Dark Sectors in FerMINI & Neutrino Experiments: Millicharged Particles

Yu-Dai Tsai, Fermilab/U.Chicago

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

with Kelly (1812.03998, submitted to PRL)

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
Outline

• Motivations
• Dark Sectors @ Fixed-Target & Neutrino Experiments
• Millicharged Particle (mCP)
• Bounds & Projections @ Neutrino Detectors
• The FerMINI Experiment
• Discussion

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Neutrino & Proton Fixed-Target (FT) Experiments:
Some natural habitats for signals of weakly interacting / long-lived / hidden particles:

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Exploration of the Dark Sectors

Dark Sector Candidates, Anomalies, and Search Techniques

Ultralight DM, Axions, and ALPs

Thermal Dark Matter

SIMPs/ELDERs

Black Holes

WIMPs

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

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:
Rely on modeling/observations of (extreme/complicated/rare) astro systems

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

Cosmology: assume cosmological history, species, etc

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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? (systematics?)

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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
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)

Inspired by …
  deNiverville, Pospelov, Ritz, ‘11,
  Batell, deNiverville, McKeen, Pospelov, Ritz, ‘14
  Kahn, Krnjaic, Thaler, Toups, ‘14 …
New Physics in Proton FT Experiments

- **Millicarged Particles** in FerMINI Experiments
  Kelly & YT, [1812.03998](https://arxiv.org/abs/1812.03998)
  (EDGES Anomaly)

- **Dark Neutrino** at Scattering Experiments: CHARM-II & **MINERvA**!
  Argüelles, Hostert, YT, [1812.08768](https://arxiv.org/abs/1812.08768), submitted to *PRL*
  (MiniBooNE Anomaly)

Yu-Dai Tsai, Fermilab

Two Recent Papers!
Happy to talk about these during the coffee break.
Millicharged Particles

Is electric charge quantized?

Other Implications

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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, also see Julian’s)
Millicharged Particle: Models

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mCP Model

• Small charged particles under $U(1)$ hypercharge

\[ \mathcal{L}_{m\text{CP}} = i\bar{\psi} (\not\!\!\!\!\phi - i\epsilon' e\not\!\!\!B + M_{m\text{CP}})\psi \]

• 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

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

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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Important Notes!

• Our search is simply a search for particles (fermion $\chi$) with

\[
\{\text{mass, electric charge}\} = \{m_\chi, e e\}
\]

• **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 / light dark photon (finding MCP in the regime light/massless A’ is strongly constraint!)

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

• Testing some GUT models, and String Compactifications (!!)

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

Some Reference of MCP DM 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, arXiv:1807.11482,
Harnik, Liu, Ornella, 1902.03246, Dvorkin, Lin, Schutz, 1902.08623
Millicharged Particle: Signature

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

- **Production:**
  - Meson decays

- **Detection:**
  - Scattering electron

- **BR(π^0 → 2γ) = 0.99**
- **BR(π^0 → γe^-e^+) = 0.01**
- **BR(π^0 → e^-e^+) = 6 \times 10^{-6}**
- **BR(J/ψ → e^-e^+) = 0.06**

- **Heavy mesons are important for higher mass mCP’s in high enough beam energy**
- **Important and often neglected!**
We use PYTHIA to generate neutral meson Dalitz or direct decays from the pp collisions and rescale by considering,

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

- 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 $\sigma_{e\chi} = 4\pi \alpha^2 \varepsilon^2 / Q_{\text{min}}^2$.

• 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**,

MCP @ Neutrino Detectors

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MCP Signals

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

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

- $N_\chi(E_i)$: 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, $s_{\text{event}} \propto \varepsilon^4 \cdot \varepsilon^2$ from $N_\chi$ and $\varepsilon^2$ from $\sigma_{ex}$.

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

- Roughly, $\varepsilon_{\text{sensitivity}} \propto E_{e, R, \text{min}}^{1/4} B g^{1/8}$.
Sensitivity and Contributions

- $N_{\text{eff}}$: Bœhm, Dolan, and McCabe (2013)
Summary Table

<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>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^0 )</td>
<td>( \eta )</td>
<td>1 MeV</td>
<td>100 MeV</td>
</tr>
<tr>
<td>LSND (0.8 GeV, 1.7 ( \times 10^{23} ))</td>
<td>130</td>
<td>—</td>
<td>20</td>
</tr>
<tr>
<td>mBooNE (8.9 GeV, 2.4 ( \times 10^{21} ))</td>
<td>17</td>
<td>0.56</td>
<td>1.2</td>
</tr>
<tr>
<td>mBooNE* (8.9 GeV, 1.9 ( \times 10^{20} ))</td>
<td>1.3</td>
<td>0.04</td>
<td>1.2</td>
</tr>
<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>
</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>
</tr>
<tr>
<td>DUNE (80 GeV, 3.0 ( \times 10^{22} ))</td>
<td>830</td>
<td>16</td>
<td>3.3</td>
</tr>
<tr>
<td>SHiP (400 GeV, 2.0 ( \times 10^{20} ))</td>
<td>4.7</td>
<td>0.11</td>
<td>130</td>
</tr>
</tbody>
</table>

- \( \varepsilon \propto E_{e,R,\text{min}}^{1/4} B g^{1/8} \)
- \( \cos \theta > 0 \) is imposed (*except for at MiniBooNE’s DM run where a cut of \( \cos \theta > 0.99 \) 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 $2.4 \times 10^{21} \text{ POT}$ 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 (came out after our v1). 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?

• Background discussions:

  1) From neutrino fluxes (calculable), [i.e. $\nu_e \rightarrow \nu_e$ and $\nu_n \rightarrow \text{ep}$], greatly reduced by maximum electron recoil energy cuts $E_e(\text{max})$

  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, [arXiv:1902.03246]!
More Conservative Cuts on Threshold

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<th>$N \times 10^{20}$</th>
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<td>5.1</td>
</tr>
</tbody>
</table>
Summary

• Technique can be easily applied to more generic light dark matter and other weakling interacting particles
  - Production from heavy neutral mesons are important (very often neglected in literature)
  - Signature favor low electron-recoil energy threshold
• For more realistic analysis: include realistic background, $E_{e, \text{r,min cut}}$, etc

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

FerMINI as an example:
more to come!

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FerMINI:
Putting dedicated Minicharge Particle Detector (~1M)
@ Fermilab Beamlines: NuMI or LBNF or @ CERN: SPS
Kelly, YT, 1812.03998

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

Yu-Dai Tsai, Fermilab, 2019
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
MilliQan: General Idea

• 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


Andrew Haas, Fermilab (2017)
• 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 (P5)**.

• 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 required to reduce the **dark-current noise (the dominant background)**.
FerMINI:
A Fermilab Search for MINI-charged Particle
Kelly, YT, 1812.03998

Yu-Dai Tsai, Fermilab, 2019
Site 1: NuMI Beam & MINOS ND Hall

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

FerMINI @ NuMI-MINOS Hall

Beam Energy: 120 GeV
Site 2: LBNF Beam & DUNE ND Hall

Beam Energy: 120 GeV

There are many other new physics opportunities in the near detector hall!
Signature: Triple Coincidence

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

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

- \( \langle dE/dx \rangle \) is the ”mass stopping power” (PDG 2018)
- \( \rho_{\text{scint}} \): density
- \( l_{\text{scint}} \): length of scintillation bar
- \( LY \): light yield
- \( e_{\text{det}} \): detection efficiency

\[ N_{PE} \sim \epsilon^2 \times 10^6, \quad \epsilon \sim 10^{-3} \] roughly gives one PE in one meter scintillation bar

• 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:

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

• \( N_{x,\text{detector}} = N_x \times P. \)
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 Source!**

  - dark-current frequency to be $v_B = 500$ 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 $v_B^3 \Delta t^2 = 2.8 \times 10^{-8}$ Hz, for $\Delta t = 15$ ns.

  - There are 400 such set in the nominal design.

  - The total background rate is $400 \times 2.8 \times 10^{-8} \sim 10^{-5}$ Hz

• ~**300 events** in one year of trigger-live time
Yu-Dai Tsai, Fermilab

- Got support from milliQan members
- Recruiting young experimentalists to take charge of the Fermilab LDRD proposal/experimental Implementation
FerMINI @ DUNE

- Scheduled meeting with DUNE near detector conveners
- Try to incorporate it into the near detector proposal
- Experimentalists like it. FerMINI is probably happening

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Compilation

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NuMI (MINOS) / LBNF (DUNE)
Now and the future bests in POTs

• Fermilab (FT):
  - NuMI beam: $1 - 4 \times 10^{20}$ POT/yr (beam: 120 GeV)
    [Link](http://www.int.washington.edu/talks/Workshops/int_06_2b/People/Gran_R/gran-NuMI.pdf)
  - LBNF beam: $1 - 2 \times 10^{21}$ POT/yr (120 GeV)
    [Link](https://indico.fnal.gov/event/12571/contribution/4/material/slides/0.pdf)

• CERN SPS (FT): (400 GeV)
  - NA62: up to $3 \times 10^{18}$ POT/yr (see Gaia’s talk)
  - SHiP: up to $10^{19}$ POT/yr (see Gaia’s talk)

• FASER (collider, forward): $10^{16} - 10^{17}$ POT/yr
  (see Iftah’s talk), much higher energy
Advantages: 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**
FerMINI: Alternative Designs & New Ideas

Yu-Dai Tsai, Fermilab, 2019
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:

<table>
<thead>
<tr>
<th>Material</th>
<th>Photons/keV</th>
<th>Density (g/cm³)</th>
<th>* Length needed (cm)</th>
<th>Speed (ns)</th>
<th>Cost for 5x5 cm ($)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic BC408</td>
<td>10</td>
<td>1.03</td>
<td>145</td>
<td>~2</td>
<td>~200</td>
<td>Current choice</td>
</tr>
<tr>
<td>NaI</td>
<td>38</td>
<td>3.67</td>
<td>11</td>
<td>~230</td>
<td>~800</td>
<td>Slow, fragile</td>
</tr>
<tr>
<td>LaBr₃(Ce)</td>
<td>63</td>
<td>5.08</td>
<td>5</td>
<td>~16</td>
<td>~3000</td>
<td>Radioactive</td>
</tr>
<tr>
<td>Liquid Xe</td>
<td>62</td>
<td>2.95</td>
<td>8</td>
<td>~2 / ~34</td>
<td>~1000?</td>
<td>Cryogenic, ultraviolet</td>
</tr>
</tbody>
</table>

- 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](mailto:ytsai@fnal.gov))
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, 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**

• Many new papers to come!
Thank You!
Thanks for the nice conference!

Yu-Dai Tsai, Fermilab, 2019
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),
     [i.e. $\nu_e \rightarrow \nu_e$ and $\nu_n \rightarrow e^+ p$], greatly reduced by maximum electron recoil energy cuts $E_e(\text{max})$
  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
Beam Related Background (can skip)

- Shielding: including absorber and rocks.
- Controlled: muon monitors.
- Can determine the SM charged particle rate on site
- Vetoed similar to the previous veto of cosmic muons.
- Neutrino produced hard-scattering background: $O(10^{-19})$, negligible.
- To be conservative, we assume the beam related background $\approx$ dark current background for our sensitivity determination.
- Based on SENSEI experience, beam produced charge background is weaker than cosmic, but of course energy dependence
- Assumed to be at the same level of detector background
MilliQan: Location!

- Placed in CMS “drainage gallery” above the detector

- “Drainage Gallery” - an interlocked tunnel above CMS Point 5

Beam backgrounds shielded by 14m of rock

30m from interaction point
Small angle from vertical

Andrew Haas, Fermilab (2017)
MCP productions

• For $\eta$ & $\pi^0$, Dalitz decays: $\pi^0/\eta \to \gamma \chi \bar{\chi}$ dominate

• For $J/\psi$ & $\Upsilon$, direct decays: $J/\psi, \Upsilon \to \chi \bar{\chi}$ dominate. Important for high-mass mCP productions!

• The branching ratio for a meson, $M$, to mCPs is given roughly by

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

• $M$: the mass of the parent meson, $X$: any additional particles, $f(m_\chi/M)$: phase space factor as a function of $m_\chi/M$.

• Also consider Drell-Yan production of mCP from $q$ $q$-bar annihilation.
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.
• 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].]
FerMINI: Increasing scintillation photons

- Elongating the scintillator bar does not affect the background from dark current (basically determined by the number of PMTs)

- So we estimate the sensitivity of FerMINI at DUNE for **five times larger scintillation capability**

- And estimate the sensitivity of FerMINI at NuMI for **five times more scintillation capability but five times less scintillator bar-PMT sets** (actually reduce dark current background!)
Detection Limitation: $N_{\text{photon}} \leq 1$

- **Define**: $\varepsilon_{\text{low}}$ as $N_{\text{scintillator photon}} = 1$

- Roughly around or below this, one really have to worry about scintillator performance.

- One can elongate the scintillator or consider alternative materials to help.

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

- **Andy Haas, Fermilab, 2017**

* Length needed to get 3 photons for charge 1/1000 e
For moderately small epsilon and heavy enough MCP (>> electron mass), one can use Bethe equation to estimate average energy loss.

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

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

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

- 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](https://arxiv.org/abs/1812.03998)