Search for light DM and mediators: results and prospects at FNAL

Nhan Tran + input from Corrado Gatto, Ornella Palamara, Matt Toups

FIPS 2022

October 19, 2022

Overview

Status

- MicroBooNE - *See Stefan's talk*
- **ArgoNEUT, SBND** - millicharged particles
- **SpinQuest & DarkQuest** - dark mediator spectrometer searches

Prospects

- **PIP-II Beam Dump, SBN Beam Dump** - DM rescattering with proton beams
- **M^3 and muon beam dump (3 GeV)** - muon-specific couplings
- **REDTOP** - η factory
- DUNE - *See Joachim's talk*

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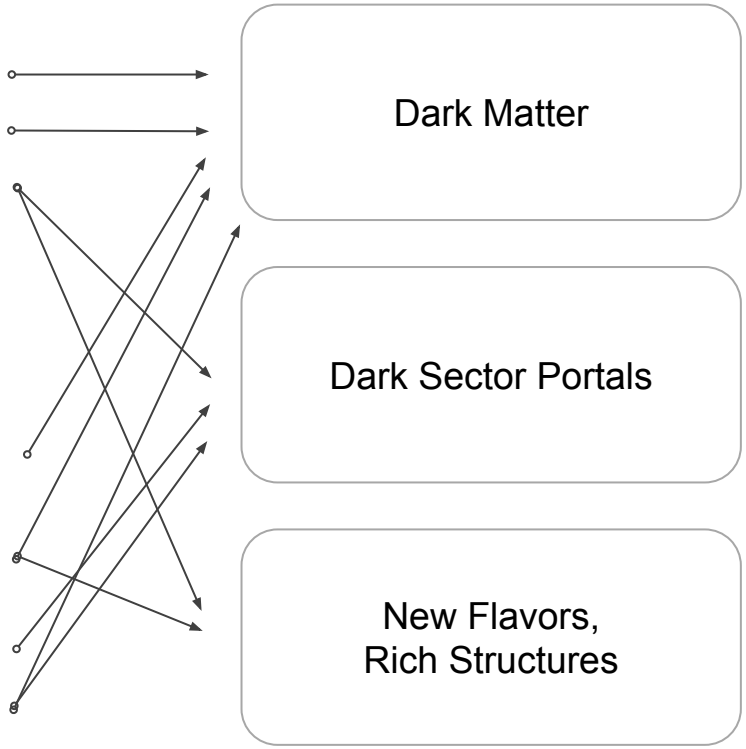
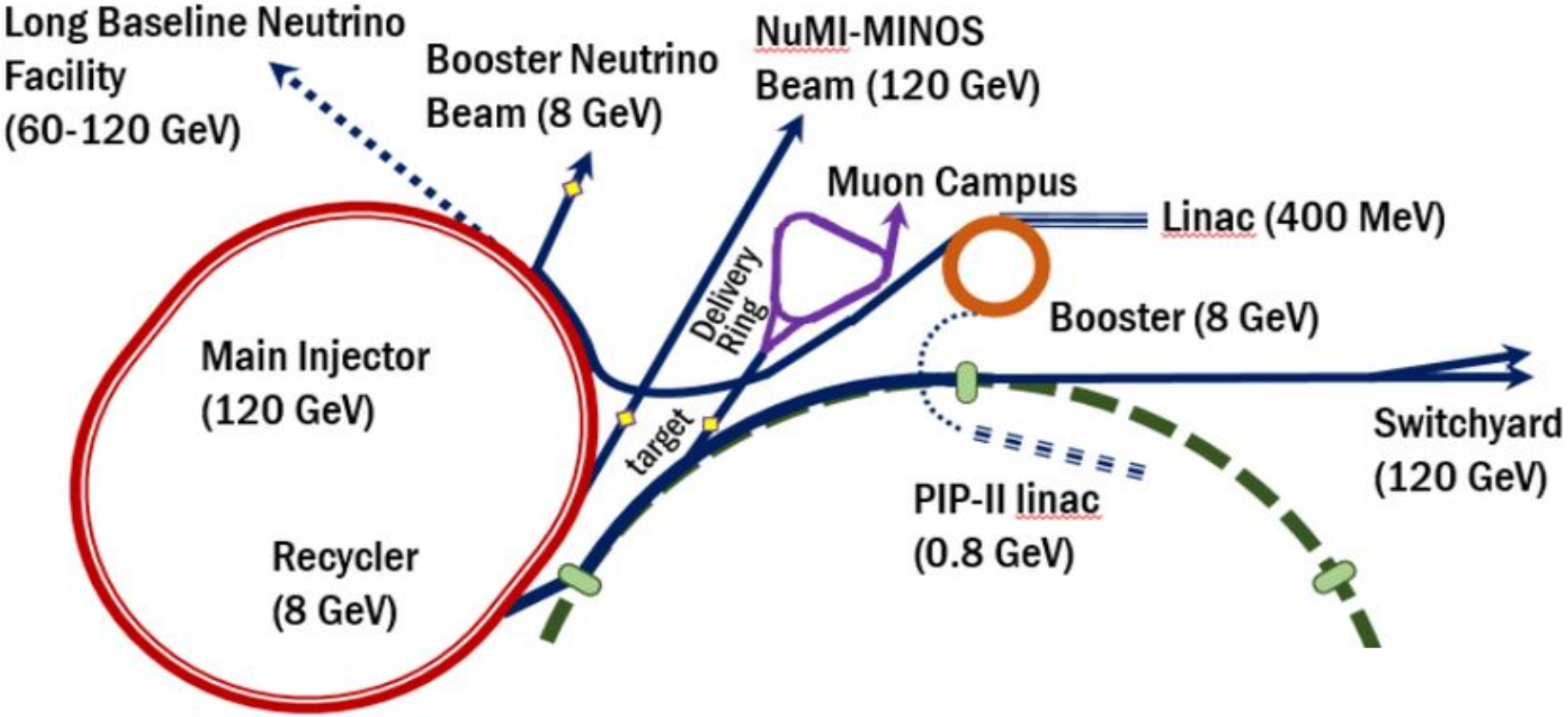
Physics drivers
see arXiv:2209.04671



Fermilab accelerator complex



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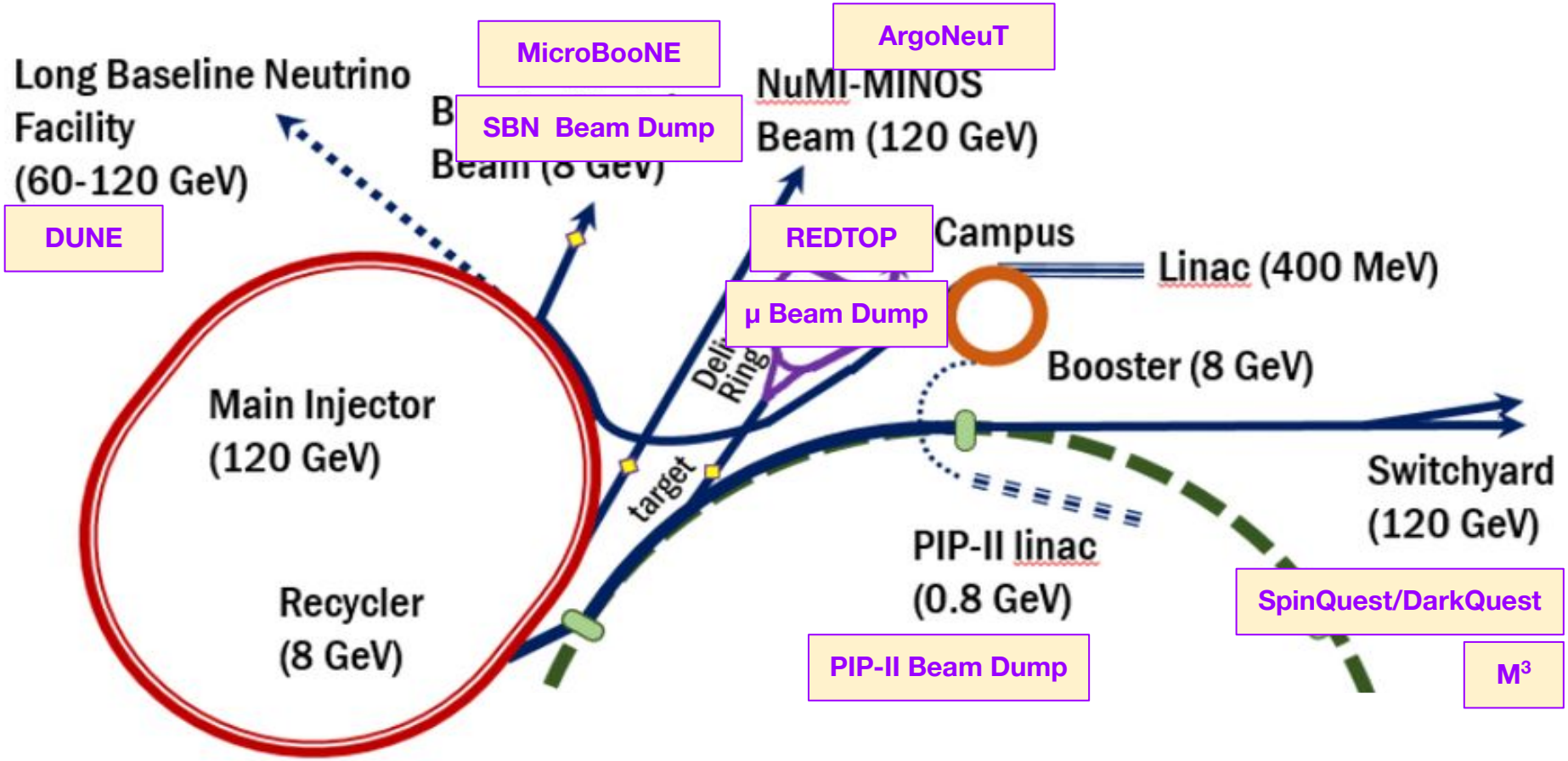
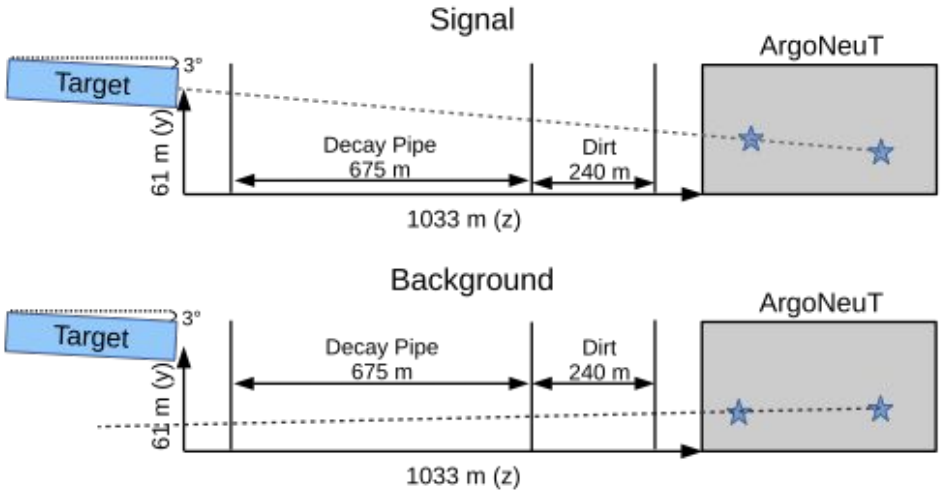
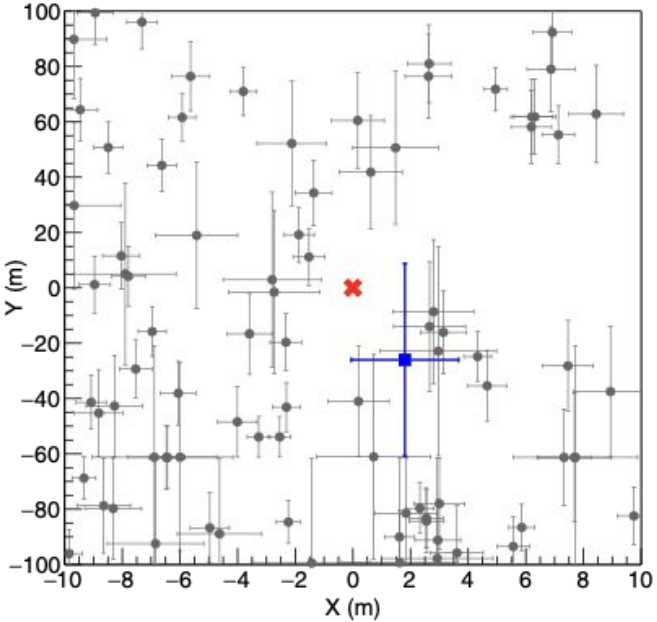


ArgoNeuT millicharged particle search

Phys. Rev. Lett. **124**, 131801
POC: Ornella Palamara

NuMI 120 GeV beam, analysis with 1e20 PoT, data from 2009-2010





First search for mCPs with LArTPC neutrino detector

Search strategy:

Two low threshold (<MeV) electromagnetic hits pointing back to the target

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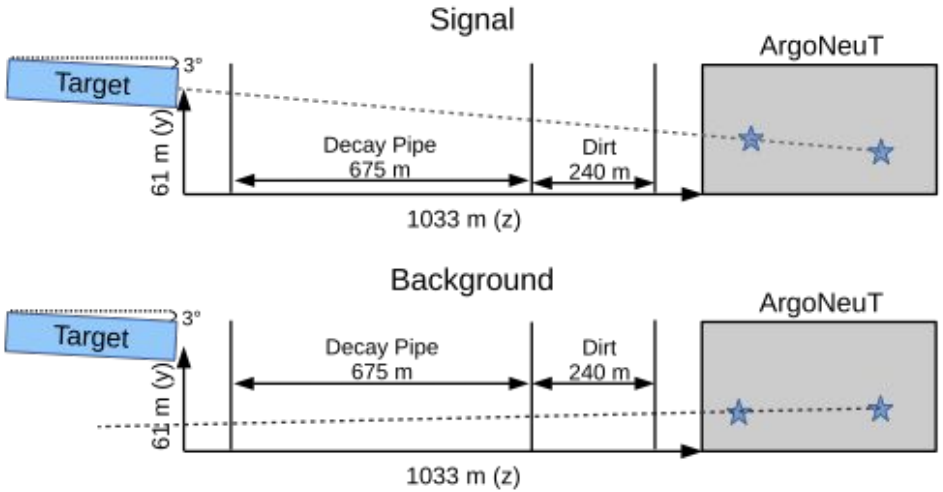

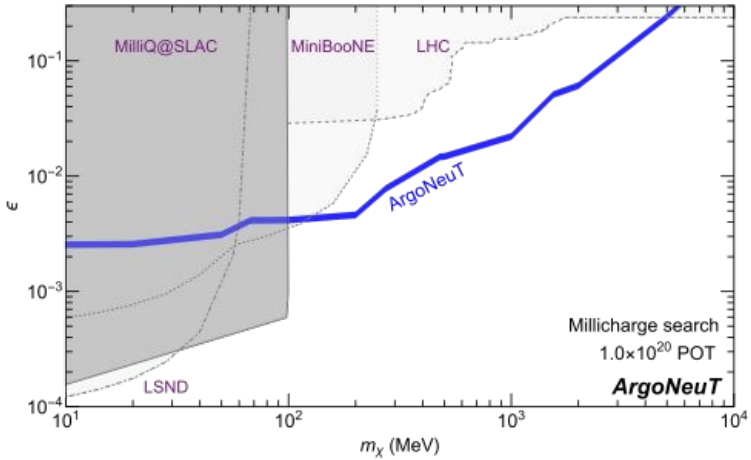

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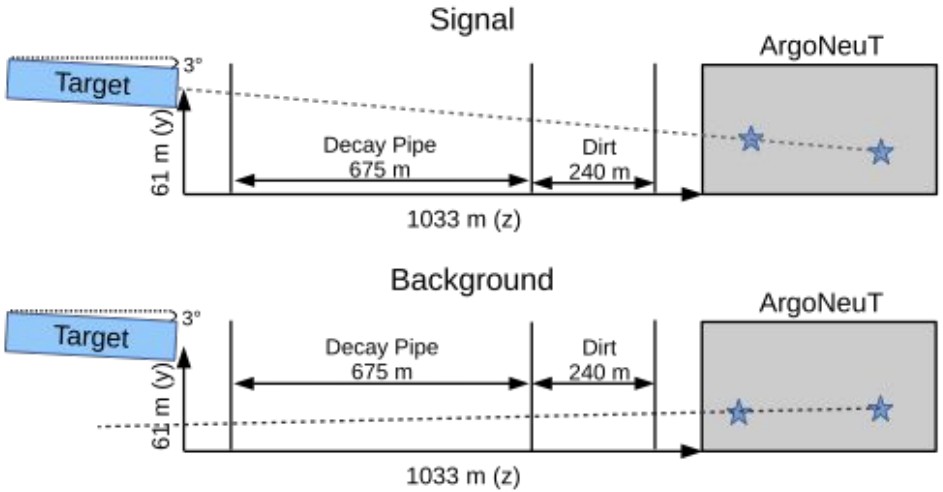

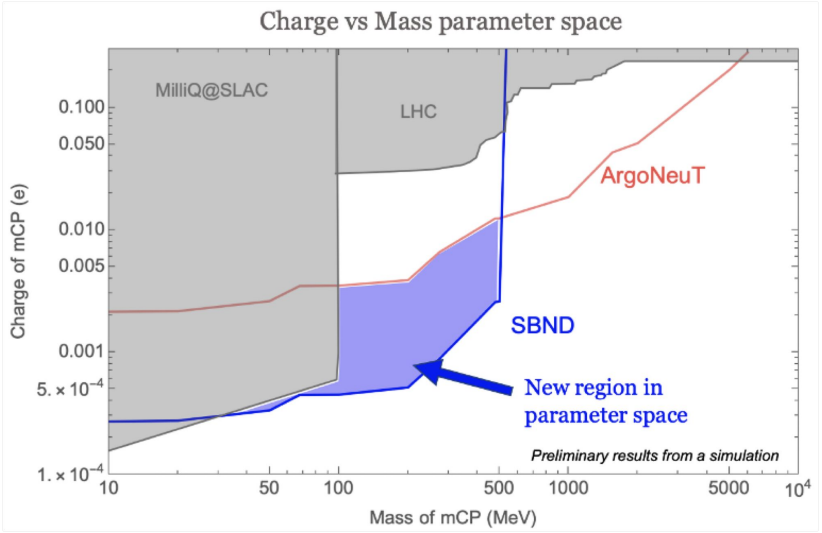

First search for mCPs with LArTPC neutrino detector

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Two low threshold (<MeV) electromagnetic hits pointing back to the target

SBND: 8 GeV beam, closer detector (110m), lower threshold (50 keV)

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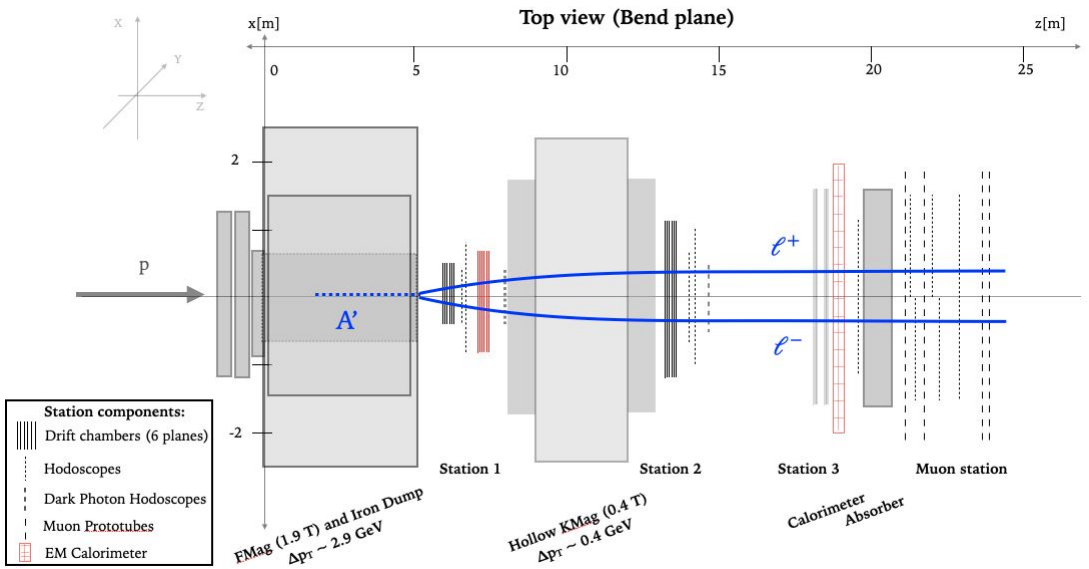
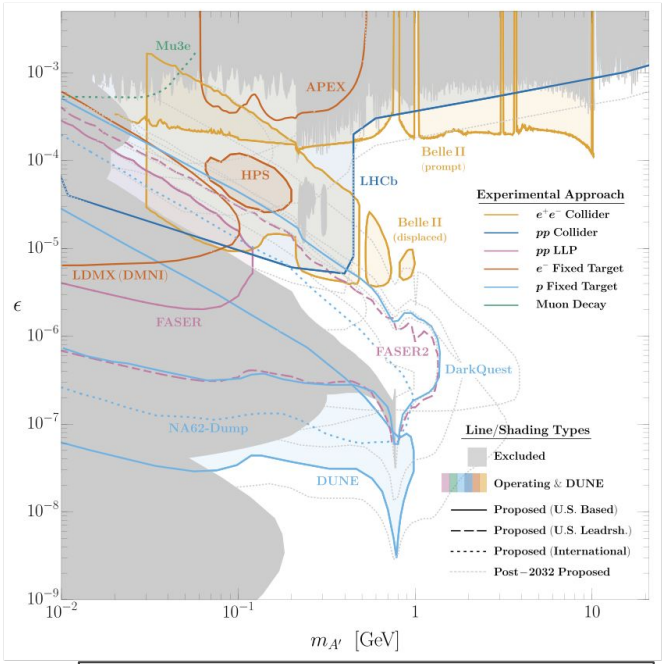
DarkQuest

DarkQuest, 2203.08322
Snowmass report, 2209.04671

- DarkQuest is EMCal upgrade to SeaQuest/SpinQuest proton beam dump experiment at 120 GeV at Fermilab Main Injector – high impact, near-term, modest-cost





+ additional sensitivity to several other signatures (SIMPS, mu-philic scalar, etc.)

DarkQuest

DarkQuest, 2203.08322
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- Dark sector community formalizing collaboration with SpinQuest
- Snowmass white paper includes several new studies to develop detector concept and simulation – advance dark sector physics case and experimental plan
- Upgrade physics case presented to / endorsed by Fermilab PAC in June
    - Target Timescale: FY25

Meanwhile…

- SpinQuest is getting ready to run this winter!
- Goal: displaced dimuon search ($m_{A'} > 2m_{\mu}$), triggers implemented in FW
- Design and testing of EMCal electronics on-going

EMCal
teststand

PIP2-BD

POC: Matt Toups, Jacob Zettlemoyer

- PIP2-BD is a low-threshold argon scintillation-only detector placed just downstream of a ~1 GeV PIP-II beam dump
- Makes use of the proton beam power capabilities of PIP-II but requires addition of an accumulator ring
- Developed detector concept, simulation to study dark sector, sterile neutrino sensitivities for 3 different accumulator rings
  - PIP-II Accumulator Ring
  - Compact PIP-II Accumulator Ring
  - New Rapid Cycling Synchrotron Accumulator Ring
- Strong synergies with the Advanced Muon Facility
- Snowmass white paper will be updated and submitted to PRD this year

PIP2-BD: GeV Proton Beam Dump at Fermilab's PIP-II Linac

M. Toups,* S.J. Brice, Jeff Eldred, Roni Harnik, Kevin J. Kelly, Tom Kobilarcik, Gordan Krnjaic, Pedro A. N. Machado, V. Pandey, Z. Pavlovic, William Pellico, Jacob Zettlemoyer, and Bob Zwaska
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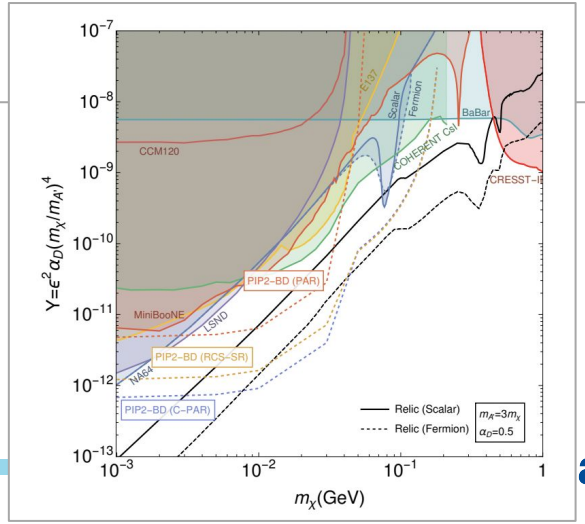
arxiv:2203.08079



SBN-BD

POC: Matt Toups, Jacob Zettlemoyer

- SBN-BD is a proton beam dump for the BNB as a follow-on to MiniBooNE-DM
- Makes use of the excess Booster beam power capabilities in the PIP-II era
- Dark sector and sterile neutrino sensitivities studied for 2 different detectors
  - SBND
  - KPipe (Phys. Rev. D 92, 092010)
- Snowmass white paper submitted to topical groups focused on dark sector studies at high intensities and BSM searches at neutrino experiments

FERMILAB-FN-1157, LA-UR-22-22524

SBN-BD: $\mathcal{O}$(10 GeV) Proton Beam Dump at Fermilab's PIP-II Linac

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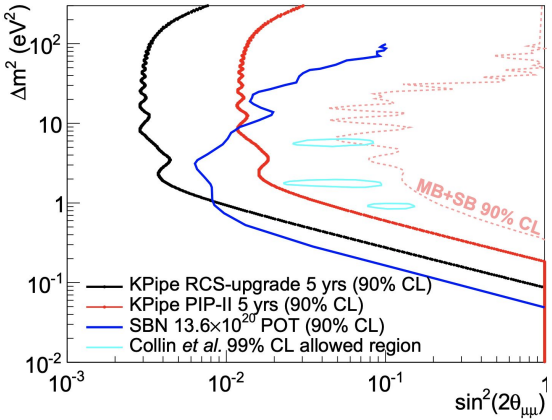
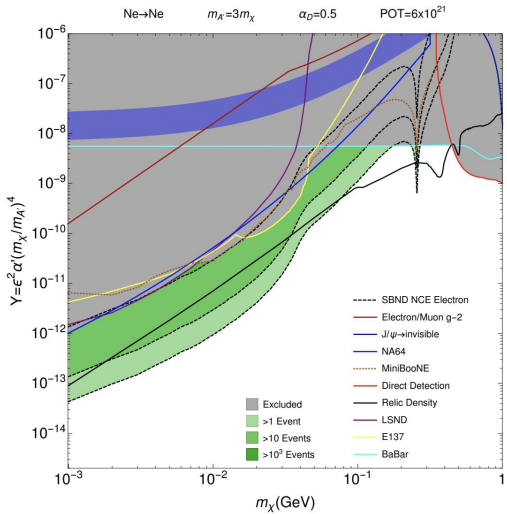
arxiv:2203.08278





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What about g-2?

https://indico.fnal.gov/event/48936

A No-Lose Theorem for Discovering the New Physics of $(g-2)_\mu$ at Muon Colliders

Rodolfo Capdevilla, David Curtin, Yonatan Kahn, Gordan Krnjaic

https://arxiv.org/abs/2101.10334

Discovering the new physics of g-2 with fixed target muon facilities at Fermilab

Tuesday Jun 22, 2021, 12:00 PM → 5:00 PM US/Central

Andrew Whitbeck (Texas Tech University), Christian Herwig (FNAL), Cristina Ana Mantilla Suarez (FNAL), Gordan Krnjaic (Fermilab), Nhan Tran (FNAL), Yonatan Kahn (University of Illinois at Urbana-Champaign)

Introduction
Introductory slides

Theory motivations
Speaker: Gordan Krnjaic (Fermilab)
MiniMuWorkshop.pdf

Theory phenomenology
Speaker: Brian Batell (University of Pittsburgh)
Batell-muon-pheno....

Muon beam options at Fermilab Accelerator Facility and discussion
Speaker: Nhan Tran (FNAL)
muon-beams-nt.pdf

(Minimal) M^3
Speaker: Cristina Ana Mantilla Suarez (FNAL)
CMS_M3_Jun22.pdf

Muon beam dumps at muon campus
Speaker: Yiming Zhong (Boston University)
muon_beam_dump_...

DarkQuest
Speaker: David Sperka
DarkQuest_g2works...

M^3 in SpinQuest
Speaker: Philip Harris (MIT)
PCH_DQforM3_14_...

	Invisible			Visible			
final state/ mediator	Long-lived	neutrinos $\nu\nu$	DM $\chi\chi$	photons $\gamma\gamma$	electrons e^+e^-	muons $\mu^+\mu^-$	hadrons $\pi\pi, \ldots$
	no(?)	yes	yes	no	no(?)	yes* $(m_V > 2m_\mu)$	no(?)
vector	• $L_\mu - L_\tau$ gauge boson: UV complete, automatic coupling to neutrinos, easy to couple to DM. (* $m_V > 2m_\mu$ constrained by dedicated *BABAR* search) • Challenging to build viable models with sizable couplings of vector mediator to electrons or hadrons (gauge anomalies, constraints from neutrino physics)						
scalar	yes $(m_S < 2m_\mu)$	yes	yes	yes $(m_S < 2m_\mu)$	yes $(m_S < 2m_\mu)$	yes $(m_S > 2m_\mu)$	yes $(m_S > 2m_\pi)$
	• All minimal signatures can be realized in scalar simplified models. • UV complete models require new SM-charged states above weak scale with special flavor structure (such states can in principle affect (g-2) • More phenomenological studies needed to chart the parameter space						
signature	missing momentum			prompt or displaced resonance			

Credit: Brian Batell

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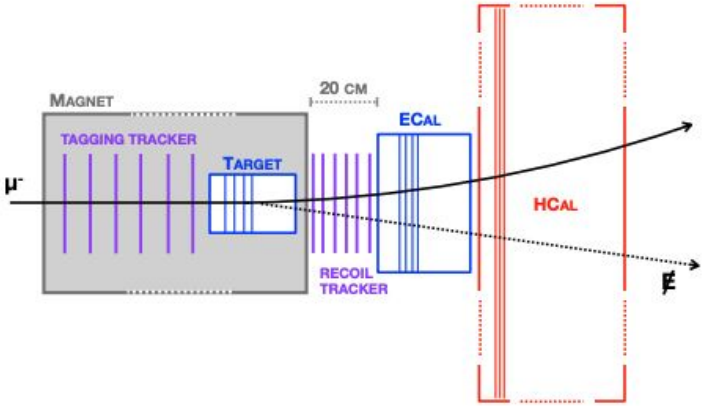
M^3 and muon beam dump

arXiv:1701.07437
arXiv:1804.03144

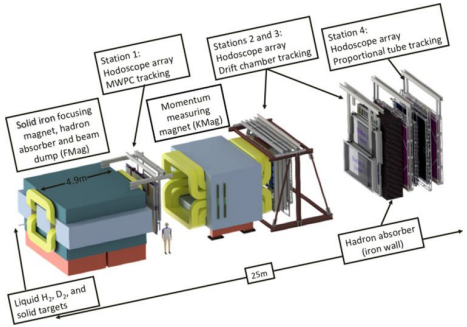
M^3: invisible search

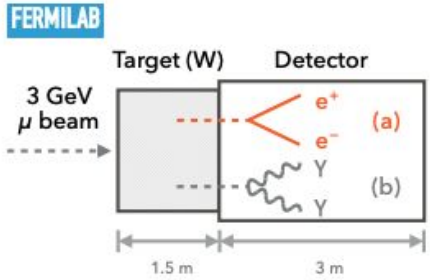
Work on-going to understand if muon flux can be achieved in NM4 hall (SpinQuest)



Visible searches

3 GeV muon beam dump and **DarkQuest** could cover remaining ground in visible ee and γγ final states, μμ final states to be understood





What does a worldwide program look like to systematically explore sub-GeV solutions to g-2?

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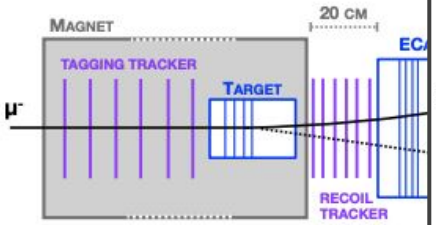
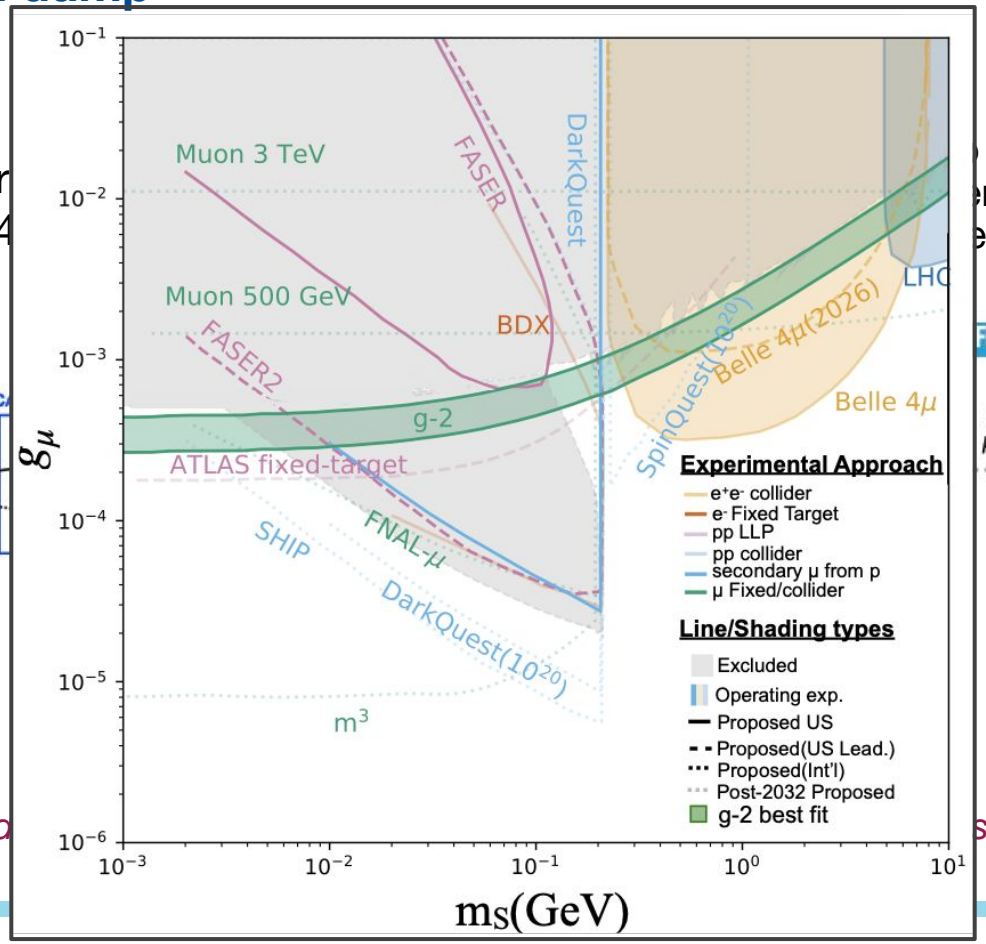
M^3 and muon beam dump

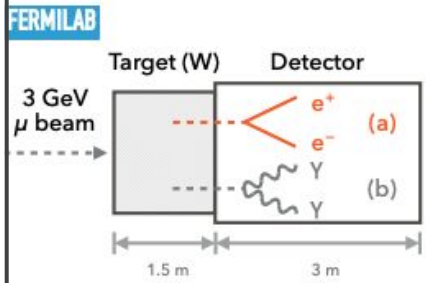
Snowmass report, 2209.04671

M^3: invisible search

Work on-going to under … (Yiming Zhong, UC) and can be achieved in NM4 … emaining ground in … es, μμ final states to be







What does a worlo … solutions to g-2?

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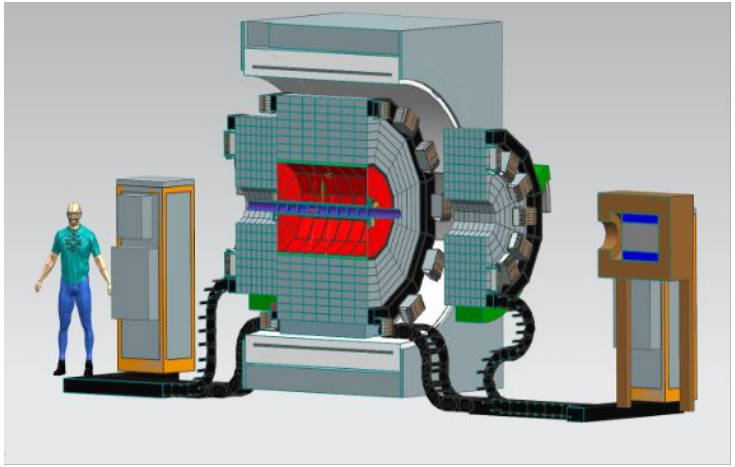
REDTOP

a η/η' factory to search for Dark Matter and CP-violation

https://arxiv.org/abs/2203.07651
POC: Corrado Gatto
redtop.fnal.gov



C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^0 \pi^+ \pi^-$
- CP Violation (Type I – P and T odd, C even): $\eta \to 4\pi^0 \to 8\gamma$
- CP Violation (Type II – C and T odd, P even): $\eta \to \pi^0 e^+ e^-$ **and** $\eta \to 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+ \mu^-$
- CP inv. via γ^* polarization studies: $\eta \to \pi^+ \pi^- e^+ e^-$ & $\eta \to \pi^+ \pi^- \mu^+ \mu^-$
- CP invariance in angular correlation studies: $\eta \to \mu^+ \mu^- e^+ e^-$
- CP invariance in angular correlation studies: $\eta \to \mu^+ \mu^- \pi^+ \pi^-$
- CP invariance in μ polar. in studies: $\eta \to \pi^0 \mu^+ \mu^-$
- T invar. via μ transverse polarization: $\eta \to \pi^+ \mu^+ \mu^-$ and $\eta \to \gamma \mu^+ \mu^-$
- CPT violation: μ polar. in $\eta \to \pi^+ \mu^- \nu$ vs $\eta \to \pi^+ \mu^- \nu$ – γ polar. in $\eta \to \gamma\gamma$

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \to \mu^+ e^- + c.c.$
- Radiative Lepton Flavor Violation: $\eta \to \gamma (\mu^+ e^- + c.c.$
- Double lepton Flavor Violation: $\eta \to \mu^+ \mu^+ e^- e^- + c.c.$

Non- η/η based BSM Physics

- Neutral pion decay: $\pi^0 \to \gamma A' \to \gamma e^+ e^-$
- ALP's searches in Primakoff processes: $p Z \to p Z a \to l^+ l^-$ (F. Kahlhoefer)
- Charged pion and kaon decays: $\pi^+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$ and $K^+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$
- Dark photon and ALP searches in Drell-Yan processes: $q\bar{q} \to A'/a \to l^+ l^-$

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \to \pi^0 H$ with $H \to e^+ e^-$ and $H \to \mu^+ \mu^-$
- Dark photon searches: $\eta \to \gamma A'$ with $A' \to e^+ e^-$
- Protophobic fifth force searches: $\eta \to \gamma X_{17}$ with $X_{17} \to \pi^+ \pi^-$
- QCD axion searches: $\eta \to \pi\pi a_{17}$ with $a_{17} \to e^+ e^-$
- New leptophobic baryonic force searches: $\eta \to \gamma B$ with $B \to e^+ e^-$ or $B \to \gamma \pi^0$
- Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \to \mu^+ \mu^-$ and $\eta \to e^+ e^-$
- Search for true muonium: $\eta \to \gamma (\mu^+ \mu^-)|_{2M_\mu} \to \gamma e^+ e^-$
- Lepton Universality
- $\eta \to \pi^0 H$ with $H \to \nu N_2$, $N_2 \to H N_1$, $H \to e^+ e^-$

Other Precision Physics measurements

- Proton radius anomaly: $\eta \to \gamma \mu^+ \mu^-$ vs $\eta \to \gamma e^+ e^-$
- All unseen leptonic decay mode of η / η' (SM predicts 10^{-6}–10^{-9})

High precision studies on medium energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for g-2)

sensitive to all 4 DM portals

- Sensitive to DM from 10 MeV up to ~η' mass
- Modest beam reqr's: 1.8 GeV proton – 30 W (for 1014 h)
- Moderate cost: $55M (+ contingency & labor)
- Latest detector technologies: dual-readout, LGAD,…

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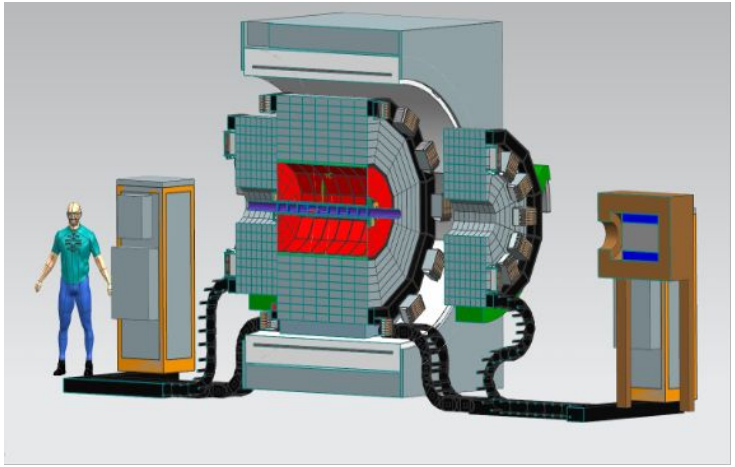

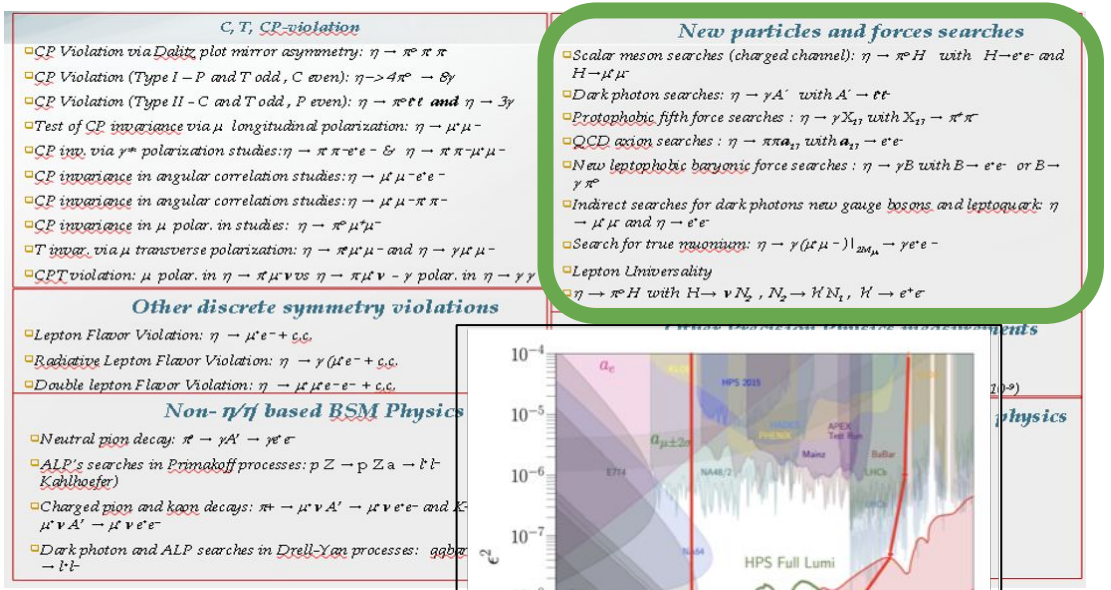

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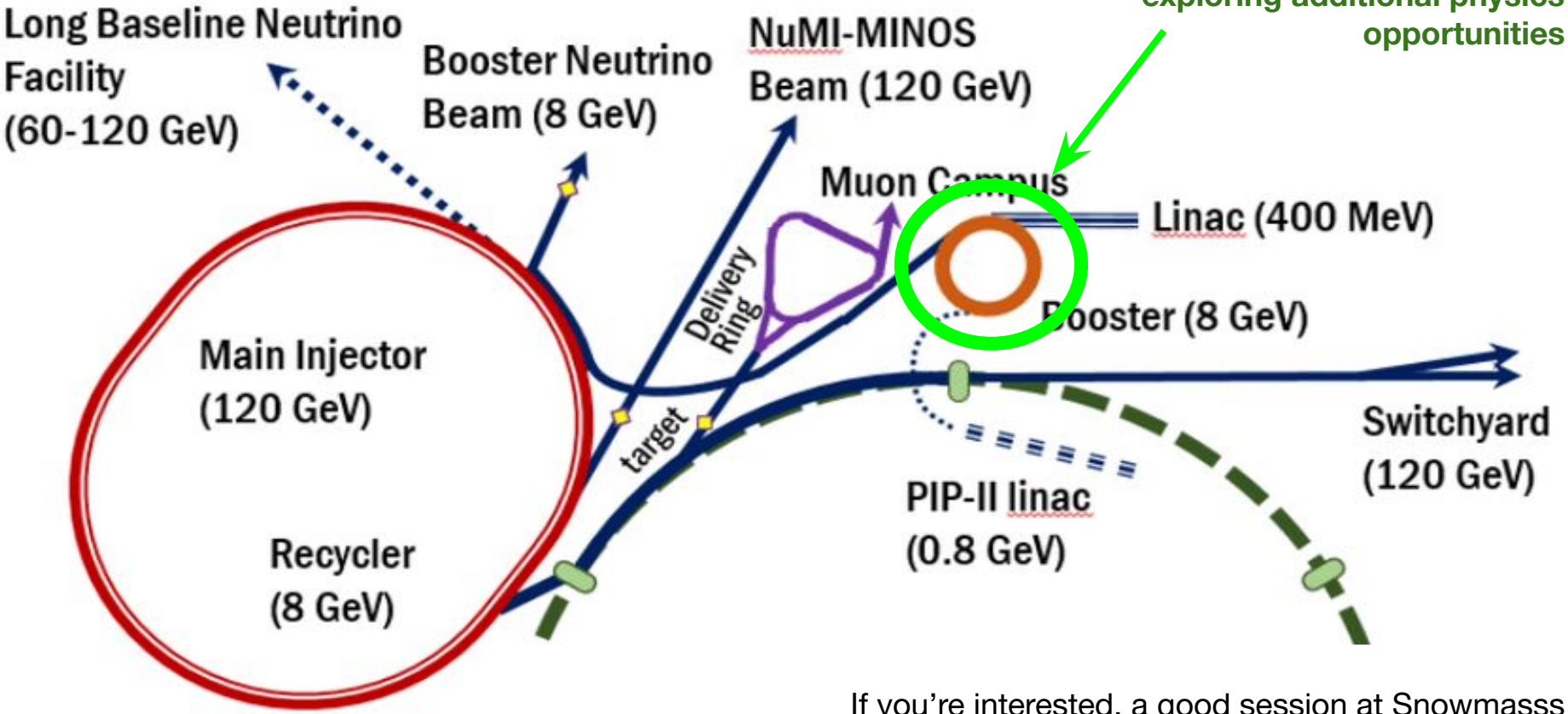
Proton intensity upgrade

To upgrade DUNE to 2.4 MW, the Booster needs to be upgraded. Fermilab currently exploring additional physics opportunities



If you're interested, a good session at Snowmasss
https://indico.fnal.gov/event/22303/sessions/20651/#20220720

Outlook

Active program at the Fermilab accelerator complex to search for light DM and mediators

See also talk's by Stefan (MicroBooNE) and Joachim (DUNE) on Friday

Current program leveraging neutrino detectors and existing infrastructure (e.g. SpinQuest)

Exciting prospects for future experiments in concert with planned accelerator facility upgrades PIP-II and Proton Intensity Upgrade (Booster replacement)

PIP-II shutdown ~FY27, target operation in FY29