Physics opportunities at vSTORM

Luis Alvarez Ruso*
(on behalf of the collaboration)

* https://orcid.org/0000-0001-5184-0622

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Neutrinos from Stored Muons

\[ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]
\[ \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \]

Precisely known flux:
- Normalization (< 1%)
- Flavor composition
- Energy spectrum

Feasibility at CERN: Ahdida et al., CERN-PBC-REPORT-2019-003
**νSTORM: physics opportunities**

- **Precise** (% level) and **detailed** neutrino **cross section** measurements
- Short-baseline **flavor transition** and **sterile** neutrino searches (following **SBN @ Fermilab**)

Precise (% level) and detailed neutrino cross section measurements:
- Elementary processes
- Neutrino-nucleus scattering

Crucial to reduce systematic uncertainties in oscillation studies.
Allows to study the axial structure of hadrons and nuclei.
Precise (% level) and detailed neutrino cross section measurements

**Elementary processes:** \( \nu \)-nucleon interactions

- poorly known
- priceless input for event generators
- valuable information about hadron structure (axial sector)

Neutrino-nucleus scattering (mismodeling in event generators can lead to **systematic errors** even if tuned to the best data)
**$\nu$ cross sections**

- **Precise** (% level) and **detailed** neutrino cross section measurements

- **Elementary processes**: $\nu$ – nucleon interactions
  - poorly known
  - priceless input for event generators
  - valuable information about hadron structure (axial sector)

- should be experimentally studied either
  - directly: measurements on H/D
  - or
  - indirectly: H-enriched targets + kinematic subtraction
    - High pressure TPC (CH$_4$) using transverse kinematic invalance
    - Subtraction using CH$_2$ and C solid targets

- **$\nu$STORM**: precision, e and $\mu$ (anti)neutrino flavors
  - radiative corrections
  - non-standard interactions
Elementary processes

- **Quasielastic scattering:**
  
  **CCQE**:
  \[ \nu(k) + n(p) \rightarrow l^-(k') + p(p') \]
  
  \[ \bar{\nu}(k) + p(p) \rightarrow l^+(k') + n(p') \]

  **NCE**:
  \[ \nu(k) + N(p) \rightarrow \nu(k') + N(p') \]
  
  \[ \bar{\nu}(k) + N(p) \rightarrow \bar{\nu}(k') + N(p') \]

- Determination of the **nucleon axial form factor**
- “Standard candle” to constrain neutrino fluxes
Elementary processes

- Quasielastic scattering
- Inelastic scattering:
  - \(1\pi\) production: dominated by \(\Delta(1232)\) excitation
  - interference between RES and NonRES amplitudes, unitarity
- Above the \(\Delta(1232)\) peak \(W>1.3\) GeV:
  - several overlapping resonances
  - non-trivial interference
  - coupled channels
  - other processes: \(\nu_l \, N \rightarrow l \, N' \, \pi\pi\)
    \(\nu_l \, N \rightarrow l \, N' \, \eta\)
    \(\nu_l \, N \rightarrow l \, \Lambda(\Sigma) \, \bar{K}\)
- Very limited information about the axial current at \(q^2 \neq 0\)
Elementary processes

- Quasielastic scattering
- Inelastic scattering
- Shallow inelastic scattering:
  - transition from RES to DIS
  - very relevant for DUNE
  - role of Quark-Hadron duality
- Deep inelastic scattering: $W > 2 \text{ GeV}, Q^2 > 1 \text{ GeV}^2$
  - Parton distribution function (PDF) determination
    - Impact of higher twists
  - Hadronization: exclusive channels

Elementary processes

- Quasielastic scattering
- Inelastic scattering
- Shallow inelastic scattering
- Deep inelastic scattering

\[ 1 \lesssim p_\mu \lesssim 6 \text{ GeV/c} \]
Neutrino interactions on nuclei

**νSTORM:** precise measurements of $\nu$ cross sections on heavy targets:
- characterization of $\nu_e$ vs $\nu_\mu$ differences
- Particularly important at low energy/momentum transfers (in Lab)

![Graphs showing $d^2\sigma/d^2(\omega \theta)$ for various energies and angles]
Neutrino interactions on nuclei

- **νSTORM**: precise measurements of $\nu$ cross sections on heavy targets:
  - characterization of $\nu_e$ vs $\nu_\mu$ differences
  - Particularly important at low energy/momentum transfers (in Lab)
  - high-statistics for $\nu_e$ cross section and the $\sigma(\nu_e)/\sigma(\nu_\mu)$ ratio
  - Among the largest systematic uncertainties @ DUNE
  - Required sensitivity to CP violation can be achieved with a smaller exposure
Neutrino interactions on nuclei

- $\nu$STORM: precise measurements of $\nu$ cross sections on heavy targets:
  - characterization of $\nu_e$ vs $\nu_\mu$ differences
  - better understanding of the initial state
  - study of meson-exchange currents (or 2p2h)
Two-nucleon currents

- 2-nucleon EW currents are allowed by symmetries
- Sizable contribution can be inferred from $A(e,e')X$

Megias et al., PRD 94 (2016)
Gallsmeiter et al., PRD 94 (2016)
Two-nucleon currents

- 2-nucleon EW currents are allowed by symmetries

- together with better QE nuclear models can explain MiniBooNE data with $M_A \approx 1$ GeV

Martini et al.

Nieves et al.
Neutrino interactions on nuclei

- **νSTORM**: precise measurements of $\nu$ cross sections on heavy targets:
  - characterization of $\nu_e$ vs $\nu_\mu$ differences
  - better understanding of the initial state
  - study of meson-exchange currents (or 2p2h)
    - help understand **discrepancies with theory** found @ MINERvA
New precise measurements of cross sections on heavy targets:
- characterization of $\bar{\nu}_e$ vs $\bar{\nu}_d$ differences
- better understanding of the initial state
- study of meson-exchange currents (or 2p2h)

Help understand discrepancies with theory found at MINERvA & NOvA

MINERvA inclusive CC data [Rodrigues et al. PRL (2016) vs T2K ref. model (NEUT)]

P. Stowell, PhD dissertation (2019)
Neutrino interactions on nuclei

- **νSTORM**: precise measurements of $\nu$ cross sections on heavy targets:
  - characterization of $\nu_e$ vs $\nu_\mu$ differences
  - better understanding of the initial state
  - study of meson-exchange currents (or 2p2h)
  - help understand discrepancies with theory found @ MINERvA & NOvA

Acero et al., EPJ C 80 (2020)
Neutrino interactions on nuclei

- **νSTORM**: precise measurements of $\nu$ cross sections on heavy targets:
  - characterization of $\nu_e$ vs $\nu_\mu$ differences
  - better understanding of the initial state
  - study of meson-exchange currents (or 2p2h)
  - study of exclusive final states
    - one- and two-nucleon knockout
    - single and multiple pion production
    - largely influenced by FSI
$1\pi$ production on nuclei

- **GiBUU** Leitner, LAR, Mosel, PRC 73 (2006)
- Effects of **FSI** on pion kinetic energy spectra
  - Strong absorption in Δ region
  - Side-feeding from dominant $\pi^+$ into $\pi^0$ channel
  - Secondary pions through FSI of initial QE protons

$$\nu_\mu + ^{56}Fe \rightarrow \mu^- \pi X \quad E_\nu = 1 \text{ GeV}$$
Neutrino interactions on nuclei

\textbf{\nuSTORM:} precise measurements of \( \nu \) cross sections on heavy targets:
- characterization of \( \nu_e \) vs \( \nu_\mu \) differences
- better understanding of the initial state
- study of meson-exchange currents (or 2p2h)
- study of exclusive final states
  - one- and two-nucleon knockout
  - single and multiple pion production
  - largely influenced by FSI
  - relevant for calorimetric \( E_\nu \) determination
Neutrino interactions on nuclei

- **νSTORM**: precise measurements of ν cross sections on heavy targets:
  - characterization of \( \nu_e \) vs \( \nu_\mu \) differences
  - better understanding of the initial state
  - study of meson-exchange currents (or 2p2h)
  - study of exclusive final states
    - one- and two-nucleon knockout
    - single and multiple pion production
    - “Rare” processes
    - strangeness production
    - e.g. single photon emission
  - possible BSM explanations of the MiniBooNE anomaly

P. Machado @ NeuTel 2021 (Feb. 25)
Neutrino interactions on nuclei

- **νSTORM**: precise measurements of ν cross sections on heavy targets:
  - precise measurements of ν energies
  - μBooNE
  - \( \varepsilon \) vs \( \varepsilon' \) (or 2p2h)
  - better understanding of the initial state
  - study of meson-exchange currents (or 2p2h)
  - one- and two-nucleon knockout
  - single and multiple pion production
  - "Rare" processes
    - strangeness production
    - e.g. single photon emission
    - possible BSM explanations of the MiniBooNE anomaly
  - under study @ MicroBooNE
  - M. Ross-Lonergan @ NeuTel 2021 (Feb 24)
Neutrino interactions on nuclei

- **νSTORM**: precise measurements of $\nu$ cross sections on heavy targets:
  - characterization of $\nu_e$ vs $\nu_\mu$ differences
  - better understanding of the initial state
  - study of meson-exchange currents (or 2p2h)
  - study of exclusive final states
  - Nuclear effects on PDF
    - understand the different nuclear effects in weak vs em processes
    - clarify the tensions between measurements with neutrinos and charged leptons
Short-baseline flavor transitions

- **νSTORM** has a **unique sensitivity** to short-baseline **flavor** transitions.
- Concept: using $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ search for
- $\nu_\mu$ **appearance** from $\nu_e \rightarrow \nu_\mu$
  - observing $\mu^-\mu^+$ in large $\mu^+$ background
  - requires good charge ID
- $\bar{\nu}_\mu$ **disappearance** from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - observing $\mu^+\mu^-$ spectral distortion
  - requires accurate momentum measurement

- Non-unitarity of $\nu$ mixing matrix
- Non-standard interactions
- Lorentz invariance and CPT violation
  - $\nu_e \rightarrow \nu_\mu$ appearance and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance are CPT conjugates
- eV-scale sterile neutrinos
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e \leftarrow$ LSND anomaly
Sterile $\nu$ search

- $\nu$STORM has a unique sensitivity to light sterile neutrinos.
- $\nu_\mu$ appearance from $\nu_e \to \nu_\mu$
- $\bar{\nu}_\mu$ disappearance from $\bar{\nu}_\mu \to \bar{\nu}_e$
- $10^{21}$ POT $\approx 2 \times 10^{18} \mu^+$ decays
- 1.3 kt FD located $\sim 2$ km away from the ND
- In a $3+1$ sterile model:

Adey et al., PRD89 (2014)
Our present understanding of (few-GeV) neutrino interactions with matter would be **greatly improved** by new precise measurements with well-understood $\nu$STORM flux at **advanced detectors**.

The future neutrino oscillation program can **greatly benefit**.

Progress in **hadron** and **nuclear physics**.

Potential to **discover/constrain** non-standard interactions.

Sensitive searches for **short-baseline flavor transitions**: potential to **discover sterile neutrinos** or **exclude** (10 $\sigma$) the presently allowed parameter space.