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

HPgTPC

3DST

LArTPC

ECAL
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:

\[ \mathcal{L} = \text{a particle with charge } \varepsilon. \]
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

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   heavy particles charged under both. 

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

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

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  heavy particles charged under both.

Our $U(1)^{EM}$ + our matter

$\varepsilon F_{\mu\nu} F'_{\mu\nu}$

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.

- Consider ArgoNeuT: A Small LAr TPC in NuMI.

  \( \sim 0.5 \text{ m} \times 0.5 \text{ m} \times 1 \text{ m}, \ 10^{20} \text{ POT} \)
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 \( \sim 500 \) meters of dirt.
- A random walk of soft scatterings (off nuclei) leads to small angular deflection

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

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

The mCPs point back to the target.
Detecting mCPs

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

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

Detection of de-excitation γs and neutrons.

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.

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

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

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

1 in \(10^6\) mCPs hit twice.

... (recall, for \(\epsilon\sim10^{-2}\) we can have billions of mCPs)

Double hits point back to target:
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.
1 vs 2 hits

- Excellent spatial resolution $\rightarrow$ BG can be reduced by requiring alignment with target.

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-charge particle production](image)

- Milli-charge particle production as a function of mass, with different decay modes and acceptance by DUNE.

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. \( B \rightarrow \sqrt{B} \).

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

We study the reach for these 3 options ...
FIG. 6. 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.
HP Gas Detector

- The HPgTPC will have lower threshold.

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

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.

none of these hits above noise locally...

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.