Detectors for proton beam-dump experiments

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Intensity Frontier: New Light Weakly-Coupled Particles
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Outline

Motivation.
Proton beam –dump examples.
One example of using existing detectors.
A design for a new detector.
Three goals for this meeting.
Why look to existing neutrino Near Detectors (at first).

- Design
  - Aimed for energy and direction reconstruction of protons, neutrons, muons, electrons, and photons.

- Precedent
  - There have been observed significant unexplained electron/photon-like excesses in both neutrino and anti-neutrino mode.

- Investment
  - Significant effort by the Intensity Frontier projects for high POT and event readout (timing ~nsec)

- Geometry
  - makes them sensitive to heavy (> MeV) subluminal particles.
NLWCp from proton beam-dumps

• Each model each usually predicts specific processes producing NLWCp in the target/beam-dumb and specific signatures.

• The most prominent signatures in a detector can be:
  • Elastic scattering on nucleons.
  • ALPs, Light-DM.
  • Particle decay on flight into di-leptons within the detector.
  • Axions, ALPs, other Hidden Sector particles, etc.
  • Single photons, di-muons.
  • Heavy neutrinos.

For references see the Project-X book from FNAL:
Example of using existing Near Detectors

Large number of protons on target ($10^{21}$ POT per year).

Exotic particle flux is very forward collimated and remains constant with distance from the target (for the range of these near detectors).

Fair distance from the target

- Backgrounds from neutrino interactions are low ($\sim 1/R^2$),

Diagram:

- Target
- Proposal at SNS (100-1000m)
- K experiments (KOTO, ORKA) (100m)
- ND280-T2K (280m)
- MINOS, NOvA (990m)
- 2k LAr (proposal at T2K) (2km)

- MiniBooNE/MicroBooNE (540m)
### 1 GeV Program of Project X

<table>
<thead>
<tr>
<th></th>
<th>Stage 1</th>
<th>Stage 2</th>
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</thead>
<tbody>
<tr>
<td>Beam Power</td>
<td>984</td>
<td>980</td>
</tr>
<tr>
<td>Protons per second</td>
<td>$6.2 \times 10^{15}$</td>
<td>$6.2 \times 10^{15}$</td>
</tr>
<tr>
<td>Pulse length</td>
<td>CW</td>
<td>CW</td>
</tr>
<tr>
<td>Bunch spacing**</td>
<td>Programmable</td>
<td>Programmable</td>
</tr>
<tr>
<td>Bunch length (FWHM)</td>
<td>.04</td>
<td>.04</td>
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</tbody>
</table>

#### Low energy proton accelerator sources

**Proton beam energy – 1.0 → 1.4 GeV**

- **Intensity** - $9.6 \cdot 10^{15}$ protons/sec
- **Pulse duration** - 380ns (FWHM)
- **Repetition rate** - 60Hz
- **Total power** – 1.0 → 3 MW
- **Liquid Mercury target**

**SNS**

*Spallation Neutrino Source*
Medium and High Energy sources

Figure 1: A schematic drawing of the MiniBooNE experiment.

Target Hall
Baffle, Target, and Horns

Beam Absorber

Primary Beamline
Beam from MI to Target

Decay Pipe
Decay pipe window
Protons
$E_p = 120\ \text{GeV}$
$10^{15}\ \text{bunch}$, $2.2\ \text{sec cycle}$

$\Delta \phi = 23.7^\circ$

Different decay path for different points of creation
Decay Path sensitivity at different target/beam dumps

Examples at an 1 GeV accelerator source

Examples at >4 GeV source (FNAL Booster ?)

Decay path measured from the point of creation: in the target, decay pipe, final absorber, etc

ORNL SNS

FNAL Project-X

Examples from a source >10 GeV (FNAL NuMI ?)
Model independent measurement at NOvA ND

\[ N_{A' \rightarrow e^+e^-} (M_{A'}) = \int F_{\text{flux}} \left( 1 - e^{-\frac{P_{\text{path}} \cdot M_{A'}}{\tau_{A'}}} \right) \cdot \epsilon_{\text{pair eff}} \cdot A_{\text{accept}} dP_{\text{path}} d\Omega \]

Number of pairs

Flux of A' from the target

Momentum and Decay path distributions, from Mass, and lifetime of an A'

Pair detection efficiency from calibration/reconstruction, and detector acceptance from dimensions and position.

Background: pairs from unrecognized \( \pi_0 \) + p

\( M_{A'} \) options from the NuMI beam.

G4NuMI

Particles in all generations
Decay-path scans: Movable detectors

Fully active scintillator bar based.

Example: SciBar = 15k bars, 1x2cm² x 3m, 1mm WLS fibers, 64 layers.

Example of cost from SciNOvA report $2M and 23 month construction.

For a truck-able system on the surface an extra active cosmic veto is necessary.

Limitation in weight.
  • Can be divided to platforms
    • (1 detector + 1 electronics)

Much wider decay-path scans.
  • Covers wider ranges of the parameter phase-space.
Movable detector at the ORNL SNS

Rails can carry a detector as big as a container, larger acceptance options. Permanent arrangement may not be a problem (different state, and different funding source than the FNAL)
Detector design

High granularity fully active
• Examples:
  • SciBar from K2K
  • Pi0Det or FDG from T2K ND280 project.

Adaptation for use in NLWCP searches:
• 1x2 cm x 2m bars
• Double the depth to 120 layers.
• Added active veto, covering all 6 sides.

Leveraging from exiting proposals:
• Designs
  • SciBar@FNAL, hep-ex/0601022 of 2006.
  • SciNOvA P-1003, FNAL PAC 11/2010.
• Proven technologies.
  • Readout with SiPMs as in ND280.
  • DAQ & Slow controls as in MicroBooNE.
  • Analysis methodology from NOvA-NDUG.
Active muon veto design.

Scintillator based/ 2x4 cm²/ 6-10 layers/ X-Y orientation.
Covers large areas economically.
Proven technique to id cosmic tracks within 1mm.
Readout by the same method as DAQ system.
Truck-able detector at FNAL

Positioned in a straight line with the 3GeV beam beyond the beam dump of the muon campus.
Proposed detectors for NLWCP at Project X campus

A truck-able detector can take advantage of the extends of the new campus.

May require renting space from the county if it can be placed outside.
Discussion and outlook

Experimental strategy: Economy reasoning favors multi-purpose experiments.
- Small: in particle physics scales (and costs).
- Making a detector mobile can scan various ranges of mass.
  - It improves sensitivity (for each mass, scans lifetime ranges instead of a value).
  - Can be included in smaller grants, built by smaller collaborations.
- Beam-dump: rarely prime area for competing experiments
  - Can share source (dump) with other experimental efforts/ideas.

Detector design: Tracker /calorimeter combination.
- Popular around neutrino experiments, proven technique.
- Good vertex and mass reconstruction can scan decay vertices closer to the interaction point.
  - Slower /heavier particles. Increase the scanned phase space.

Signature: Di-particle with vertex in the beam-line.
- Electron, muon, or pion pairs depending on the mass and the type.
- Mass reconstruction provides the particle mass.
- Overall measurement is model independent
  - Signal excess gives the coupling strength.
  - Life time and mass are measured independently from each other.

Future technologies expectations
- Detectors for vertex searches (pixel).
  - Fast, radiation hard.
  - Faster DAO, High-level Triggering.
My Goals for this meeting

- Beam dumps are important.
  - not an “not-important” end but a source for others.
  - if no model exists we get 10e15 pot /min.
    - if they are there we will see them.
  - The civil engineering of the new machines must include accessibility.

- Technology leveraging.
  - We can create economical detection systems by combining technologies.
  - The neutrino experiment investment in technology and s/w.

- Periodical testing.
  - Every 10 years or
  - when there is a major upgrade to intensity or readout tech.
Extra slides
Light mediators: $\pi^0$

$$N_{\text{signal}}\frac{\text{bkgd}}{} = N_{\pi^0} * BR(\pi^0 \rightarrow \gamma A') * BR(A' \rightarrow e^+ + e^-) * \epsilon_{\text{pair eff}} * A_{\text{accept}}$$

From beam simulations

This is what it is estimated from the measurement

Detector properties

SINDRUM: $M_{A'} = 25-120\text{MeV}$, $BR \sim 10^{-6}$

WASA: $M_{A'} = 30-90\text{MeV}$, $BR \sim 10^{-6}$

NOMAD: $(M_{A'}, P_{A'}) = (<95\text{MeV}, 4\text{GeV}) \Rightarrow BR \sim 10^{-15}$
Heavy neutrinos in Near detectors

- NOMAD set limits, if the hypothetical single photon has a momentum distribution similar to that of a photon from the coherent $\pi^0$ decay

\[
\frac{\sigma(\text{Single, Forward} - \gamma)}{\sigma(\nu_\mu A \rightarrow \mu^- X)} \leq 1.6 \times 10^{-4} \, (90\% \, CL)
\]

- By using the enhanced flux from NuMI beam and good photon reconstruction we can attempt to try and see how signals for this heavy neutrino can be seen at NOvA ND. We can try and use other decay modes if the heavy neutrino could be of a greater mass, by supplementing with other particle recognition algorithms.

if the mass of $\nu_h > 140\text{MeV}$ then other decay channels are also possible i.e $\nu_\mu e e, \nu_\mu \pi^0, \nu_\mu \nu\nu, \mu\pi$. 

\[\begin{align*}
U^2 & \quad \rightarrow \quad \nu_\mu^* \\
W & \quad \rightarrow \quad (\mu^+ (e^+ \nu_e \pi^+))
\end{align*}\]