Physics Opportunities with Booster Replacement Options

Matt Toups, Fermilab

With thanks to Kevin Kelly, Nhan Tran, Yi-Ming Zhong, Dan Kaplan, Katsuya Yonehara, Evan Niner, Yannis Semertzidis, Bill Morse, Anna Mazzacane, Josh Barrow

Snowmass

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Brief Introduction

- 2014 P5 recommended building multi-MW LBNF beam power capacity for DUNE
  - Current Booster cannot support this → “Booster Replacement”
- Virtual workshop held May 19, 2020 to solicit input from the community about potential physics opportunities that could inform accelerator design
- Proceedings submitted as a Snowmass white paper: [arXiv:2203.03925](https://arxiv.org/abs/2203.03925)

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Physics Opportunities for the Fermilab Booster Replacement

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White paper overview

- Many ideas on the table spanning a range of physics topics
  - Opportunity to define future program alongside DUNE
- Beyond neutrino physics, two central physics themes emerged
  - Dark sector searches
  - Opportunities with muons
    - Including muon collider R&D
- This talk will overview these as well as other exciting physics ideas contributed during this process

Experiment	Dark Sectors	ν Physics	CLFV	Precision tests	R&D
Lepton flavor violation: μ-to-e conversion			■	■	
Lepton flavor violation: μ decay	■		■	■	
PIP2-BD: ~GeV Proton beam dump	■	■			
SBN-BD: ~10 GeV Proton beam dump	■	■			
High energy proton fixed target	■			■	
Electron missing momentum	■	■			
Nucleon form factor w/ lepton scattering		■		■	
Electron beam dumps	■				
Muon Missing Momentum	■			■	
Muon beam dump	■				
Physics with muonium	■			■	
Muon collider R&D and neutrino factory		■			■
Rare decays of light mesons	■			■	
Ultra-cold neutrons				■	
Proton storage ring for EDM and axions	■			■	
Tau neutrinos		■			
Proton irradiation facility					■
Test-beam facility					■

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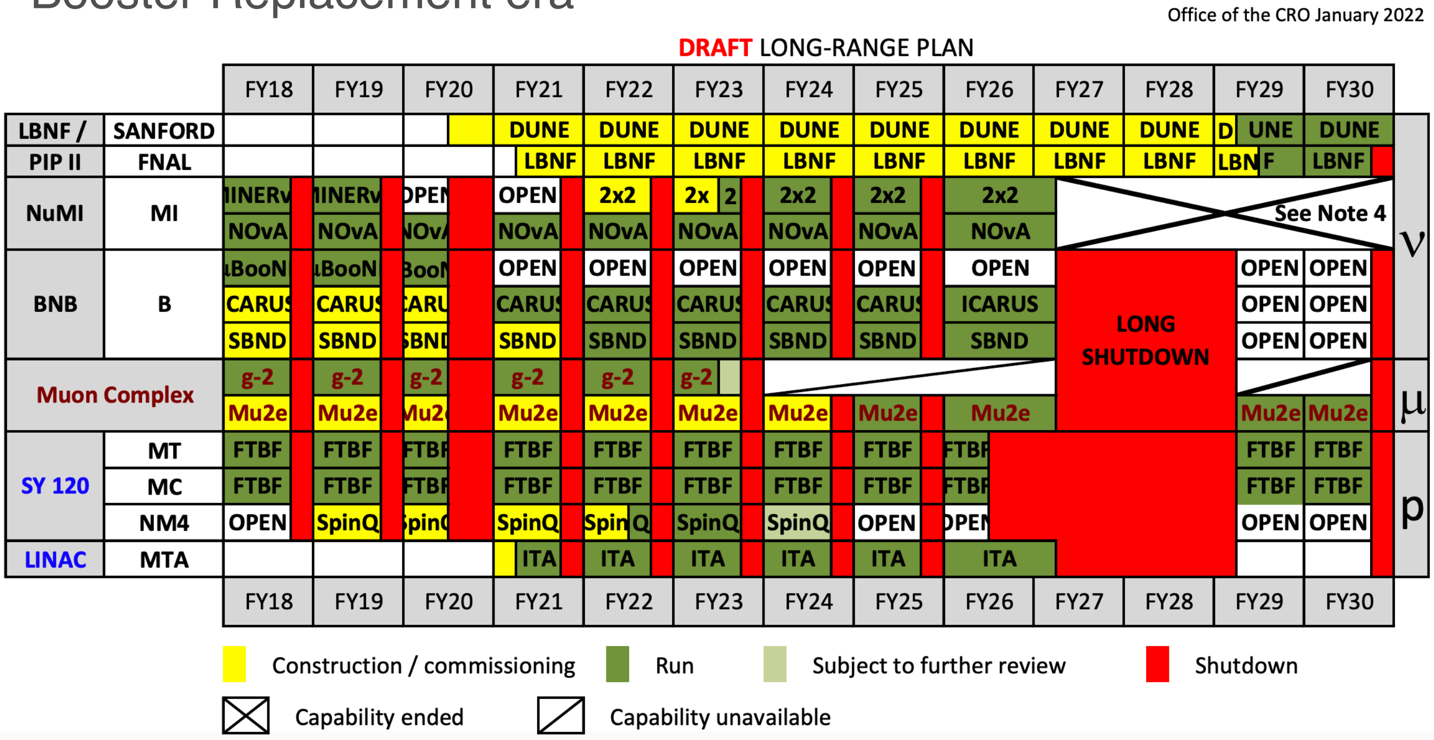
Timeline

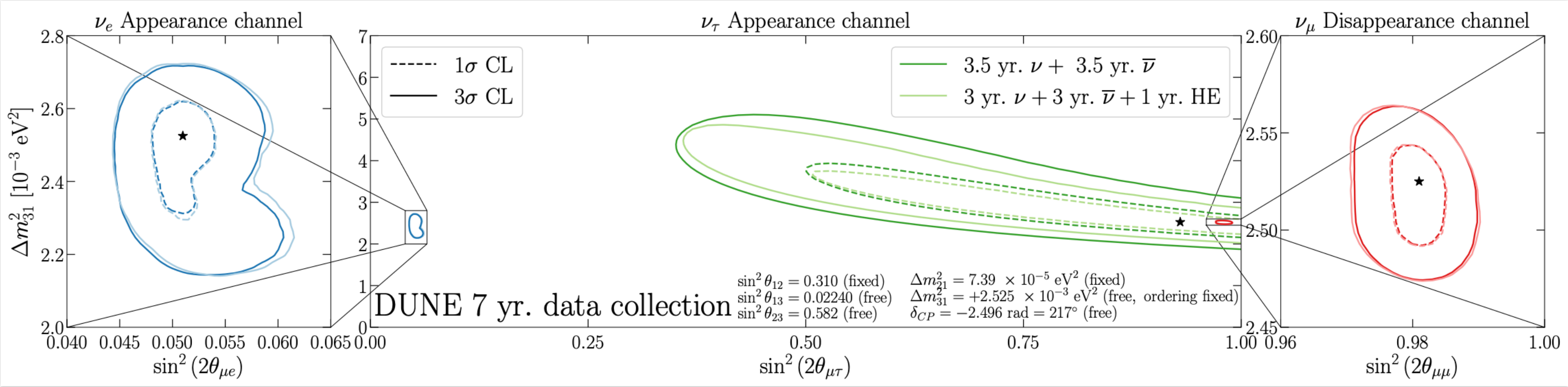
- 2029 - 2037: “PIP-II era”
- >2037: “Booster Replacement era”



DUNE & the Booster Replacement

- DUNE phase II calls for 2.4 MW to LBNF → main physics driver
  - For impacts on DUNE physics program, see Chris Marshall's talk
- Future beam configurations may give new/expanded DUNE physics opportunities
  - Examples: "target-less" running, ν_τ appearance tests of the 3 neutrino flavor picture with high energy beam tune

de Gouvêa et al, [1904.07265]



(light contours: substitute one year of running with a hypothetical high-energy beam tune)

Dark Sector Searches

- The existence of dark matter motivates a dark sector
- Intense particle beams represent an excellent opportunity to search for these
- New physics posited to be neutral (“dark”) under SM forces (EM, weak, strong)
- Connects to SM through finite list of “portal” operators, enabling systematic exploration

$B_{\mu\nu}$	x	$\epsilon/2\, F'^{\mu\nu}$	Vector portal
$\lvert h\rvert^2$	x	$\mu S + \lambda \lvert\phi\rvert^2$	Higgs portal
hL	x	$y_N N$	Neutrino portal

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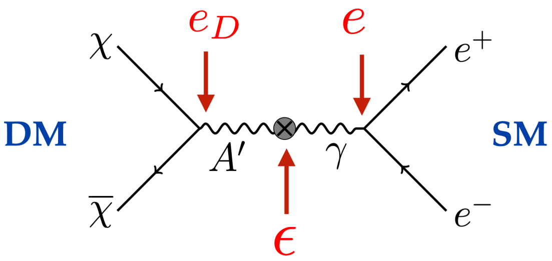
Dark Sectors - Light Dark Matter

- Minimal models can explain the thermal relic abundance of dark matter and predict sub-GeV dark matter that can be **produced** and **detected** at accelerator-based neutrino facilities (see MiniBooNE results, PRL 118, 221803 (2017), PRD98, 112004 (2018))

- Representative model: vector portal dark matter with $m_{A'} > m_\chi$



$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

- Minimum SM coupling ϵ required for thermal freeze out

- Complementary benchmarks exist that preferentially couple to e.g. hadrons, muons

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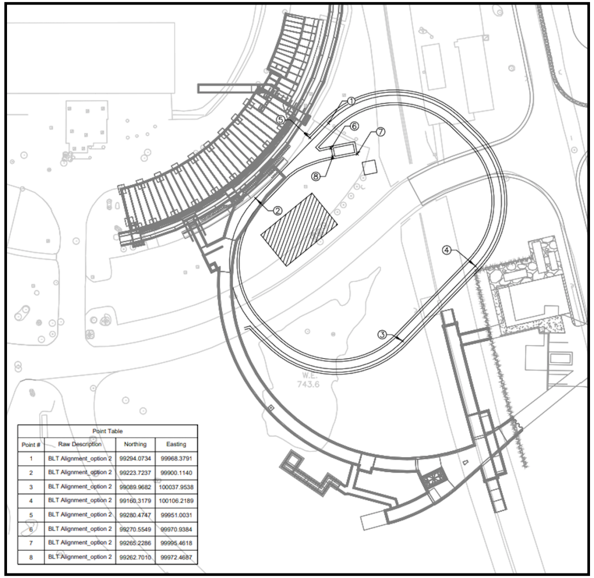
Proton Beam Dump @ 1 GeV: PIP2-BD

- PIP-II can provide up to 1.6 MW of 800 MeV protons concurrently with 1.2 MW of 120 GeV protons to LBNF

- Continuous-wave beam needs to be bunched into short pulses to be suitable for dark sector searches

- Booster replacement era option
  - Rapid Cycling Synchrotron Storage Ring (RCS-SR)

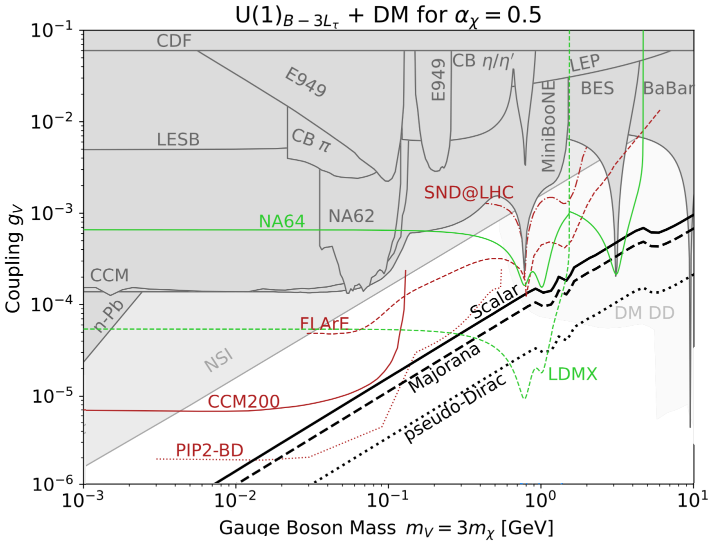
- PIP-II era options (less expensive)
  - PIP-II accumulator ring (PAR)
  - Compact PIP-II accumulator ring (C-PAR)

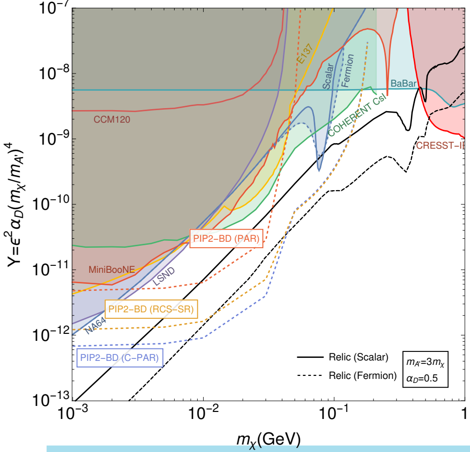


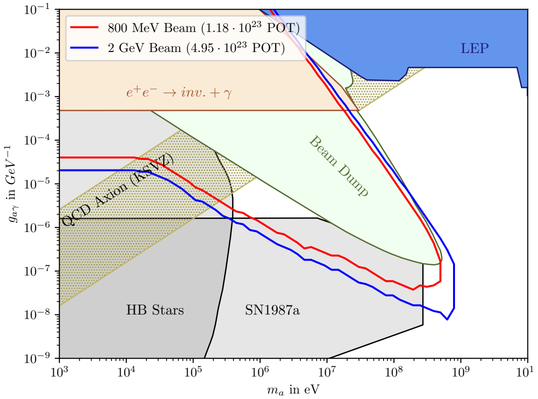
Facility	Beam energy (GeV)	Repetition rate (Hz)	Pulse length (s)	Beam power (MW)
PAR	0.8	100	2×10^{-6}	0.1
C-PAR	1.2	100	2×10^{-8}	0.09
RCS-SR	2	120	2×10^{-6}	1.3

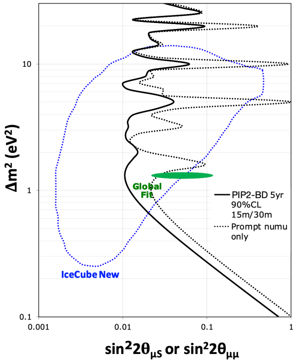
Proton Beam Dump @ 1 GeV: PIP2-BD

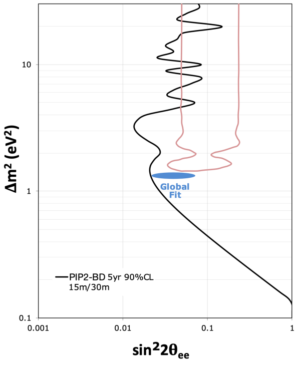
- Single-phase, 100 ton scintillation-only liquid argon detector located 18 m downstream, on axis
  - Same technology as CENNS-10, CCM-200
- World-leading dark sector sensitivity, especially to hadrophilic dark matter, ALPs
  - Also supports definitive active-sterile neutrino oscillation search, neutrino cross sections measurements, etc.

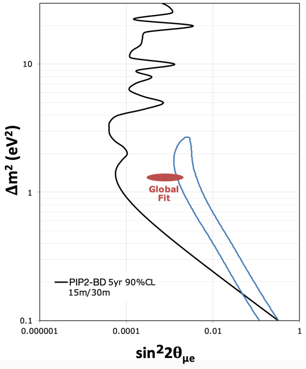






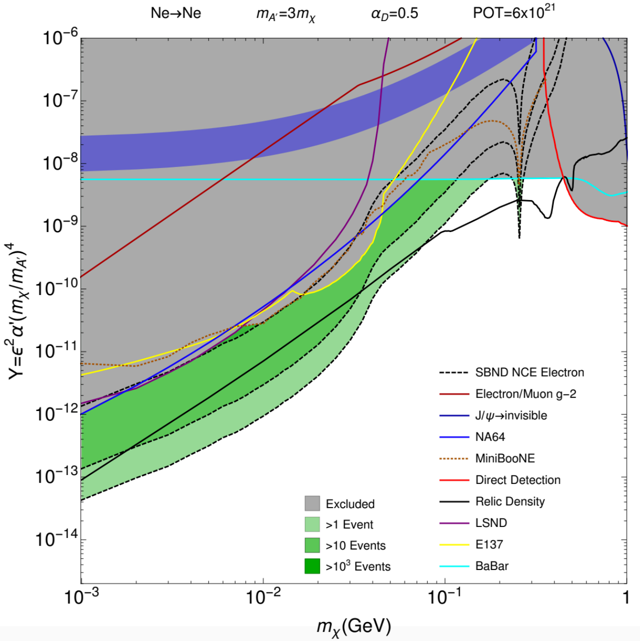


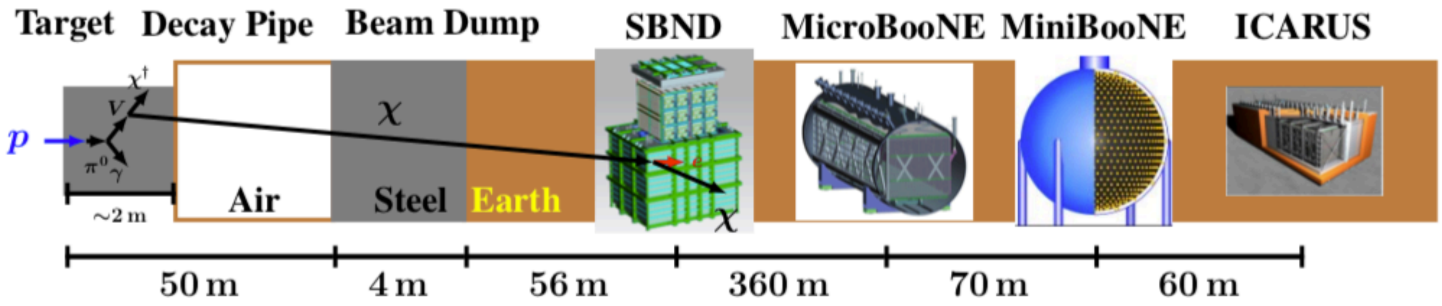




Proton Beam Dump @ 8 GeV: SBN-BD

- Up to 80 kW Booster beam available in PIP-II era in excess of DUNE needs; BNB target limited to 35 kW
- Concurrent neutrino and beam dump mode BNB running possible using existing SBND detector
- x10 signal-to-background improvement over MiniBooNE-DM search; also sensitive to hadrophilic dark sector mediators
  - Setup also supports KPipe-style sterile neutrino search
- Program can be further extended in Booster replacement era with higher-power O(10 GeV) proton beam



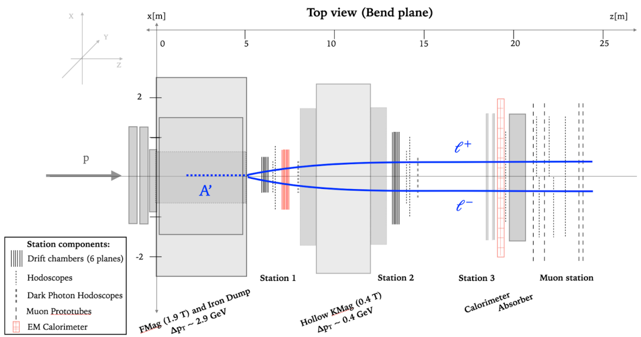


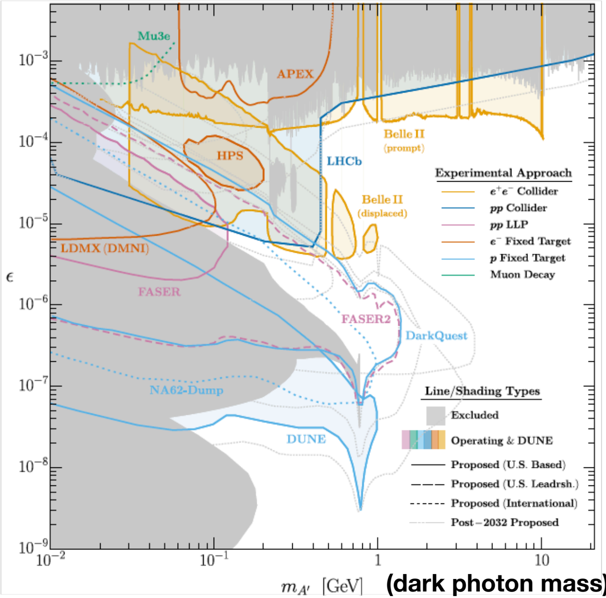
Proton Beam Dump @ 120 GeV: SpinQuest & DarkQuest

- **High-impact HEP dark sectors and NP/spin physics;** strong complementarity with Fermilab capabilities and timelines for modest resources
  - Capitalize on high-intensity 120 GeV proton beam, and unique and ready-made detector

- **SpinQuest (now!)**
  - Cover open g-2 phase space, prompt S/V → μμ
  - Initial long-lived dark photon (μμ) searches

- **DarkQuest (soon ~ 2024-2025!)**
  - Large increase in sensitivity to dark photon phase space
  - Cover open g-2 phase space, displaced S/V → ee,γγ
  - Enable searches for inelastic DM, SIMPs, ALPs, etc.

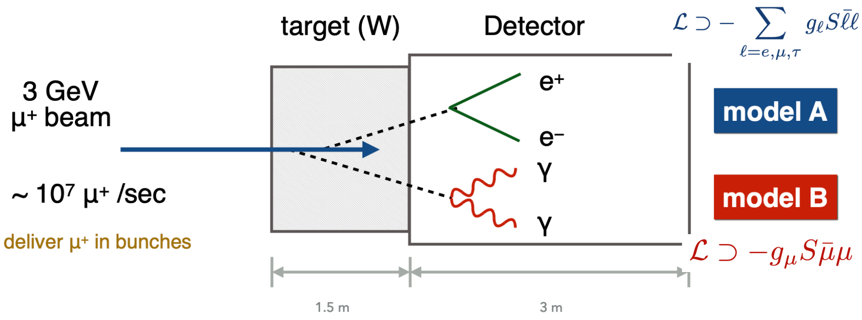




(dark photon mass)

Muon Beam Dump @ 3 GeV: FNALμ

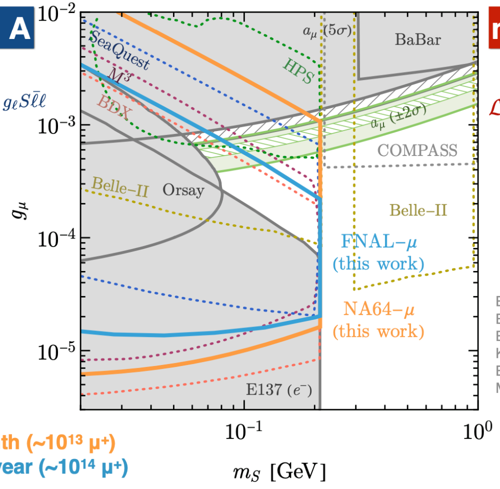
- Search for minimal dark sector model needed to solve muon g-2 anomaly
- Introduce a new light scalar S that couples to muons, not quarks, not DM (MeV< m_S < $2m_\mu$)
- FNAL setup:
  - Simple
  - Compact (could go into g-2 hall)
  - Could run in parallel w/ g-2 exp



Tracks from displaced vertices/anomalous energy deposit

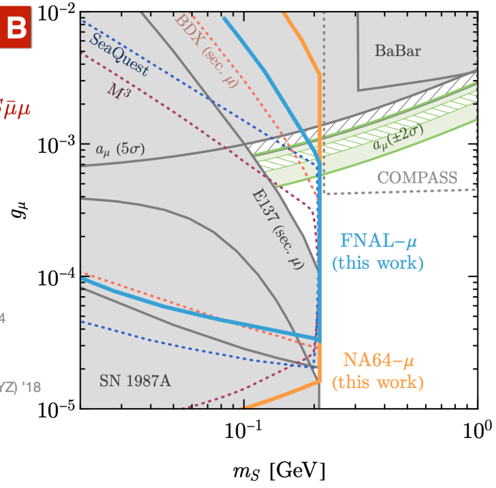
model A

$\mathcal{L} \supset -\sum_{\ell=e,\mu,\tau} g_\ell S\bar{\ell}\ell$



model B

$\mathcal{L} \supset -g_\mu S\bar{\mu}\mu$

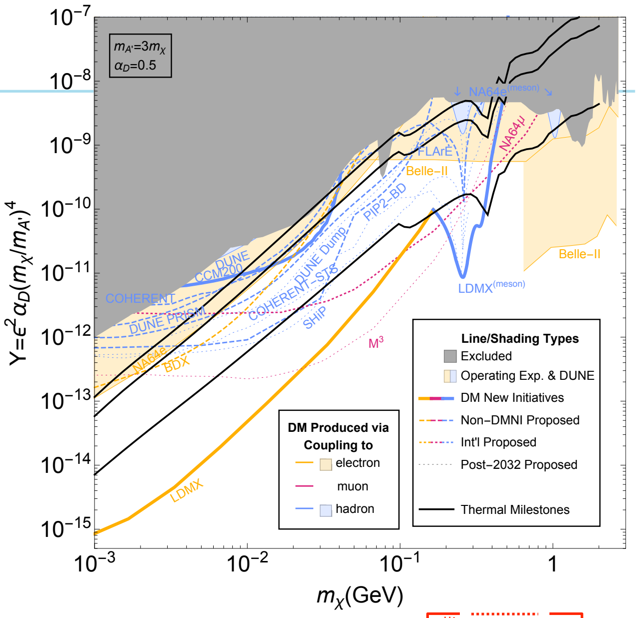


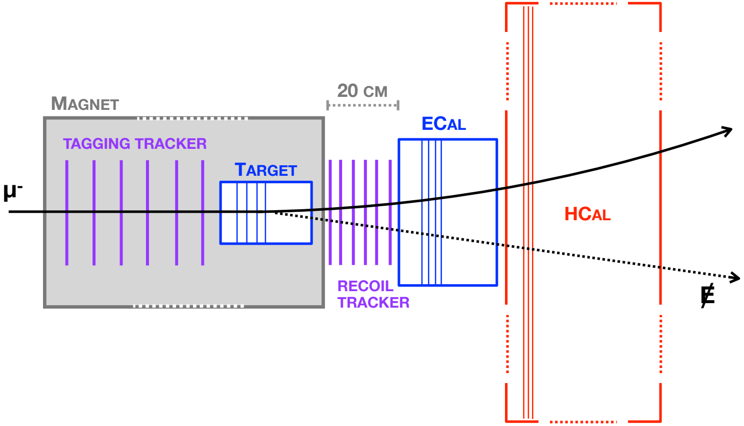
Essig+ '10
Battaglieri+ '14
Batell+ '16
Kahn+ '18
Berlin+ '18
Marsicano + (YZ) '18

NA64: 3-month (~10^{13} μ+)
Fermilab: 1-year (~10^{14} μ+)

Muon Missing Momentum @ >10 GeV: M³

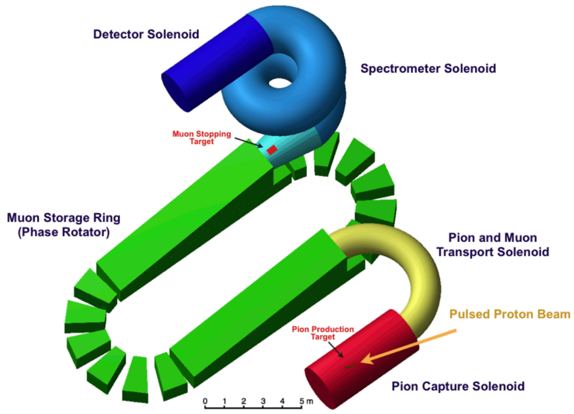
- Similar concept to electron missing momentum (LDMX) – still quite conceptual
- Based on secondary muon beam with individually identified muons – very low current at ~15 GeV
  - needs to be at least > 10 GeV
- Physics drivers
  - **Contributes leading DM sensitivity at ~100 MeV**
  - **If g-2 persists, best way to find new physics in invisible final states**



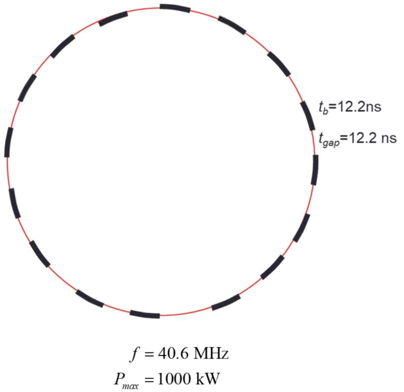


Charged Lepton Flavor Violation Searches with Muons

- Sensitive probe of physics beyond the SM
  - Mu2e has x10,000 better sensitivity than SINDRUM-II
  - Mu2e-II uses 100 kW of 800 MeV protons for x10 the statistics of Mu2e and can be staged in the PIP-II era
  - ENIGMA targets μ-to-e conversion on gold and uses 1-3 GeV protons at beam powers of up to 2 MW



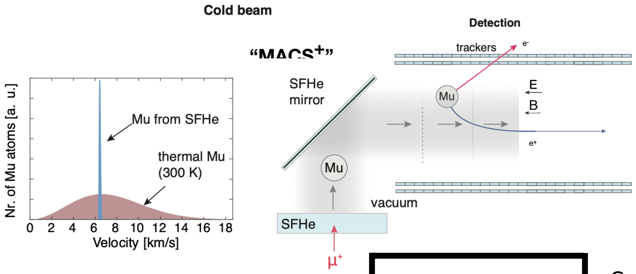
- ENIGMA requires a completely different beam structure relative to Mu2e/Mu2e-II
  - Fixed-field alternating gradient accelerator (FFA) used as a muon storage ring/manipulator
  - Proton bunch compressor used to deliver $>10^{12}$ protons with a pulse length <30 ns at a rate of 100-1000 Hz
    - Similar parameters as C-PAR

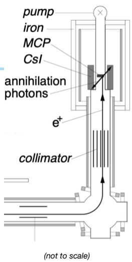


- PIP-II beam power can provide $>10^{10}$ useful μ/s that could be delivered by the FFA to decay experiments providing x100 improvement for μ → eγ and μ → 3e

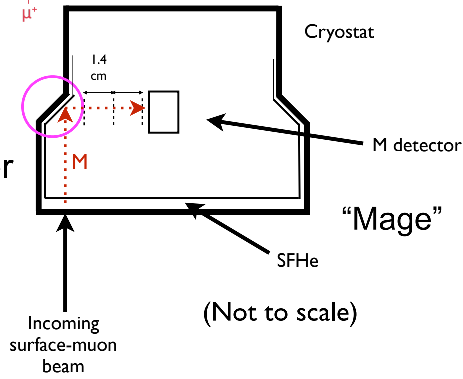
Slow Muonium Experiments

- Muonium (M): μ^+e^- bound state, studied at very low energy at PSI, TRIUMF, ISIS, J-PARC
- M 1S-2S and hyperfine frequencies:
  - M is pure QED atom of point-like leptons
  - QCD corrections negligible
  - High precision feasible, theoretically & experimentally
- M-$\bar{\text{M}}$ oscillation search:
  - doubly charged-lepton flavor violating!
  - forbidden only by lepton-flavor conservation
  - background negligible
- M gravity:
  - unique 2nd-generation antilepton equivalence-principle test
- 400 MeV Linac
  - competitive w/ world leader (PSI)?





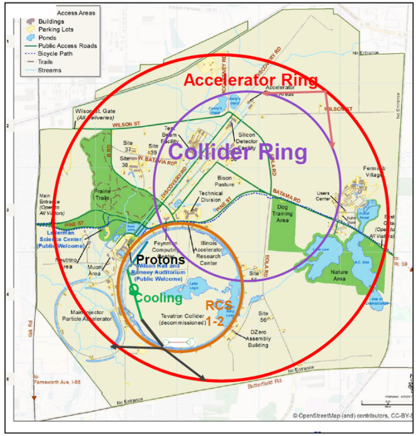
previous results >20 years old – can now do substantially better

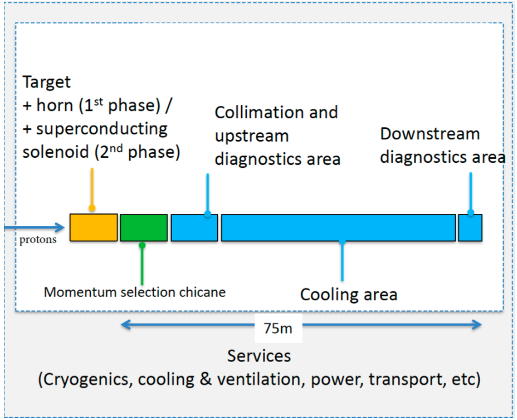


new techniques will soon make feasible For the first time

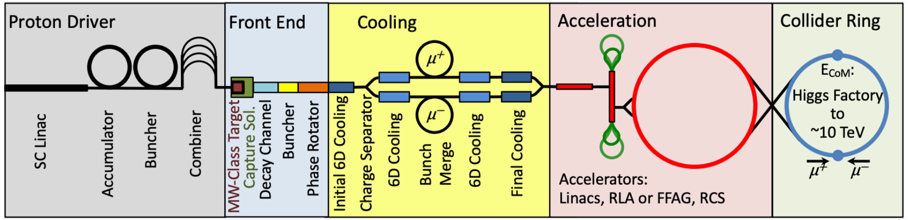
Muon Collider R&D

- High luminosity, high energy (10 TeV) muon Collider for BSM
- Requires 5-30 GeV protons with $10^{12} – 10^{13}$ protons per bunch, bunch length 1-3 ns at a rate of 5-50 Hz
  - Design of accumulator & buncher rings exists
- Demonstrate 6D muon beam cooling (muon momentum < 1 GeV/c) at PIP-II
  - One of the key technical hurdles to overcome
- Share high energy μ/K beam after target
  - nuSTORM (μ momentum 1 < p < 6 GeV/c)
  - ENUBET (K)





Y. Alexahin and V. Lebedev



Fermilab Test Beam Facility (FTBF) and Irradiation Test Area (ITA)

- FTBF maxed out at ~20 experiments and 200+ users per year
  - Located at end of aging beamline with increased upkeep, downtime
  - Increased demand for clean, low energy electron, muon, mixed particle beams challenging for existing facility

- Existing ITA operational until Linac turns off for PIP-II in ~2026

- Jointly locate new test beam and irradiation facility central to accelerator complex, drawing beam from PIP-II, Booster replacement, Main Injector
  - 4-6 beamlines + clean secondary lines for e, μ, π

- PIP-II accelerator could reach radiation levels predicted at FCC (~10^{18} 1-MeV neq / cm^2) in ~days
- Flexible beam intensity and size to also support single event effect and electronics studies
- Irradiations with other particles or energies

Additional details: arXiv:2203.09944

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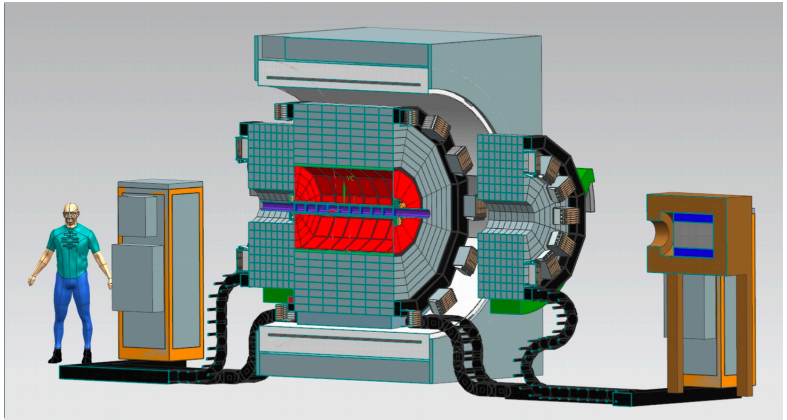
REDTOP: ~10^{14} η mesons/yr and ~10^{12} η’ mesons/yr

Main Physics Goals

- Test of CP invariance via Dalitz plot mirror asymmetry: $\eta \rightarrow \pi^0\pi^+\pi^-$
  - Search for asymmetries in the dalitz plot with very high statistics
- Test of CP invariance via μ polarization studies: $\eta \rightarrow \pi^0\mu^+\mu^-$, $\eta \rightarrow \gamma\mu^+\mu^-$, $\eta \rightarrow \mu^+\mu^-$,
  - Measure the angular asymmetry between spin and momentum
- Dark photon searches: $\eta \rightarrow \gamma A'$, with $A' \rightarrow \mu^+\mu^-$, $\eta \rightarrow e^+e^-$
  - Need excellent vertexing and particle ID
- QCD axion and ALP searches: $\eta \rightarrow \pi\pi a$, with $a \rightarrow \gamma\gamma$, $a \rightarrow \mu^+\mu^-$, $\eta \rightarrow e^+e^-$
  - Dual (or triple!) calorimeters and vertexing
- Dark scalar searches: $\eta \rightarrow \pi^0 H$, with $H \rightarrow \mu^+\mu^-$, $H \rightarrow e^+e^-$
  - Dual (or triple!) calorimeters and particle ID
- Lepton Flavor Universality studies: $\eta \rightarrow \mu^+\mu^- X$, $\eta \rightarrow e^+e^- X$
  - Need excellent particle ID



Running Modes

- Baseline option – medium-energy CW proton beam
  - p on Li/Be target: ~1.8 GeV – 30 W (10^{11} POT/sec)
- Pion beam option – low-energy pion beam
  - π^+ on Li/Be or π^- on LH: ~750 MeV – 2.5×10^9 πOT/sec
- Ultimate option: Tagged η/η’ mesons (via He_3^{++})
  - High intensity proton beam on De target: ~0.9 GeV ; 0.1-1 MW

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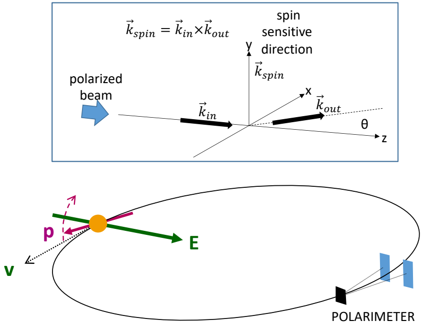
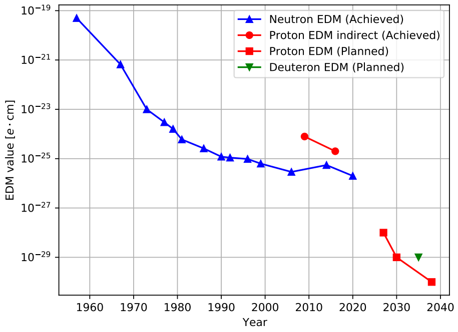
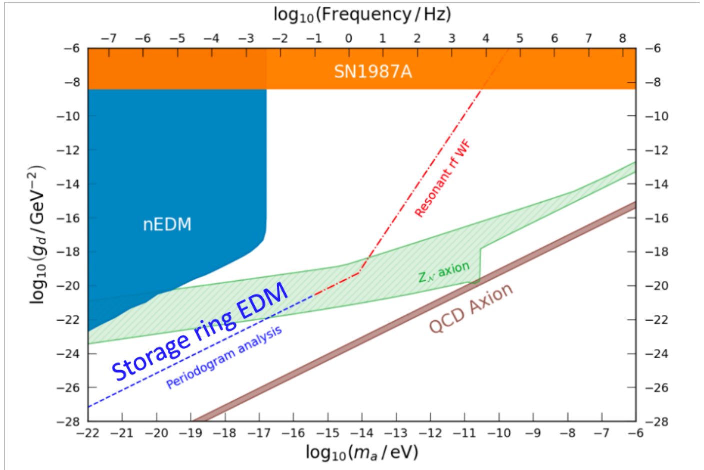
Storage ring proton EDM at 10^{-29} e-cm

- Frozen spin method:
  - Spin aligned with the momentum vector
  - Radial E-field precesses EDM/spin vertically
  - Monitoring the spin using a polarimeter
- Competitive EDM sensitivity:
  - New-Physics reach at 10^3 TeV
  - Best probe on Higgs CPV, Marciano: proton is better than $H \rightarrow \gamma\gamma$, and 30x more sensitive than electron with same EDM
  - Three orders of magnitude improvement in θQCD sensitivity
  - Direct axion dark matter reach (best exp. sensitivity at very low frequencies)
- Experience with muon g-2 experiment; possible to have interesting results within the decade

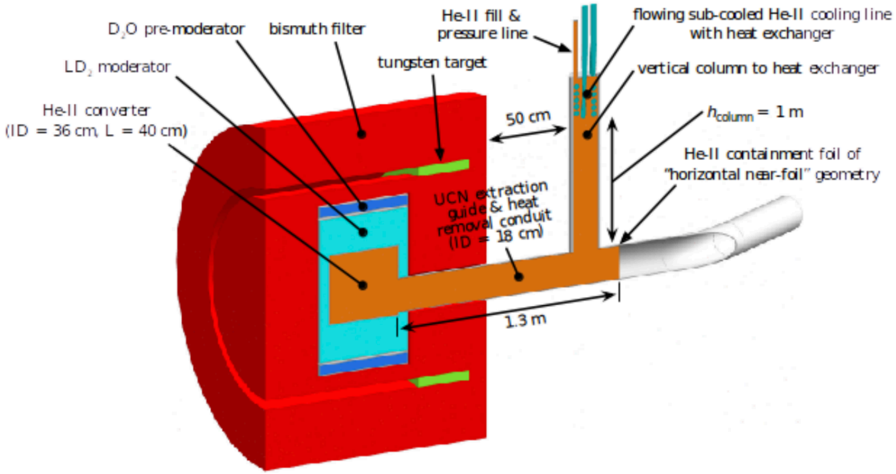






Cold Neutron Source For n $\leftrightarrow \bar{n}$ Oscillations And Fundamental Physics

- Neutron electric dipole moments (EDMs) and neutron-antineutron oscillations ($n \rightarrow \bar{n}$) provide some of our most sensitive low energy constraints on BSM physics
- Experimental limits for neutron EDMs and $n \rightarrow \bar{n}$ are typically limited by available densities/fluxes of neutrons
- Conceptual design for an ultra cold neutron source allows for continuous proton beam powers in excess of 1 MW (at an assumed 800 MeV proton beam energy) from PIP-II incident on the spallation target
- At 1 MW of proton beam power, inside the converter a UCN production rate of 2×10^9 s^{-1} and density of 5×10^4 UCN/cm^3 can be reached
- Expected delivery to an external experiment would be a UCN integrated flux of 5×10^8 UCN/s and a density of 1×10^4 UCN/cm^3 .
- With these parameters, this source would have the highest integrated flux in the world, and ideally suited for an optimized $n \rightarrow \bar{n}$ experiment, for example



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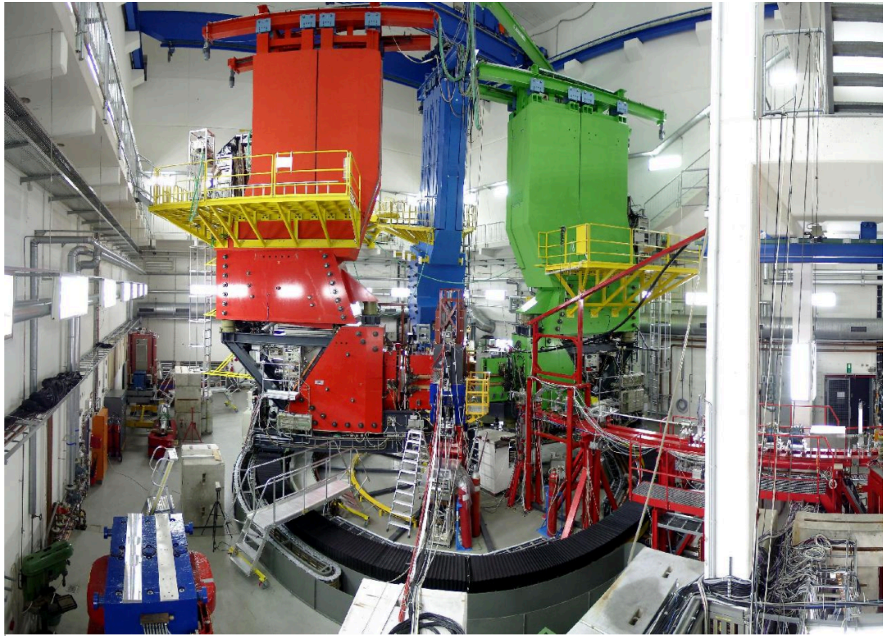
Nucleon Electromagnetic Form Factors From Lepton Scattering

- Tension in determination of the magnetic form factor of the proton using A1@MAMI or global data
- Also precision and kinematic range of neutron form factor data is lacking
- Motivates hydrogen and deuterium targets in a high-intensity electron or muon beam to improve on the precision of proton and neutron form factors
  - To evaluate cross sections with muon and electron neutrinos, form factors should be measured at $Q^2 < 1$ GeV^2
- Assuming angular coverage of the detector up to 150 degrees, energies above 900 MeV are required to probe the $Q^2 < 1$ GeV^2 range
  - For a measurement using a very forward-angle detector, similar to the PRAD experiment at Jefferson Lab, larger energies (1–3 GeV) would be desired.
- Electron beam currents of roughly 1 nA are sufficient for forward-angle measurements, and up to 1–10 μA for coverage of a wider range of kinematics
  - For muon measurements, 10^7–10^8 μ/s would permit forward-angle measurements and open up the desired kinematic range



Wrap up and conclusion

- Upgraded Fermilab accelerator complex enables a wide array of physics opportunities spanning different subfields
- Themes of dark sector and muon-based searches featured prominently in white paper contributions
- Many of these ideas required an accumulator ring to bunch PIP-II protons into pulses
- Most of the ideas covered here are actually planned for the PIP-II era, rather than the Booster replacement era

Thank you for your attention!

Pion decay-at-rest facilities