Milli-Charged Particles in ArgoNeuT and future LAr TPCs

POND²

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Work with Zhen Liu and Ornella Palamara coming very soon to an arxiv near you.

see also - Yu-Dai’s talk from yesterday and work with K. Kelly.
Multi-Purpose Detectors
Multi-Purpose Detectors
Multi-Purpose Detectors

HPgTPC

3DST

LArTPC

ECAL
Multi-Purpose Detectors

- A broad menu of searches is being developed for LAr near (and far) detectors. Many covered in this workshop.
  - di-lepton resonances.
  - displaced decays
  - mono potons
  - millicharged particles
  - ....
Milli-Charged Particles

- A very simple model:

\[ L = \text{a particle with charge } \varepsilon. \]
Milli-Charged Particles

- Even if you don't like such fractional charges, it's easy to start with integer charges and get milli-charges. Start with 2 sectors:

  - Our $U(1)_{EM}$ + our matter
  - another massless $U(1)'$ + matter'
Milli-Charged Particles

Even if you don’t like such fractional charges, it’s easy to start with integer charges and get milli-charges. Start with 2 sectors:

heavy particles charged under both.

\[ \varepsilon F_{\mu\nu} F'_{\mu\nu} \]

Our \( U(1)_{EM} \) + our matter

another massless \( U(1)' \) + matter'
Milli-Charged Particles

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Our \( U(1)_{EM} \) + our matter

After we diagonalized everything, matter picks up a charge of \( \varepsilon \) under our EM.
Outline

- mCP production
- mCP Interaction
  - mCP propagation through matter
  - mCP Detection
- An mCP search in ArgoNeuT
- Implications for the DUNE ND
Production

- mCP are produced in abundance in proton interactions: meson decay and DY.

\[
\begin{align*}
\text{Target} & \rightarrow P \\
& \rightarrow \pi^0 \rightarrow 2\gamma \\
& \rightarrow \pi^+ \rightarrow e^+ + \nu_e \\
& \rightarrow J/\psi \rightarrow e^+ + e^- \\
& \rightarrow e^- \rightarrow e^- + \nu_e
\end{align*}
\]

- Consider ArgoNeuT: A Small LAr TPC in NuMI.

\[\sim 0.5 \text{ m} \times 0.5 \text{ m} \times 1 \text{ m}, \quad 10^{20} \text{ POT}\]
Production

Milli–charged particle production $10^{20}$ POT 120 GeV

$\pi^0$  $\eta$  $\eta'$  $\rho$  $\omega$  $\phi$  $J/\psi$  DY

$\epsilon = 10^{-2}$

Many many mCPs!!
Production

mCPs produced boosted, w/ energy ~ 5-50 GeV.
Milli-Charge Interactions

- What do milli-charged do in matter?
- Same as charged particles. Ionize, Scintillation...
- But they do it in “slow motion”.

Most “hits” are soft.

\[
\frac{d\sigma}{dE_r} \propto \frac{\varepsilon^2}{E_r^2}
\]

\[
\sigma(E_{th}) \propto \frac{\varepsilon^2}{E_{th}}
\]
Matter Effects

- En route to the detector, mCPs travel through ~500 meters of dirt.
- A random walk of soft scatterings (off nuclei) leads to small angular deflection

\[
\Delta \theta_X \sim \langle \theta_X \rangle \sqrt{N_{col}} = \text{average deflection per collision.} \times \text{sqrt # of collisions.}
\]

\[
\sim 2 \times 10^{-3} \left( \frac{5 \text{ GeV}}{E_X} \right) \left( \frac{\epsilon}{10^{-2}} \right) \left( \frac{L_{dirt}}{500 \text{ meters}} \right)^{1/2}
\]

The mCPs point back to the target.
Detecting mCPs

\[ \frac{d\sigma}{dE_r} \propto \frac{\varepsilon^2}{E_r^2} \]
\[ \sigma(E_{th}) \propto \frac{\varepsilon^2}{E_{th}} \]

Again, most "hits" are soft.

Lower threshold is better.
How low can LAr go?
Demonstration of MeV-Scale Physics in Liquid Argon Time Projection Chambers Using ArgoNeuT

find a detection efficiency of 50% and energy resolution of 24% at 0.5 MeV, and an efficiency of almost 100% and energy resolution of 14% at 0.8 MeV.

Detection of de-excitation γs and neutrons.

see also Nov 30th wine and cheese talk by I. Lepetic and Palamara’s talk on Friday.
mCP Signal in ArgoNeut

\[ \lambda(E_r^{\text{min}}) = \frac{1}{Z n_{\text{det}} \sigma(E_r^{\text{min}})} \approx \left( \frac{10^{-2}}{\epsilon} \right)^2 \left( \frac{E_r^{\text{min}}}{1 \text{ MeV}} \right) \text{ 1 km.} \]

for \( \epsilon=10^{-2} \): 1 in 10\(^3\) mCPs hit once.
1 in 10\(^6\) mCPs hit twice.

Double hits point back to target:

(recall, for \( \epsilon\sim10^{-2} \) we can have billions of mCPs)
mCP search in ArgoNeuT

- For ArgoNeuT's $10^{20}$ POT run, most events were "empty frames" (no neutrino).
  A few $\times 10^6$

- Control sample $\rightarrow$ signal region!

- Of empty frames:
  12% had one MeV hit.
  About 1% had two MeV hits.

... 

A large background.
Orders of magnitude more than $\nu$ BG.
In going from 1 to 2 hits, BG can be reduced by $10^5$ or more!
ArgoNeuT Sensitivity

An ArgoNeuT analysis is underway.
How will this scale for DUNE ND?
Production in DUNE

- Detector is a bit closer.
- Different angular coverage.

![Graph showing milli-charged particle production](image)

Many many mCPs!
BG at DUNE

- Two benchmarks to scale BG's to DUNE:
  1) ArgoNeuT rate x volume factor.
  2) ArgoNeuT rate x volume x POT.  (beam related BG)

30 - 300 hits per frame..... plus a few neutrino events.
(10^9-10^{10} total hits. a very big background.)

- In our projections we show bands that cover the range of these two benchmarks.
BG at DUNE

- Note: the number of pairs of hits scales as $n^2$. That is 500-50000 pairs per frame. Diminishing returns for 2-hits?

- But: The angular distribution may be a handle. Statistical BG uncertainty. $B \rightarrow \checkmark B$.

- But, occupancy may be reduced with timing using light. Say by a factor of 100.

We study the reach for these 3 options ...
Projections for DUNE

The physics reach in the $m_\chi$-$\epsilon$ plane for millicharged particles achievable by the DUNE experiment with our projection. The reach of a single-hit analysis is shown in blue and that of a double-hit analysis, requiring that the two hits line up with the target, is shown in red. Existing limits from other experiments are shown in grey. The bands indicate the different assumption on the scaling of the background at DUNE from ArgoNeuT data, upper lines corresponding to an estimation where the background scaled as the product of the detector volume, the solid angle and total POT, and lower lines corresponding to scaling with detector volume only. The solid band corresponds to the results after considering possible 2-hits background reduction through side band calibration.

The estimated sensitivity above, however, may be qualitatively improved by making use of additional features of bigger neutrino detectors:

- **Timing and light collection:** The DUNE near detector is planned to be segmented into of order 20 modules, each of which will have a separate light collection system. The light collection allows for excellent timing resolution, of order $10^{-3}$. If each of the, say, 3000 hits in a frame can be associated with a hit time at this resolution, a sizable fraction of the signal-like double-hit events can be rejected. In effect, a good resolution on timing can increase the number of frames and thus reduce the Occupancy per frame. This capability depends strongly on the performance of the light collection system and should be explored further.

- **Argon Gas TPC:** In order to mitigate the high occupancy in the near detector a high pressure gaseous argon TPC detector is proposed. Naively, argon gas, with its lower density, will produce less signal event because the mean free path for a mCP is of order $(\eta n)^{-1}$. However, precisely because of the lower density, charged particles travel in gas farther than they do in liquid argon. As a result the effective energy threshold will be much lower, as low as 10 keV. As we showed in Equations (6) or (9), the scattering cross section is inversely proportional to the detection threshold. The total signal event rate in a gas TPC is thus expected to be parametrically similar to that in a liquid detector. The backgrounds in a gas detector may, however, be significantly lower, potentially leading to enhanced sensitivity. Further advantages may be had by combining hits in the LAr and the gas TPC, as well as making use of the planned electromagnetic calorimeter.

- **O$^{-}$axis detectors:** The dominant source of soft hits in near detectors is likely to be beam related. Since the charged pions are collimated in the magnetic horns, the backgrounds may be highly peaked in the forward region. In and is was shown that dark sector signals which are produced by the decay of neutral particles are produced in a much wider beam than the neutrino beam and that and thus the signal to background ratio is higher in o$^{-}$axis detectors. Fortunately, microBooNe and ICARUS, two LAr detectors, are located about 6 o$^{-}$axis, an ideal angle for this purpose. In fact the angular distribution of mCPs is similar to that of secluded dark matter and is shown in . Within the LBNF beam, the proposed DUNEprism detector will also be able to cover o$^{-}$axis angles.

- **Faint tracks - a dedicated millicharge reconstruction:** The standard track reconstruction in LAr TPCs is geared...
The HPgTPC will have lower threshold.

\[ \lambda(E_r^{\text{min}}) = \frac{1}{Z n_{\text{det}} \sigma(E_r^{\text{min}})} \]

lower \quad \text{higher}

Signal rates in HPgTPC are parametrically the same as LArTPC.

But backgrounds may be lower....
Off Axis

- The soft hit background may be beam related and induced by charged pions. May be focused.
- The MCP beam is wide.
- Going off axis may enhance S/B.
- MicroBoone and ICARUS may be ideally located off the NuMI beam.
- DUNE PRISM for LBNF

Applies to a broadest of models (see next talk!)
Dedicated mCP Reconstruction

- A dedicated effort to reconstruct “faint tracks” may allow to lower thresholds.
- Standard analyses start by identifying localized hits above noise floor.
- Looking for an excess above noise along lines may allow to integrate noise down.

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none of these hits above noise locally...

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but combined charge+light may be above noise along line.
Conclusions

- The ArgoNeuT demonstration of sensitivity to MeV depositions enables searches for new physics.
- Can set new limits on mCPs with exiting data using double hits.
- Interesting prospects for the DUNE ND.

PONDD INDEEDD.