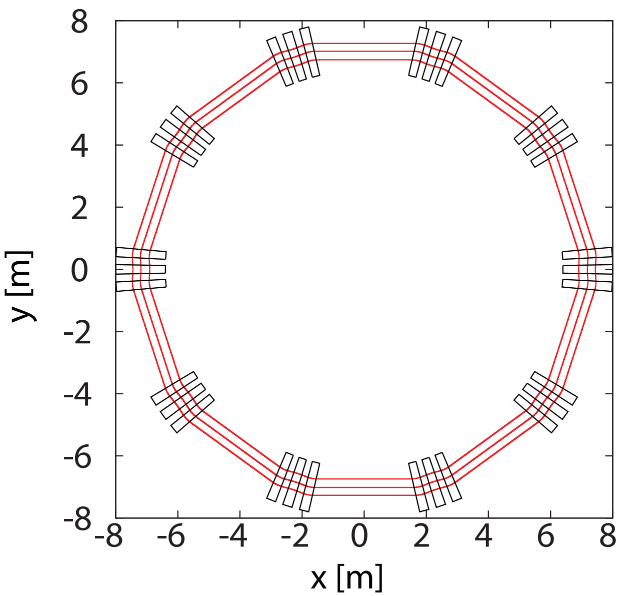
- π's decay during phase rotation, can achieve required suppression

PRISM (Phase Rotated Intense Source of Muons)
(arXiv:1310.0804 [physics.acc-ph])

- can have counter-circulating positive and negative beams

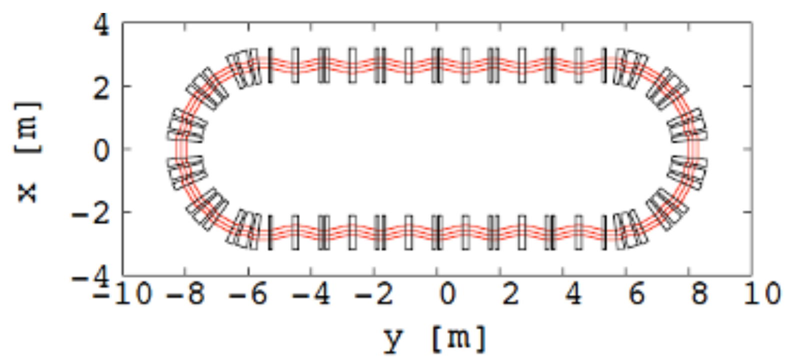
Overview of FFA Design: Injection/Extraction

- if we want both signs, probably need a racetrack for separate injection/ extraction systems



like a NuSTORM racetrack

μ^- injection/extraction



μ^+ injection/extraction

can always alternate between charges if needed

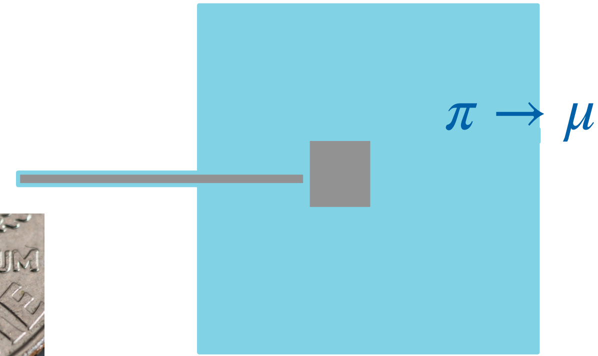
PRISM:

Pasternak, https://indico.cern.ch/event/300521/

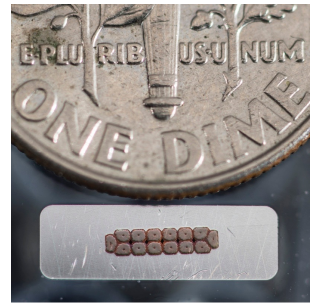
- if central momentum too high, use an induction linac to decelerate the beam

Making the Muon Beam: Production Solenoid

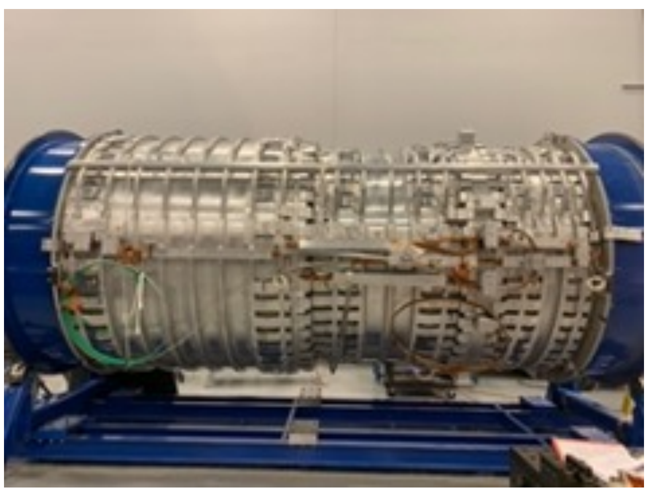
Front End



- AMF wants as high-power as we can go, but we can accept 100 kW on up
- We are a “test-bed” for the Muon Collider



- Mu2e: 8 kW
  - Al Stabilized $NbSn_3$ superconductor
  - Target cooled convectively (we were worried about failure of water cooling, cost, …)



Production/Capture Solenoid under construction

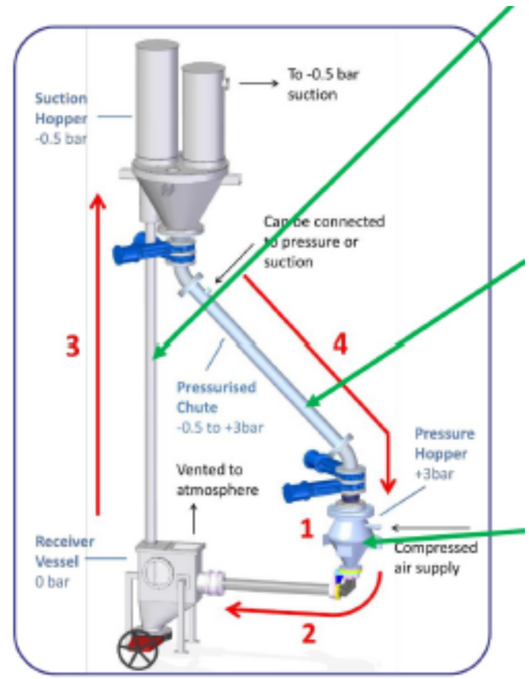
Heat and Radiation Shield

Target

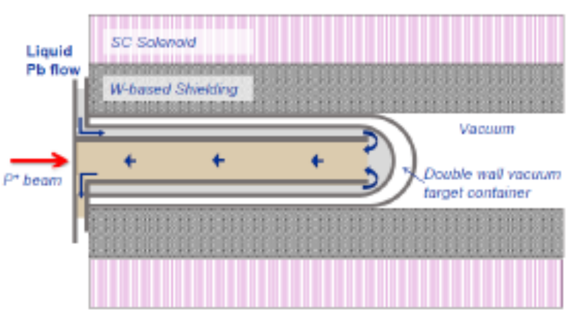
Mu2e Upgrades for Target

- Mu2e is considering an upgrade (Mu2e-II) at PIP-II: 800 MeV, 100 kW
  - Mu2e Target won't work at our repetition rate
- Considering "moving mass" targets
  - conveyor belt, moving spheres,…
- MuC options at 1MW:

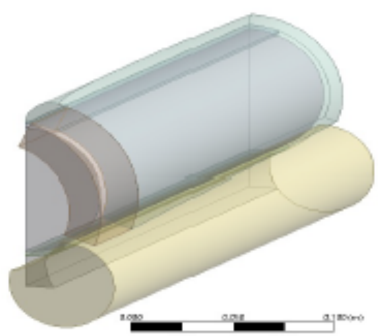
Fluidized Tungsten



Liquid Lead Flow



Lead Curtain



Liquid jet

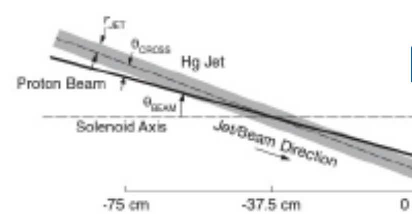
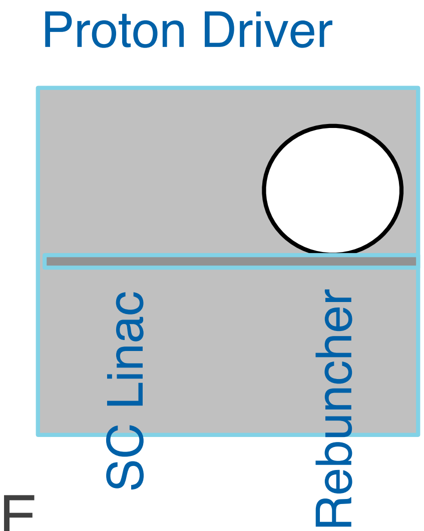


FIG. 3. The mercury jet target geometry. The proton beam and mercury jet cross at $z = -37.5$ cm.

Fermilab

PIP-II Front End



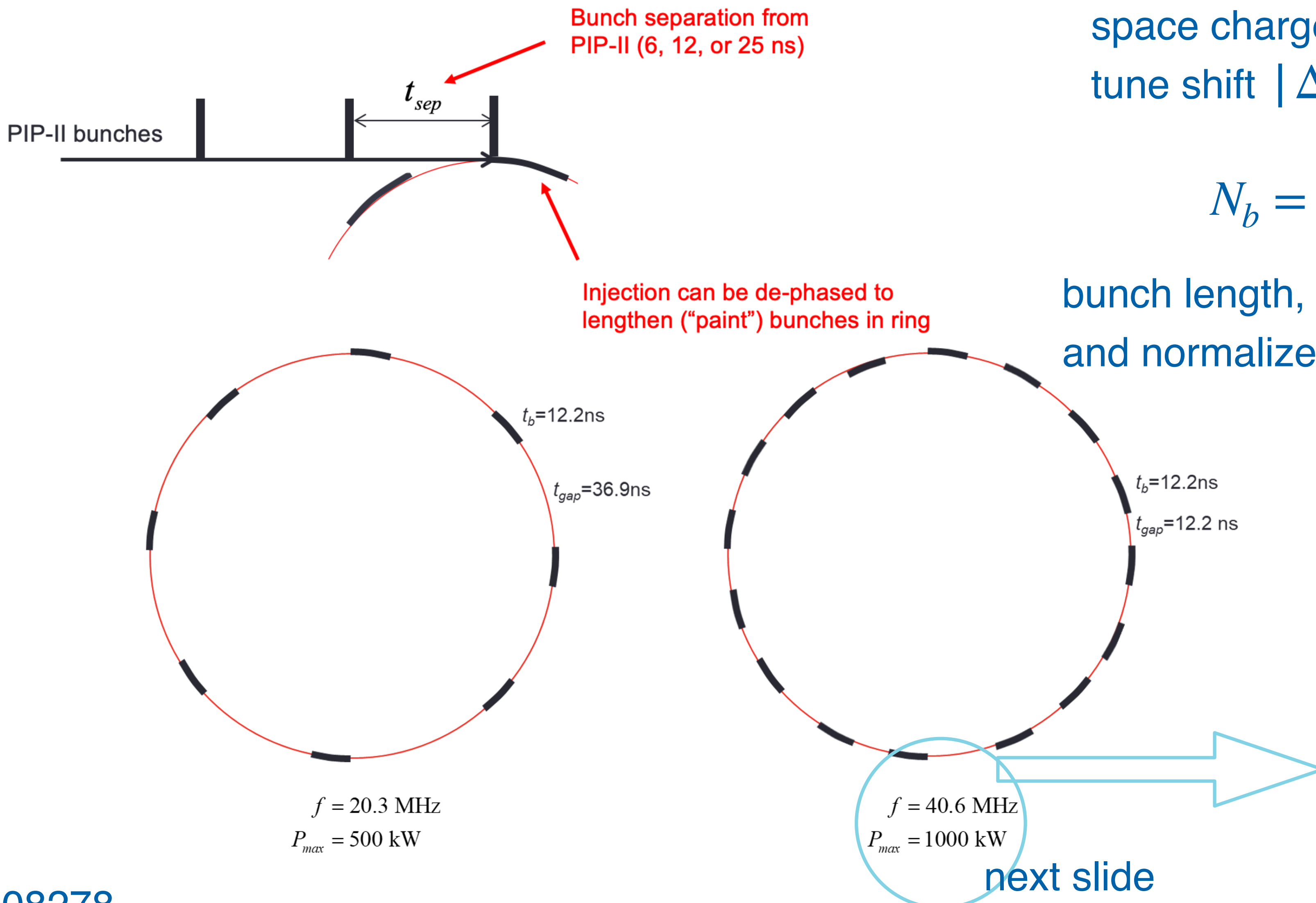
- PIP-II is 800 MeV but later stages up to ~ 3 GeV
  - some options have an 8 GeV RCS
- Potentially ≥ 1MW of protons left for this program after DUNE
  - neutrino program uses only a small amount of the beam power
- PIP-II has tunable bunch separation (6, 12 or 25 ns)
  - but individual bunches are very short in time
- FFA needs proton bunches of order 10 ns at 100-1000 Hz
  - perform phase rotation on those bunches
  - at 100-1000 Hz, output of PIP-II would be too small to be useful: gather them up!

AMF Front End: Compressor Ring

limitation is
space charge
tune shift $|\Delta\nu| < 0.2$

$$N_b = \frac{t_b}{\tau}\epsilon_N$$

bunch length, period,
and normalized emittance



to
Production
Solenoid

next slide

2203.08278

AMF Rates

- Compressor Ring:
  - Respecting $|\Delta\nu| < 0.2$ in a 100 m circumference ring and the max PIP-II rate of 41 MHz

Power (kW)	100	500	1000
$N_b[10^{12}]$	7.8	39.1	78.1

- Production Solenoid
  - Mu2e is about $1.5 \times 10^{-3} \mu^- / p$; lower energy beam could yield about x3 more; precise optimization is a function of available field and solenoid design

    Estimate $5 \times 10^{-3} \mu^- / p$

- FFA: assuming perfect transfer from compressor to FFA, and perfect transfer from FFA to the experiment:
  - $(78 \times 10^{12}) \times (5 \times 10^{-3}) \times 1000 = 4 \times 10^{14}\ \mu^-/\mathrm{sec}$ at 1000 Hz kicker

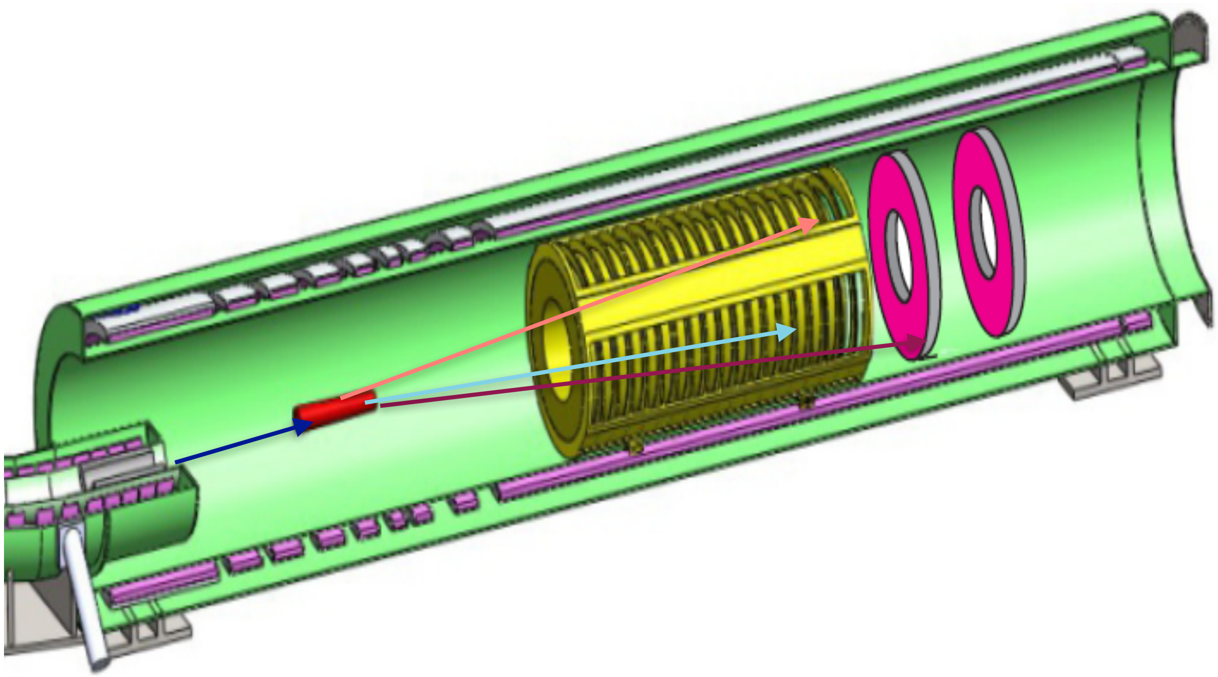
    so $4 \times 10^{11} \mu^-/\mathrm{pulse}$ at 1kHz is the highest rate we envisage

  - for comparison, Mu2e is ~ $6 \times 10^4\ \mu^-/\mathrm{pulse}$ at 600 kHz

AMF Detector Challenges

- Various effects (decay in FFA, etc.) reduce AMF rate by roughly x100
  - Precise calculation not important in that Lobashev scheme won't work

- Muon capture ejects many particles, which will deaden detector
  - separate effect from beam flash!
  - Mu2e detector solenoid is straight: detector sees the muon capture products



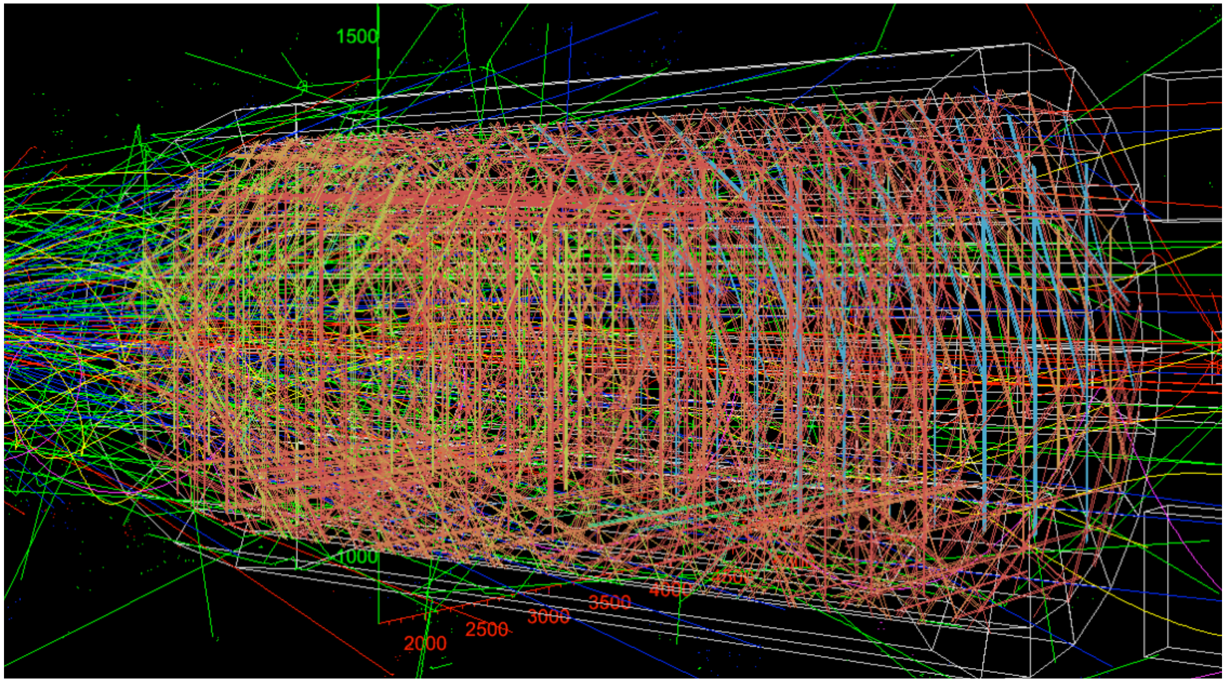
n, p, γ

And even worse:

- These are the Mu2e tracker hits integrated over one spill (every 1695 ns)

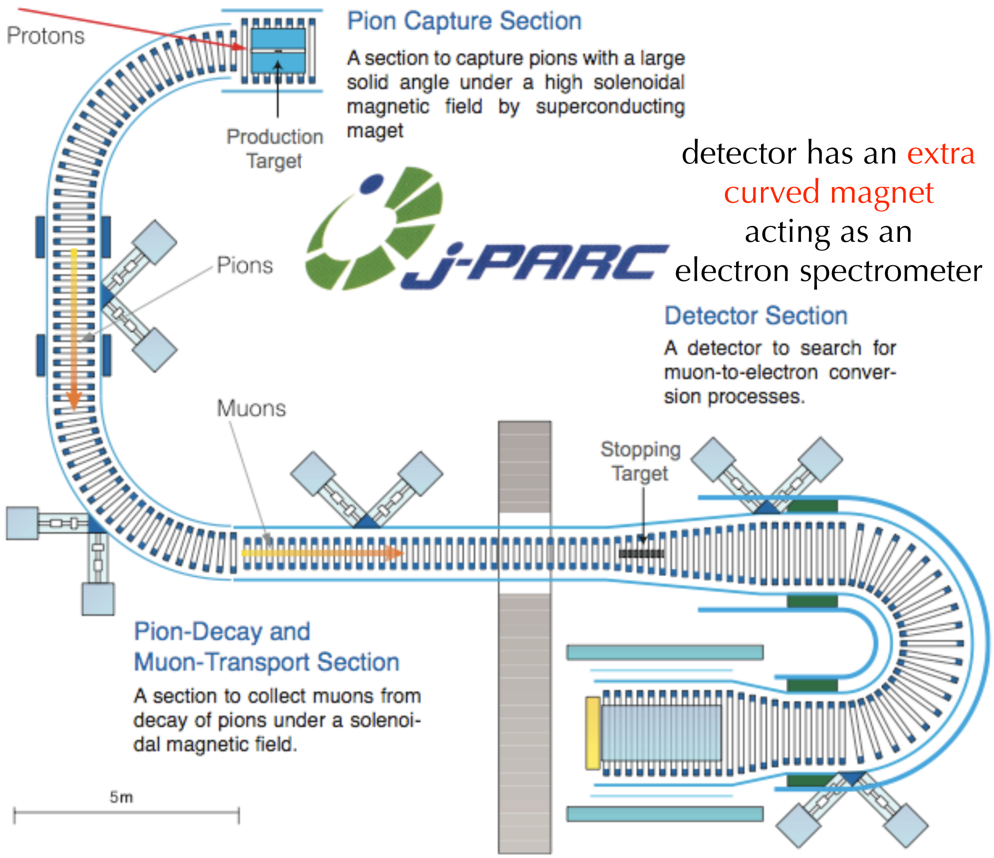
- Almost all comes from initial beam blast from hitting our target in
  $p + \mathrm{W} \to \pi^{o\prime}s \to \gamma \to e^+e^-$, and e^- are transported to the detector

- Occurs over first few hundred ns. Can't see anything in Au lifetime of 73 ns



How do we solve this?

- Use some sort of curved solenoid between target and detector, like COMET



detector has an extra curved magnet acting as an electron spectrometer

"guggenheim scheme"

- only high momentum signal transported through curved solenoid gets to detector elements

Curved vs. Straight:

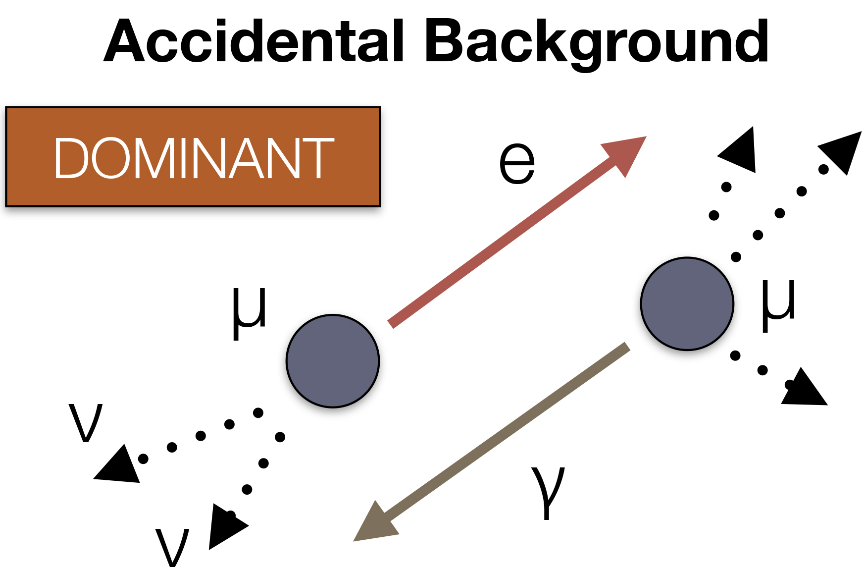
- Mu2e Scheme with a straight solenoid:
  - can measure π induced backgrounds in-situ: they eventually produce e^+e^-; measure e^+ and can predict the corresponding e^- background without unblinding
  - can measure the $\Delta L = 2$ process $\mu^- N \to e^+ N'$

- COMET curved scheme:
  - In a curved solenoid, you can't measure the backgrounds in-situ and the $\Delta L = 2$ measurement requires a separate run with flipped fields.
  - But COMET curved scheme has other advantages, especially for the detector: they don't see muon capture, which is a complication for Mu2e
  - Good we're doing it both ways! And they will solve many curved solenoid issues for AMF!

- However, in this FFA scheme there are no π backgrounds!
  They decay in the FFA
  - still lose $\Delta L = 2$ measurement
  - but at these intensities have no choice; can't deal with muon capture and need curved

Running μ^+

- Decay experiments are limited by accidentals



Standard Model weak decay
in coincidence with
photon created from stopped muon

- pulses are best for conversion experiments

- decay experiments ($\mu \to e\gamma$, $3e$) don't want the scheme just outlined, but would prefer to "slow-spill" entire ring out over a long time
- in addition, new experiment design required to take advantage of AMF rates: work underway: Renga, https://indico.fnal.gov/event/57834;Voena, this conf.

AMF: Next Steps

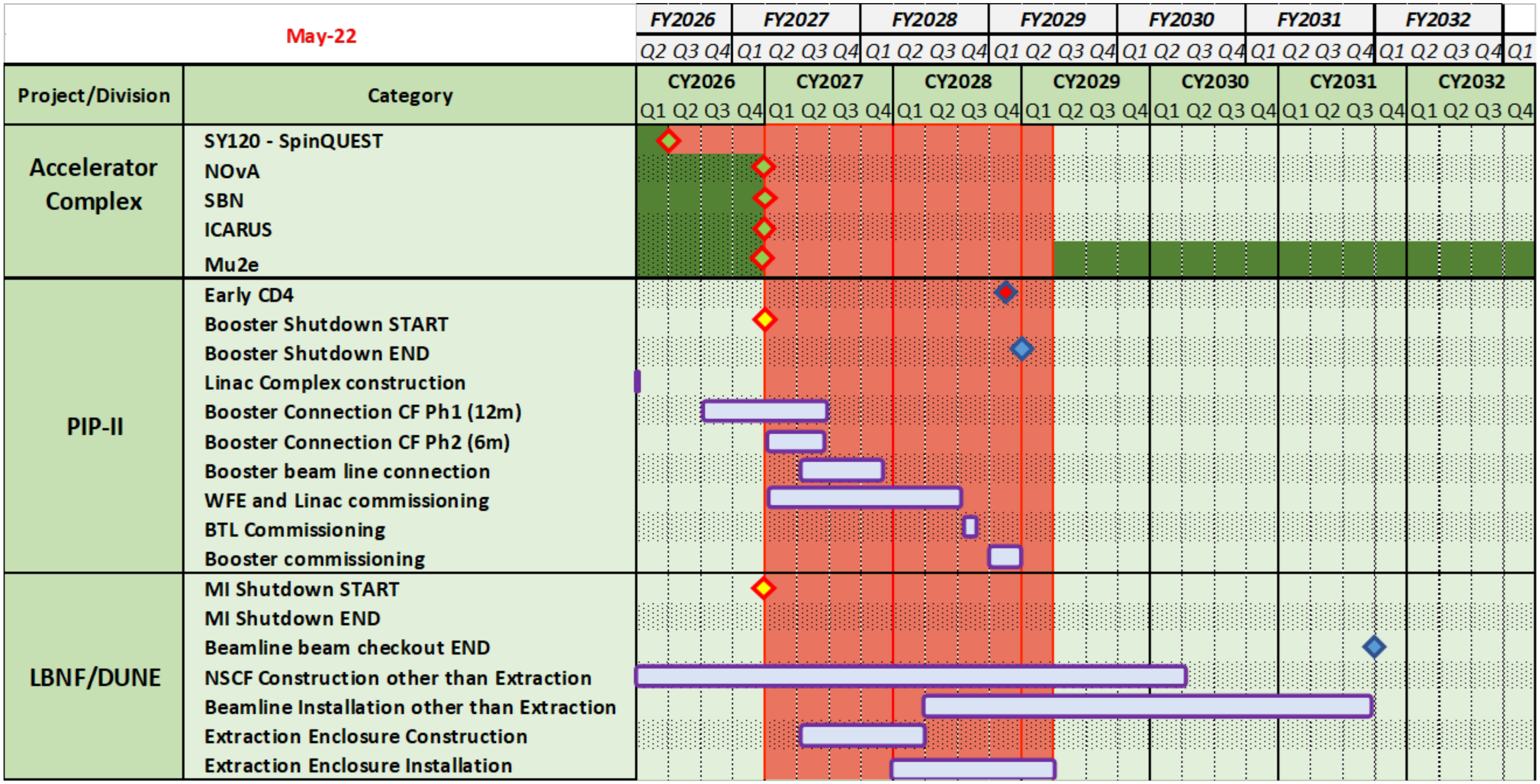
- Production Solenoid
  - 100 kW seems quite possible, can we achieve 1MW?
  - this will define level of difficulty and details of the solution for everything downstream
  - and great overlap with MuCol, so we should proceed together

- FFA
  - one sign of muon or both? (can always alternate runs)
    - both signs adds complications
    - extraction different for each sign since conversion experiments want pulsed, decay experiments want stopped
    - working on scheme for both experiments
  - detailed design and central momentum
    - if central momentum is too high, we will need an induction linac or other method to slow beam as much as possible (10-30 MeV range)

- Match PIP-II to the compressor ring to the production solenoid to the FFA

- Detectors
  - need semi-real simulation to determine conversion experiment design, focused on eliminating products from SM Michel decay and muon capture
  - new design for decay experiments: probably photon conversion $(\mu \to e\gamma, \gamma \to e^+e^-)$ and then three tracks to make a vertex. Lose ~x100 since need a thin converter

When Might This Happen?



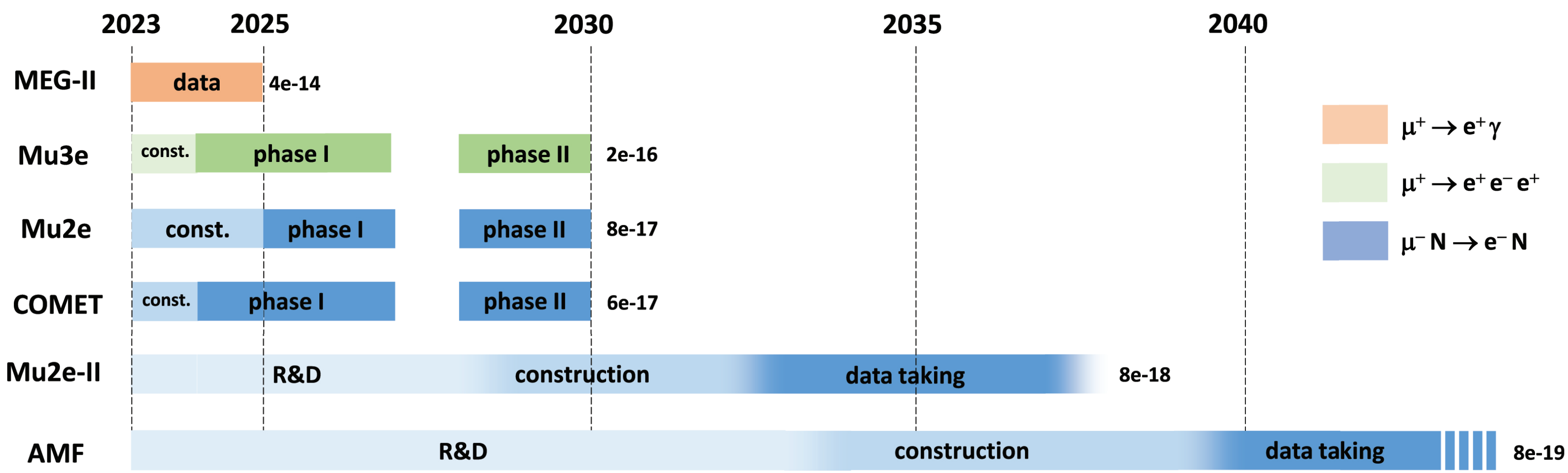
1st Phase: LBNF/DUNE at 1.2 MW starting in Calendar Year 2027

- **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!

Snowmass Long-Term View

Snowmass Rare and Precision Frontier Report (2210.04765)



in order:

1) **Perform Mu2e! (done by end of 2020's)**

2) **Plan Mu2e-II: depends on FNAL schedule, Mu2e outcome, etc. but Mu2e-II is not a major new facility or extensive R&D problem**

3) **AMF: $1B class, extensive R&D**

Summary

- AMF is an ambitious program that will reach several orders of magnitude in muon CLFV in all muon modes
  - any signal here is an unambiguous sign of new physics; not dependent on theory calculations
  - Could create a > 500 physicist community sharing techniques and effort
- US needs to settle on the details of PIP-II design and upgrades (energy of beam can be 800 MeV up to 2-3 GeV)
- P5 needs to endorse R&D for a muon program in the US
  - which could overlap, especially in the production solenoid, with Muon Collider
- Between AMF and the Muon Collider, muons are the future!