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

Yu-Dai Tsai, Fermilab Theorist (WH674W) / U. Chicago

Magill, Plestid, Pospelov, Tsai (YT) (1806.03310, PRL '19)

Kelly, YT (1812.03998, under PRD review)

DOE Proposal: Dark Matter New Initiatives LAB 19-2112, 0000248676

Email: ytsai@fnal.gov, arXiv: https://arxiv.org/a/tsai_y_1.html
Long-Lived Particles in the Energy Frontier of the Intensity Frontier

- Light Scalar & Dark Photon at Borexino & LSND, 1706.00424 (proton-charge radius anomaly)
- Dipole Portal Heavy Neutral Lepton, 1803.03262 (LSND/MiniBooNE anomalies)
- Dark Neutrino at Scattering Exp: CHARM-II & MINERvA! 1812.08768, (MiniBooNE Anomaly)
- General purpose experiments: coming out soon!

Yu-Dai Tsai, Fermilab/U.Chicago
Current FerMINI Collaboration

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OSU

Andy Haas
NYU

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Fermilab

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Joe Bramante
Queen’s U

Bithika Jain
ICTP-SAIFR
Outline

• Introduction to Millicharged Particles (MCP)
• Sensitivity
  I) MCP in Neutrino (Proton Fixed-Target) Facilities
  II) FerMINI Experiment (adding a low-cost detector in the ND complex, to provide the leading MCP sensitivity)
• FerMINI Demonstrator at NuMI Beam
  Recruiting experimentalists (especially at Fermilab)!
  Join the team!

Thanks for the invitation!
Intro to Millicharged Particles

Electric charge quantization?
Other implications (dark sector, etc)
Connection to light dark matter (LDM)

Yu-Dai Tsai, Fermilab, ytsai@fnal.gov
Finding Minicharge

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

• U(1) allows arbitrarily small (any real number) charges. Why don’t we see them in electric charges? Motivates *Dirac quantization, Grand Unified Theory (GUT), etc*, to explain such quantization

• A test to see 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 ∼*Sub-GeV DM as MCP* to explain the EDGES anomalous 21-cm absorption spectrum
Millicharged Particle: Models

Yu-Dai Tsai, Fermilab
mCP Model

• Small charged particles under U(1) hypercharge

\[ \mathcal{L}_{m\text{CP}} = i \bar{\psi} (\phi - i e' e B + M_{m\text{CP}}) \psi \]

• 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

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{\kappa}{2} B_{\mu\nu} B^{\mu\nu} + i \bar{\psi}(\phi + ie'B' + i M_{\text{mCP}})\psi \]

See, Holdom, 1985

• New Fermion \( \psi \) 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 \( \psi \)):
  \[ Q = \kappa e' \cos \theta_W \quad \epsilon \equiv \kappa e' \cos \theta_W / e. \]
The Rise of Dark Sector

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Strong Interacting Dark Matter

- MCP as DM candidate
- Strongly interacting dark matter may generally skip the direct detection of dark matter
IMPORTANT NOTE

• Our search is simply a search for particles (fermion $\chi$) with 
  \{mass, electric charge\} = \{m_\chi, e_\epsilon\}

• Minimal theoretical inputs/parameters

• 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

• There are additional motivations to search for “pure” MCP!
Millicharged Particle: Signature

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**MCP (or general light DM): production & detection**

- **production:** meson decays
- **detection:** scattering electron

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

### Decays

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 \rightarrow 2\gamma$</td>
<td>0.99</td>
</tr>
<tr>
<td>$\pi^0 \rightarrow \gamma e^- e^+$</td>
<td>0.01</td>
</tr>
<tr>
<td>$\pi^0 \rightarrow e^- e^+$</td>
<td>$6 \times 10^{-6}$</td>
</tr>
<tr>
<td>$J/\psi \rightarrow e^- e^+$</td>
<td>0.06</td>
</tr>
</tbody>
</table>
We use PYTHIA to generate neutral meson Dalitz or direct decays from the pp collisions and rescale by considering, $\text{BR}(M \to \chi \bar{\chi}) \approx \varepsilon^2 \times \text{BR}(M \to X e^+e^-) \times f\left(\frac{m_\chi}{M}\right)$.

- M: mass of the parent meson, X: additional particles, $f(m_\chi/M)$: phase space factor

We also include Drell-Yan production for the high mass MCPs (see arXiv:1812.03998)
MCP Detection: electron scattering

- **Light mediator:** the total cross section is dominated by the small $Q^2$ contribution, we have $\sigma_{e\chi} = \frac{4\pi \alpha^2 \varepsilon^2}{Q_{\text{min}}^2}$.

- 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

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

- Sensitivity greatly enhanced by accurately **measuring low energy electron recoils for MCP’s & light dark matter - electron scattering**, 

- See e.g., Magill, Plestid, Pospelov, **YT, 1806.03310** & deNiverville, Frugiuele, **1807.06501** (for sub-GeV DM)
Sensitivity and Contributions

- Magill, Plestid, Pospelov, Tsai (1806.03310, PRL ’19)
- $N_{\text{eff}}$: Bœhm, Dolan, and McCabe (2013)
FerMINI Proposal:

Putting dedicated Minicharged Particle Detector in the Fermilab Beamlines: NuMI or LBNF

Extend the MCP sensitivity reach far beyond neutrino detectors

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Dedicated MCP Detector: General Idea

- 1 m × 1 m (transverse plane) × 3 m (longitudinal) plastic scintillator array, with many 1-meter scintillator bars (400 in total)
- Require triple incidence in small time window (15 nanoseconds)
- With Q down to $10^{-3}$ e, each MCP produce averagely ~ 1 photo-electron observed per ~ 1 meter long scintillator
• Total: 1 m × 1 m (transverse plane) × 3 m (longitudinal) plastic scintillator array.
• Array oriented such that the long axis points at the CMS Interaction Point.
• The array is subdivided into 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 will be required in order to reduce the dark-current noise (the dominant background).
FerMINI:
A Fermilab Search for Minicharged Particle

Yu-Dai Tsai, Fermilab, ytsai@fnal.gov
Site 1: NuMI Beam & MINOS ND Hall

Beam Energy: 120 GeV, $10^{20}$ POT/yr

NuMI: Neutrinos at the Main Injector (See Todd’s talk)
MINOS: Main Injector Neutrino Oscillation Search, ND: Near Detector
(MINERvA: Main Injector Experiment for v-A is also here)
Site2: LBNF Beam & DUNE ND Hall

Beam Energy: 120 GeV


Jonathan Asaadi – University of Texas Arlington
We use PYTHIA to generate neutral meson Dalitz or direct decays from the pp collisions and rescale by considering,

\[ BR(M \rightarrow \chi \bar{\chi}) \approx e^2 \times BR(M \rightarrow X e^+ e^-) \times f \left( \frac{m_X}{M} \right), \]

where:
- \( M \): mass of the parent meson,
- \( X \): additional particles,
- \( f(m_X/M) \): phase space factor.

We also include Drell-Yan production for the high mass MCPs.
FerMINI Demonstrator @ MINOS Hall

Planning to build a 15% size demonstrator
Demonstrator can be moved into DUNE ND complex
Signature: Triple Incidence

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

\[ N_{PE} \approx \rho_{scint} \times \left\langle -\frac{dE}{dx} \right\rangle \times l_{scint} \times LY \times e_{det}. \]

  - LY: light yield
  - \( e_{det} \): detection efficiency

- 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 photoelectron is:

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

- \( N_{x,detector} = N_x \times P. \)
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
  ~ 300 events in one year of trigger-live time
Dark Current Background @ PMT

- **Major Background Source!**
  - dark-current frequency to be $v_B = 500 \text{ Hz}$ for estimation. (from 1607.04669, milliQan L.O.T.)
  - For each tri-PMT set (each connect to the three connected scintillation bar), the background rate for triple incidence is
    
    $$v_B^3 \Delta t^2 = 2.8 \times 10^{-8} \text{ Hz}, \text{ for } \Delta t = 15 \text{ ns}.$$  
  - There are 400 such set in the nominal design.
  - The total background rate is $400 \times 2.8 \times 10^{-8} \sim 10^{-5} \text{ Hz}$
  - $\sim 300 \text{ events}$ in one year of trigger-live time
NuMI/MINOS Hall is a viable alternative site
One can combine the MCP detector with neutrino detector to improve sensitivity or reduce background.
Assuming MCP is dark matter...

- One can fill up the gap of strongly interacting dark matter with FerMINI
Advantages:
Timeliness, Low-cost, Movable, Tested, Easy to Implement, ...

1. LHC entering long shutdown
2. Can develop at NuMI/MINOS and then move to DUNE
3. NuMI operating, shutting down in 5 years (DO IT NOW!)
4. Sensitivity better than milliQan for MCP below 5 GeV and don’t have to wait for HL-LHC
5. Bring the focus of new physics discovery (MCP) back to Fermilab! USA!

JOIN THE PROPOSAL! ytsai@fnal.gov
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Alternative Detector Setup & New Ideas

- Combine with *neutrino detector*: behind, in front, or sandwich them: **mixed signature**
- Combine with *DUNE PRISM*: moving up and down
- *FerMINI+DUNE 3DST*
- **Better scintillator material**
- **Can search for millicharged quarks, fermions with small electric dipole**
- New ideas from you are welcomed!

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Other New Physics Probes in Neutrino / Fixed-Target Facilities

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Anomaly & New Physics in Fixed Target Experiments

1) Light Scalar & Dark Photon at Borexino & LSND
   Pospelov & YT, PLB ‘18, 1706.00424 (proton charge radius anomaly)

2) Dipole Portal Heavy Neutral Lepton
   Magill, Plestid, Pospelov & YT, PRD ‘18, 1803.03262
   (Short-baseline LSND/MiniBoonE anomalies) See Ian’s talk for more!

3) Millicharged Particles in Neutrino Experiments
   Magill, Plestid, Pospelov & YT, PRL ‘19, 1806.03310
   (EDGES 21-cm measurement anomaly)

Yu-Dai Tsai, Fermilab
MeV – GeV + anomalies: Not just search in the dark

4) Millicharged Particles in FerMINI Experiments
   Kelly & YT, 1812.03998
   (EDGES Anomaly)

5) Dark Neutrino at Scattering Experiments: CHARM-II & MINERvA
   Argüelles, Hostert, YT, 1812.08768
   (MiniBooNE Anomaly) Also see Pedro/Ian’s talk for more!

Yu-Dai Tsai, Fermilab

Two new papers OUT!
Happy to chat
Thank You
Thanks for the invitation again!

Yu-Dai Tsai, Fermilab
Looking Ahead

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

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

• Other new **low-cost alternatives/proposals (~ $1M)** to probe hidden particles and new forces (**FerMINI is just a beginning!**)

• **New Physics at DUNE Near Detector** is very exciting
Connection to Light Dark Matter

- **LDM**: dark matter particles couple to a massive $A'$ mediator slides)

- **Millicharged particles**: dark matter particles couple to just photons with small charge (or massless $A'$)

- **Similar production channels**: show later

- **Both have electron scattering signature**: MCP has low electron-recoil enhancement
MCP @ Neutrino Detectors

Yu-Dai Tsai, Fermilab
MCP Signals in Neutrino Detector

- **signal events** $n_{\text{event}}$

  $$n_{\text{event}} \sim \sum_{\text{Energies}} N_{\chi}(E_i) \times \frac{N_e}{\text{Area}} \times \sigma_{e\chi}(E_i; m_{\chi}) \times \mathcal{E}.$$  
  
- $N_{\chi}(E_i)$: 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, $n_{\text{event}} \propto \varepsilon^4 \varepsilon^2$ from $N_x$ and $\varepsilon^2$ from $\sigma_{ex}$.

- Throughout this paper, we choose a credibility interval of $1 - \alpha = 95\%$ (~2 sigma).

- Roughly, $\varepsilon_{\text{sensitivity}} \propto E_{e,R,\text{min}}^{1/4} Bg^{1/8}$.
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 $2.4 \times 10^{21} \text{POT}$ for which we take the single electron background to be $2.0 \times 10^{3}$ events and the measured rate to be $2.4 \times 10^{3}$

- **MiniBooNE* (DM run)**: arXiv:1807.06137 (see Bishai’s talk). Electron recoil analysis
  
  $\cos \theta > 0$ is imposed (*except for at MiniBooNE's dark matter run where a cut of $\cos \theta > 0.99$ effectively reduces backgrounds to zero [Dharmapalan, MiniBooNE, (2012)])

- We did not include their timing cuts in our calculations, since they were optimized by the MiniBooNE collaboration
Background for Future Measurements

- Single-electron background for ongoing/future experiments for MicroBooNE, SBND, DUNE, and SHiP?
- Two classes of backgrounds:
  1) From neutrino fluxes (calculable),
     
     \[ \text{i.e. } v_e \rightarrow v_e \text{ and } v_n \rightarrow e^+ p \], greatly reduced by maximum electron recoil energy cuts \( E_e(\text{max}) \), because no low \( Q^2 \) enhancement (through W/Z, not \( \gamma \))
  
  2) Other sources such as beam related: dirt related events, mis-id particles external: cosmics, multiply a factor of the neutrino-caused background to account for these background
Multi-Hit Signature to Reduce Background

- Directly from Harnik, Liu, Ornella, arXiv: 1902.03246
- MeV-Scale Physics in Lar-TPC: ArgoNeuT, 1810.06502 (Ivan Lepetic +)
More Conservative Cuts on Threshold

<table>
<thead>
<tr>
<th>Exp. (Beam Energy, POT)</th>
<th>$N \times 10^{20}$</th>
<th>$A_{\text{geo}}(m_{\chi}) \times 10^{-3}$</th>
<th>Cuts [MeV]</th>
<th>$E_{e}^\text{min}$</th>
<th>$E_{e}^\text{max}$</th>
<th>Bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$BooNE (8.9 GeV, 1.3 $\times 10^{21}$)</td>
<td>9.2</td>
<td>0.31</td>
<td>0.09</td>
<td>0.05</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>SBND (8.9 GeV, 6.6 $\times 10^{20}$)</td>
<td>4.6</td>
<td>0.15</td>
<td>4.6</td>
<td>2.6</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>DUNE (80 GeV, 3.0 $\times 10^{22}$)</td>
<td>830</td>
<td>16</td>
<td>3.3</td>
<td>5.1</td>
<td>30</td>
<td>70</td>
</tr>
</tbody>
</table>
### Summary Table

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<th>$E_{e,\text{max}}$</th>
<th>Bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND (0.8 GeV, $1.7 \times 10^{23}$)</td>
<td>130</td>
<td>20</td>
<td>18</td>
<td>52</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>mBooNE (8.9 GeV, $2.4 \times 10^{21}$)</td>
<td>17</td>
<td>1.2</td>
<td>130</td>
<td>530</td>
<td>2k</td>
<td></td>
</tr>
<tr>
<td>mBooNE* (8.9 GeV, $1.9 \times 10^{20}$)</td>
<td>1.3</td>
<td>1.2</td>
<td>75</td>
<td>850</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$\mu$BooNE (8.9 GeV, $1.3 \times 10^{21}$)</td>
<td>9.2</td>
<td>0.09</td>
<td>2</td>
<td>40</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>SBND (8.9 GeV, $6.6 \times 10^{20}$)</td>
<td>4.6</td>
<td>4.6</td>
<td>2</td>
<td>40</td>
<td>230</td>
<td></td>
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<td>830</td>
<td>3.3</td>
<td>2</td>
<td>40</td>
<td>19k</td>
<td></td>
</tr>
<tr>
<td>SHiP (400 GeV, $2.0 \times 10^{20}$)</td>
<td>4.7</td>
<td>130</td>
<td>100</td>
<td>300</td>
<td>140</td>
<td></td>
</tr>
</tbody>
</table>

- $\varepsilon \propto E_{e,R,\text{min}}^{1/4} B g^{1/8}$
- At LArTPC, the wire/pixel spacing is assumed to be around 3 mm, the ionization stopping power is approximately 2.5 MeV/cm: electrons with total energy larger than at least 2 MeV produce tracks long enough to be reconstructed across two wires/pixels. DUNE LArTPC ND, Using CDR config. Efficiency of 0.2 for Cherenkov detectors, 0.5 for nuclear emulsion detectors, and 0.8 for liquid argon time projection chambers.
Neutrino & Proton Fixed-Target (FT) Experiments: Natural habitats for signals of weakly interacting / long-lived / hidden particles
But why? Why MeV - GeV+?

Yu-Dai Tsai, Fermilab, 2019
Dark Matter/Hidden Particles Exploration

US Cosmic Visions 2017

• Proton fix-target/neutrino experiments are important for MeV ~ 10 GeV!
Hidden Particles in Neutrino Experiments

• Neutrinos are weakly interacting particles. Just like **Milliccharged particles**

• High statistics, e.g. DUNE plans $\sim 10^{22}$ Protons on Target (POT)

• Shielded/underground: low background (e.g. solar $\nu$ programs)

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

• Produce hidden particles (from the beam!) without **DM-abundance or cosmological history assumptions**: more “direct” than astrophysics/cosmological probes.

• Relatively high energy (LBNF/NuMI: 120 GeV; SPS: 400 GeV)
Not all bounds are created with equal assumptions
Beam-based bounds are almost *inevitable*

---

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

**Assumptions**

**Technical**

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

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

**Different**

Dark matter direct/indirect detection: abundance, velocity distribution, etc *(reveal true story of DM)*

Cosmology: assume cosmological history, species, etc

Yu-Dai Tsai, Fermilab, 2019
Signals of discoveries grow from anomalies
Maybe nature is telling us something so we don’t have to search in the dark? (systematics?)

Yu-Dai Tsai, Fermilab, 2019
Some anomalies involving MeV-GeV+ Explanations

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

Below ~ MeV there are also strong astrophysical/cosmological bounds
Dark Matter/Hidden Particles Exploration

US Cosmic Visions 2017

- Proton fix-target/neutrino experiments are **important for** MeV ~ 10 GeV!
- Many anomalies & anomaly explanations in this range!
Anomaly & New Physics in Neutrino FT Experiments

1) Light Scalar & Dark Photon at Borexino & LSND
   Pospelov & YT, PLB ‘18, 1706.00424 (proton charge radius anomaly)

2) Dipole Portal Heavy Neutral Lepton
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