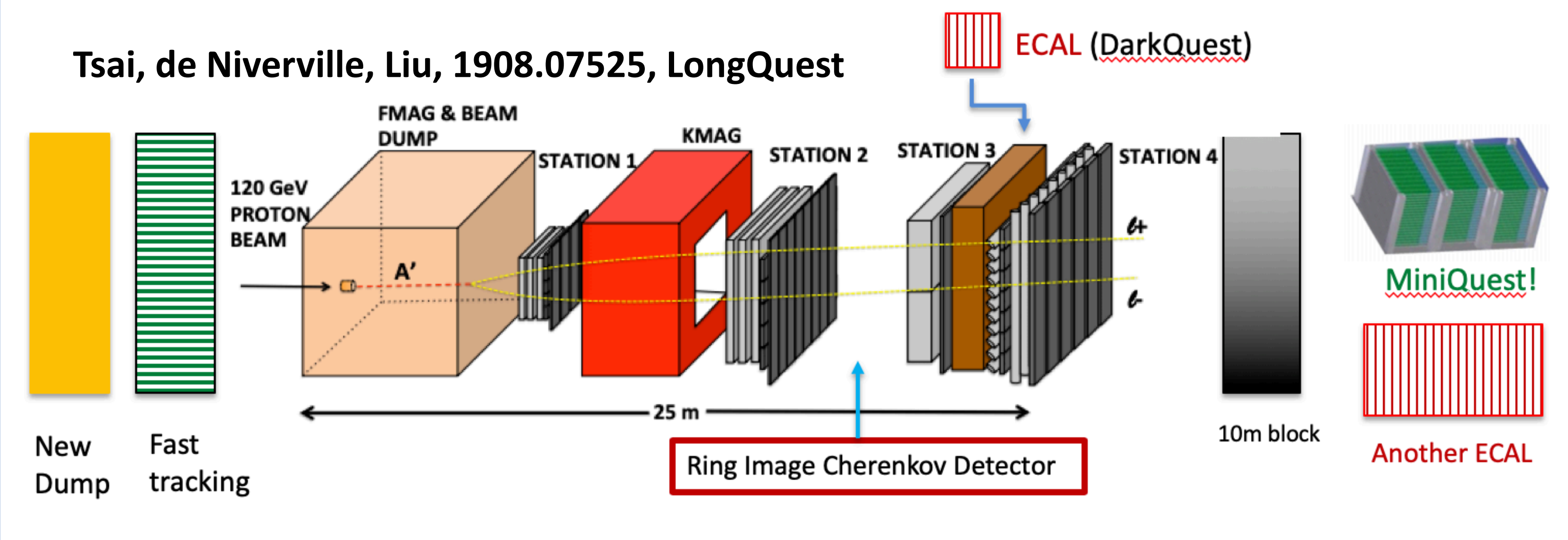
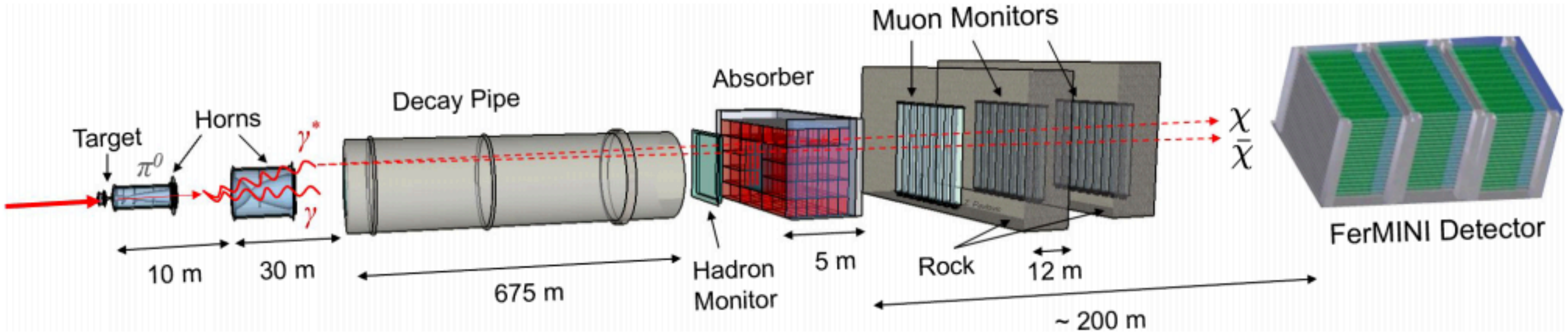

Tsai, de Niverville, Liu, 1908.07525, LongQuest

Long-Lived Particle Searches in the High-Energy Frontier of the Intensity Frontier: FerMINI & LongQuest

- Light Scalar & Dark Photon at BoreXino & LSND, 1706.00424
- Dipole Portal Heavy Neutral Lepton, 1803.03262 (LSND/MiniBooNE anomalies)
- Dark Neutrino at Scattering Exp: CHARM-II & MINERvA! 1812.08768 (MiniBooNE anomaly)
- Closing **dark photon and inelastic dark matter windows (muon g-2 anomaly)**

  the LongQuest Proposal! It's out now: 1908.07525!



FerMINI - Fermilab Search for Millicharged Particles & Strongly Interacting Dark Matter

Yu-Dai Tsai, **Fermilab/U.Chicago** **(WH674)**

with Magill, Plestid, Pospelov (1806.03310, ***PRL '19***),

with Kelly (1812.03998, ***PRD '19***)

New paper out: 1908.07525

Email: ytsai@fnal.gov; arXiv: https://arxiv.org/a/tsai_y_1.html

FerMINI Proposal May ‘19


Chris Hill
OSU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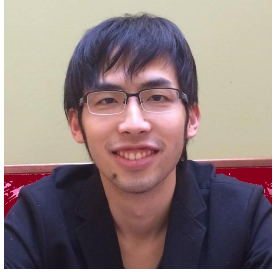
Jim Hirschauer
Fermilab

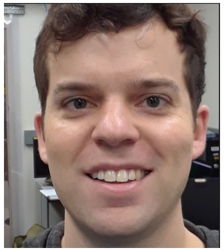

David Miller
U Chicago


David Stuart
UCSB


Zarko Pavlovic
Fermilab


Yu-Dai Tsai
Fermilab/U.Chicago


Cindy Joe
Fermilab


Ryan Heller
Fermilab


Maxim Pospelov
Minnesota / Perimeter


Ryan Plestid
McMaster


Albert de Roeck
CERN


Joe Bramante
Queen’s U


Bithika Jain
ICTP-SAIFR

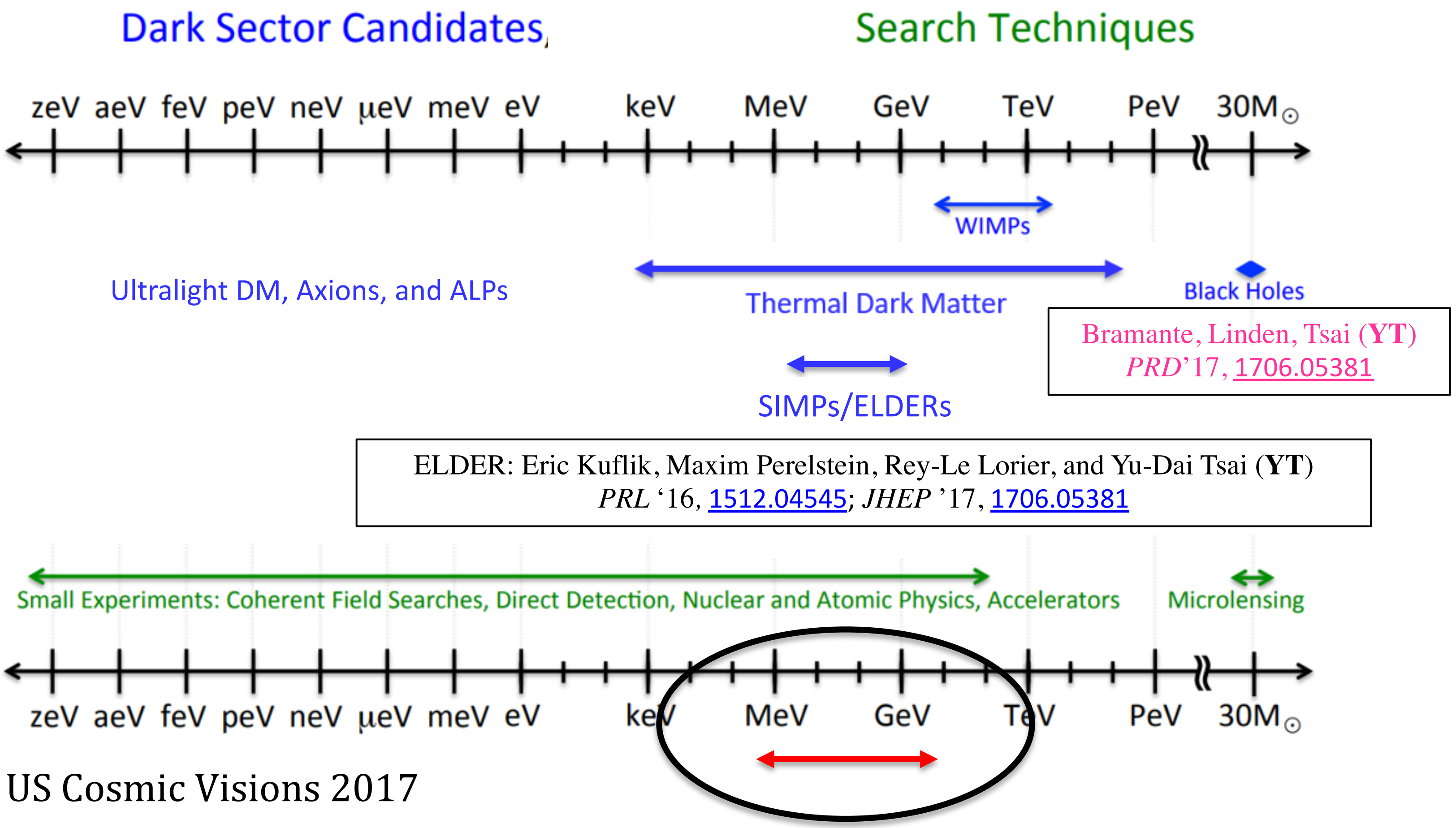
Outline: Part I

- **Motivations**
- **Dark Sectors @ Fixed-Target & Neutrino Experiments**
- **Millicharged Particle (mCP)**
- Bounds & Projections @ Neutrino Detectors
- **The FerMINI Experiment**
- **Connect to Strongly Interacting Dark Matter**

Neutrino & Proton Fixed-Target (FT) Experiments:

Some natural habitats for signals of weakly interacting / long-lived / hidden particles

Exploration of Dark Matter & Dark Sector



Bramante, Linden, Tsai (**YT**)
PRD'17, 1706.05381

ELDER: Eric Kuflik, Maxim Perelstein, Rey-Le Lorier, and Yu-Dai Tsai (**YT**)
PRL '16, 1512.04545; *JHEP* '17, 1706.05381

US Cosmic Visions 2017

- **Astrophysical/cosmological observations** are important to reveal the **actual story of dark matter (DM).**
- **Why Neutrino/FT experiments? And why MeV – GeV+?**

Neutrino & Proton FT Experiments

- Neutrinos are **weakly interacting particles**.
- High statistics, e.g. LSND has 10^{23} Protons on Target (POT)
- Shielded/underground: lower background
- Many of them existing and many to come:

  strength in numbers
- Relatively high energy proton beams on targets exist

  O(100 – 400) GeV (I will compare Fermilab/CERN facilities)
- Produce hidden particles / involve less assumptions

Not all bounds are created with equal assumptions

Accelerator-based: Collider, Fixed-Target Experiments
Some other ground based experiments

techinical ↓

Astrophysical productions (not from ambient DM): energy loss/cooling, etc:
Rely on modeling/observations of (extreme/complicated/rare) systems (SN1987A)

Dark matter direct/indirect detection: abundance, velocity distribution, etc

Cosmology: assume cosmological history, species, etc

different

→ "Assumptions"

Or, how likely is it that theorists would be able to argue our ways around them

Why study MeV – GeV+ dark sectors?

Signals of discoveries grow from anomalies

Maybe nature is telling us something so we don't have to search in the dark? ~~(most likely systematics?)~~

Yu-Dai Tsai, Fermilab, 2019

Some anomalies involving MeV-GeV+ Explanations

⋮

- **Muon g-2**
- **LSND & MiniBooNE anomaly**
- **EDGES result**
- ~~**Proton charge radius anomaly**~~

⋮

Below ~ MeV there are also **strong astrophysical/cosmological bounds** that are hard to avoid even with very optimistic assumptions

ν Hopes for New Physics: Personal Trilogy

⋮

- **Light Scalar** & **Dark Photon** at Borexino & LSND

  Pospelov & **YT**, PLB '18, 1706.00424 (**proton charge radius anomaly**)

- **Dipole Portal Heavy Neutral Lepton**

  Magill, Plestid, Pospelov & **YT** , PRD '18, 1803.03262

  (**LSND/MiniBooNE anomalies**)

- **Millicharged Particles** in Neutrino Experiments

  Magill, Plestid, Pospelov & **YT**, PRL '19, 1806.03310

  (**EDGES 21-cm measurement anomaly**)

⋮

deNiverville, Pospelov, Ritz, '11,

Batell, deNiverville, McKeen, Pospelov, Ritz, '14

Kahn, Krnjaic, Thaler, Toups, '14 …

New Physics in Proton FT Experiments

- **Millicharged Particles** in **FerMINI Experiments**

  Kelly & **YT,** 1812.03998

  (**EDGES Anomaly**)

- **Dark Neutrino** at Scattering Experiments: CHARM-II & **MINERvA!**

  Argüelles, Hostert, **YT**, 1812.08768, submitted to *PRL*

  (**MiniBooNE Anomaly**)

- Probing Dark Photon, Inelastic Dark Matter, and Muon g-2

  Windows + **LongQuest Proposal,**

  YT, de Niverville, Liu (1908.07525)

⋮

Happy to talk about these during the coffee break;

Proton FT Experiment: Scattering vs Decaying

Decay vs Scattering

There are roughly two type of
proton fixed target experiments:
decay and scattering experiment
(or multi-purpose)
We will focus on high energy decay
detectors.

Scattering Detector

There is also a set of "scattering detectors", most have their primary goals to study neutrino scattering and neutrino oscillation (they can handle the decay study but not optimized for it),
including **MINERvA, MiniBooNE, SBND, MicroBooNE, DUNE Near Detector (ND)**.

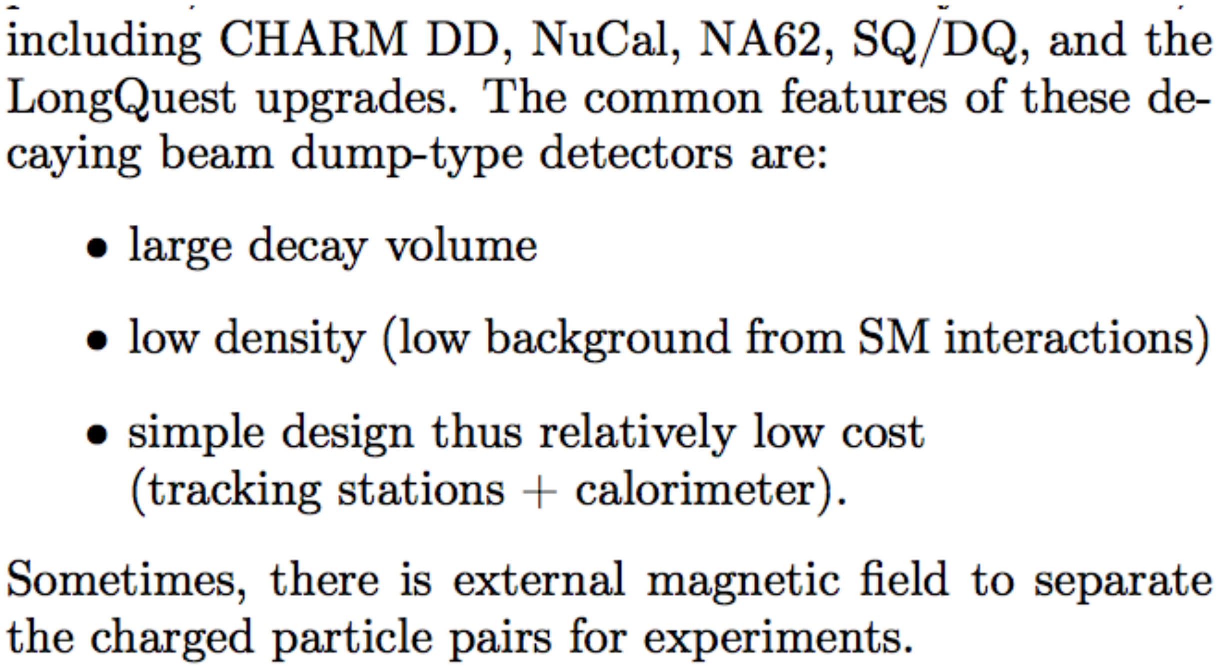
Usually higher density to capture the scattering events and have more complicated design to for neutrino physics.

- higher density
- complicated design compared to the decaying detector.
- smaller volume

These detectors can also potentially provide constraints and new sensitivity reaches. But we focus on decaying sig.

Decay Detector

high energy and high intensity experiments that are optimized to study decaying particles, which can be referred to as "decay detectors,"



including CHARM DD, NuCal, NA62, SQ/DQ, and the LongQuest upgrades. The common features of these decaying beam dump-type detectors are:

- large decay volume
- low density (low background from SM interactions)
- simple design thus relatively low cost (tracking stations + calorimeter).

Sometimes, there is external magnetic field to separate the charged particle pairs for experiments.

Millicharged Particles

Is electric charge quantized?

Other Implications

Finding Minicharge

- **Is electric charge quantized and why?** A long-standing question!

- U(1) allows arbitrarily small (any real number) charges.
  Why don't we see them in e charges? Motivates
  Dirac quantization, Grand Unified Theory (GUT), etc, to explain such quantization (anomaly cancellations fix some SM $U(1)_Y$ charge assignments)

- Testing if **e/3 is the minimal charge**

- MCP could have natural link to **dark sector** (dark photon, etc)

- Could account for dark matter (DM) (WIMP or Freeze-in scenarios)

\- Used for the cooling of gas temperature to explain the EDGES result [EDGES collab., Nature, (2018), Barkana, Nature, (2018)].
A small fraction of the DM as MCP to explain the EDGES anomaly (severely constrained, see **more reference later**)

Millicharged Particle: Models

Yu-Dai Tsai, Fermilab, 2019

mCP Model

- Small charged particles under U(1) hypercharge

$$\mathcal{L}_{\rm MCP} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\rm MCP})\chi$$

- Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon), one can call this a “pure” MCP

- Or this could be from Kinetic Mixing
  - give a nice origin to this term
  - an example that gives rise to **dark sectors**
  - easily compatible with Grand Unification Theory
  - I will not spend too much time on the model

Kinetic Mixing and MCP Phase

- **Coupled to new dark fermion χ**

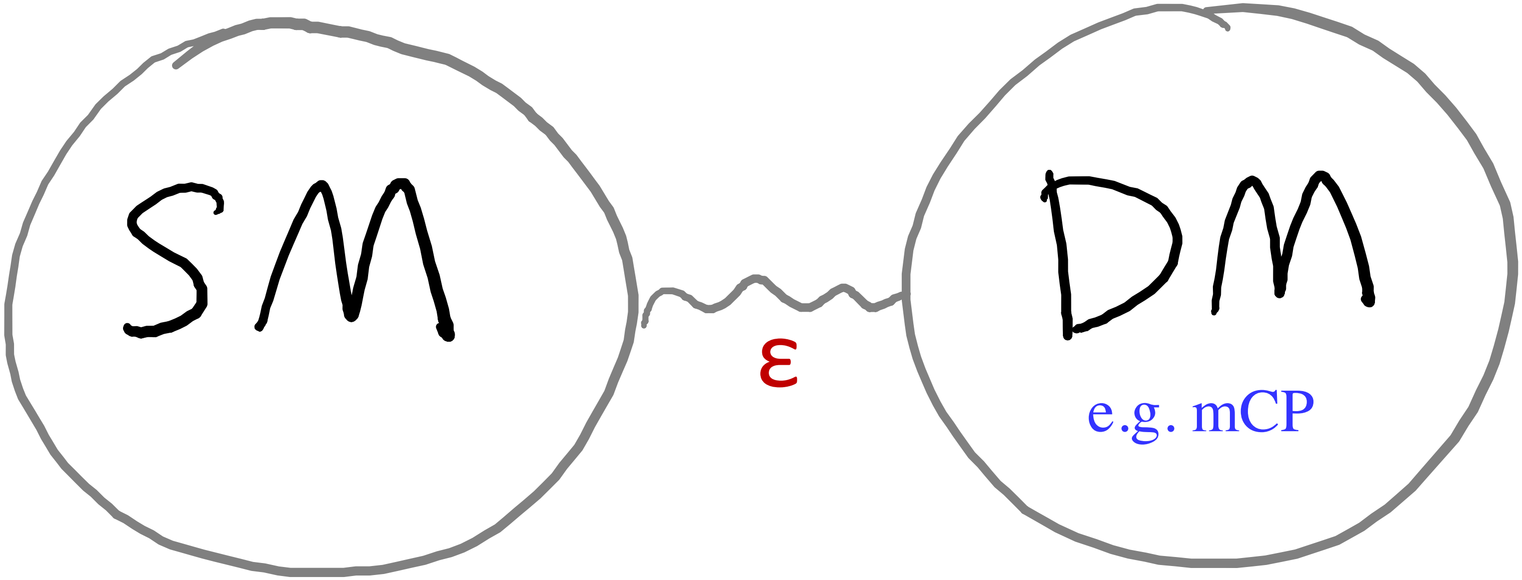
(SM: Standard Model)

See, Holdom, 1985

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4} B'_{\mu\nu} B^{\mu\nu} - \frac{\kappa}{2} B'_{\mu\nu} B'^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\mathrm{MCP}})\chi$$

- New Fermion χ charged under U(1)’
- Field redefinition into a more convenient basis for massless B', $B' \rightarrow B' + \kappa B$
- new fermion acquires an small EM charge Q (the charge of mCP χ): $Q = \kappa e' \cos\theta_W$ $\epsilon \equiv \kappa e' \cos\theta_W / e.$

The Rise of Dark Sector



Important Notes!

- Our search is simply a search for particles (**fermion χ**) with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$
- **Minimal theoretical inputs/parameters** (hard to probe in MeV – GeV+ mass regime)

- **mCPs do not have to be DM in our searches**
- The bounds we derive **still put constraints on DM as well as dark sector scenarios.**

- Not considering bounds on dark photon (**not necessary** for mCP particles)
- Similar bound/sensitivity applies to scalar mCPs

Additional Motivations

- Won’t get into details, but it’s interesting to find

  “pure” MCP, that is WITHOUT a massless or light dark photon

  (finding MCP in the regime massless or light A’ is strongly constrained by cosmology!)

- More **violent violation of the charge quantization**

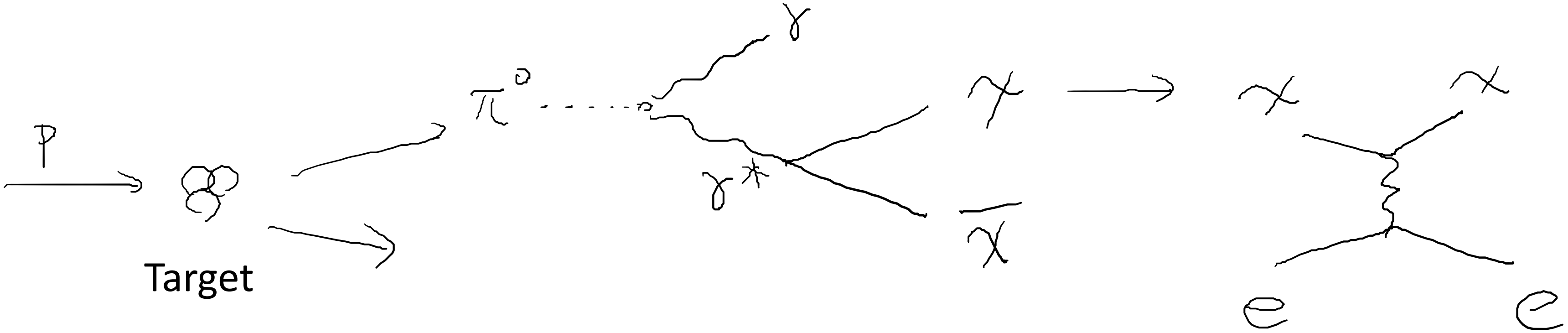
  (if not generating millicharge through kinetic mixing)

- Test of some **GUT models**, and **String Compactifications**

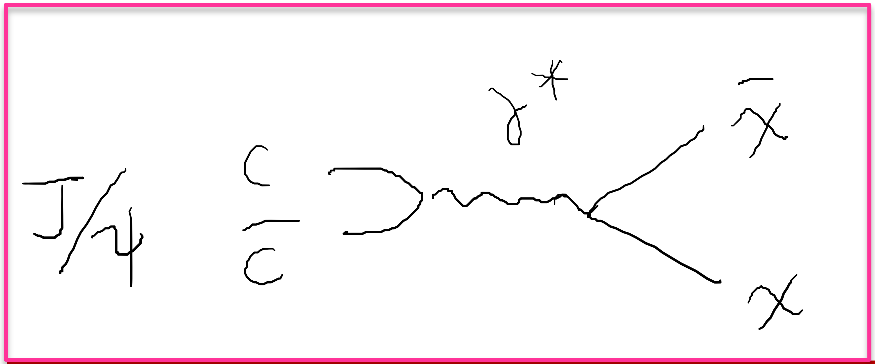
  see Shiu, Soler, Ye, arXiv:1302.5471, PRL ’13 for more detail.

Millicharged Particle: Signature

MCP (or light DM with light mediator): production & detection



- production:
  meson decays
- detection:
  scattering electron



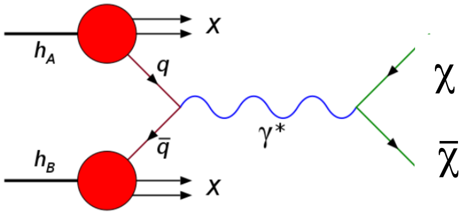
BR($\pi^0 \rightarrow 2\gamma$) = 0.99

BR($\pi^0 \rightarrow \gamma e^- e^+$) = 0.01

BR($\pi^0 \rightarrow e^- e^+$) = $6 * 10^{-6}$

BR($J/\psi \rightarrow e^- e^+$) = 0.06

- **Heavy mesons are important for higher mass mCP's in high enough beam energy**
- **Important and often neglected!**

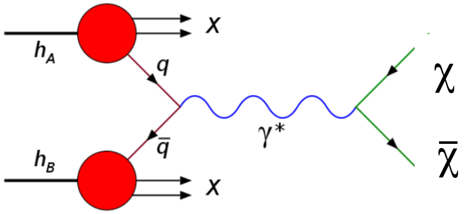


MCP productions

- For **η** & **π^0**, Dalitz decays: $\pi^0/\eta \rightarrow \gamma\,\chi\,\bar{\chi}$ dominate
- For **J/ψ** & **Y**, direct decays: J/ψ, Y $\rightarrow \chi\,\bar{\chi}$ dominate.
  Important for high-mass mCP productions!
- The branching ratio for a meson, *M*, to mCPs is given roughly by

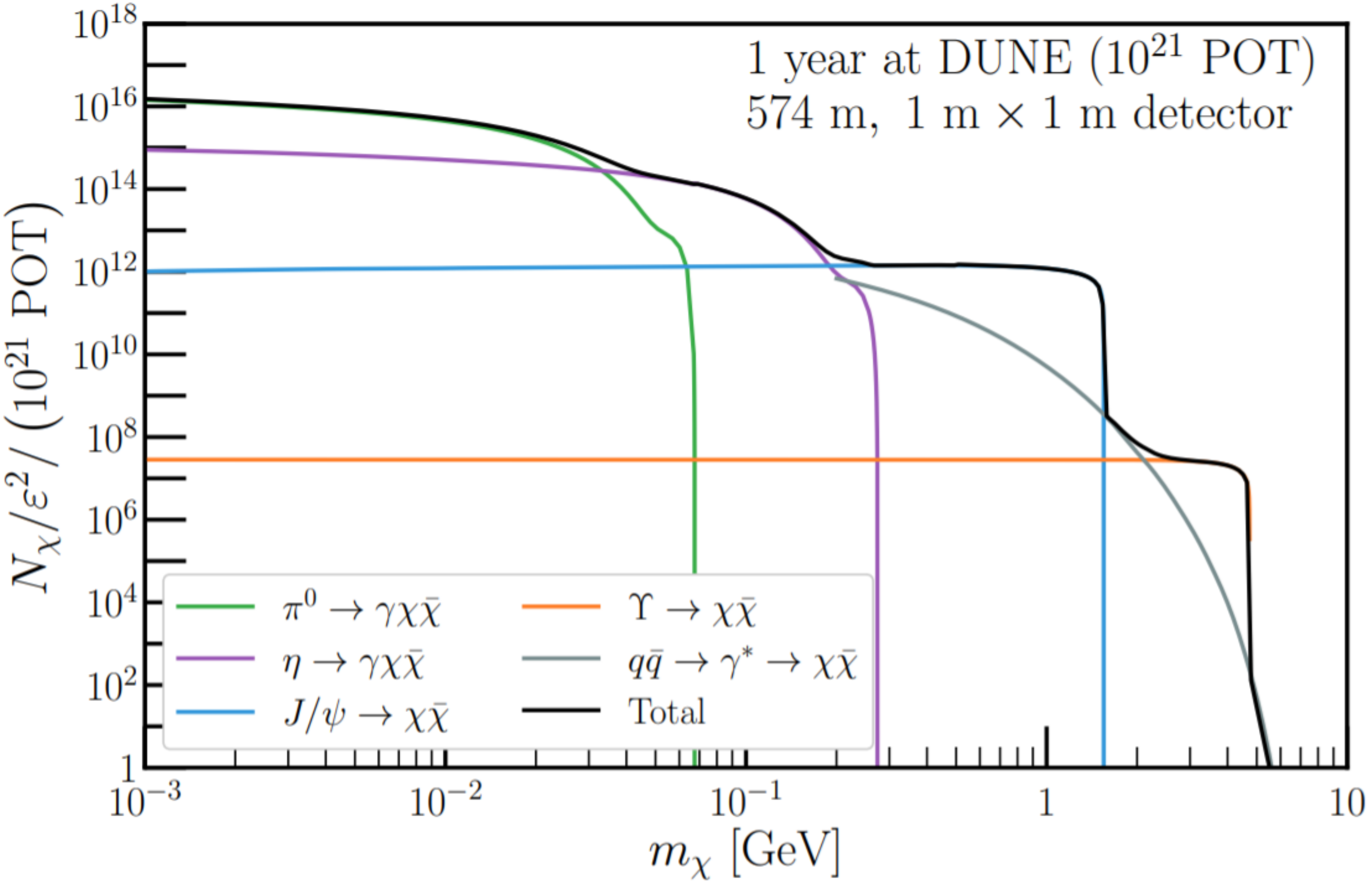
$$\mathrm{BR}(\mathcal{M} \to \chi\bar{\chi}) \approx \epsilon^2 \times \mathrm{BR}(\mathcal{M} \to X e^+ e^-) \times f\left(\frac{m_\chi}{M}\right),$$

- M: the mass of the parent meson, X:any additional particles, f(m_χ/M): phase space factor as a function of m_χ/M.
- Also consider **Drell-Yan production of mCP** from **q q-bar annihilation**.



https://en.wikipedia.org/wiki/Drell%E2%80%93Yan_process

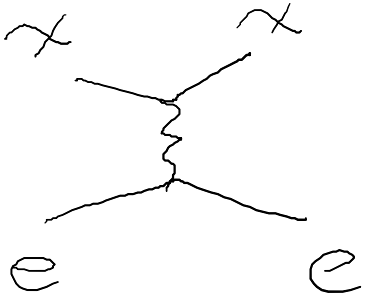
MCP Production/Flux



- We use PYTHIA to generate neutral meson Dalitz or direct decays from the pp collisions and rescale by considering, $\mathrm{BR}(\mathcal{M} \to \chi\bar{\chi}) \approx \epsilon^2 \times \mathrm{BR}(\mathcal{M} \to X e^+ e^-) \times f\left(\frac{m_\chi}{M}\right)$,
- M: mass of the parent meson, X:additional particles, f(m_χ/M): phase space factor
- We also include Drell-Yan production for the high mass MCPs (see arXiv:1812.03998)

Detection: **MCP Elastic Scattering with Electrons**

$$\frac{\mathrm{d}\sigma_{e\chi}}{\mathrm{d}Q^2} = 2\pi\alpha^2\epsilon^2 \times \frac{2(s-m_\chi^2)^2 - 2sQ^2 + Q^4}{(s-m_\chi^2)^2 Q^4}.$$



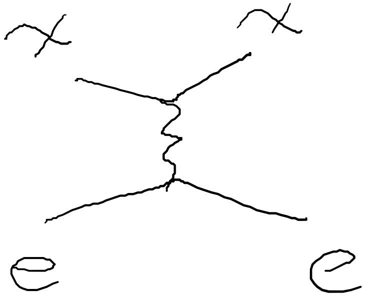
- $\boldsymbol{Q^2}$ is the squared 4-momentum transfer.
- Integrate over Q^2, total cross section dominated by the small Q^2 contribution, we have $\sigma_{e\chi} = 4\pi\,\alpha^2\varepsilon^2/Q_{min}{}^2$.
- **Light mediator:** the total cross section is dominated by the small Q^2 contribution

MCP Detection: electron scattering

- lab frame: $Q^2 = 2m_e\,(E_e - m_e)$, $E_e - m_e$ is the electron recoil energy.
- Expressed in **recoil energy threshold**, ${E_e}^{(min)}$, we have

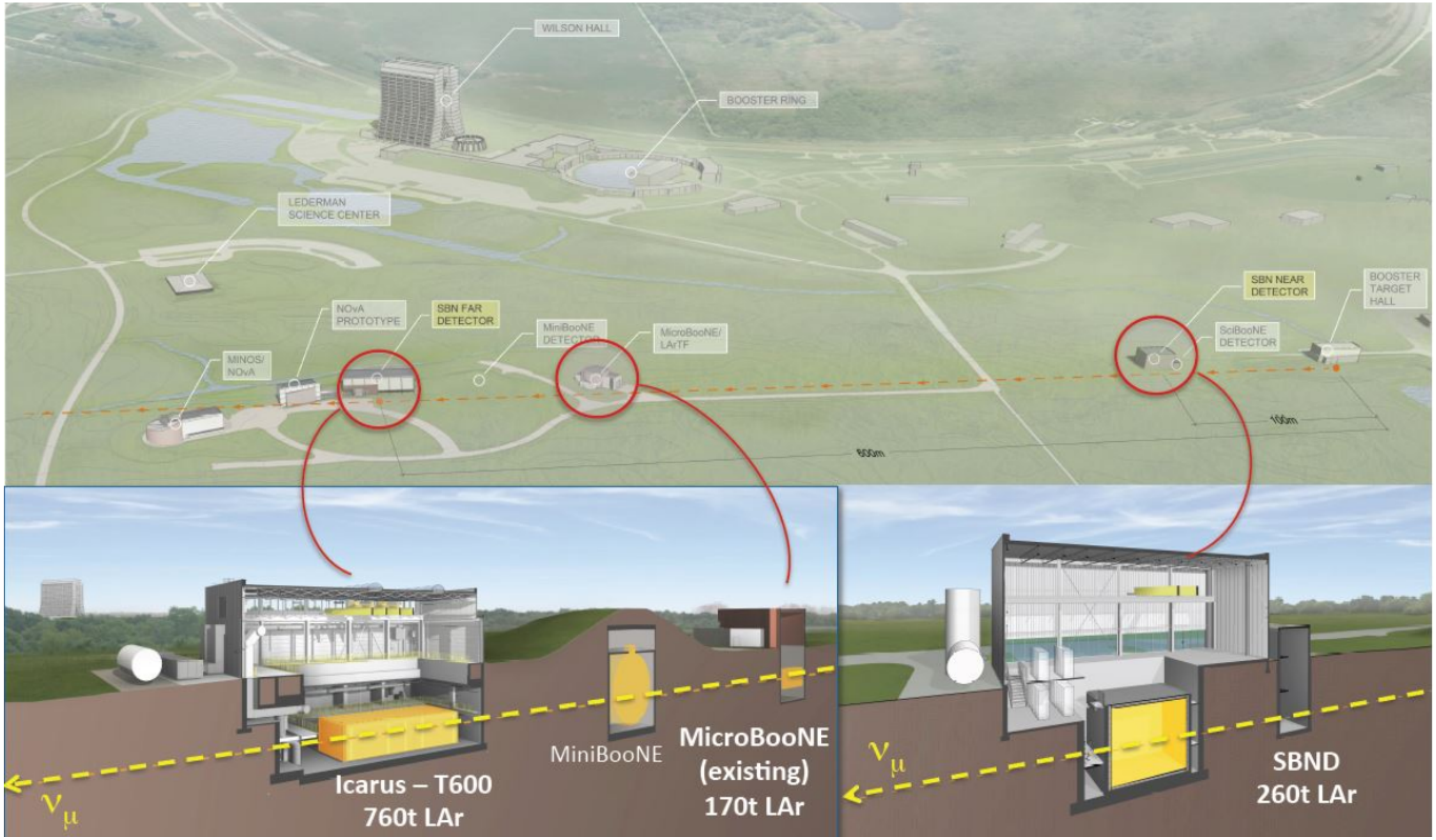
$$\sigma_{e\chi} = 2.6 \times 10^{-25}\mathrm{cm}^2 \times \epsilon^2 \times \frac{1\ \mathrm{MeV}}{E_e^{(\mathrm{min})} - m_e}.$$

- Sensitivity greatly enhanced by accurately **measuring low energy electron recoils for mCP's & light dark matter - electron scattering,**
- See e.g., Magill, Plestid, Pospelov, **YT**, 1806.03310 & deNiverville, Frugiuele, 1807.06501 (for sub-GeV DM)



MCP @ Neutrino Detectors

Neutrino Experiments



https://web.fnal.gov/collaboration/sbn_sharepoint/SitePages/Civil_Construction.aspx

SBND: Short Baseline Near Detector of Booster Beam
MiniBooNE: Mini-Booster Neutrino Experiment
ICARUS (Imaging Cosmic And Rare Underground Signals):
Now a Far Detector of Booster Beam

MCP Signals

- **signal events** s_{event}

$$s_{event} \simeq \sum_{\text{Energies}} N_\chi(E_i) \times \frac{N_e}{\text{Area}} \times \sigma_{e\chi}(E_i;\ m_\chi) \times \mathcal{E}\,.$$

detection efficiency

- $N_\chi(E_i)$: number of mCPs with energy E_i arriving **at the detector**.
- N_e: **total number of electrons** inside the active volume of the detector
- Area: active volume divided by the average length traversed by particles inside the detector.
- $\sigma_{e\chi}(E_i)$: **detection cross section consistent** with the angular and recoil cuts in the experiment
- Here, $s_{event} \propto \varepsilon^4$. ε^2 from N_x and ε^2 from $\boldsymbol{\sigma}_{ex}$
- Throughout this paper, we choose a credibility interval of $1 - \alpha = 95\%$ (~ 2 sigma)
- Roughly, $\varepsilon_{sensitivity} \propto E_{e,\,R,min}^{1/4}\ Bg^{1/8}$

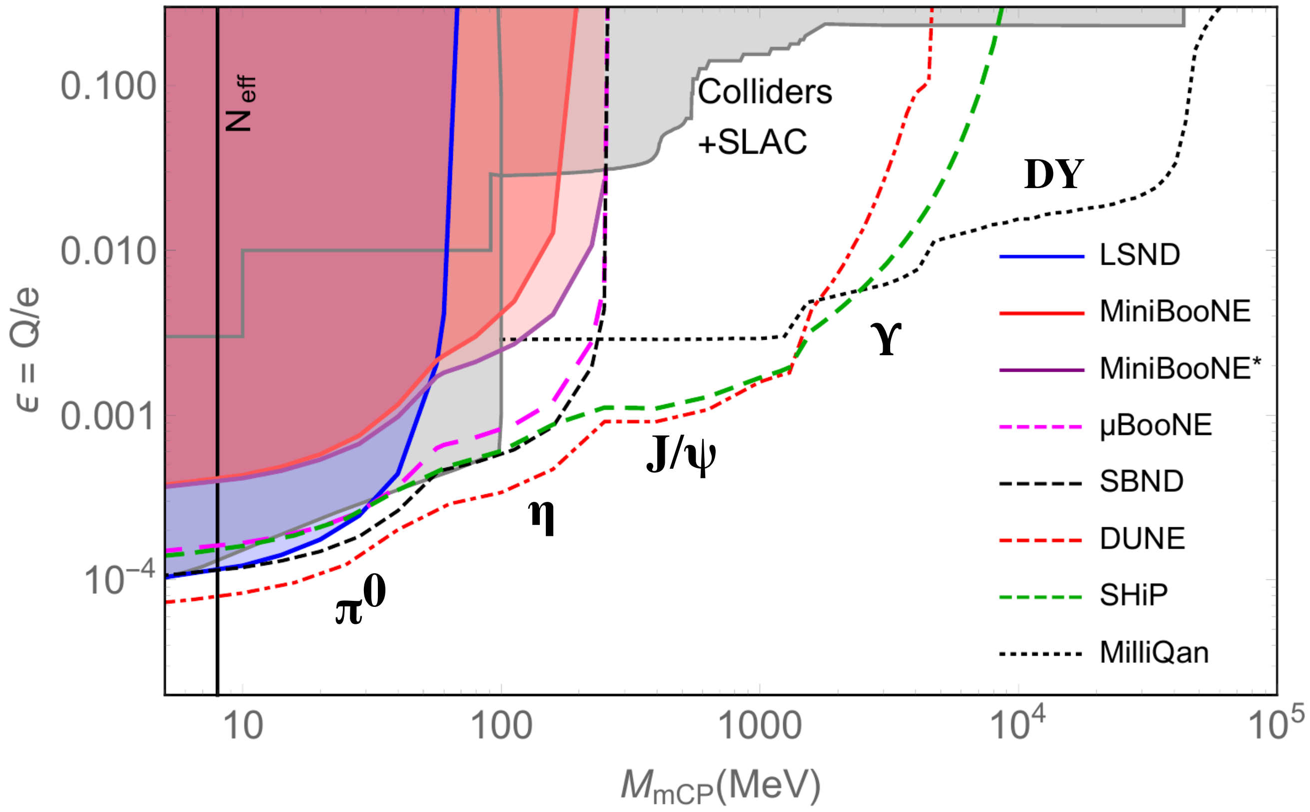
MCP Bound/Sensitivity

- **signal events s_{event}**

$$s_{event} \simeq \sum_{\text{Energies}} N_\chi(E_i) \times \frac{N_e}{\text{Area}} \times \sigma_{e\chi}(E_i;\ m_\chi) \times \mathcal{E}.$$

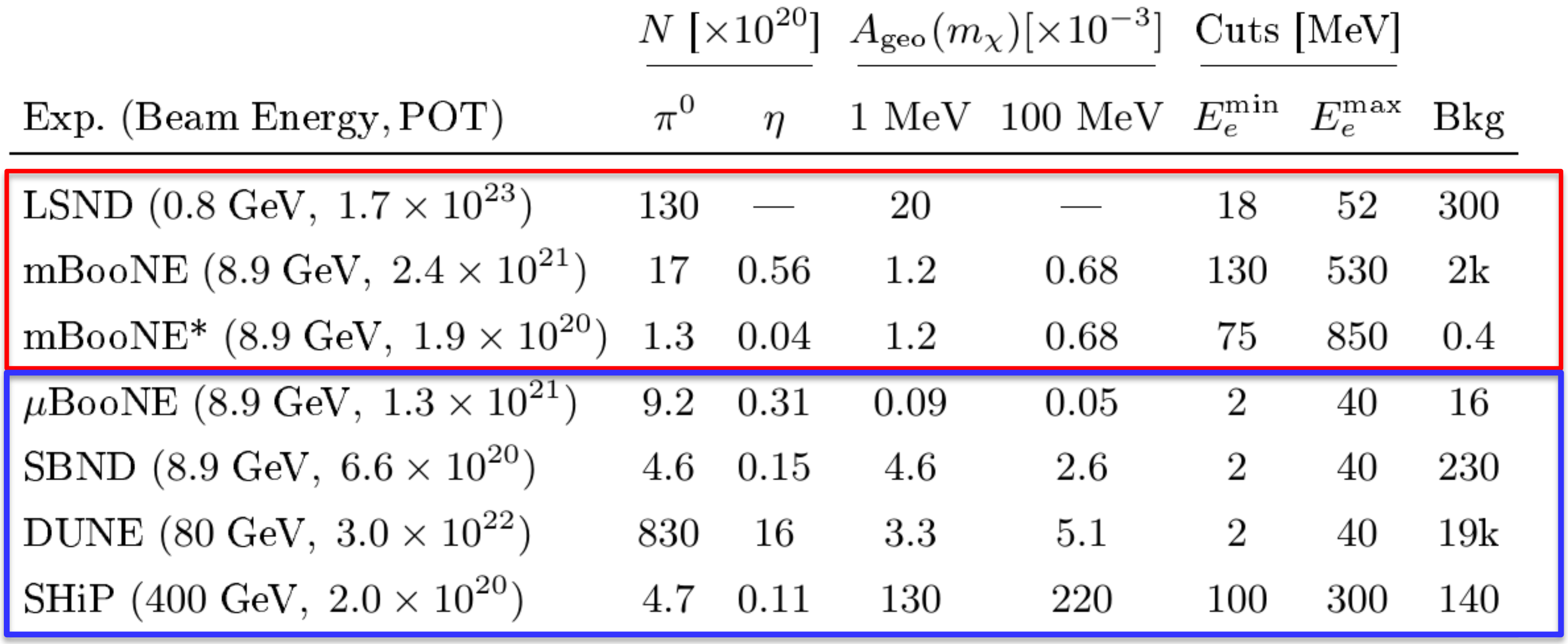
- Our sensitivity curves are obtained by performing a standard sensitivity analysis [PDG, PLB 2010]:
- Given a number of background events b and data n, the number of signal events s_{event} . The $(1 - \alpha)$ credibility level is found by solving the equation $\alpha = \Gamma(1 + n, b + s_{event})/\Gamma(1 + n, b)$, where $\Gamma(x, y)$ is the upper incomplete gamma function.
- Throughout this paper, we choose a credibility interval of $1 - \alpha = 95\%$ (~ 2 sigma)

Sensitivity and Contributions



- MilliQan: Haas, Hill, Izaguirre, Yavin, (2015), + (LOT arXiv:1607.04669)
- N_{eff}: Bœhm, Dolan, and McCabe (2013)
- Colliders/Accelerator: Davidson, Hannestad, Raffelt (2000)
- SLAC mQ: Prinz el al, PRL (1998);

Summary Table



		N [$\times 10^{20}$]		$A_{\rm geo}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
	Exp. (Beam Energy, POT)	π^0	η	1 MeV	100 MeV	$E_e^{\rm min}$	$E_e^{\rm max}$	Bkg
Existing	LSND (0.8 GeV, 1.7×10^{23})	130	—	20	—	18	52	300
	mBooNE (8.9 GeV, 2.4×10^{21})	17	0.56	1.2	0.68	130	530	2k
	mBooNE* (8.9 GeV, 1.9×10^{20})	1.3	0.04	1.2	0.68	75	850	0.4
Future	μBooNE (8.9 GeV, 1.3×10^{21})	9.2	0.31	0.09	0.05	2	40	16
	SBND (8.9 GeV, 6.6×10^{20})	4.6	0.15	4.6	2.6	2	40	230
	DUNE (80 GeV, 3.0×10^{22})	830	16	3.3	5.1	2	40	19k
	SHiP (400 GeV, 2.0×10^{20})	4.7	0.11	130	220	100	300	140

- $\varepsilon \propto E_{e,\,R,min}^{1/4}\; Bg^{1/8}$
- cos θ > 0 is imposed (∗except for at MiniBooNE's DM run where a cut of cos θ > 0.99 effectively reduces backgrounds to zero [Dharmapalan, MiniBooNE, (2012)]).
- Efficiency of 0.2 for Cherenkov detectors, 0.5 for nuclear emulsion detectors, and 0.8 for liquid argon time projection chambers.

Recasting Existing Analysis:
LSND, MiniBooNE, and MiniBooNE* (DM Run)

- **LSND**: hep-ex/0101039. Measurement of **electron-neutrino electron elastic scattering**
- **MiniBooNE**: arXiv:1805.12028.
  Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment, combines data from both **neutrino and anti-neutrino runs** and consider a sample of **2.4×10^{21}POT** for which we take the **single electron background to be 2.0×10^{3}** events and the **measured rate to be 2.4×10^{3}**
- **MiniBooNE* (DM run)**: arXiv:1807.06137 (came out after our v1)**.**
  Electron recoil analysis.
  Thick target + no horn focusing +
  A cut of cos $\theta > 0.99$ effectively reduces backgrounds to basically zero [Dharmapalan, MiniBooNE, (2012)]).

Background for Future Measurements

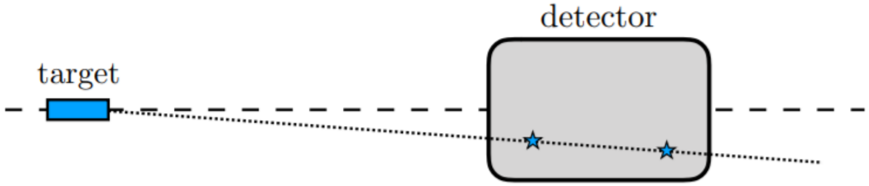
- Single-electron background for ongoing/future experiments for **MicroBooNE, SBND, DUNE, and SHiP?**
- Background discussions:

  1) From neutrino fluxes (calculable),

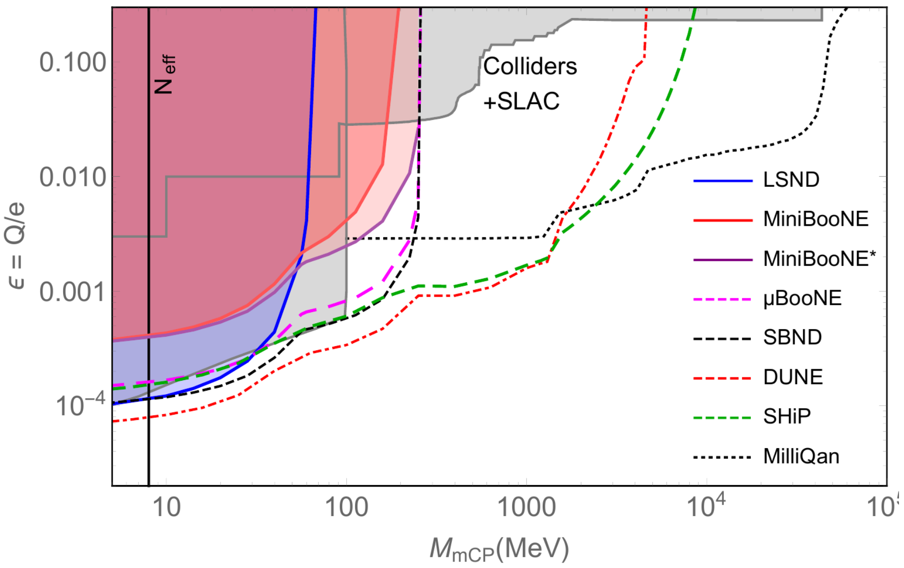
     [i.e. **ve** → **ve** and **vn** → **ep**], greatly reduced by **maximum electron recoil energy cuts E_e(max)**

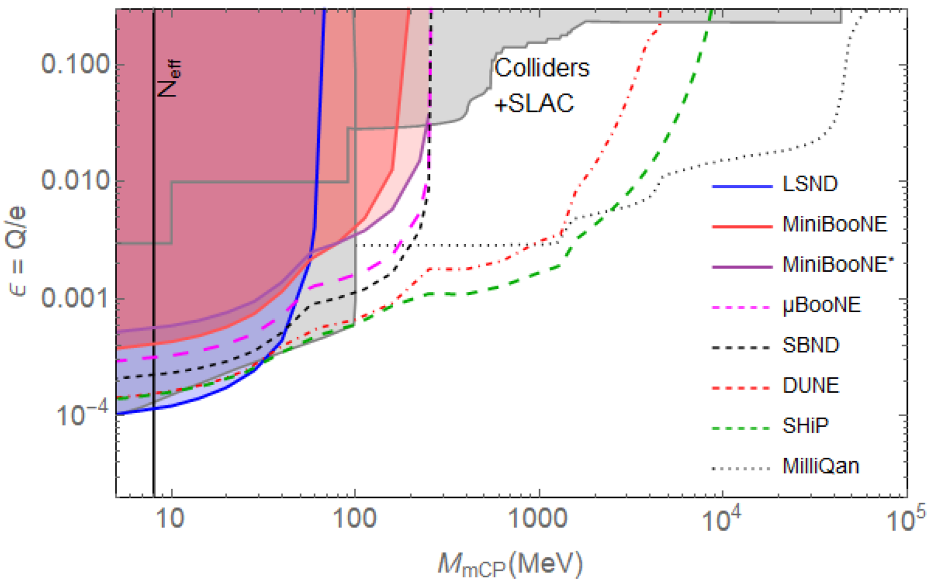
  2) other: times a factor (10-20) to account for these

  3) Harnik, Liu, Ornella: multi-scattering, point back to target to reduce the background (ArgoNeuT), arXiv:1902.03246!



More Conservative Cuts on Threshold





$$\boxed{\varepsilon \propto E_{e,R,min}^{1/4}}$$

Exp. (Beam Energy, POT)	Cuts [MeV]	
	E_e^{min}	E_e^{max}
μBooNE (8.9 GeV, 1.3×10^{21})	2	40
SBND (8.9 GeV, 6.6×10^{20})	2	40
DUNE (80 GeV, 3.0×10^{22})	2	40

Cuts [MeV]	
E_e^{min}	E_e^{max}
30	70
30	70
30	70

Summary

- Technique can be easily applied to more generic **light dark matter** and other **hidden particles with light mediators**

  - Production from **heavy neutral mesons** are important (often neglected in literature)

  - Signature favor **low electron-recoil energy threshold**

- For more realistic analysis: include realistic **background,** $E_{e,\,R,min}$ **cut**, etc

Low-cost Fixed-target Probes of Long-Lived Particles

FerMINI as an example: more to come!

Yu-Dai Tsai, Fermilab, 2019

FerMINI:

Putting dedicated Minicharge Particle Detector (~$2M)
@ Fermilab Beamlines: NuMI or LBNF or @ CERN: SPS
Kelly, **YT**, arXiv:1812.03998 (PRD’19)

(can also probe other new physics scenarios like
small-electric-dipole dark fermions, or quirks, etc)

MilliQan at CERN

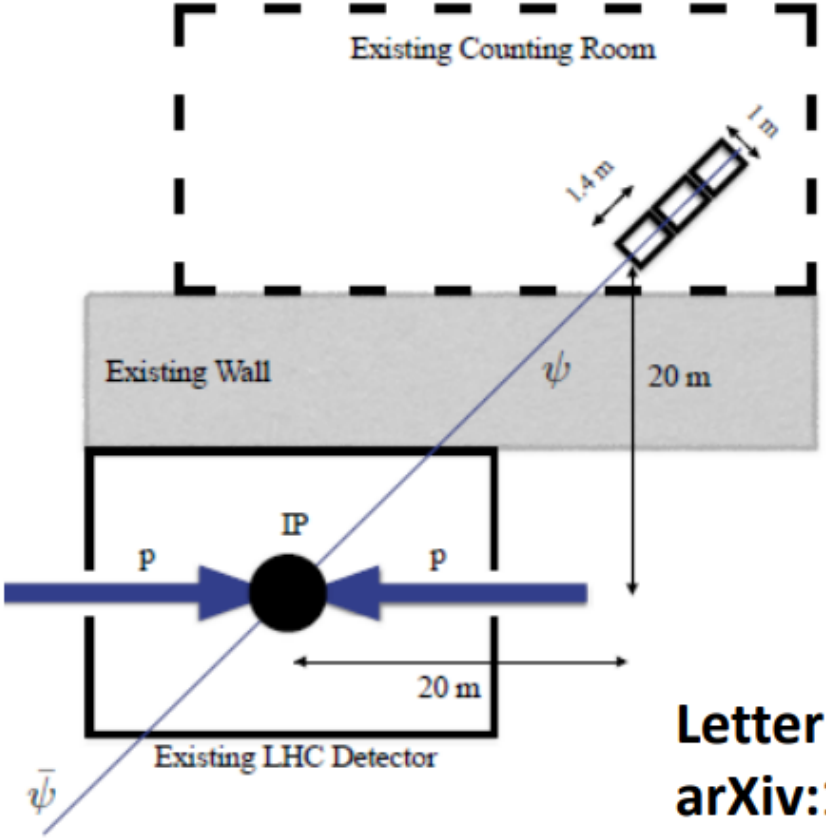
Austin Ball, Jim Brooke, Claudio Campagnari, Albert De Roeck, Brian Francis, Martin Gastal, Frank Golf, Joel Goldstein, **Andy Haas, Christopher S. Hill, Eder Izaguirre**, Benjamin Kaplan, Gabriel Magill, Bennett Marsh, David Miller, Theo Prins, Harry Shakeshaft, David Stuart, Max Swiatlowski, **Itay Yavin**

arXiv:1410.6816, PRD ’15

arXiv:1607.04669, Letter of Intent (LOT)

MilliQan: General Idea

- Require **triple coincidence in small time window (15 nanoseconds)**
- Q down to 10^{-3} e, each MCP produce averagely ~ 1 photo-electron (PE) observed per ~ 1 meter long scintillator



Letter of intent: arXiv:1607.04669

Andrew Haas, Fermilab (2017)

MilliQan: Design

- Total: **1 m × 1 m** (transverse plane) × **3 m** (longitudinal) **plastic scintillator array.**
- Long axis points at the **CMS Interaction Point (P5)**.
- **3 sections** each containing **400 5 cm × 5 cm × 80 cm scintillator bars** optically coupled to **high-gain photomultiplier (PMT).**
- A **triple-incidence within a 15 ns time window** along longitudinally contiguous bars in each of the 3 sections required to reduce the **dark-current noise (the dominant background)**.

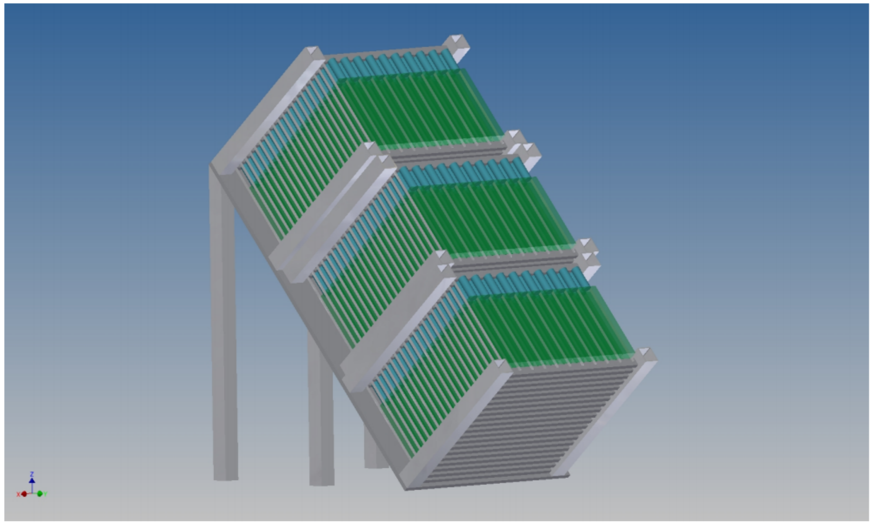


Figure from 1607.04669 (milliQan LOT)

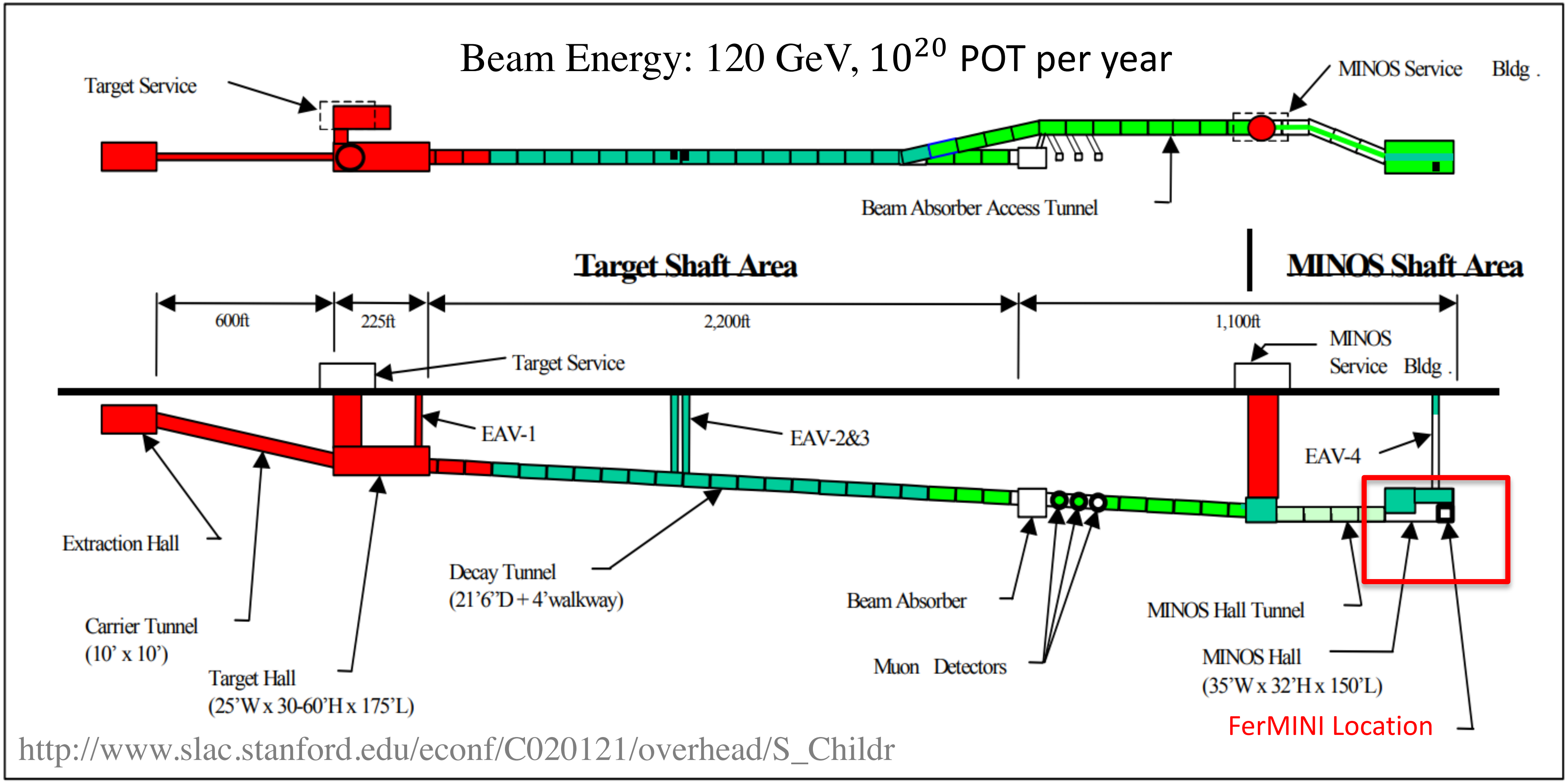
FerMINI:

A Fermilab Search for MINI-charged Particle

Kelly, **YT**, arXiv:1812.03998 (PRD`19)

visually “an experiment made of stacks of light sabers”

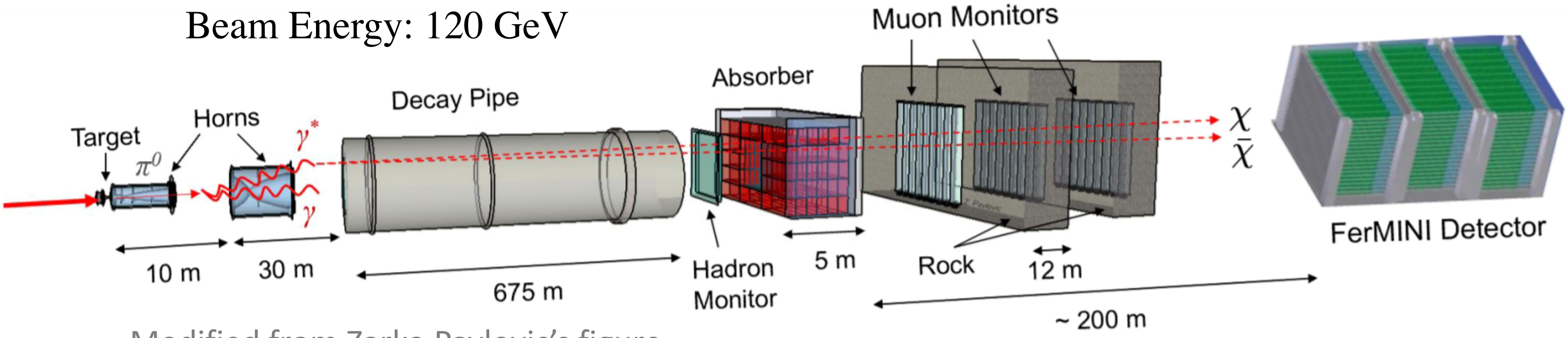
Site 1: NuMI Beam & MINOS ND Hall


Beam Energy: 120 GeV, 10^{20} POT per year

http://www.slac.stanford.edu/econf/C020121/overhead/S_Childr

NuMI: Neutrinos at the Main Injector
MINOS: Main Injector Neutrino Oscillation Search, ND: Near Detector
(**MINERvA**: Main Injector Experiment for v-A is also here)

FerMINI @ NuMI-MINOS Hall



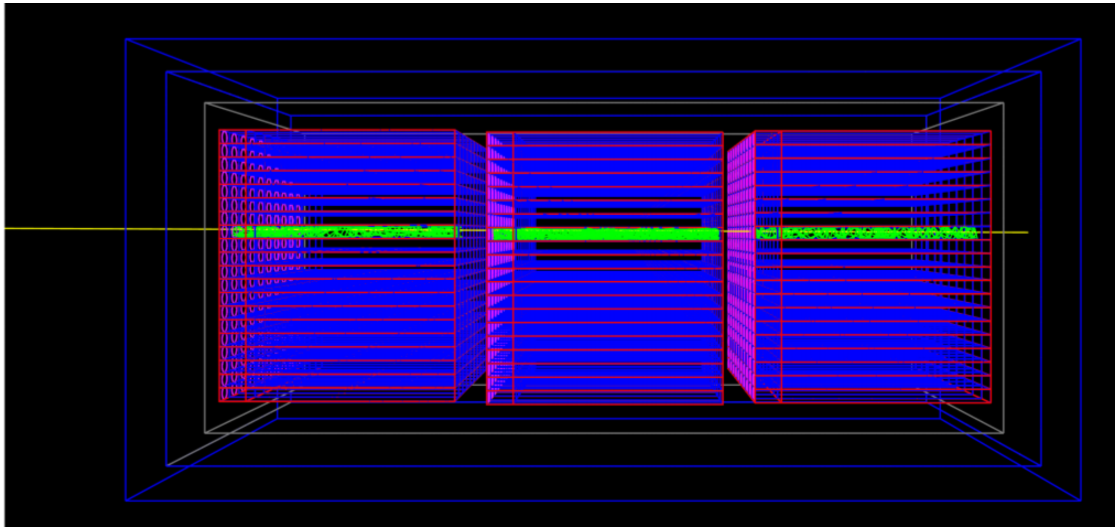
Modified from Zarko Pavlovic's figure

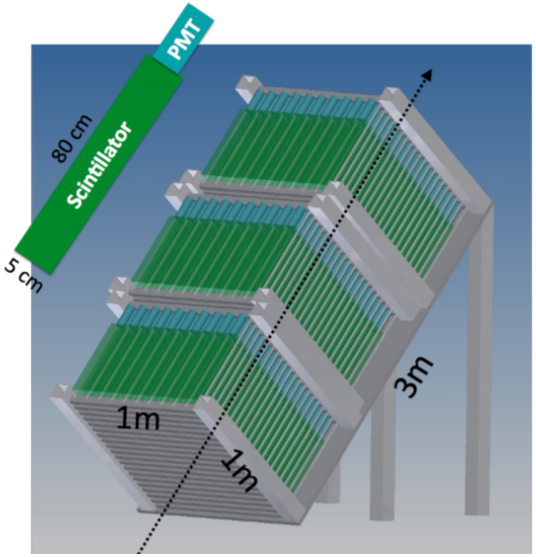
An illustration of the FerMINI experiments utilizing the NuMI facility.

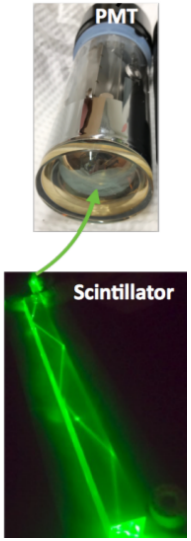
MINOS hall downstream of NuMI beam

MilliQan Concept

$$(\Delta t)_{\text{offline}} = 15$$

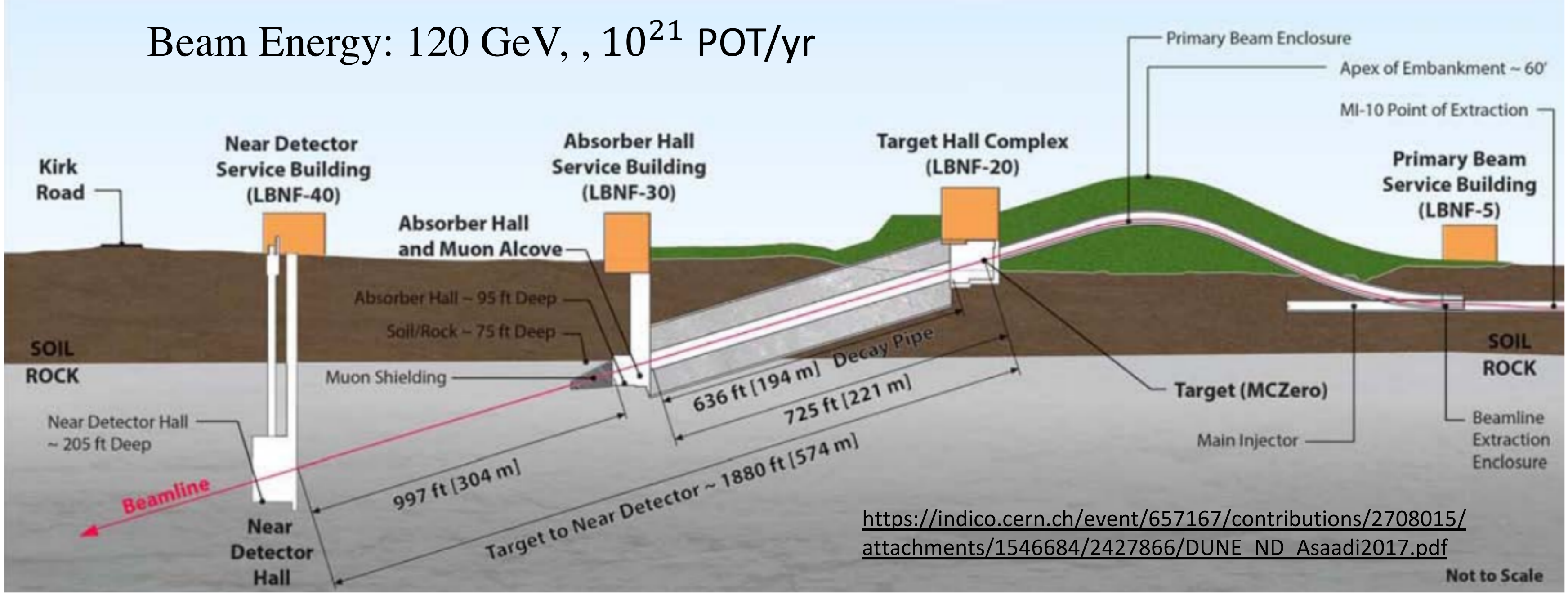






See arXiv:1607.04669; arXiv:1810.06733

Site 2: LBNF Beam & DUNE ND Hall


Beam Energy: 120 GeV, , 10^{21} POT/yr

https://indico.cern.ch/event/657167/contributions/2708015/attachments/1546684/2427866/DUNE_ND_Asaadi2017.pdf

Jonathan Asaadi – University of Texas Arlington

LBNF: Long-Baseline Neutrino Facility

There are many other **new physics opportunities** in the **near detector hall**!

Photoelectrons (PE) from Scintillation

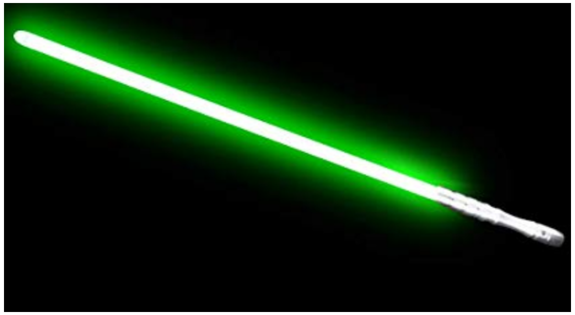
- **The averaged number of photoelectron (PE)** seen by the detector from single MCP is:

$$N_{PE} \propto \left\langle -\frac{dE}{dx} \right\rangle \times l_{scint}, \quad \left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$

$\langle dE/dx \rangle$ is the "mass stopping power" (PDG 2018)

One can use Bethe-Bloch Formula to get a good approximation

- $\boldsymbol{N_{PE} \sim} \epsilon^{\mathbf{2}}$ x $\mathbf{10^6}$, $\epsilon \sim \mathbf{10^{-3}}$ roughly gives one PE in one meter scintillation bar

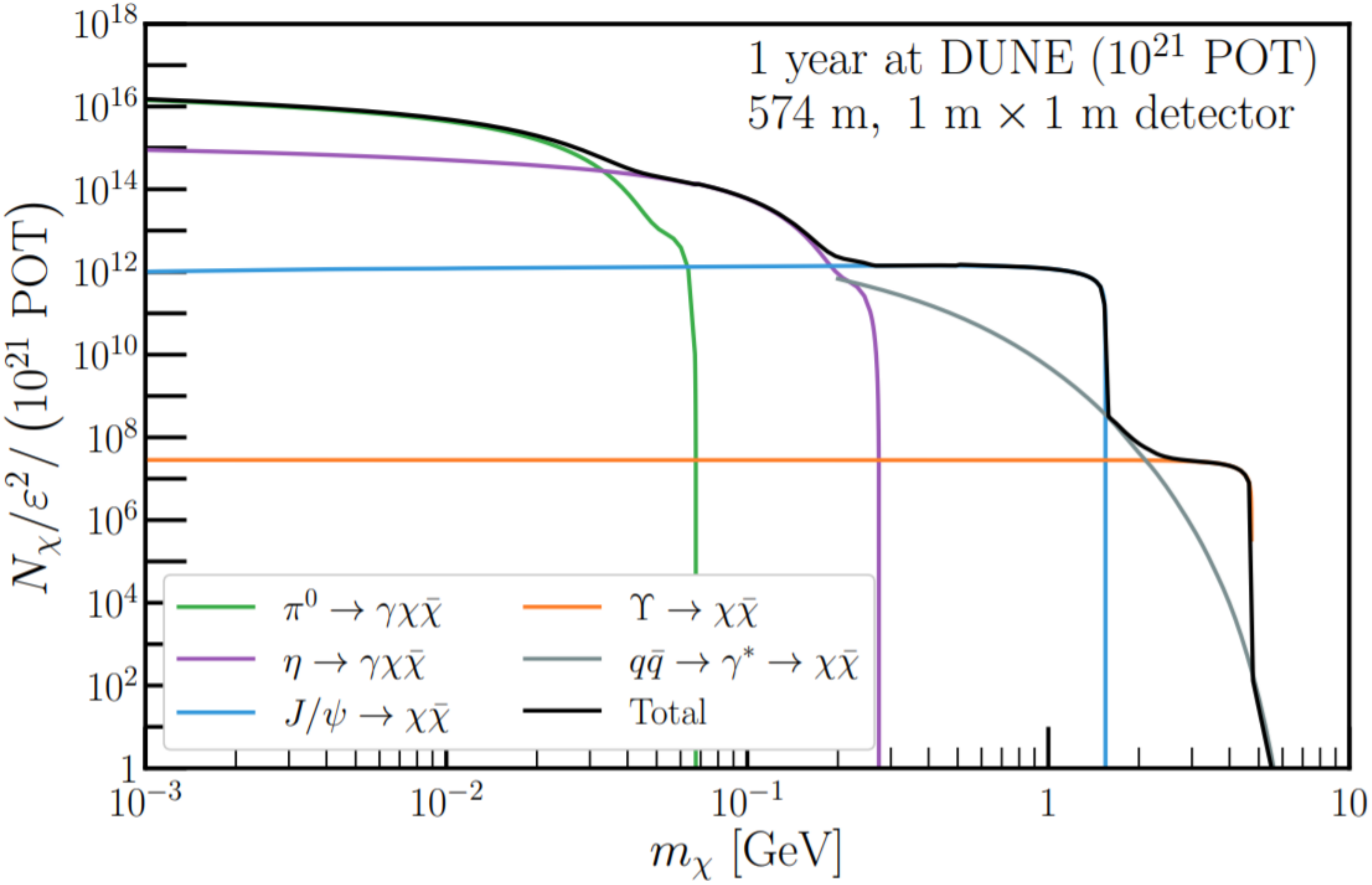


Signature: Triple Coincidence

- Based on Poisson distribution, zero event in each bar correspond to $\boldsymbol{P_0} = \boldsymbol{e^{-N_{PE}}}$, so the probability of seeing triple incident of one or more photoelectron is:
- $\boldsymbol{N_{x,detector}} = \boldsymbol{N_x}$ x **P .**

$$P = \left(1 - e^{-N_{PE}}\right)^3$$

MCP Production/Flux



Detector Background

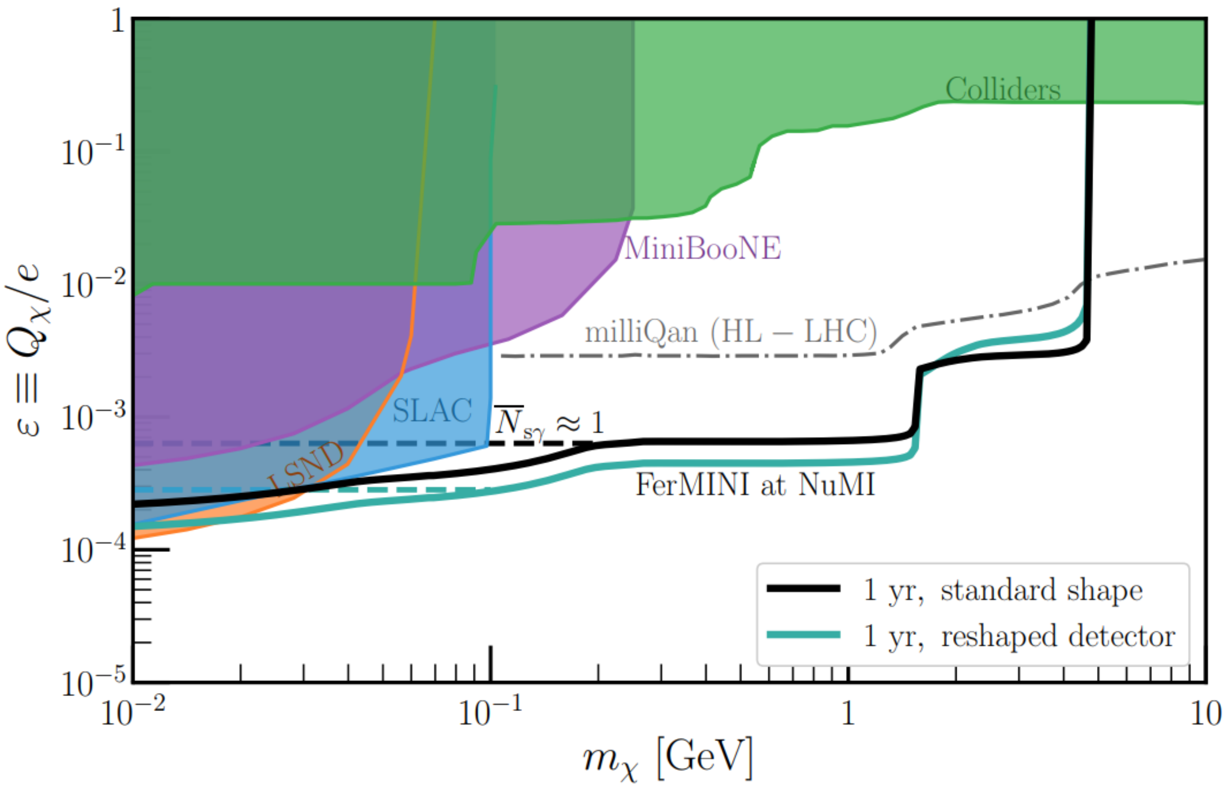
- We will discuss two major **detector backgrounds** and the **reduction technique**
- **SM charged particles from background radiation (e.g., cosmic muons):**
  - Offline veto of events with > 10 PEs
  - Offset middle detector
- **Dark current: triple coincidence**

Dark Current Background @ PMT

- **Major Background (BG) Source!**
- dark-current frequency to be $\boldsymbol{v_B}$**= 500 Hz** for estimation (1607.04669)
- For each tri-PMT set, the background rate for triple incidence is

  $\boldsymbol{v_B^3}$ **Δt^2 = 2.8 x $\mathbf{10^{-8}}$ Hz**, for **Δt = 15 ns.**
- There are 400 such set in the nominal design.
- The total background rate is 400 x 2.8 x 10^{-8} ~ 10^{-5} Hz
- ~ **300 events** in one year of trigger-live time
- **Quadruple coincidence can reduce this BG to essentially zero!**

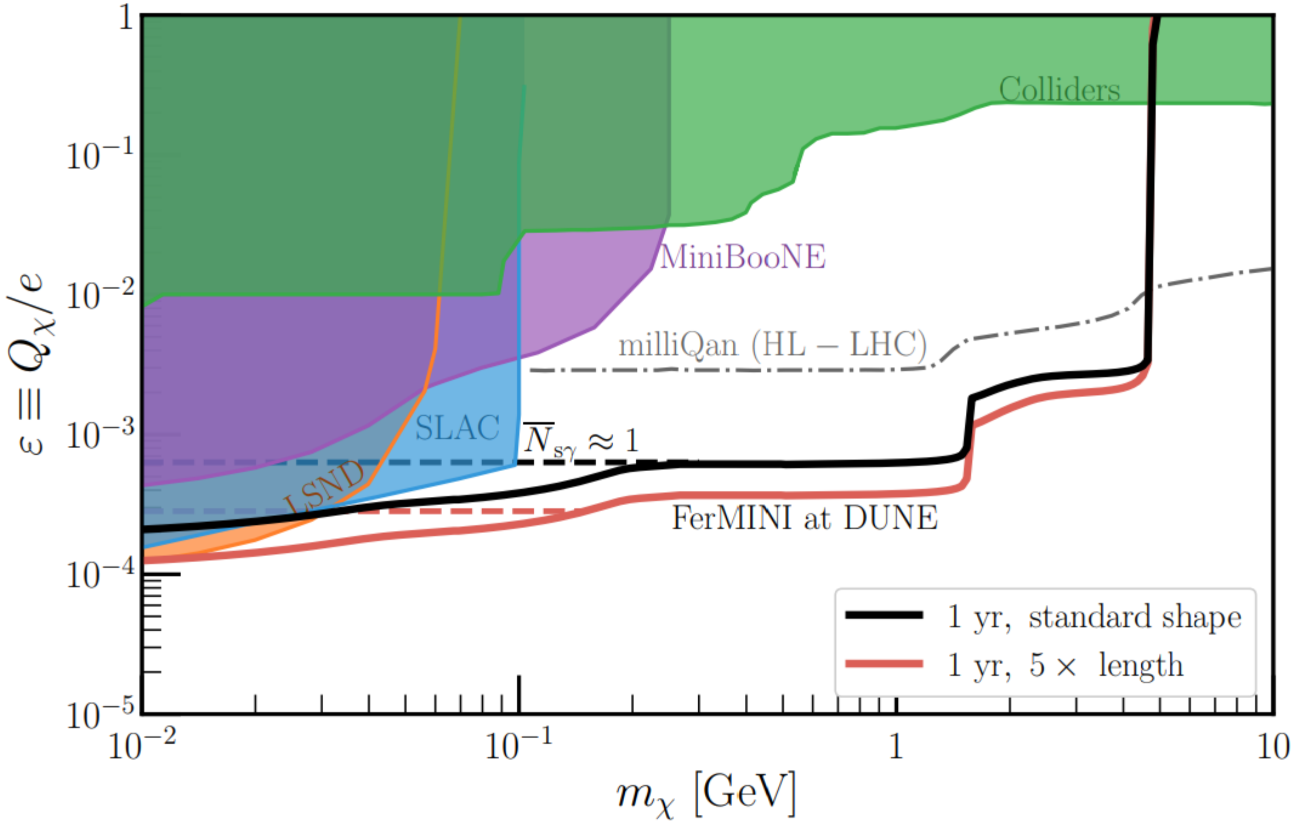
FerMINI @ MINOS



Yu-Dai Tsai, Fermilab

- Got support from **milliQan members**

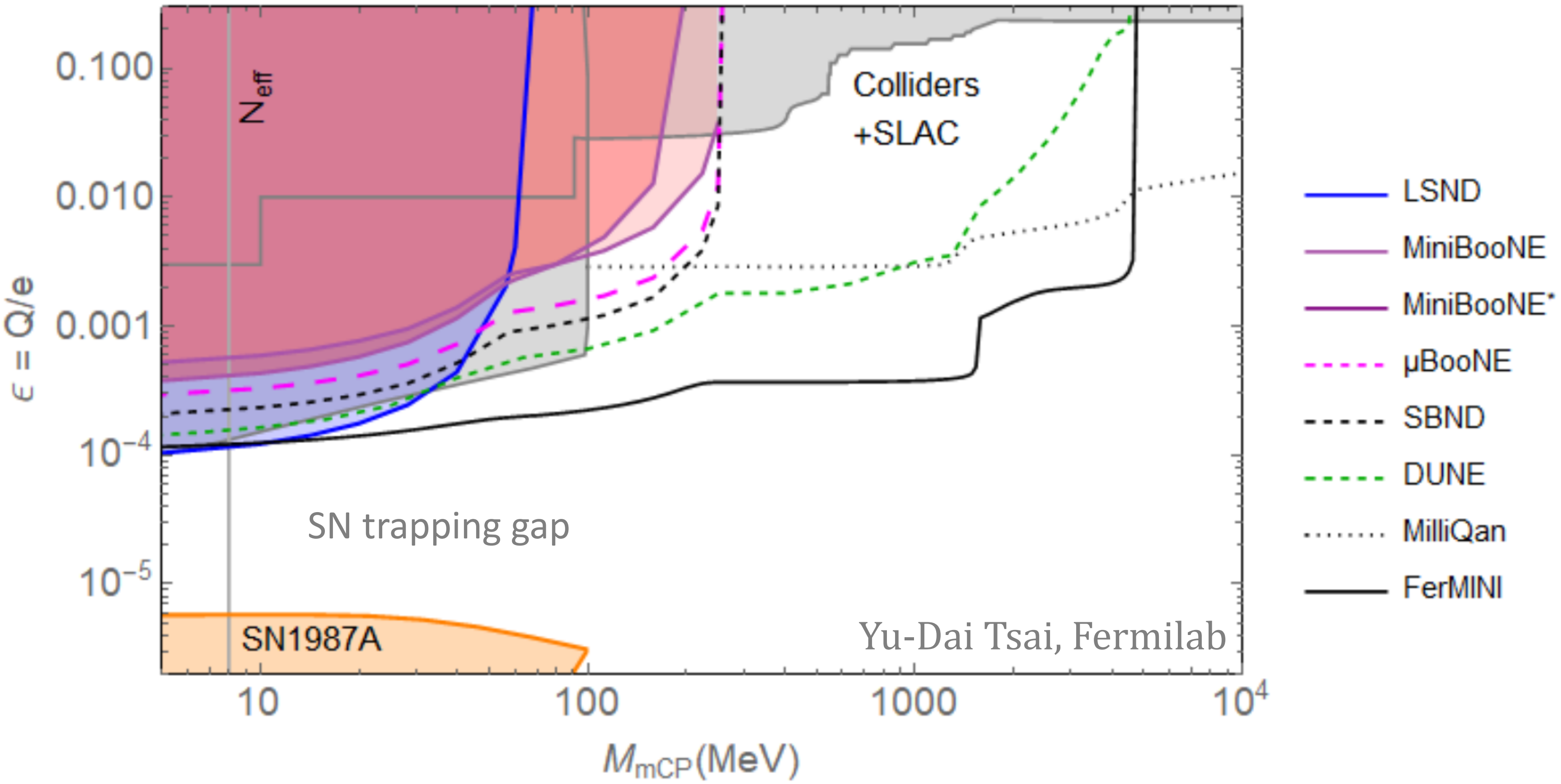
FerMINI @ DUNE



Yu-Dai Tsai,
Fermilab

- **Hope to Incorporate it into the near detector proposal.**

Compilation of MCP Probes

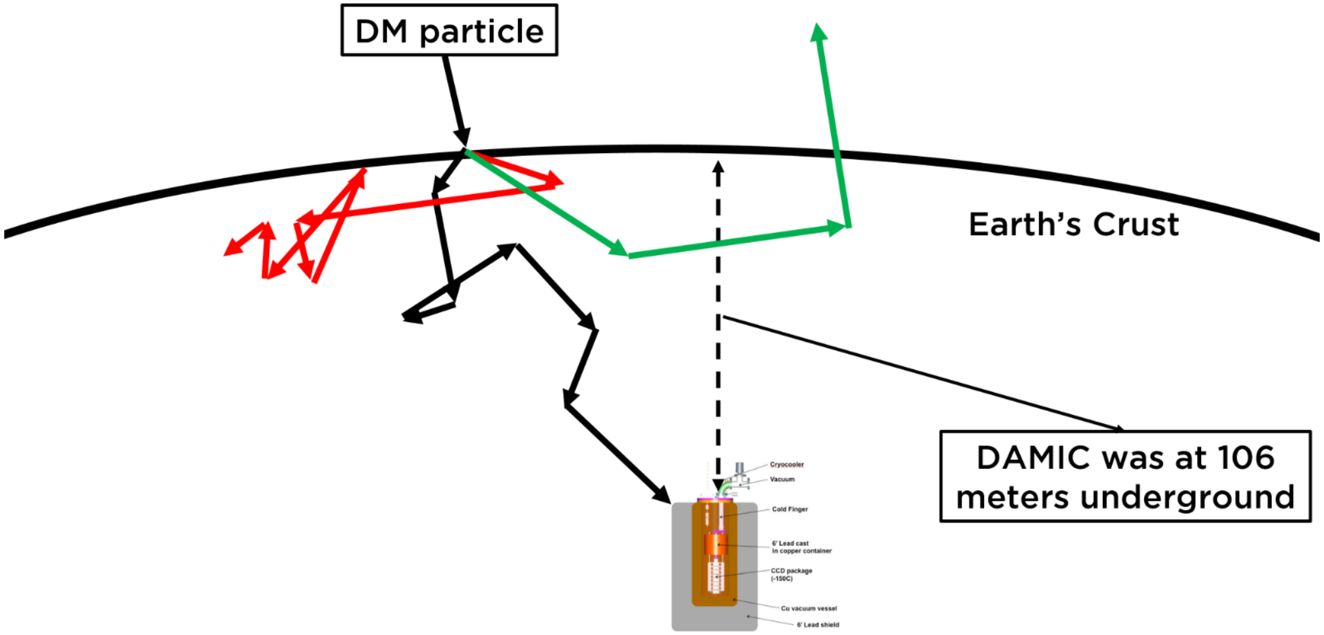


- One can **combine the MCP detector with neutrino detector** to improve sensitivity or reduce background
- Filling up the MCP "cavity"

Strongly Interacting Dark Matter

Strongly Interacting Dark Matter

DM-SM Interaction too strong that attenuation stop the particles from reach the direct detection detector



DMATIS (Dark Matter ATtenuation Importance Sampling), Mahdawi & Farrar '17

Strongly Interacting Dark Matter

See, e.g., arXiv:1905.06348 (Emken, Essig, Kouvaris, Sholapurkar '19)

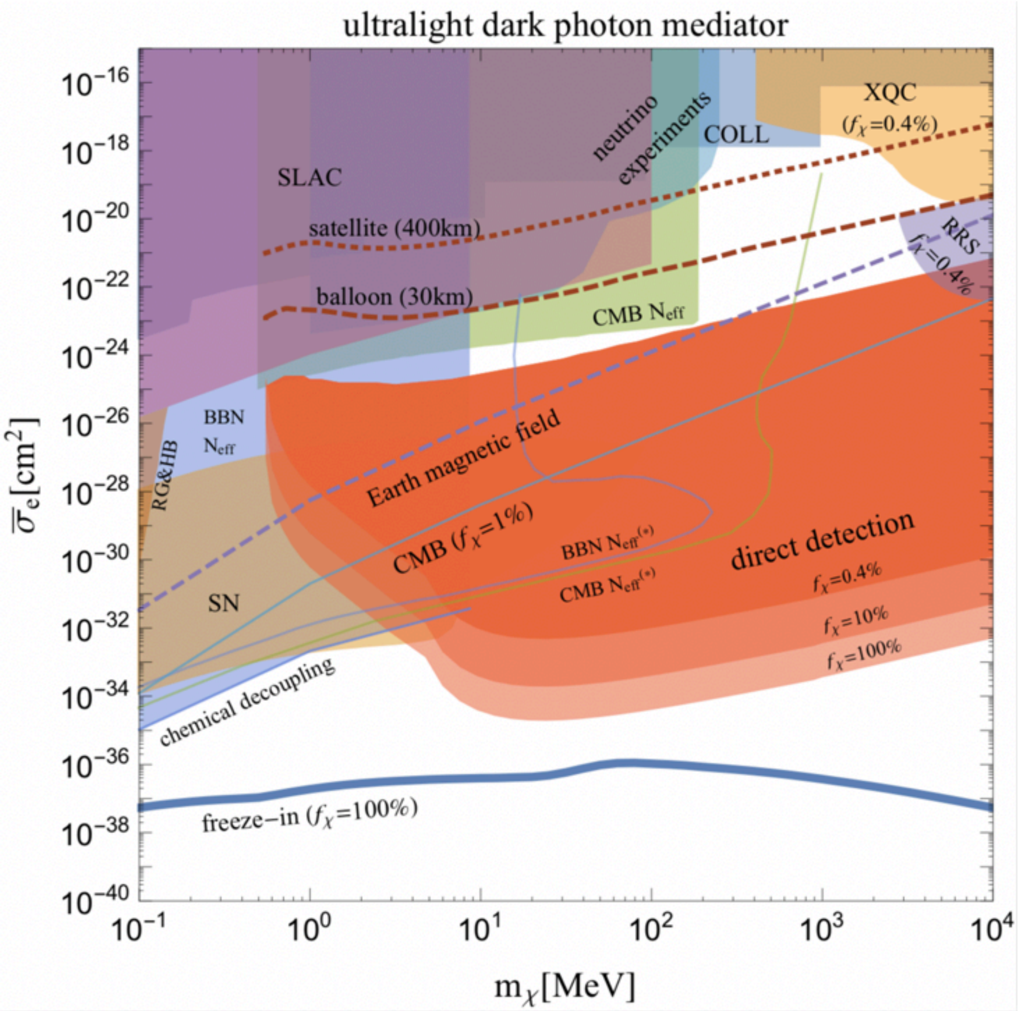
Scatterings both on electrons and nuclei in the **Earth's crust, atmosphere**, and **shielding material** attenuate the expected **local dark matter flux** at a terrestrial detector, so that such experiments lose sensitivity to dark matter above some **critical cross section**.

Limits of the underground Direct Detection (DD) Experiments, including **SENSEI, CDMS-HVeV, XENON10, XENON100, and DarkSide-50**

One can call the DM that could escape the DD bound this way as **Strongly Interacting Dark Matter (SIDM)**

Not to confuse with Self Interacting Dark Matter (also SIDM)

Millicharged (with ultralight A’) SIDM Window



From arXiv:1905.06348, they defined **reference cross section:**

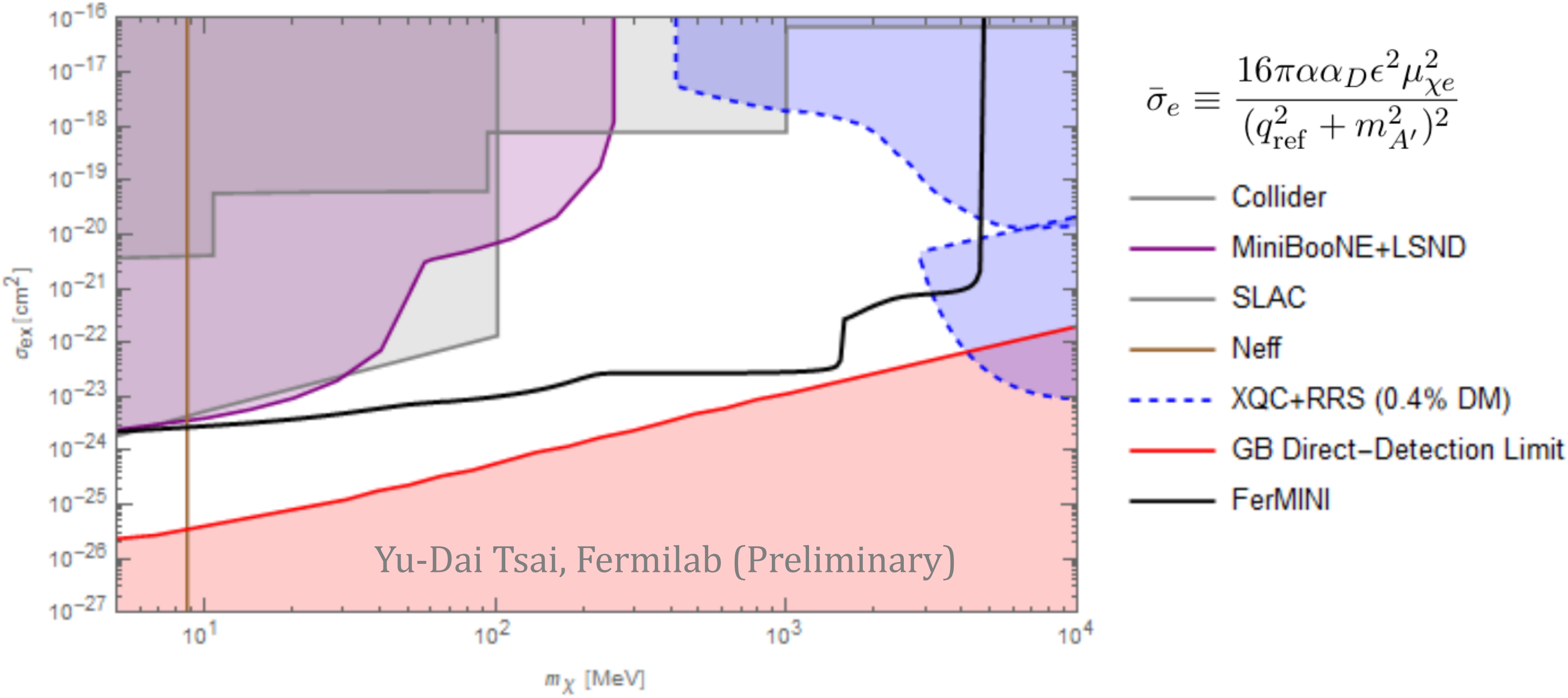
$$\bar{\sigma}_e \equiv \frac{16\pi\alpha\alpha_D\kappa^2\mu_{\chi e}^2}{(q_{ref}^2 + m_{A'}^2)^2},$$

$$m_{A'} \to 0,\ q_{ref} = \alpha m_e$$

q_{ref} is chosen as the typical momentum transfer in DM-electron collisions for noble-liquid / semiconductor targets.

Agonistic to the abundance setting mechanism for the SIDM window.

FerMINI Probe of Millicharged SIDM

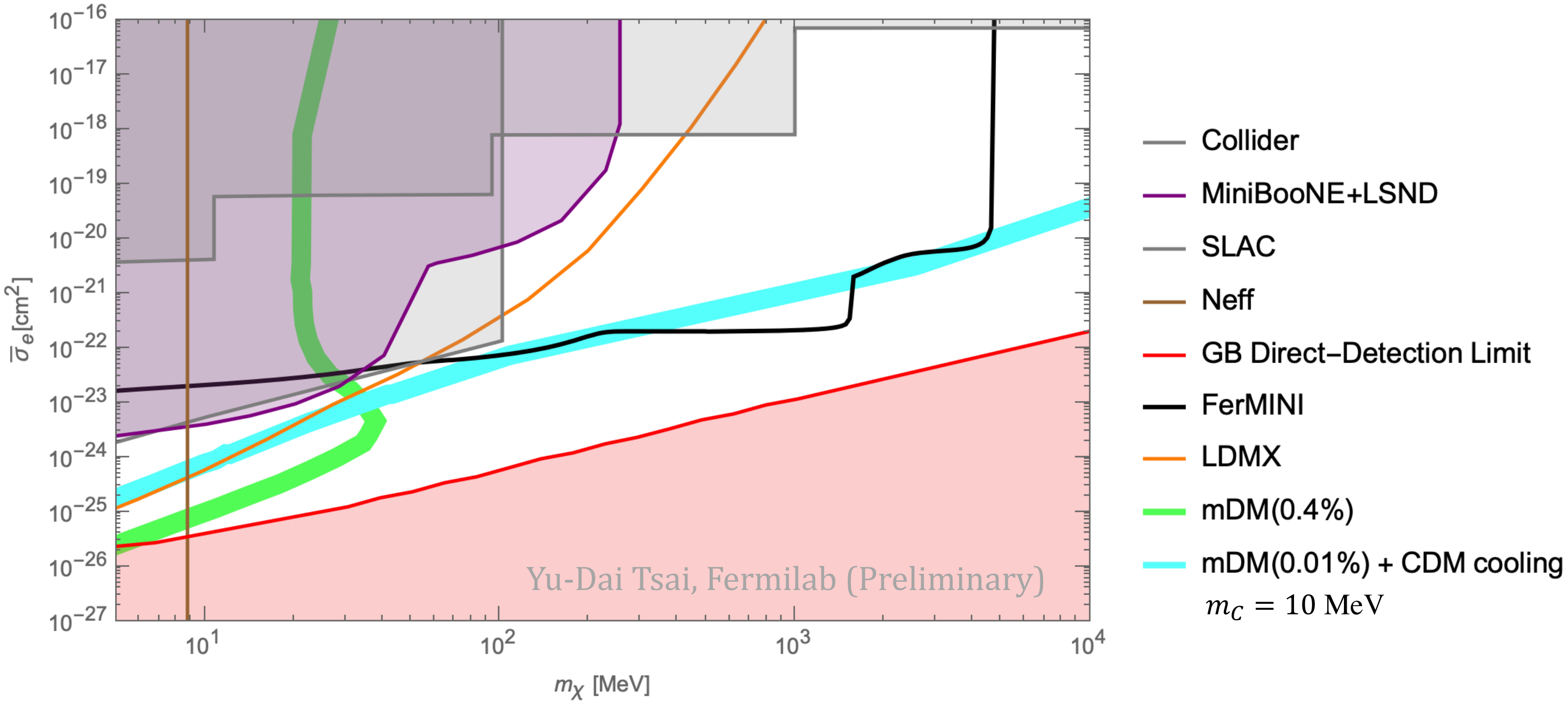


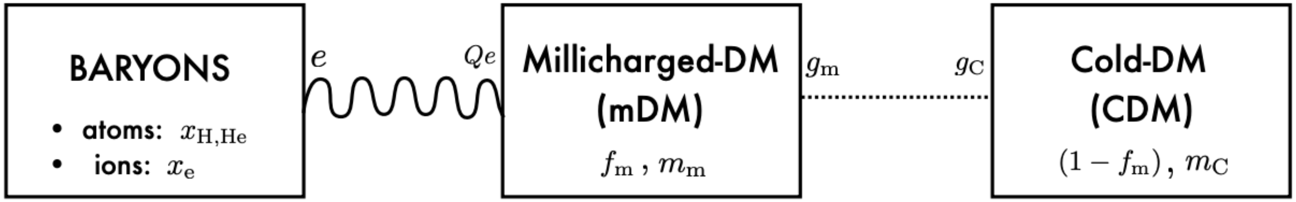
$$\bar{\sigma}_e \equiv \frac{16\pi\alpha\alpha_D\epsilon^2\mu_{\chi e}^2}{(q_{\rm ref}^2 + m_{A'}^2)^2}$$

Yu-Dai Tsai, Fermilab (Preliminary)

- Here we plot the **electron-scattering Millicharged SIDM**
- **FerMINI can help close the Millicharged SIDM window!**

Reviving mDM for EDGES





Backup
Slides

Liu, Outmezguine, Redigolo, Volansky, ‘19

Advantages of FerMINI: Timeliness, Low-cost, Movable, Tested, Easy to Implement, …

1. **LHC** entering **long shutdown**

2. **NuMI operating**, shutting down in 5 years
(DO IT NOW! Fermilab! USA!)

3. Broadening the physics case for fixed-target facilities

4. **DUNE near detector design** still underway

5. Can develop at NuMI/MINOS and then move to DUNE

6. **Sensitivity better than milliQan for MCP up to 5 GeV** and don't have to wait for HL-LHC

7. Synergy between **dark matter**, **neutrino**, and **collider** community.
Join us on the proposal! (ytsai@fnal.gov)

FerMINI:
Alternative Designs
& New Ideas

Alternatives (Straightforward)

1. **Quadruple incidence:** further background reduction, sacrifice event rate but potentially gain better control of background, reduce the background naively by **10^{-5}**
   Basically zero dark-current background experiment?

2. Different lengths for each detectors

3. Different materials:

Material	Photons/keV	Density (g/cm^3)	* Length needed (cm)	Speed (ns)	Cost for 5x5 cm ($)	Notes
Plastic BC408	10	1.03	145	~2	~200	Current choice
NaI	38	3.67	11	~230	~800	Slow, fragile
LaBr3(Ce)	63	5.08	5	~16	~3000	Radioactive
Liquid Xe	62	2.95	8	~2 / ~34	~1000?	Cryogenic, ultraviolet

- Andy Haas, Fermilab, 2017

* Length needed to get 3 photons for charge 1/1000 e

New Ideas …

- **Combine with neutrino detector**: behind, in front, or sandwich them
- Combine with **DUNE PRISM**: moving up and down
- **FerMINI + DUNE 3-D scintillation detector (3DST)**
- Combine with **SPS/SHiP facilities**
- Can potentially probe (electric) **dipole portal dark fermion**, **quirks**, etc.
- **Detail Proposal:** Kelly, Plestid, Pospelov, **YT** + milliQan people (ytsai@fnal.gov)

Part II

Dark Photon, **Inelastic Dark Matter**, and **Muon g – 2 Windows** at CHARM, NuCal, NA62, DarkQuest/SeaQuest, & LongQuest!

NuMI (MINOS) / LBNF (DUNE)

Now and the future bests in POTs

- **LSND:** total of 10^{23} POT (beam: 800 MeV)
- **Fermilab (FT):**

- NuMI beam: 1 - 4 x 10^{20} POT/yr (120 GeV)
- LBNF beam: 1 - 2 x 10^{21} POT/yr (120 GeV)

- **CERN SPS (FT):**

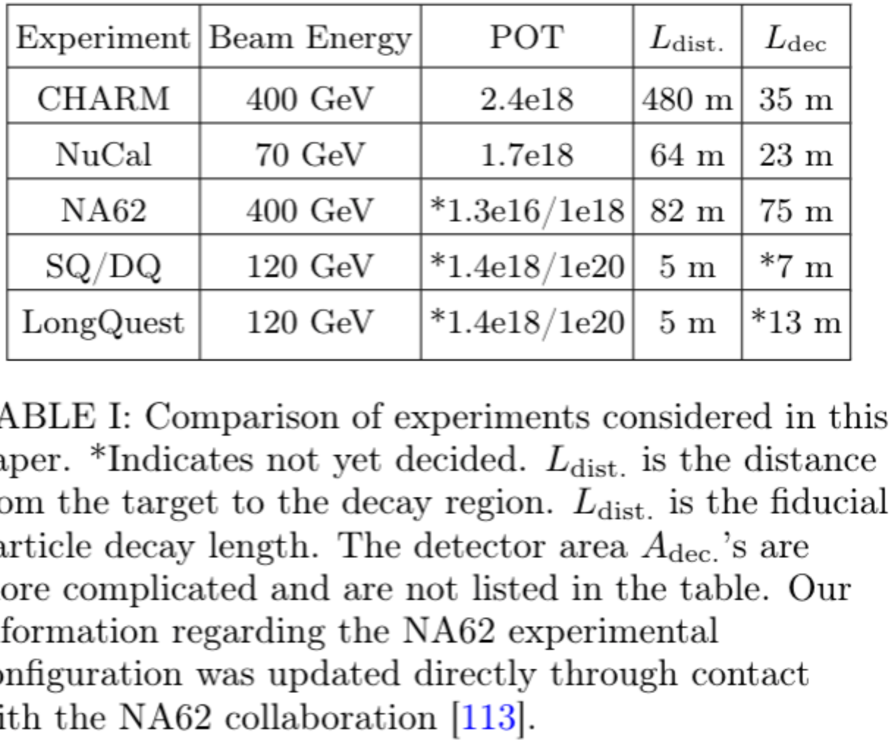
- NA62: up to 3 x 10^{18} POT/yr (400 GeV)
- SHiP: up to 10^{19} POT/yr (400 GeV)

- **FASER (collider, forward)**: 10^{16}-10^{17} POT/yr

  much higher energy

Energy Summits! Proton Fixed Target

NuMI 120 GeV. 1e20. 200/1K O(5-10) m



Experiment	Beam Energy	POT	$L_{\text{dist.}}$	L_{dec}
CHARM	400 GeV	2.4e18	480 m	35 m
NuCal	70 GeV	1.7e18	64 m	23 m
NA62	400 GeV	*1.3e16/1e18	82 m	75 m
SQ/DQ	120 GeV	*1.4e18/1e20	5 m	*7 m
LongQuest	120 GeV	*1.4e18/1e20	5 m	*13 m

TABLE I: Comparison of experiments considered in this paper. *Indicates not yet decided. $L_{\text{dist.}}$ is the distance from the target to the decay region. $L_{\text{dist.}}$ is the fiducial particle decay length. The detector area $A_{\text{dec.}}$'s are more complicated and are not listed in the table. Our information regarding the NA62 experimental configuration was updated directly through contact with the NA62 collaboration [113].

450 GeV

- How about NuTeV (800 GeV!), DUNE, and SHiP? (NOMAD: weaker)
- NuTeV: information lost … / DUNE & SHiP: far in the future.

Variere-Lifetime Particles (VLP)

- next-to-minimal class of models.
- VLP here are loosely defined as long-lived particles that their production and decay (signatures) can be governed by different physics or distinctive parameters.
- Often designed to avoid experimental constraints while explaining the observation and anomalies.
- Examples: Inelastic Dark Matter (iDM), very long-lived, and dark neutrino, short-lived

Inelastic Dark Matter (iDM)

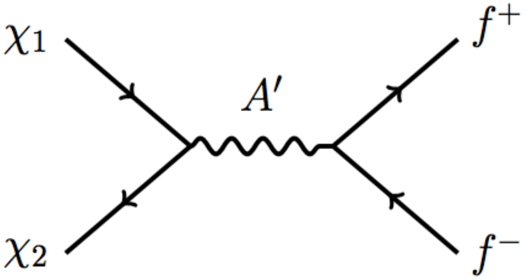


FIG. 1. Leading order diagram for $\chi_1\chi_2 \to f^+f^-$ coannihilation, which sets the DM relic abundance in the $m_{A'} > m_{1,2}$ regime.

- iDM avoids strong constraints like those from the **Cosmic Microwave Background (CMB)** by heavily suppressing the dark matter (co-)annihilation cross section.
- iDM thus provides one of the few viable GeV/sub-GeV thermal DM scenarios that freezes out to the right relic abundance, also called "**thermal targets**", since many future experiments are proposed to explore these models.

$$m_1 \sim \frac{\epsilon\,(\alpha_D\,\alpha_{\rm em}\,T_{\rm eq}\,m_{\rm pl})^{1/2}}{(m_{A'}/m_1)^2}\,e^{-x_f\Delta/2}\,,$$

Inelastic Dark Matter (iDM) Model

$$\mathcal{L}_{\text{kin. mix.}} = \frac{\epsilon}{2} A'_{\mu\nu} B^{\mu\nu}.$$

$$\mathcal{L}_{\text{int}} \supset \epsilon e A'_{\mu} \mathcal{J}^{\mu}_{\text{EM}} + g_D A'_{\mu} \mathcal{J}^{\mu}_{\text{D}}, \qquad \mathcal{L} \supset -m_D \eta \xi - \frac{1}{2}\delta_\eta \eta^2 - \frac{1}{2}\delta_\xi \xi^2 + \text{h.c.}$$

Consider a Dirac pair of two-component Weyl spinors, η and ξ, oppositely charged under U(1)_D.

$\delta_\eta, \delta_\xi \ll m_D$, are technically nature since they break U(1) symmetry.

After the mass diagonalization, the Lagrangian can be written with mass eigenstate χ , as

$$\mathcal{L} \supset \sum_{i=1,2} \bar{\chi}_i (i\partial\!\!\!/ - m_{\chi_i})\chi_i - (g_D A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2 + \text{h.c.}).$$

$$\Delta \equiv \frac{m_2 - m_1}{m_1} \simeq \frac{\delta_\eta + \delta_\xi}{m_D}.$$

The elastic interactions are suppressed by a factor of δ/mD. δ << mD is again technically natural because the U(1) breaking would be restored when δ → 0. Note that the elastic interaction vanishes as δη = δξ.

Inelastic Dark Matter (iDM) Model

$$\mathcal{L}_{\text{kin. mix.}} = \frac{\epsilon}{2} A'_{\mu\nu} B^{\mu\nu}.$$

$$\mathcal{L}_{\text{int}} \supset \epsilon e A'_{\mu} \mathcal{J}^{\mu}_{\text{EM}} + g_D A'_{\mu} \mathcal{J}^{\mu}_{\text{D}}, \qquad \mathcal{L} = i\overline{\psi} \not{D} \psi + M\bar{\psi}\psi + \lambda\phi\,\overline{\psi^c}\psi + h.c.,$$

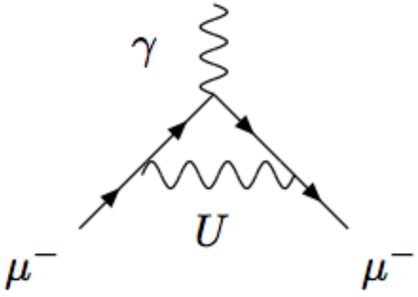
$$\psi = (\xi, \eta^{\dagger})$$

ϕ is a scalar whose vacuum expectation value vD breaks U(1)_D symmetry

In this construction, the elastic interaction vanishes as δη = δξ.

$$\mathcal{L} \supset \sum_{i=1,2} \bar{\chi}_i (i\not{\partial} - m_{\chi_i})\chi_i - (g_D A'_{\mu} \bar{\chi}_1 \gamma^{\mu} \chi_2 + \text{h.c.}).$$

Dark photon muon g-2 Exp. (Minimal models ruled out!)



$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{th} = (274 \pm 73) \times 10^{-11},$$

For a U with a *vector coupling* to the muon, one has, as in (63),

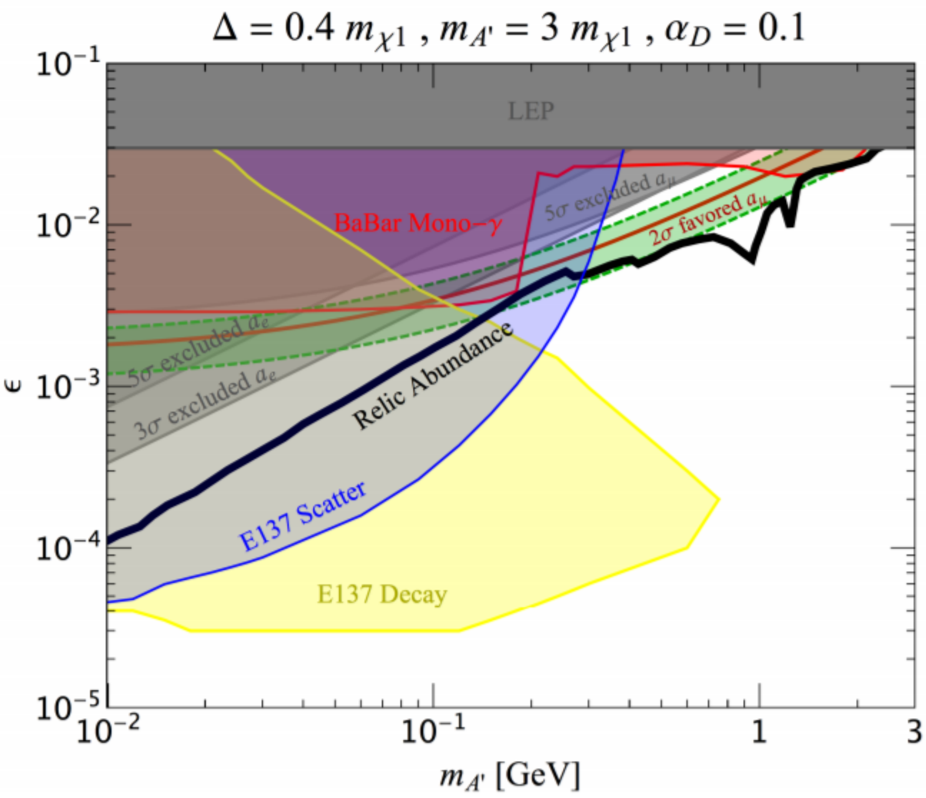
$$\delta a_\mu \simeq \frac{f_{\mu V}^{\,2}}{4\,\pi^2} \int_0^1 \frac{m_\mu^2\, x^2\,(1-x)\, dx}{m_\mu^2\, x^2 + m_U^2\,(1-x)} \simeq \frac{f_{\mu V}^{\,2}}{8\,\pi^2}\; G\,(\frac{m_U}{m_\mu})\;, \tag{79}$$

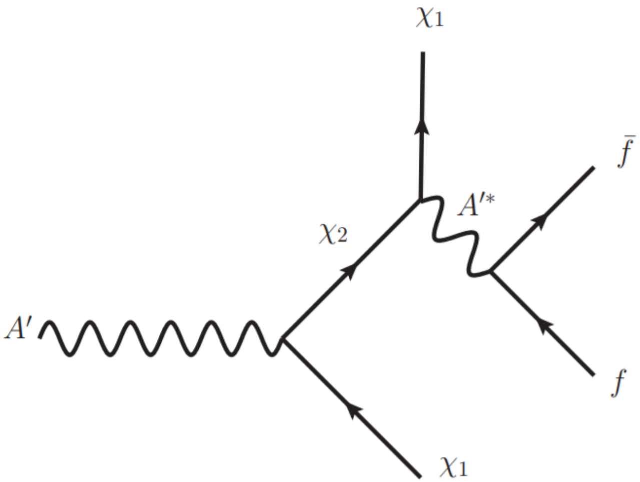
which reduces to $\frac{f_{\mu V}^{\,2}}{8\,\pi^2}$, in the limit of a light U as compared to m_μ. If the U is not sufficiently light, we tabulate the function

$$G\,(\frac{m_U}{m_l}) \;=\; \frac{2}{3}\,\frac{m_l^2}{m_U^2}\;F\,(\frac{m_U}{m_l})\;\;, \tag{80}$$

Fayet, 2007 (hep-ph/0702176)

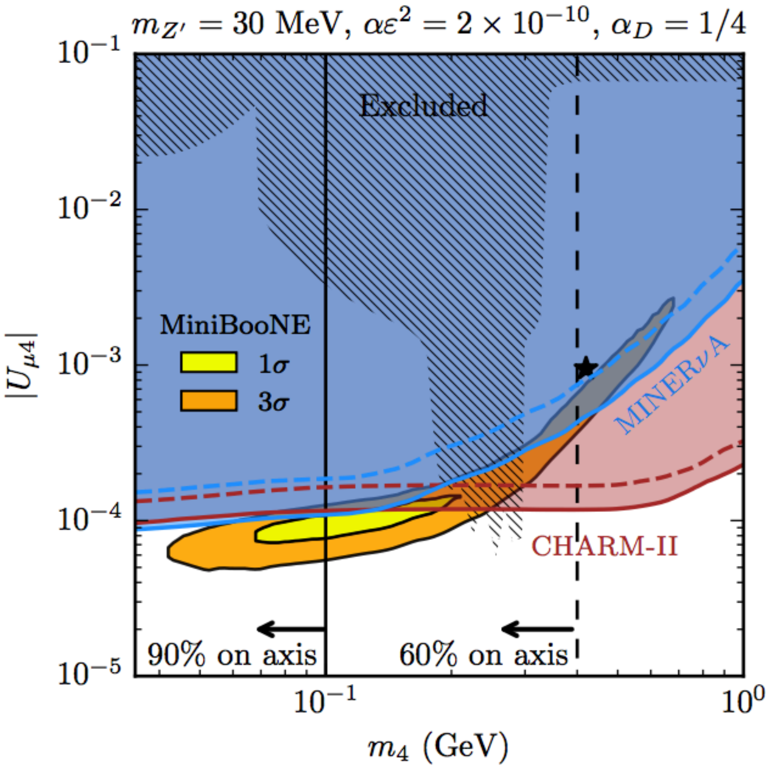
Dark photon+ iDM muon g-2 Exp. (Still Alive!)

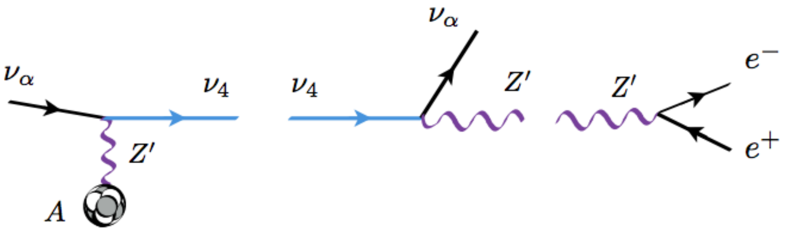




Mohlabeng, ‘19 (1902.05075)

Variere-Lifetime Particle: Dark Neutrino



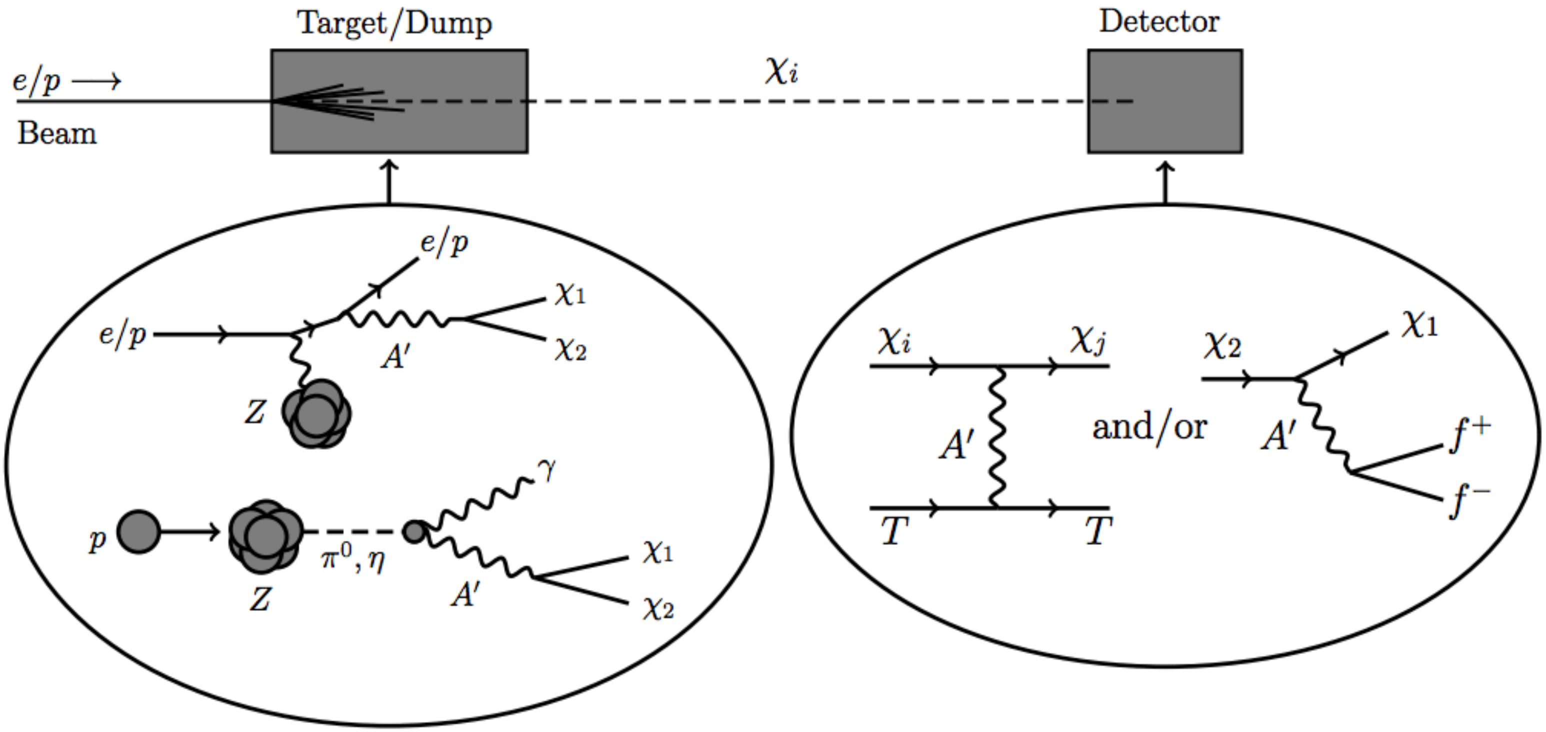


arXiv:1807.09877
arXiv:1812.08768 + …

General Point

- These high energy proton fixed target experiments provide robust and strong bounds for VLP in MeV to GeV + regime
- Towards closing the iDM thermal target window
- Can probe iDM muon g-2 window, but need future upgrades
- We revisited minimal dark photon bounds, added NA62 projection (done properly), and found some discrepancy with old CHARM and NuCal
- And future probes!

iDM Searches

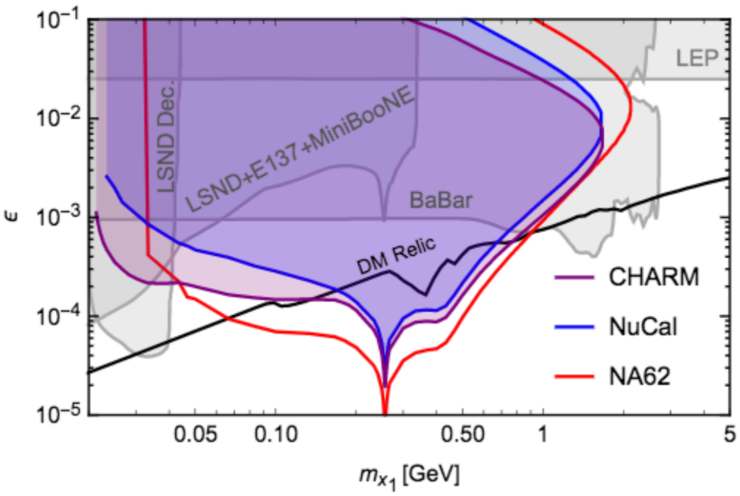


$$\Gamma(A^{'} \to \chi_1\chi_2) \simeq \frac{\alpha_D m_{A'}}{3}\sqrt{1-\frac{4m_1^2}{m_{A'}^2}}\left(1+\frac{2m_1^2}{m_{A'}^2}\right)$$

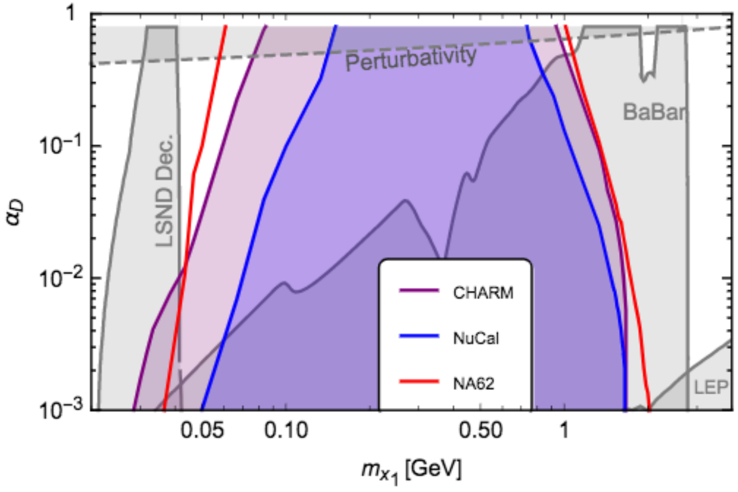
$$\Gamma(\chi_2 \to \chi_1 l^+ l^-) \simeq \frac{4\epsilon^2\alpha_{\mathrm{em}}\alpha_D\Delta^5 m_1^5}{15\pi m_{A'}^4}$$

arXiv: 1703.06881

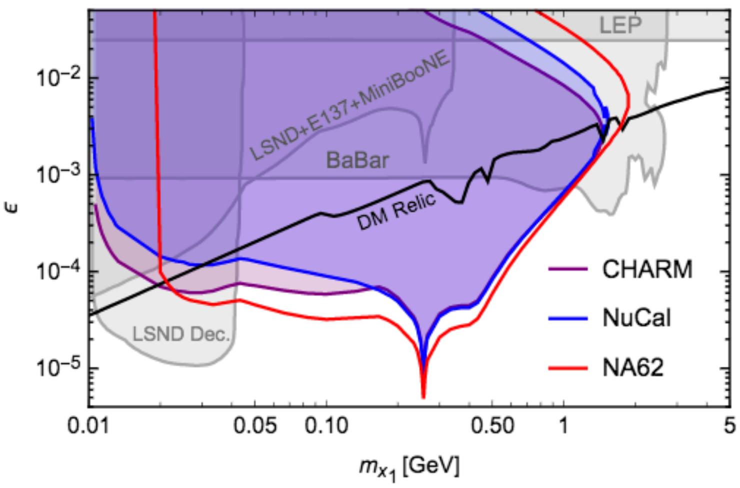
Results: iDM Thermal Target (small delta)



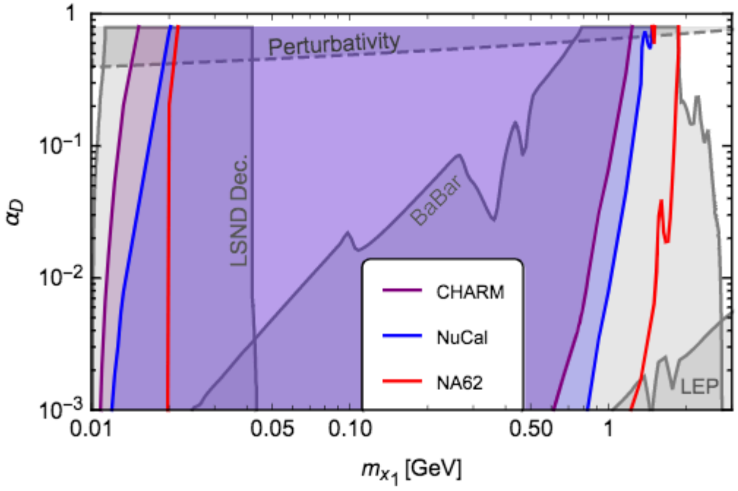
(a) iDM: $\Delta = 0.05$, α_D=0.5.



(b) iDM Thermal Target: $\Delta = 0.05$, $\epsilon = \epsilon_{\text{relic}}$.

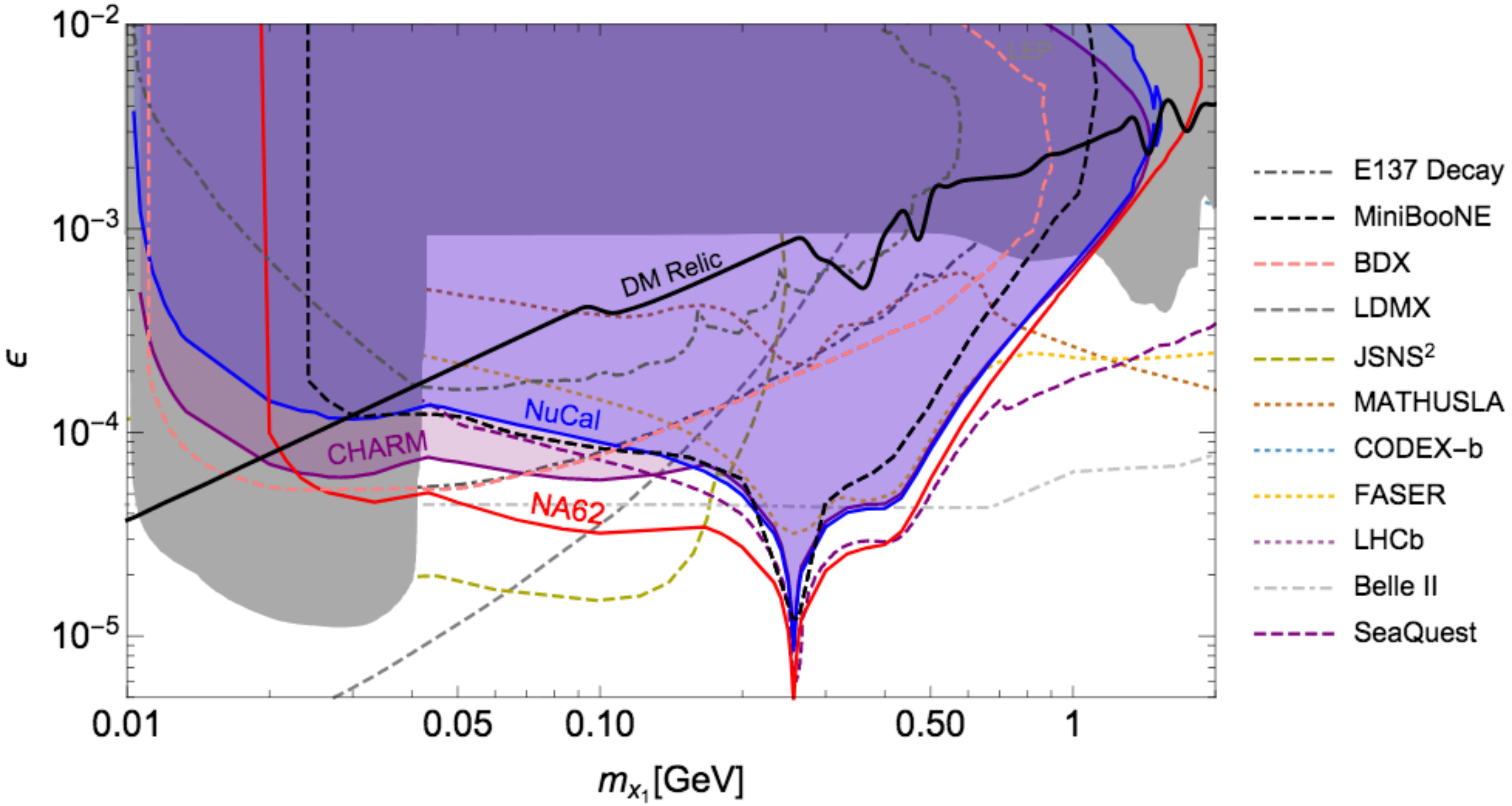


(c) iDM: $\Delta = 0.1$, α_D=0.1.



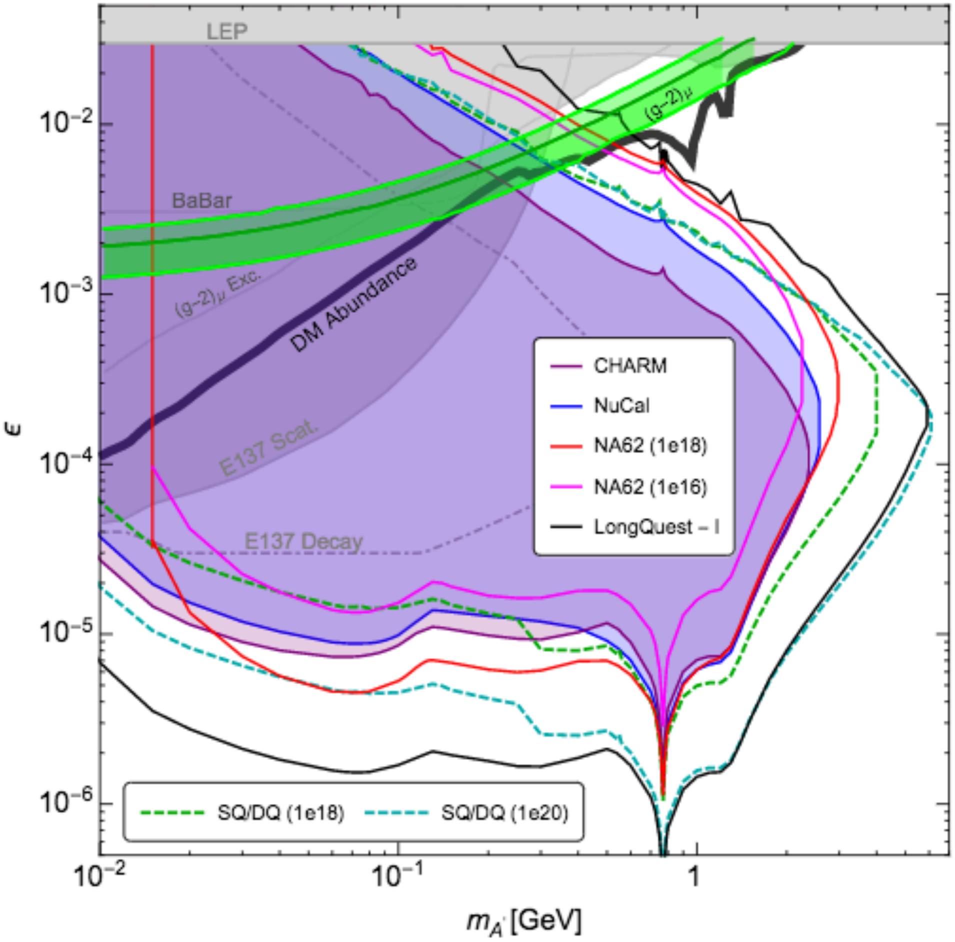
(d) iDM Thermal Target: iDM $\Delta = 0.1$, $\epsilon = \epsilon_{\text{relic}}$.

Result I: iDM Thermal Target (Compilation)



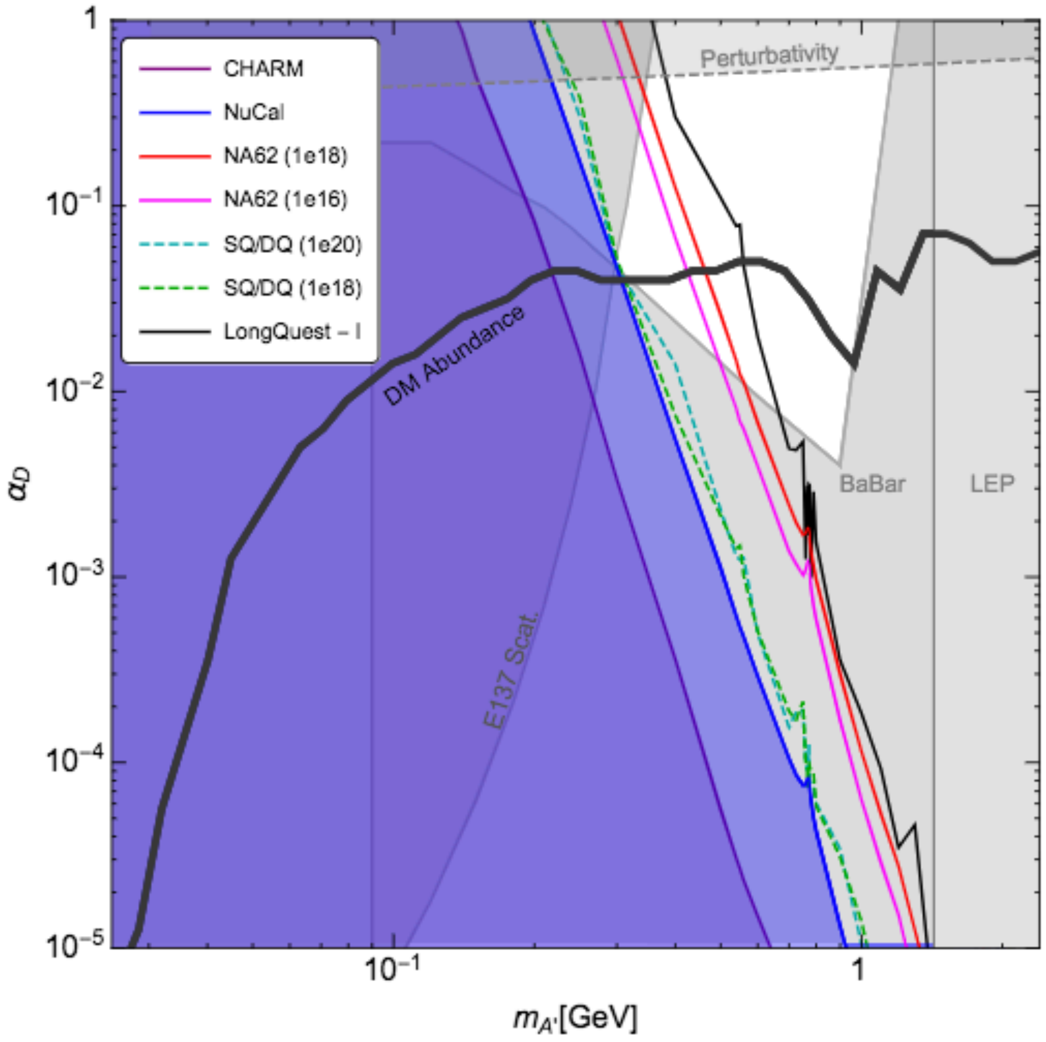
(e) Compilation of relevant constraints and sensitivity projections for iDM with $\alpha_D = 0.1$ and $\Delta = 0.1$.

Result II: iDM g-2



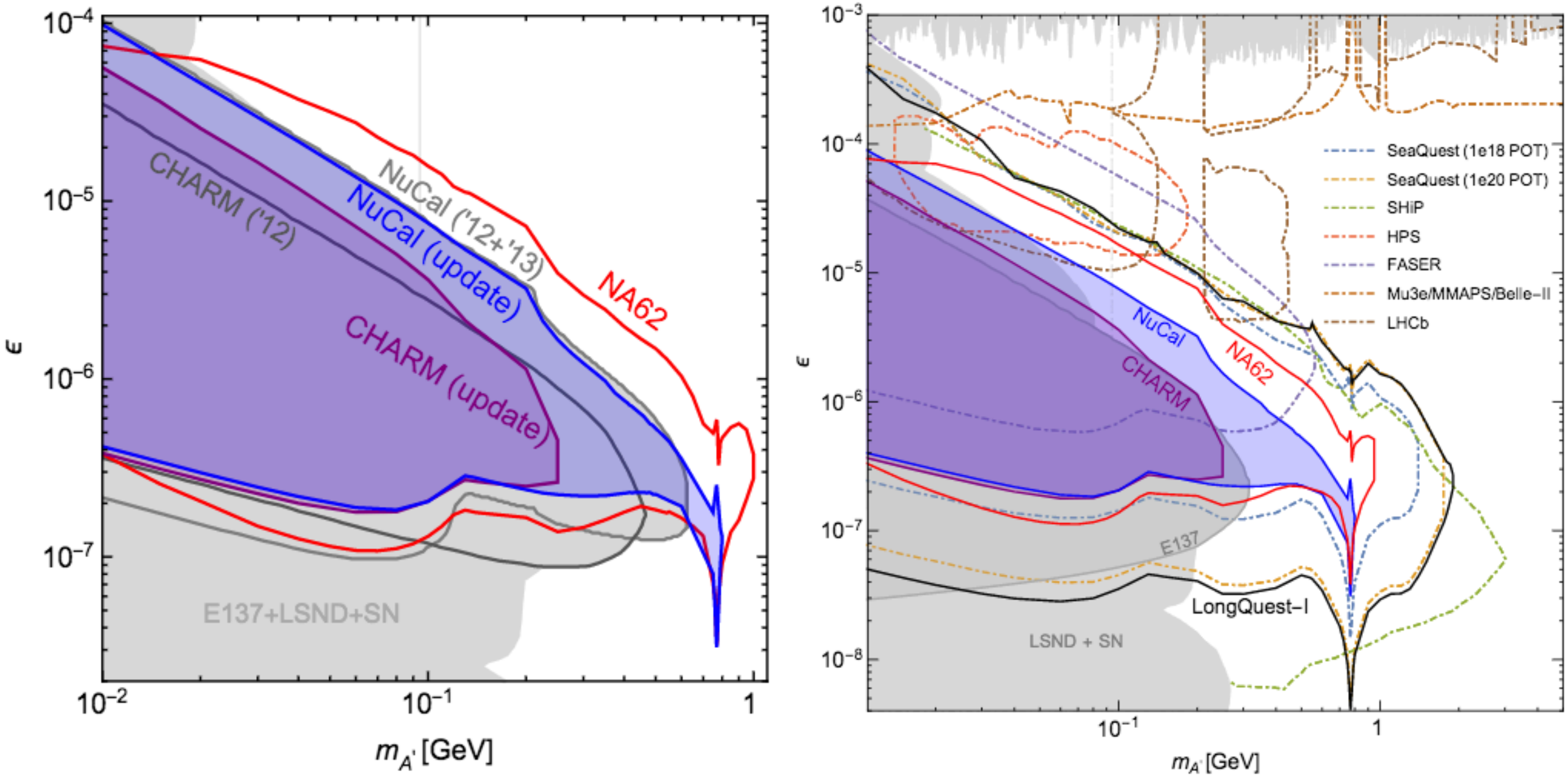
(a) iDM: $\Delta = 0.4$, α_D=0.1. With muon $g-2$ and DM regimes.

Result II: iDM g-2



(b) iDM Muon $g-2$ Target: $\Delta = 0.4$, $\epsilon = \epsilon_{(g-2)_\mu}$.

Result III: Minimal Dark Photon



(a) Updates on dark photon bounds and NA62 projection.

(b) Compilation of projections and constraints on dark photon.

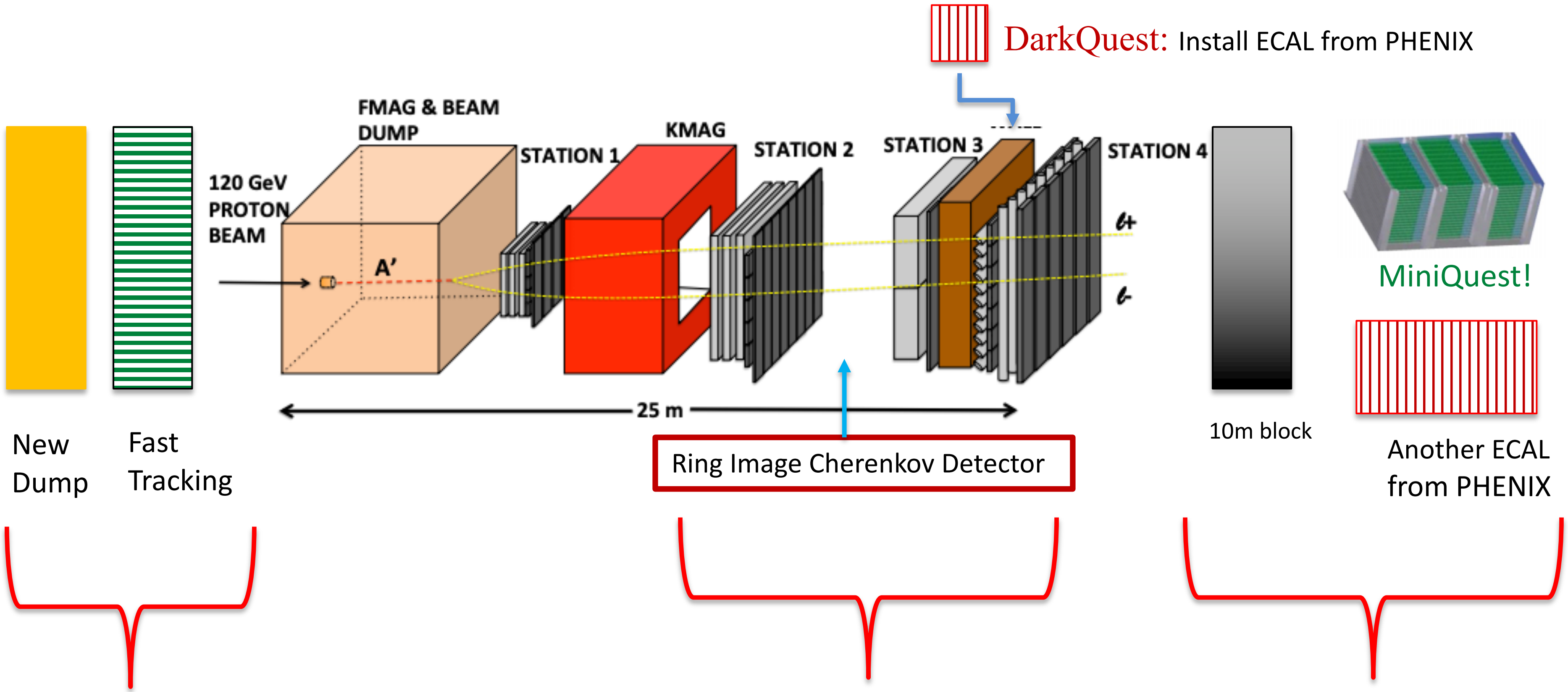
LongQuest (I-III)

- A proposal I am working on with Ming Liu, Kun Liu, and Patrick
- "A search for long-lived particles with extended decay length, improved decay detectors, and additional long based-line detectors at SeaQuest/SpinQuest"

龍 lóng

LongQuest: Three Stage Retool of SpinQuest, as Dedicated Long-Lived Particle Experiment

arXiv:1908.07525, Tsai, de Niverville, Liu '19



DarkQuest: Install ECAL from PHENIX

New Dump

Fast Tracking

Ring Image Cherenkov Detector

10m block

MiniQuest!

Another ECAL from PHENIX

LongQuest III

Front dump and fast tracking

LongQuest I

Add RICH (from PHENIX exp.) or HBD for particle id.

LongQuest II

Far Detectors: low bkg.
Millicharge detector
Or another ECAL!

Yu-Dai Tsai, Fermilab, 2019

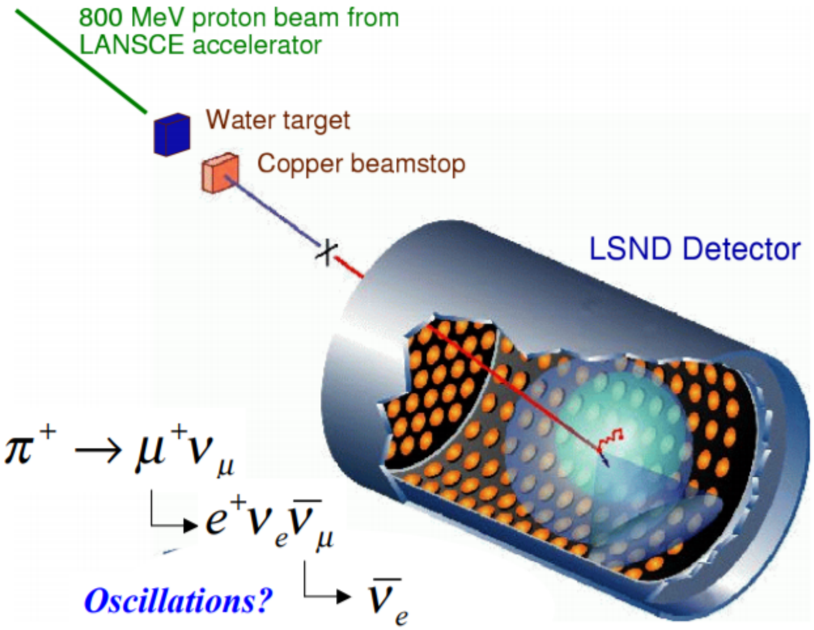
Thank You!

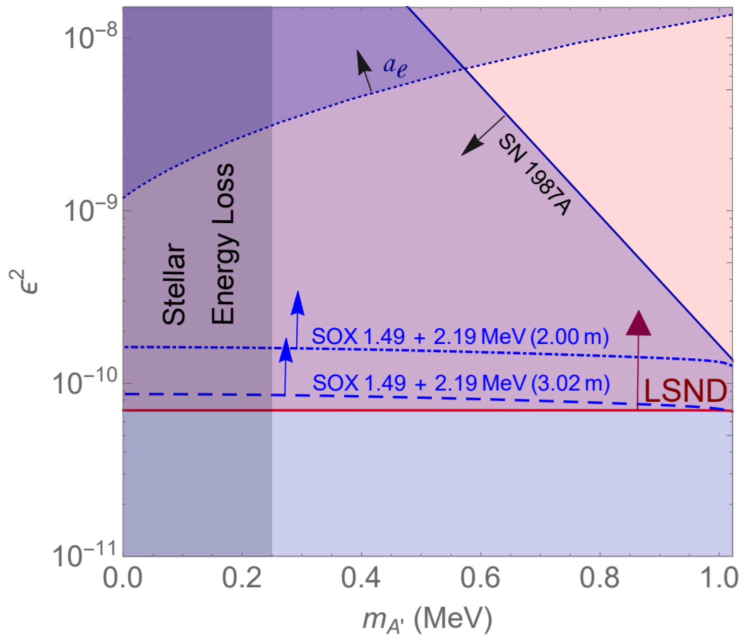
Thanks for the workshop. Especially thank Francesco & Andrea.

Other New Physics Probes

Dark Photon @ LSND

$$\mathcal{L}_{\text{d.ph.}} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 (A'_\mu)^2 + \epsilon A'^\mu J_\mu^{EM}.$$

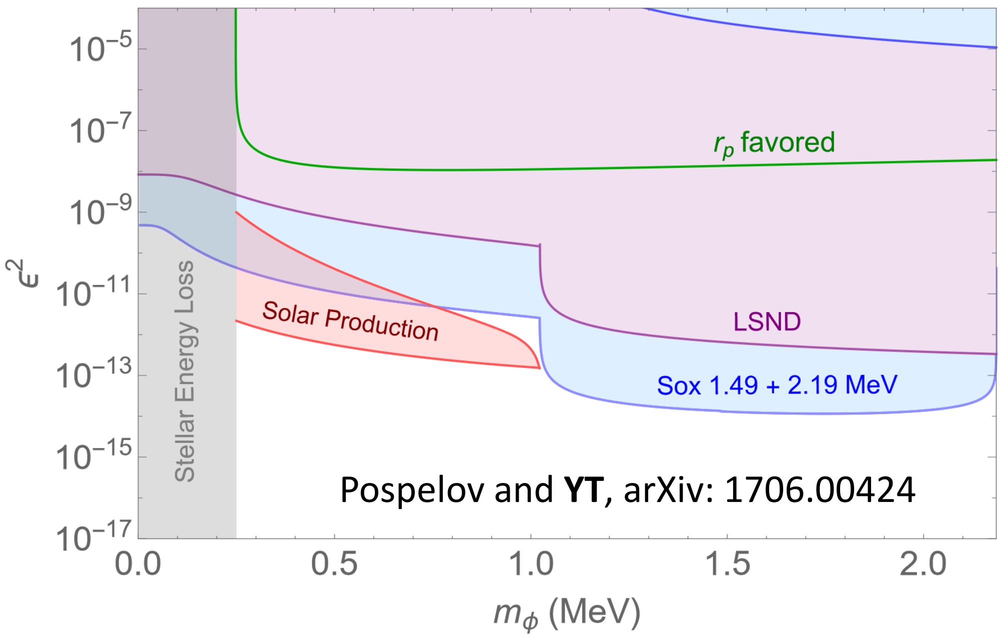




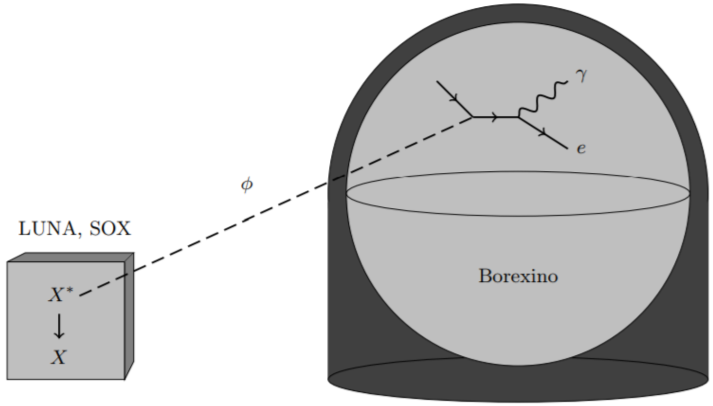
- Major energy depositions: $e + A' \to e + \gamma.$

Light Scalar @ LSND & Borexino

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + (g_p\bar{p}p + g_n\bar{n}n + g_e\bar{e}e + g_\mu\bar{\mu}\mu + g_\tau\bar{\tau}\tau)\phi.$$



Pospelov and **YT**, arXiv: 1706.00424



- β^- decay chain:

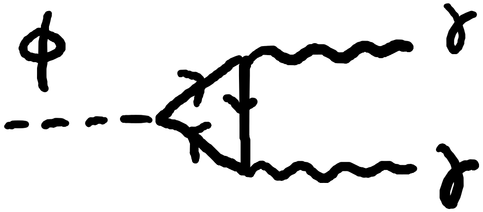
$^{144}\text{Ce} \to {}^{144}\text{Pr} + e^- + \bar{\nu}_e$

$\searrow$ $^{144}\text{Nd} + e^- + \bar{\nu}_e$

$e\phi \to e\gamma$ $\phi \to \gamma\gamma$ $\phi \to e^+e^-$

$\boxed{\epsilon^2 \equiv g_e g_p/e^2}$

$g_e = (m_e/m_\mu)g_\mu, \; g_\tau = (m_\tau/m_\mu)g_\mu, \; g_p = (m_p/m_\mu)g_\mu,$

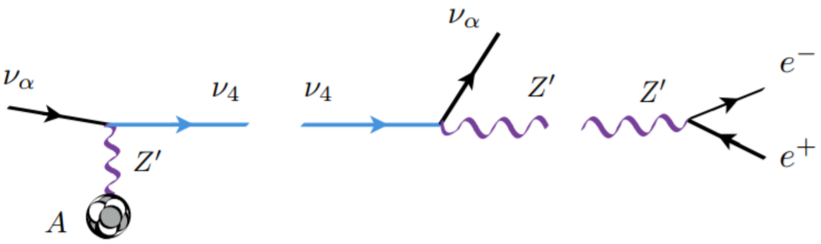


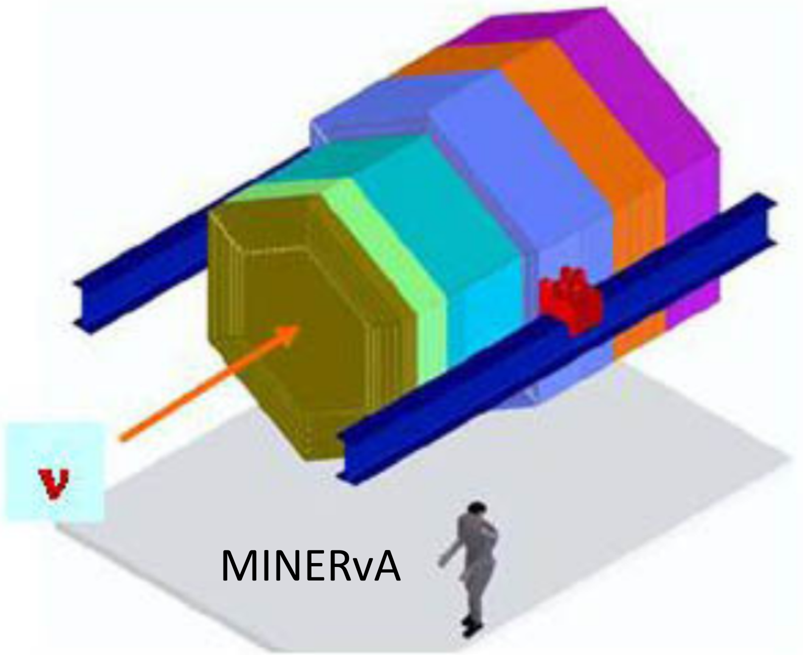
diphoton decay

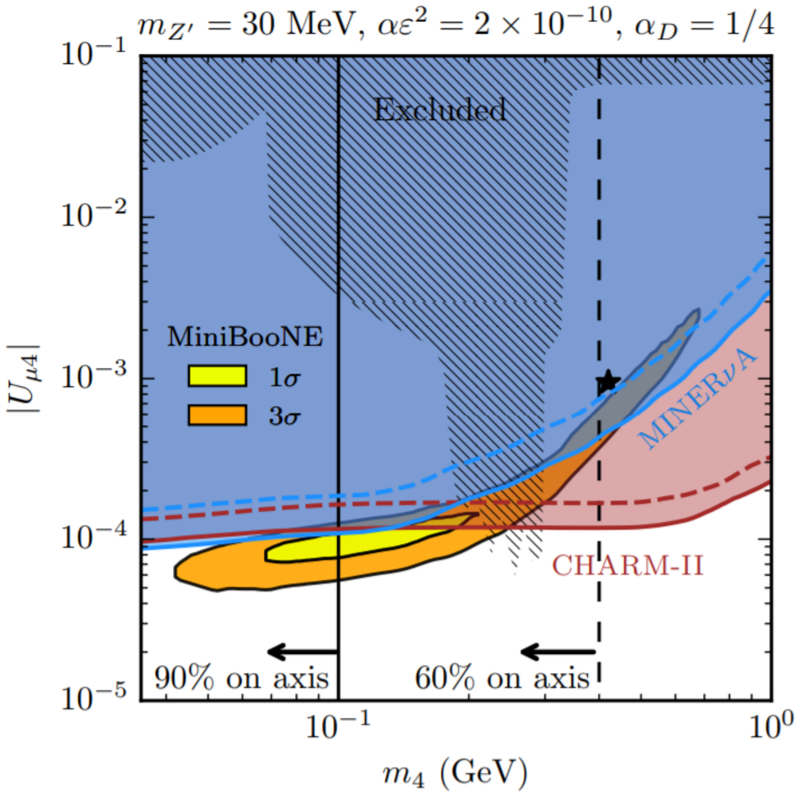
Dark Neutrino at CHARM & MINERvA

$$\mathscr{L}_{\rm int} \supset \quad g_D \bar{\nu}_D \gamma_\mu \nu_D Z'^{\mu} + e\varepsilon Z'^{\mu} J^{\rm EM}_{\mu},$$

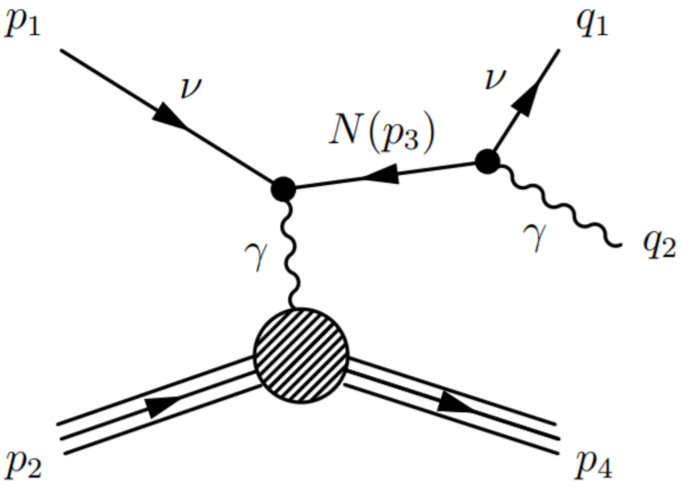
$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\nu_i, \quad (\alpha = e, \mu, \tau, D).$$





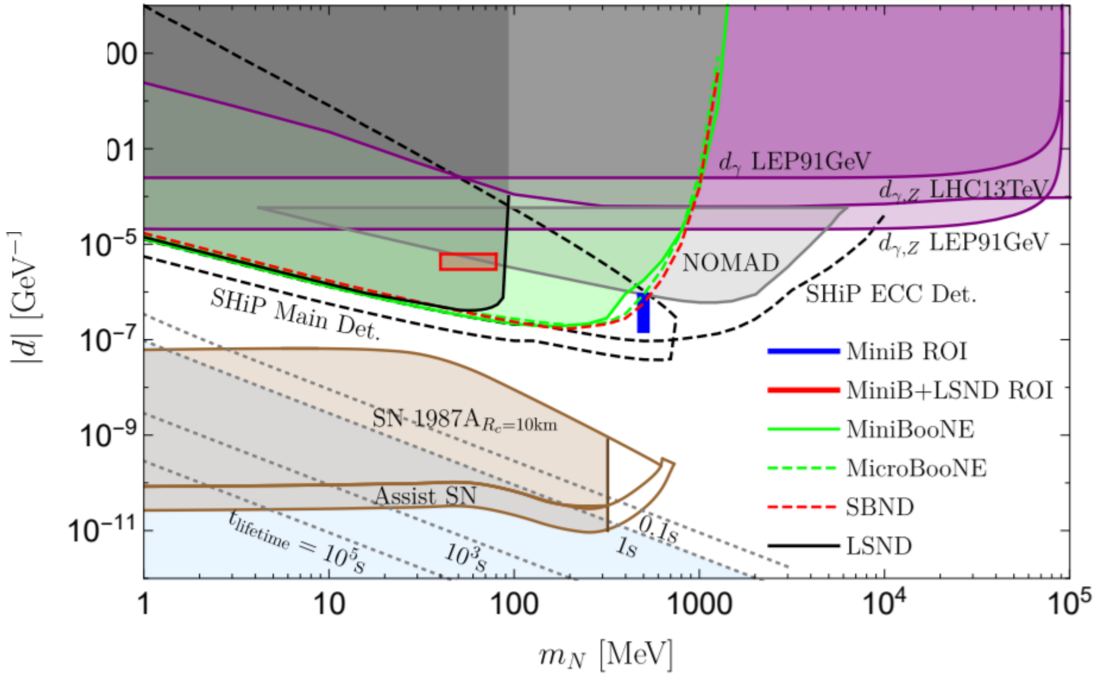


Dipole-Portal Heavy Neutral Lepton



$$\mathcal{L} \supset \bar{L}\left(d_{\mathcal{W}}\mathcal{W}^{a}_{\mu\nu}\tau^{a} + d_B B_{\mu\nu}\right)\tilde{H}\sigma_{\mu\nu}N_D + h.c.$$

$$\mathcal{L} \supset \bar{N}(i\partial\!\!\!/ - m_N)N + (d\bar{\nu}_L\sigma_{\mu\nu}F^{\mu\nu}N + h.c).$$



Looking Ahead

- Exploring **Energy Frontier of the Intensity Frontier** (complementary to and **before HL-LHC upgrade**)
- **Cosmology-driven models/ more motivated models.**
- Near-future (and almost free) opportunity (**NuMI Facility, SBN program, DUNE Near Detector**, etc.)
- Other new **low-cost alternatives/proposals (~ \$1M)** to probe hidden particles and new forces **(FerMINI is just a beginning!)**
- **Dark sectors in neutrino telescopes**

Thank You Again!

Yu-Dai Tsai, Fermilab, 2019

(detail) Meson Production Details

- At LSND, the π0 (135 MeV) spectrum is modeled using a Burman-Smith distribution
- Fermilab's Booster Neutrino Beam (BNB): π0 and η (548 MeV) mesons. π0's angular and energy spectra are modeled by the **Sanford-Wang distribution**. η mesons by the Feynman Scaling hypothesis.
- SHiP/DUNE: pseudoscalar meson production using the **BMPT distribution**, as before, but use a beam energy of 80 GeV
- J/ψ (3.1 GeV), we assume that their energy production spectra are described by the distribution from **Gale, Jeon, Kapusta, PLB '99**, nucl-th/9812056.
- Upsilon, Y (9.4 GeV): Same dist. , normalized by data from HERA-B, I. Abt et al., PLB (2006), hep-ex/0603015.
- Calibrated with existing data [e.g. NA50, EPJ '06, nucl-ex/0612012, Herb et al., PRL '77]. and simulations from other groups [e.g. deNiverville, Chen, Pospelov, and Ritz, Phys. Rev. D95, 035006 (2017), arXiv:1609.01770 [hepph].]

(Detail) dE/dx formula

- For moderately small epsilon and heavy enough MCP (>> electron mass), one can use Bethe equation to estimate average energy loss.

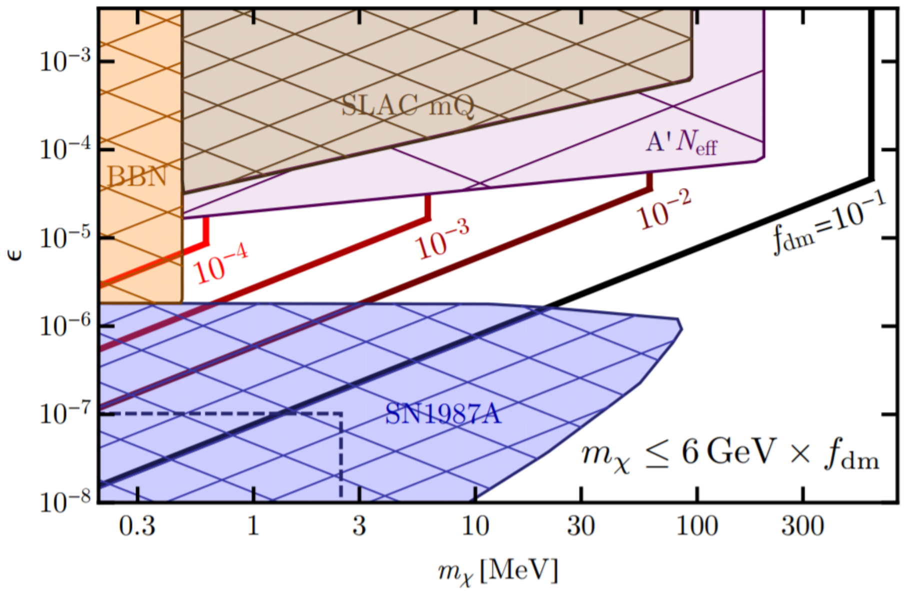
$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] .$$

z	charge number of incident particle	
Z	atomic number of absorber	
A	atomic mass of absorber	g mol^{-1}
K	$4\pi N_A r_e^2 m_e c^2$ (Coefficient for dE/dx)	0.307 075 MeV mol^{-1} cm^2
I	mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	density effect correction to ionization energy loss	

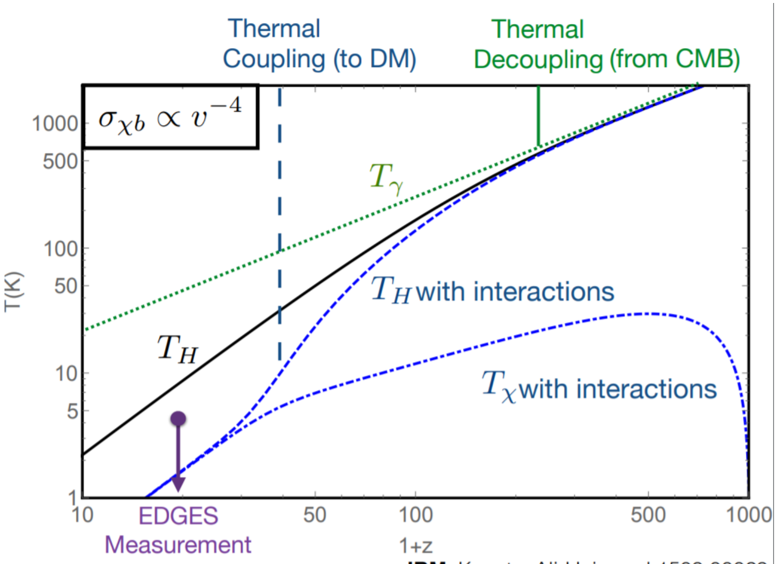
$$W_{\max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2} .$$

- M: charged particle mass
- For **very small epsilon** (related to the finite length effect), one have to consider **most probable energy deposition & consider landau distribution** for the energy transfer, see arXiv:1812.03998

EDGES ANOMALY and MCP Solution



JBM and Loeb 1802.10094



JBM, Kovetz, Ali-Haimoud 1509.00029