WHAT IS nuSTORM?
Neutrinos from stored muons

- Scientific 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

- $\pi \rightarrow \mu^+$ injection pass:
  - "Flash" of muon neutrinos
• Fast extraction at $>\sim 100$ GeV

• Conventional pion production and capture (horn)
  – Quadrupole pion-transport channel to decay ring
• Neutrino flux

- **νμ flash:**
  - Pion: $6.3 \times 10^{16} \, \text{m}^{-2}$ at 50m
  - Kaon: $3.8 \times 10^{14} \, \text{m}^{-2}$ at 50m
  - Well separated from pion neutrinos

- **νe and νμ from muon decay:**
  - ~10 times as many νe as, e.g. J-PARC beam
  - Flavour composition, energy spectrum
  - Use for energy calibration
WHY STUDY NEUTRINO INTERACTIONS?
To understand the nucleus, nucleon and contribute to nuclear physics

... but also ...
Search for CPiV in lbl oscillations

• Seek to measure asymmetry:
  \[ P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \]

• Event rates, convolution of:
  – Flux, cross sections, detector mass, efficiency, \( E \)-scale
    • Measurements at %-level required
  – Theoretical description:
    • Initial state momentum, nuclear excitations, final-state effects
Systematic uncertainty and/or bias

Uncertainty (cross section and ratio)

Event mis-classification

Energy scale mis-calibration

Missing energy (neutrons)
Search for CPiV in lbl oscillations

• Seek to measure asymmetry:
  \[ P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \]

• Event rates convolution of:
  – Flux, cross sections, detector mass, efficiency, \( E \)-scale
    • Measurements at %-level required

• Lack of knowledge of cross-sections leads to:
  – Systematic uncertainties; and
  – Biases; pernicious if \( \nu \) and \( \bar{\nu} \) differ
THE BENEFIT OF nuSTORM
$\nu_e N$ cross section measurements

The result and the prediction from GENIE 2.6.2 are statistically consistent.
Systematic uncertainties

- - - Statistical uncertainty

- Background models
  + resonant interactions affect background subtraction

- CCQE / 2p2h model
  + dominated by uncertainty in correlation effect strength

- Final-state interactions
  + pion absorption dominates

- Flux
  + beam focusing
  + tertiary hadron production
  + reweight to other experiments

- Muon reconstruction
  + muon energy scale dominates
  + tracking efficiency
  + muon angle and vertex position

- Recoil reconstruction
  + detector response to different particles - neutron dominates

Uncertainties projected onto longitudinal muon momentum

Cheryl Patrick, Northwestern University
CCQE measurement at nuSTORM

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

- Require to demonstrate:
  - ~<1% precision on flux

10.1103/PhysRevD.89.071301; arXiv:1305.1419

Individual $\nu_e$ measurements from T2K and MINERvA

nuSTORM & THE CERN PHYSICS BEYOND COLLIDERS STUDY GROUP
Physics Beyond Colliders study group

http://pbc.web.cern.ch
Elements of study

- **Physics case:**
  - Neutrino-scattering for:
    - Oscillation
    - Nuclear

- **Considerations:**
  - Energy range:
    - Long- and short-baseline neutrino
    - Nuclear and particle physics
  - Acceptance:
    - Rate
    - Neutrino-energy calibration

- **Accelerator:**
  - Full simulation that demonstrates ~1% flux precision
  - Energy range (i.e. sweep down from max)

- **Implementation:**
  - Feasibility at CERN (see next slide)

- **Detector:**
  - Others are “on this”, so:
    - Adopt performance of typical, or assumed, detector
• A credible proposal for siting at CERN, including:
  – SPS requirements
  – Fast extraction, beam-line
  – Target and target complex
  – Horn
  – Siting
  – Civil engineering
  – Radio-protection implications
Conclusions
Conclusions

• Muon accelerators have the potential to:
  – Revolutionise neutrino physics
  – Provide multi-TeV lepton-anti-lepton collisions

• nuSTORM can deliver:
  – $nN$ scattering measurements with precision required to:
    • Serve the long- and short-baseline neutrino programmes
    • Provide a valuable probe for nuclear physics

• CERN PBC study: opportunity to define innovative programme:
  • nuSTORM:
    – Delivers critical measurement: $\nu_e/\nu_\mu N$ scattering;
    – Has discovery potential: sterile neutrinos;
    – Potential for 6D ionization-cooling programme to follow MICE
nuSTORM collaboration and FNAL study of nuSTORM (A.Bross et al) and especially
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>

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