Neutrinos from stored muons

nuSTORM
Acknowledgements

• A. Bross, A. Liu, D. Neuffer, R. Bayes, P. Soler and the nuSTORM collaboration

A little history

• nuSTORM was presented to SPSC in 2013:
  – Received with interest
  – Considered that:
    • “... in line with the recently updated European Strategy, an involvement in nuSTORM could be part of the CERN contributions to the development of future neutrino programmes.”
• Motivation

• Facility

• Benefit and opportunity
Neutrinos from stored muons

MOTIVATION
Physics beyond colliders?

• Neutrino oscillations; physics beyond the SM
  – New particles, new forces or both?
  – Dirac or Majorana?
  – Sterile neutrinos?

• Window on physics at very high scales?
  – See-saw mechanism?
  – Relationship between quarks and leptons?

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{\lambda}{M} \mathcal{O}(5) \]
\[ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathcal{U}_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \]

\[
\mathcal{U}_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \text{e}^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13} \text{e}^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \times \text{diag}(1, \text{e}^{i\phi_1}, \text{e}^{i\phi_2})
\]

"Standard Neutrino Model (SνM)"
CP-invariance violation; where do we stand?

- **T2K:**
  - Preference for CP-invariance violation at 90% CL

- **Marone:** preliminary global fit for Neutrino 2016:
  - Indication that CP-invariance disfavoured at >2σ
Systematic uncertainty and/or bias

- Cross section error makes a critical contribution:
  - To systematic error
  - Potential source of (pernicious) bias
• Objectives:
  1. %-level ($\nu_eN$) cross sections
     • Double differential
  2. Sterile neutrino search
     • Beyond Fermilab SBN

• Precise neutrino flux:
  – Normalisation: < 1%
  – Energy (and flavour) precise

• $\pi \rightarrow$ injection pass:
  – “Flash” of pion decay neutrinos
Example: CCQE cross section

- **CCQE at nuSTORM:**
  - Six-fold improvement in systematic uncertainty compared with “state of the art”
  - Electron-neutrino cross section measurement unique

10.1103/PhysRevD.89.071301; arXiv:1305.1419

Individual $\nu_e$ measurements from T2K and MINERvA
Light sterile neutrino sensitivity

- Capability:
  - Continue the search; or
  - Study new phenomena

Neutrinos from stored muons

FACILITY
nuSTORM overview

- Fast extraction at >~ 100 GeV from:
  - Main Injector at FNAL or SPS at CERN
- Conventional pion production and capture (horn)
  - Quadrupole transport of pions to decay ring
- “Stochastic injection” in “orbit combination section”
  - 52% pions decay to muons before first arc
- Neutrino flux:
  - $\nu_\mu$ flash from pions (and kaons) passing through injection straight
  - $\nu_\mu$ and $\nu_e$ from muons; around 30 turns in one “lifetime”
Decay ring

- Quad-focusing FODO ring
  - Low-beta optics in production straight
  - Chicane to minimise “off-momentum” muon decays

Alternative:
- Fixed-field alternating gradient (FFAG) ring

3.8 GeV ± (16—19)%
Transverse acceptance: 1π mm
• Pion energy (5 GeV) > stored muon energy (3.8 GeV)
  – “Stochastic injection”: pion decay places muons in orbit
Horn optimised for pion capture in magnetic channel

- Example:
  - Phase space obtained in optimisation of horn using inconel target
Neutrino flux

- $\nu_\mu$ flash: and
  - Pion: $6.3 \times 10^{16}$ m$^{-2}$ at 50m
  - Kaon: $3.8 \times 10^{14}$ m$^{-2}$ at 50m

- $\nu_e$ and $\nu_\mu$ from muon decay:
  - High rate: $\sim$10 times as many $\nu_e$ as, e.g. J-PARC beam
  - Precise flavour composition and energy spectrum
  - Can be used to calibrate pion and kaon beams
Event rates

Per $10^{21}$ POT illuminating 100 Tonne LAr detector at 50m

<table>
<thead>
<tr>
<th>$\mu^+$ Channel</th>
<th>$N_{evts}$</th>
<th>$\mu^-$ Channel</th>
<th>$N_{evts}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_\mu$ NC</td>
<td>1,174,710</td>
<td>$\bar{\nu}_e$ NC</td>
<td>1,002,240</td>
</tr>
<tr>
<td>$\nu_e$ NC</td>
<td>1,817,810</td>
<td>$\nu_\mu$ NC</td>
<td>2,074,930</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ CC</td>
<td>3,030,510</td>
<td>$\bar{\nu}_e$ CC</td>
<td>2,519,840</td>
</tr>
<tr>
<td>$\nu_e$ CC</td>
<td>5,188,050</td>
<td>$\bar{\nu}_\mu$ CC</td>
<td>6,060,580</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\pi^+$ Channel</th>
<th>$N_{evts}$</th>
<th>$\pi^-$ Channel</th>
<th>$N_{evts}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ NC</td>
<td>14,384,192</td>
<td>$\bar{\nu}_\mu$ NC</td>
<td>6,986,343</td>
</tr>
<tr>
<td>$\nu_\mu$ CC</td>
<td>41,053,300</td>
<td>$\bar{\nu}_\mu$ CC</td>
<td>19,939,704</td>
</tr>
</tbody>
</table>

- $\nu_\mu$ flash: and
  - Pion: $6.3 \times 10^{16}$ m$^{-2}$ at 50m
  - Kaon: $3.8 \times 10^{14}$ m$^{-2}$ at 50m

- $\nu_e$ and $\nu_\mu$ from muon decay:
  - High rate: $\sim$10 times as many $\nu_e$ as, e.g. J-PARC beam
  - Precise flavour composition and energy spectrum
  - Can be used to calibrate pion and kaon beams
Neutrinos from stored muons

BENEFIT AND OPPORTUNITY
• CP-invariance violation: discovery potential:
  – DUNE and Hyper-K alone (±90°) or in combination
• Towards the end of this decade:
  – Mature $\nu N$ scattering programme at FNAL and J-PARC
  – Near-detector programme of DUNE & Hyper-K defined
  – Short Baseline Neutrino programme delivering data
• Natural time to consider benefits of muon-based beams:
  – High $\nu_e$ flux; low beam systematics; excellent calibration
3.2: Results from the SBN Program and other sterile-neutrino-search experiments will be available by \( \approx 2020 \). It will then be timely to decide on the future direction of the accelerator-based sterile-neutrino-search programme.

**Decision point 3.1: \( \approx 2020 \): Decide on the future direction of the accelerator-based sterile-neutrino-search programme.**

3.3: Beyond the SBN Program, the way forward will depend on the strength of the evidence for sterile neutrinos.

**Recommendation 3.2:** The sensitivity, cost, schedule and relative strengths of the proposed next-generation accelerator-based sterile-neutrino-search experiments (IsoDAR, nuSTORM) should be evaluated in preparation for a decision to be made on the future direction of the sterile-neutrino-search programme in \( \approx 2020 \). In the mean time, the R&D programme necessary to establish the requisite capabilities should be carried out.

4.6: Captain-MINER\( \nu \)A, which has Stage I approval from the Fermilab PAC, and the near detectors that form part of the DUNE and Hyper-K programmes will take the neutrino-scattering programme forward. If approved, Captain-MINER\( \nu \)A will provide valuable, detailed information on neutrino-argon scattering by the end of the present decade. The detailed specification of the DUNE and Hyper-K near detectors will be resolved over a similar timescale. It will therefore be timely to decide on the long-term development of the \( \bar{\nu} N \)-scattering programme around \( \approx 2020 \).

**Decision point 4.3: \( \approx 2020 \): Decide on the future direction of the neutrino-nucleus-scattering programme based on experimental and theoretical progress and the needs of the future neutrino programme.**

4.7: The requirements of DUNE and Hyper-K will drive the specification of the neutrino-cross-section-measurement programme. The path forward, beyond the present generation of \( \bar{\nu} N \) scattering experiments, will be determined by the degree to which existing techniques (on and off-axis near detectors illuminated with pion-decay beams) can deliver measurements of the requisite precision.

**Recommendation 4.4:** The proposed next-generation neutrino-scattering experiments, for example nuSTORM, should be evaluated in preparation for a decision on the future direction of the neutrino-scattering programme to be made in \( \approx 2020 \).
Opportunity

- **nuSTORM** has the potential to:
  - **Serve neutrino-oscillation discovery programme:**
    - **High-precision neutrino-nucleus scattering programme**
      - Uniquely precise electron-neutrino measurements
    - Pursue light-sterile-neutrino searches beyond SBN

- **Physics Beyond Colliders workshop:**
  - Study implementation of nuSTORM at CERN
  - Review potential scientific impact

Opportunity to establish a new technique for the study of fundamental particles and their interactions
Neutrinos from stored muons
North Area

- Ring “just” below surface provides shielding

- EHN1 extension possible site for detectors