ASFAE ASTROFÍSICA Y FÍSICA DE ALTAS ENERGÍAS

Status of the ASFAE project on neutrino interactions

Weak Hyperon production

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GVANEXT Fondos Next Generation en la Comunitat Valenciana

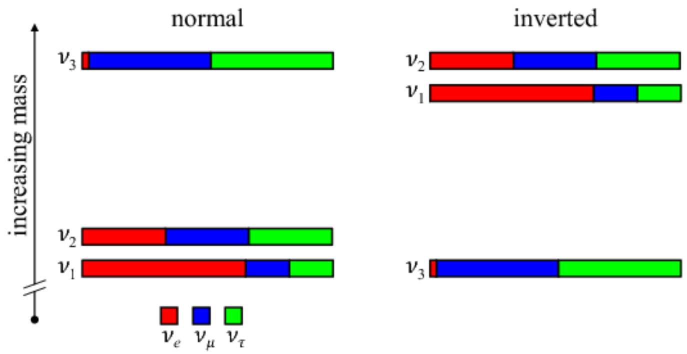
Context

- Neutrino Oscillations
  - Precise measurement of oscillation parameters

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j}^{n} \mathrm{Re}[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}]\sin^2 X_{ij}$$
$$+ 2\sum_{i<j}^{n} \mathrm{Im}[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}]\sin 2X_{ij}\,,$$

$$X_{ij} = \frac{(m_i^2 - m_j^2)L}{4E}$$

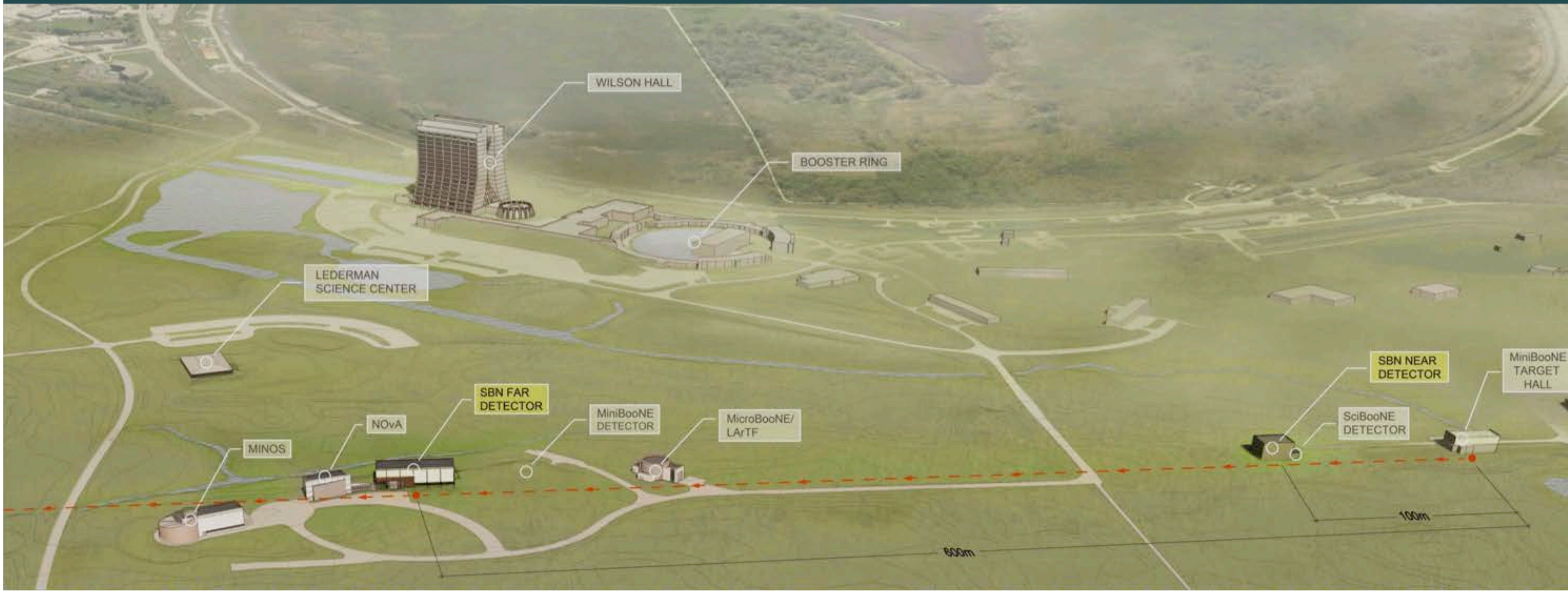
  - ν mass hierarchy, CP violation



Context

- Neutrino experiments (with accelerator ν)
- Future:

Short Baseline Neutrino Program



Context

- Neutrino experiments (with accelerator ν)
- Future:

Neutrino Interactions

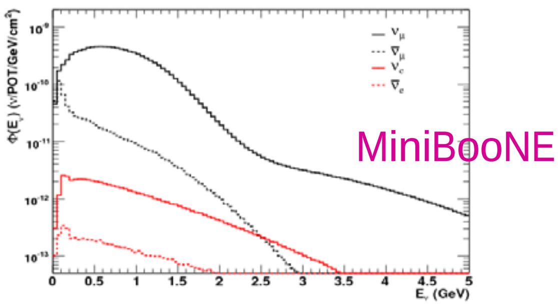
- Doorway to neutrino fundamental properties
  - ν detection
  - flavor identification
  - E_ν reconstruction: using kinematics and/or calorimetry

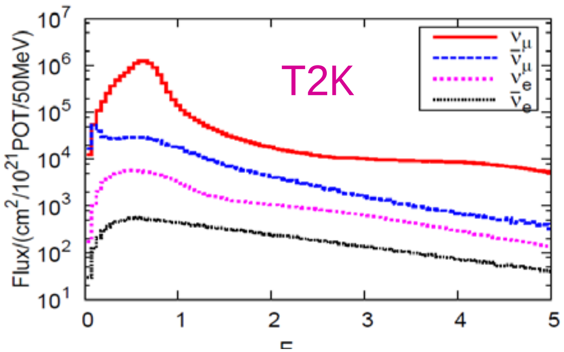
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j}^{n} \mathrm{Re}[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}] \sin^2 X_{ij}$$
$$+ 2\sum_{i<j}^{n} \mathrm{Im}[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}] \sin 2X_{ij} \,,$$

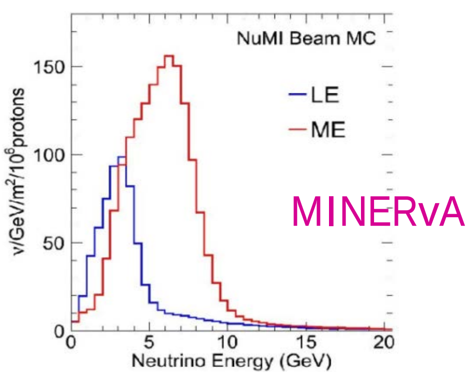
$$X_{ij} = \frac{(m_i^2 - m_j^2)L}{4E}$$

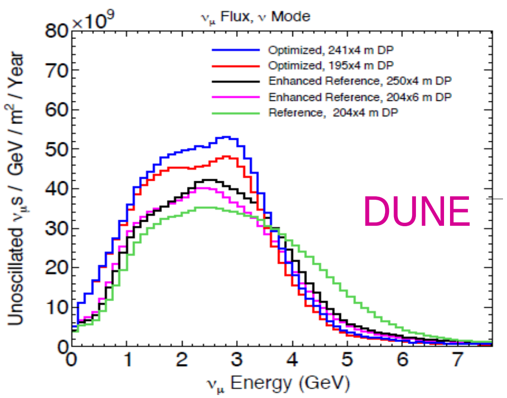
Neutrino Interactions

- Doorway to neutrino fundamental properties
  - ν detection
  - flavor identification
  - E_ν reconstruction: using kinematics and/or calorimetry
    - Neutrino beams are not monochromatic





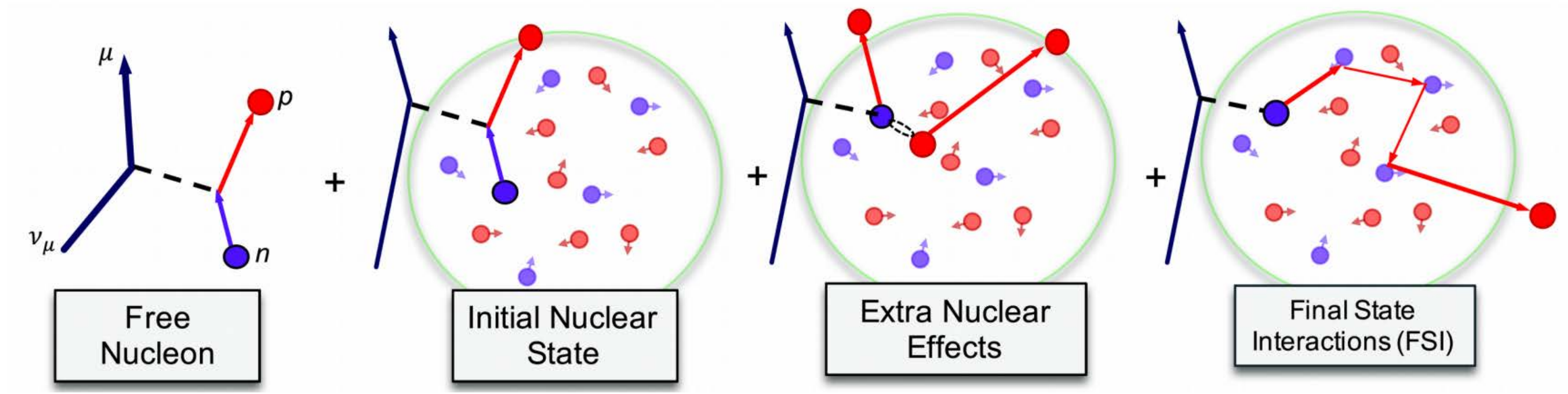




Neutrino Interactions

- Doorway to neutrino fundamental properties
  - ν detection
  - flavor identification
  - E_ν reconstruction: using kinematics and/or calorimetry
- Provide information/constrains on non-standard/generalized interactions

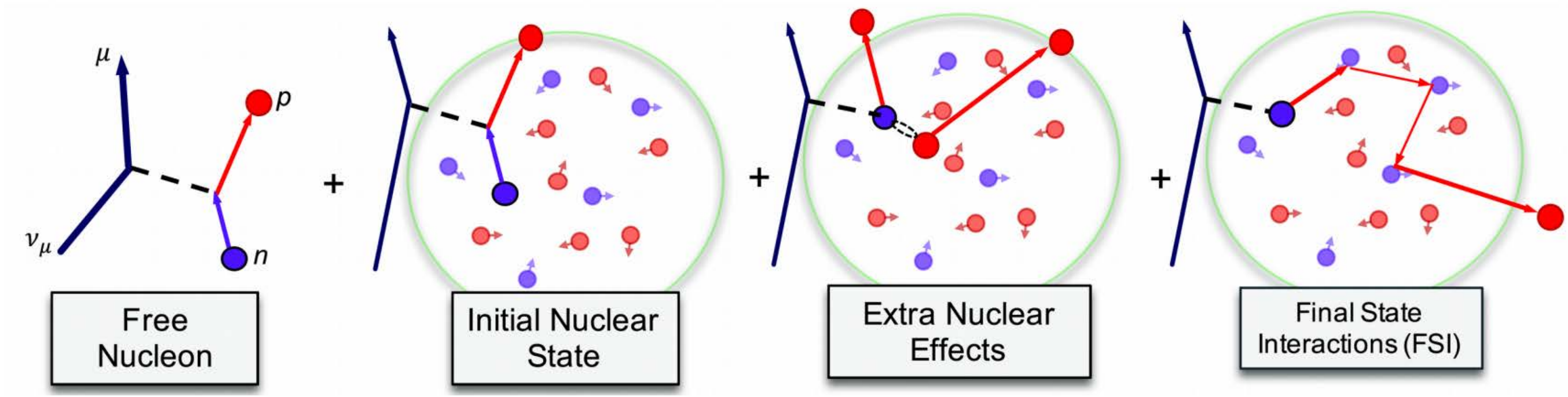
Neutrino Interactions



C. Wilkinson

- Need for neutrino interaction theory:
- Experiments (partially) rely on theory-based simulations for:
  - background subtraction
  - flux calibration
  - E_ν reconstruction
  - efficiency and acceptance determination
  - $\sigma(\nu_\mu)$ to $\sigma(\nu_e)$, target extrapolations
  - future projections
- Mismodeling can lead to systematic errors even if tuned to the best data.

Neutrino interaction theory



C. Wilkinson

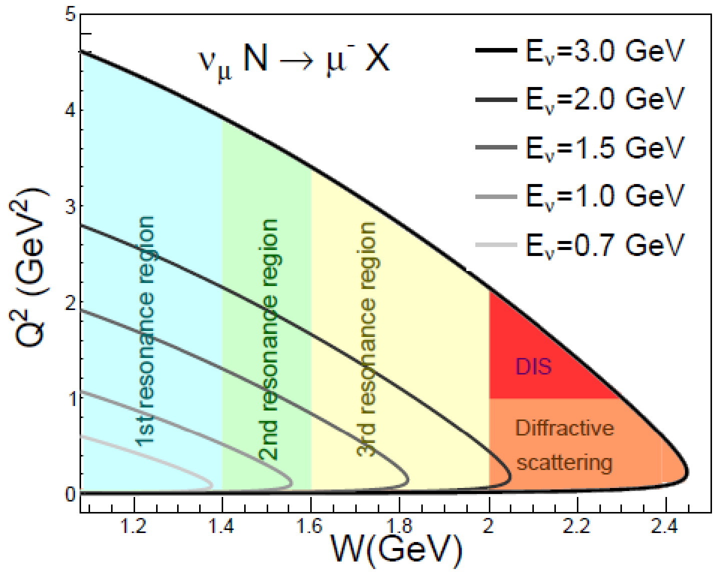
- @ IFIC: 15+ years developing advanced theoretical models and simulations of few-GeV neutrino interaction with matter:
  - Quasi-elastic scattering on nuclear targets.
  - Two-body currents.
  - Meson production on nucleons and nuclei.
  - Photon emission
  - Coherent processes
  - Strangeness production
  - Deep inelastic scattering

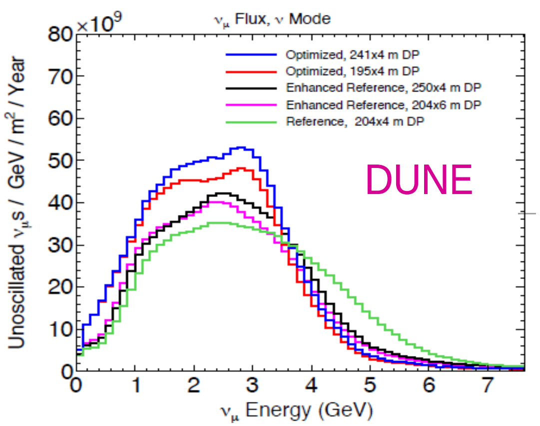
Neutrino interaction theory

- ASFAE project: Modeling neutrino interactions with matter for current and future experiments
- Current activity:
- Weak pion production of the nucleon over a broad kinematic range.
  Collaborator: M. Gorchtein (Mainz)
- Photon emission in NC interactions with nucleon knockout.
  Collaborator: M. Benítez (Granada)
- Meson production in $\bar{\nu}\, e^{-}$ collisions at FASERν (CERN)
- NC neutrino-nucleon scattering in presence of non-standard interactions.
  Collaborators: Ilma, R. Alam (Aligarh), I. Ruiz Simó (Granada)
- Weak hyperon production
  Collaborators: R. Alam (Aligarh), M. Benítez, I. Ruiz Simó (Granada)

Modeling neutrino interactions

- Weak pion production of the nucleon over a broad kinematic range.
  Collaborator: M. Gorchtein (Mainz)
- The most important inelastic process
  - Source of background eg NCπ^0 in Cherenkov detectors
- Proceeds predominantly through the excitation of nucleon resonances

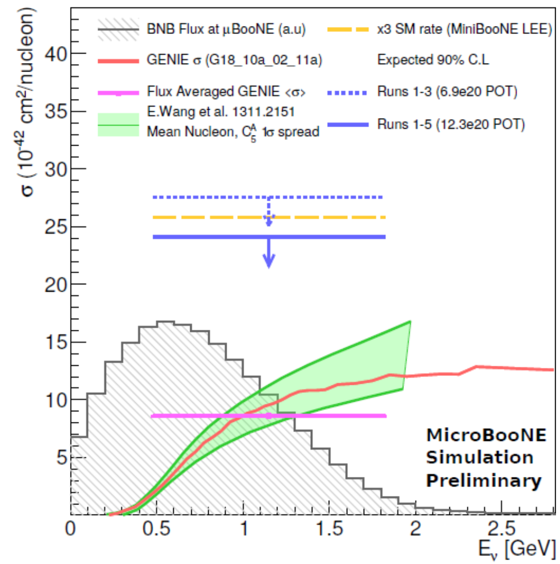




- Mainz Unitary Isobar Model for Pion Photo- and Electroproduction on the Nucleon (MAID) extended to the axial sector.
  - To be implemented in GENIE.

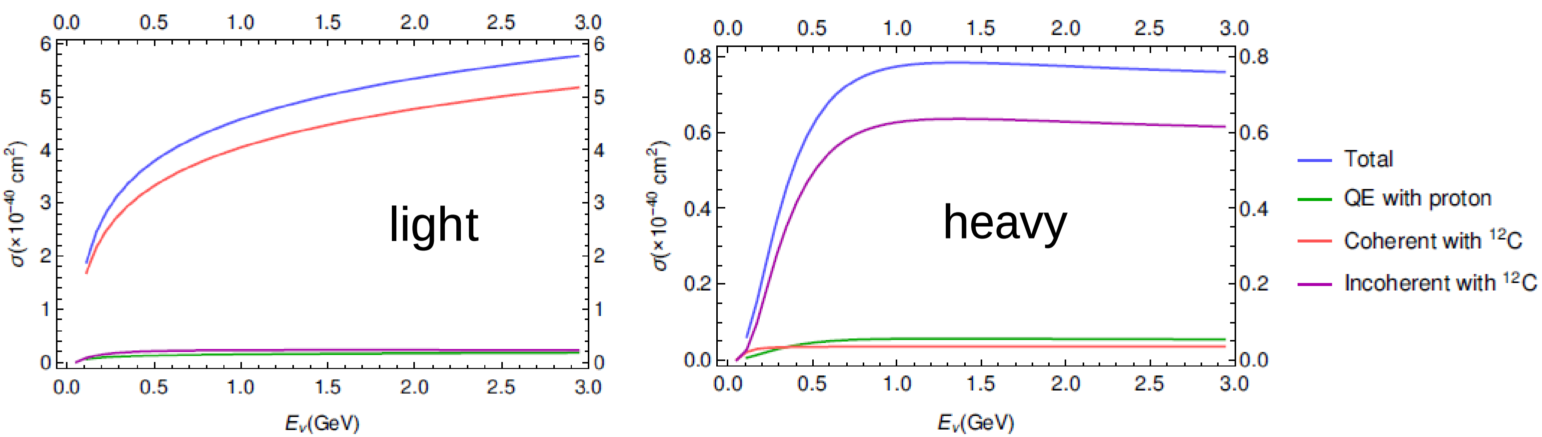
Modeling neutrino interactions

- Photon emission in NC interactions with nucleon knockout.
  Collaborator: M. Benítez (Granada)
- Electronlike background
  - Candidate to explain the MiniBooNE anomaly
    - **SM** and **BSM** mechanisms
- Upper bounds by T2K and MicroBooNE ➡



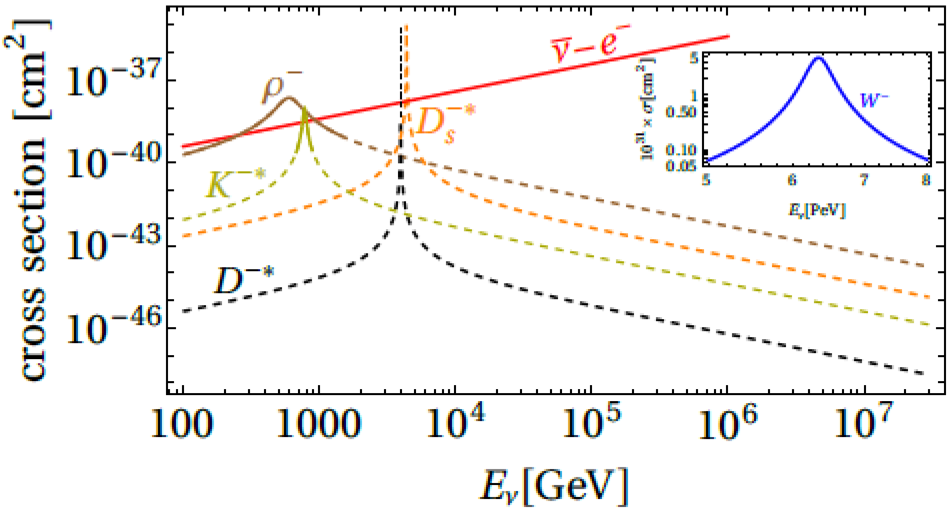
K. Sutton, PoS (NuFact 2021)

- Our task: Extend our study of $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$ to the exclusive γ p channel
- Comparisons to MicroBooNE and SBND future data
- Test the role of heavier **BSM** mediators:



Modeling neutrino interactions

- Meson production in $\bar{\nu}\, e^-$ collisions at FASERν (CERN)
  - High-energy (anti)neutrinos from collider
  - Brdar et al PRD 105 (2022) $\bar{\nu}\, e^- \to$ meson pairs ($\pi\pi$, πK, ...)



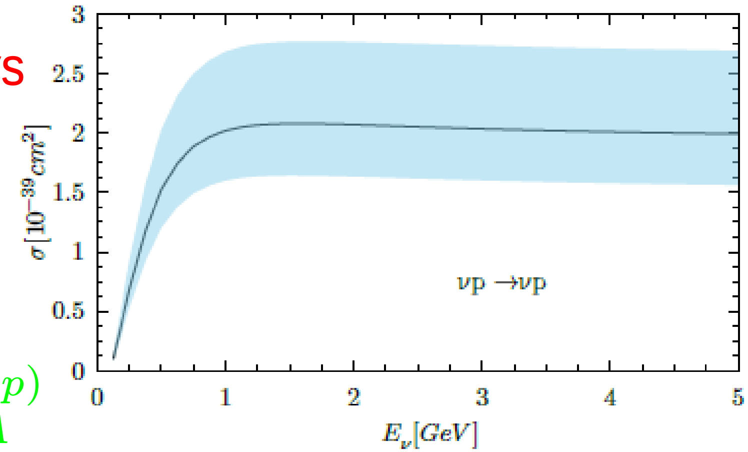
  - Our task:
    - Improve the calculation, particularly for πK
    - Extend the study to 3 mesons (through the axial current)
    - Complementary to τ decays
  - Lab threshold energies: E_ν= 78 GeV (2π), 176 (3π)

Modeling neutrino interactions

- NC neutrino-nucleon scattering in presence of non-standard interactions.
  Collaborators: Ilma, R. Alam (Aligarh), I. Ruiz Simó (Granada)
- Non-standard/generalized ν interactions can be (potentially) accessed in:
  - Oscillations (matter effects)
  - τ, β, (heavy) hadron semi-leptonic decays
  - ν scattering: ν-e , CEνNS, DIS
    - Other possibilities: eg $\nu\, p \to \nu\, p$

$$\langle p | J^\mu | p \rangle = \bar{u}(p')\Gamma^\mu u(p) = \mathcal{V}^\mu - \mathcal{A}^\mu$$

$$\Gamma^\mu = \gamma^\mu \tilde{F}_1^{(p)} + \frac{i}{2M}\sigma^{\mu\nu}q_\nu \tilde{F}_2^{(p)} - \gamma^\mu\gamma_5 \tilde{F}_A^{(p)}$$



- In presence of NSI:

$$\tilde{F}_{1,2}^{(p)} = \left(\frac{1}{2} - 2s_W^2 + 2\epsilon^{uV} + \epsilon^{dV}\right) F_{1,2}^{(p)} + \left(-\frac{1}{2} + 2\epsilon^{dV} + \epsilon^{uV}\right) F_{1,2}^{(n)} - \frac{1}{2} F_{1,2}^{(s)}$$

$$2\tilde{F}_A^{(p)} = \left(1 + \epsilon^{uA} - \epsilon^{dA}\right) F_A^{iv} + \left(\epsilon^{uA} + \epsilon^{dA}\right) F_A^{is} - F_A^{(s)}$$

  - Reliable (flavor decomposed) input from LQCD required
  - Complementary to DIS

Weak hyperon production

- ΔS = -1: $W^- u \to s$
- Cabibbo reduced ($V_{us} = 0.23$)
- Via Y$\to \pi$ N, Y are a source of low energy π in $\bar{\nu}$ scattering
- Y production could be used to constrain $\bar{\nu}$ contamination in ν beams

Weak hyperon production

- ΔS = -1: $W^{-}u \to s$
- Cabibbo reduced ($V_{us} = 0.23$)
- Quasielastic:
  - Lowest threshold: W ≥ 1.1 GeV $\Leftrightarrow$ $\boldsymbol{E_{\nu}}$ ≥ 0.2 GeV
  - Y:

$$\begin{aligned} \bar{\nu}_l\, p &\to l^+\, \Sigma^0(\Lambda) \\ \bar{\nu}_l\, n &\to l^+\, \Sigma^- \end{aligned}$$

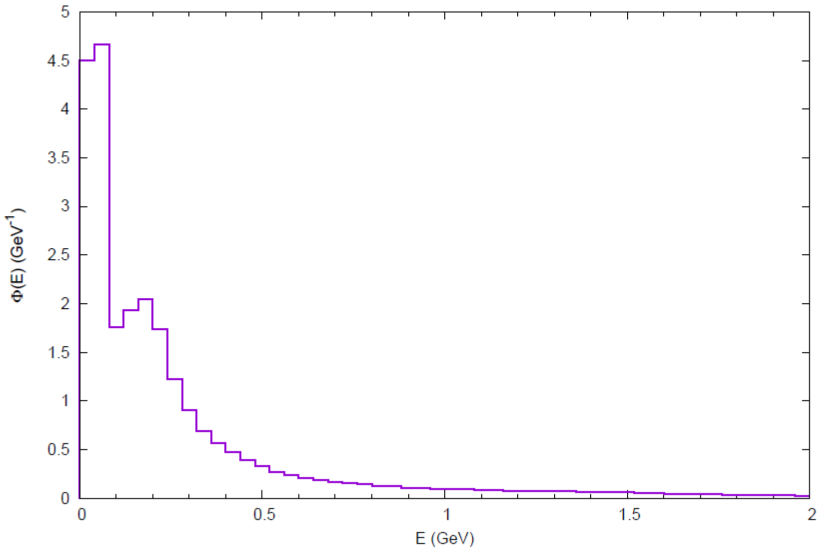
- Inelastic:
  - Yπ:

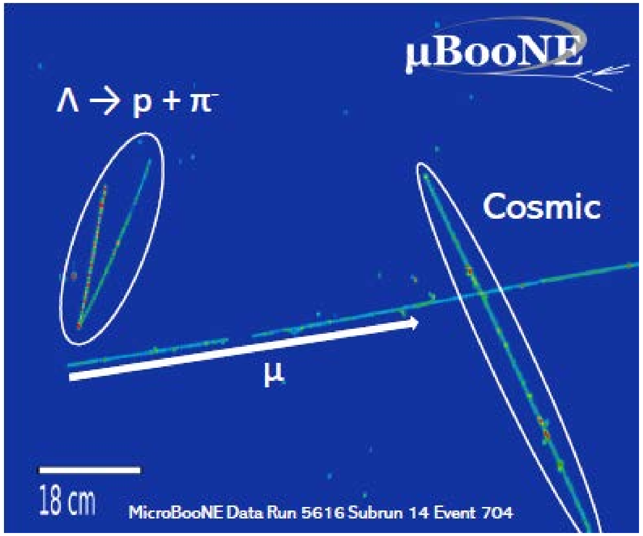
$$\begin{aligned} \bar{\nu}_l\, p &\to l^+\, \Sigma^0(\Lambda)\, \pi^0 & \bar{\nu}_l\, n &\to l^+\, \Sigma^0(\Lambda)\, \pi^- \\ \bar{\nu}_l\, p &\to l^+\, \Sigma^+\, \pi^- & \bar{\nu}_l\, n &\to l^+\, \Sigma^-\, \pi^0 \\ \bar{\nu}_l\, p &\to l^+\, \Sigma^-\, \pi^+ \end{aligned}$$

  - Higher threshold: W ≥ 1.3 GeV $\Leftrightarrow$ $\boldsymbol{E_{\nu}}$ ≥ 0.4 GeV
  - can proceed through the excitation of Λ or Σ resonances
    - in particular: Σ^*(1385), Λ(1405)

MicroBooNE measurement

- First measurement of $\bar{\nu}\,\mathrm{Ar} \to \mu^+\,\Lambda\,X$ PRL 130 (2023)
  - X=additional final state particles with no strangeness





Area-normalized accumulated off-axis NUMI flux.
Courtesy of C. Thorpe.

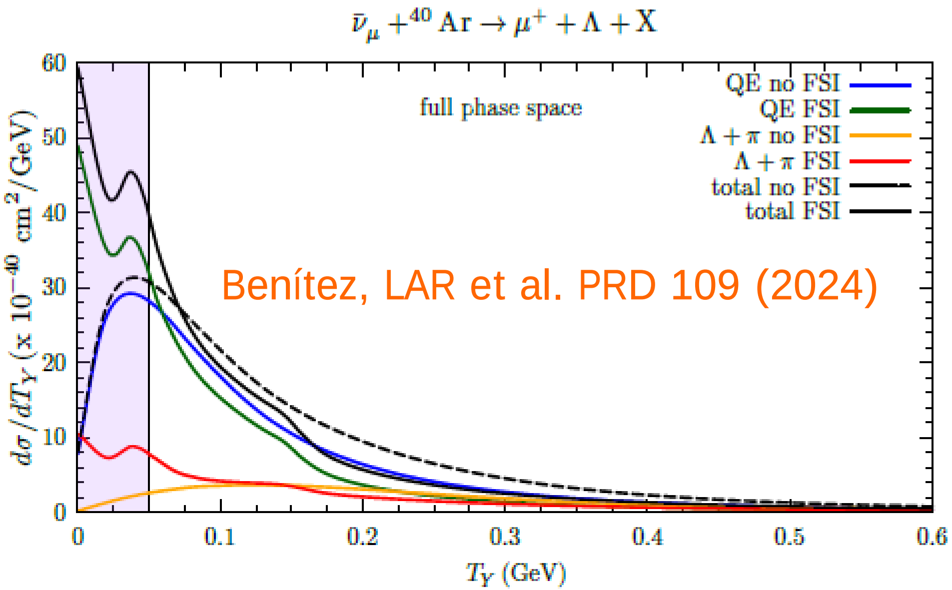
- 5 events, but (~ 4 times) more to come...
- Phase-space restricted flux-averaged cross section:

$$\boldsymbol{\sigma}_* = 2.0^{+2.1}_{-1.6} \times 10^{-40}\ \mathrm{cm}^2/\mathrm{Ar}$$

Nuclear Final State Interactions

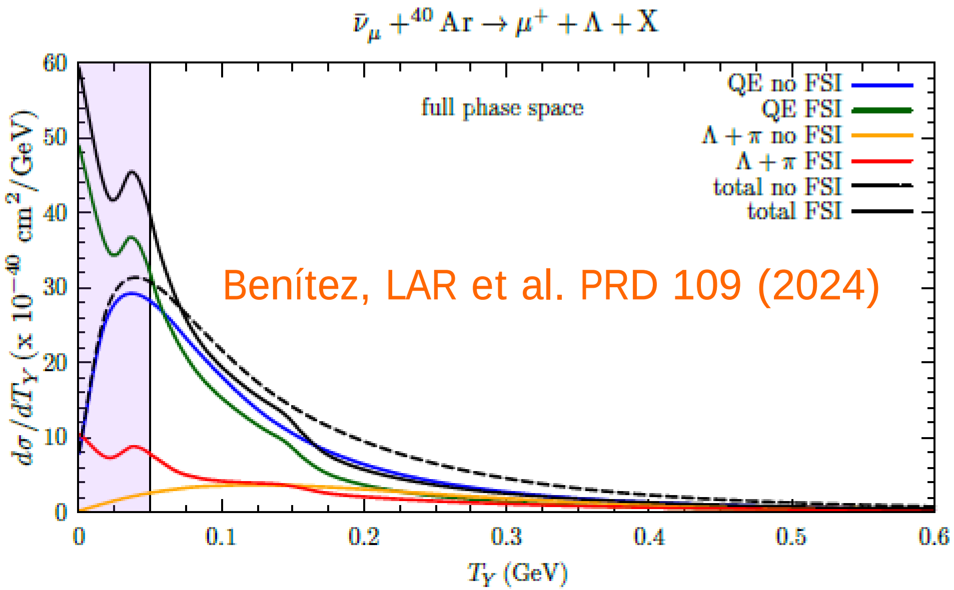
- Intranuclear cascade: semiclassical Monte-Carlo simulation
  - Experimental input for Y N $\rightarrow$ Y' N' cross sections (poorly known)
    - Isotropic angular distributions in the CM frame
    - Pauli blocking
  - Real part of the Λ nuclear potential:
    - $V(r) \approx -30\,\frac{\rho(r)}{\rho(0)}$ MeV

Comparison to MicroBooNE

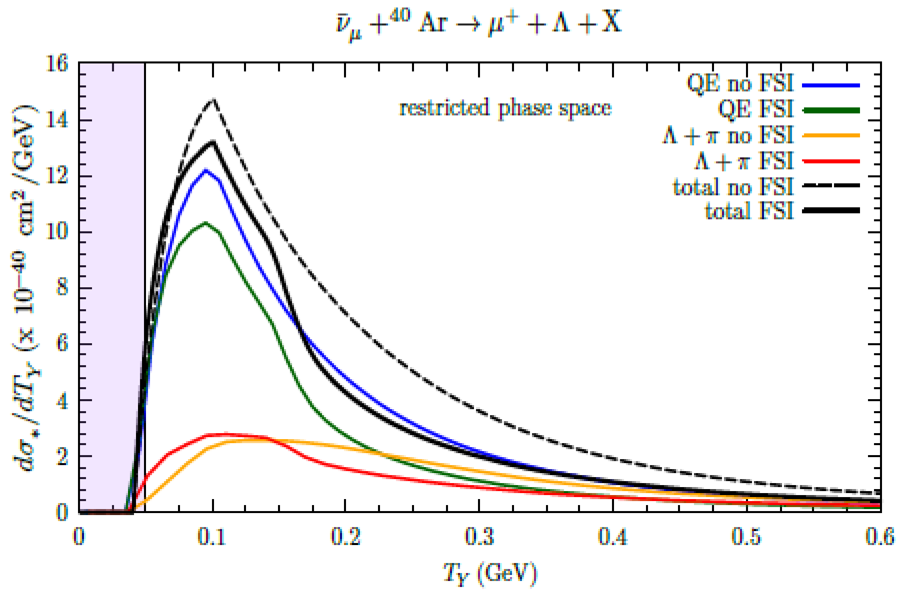


- Before phase space restrictions:
- Large enhancement at $T_\Lambda < 50$ MeV due to FSI : $\Sigma \to \Lambda$ conversion
- ~ 15% contribution from $\Lambda\pi$

Comparison to MicroBooNE

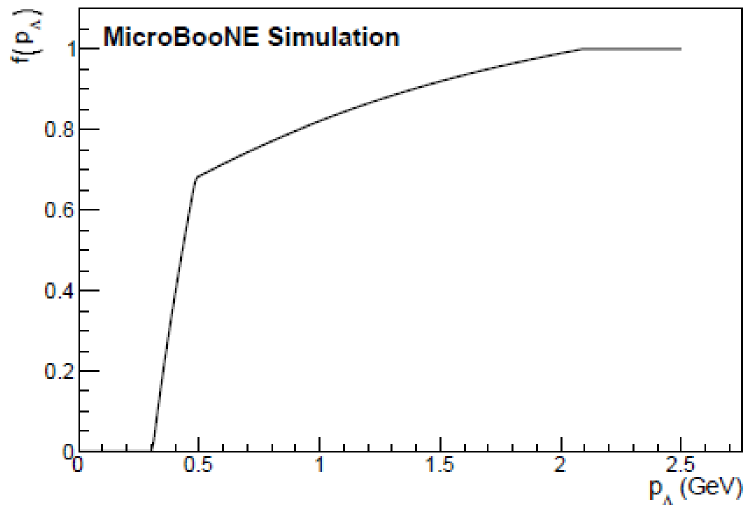


Benítez, LAR et al. PRD 109 (2024)



- After phase space restrictions:
- Large c. s. reduction; smaller impact of FSI
- ~ 33% contribution from $\Lambda\pi$

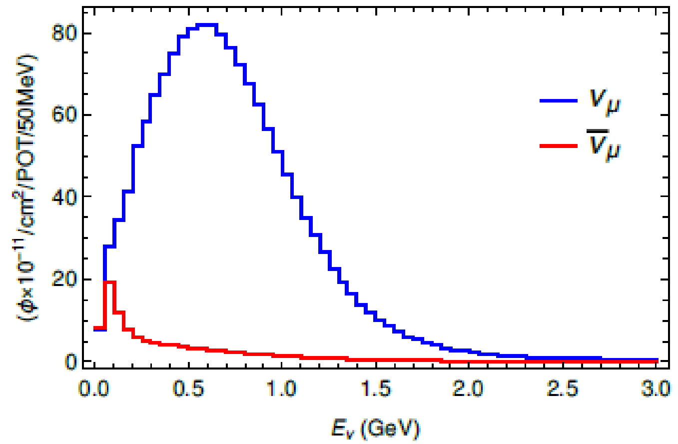
	σ_* ($\times 10^{-40}$ cm^2/Ar)
MicroBooNE	$2.0^{+2.1}_{-1.6}$
QE + $Y\pi$, full model	2.13
QE	1.44
$Y\pi$	0.69

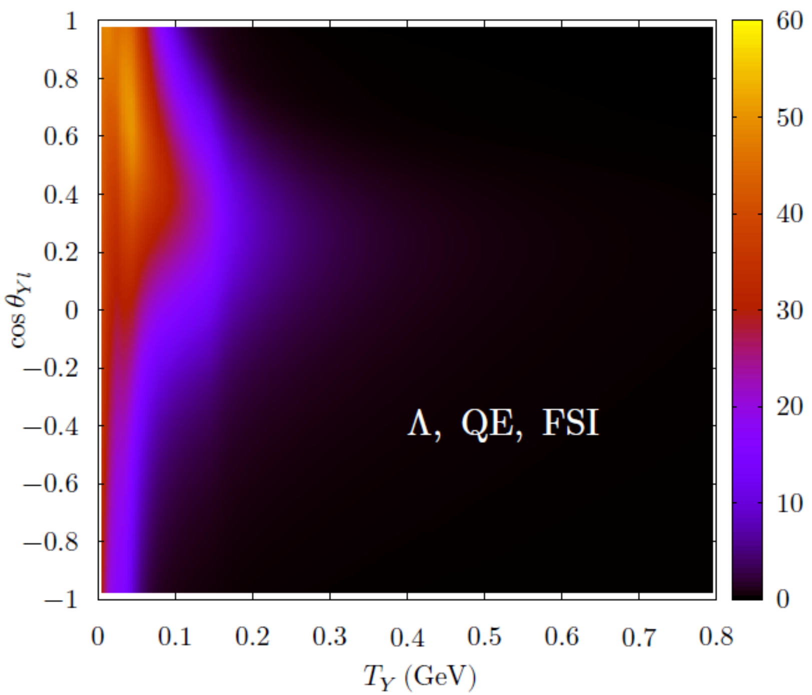


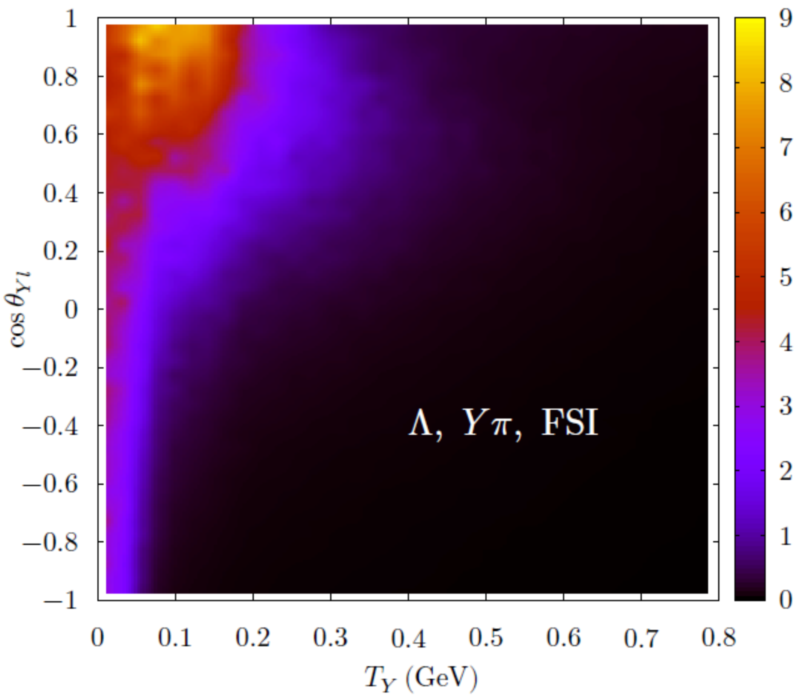
MicroBooNE, PRL 130 (2023)

SBND

- 10-13 $\times$ 10^{20} POT (3 years)
- Expected events before detection thresholds:
  - N_Λ = 1300 – 1700 (QE)
  - N_Λ = 240 – 300 ($\Lambda\pi$)







Flavor Changing Neutral Currents

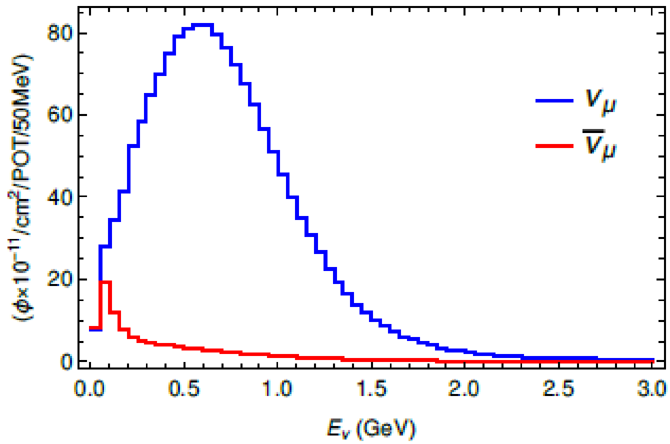
- Suppressed in the **SM**
- $d \to s$ using $\begin{aligned} \nu_l\, n &\to \nu_l\, \Lambda \\ \nu_l\, p &\to \nu_l\, \Sigma^+ \end{aligned}$
- Effective Hamiltonian:

$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \{\epsilon_V\, [\bar{s}\gamma_\mu d] + \epsilon_A\, [\bar{s}\gamma_\mu \gamma_5 d]\}\, [\bar{\nu}\gamma_\mu (1-\gamma_5)\nu]$$

  - Only left handed ν
  - Same matrix elements (up to isospin rotations) vs $W^- u \to s$
- Constraints from K decays: Geng, Martin Camalich, Shi, JHEP 02 (2022) 178
  - $K \to \pi\, \nu\bar{\nu}$ $\epsilon_V < 10^{-6} \approx 0$
  - $K \to \pi\pi\, \nu\bar{\nu}$ $|\epsilon_A| < 7.6 \times 10^{-3}$

FCNC searches with neutrinos

- At SBND
- $d \to s$ using $\nu_l \, n \to \nu_l \, \Lambda$
  $\nu_l \, p \to \nu_l \, \Sigma^+$



- $N_{\mathrm{FCNC}\,\Lambda} \approx 466\,|\epsilon_A|^2 N_{\mathrm{CC}\,\Lambda}$
- With $N_{\mathrm{CC}\Lambda}$ = 1300 – 1700 ($\bar{\nu}$) and the upper bound $|\epsilon_A| < 7.6\times10^{-3}$
- $N_{\mathrm{FCNC}\,\Lambda}$ < 46 - 60 events (x 3)
- At DUNE
  - More possible final states: $\nu_l \, N \to \nu_l \, Y \,, Y \, \pi \,, N' \, \bar{K} \,, N' \, \bar{K} \, \pi$
  - More statistics (particularly with a gas TPC)
  - Background from $\nu_l \, N \to \nu_l \, Y \, K$

Outlook

- ASFAE project: Modeling neutrino interactions with matter for current and future experiments
  - Making progress in our understanding of neutrino interactions with matter in the SM
  - Searching for processes and observables sensitive to BSM non-standard, flavor changing NC interactions