Millicharged Dark Sectors from Fixed-Target and Cosmic-Ray Productions

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

[1] The FerMINI Experiment (1812.03998, PRD ‘19)


Email: ytsai@fnal.gov; arXiv: https://arxiv.org/a/tsai_y_1.html
Our Three Ways to Produce/Study MCPs

More reference shown in following slides!

(I) MCPs in fixed-target neutrino experiments, 1812.03998

(II) Fixed-target produced MCP detected by specialized detector (FerMINI), 1812.03998

(II) Cosmic-ray production and detection in large neutrino observatories, 2002.11732

by Chantelaue, Staffi, and Bret

Outline

• Intro

• MCP in Neutrino Experiments

• Specialized experiment: FerMINI

• Cosmic-Ray Production and Neutrino Observatories

• Strongly Interacting Dark Matter

• Why study dark-sector direct production?
Millicharged Particle & Dark Matter

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Finding Minicharge

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

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

- Link to **string compactification** and **quantum gravity** (Shiu, Soler, Ye, PRL ’13)

- 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) abundance**

- Used for the cooling of gas temperature to explain the **EDGES anomaly** [EDGES collab., Nature, (2018); Barkana, Nature, (2018)]. A small fraction of the DM as MCP can potentially explain EDGES observation
MCP Model

• A particle fractionally charged under SM U(1) hypercharge

\[ \mathcal{L}_{\text{MCP}} = i \bar{\chi} (\bar{\phi} - ie' \mathcal{B} + M_{\text{MCP}}) \chi \]

• Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon). **Completely legal!** Naively violating the empirical charge quantization (cool!).

• We are only probing MCP here! **Minimal assumptions. Most robust constraints.**

• This could be from vector portal **Kinetic Mixing** (Holdom, ‘85)
  - a nice origin to the above term
  - help give rise to **dark sectors**
  - easily compatible with **Grand Unification Theory**
Kinetic Mixing and MCP Phase

- Coupled to new dark fermion $\chi$

![Diagram of kinetic mixing and MCP phase](image)

See, Holdom, 1985

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu} + i\tilde{\chi}(\tilde{\phi} + i e' B' + i M_{\text{MCP}})\chi$$

- New fermion $\chi$ charged under new gauge boson $B'$.

- Millicharged particle (MCP) can be a low-energy consequence of massless dark photon (a new U(1) gauge boson) coupled to a new fermion (become MCP in a convenient basis.)
Millicharged Particle: Signature

Yu-Dai Tsai, Fermilab, 2019
Production of MCP

- Production: Meson Decays
- Production: Drell-Yan

Heavy (vector) mesons are important for high-mass mCP’s in high-energy beams

\[
\text{BR}(\pi^0 \rightarrow 2\gamma) = 0.99
\]
\[
\text{BR}(\pi^0 \rightarrow \gamma e^- e^+) = 0.01
\]
\[
\text{BR}(\pi^0 \rightarrow e^- e^+) = 6 \times 10^{-6}
\]
\[
\text{BR}(J/\psi \rightarrow e^- e^+) = 0.06
\]

Modified from 1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)
**MCP Detection**: Ionization or “Hard” Scattering

- **Ionization (eV-level)**: ~ very low-energy scattering:
  - FerMINI: arXiv:1812.03998, Kelly, Tsai

- **“Hard” (MeV-level) electron elastic scattering**:
  - Magill, Plestit, Pospelov, Tsai, 1806.03310 (MCP in neutrino Experiments)
MCP Detection: Electron Scattering & Ionization

- $Q^2$ is the squared 4-momentum transfer.
- Lab frame: $Q^2 = 2m_e (E_e - m_e)$, $E_e - m_e$ is the electron recoil energy.
- Expressed in recoil energy threshold, $E_e^{(\text{min})}$, we have

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

- Sensitivity greatly enhanced by accurately measuring low energy electron recoils for MCP’s & light-mediator scattering.
MCP in Fix-Target Neutrino Experiment

Yu-Dai Tsai, Fermilab, 2020
MCP Produced in Fixed-Target Experiments

Beam Energy: 120 GeV

Modified from Zarko Pavlovic’s figure

Yu-Dai Tsai Fermilab
MCP Production/Flux

120 GeV proton beam on target (graphite)

1 year at NuMI \((6 \times 10^{20} \text{ POT})\)
1040 m, 1 m × 1 m det. area

\[ \frac{N_\chi}{\varepsilon^2 / (6 \times 10^{20} \text{ POT})} \]

\( m_\chi \text{ [GeV]} \)
Scattering Detectors

Other beams:
- BNB
- LBNF (future)

MiniBooNE Detector
arXiv:0806.4201
MiniBooNE collaboration

MicroBooNE Detector
arXiv:1612.05824
MicroBooNE collaboration

DUNE Near Detector

MINERvA Detector
arXiv:1109.2855
MINERvA collaboration

Sensitivity at Neutrino Detectors

- Electron recoil-energy threshold: MeV to 100 MeV
- Can use **timing information** to improve sensitivity
- Double-hit to reduce background (see next page)
Double-Hit Consideration: ArgoNeuT Study

Harnik, Liu, Ornella: multi-scattering, point back to target to reduce the background (ArgoNeuT & DUNE), arXiv:1902.03246 /
ArgoNeuT collaboration: arXiv:1911.07996
FerMINI: A specialized scattering detector

Yu-Dai Tsai, Fermilab, 2020
FerMINI Collaboration (BRN proposal)

- Chris Hill
  OSU

- Andy Haas
  NYU

- 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
Subsection Outline

- Motivations of Millicharged Particle (MCP)
- **The FerMINI Experiment:**
  Proton Fixed-Target Scintillation Experiment to Search for Minicharged Particles
- FerMINI as a probe of **Strongly Interacting Dark Matter**

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A Fermilab Search for MINI-charged Particle based on scintillating detectors
Kelly, Tsai, 1812.03998 (PRD19)

Directly inspired by milliQan concept (Haas, Hill, Izaguirre, Yavin, 1410.6816)

Visually “a detector made of stacks of light sabers,”

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

Yu-Dai Tsai, Fermilab, 2020
Detector Concept

\[(\Delta t)_{\text{offline}} = 15 \text{ ns}\]

1607.04669, Ball, Brooke, Campagnari, De Roeck, Francis, Gastal, Golf, Goldstein, Haas, Hill, Izaguirre, Kaplan, Magill, Marsh, Miller, Prins, Shakeshaft, Stuart, Swiatlowski, Yavin
Photoelectrons (PE) from Scintillation

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

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

\( \langle dE/dx \rangle \) is the “mass stopping power” (PDG 2018)

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

- \( N_{PE} \sim \epsilon^2 \times 10^6 \) for 1 - meter plastic scintillation bar

- \( \epsilon \sim 10^{-3} \) roughly gives one PE
Signature: Triple Coincidence

• Based on Poisson distribution, zero event in each bar correspond to

\[ P_0 = e^{-N_{PE}} \], so the probability of seeing triple incident of one or more photoelectrons is:

\[ P = (1 - e^{-N_{PE}})^3 \]

• \( N_{x,\text{detector}} = N_x \) (going through detector) \( \times P \).
FerMINI @ NuMI-MINOS Hall

Beam Energy: 120 GeV

An illustration of the FerMINI experiments utilizing the NuMI facility.

Yu-Dai Tsai
Fermilab

MINOS hall downstream of NuMI beam
Site 1: NuMI Beam & MINOS ND Hall

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

NuMI: Neutrinos at the Main Injector
MINOS: Main Injector Neutrino Oscillation Search, ND: Near Detector

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

Different epsilon now, $\varepsilon = Q/e$

Now it’s literally fraction of the charge!
Site 2: LBNF Beam & DUNE ND Hall

There are many other new physics opportunities in the near detector hall!
Combine with DUNE PRISM?

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

Jonathan Asaadi – University of Texas Arlington
LBNF: Long-Baseline Neutrino Facility

MCP Production/Flux

120 GeV proton beam on target (graphite)
Yu-Dai Tsai, Fermilab

- Hope to Incorporate it into the near detector proposal.

- + DUNE PRISM? & combine with DUNE to get timing?
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 (may skip)

- Major Background Source!
- dark-current frequency to be $v_B = 500 \, \text{Hz}$ for estimation (1607.04669)
- For each tri-PMT set, the background rate for triple incidence is
  
  $$v_B^3 \Delta t^2 = 2.8 \times 10^{-8} \, \text{Hz}, \text{ for } \Delta t = 15 \, \text{ns}.$$ 

- Consider 400 such PMT sets:
  the total background rate is $400 \times 2.8 \times 10^{-8} \sim 10^{-5} \, \text{Hz}$

- ~300 events in one year of trigger-live time

- Quadruple coincidence can reduce this BG to essentially zero!
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. (contact ytsai@fnal.gov)
One can combine the MCP detector with neutrino detector to improve sensitivity or reduce background.

Filling up the MCP “cavity”
MCP in Neutrino Observatories

by Chantelauze, Staffi, and Bret

by Yu-Dai Tsai, Fermilab

Super-Kamiokande

http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

2002.11732 (our paper) + FerMINI projection

1111.5031 (Super-K Collaboration)
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
FerMINI Probe of Millicharged SIDM

MCP / LDM with ultralight dark photon mediators, all curves except FerMINI are from arXiv:1905.06348

\[ \sigma_e \approx \frac{16\pi\alpha^2 e^2 \mu_{\chi e}^2}{q_{ref}^2}, \quad q_{ref} = \alpha m_e \]

Here we plot the **electron-scattering Millicharged SIDM** see 1905.06348 (Emken, Essig, Kouvaris, Sholapurkar)

- **FerMINI can help close the Millicharged SIDM window!**

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More on MCP/DM & 21-cm Cosmology

Some more reference of Millicharged DM (mDM) and constraints.

See, e.g.,

McDermott, Yu, Zurek, 1011.2907;
Muñoz, Dvorkin, Loeb, 1802.10094, 1804.01092;
Berlin, Hooper, Krnjaic, McDermott, 1803.02804;
Kovetz, Poulin, Gluscevic, Boddy, Barkana, Kamionkowski, 1807.11482;
Liu, Outmezguine, Redigolo, Volansky, 1908.06986:

“Reviving Millicharged Dark Matter for 21-cm Cosmology,”

Introduces a long-range force between a subdominant mDM and the dominant cold dark matter (CDM) components. Leads to efficient cooling of baryons in the early universe. Extend the range of viable mDM masses for EDGES explanation to ~ 100 GeV.
Reviving MDM for EDGES

Yu-Dai Tsai, Fermilab (Preliminary)

BARYONS
- atoms: $x_{H,He}$
- ions: $x_e$

Millicharged-DM (mDM)
- $f_m, m_m$

Cold-DM (CDM)
- $(1 - f_m), m_C$

Yu-Dai Tsai, Fermilab

Liu, Outmezguine, Redigolo, Volansky, ’19
Not all bounds are created with equal assumptions

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

**Assumptions**

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

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

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

- **Cosmology**: assume cosmological history, species, etc

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Example: Constraints on Millicharged Dark Matter

Also Consider **ambient dark matter**

*Produce dark particles* in collisions

Same mass and interaction strength.

**Different assumptions**

Details of these figures will be explained later
Looking Ahead

- Exploring **Energy Frontier of the Intensity Frontier** (complementary to and before HL-LHC upgrade)

- **Cosmology-driven models**: relaxions, baryogenesis models

- **other motivated models**: quirks, KOTO-related models

- Near-future (and almost free) opportunity
  (NuMI Facility, SBN program, DUNE Near Detector, etc.)

- Other new **low-cost alternatives/proposals (~ $1M)** to probe exotic stable particles *(FerMINI)* and new forces *(LongQuest)*

- Dark sectors in neutrino observatories
Thank You!

Yu-Dai Tsai, Fermilab, ‘20
Backup Slides
Additional Motivations

• Won’t get into details, but it’s interesting to find “pure” MCP, that is WITHOUT a massless or ultralight dark photon (finding MCP in the regime where ultralight/massless $A'$ is strongly constrained by cosmology!)

• More violent violation of the charge quantization (if not generating millicharge through kinetic mixing)

• Test of GUT models, and String Compactifications

see Shiu, Soler, Ye, arXiv:1302.5471, PRL ’13 for more detail.
Not all bounds are created with equal assumptions

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

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

**Astrophysical productions (not from ambient DM):** energy loss/cooling, etc:
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[2] The FerMINI Experiment (1812.03998, PRD ‘19)


Proton Fixed-Target: Decay vs Scattering Experiments

[5] **Light Scalar & Dark Photon** at BoreXino & LSND, 1706.00424, *PLB '18*  
(proton-charge radius anomaly) w/ Pospelov  

(LSND/MiniBooNE anomalies) w/ Magill, Plestid, Pospelov  

[7] **Dark Neutrino** at Scattering Exps: CHARM-II & MINERvA, 1812.08768, *PRL '19*  
(MiniBooNE Anomaly) w/ Argüelles, Hostert  

Email: ytsai@fnal.gov; arXiv: https://arxiv.org/a/tsai_y_1.html
Exploration of Dark Matter & Mediator

**Dark Sector Candidates**

- Ultralight DM, Axions, and ALPs
- Thermal Dark Matter
- SIMPs/ELDERs

**Search Techniques**

- Bramante, Linden, Tsai, *PRD* ‘17, [1706.05381](https://arxiv.org/abs/1706.05381)

**US Cosmic Visions, 1707.04591**

- Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators
- Microlensing

- Resonant SIDM w/ Hitoshi+; Kinetic Decoupling DM w/. Tracy+ (in prep.)
- **Astrophysical/cosmological observations**: important to reveal the actual story of dark matter (DM).
- **Why fixed-target experiments? And why MeV – GeV?**
Advantages of Proton Fixed-Target Exp.
Proton FT (& Neutrino) Experiments

• **High statistics**, e.g. LSND has $10^{23}$ **Protons on Target** (POT)

• Neutrinos are **dark-sector particles**.

• Relatively high-energy proton beams on targets:
  
  $O(100 – 400)$ **GeV** (I will compare Fermilab/CERN facilities)

• Shielded/underground: lower background

• Many of them existing and many to come: strength in numbers

• **Produce these particles with less assumptions**
Why study MeV – GeV+ dark sectors?
Revealing the dark secrets of the Universe

Yu-Dai Tsai, Fermilab, 2020
Signals of discoveries grow from anomalies
Maybe nature is telling us something so we don’t have to search in the dark? (or probably systematics?)

Yu-Dai Tsai, Fermilab, 2020
Some anomalies involving **MeV - GeV+** Explanations

- Muon g-2 anomaly
- LSND & MiniBooNE anomaly
- EDGES result
- KOTO anomaly
- Proton charge radius anomaly
- Beryllium anomaly

Below ~ MeV there are also **strong astrophysical/cosmological bounds** that are hard to avoid even with very relaxed assumptions
v Hopes for New Physics

• **Proton charge radius anomaly:**
  - Light Scalar & Dark Photon at Borexino & LSND, Pospelov, *Tsai*, PLB ‘18, 1706.00424

• **LSND/MiniBooNE Anomalies**
  - Dipole Portal Heavy Neutral Lepton,
    Magill, Plestid, Pospelov, *Tsai*, PRD ’18, 1803.03262
  - Dark Neutrino at Scattering Experiments: CHARM-II & MINERvA
    Argüelles, Hostert, *Tsai*, PRL ‘20, 1812.08768
Fixed-Target for New Physics

• **EDGES 21-cm absorption spectrum anomaly**
  - FerMINI Experiment, Kelly & **Tsai**, PRD ’19, [1812.03998](https://arxiv.org/abs/1812.03998)

• **Muon g-2 Anomaly**

  Dark Photon, Inelastic Dark Matter, and Muon g-2 Windows in
  CHARM, NuCal, NA62, SeaQuest, and LongQuest,

  **Tsai**, de Niverville, Liu, [1908.07525](https://arxiv.org/abs/1908.07525)

Happy to talk about these offline
The proton beam fixed-target facilities

that provide natural habitats for signals of weakly interacting / long-lived / dark-sector particles

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Facilities

- **LSND**: Total of $10^{23}$ POT (beam: 800 MeV), King of POT

- **Fermilab** (undergoing a Proton Improvement Plan, PIP):
  - Booster Beam (BNB): $\sim 10^{20}$ POT/yr (8 GeV), now
  - NuMI beam: $1 - 4 \times 10^{20}$ POT/yr (120 GeV), now
  - LBNF beam (future): $\sim 10^{21}$ POT/yr (120 GeV), future

- **CERN SPS beam**:
  - NA62: up to $3 \times 10^{18}$ POT/yr (400 GeV), now
  - SHiP: up to $10^{19}$ POT/yr (400 GeV), future

- **CERN LHC**: **FASER (forward)**: $10^{16}$ POT/yr, future much higher energy, very small detector
Decay Experiments/Detectors

Including **CHARM decay detector (DD), NuCAL, NA62, SeaQuest** (see, arXiv:1908.07525)

- Experiments optimized to study **decaying particles**, or simply two charged particle final states, e.g. from Drell-Yan (SeaQuest)

General features:

1. Large decay volume
2. Low density (likely vacuumed), low background
3. Simple design thus relatively low cost (tracking planes + ECal)
4. Often, there is external magnetic field
   (track separations/momentum reconstruction/filter-out soft SM radiation)
5. Usually studying **long-lived particles (mediators, e.g., dark photons)**