Cross Sections @νSTORM

Luis Alvarez-Ruso
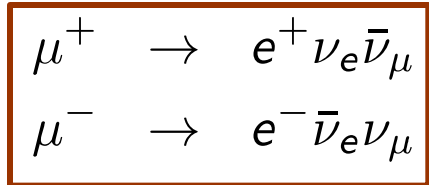
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νSTORM

- Precisely known flux:
  - Normalization
  - Flavor composition
  - Energy spectrum

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

- Ideal to measure (anti)neutrino cross sections
  - Unprecedented precision
  - For both electron and muon (anti)neutrinos
 - Energy scan

νSTORM legacy

- … concerning cross sections.
- **Beyond ancillary measurements** for ongoing/future oscillation experiments

νSTORM legacy

- ... concerning cross sections.
- Beyond ancillary measurements for ongoing/future oscillation experiments.

- Possibilities (compatible?):
  - **Elementary** cross sections (proton, deuteron)
  - **Neutrino-nucleus** cross sections
    - A-dependence (different targets)
    - Exclusive channels

  - Priorities ⇔ Detectors

Elementary processes

■ Poorly known; measured long ago (70, 80ies): ANL, BNL, FNAL,...
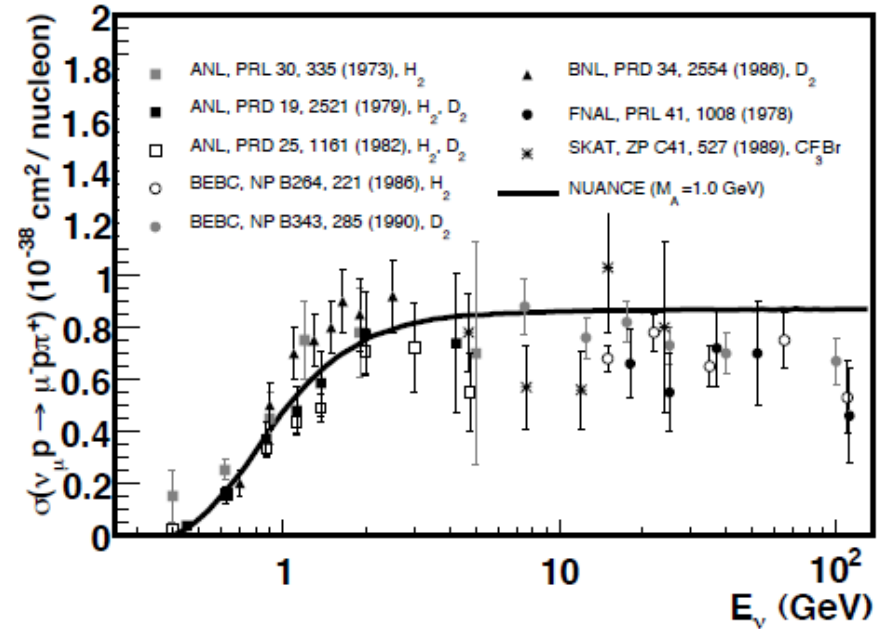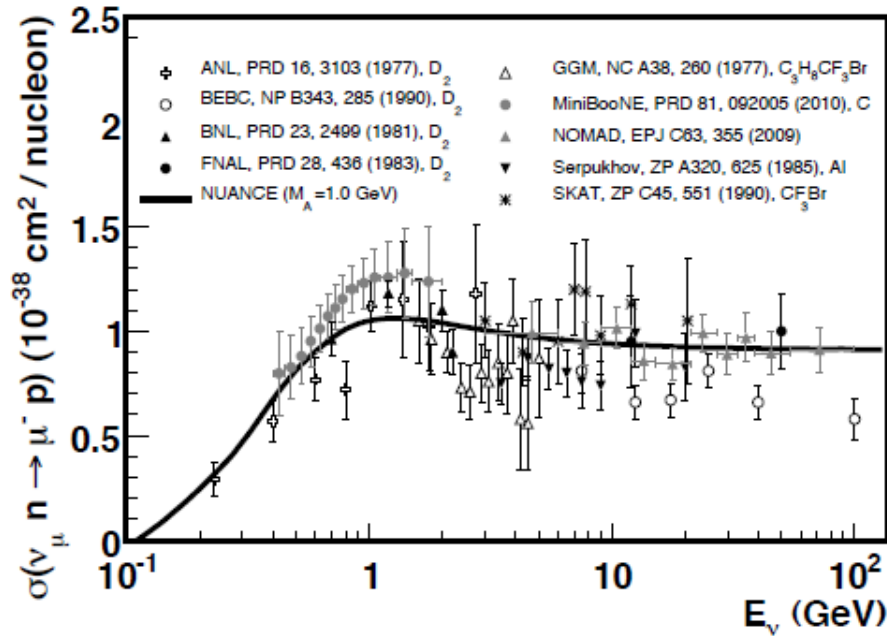

Formaggio & Zeller compilation

■ Not a priority for oscillation experiments...

  ■ ... but priceless input for event generators

■ No modern measurements

Elementary processes

- Poorly known; measured long ago (70, 80ies): ANL, BNL, FNAL,…

- No modern measurements, **except**:

  Measurement of the axial vector form factor from antineutrino–proton scattering, MINERvA, Nature (2023)

- "First high-statistics measurement (…)"
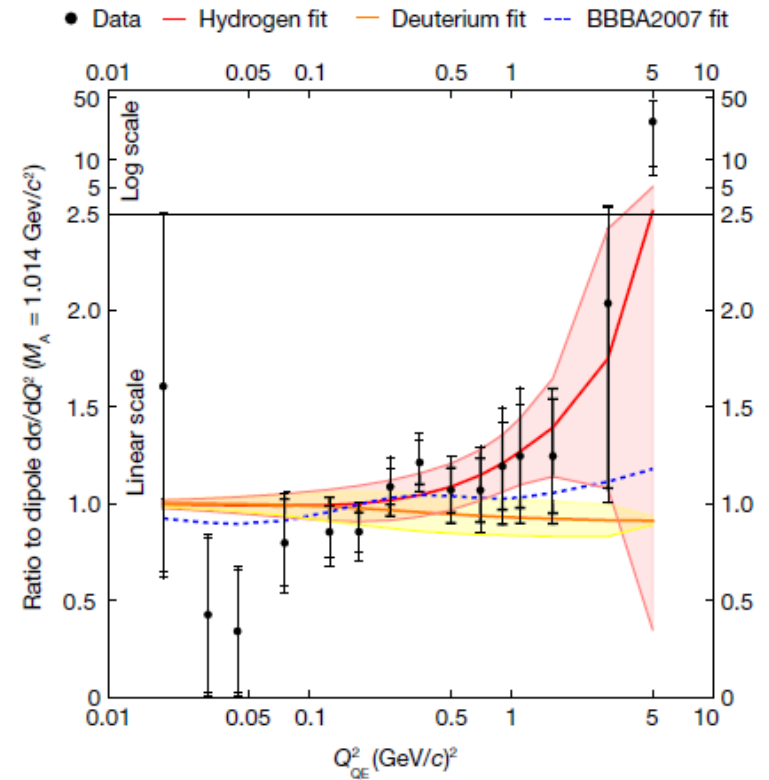
Elementary processes

- **Physics case**: LAR et al., 2203.11298 (Snowmass 2021)
- Quasielastic scattering (including Y production)
  - Axial FF determination
  - Given LQCD input for FF: constrain NSI
  - Radiative corrections (ν_e vs ν_μ)
- Inelastic scattering:
  - 1π production: dominated by $\Delta(1232)$ excitation
  - other processes: $\nu_l\, N \to l\, N'\, \pi\pi$

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

$$\nu_l\, N \to l\, \Lambda(\Sigma)\, \bar{K}$$

  strangeness production
  - Very limited information about the axial current at $q^2 \neq 0$

Elementary processes

- **Physics case**: LAR et al., 2203.11298 (Snowmass 2021)
- Quasielastic scattering
- Inelastic scattering
- Shallow inelastic scattering:
  - transition from RES to DIS
  - 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
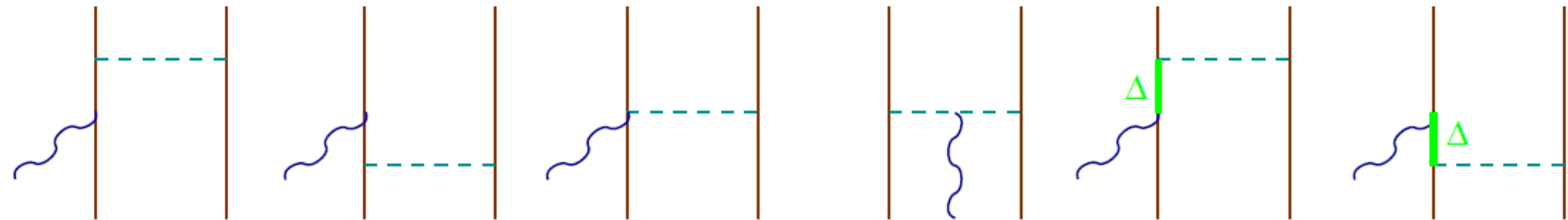 - Hadronization: exclusive channels

Neutrino-nucleus scattering

- **Physics case**:
    - Large overlap with the neutrino-nucleon physics
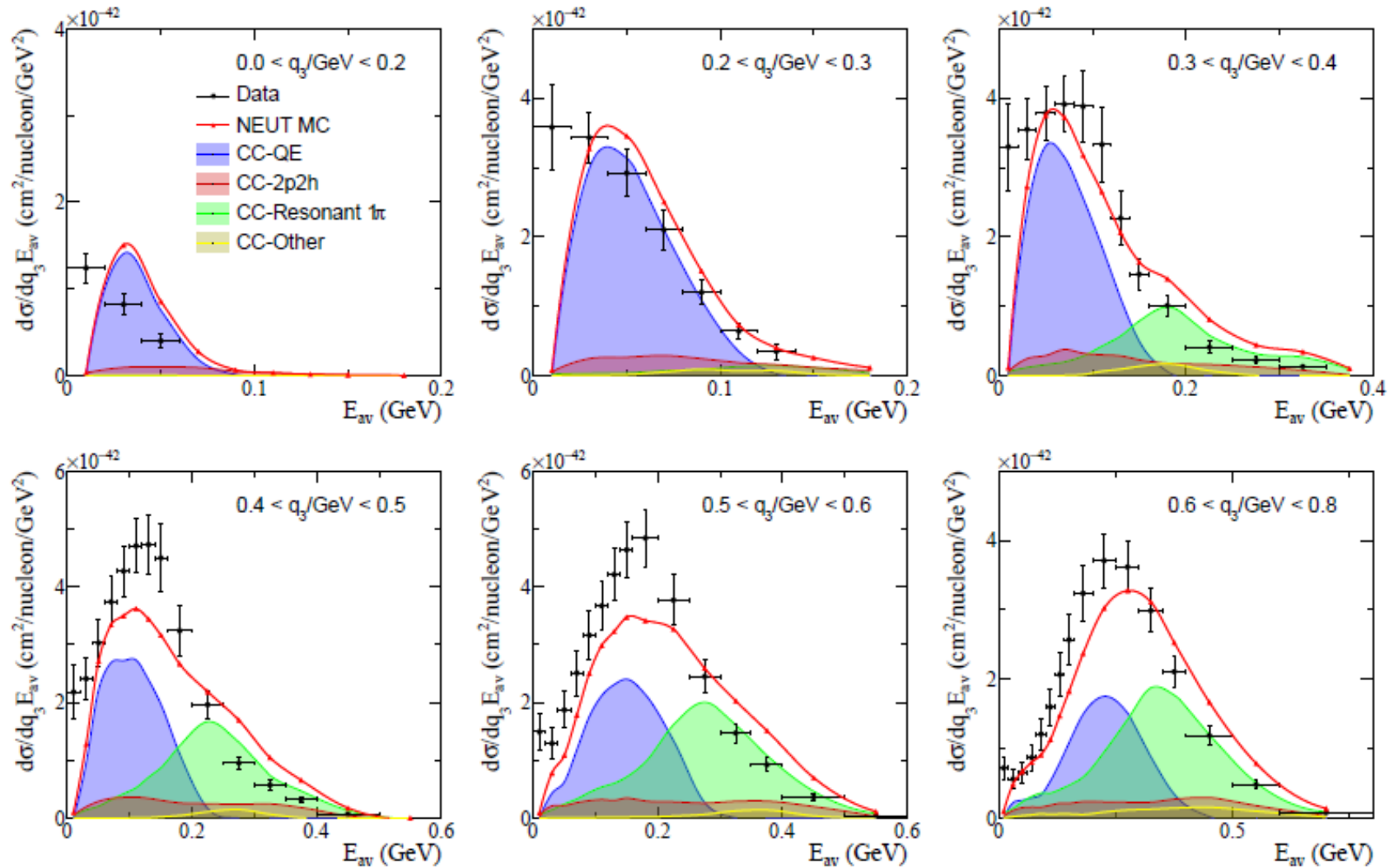   - Nuclear/multi-nucleon effects:
        - Collective modes
        - Meson-exchange currents (or 2p2h)

        - understand **discrepancies with theory** found @MINERvA, NOvA

Neutrino-nucleus scattering

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

Neutrino-nucleus scattering

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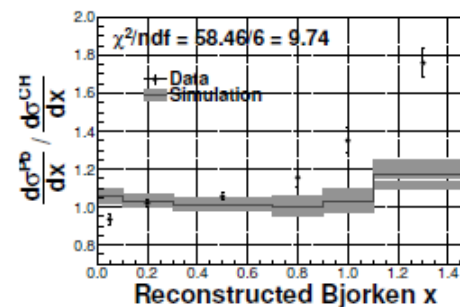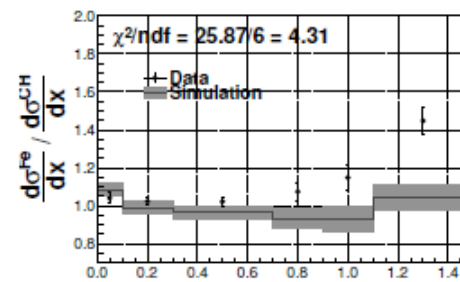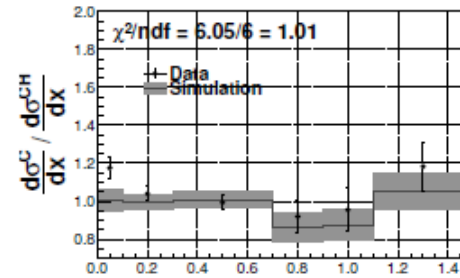   - Collective modes
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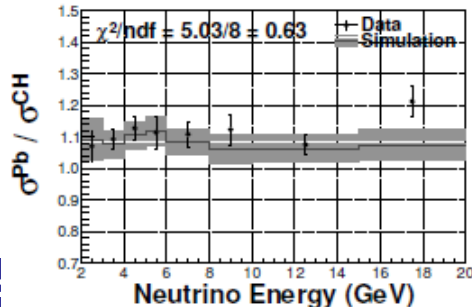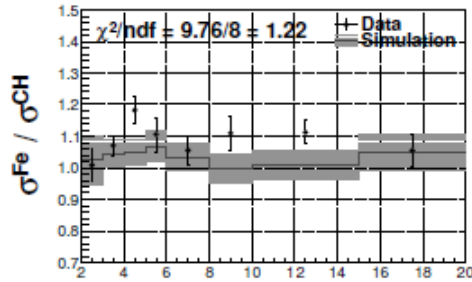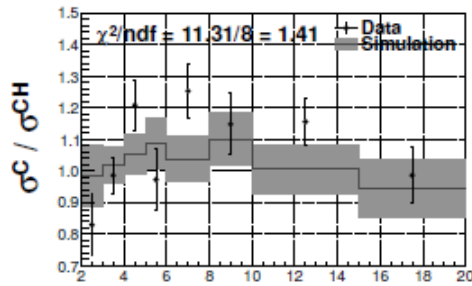   - Final State Interactions
    - Nuclear effects on PDF
    - Coherent processes

Neutrino-nucleus scattering

- Strategies:
  - A-dependence (different targets)
  - Some progress made by MINERvA:
  - Measurement of ratios of $\nu\mu$ charged-current cross sections on C, Fe, and Pb to CH at neutrino energies 2–20 GeV, Phys. Rev. Lett. 112, 231801 (2014)

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    - Simultaneous measurement of $\nu\mu$ charged-current single $\pi+$ production in CH, C, H_2O, Fe, and Pb targets in MINERvA, Phys. Rev. Lett. 131, 011801 (2023)

Neutrino-nucleus scattering

- Strategies:
  - A-dependence (different targets)
  - **Exclusive final states**:
    - one- and two-nucleon knockout
    - single and multiple pion production
      - Experimentally studied by MiniBooNE, T2K (ND280) and MINERvA
      - Tensions between data sets persist
    - largely influenced by **FSI**

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** but ν**STORM** legacy should go **beyond** it.

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

- Potential to **discover/constrain non-standard interactions** and **exotic processes.**