XIX International Workshop on Neutrino Telescopes

Physics opportunities at νSTORM

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(on behalf of the collaboration)

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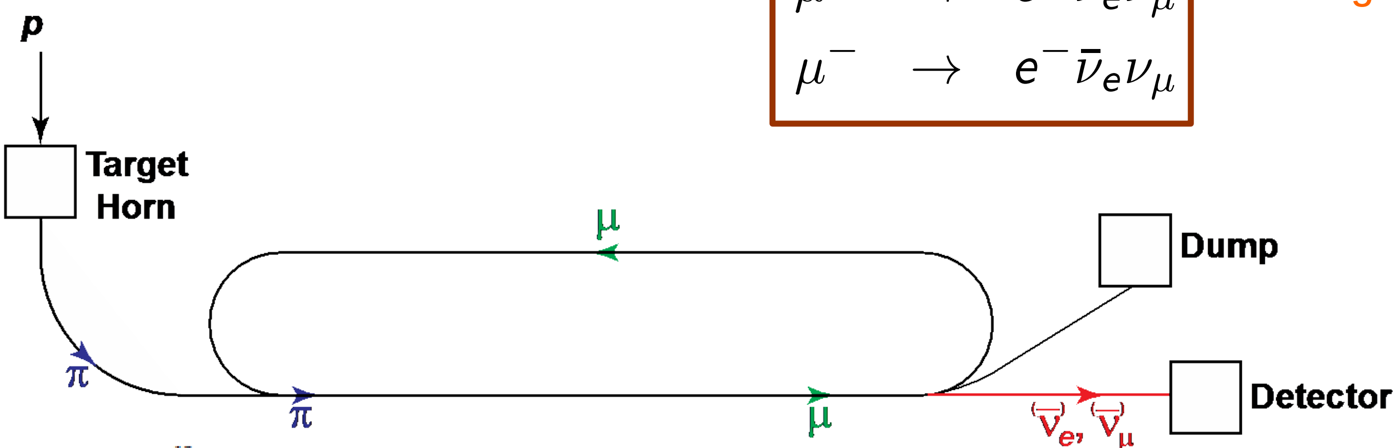
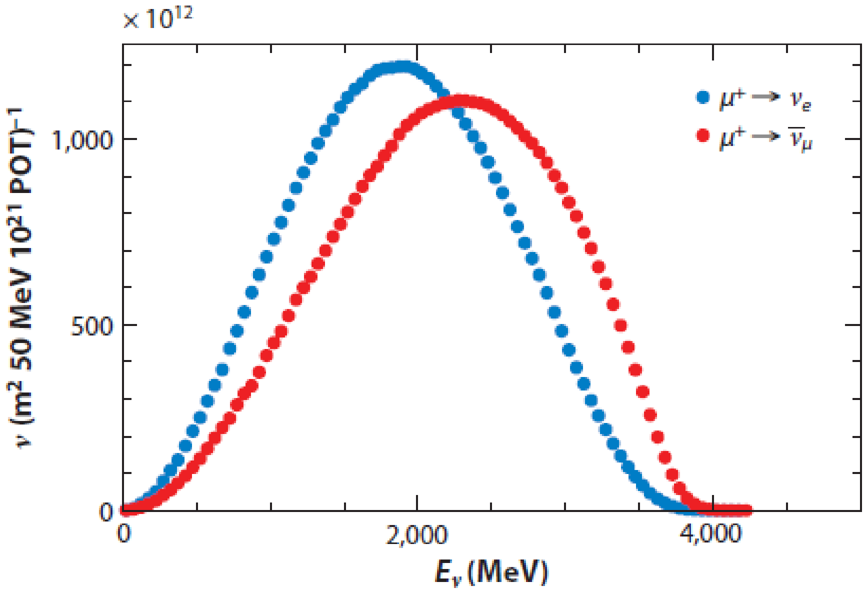
νSTORM

- Neutrinos from Stored Muons

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

C. Rogers @ NeuTel 2021 (Feb 25)





Adey et al., Annu. Rev. Nucl. Part. Sci. 2015.65

Precisely known flux:

- Normalization (< 1%)
- Flavor composition
- Energy spectrum

- Feasibility at CERN: Ahdida et al., CERN-PBC-REPORT-2019-003

νSTORM: physics oportunities

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

ν cross sections

- **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.

ν cross sections

- **Precise** (% level) and **detailed** neutrino cross section measurements
  - **Elementary processes**: ν – 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)

ν cross sections

- **Precise** (% level) and **detailed** neutrino cross section measurements
  - **Elementary processes**: ν – 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

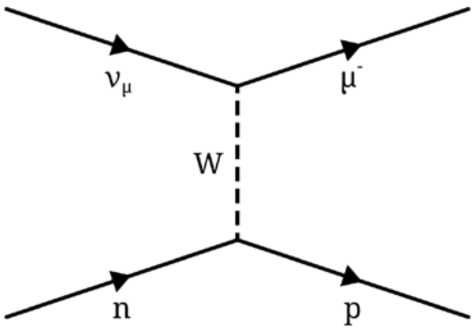
    or
    - indirectly: H-enriched targets + kinematic subtraction
      - High presure TPC (CH_4) using transverse kinematic invalance
      - Subtraction using CH_2 and C solid targets

  - **νSTORM**: precision, e and μ (anti)neutrino flavors
    - radiative corrections
    - non-standard interactions

Elementary processes

- Quasielastic scattering:

$$\begin{aligned} \text{CCQE}: \nu(k) + n(p) &\rightarrow l^-(k') + p(p') \\ \bar{\nu}(k) + p(p) &\rightarrow l^+(k') + n(p') \\ \text{NCE}: \nu(k) + N(p) &\rightarrow \nu(k') + N(p') \\ \bar{\nu}(k) + N(p) &\rightarrow \bar{\nu}(k') + N(p') \end{aligned}$$



  - Determination of the nucleon axial form factor
  - "Standard candle" to constrain neutrino fluxes

Elementary processes

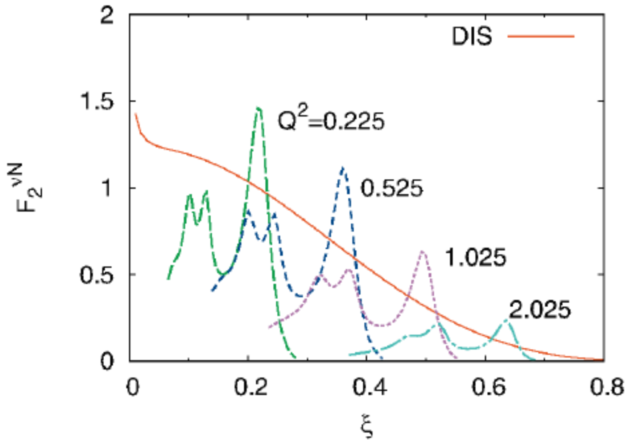
- Quasielastic scattering
- Inelastic scattering:
  - 1π production: dominated by $\Delta(1232)$ excitation
    - interference between RES and NonRES amplitudes, unitarity
- Above the $\Delta(1232)$ peak W>1.3 GeV:
  - several overlapping resonances
  - non-trivial interference
  - coupled channels
  - other processes: $\nu_l \, N \to l \, N' \, \pi\pi$

    $\nu_l \, N \to l \, N' \, \eta$

    $\nu_l \, N \to l \, \Lambda(\Sigma) \, \bar{K}$
  - Very limited information about the axial current at $q^2 \neq 0$

Elementary processes

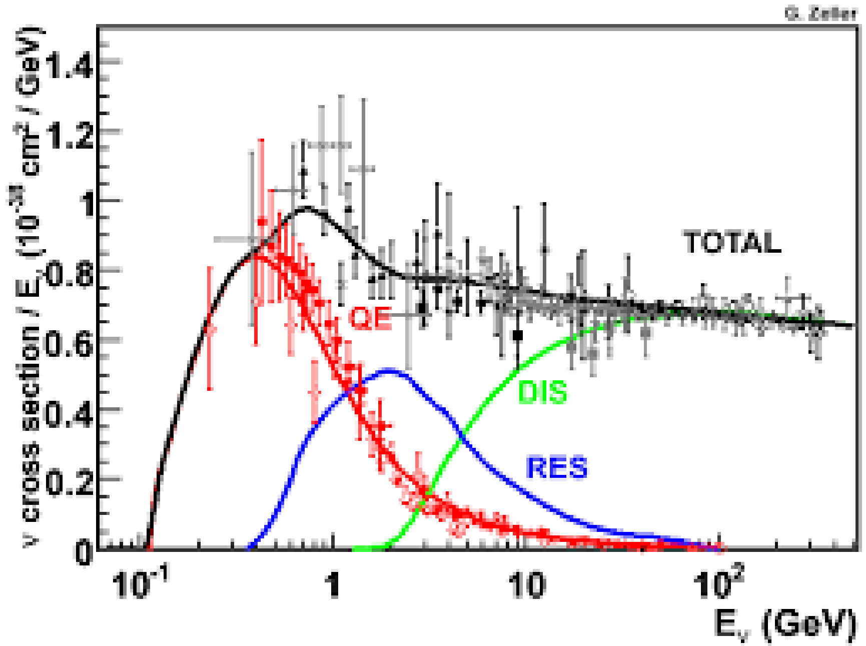
- Quasielastic scattering
- Inelastic scattering
- Shallow inelastic scattering:
  - transition from RES to DIS
  - very relevant for DUNE
  - role of Quark-Hadron duality
- Deep inelastic scattering: W>2 GeV, $Q^2 > 1$ GeV^2
  - Parton distribution function (PDF) determination
    - Impact of higher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

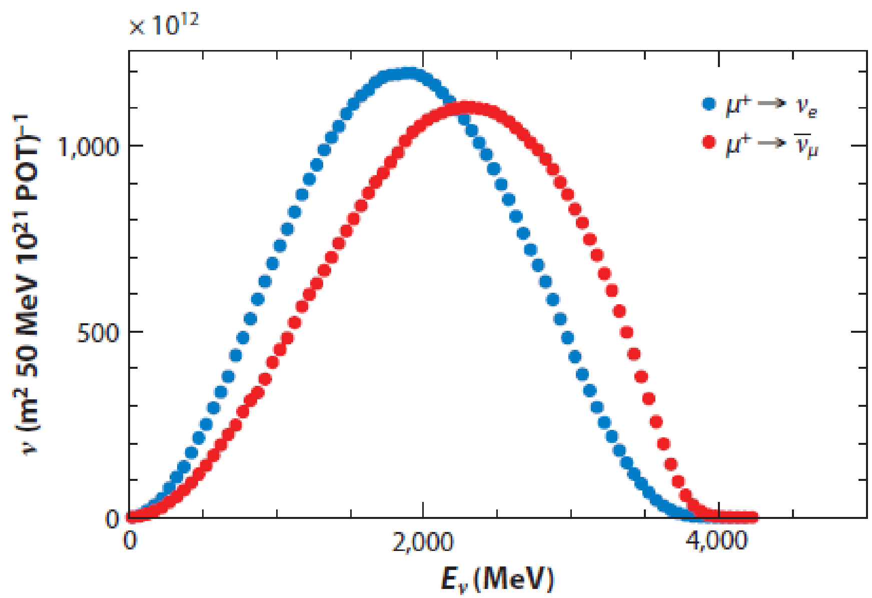


Lalakulich et al., AIP Conf. Proc. (2009)

Elementary processes

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

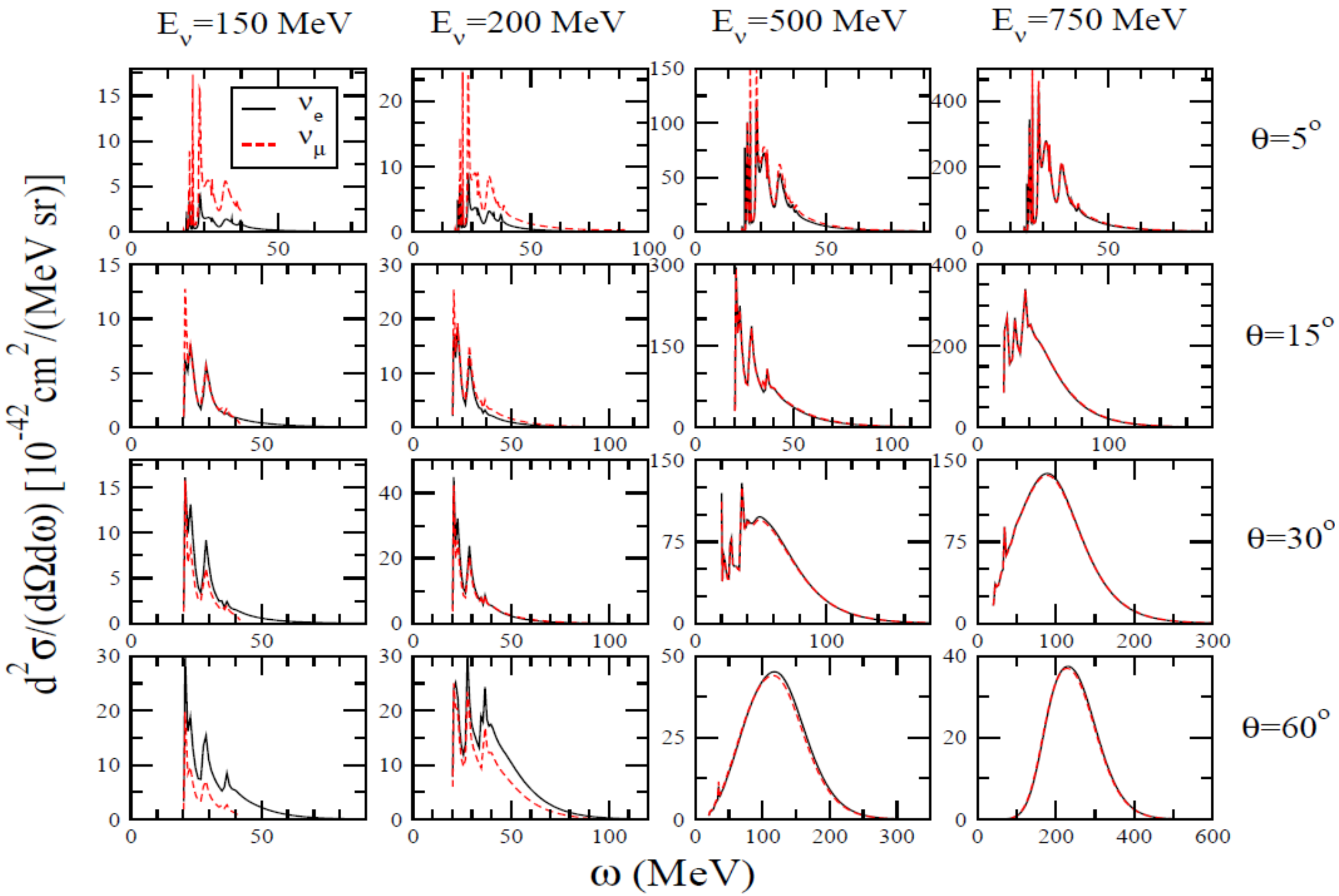




$1 \lesssim p_\mu \lesssim 6$ GeV/c

Neutrino interactions on nuclei

- ***ν*STORM:** precise measurements of ν cross sections on heavy targets:
  - characterization of ν_e **vs** ν_μ **differences**
    - Particularly important at low energy/momentum transfers (in Lab)



CRPA Gent, Jachowicz et al.

Neutrino interactions on nuclei

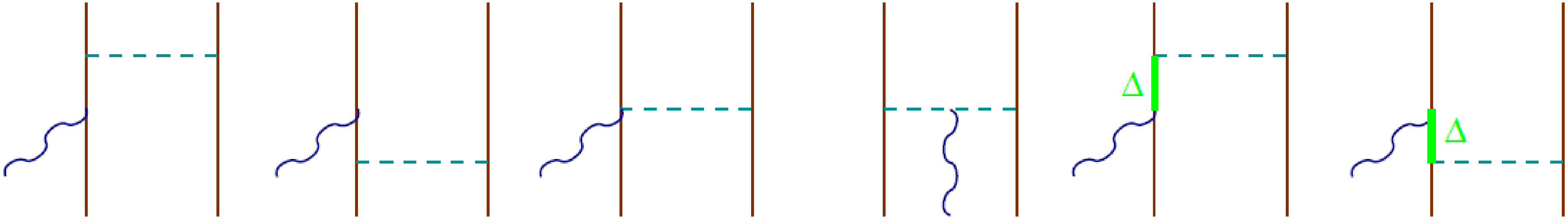
- ν**STORM:** precise measurements of ν cross sections on heavy targets:
  - characterization of ν_e **vs** ν_μ **differences**
    - Particularly important at low energy/momentum transfers (in Lab)
  - high-statistics for ν_e cross section and the $\sigma(\nu_e)/\sigma(\nu_\mu)$ ratio
    - Among the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

Neutrino interactions on nuclei

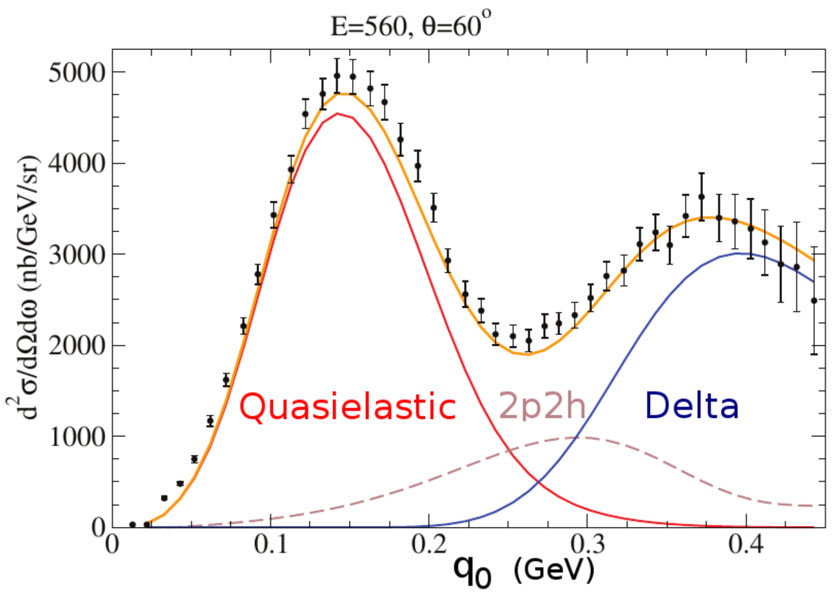
- **νSTORM:** precise measurements of ν cross sections on heavy targets:
  - characterization of **ν_e vs ν_μ differences**
  - better understanding of the initial state
  - study of meson-exchange currents (or 2p2h)

Two-nucleon currents

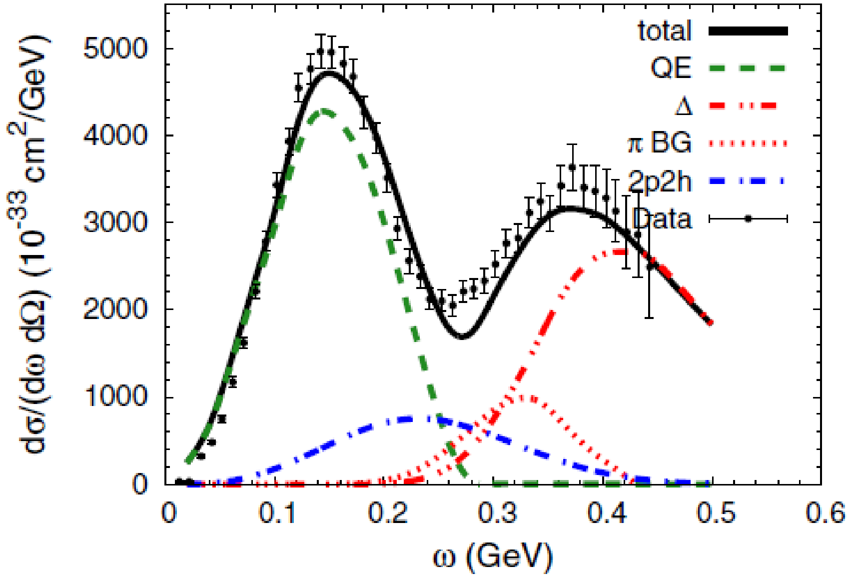
- 2-nucleon EW currents are allowed by symmetries



- Sizable contribution can be inferred from A(e,e')X



Megias et al., PRD 94 (2016)



Gallsmeiter et al., PRD 94 (2016)

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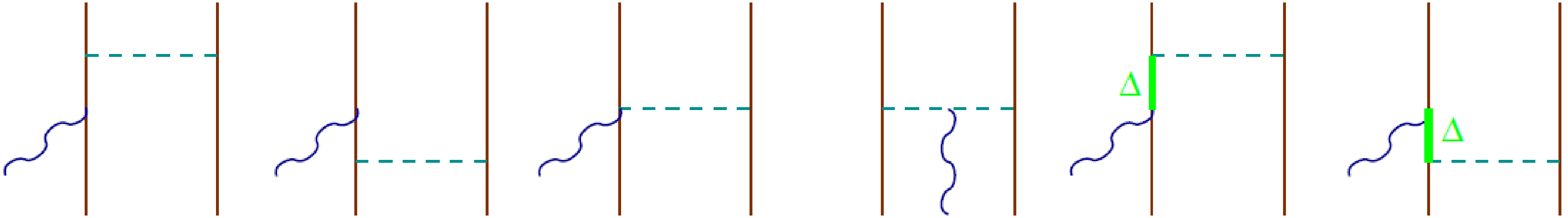
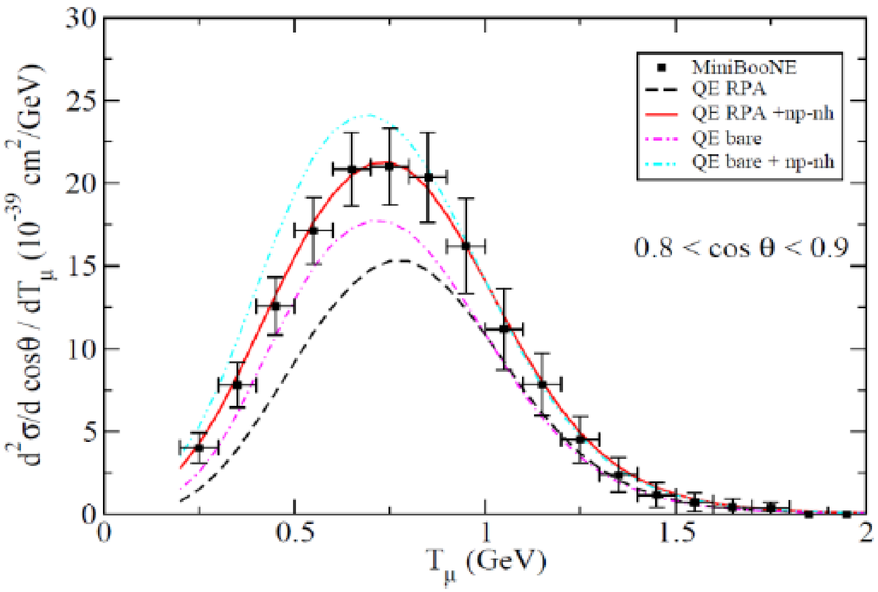
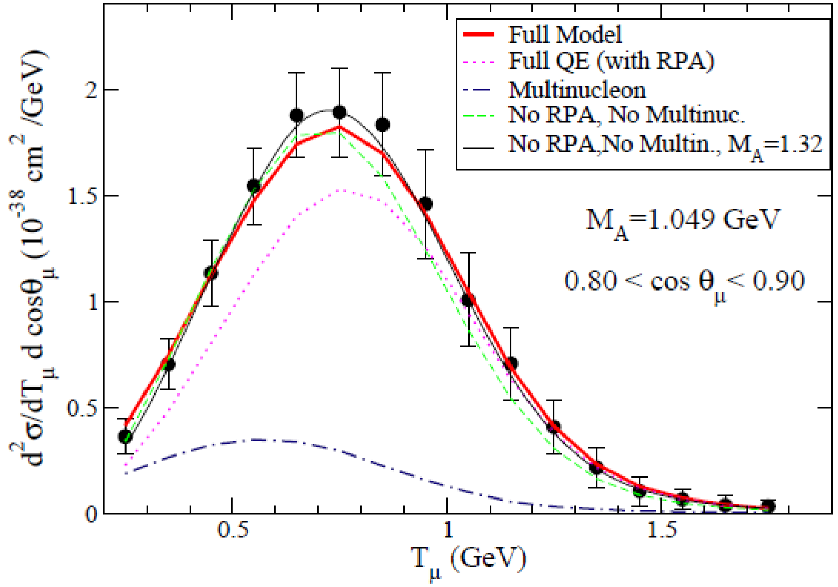


- together with better QE nuclear models can explain MiniBooNE data with $M_A \approx 1$ GeV



Martini et al.



Nieves et al.

Neutrino interactions on nuclei

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  - characterization of **ν_e vs ν_μ differences**
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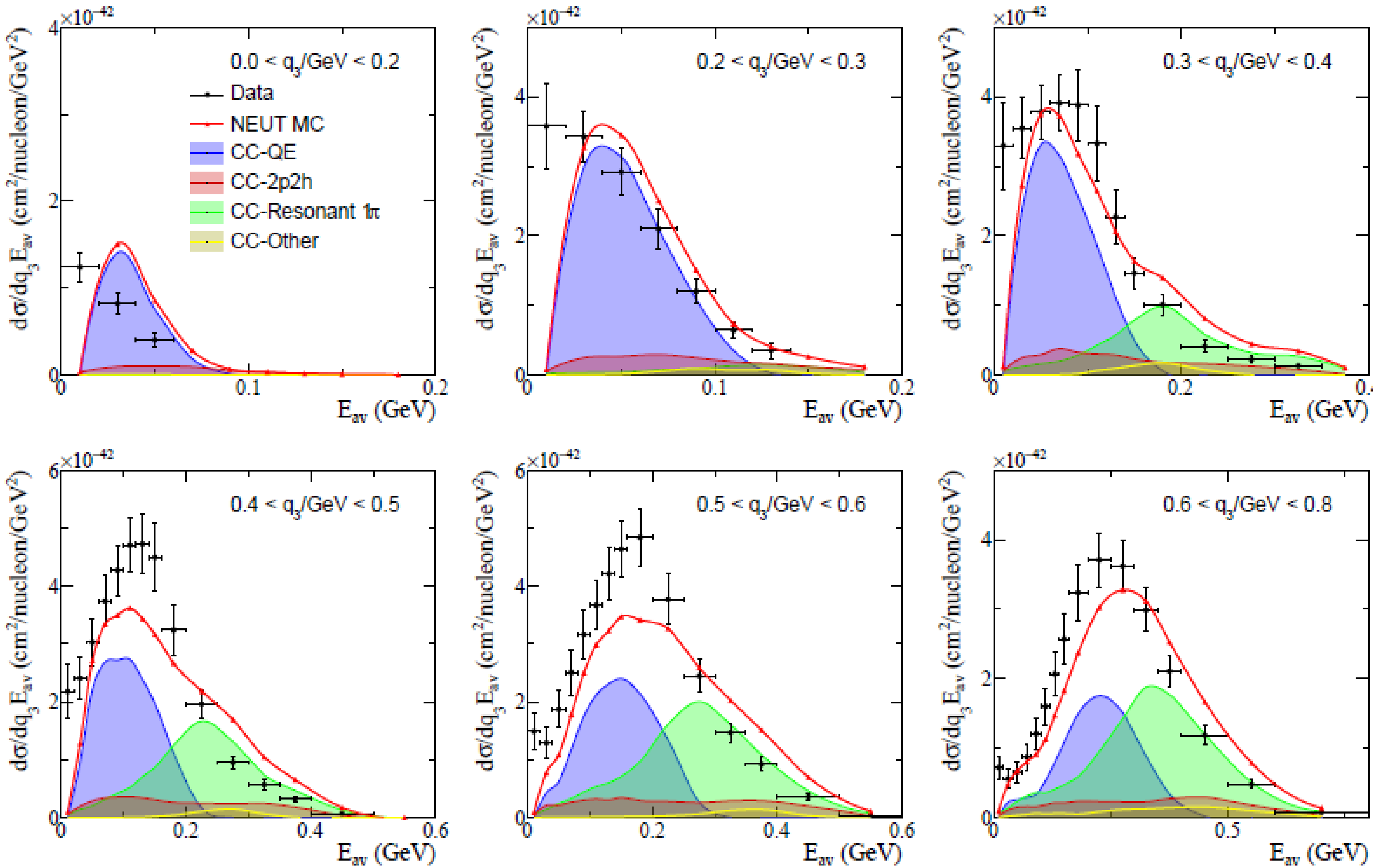
  - study of meson-exchange currents (or 2p2h)
    - help understand **discrepancies with theory** found @ MINERvA

Neutrino interactions on nuclei



MINERvA inclusive CC data [Rodrigues et al. PRL (2016) vs T2K ref. model (NEUT)
P. Stowell, PhD disertation (2019)

Neutrino interactions on nuclei

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  - characterization of ν_e **vs** ν_μ **differences**
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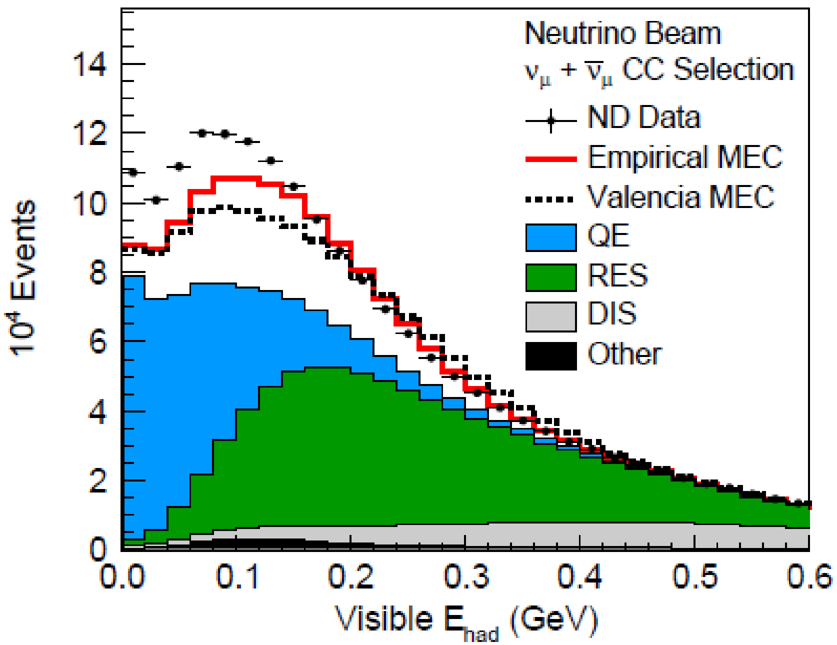
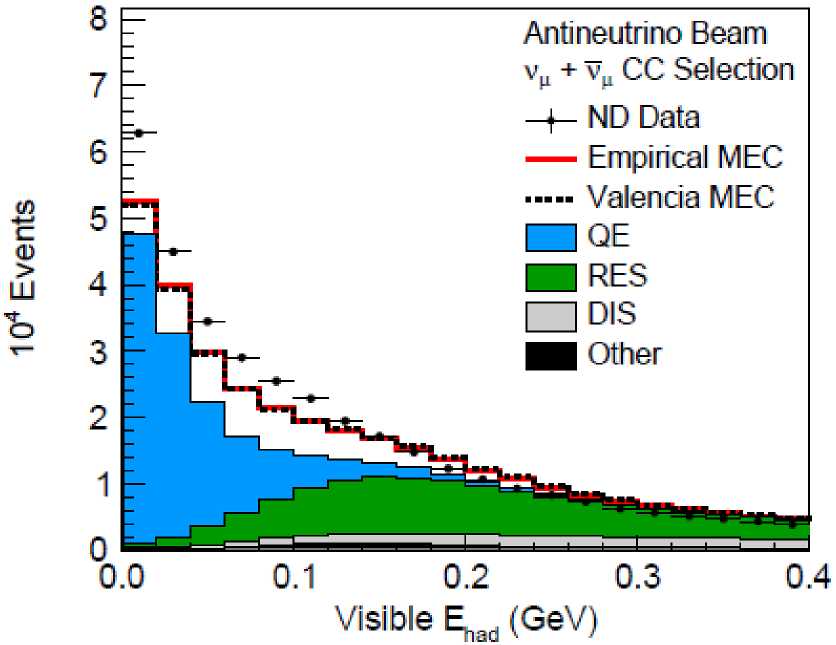
  - study of meson-exchange currents (or 2p2h)
    - help understand **discrepancies with theory** found @ MINERvA & NOvA





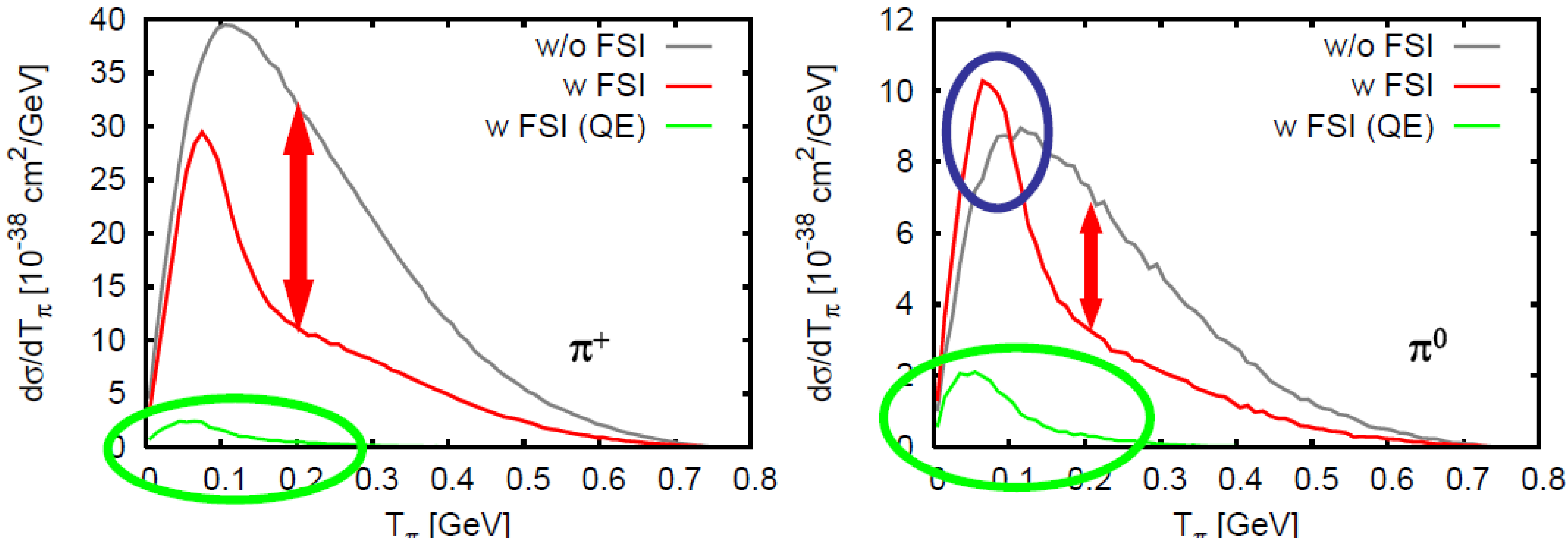
Acero et al., EPJ C 80 (2020)

Neutrino interactions on nuclei

- **νSTORM:** precise measurements of ν cross sections on heavy targets:
  - characterization of ν_e **vs** ν_μ **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**

1π 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 π^+ into π^o 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

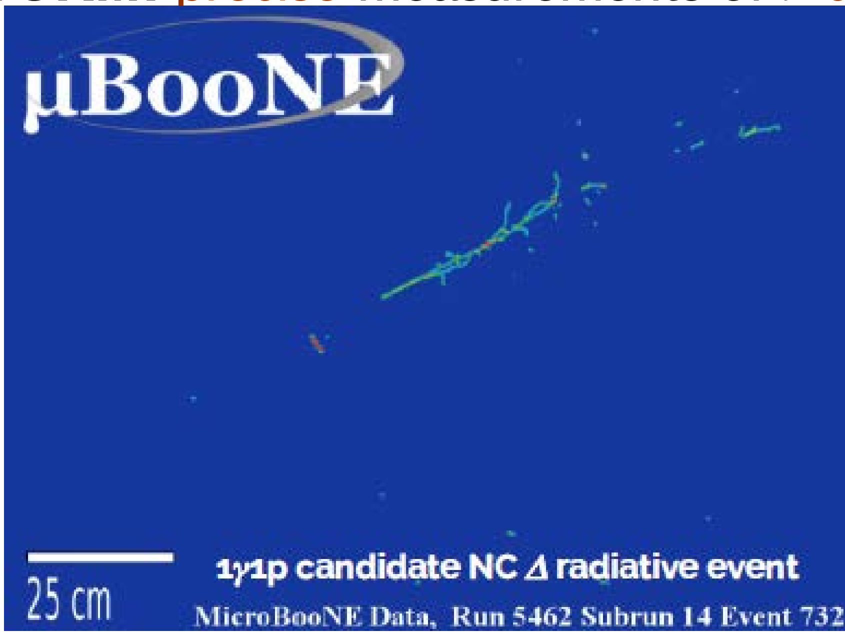
- **νSTORM:** precise measurements of ν cross sections on heavy targets:
  - characterization of **ν_e vs ν_μ differences**
  - better understanding of the initial state
  - study of meson-exchange currents (or 2p2h)
  - study of exclusive final states
    - one- and two-nucleon knockout
    - single and multiple pion production
    - largely influenced by **FSI**
    - relevant for calorimetric E_ν determination

Neutrino interactions on nuclei

- **νSTORM:** precise measurements of ν cross sections on heavy targets:
  - characterization of ν_e **vs** ν_μ **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:
  - **nces**
  - ate
  - (or 2p2h)
  - on



  - 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 ν cross sections on heavy targets:
  - characterization of ν_e **vs** ν_μ **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

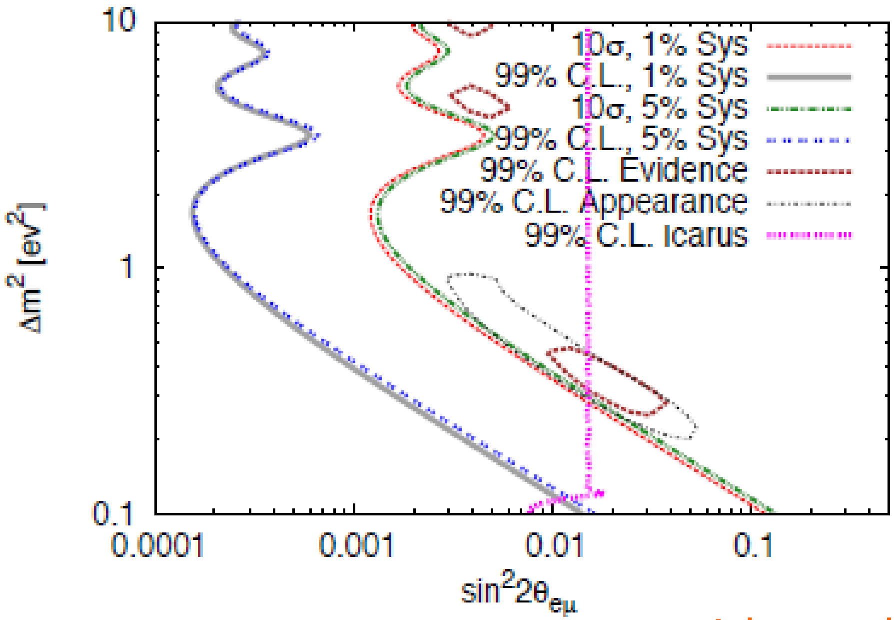
Short-baseline flavor transitions

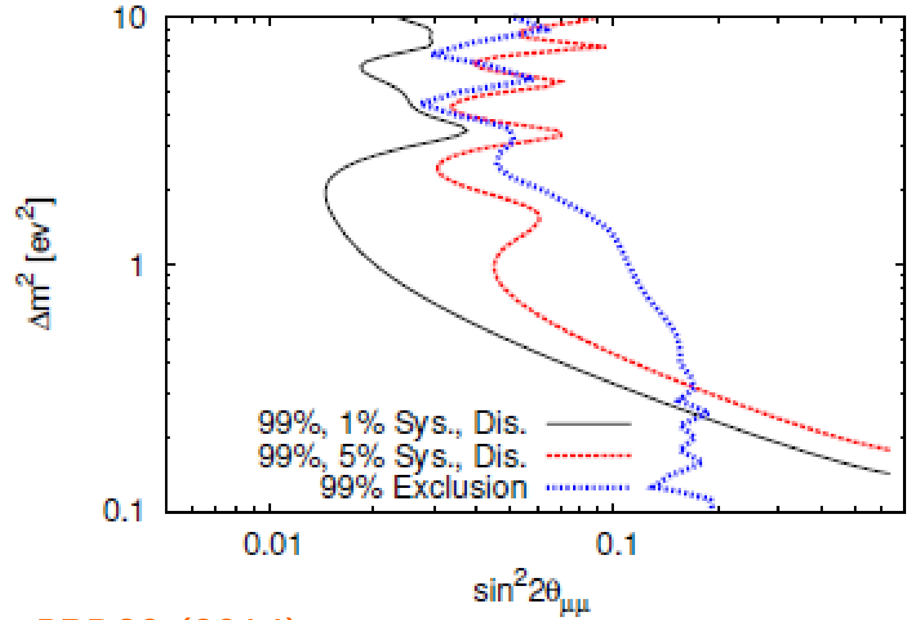
- ν**STORM** has a **unique sensitivity** to short-baseline **flavor** transitions.
- Concept: using $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ search for
- ν_μ **appearance** from $\nu_e \rightarrow \nu_\mu$
  - observing μ^- in large μ^+ background
    - requires good charge ID
- $\bar{\nu}_\mu$ **disappearance**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

- Non-unitarity of ν 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 ν search

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





Adey et al., PRD89 (2014)

Outlook

- Our present understanding of (few-GeV) neutrino interactions with matter would be **greatly improved** by new precise measurements with well-understood ν**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 σ)** the presently allowed parameter space.