NuFact 20|21

νSTORM physics reach: cross sections and exotics

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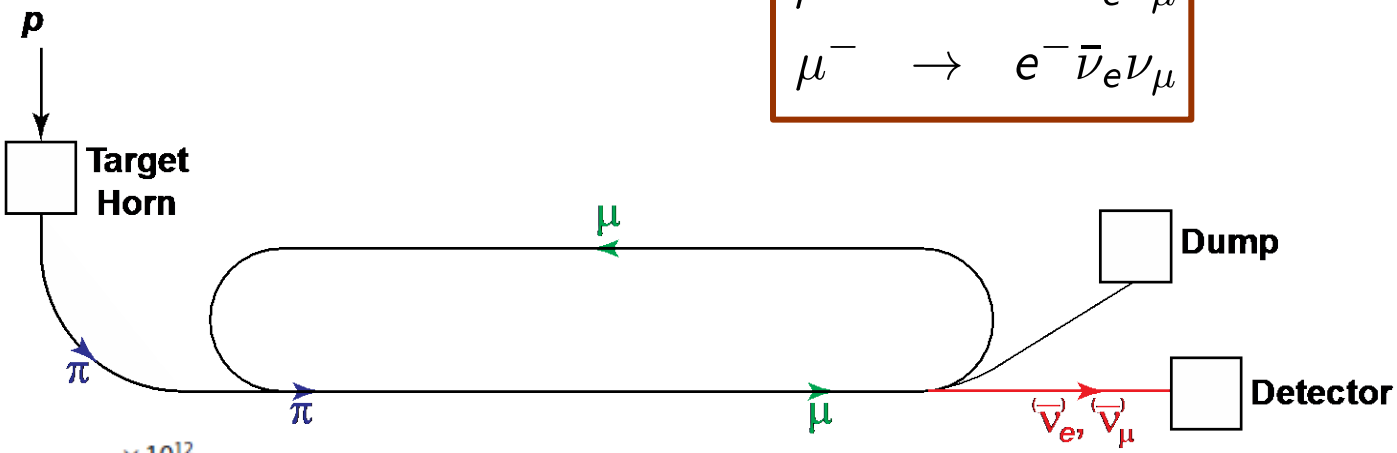
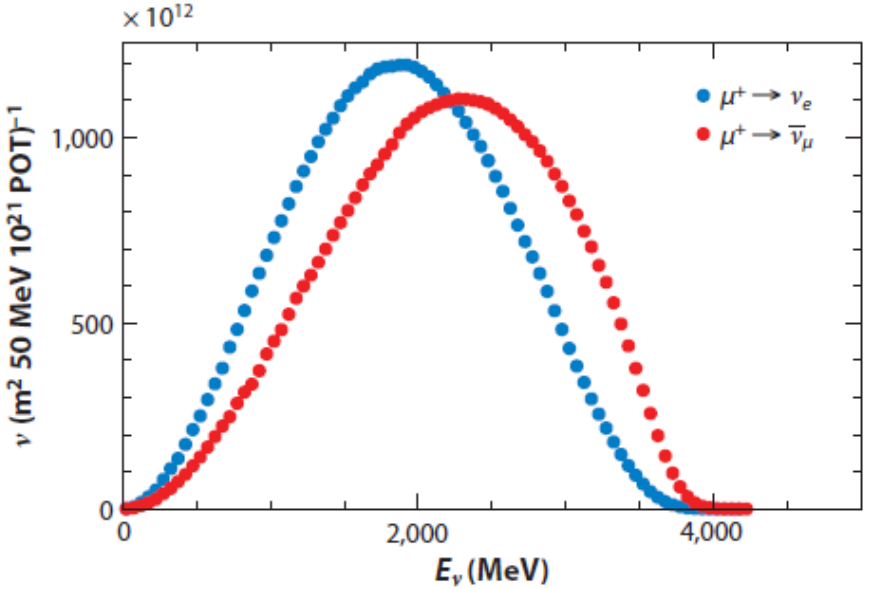
νSTORM

- Neutrinos from Stored Muons

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





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 reach:

- **Precise** (% level) and **detailed** neutrino cross section measurements
  - Exotic **BSM** reaction mechanisms
- 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.
  - Neutrino-nucleus scattering (mismodeling in event generators can lead to **systematic errors** even if tuned to the best data)
- 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)

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

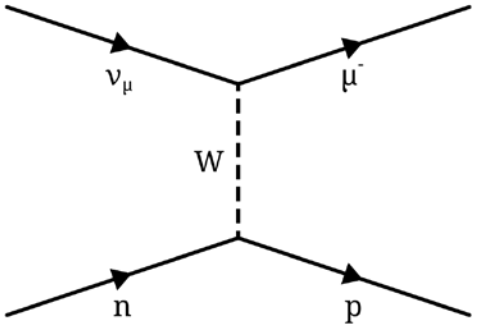
    or
    - indirectly: H-enriched targets + kinematic subtraction
      - High presure TPC (CH_4) using transverse kinematic invalance
      - Subtraction using CH_2 and C solid targets

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

Elementary processes

- Quasielastic scattering:

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



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

Elementary processes

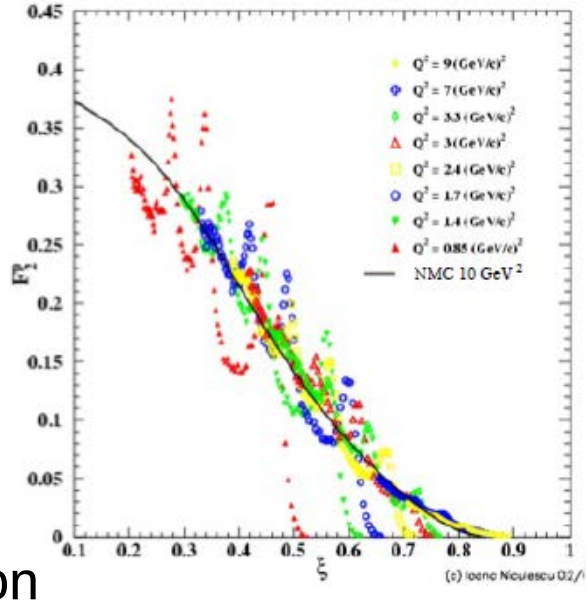
- Quasielastic scattering
- Inelastic scattering:
  - 1π production: dominated by $\Delta(1232)$ excitation
    - interference between RES and NonRES amplitudes, unitarity
- Above the $\Delta(1232)$ peak W>1.3 GeV:
  - several overlapping resonances
  - non-trivial interference
  - coupled channels
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

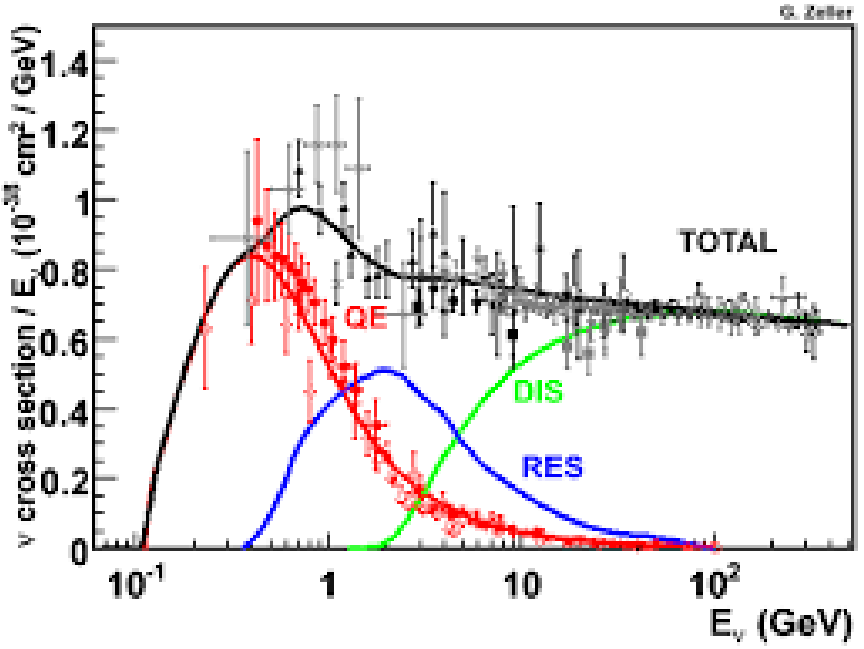


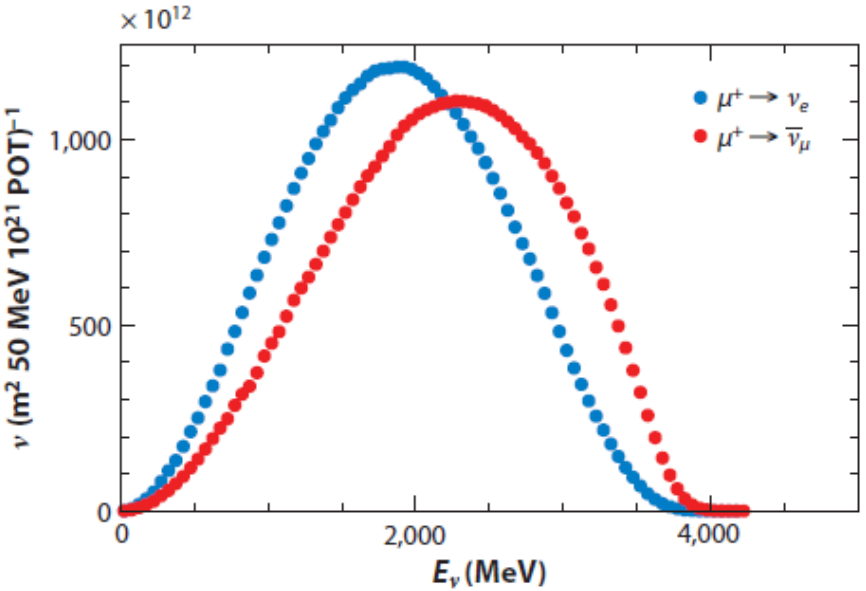
J. Morfin @ NuFact2021

- SIS & DIS covered by J. Morfin @ NuFact2021

Elementary processes

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

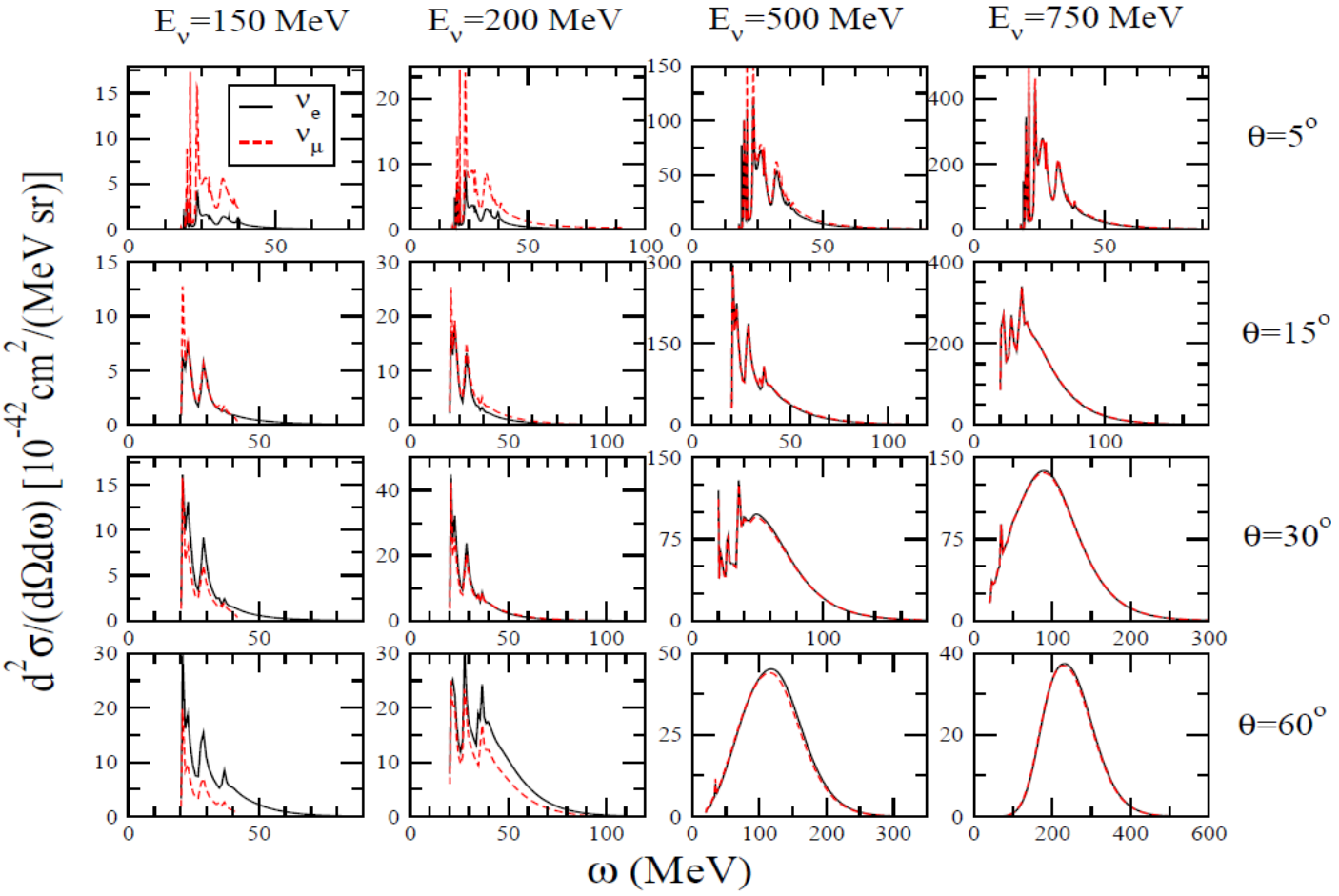




$1 \lesssim p_\mu \lesssim 6$ GeV/c

Neutrino interactions on nuclei

- **νSTORM:** 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

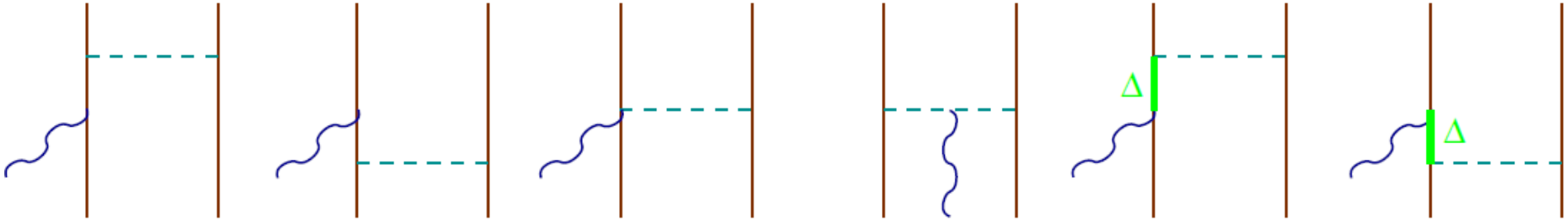
- **νSTORM:** precise measurements of ν cross sections on heavy targets:
  - characterization of ν_e **vs** ν_μ **differences**
    - Particularly important at low energy/momentum transfers (in Lab)
  - high-statistics for ν_e cross section and the $\sigma(\nu_e)/\sigma(\nu_\mu)$ ratio
    - Among the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

Neutrino interactions on nuclei

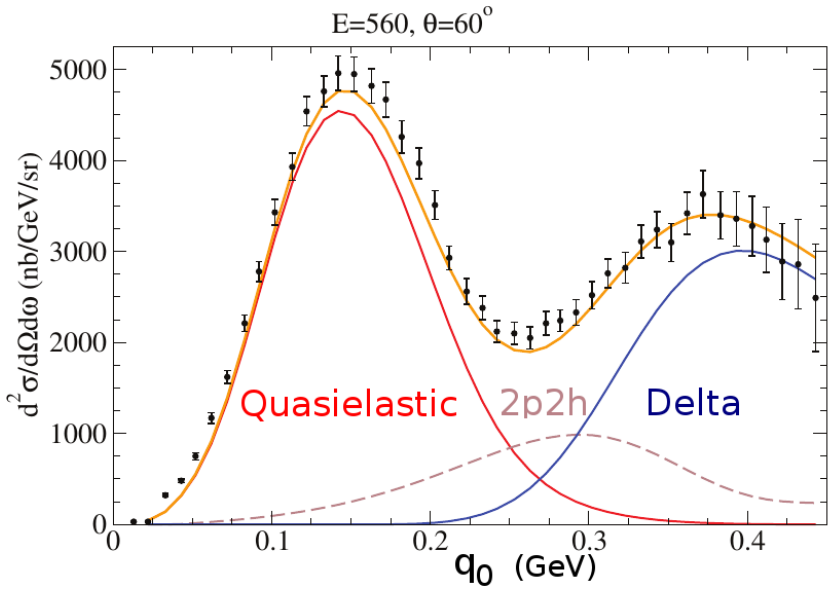
- **νSTORM:** precise measurements of ν cross sections on heavy targets:
  - characterization of ν_e **vs** ν_μ **differences**
  - better understanding of the initial state
  - study of meson-exchange currents (or 2p2h)

Two-nucleon currents

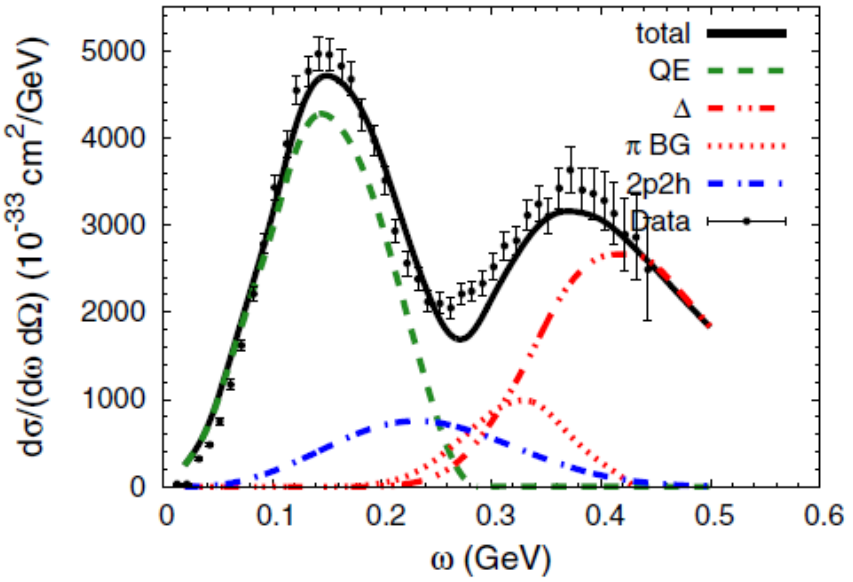
- 2-nucleon EW currents are allowed by symmetries



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



Megias et al., PRD 94 (2016)



Gallsmeister et al., PRD 94 (2016)

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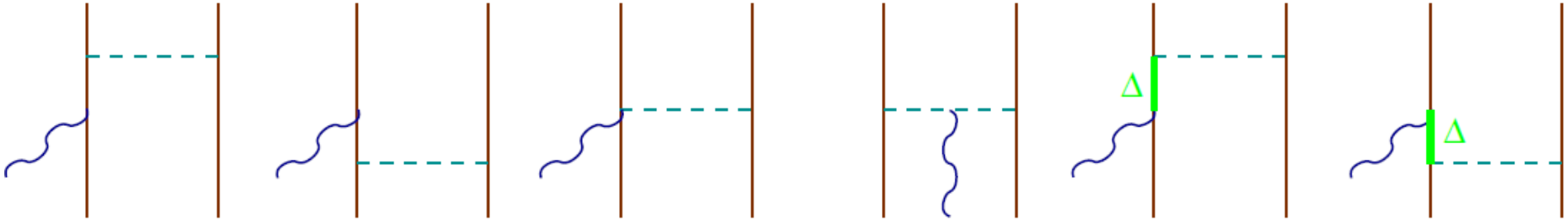
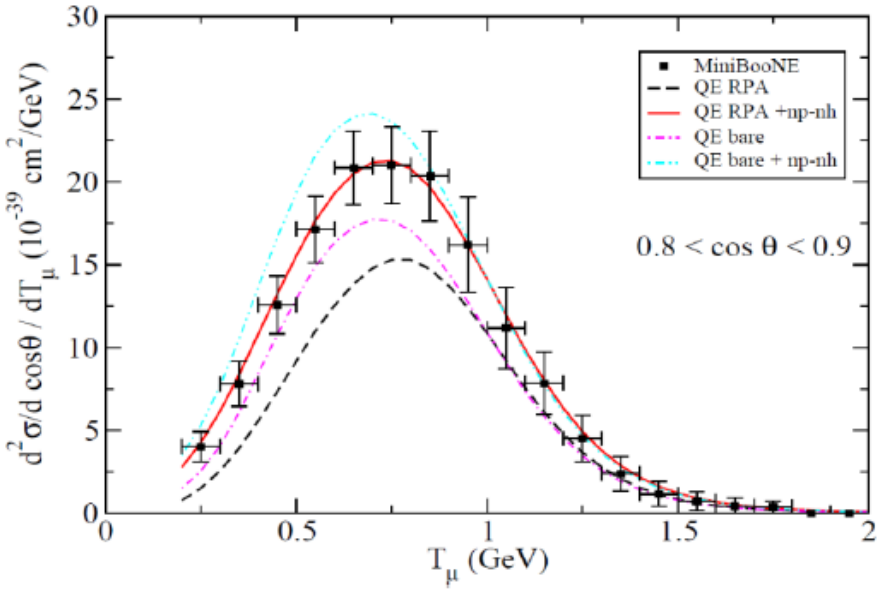
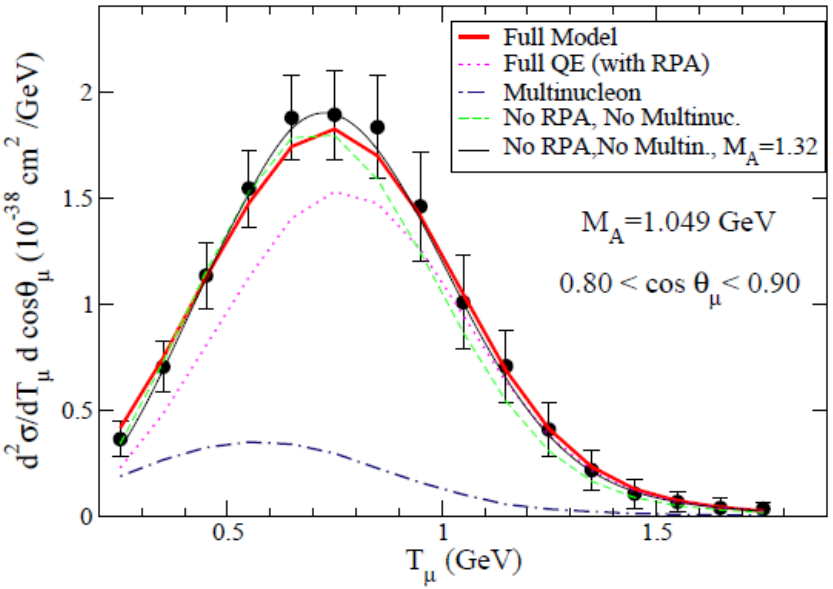


- together with better QE nuclear models can explain MiniBooNE data with $M_A \approx 1$ GeV



Martini et al.

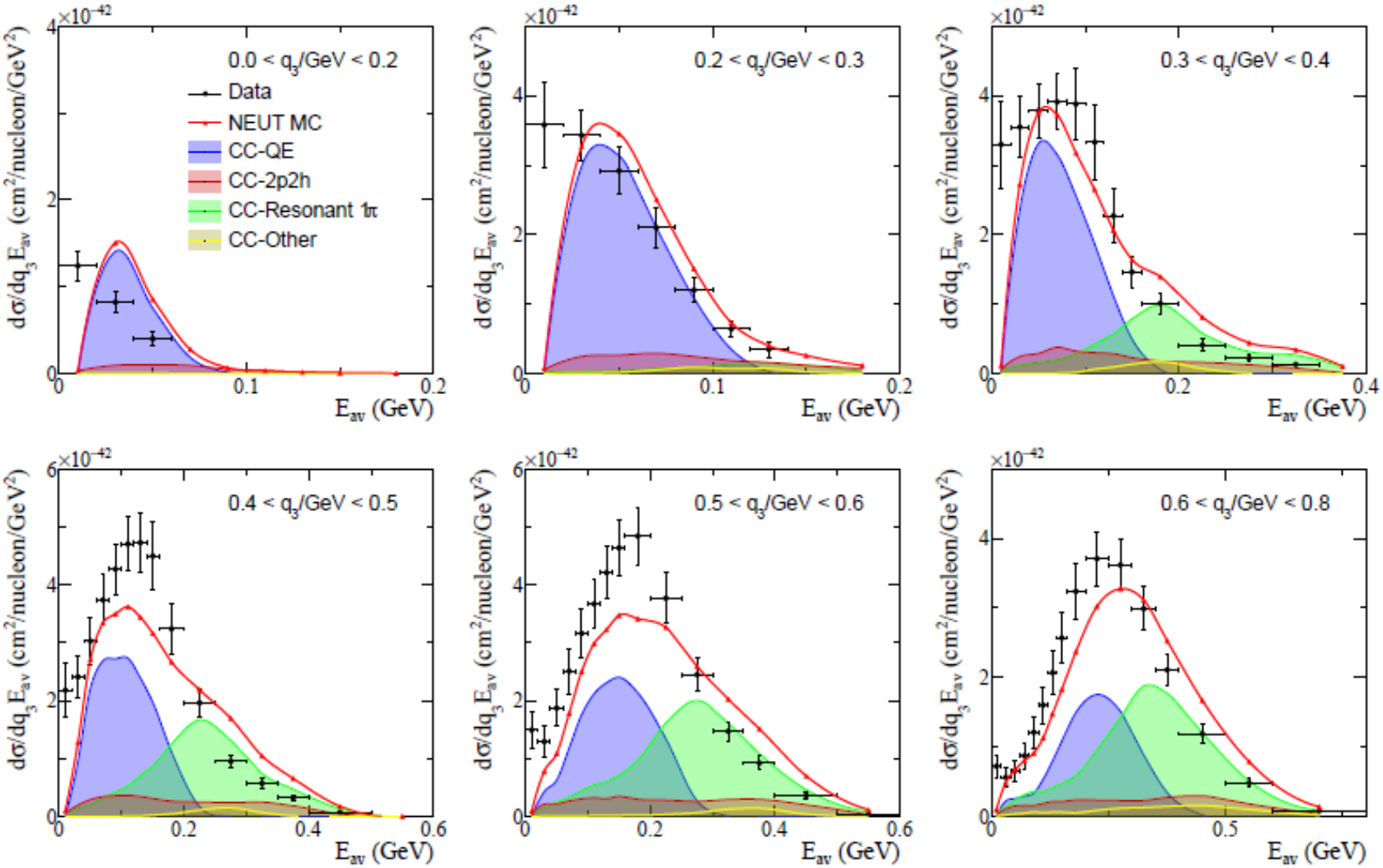


Nieves et al.

Neutrino interactions on nuclei

- **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)
    - 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)

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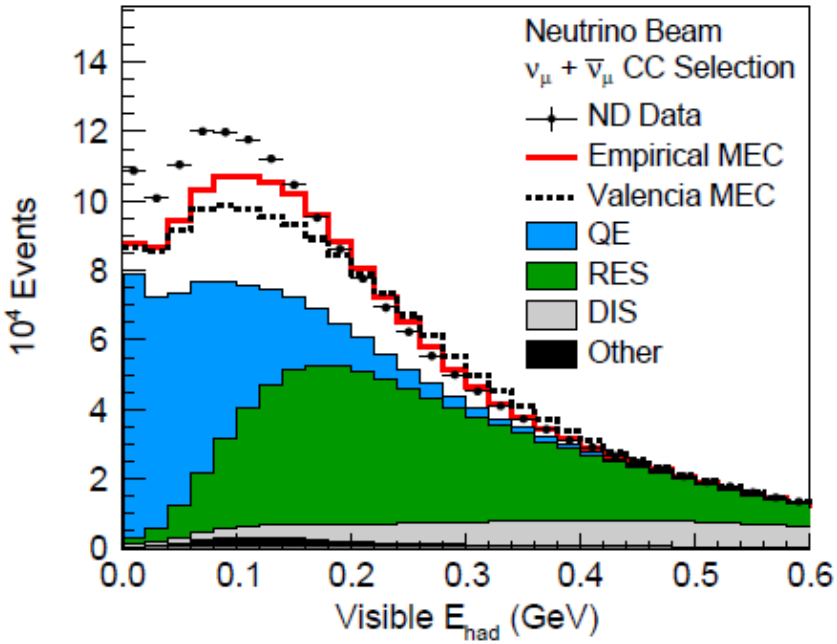

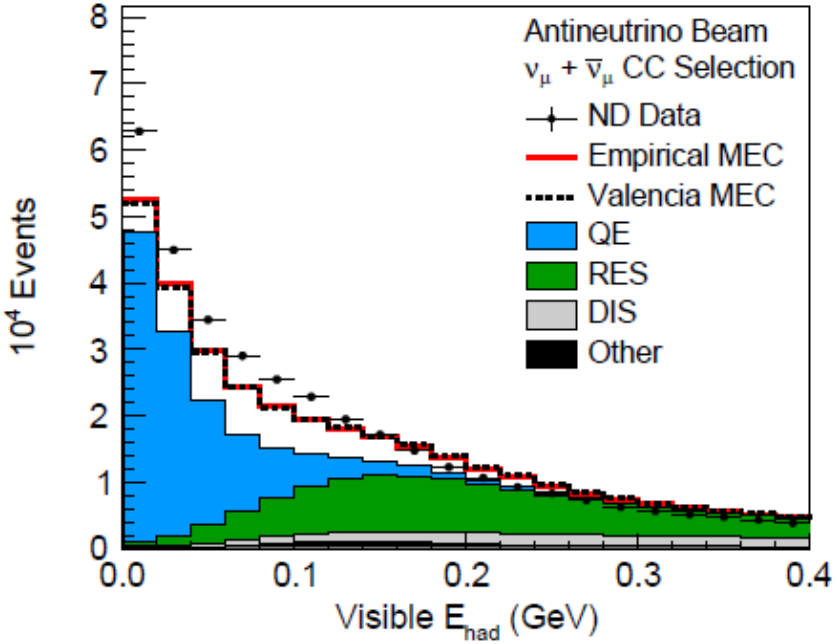

Acero et al., EPJ C 80 (2020)

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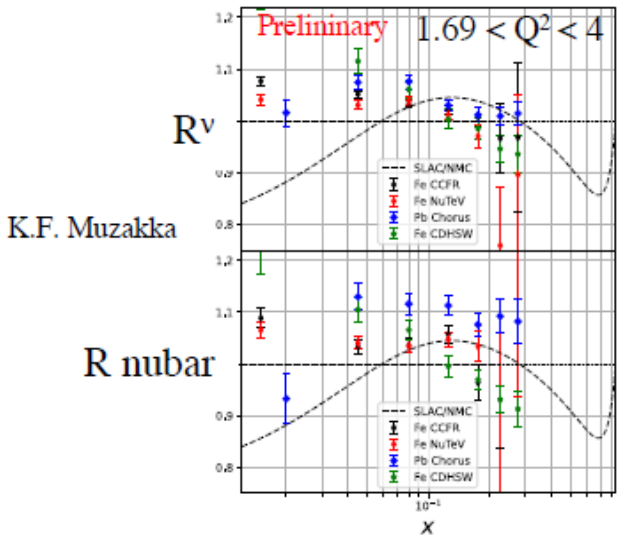
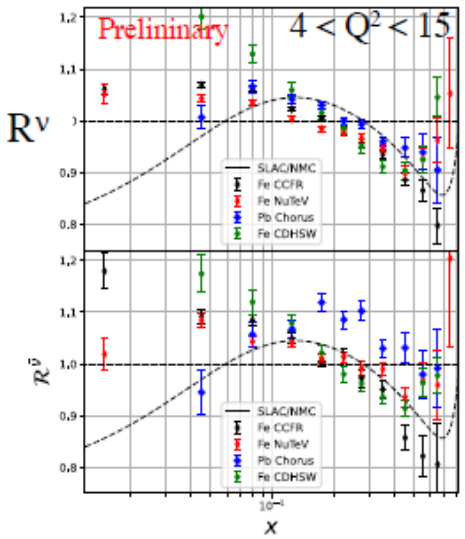
  - nuclear effects on PDF
    - understand the different nuclear effects in weak vs em processes
    - clarify the **tensions** between measurements with neutrinos and charged leptons

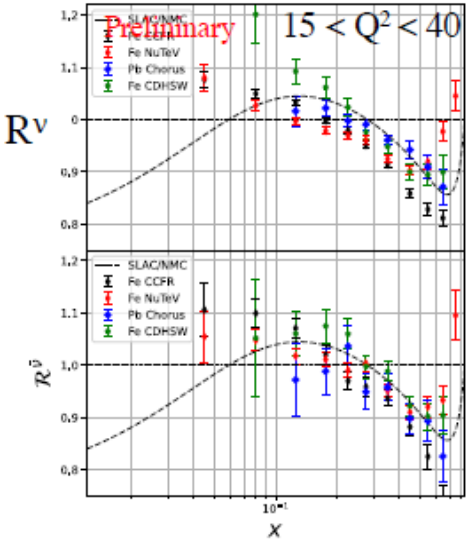
$$R = F_2(\nu - Fe;\ measured) \,/\, F_2[\nu - (n+p);\ PDFs]$$

J. Morfin @ NuFact2021



K.F. Muzakka





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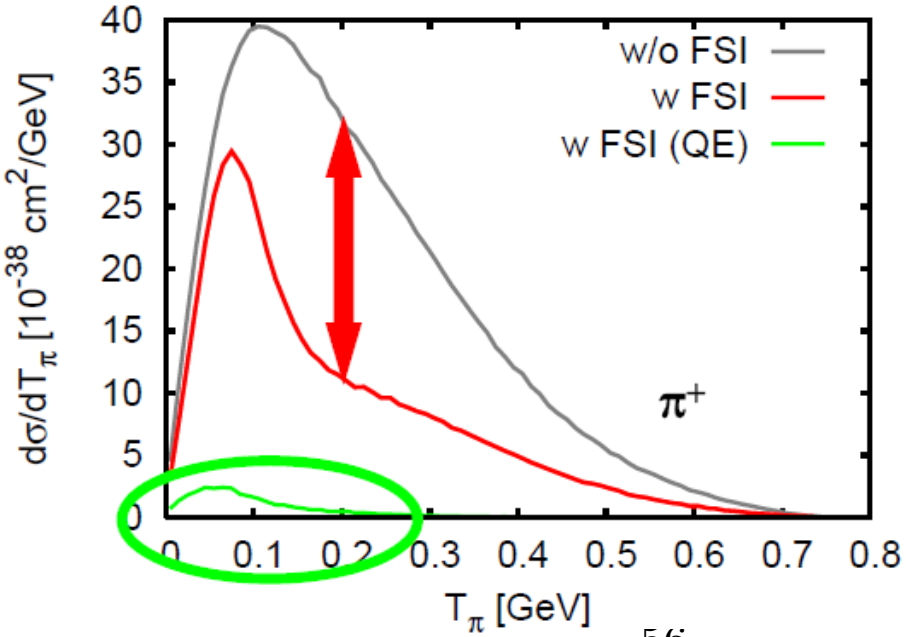
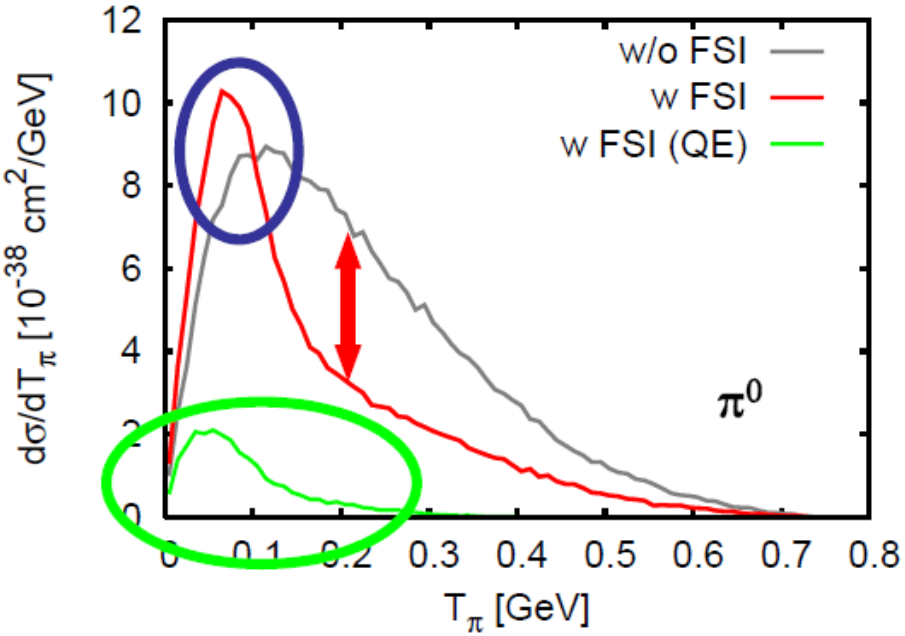
  - study of meson-exchange currents (or 2p2h)
  - nuclear effects on PDF
  - study of exclusive final states
    - one- and two-nucleon knockout
    - single and multiple pion production
    - largely influenced by **FSI**

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

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  - nuclear effects on PDF
  - 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

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    - one- and two-nucleon knockout
    - single and multiple pion production
    - **"Rare" processes**
    - strangeness production
    - coherent meson production

$$\nu_l\, A \to l^-\, m^+\, A$$
$$\bar{\nu}_l\, A \to l^+\, m^-\, A$$
$$m^\pm = \pi^\pm, K^\pm, \rho^\pm, \ldots$$

$$\nu\, A \to \nu\, m^0\, A$$
$$\bar{\nu}\, A \to \bar{\nu}\, m^0\, A$$
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Neutrino interactions on nuclei

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    - strangeness production
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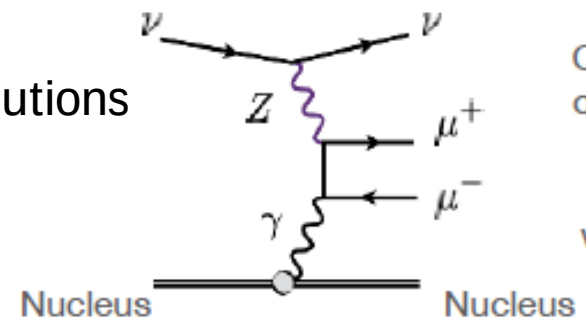
    - trident scattering
      - Possible BSM contributions

from M. Hostert



Cross section at the level of 10^{-6} of CCQE at 2 GeV

Magnetized detector with large Z nuclei is ideal.

Neutrino interactions on nuclei

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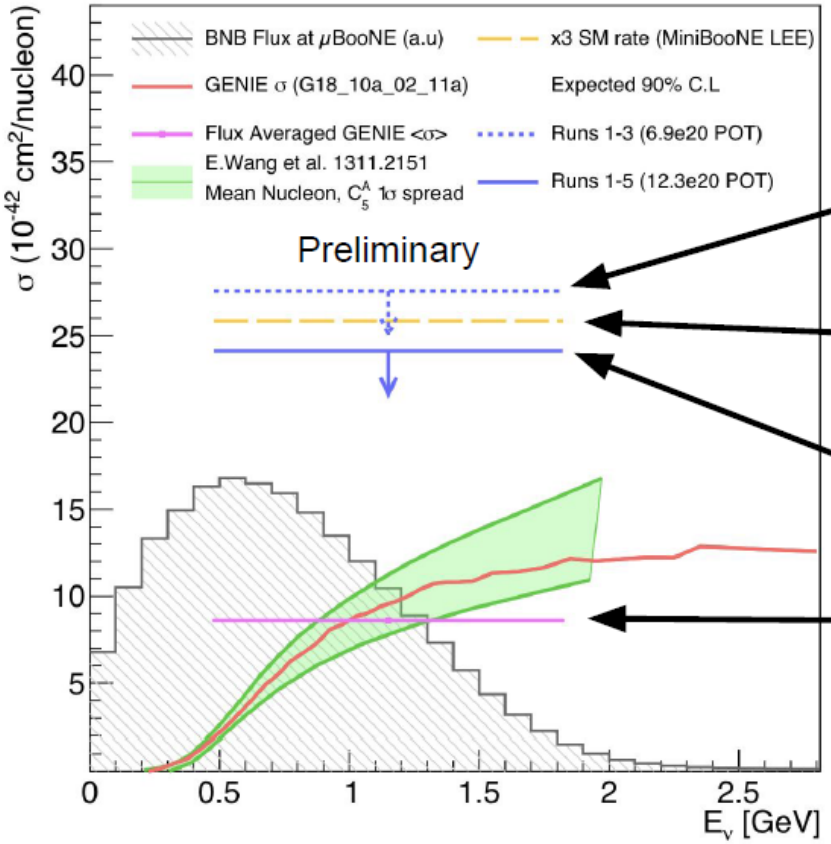
    - one- and two-nucleon knockout
    - single and multiple pion production
    - **“Rare” processes**
    - strangeness production
    - coherent meson production
    - trident scattering
    - single photon emission

MicroBooNE Projected Sensitivity



90% C.L. for **50% data**

3x SM rate $\Delta \rightarrow N\gamma$

90% C.L. for **100% data**

GENIE flux averaged xsec

- single photon emission
  - under study @ MicroBooNE K. Sutton @ NuFact 20|21
  - possible (BSM) explanations of the MiniBooNE anomaly

Exotic processes

- Heavy (1-100 MeV) neutrino production in scattering
  - Proposed as possible explanations of the MiniBooNE anomaly
  - $\nu_h \rightarrow \gamma$, e^+e^-
  - experimental γ, $e^\pm$, e^+e^- distinction required
  - ν_h can be produced:
    - EM (γ mediator), transit. mag. moment Masip et al, JHEP 1301 (2013)
    - NC (Z mediator), mixing Gninenko, PRL 103 (2009)
    - BSM (Z' mediator) Ballet et al., PRD 99 (2019)
      Bertuzzo et al., PRL 121 (2018)
      Arguelles et al., PRL 123 (2019)
      ...
  - On nuclear targets:

$$\nu_\mu(\bar{\nu}_\mu)\, A \rightarrow \nu_h(\bar{\nu}_h)\, A \quad \leftarrow \text{coherent}$$

$$\nu_\mu(\bar{\nu}_\mu)\, A \rightarrow \nu_h(\bar{\nu}_h)\, X \quad \leftarrow \text{incoherent}$$

Exotic processes

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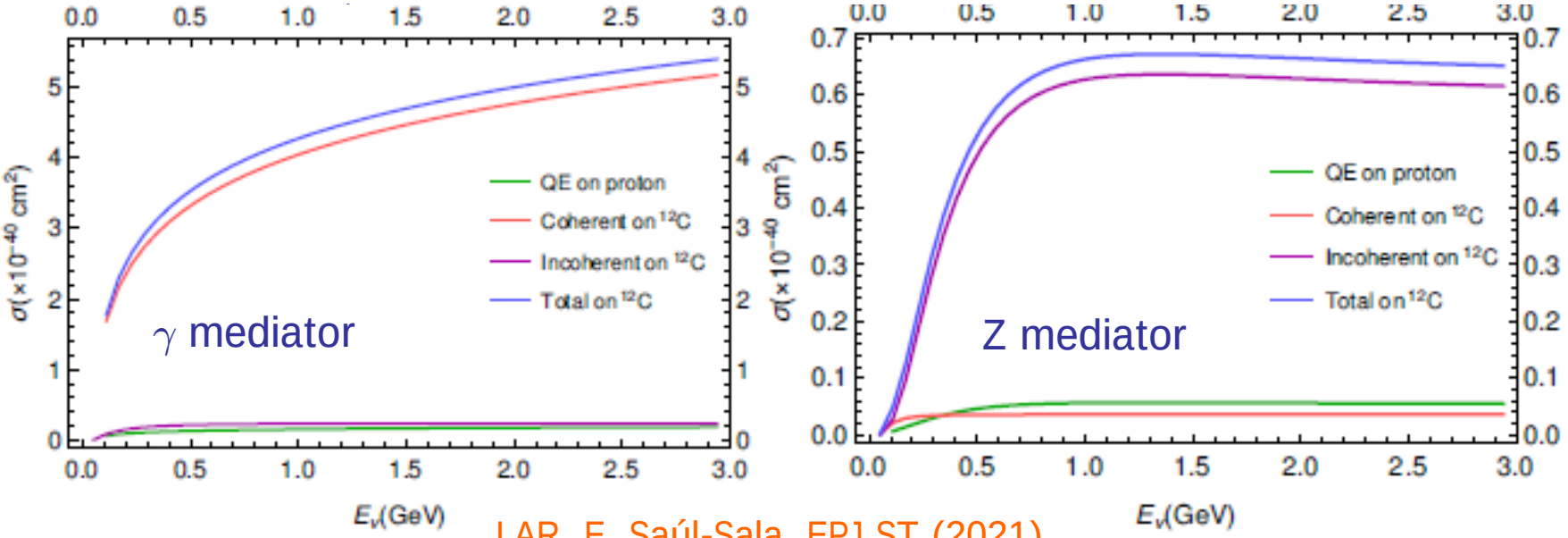
  - Proposed as possible explanations of the MiniBooNE anomaly



LAR, E. Saúl-Sala, EPJ ST (2021)

  - On nuclear targets:

$$\nu_\mu(\bar{\nu}_\mu)\, A \to \nu_h(\bar{\nu}_h)\, A \quad \leftarrow \text{coherent: light mediators}$$

$$\nu_\mu(\bar{\nu}_\mu)\, A \to \nu_h(\bar{\nu}_h)\, X \quad \leftarrow \text{incoherent: heavy mediators}$$

Exotic processes

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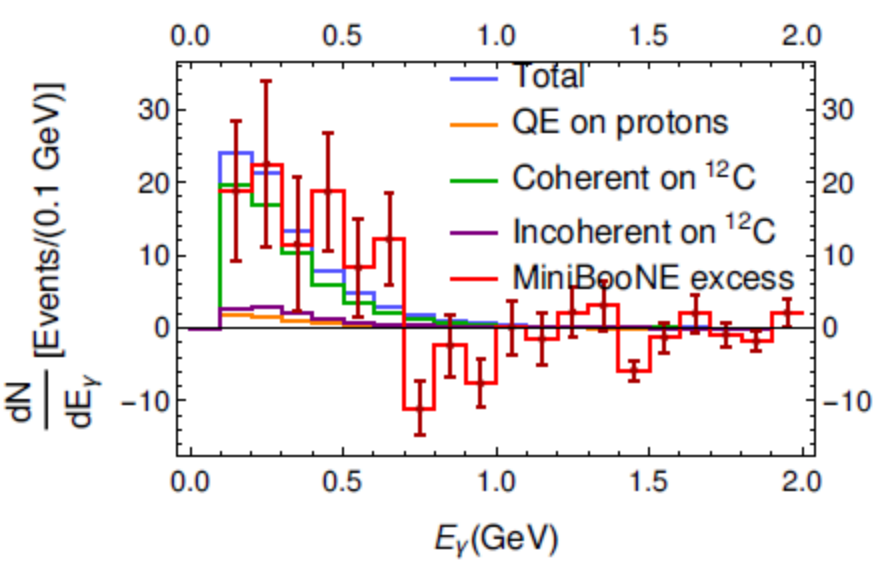

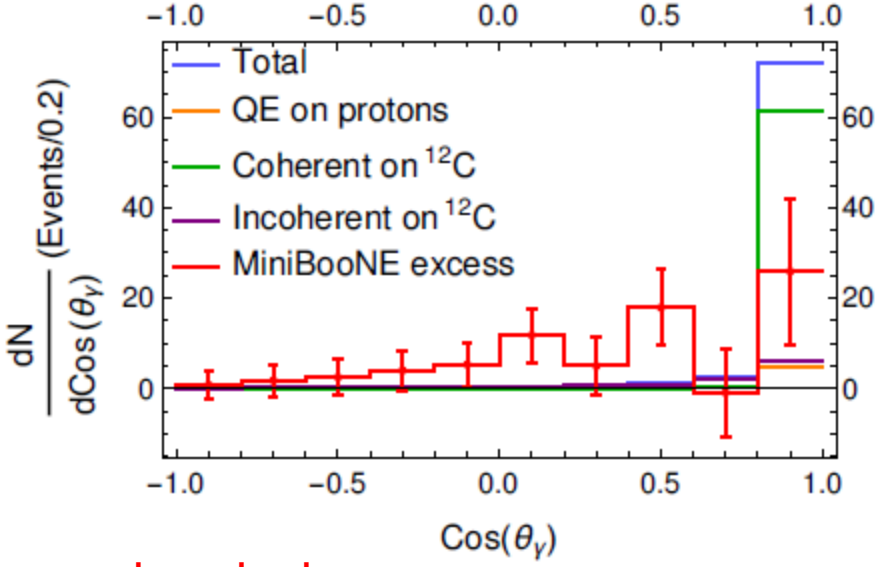

γ mediator: too forward peaked

  - On nuclear targets:

$$\nu_\mu(\bar{\nu}_\mu)\, A \to \nu_h(\bar{\nu}_h)\, A \quad \leftarrow \text{coherent: light mediators}$$

$$\nu_\mu(\bar{\nu}_\mu)\, A \to \nu_h(\bar{\nu}_h)\, X \quad \leftarrow \text{incoherent: heavy mediators}$$

Exotic processes

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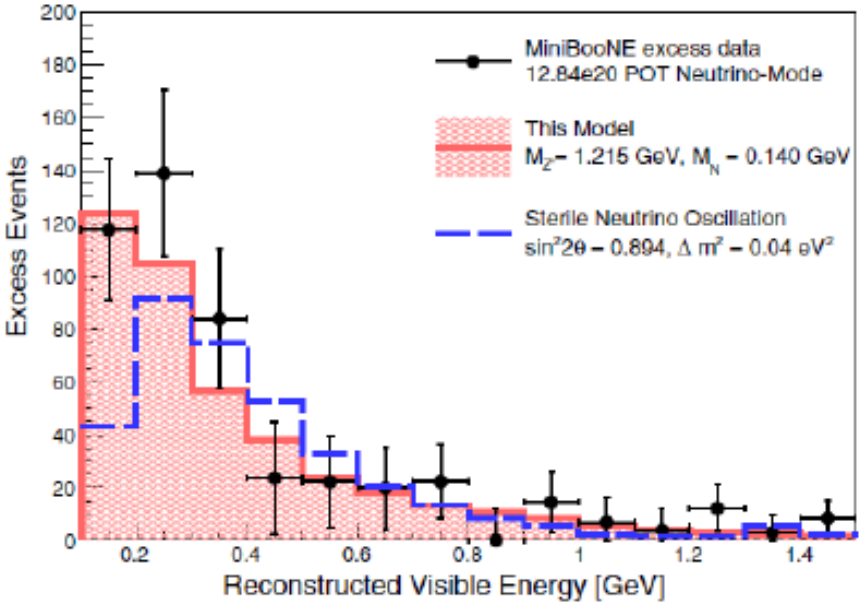
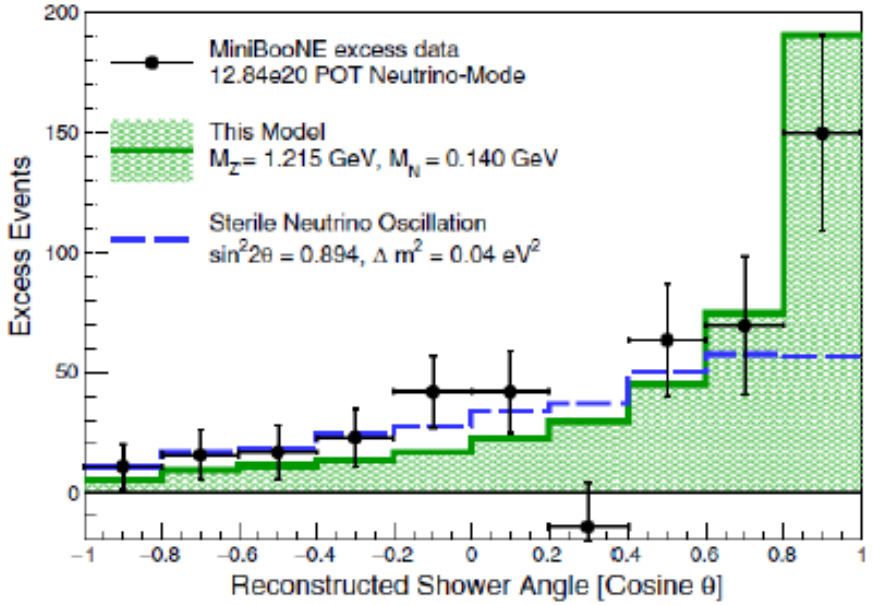




Z' mediator Ballet et al., PRD 99 (2019)

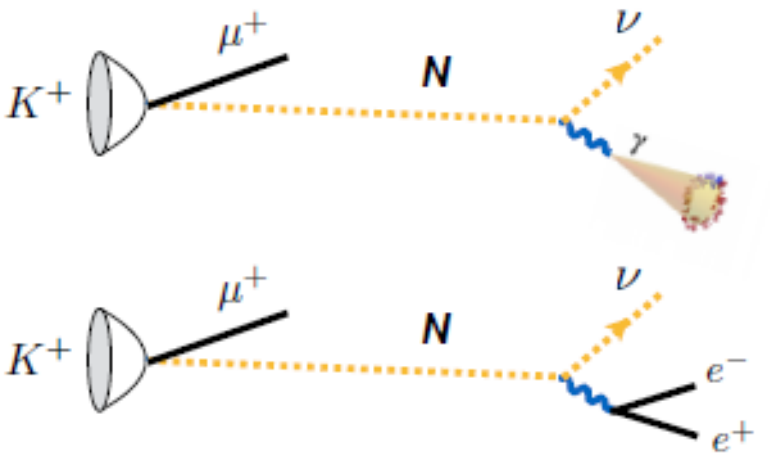
- On nuclear targets:

$$\nu_\mu(\bar{\nu}_\mu)\, A \to \nu_h(\bar{\nu}_h)\, A \quad \leftarrow \text{coherent: light mediators}$$

$$\nu_\mu(\bar{\nu}_\mu)\, A \to \nu_h(\bar{\nu}_h)\, X \quad \leftarrow \text{incoherent: heavy mediators}$$

Exotic processes

- Heavy (1-100 MeV) neutrino production in scattering
- Heavy (keV-MeV) neutrino production in decays



from M. Hostert

- experimental γ, $e^{\pm}$, e^+e^- distinction required

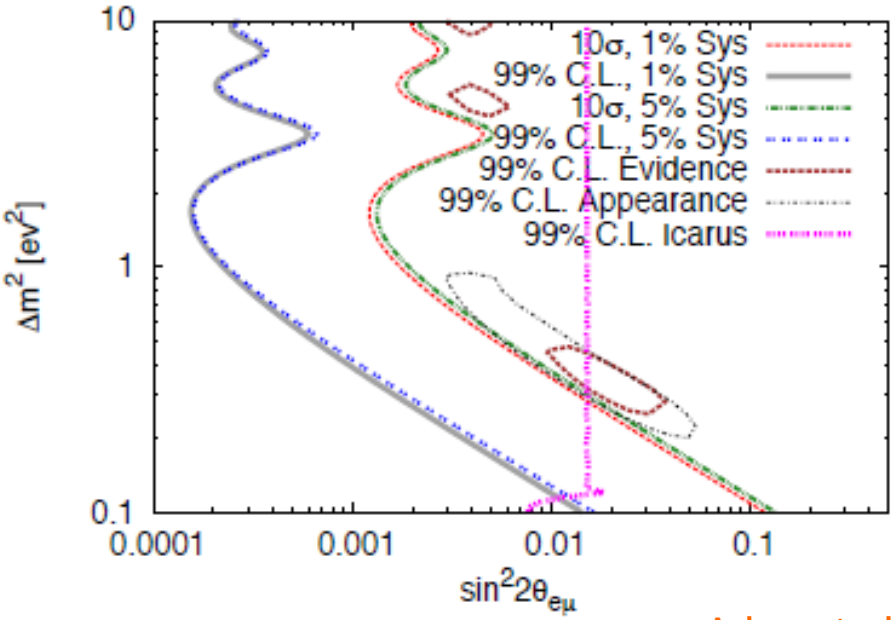
Short-baseline flavor transitions

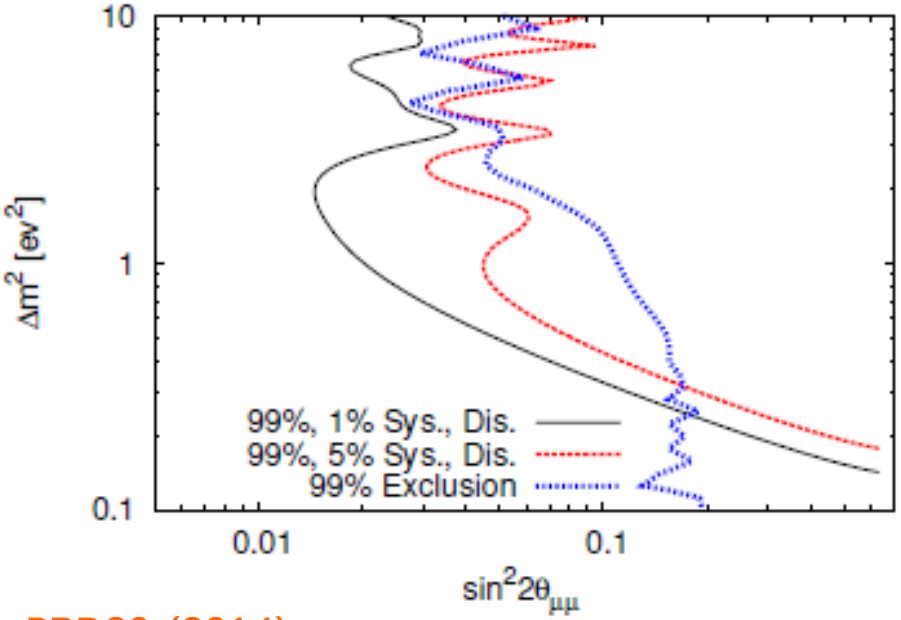
- **νSTORM** has a **unique sensitivity** to short-baseline **flavor** transitions.
- Concept: using $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ search for
- ν_μ **appearance** from $\nu_e \rightarrow \nu_\mu$
  - observing μ^- in large μ^+ background
    - requires good charge ID
- $\bar{\nu}_\mu$ **disappearance** 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 $\nu_e \rightarrow \nu_\mu$
- $\bar{\nu}_\mu$ **disappearance** from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- 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** and **exotic processes.**
- Sensitive searches for **short-baseline flavor transitions**: potential to **discover sterile neutrinos** or **exclude (10** σ**)** the presently allowed parameter space.