Phase II ND Workshop

Neutrino-nucleus interaction physics at DUNE ND

Luis Alvarez Ruso

IFIC Institut de Física Corpuscular

CSIC Consejo Superior de Investigaciones Científicas

Vniversitat de València

Financiado por la Unión Europea NextGenerationEU

Gobierno de España Ministerio de Ciencia e Innovación

Plan de Recuperación, Transformación y Resiliencia

Generalitat Valenciana Conselleria d'Innovació, Universitats, Ciència i Societat Digital

Introduction

- Near Detectors are crucial for a neutrino oscillation experiment
  - flux monitoring
  - cross section measurements
  - ...

Introduction

- Near Detectors are crucial for a neutrino oscillation experiment
  - flux monitoring
  - cross section measurements
  - ...

- Realistic neutrino interaction models are important:
  - allow for more realistic and efficient future projections
  - Neutrino scattering mismodeling in event generators can lead to **systematic errors** even if tuned to the best ND data.
  - Tunes are reliable when the fitted models contain the right physics in terms of parameters with realistic error bars.

Eur. Phys. J. C (2020) 80:978
https://doi.org/10.1140/epjc/s10052-020-08456-z

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Long-baseline neutrino oscillation physics potential of the DUNE experiment

DUNE Collaboration

Abstract The sensitivity of the Deep Underground Neutrino Experiment (DUNE) to neutrino oscillation is determined, based on a full simulation, reconstruction, and event selection of the far detector and a full simulation and parameterized analysis of the near detector. Detailed uncertainties due to the flux prediction, neutrino interaction model, and detector effects are included. DUNE will resolve the neutrino mass ordering to a precision of 5σ, for all δ_{CP} values, after 2 years of running with the nominal detector design and beam configuration. It has the potential to observe charge-parity violation in the neutrino sector to a precision of 3σ (5σ) after an exposure of 5 (10) years, for 50% of all δ_{CP} values. It will also make precise measurements of other parameters governing long-baseline neutrino oscillation, and after an exposure of 15 years will achieve a similar sensitivity to $\sin^2 2\theta_{13}$ to current reactor experiments.

1 Introduction

The Deep Underground Neutrino Experiment (DUNE) is a next-generation, long-baseline neutrino oscillation exper-

Eur. Phys. J. C (2020) 80:978
https://doi.org/10.1140/epjc/s10052-020-08456-z

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Long-baseline neutrino oscillation physics potential of the DUNE experiment

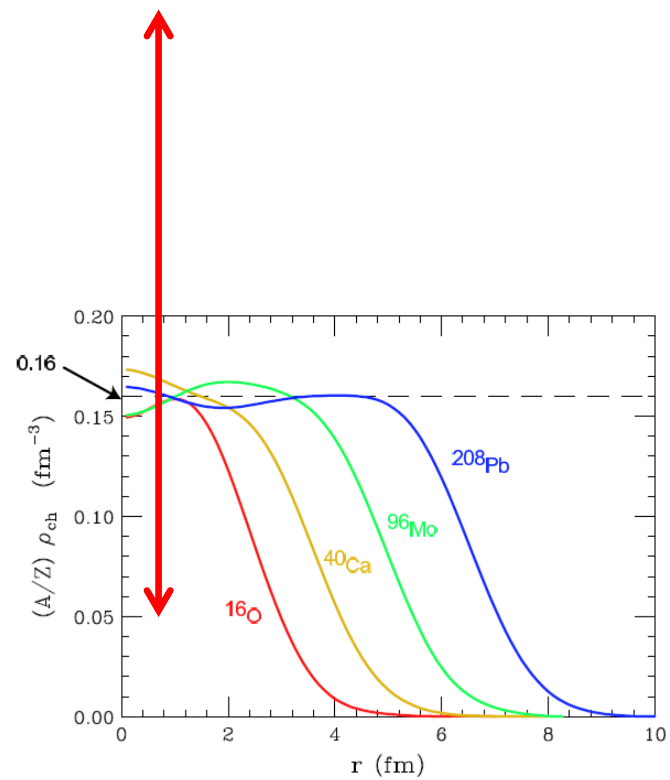
DUNE Collaboration

M_A^{QE}, Axial mass for CCQE	$^{+0.25}_{-0.15}$ GeV
QE FF, CCQE vector form factor shape	N/A
p_F Fermi surface momentum for Pauli blocking	±30%
Low W	
M_A^{RES}, Axial mass for CC resonance	±0.05 GeV
M_V^{RES} Vector mass for CC resonance	±10%

$$\rho \sim p_F^3$$

$\pm$ 30% for $p_F \Rightarrow 0.3\ \rho_o < \rho < 2.2\ \rho_o$

- The 30% p_F uncertainty can mask some interaction model deficiencies



Eur. Phys. J. C (2020) 80:978
https://doi.org/10.1140/epjc/s10052-020-08456-z

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Long-baseline neutrino oscillation physics potential of the DUNE experiment

DUNE Collaboration

Abstract The sensitivity of the Deep Underground Neutrino Experiment (DUNE) to neutrino oscillation is determined, based on a full simulation, reconstruction, and event selection of the far detector and a full simulation and parameterized analysis of the near detector. Detailed uncertainties due to the flux prediction, neutrino interaction model, and detector effects are included. DUNE will resolve the neutrino mass ordering to a precision of 5σ, for all δ_{CP} values, after 2 years of running with the nominal detector design and beam configuration. It has the potential to observe charge-parity violation in the neutrino sector to a precision of 3σ (5σ) after an exposure of 5 (10) years, for 50% of all δ_{CP} values. It will also make precise measurements of other parameters governing long-baseline neutrino oscillation, and after an exposure of 15 years will achieve a similar sensitivity to $\sin^2 2\theta_{13}$ to current reactor experiments.

1 Introduction

The Deep Underground Neutrino Experiment (DUNE) is a next-generation, long-baseline neutrino oscillation exper-

- The 30% p_F uncertainty can mask some interaction model deficiencies
- In general: unrealistically large errors
  - can hide systematic errors but also interesting physics
  - prevent a more efficient management of the resources

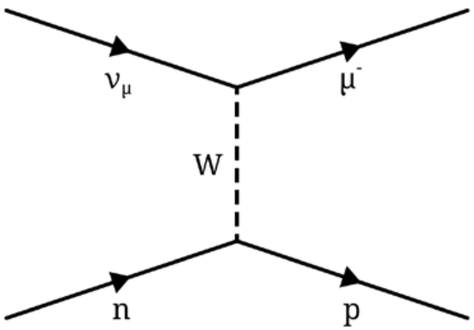
QE scattering on nucleons

- Nucleon axial form factor

$$A^a_\alpha = \bar{u}(p') \left[\gamma_\alpha \gamma_5 F_A + \frac{q_\alpha}{m_N} \gamma_5 F_P \right] \frac{\tau^a}{2} u(p) \qquad q = k - k' = p' - p$$

- Main source of uncertainty for QE scattering on nucleons:

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



Nucleon axial form factor

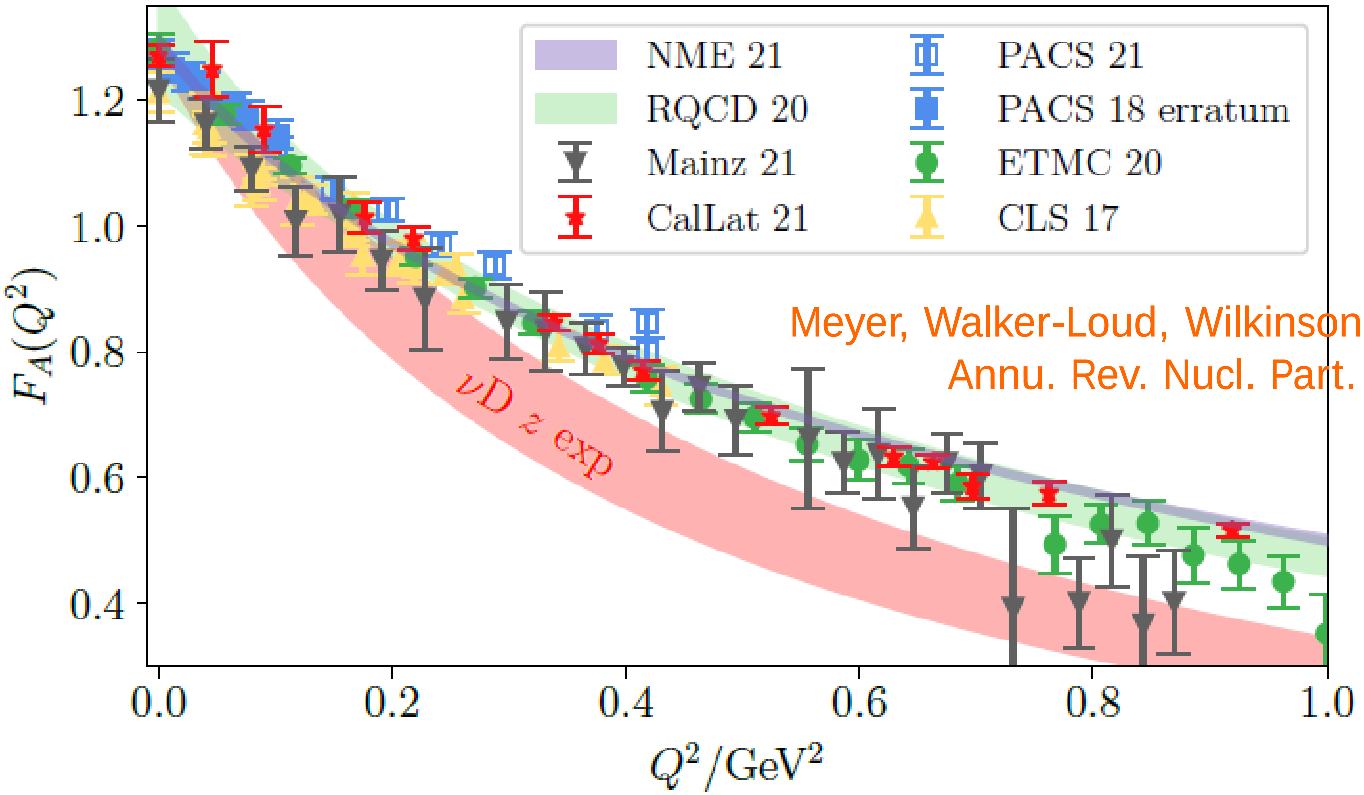
- What is known:
  - $F_A(0) = g_A \leftarrow \beta$ decay
  - $F_A(\infty) \sim Q^{-4} \leftarrow$ QCD
- Information:
  - Experiment: bubble chamber (ANL, BNL, FNAL) data
    - Most determinations:
      - $\langle r_A^2 \rangle \sim 0.47$ fm$^2 \Leftrightarrow M_A \sim 1$ GeV^2
      - different errors

$$F_A(q^2) = g_A \left[1 + \frac{1}{6}\langle r_A^2\rangle q^2 + \mathcal{O}(q^4)\right]$$

$$F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2} \qquad \langle r_A^2\rangle = \frac{12}{{M_A}^2} \qquad Q^2 = -q^2 > 0$$

  - Lattice QCD

F_A: Exp. vs LQCD



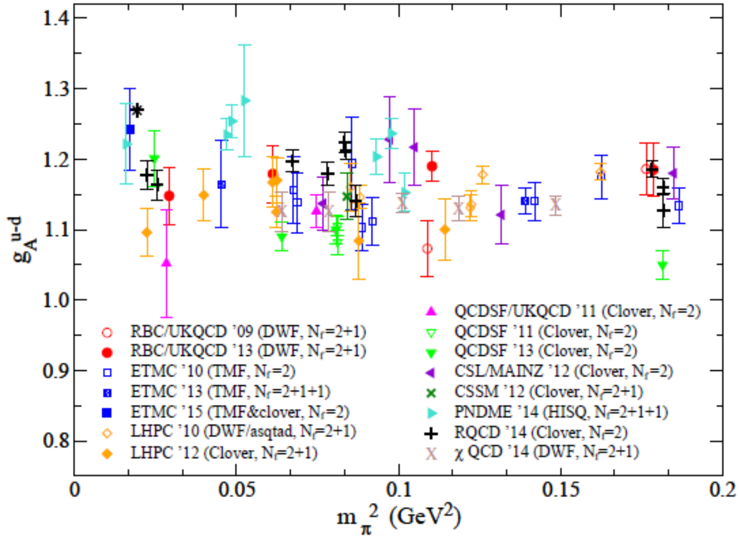
Meyer, Walker-Loud, Wilkinson, arXiv:2201.01839, Annu. Rev. Nucl. Part. Sci. 2022. 72:1–30

- How reliable are old bubble chamber experiments?
- Do LQCD present results still hide uncontrolled systematics?
  - Most systematics (extrapolation to the continuum and to physical quark masses, ...) expected to be controlled to <2% and excited-state contamination to <5% in 5 years

LAR et al., Snowmass 2021, 2203.09030

F_A & LQCD

- g_A : lower than exp. values were once obtained



Constantinou, PoS CD15 (2015) 009

$g_A = 1.2754(13)_{exp}(2)_{RC}$

M. Gorchtein and C.-Y. Seng, JHEP 53 (2021)

- Recent progress (for both g_A and F_A)
  - improved algorithms for a careful treatement of excited states
  - low pion masses

FLAG 2021
Flavour Lattice Averaging Group

$g_A = 1.246(28)$

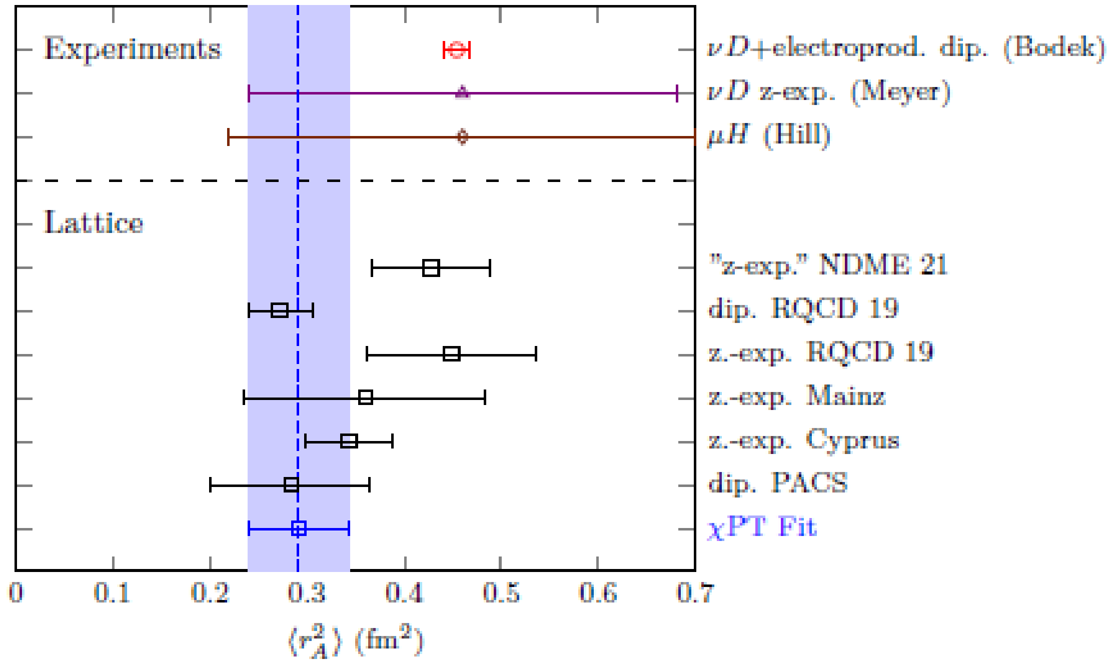
Alexandrou et al., PRD 96 (2017); PRD103 (2021)
Capitani et al., Int. J. Mod. Phys. A 34 (2019)
Gupta et al., PRD 96 (2017); Park et al., PRD 105 (2022)
Chang et al., Nature 558 (2018)
Bali et al., JHEP 05 (2020)
Shintani, PRD 99; PRD 102(erratum) (2020)

F_A & LQCD

- Baryon ChPT analysis: $Q^2 < 0.36$ GeV^2, $M_\pi < 400$ MeV , $M_\pi L > 3.5$
  - Model-independent extrapolations to the physical M_π

$$F_A(Q^2, M_\pi^2) = g + 4 d_{16} M_\pi^2 + d_{22} Q^2 + F_A^{(\mathrm{loops})} + F_A^{(wf)}$$

$$F_A(q^2) = g_A \left[1 + \frac{1}{6}\langle r_A^2 \rangle q^2 + \mathcal{O}(q^4)\right]$$



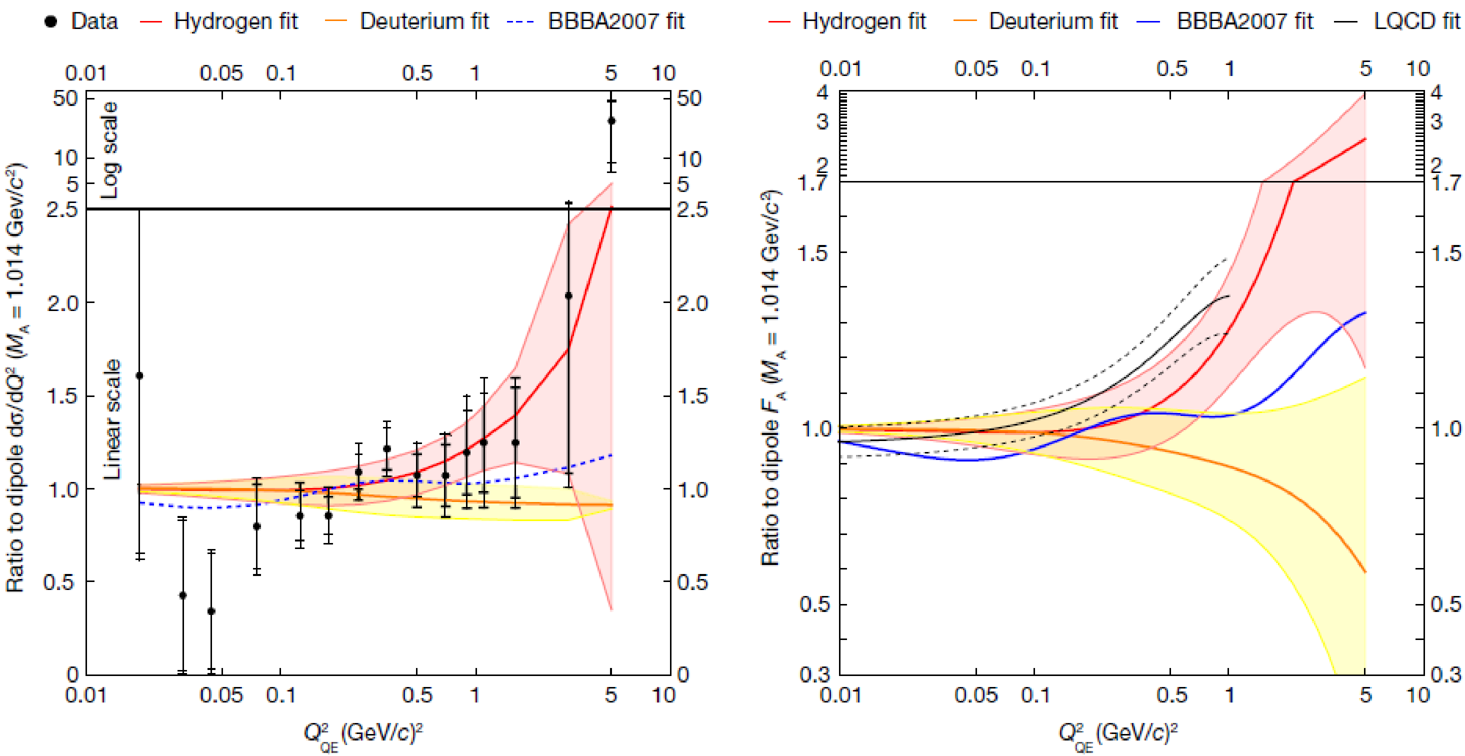
$\langle r_A^2 \rangle = 0.291(52)$ fm^2 $\Leftrightarrow$ $M_A = 1.27(11)$ GeV

F. Alvarado, LAR

in tension with empirical determinations

F_A @ MINERvA

- First high-statistics measurement of $\bar{\nu}_\mu p \to \mu^+ n$ cross section on free protons using the plastic scintillator target Cai et al., Nature 614 (2023)



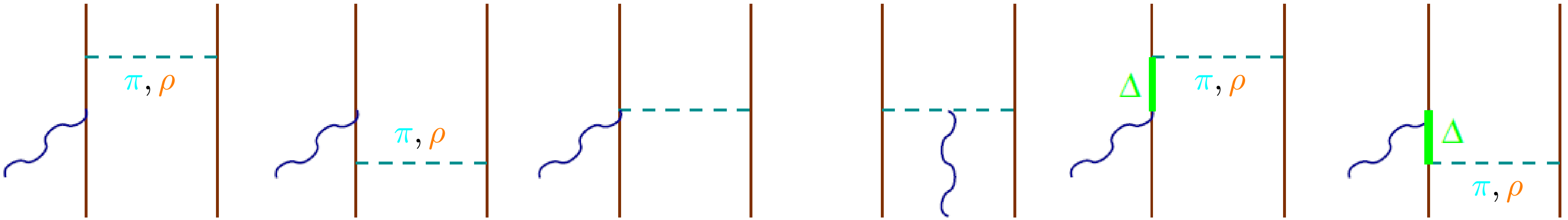
CHPT analysis of LQCD
F. Alvarado, LAR

$\langle r_A^2 \rangle = 0.291(52)$ fm² ⇔ 0.53(25) fm² ⇐ $r_A = 0.73(17)$ fm

in tension with MINERvA

0π ν-nucleus scattering

- Ab initio 1- and 2-nucleon currents
  - DOF: π, N but **no** $\Delta(1232)$; nonrelativistic; light nuclei < ^{12}C
- Phenomenological 1- and 2-nucleon currents

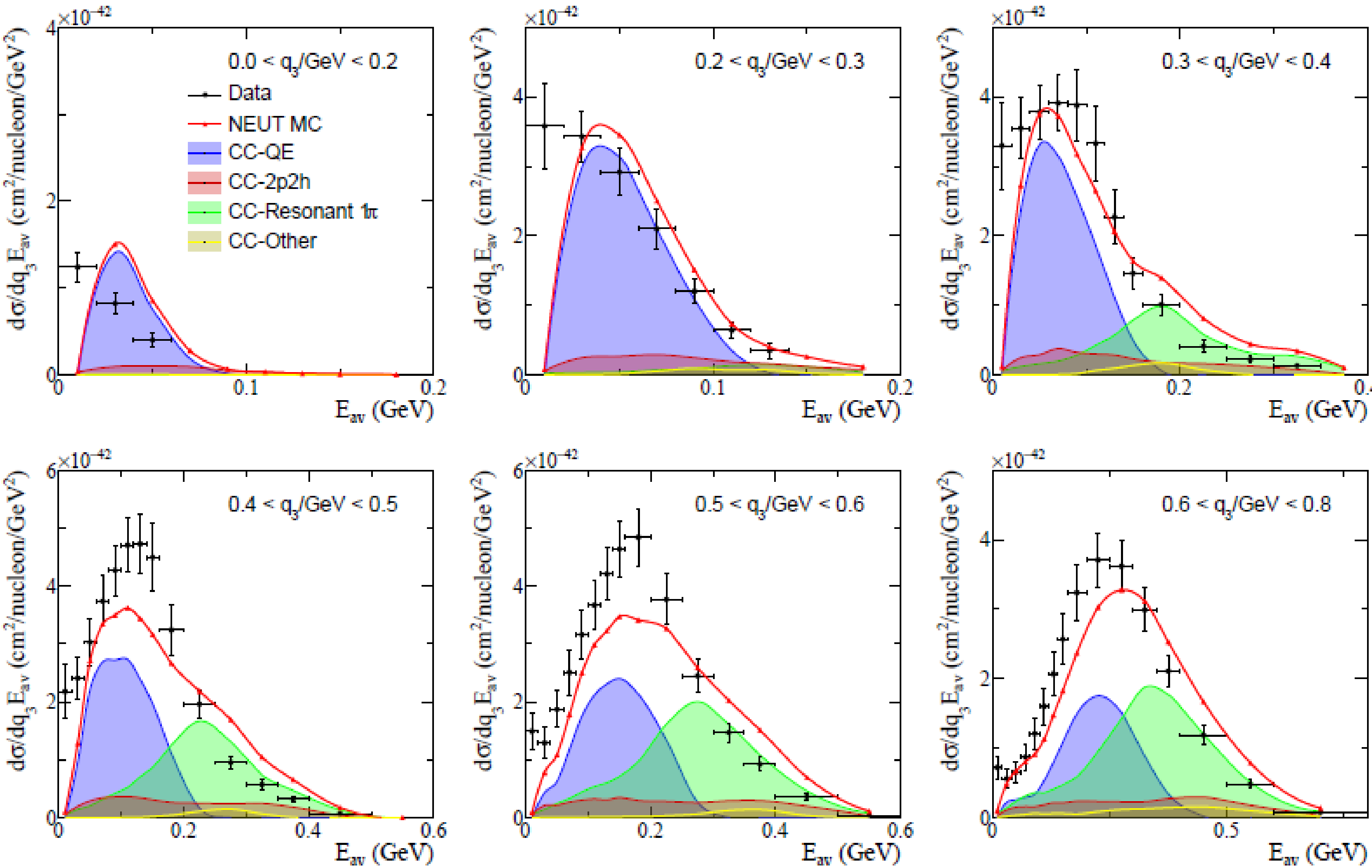


- Different descriptions of initial state nucleons:
  - Global Fermi gas
  - Local Fermi gas
  - Mean field
  - Superscaling
  - Spectral functions

Martini et al., PRC 80 (2009)
Nieves et al., PRC 83 (2011)
Amaro et al., PLB 696 (2011)
Gallmeister et al., PRC 94 (2016)
Ruiz Simo et al., JPhysG 44 (2017)
Van Cuyck et al., PRC 95 (2017)
Rocco et al., PRC 99 (2019)
...

- can explain MiniBooNE and T2K 0π data (with $M_A \approx 1$ GeV)
- Discrepancies found @ MINERvA & NOvA

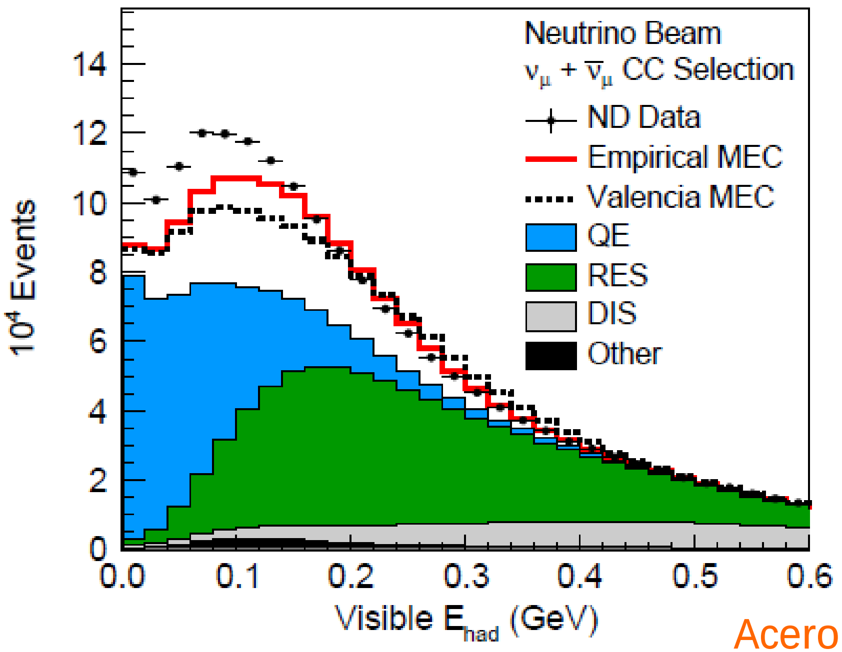
0π ν-nucleus scattering

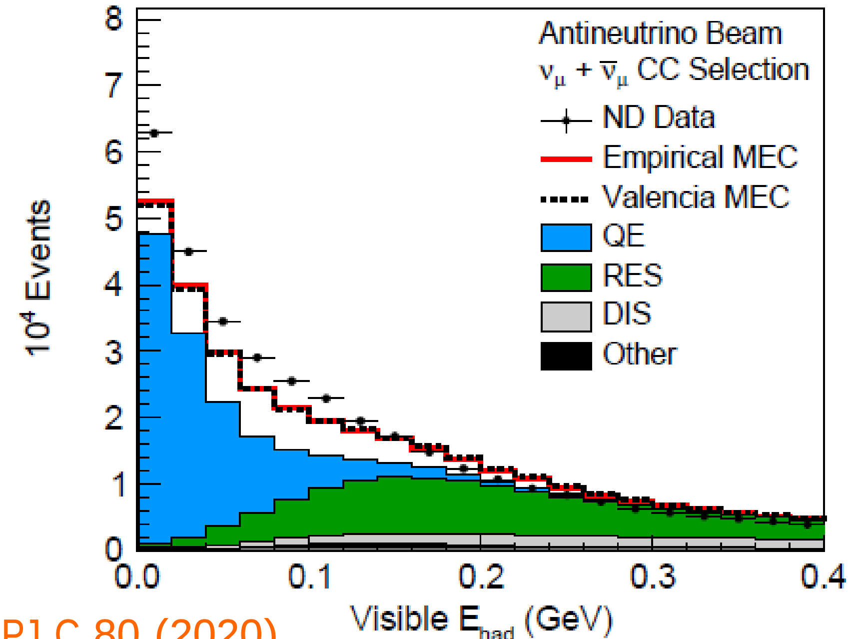


MINERvA inclusive CC data [Rodrigues et al. PRL (2016) vs T2K ref. model (NEUT)]
P. Stowell, PhD disertation (2019)

0π ν-nucleus scattering

- Discrepancies found @ MINERvA & NOvA

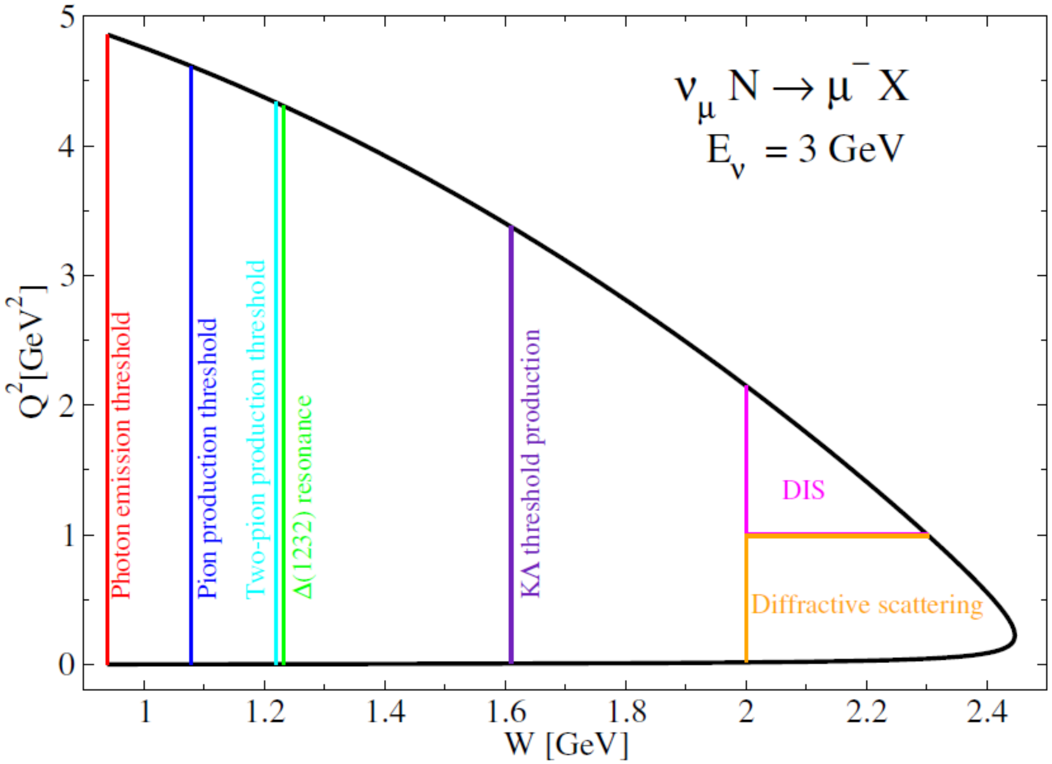


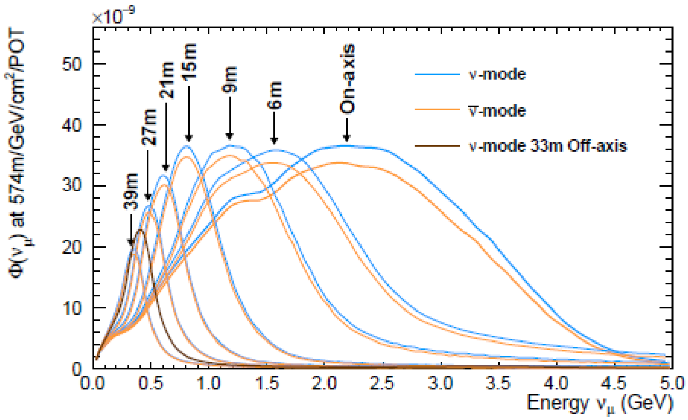


Acero et al., EPJ C 80 (2020)

- Theoretical mismodeling or imperfect/inconsistent implementation in MC?
- Progress requires:
  - improvement in theory and generator implementation
  - (exclusive) data (MINERvA, NOvA, MicroBooNE, SBND)

Inelastic scattering

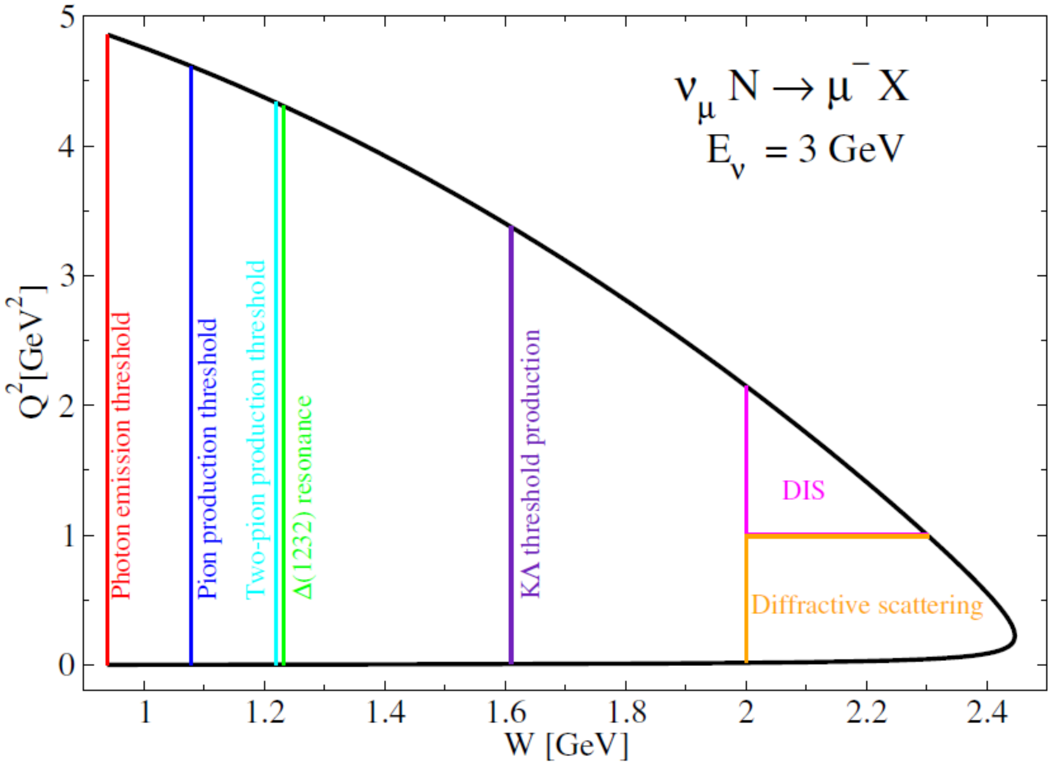


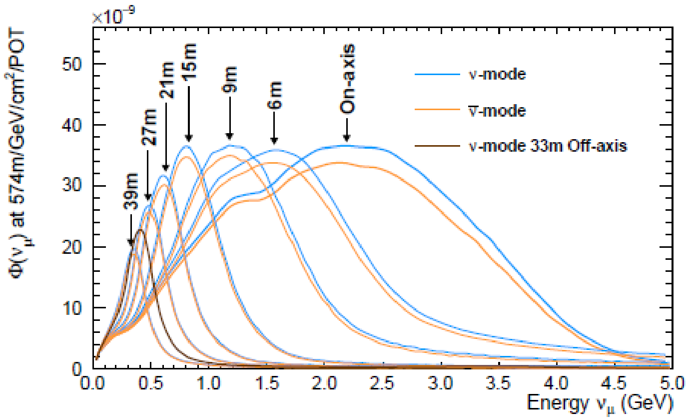


DUNE flux @ ND, 2002.03005

- Deep inelastic scattering: W>2 GeV, $Q^2 > 1$ GeV^2
  - Limited relevance @ DUNE

Inelastic scattering

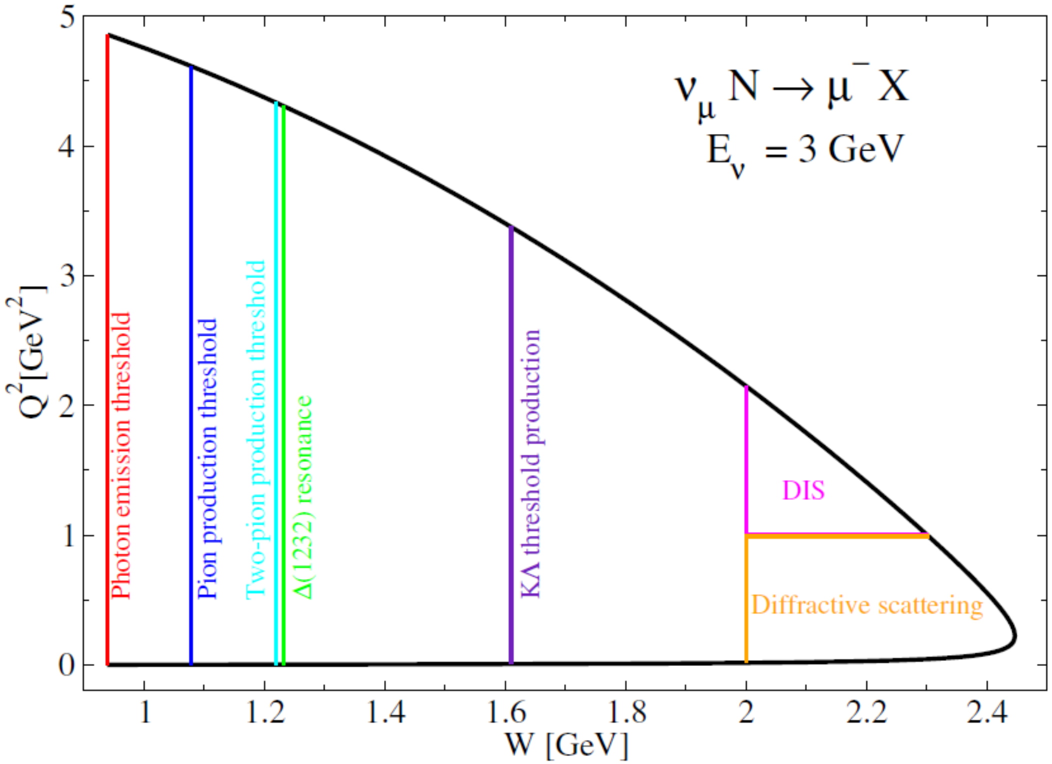


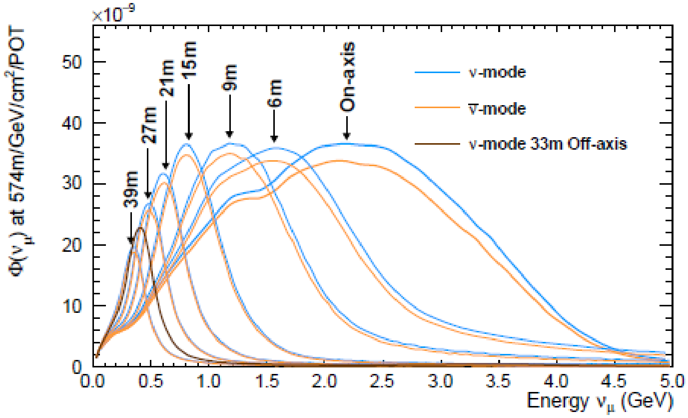


DUNE flux @ ND, 2002.03005

- 1π production: dominated by $\Delta(1232)$ excitation
  - interference between RES and NonRES amplitudes, unitarity
  - Treatable with EFT at low Q^2

Inelastic scattering





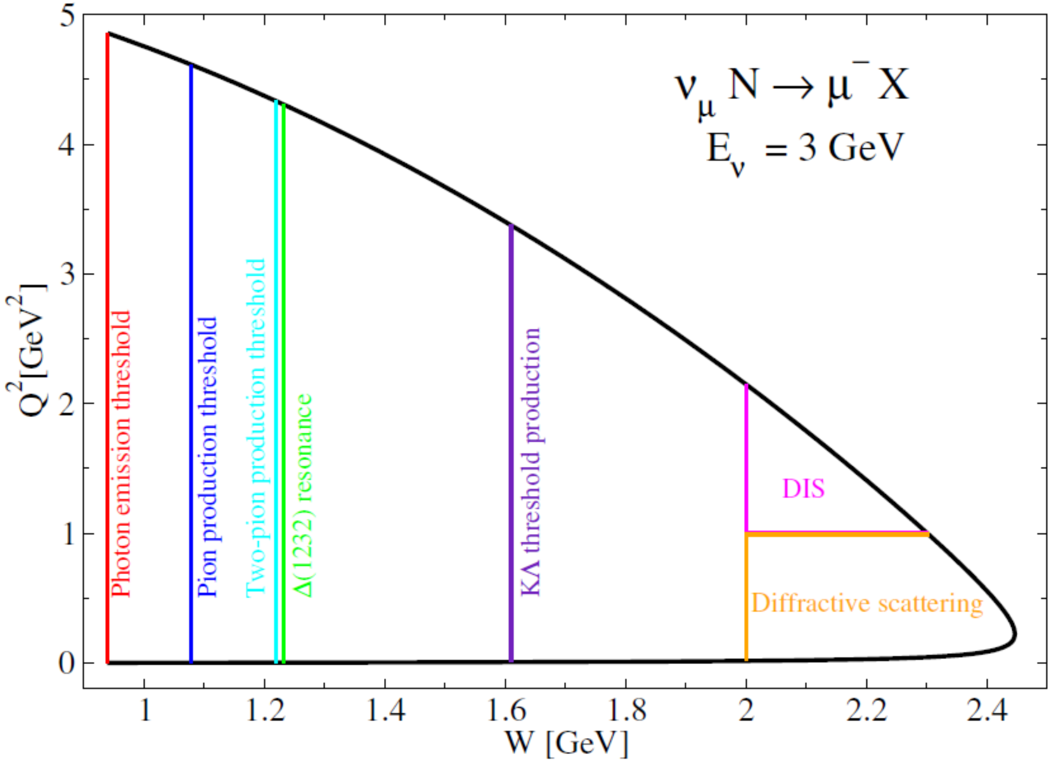
DUNE flux @ ND, 2002.03005

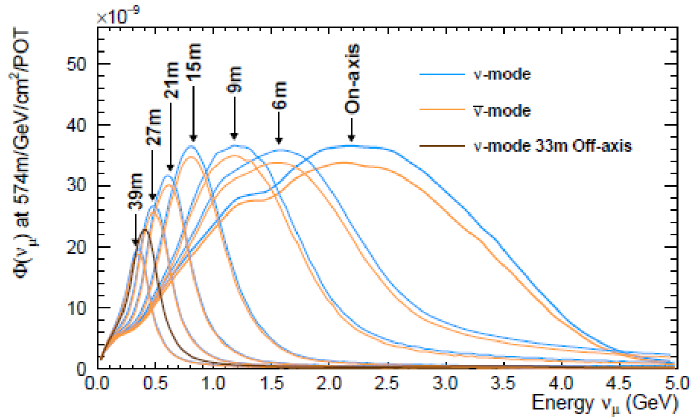
- Above the Δ(1232) peak: 1.3<W<2 GeV:
  - several overlapping resonances
  - non-trivial interference; coupled channels

$$\nu_l\, N \to l\, N'\, \pi\pi$$
$$\nu_l\, N \to l\, N'\, \eta$$
$$\nu_l\, N \to l\, \Lambda(\Sigma)\, K$$

- Different final states ⇒ different detector response

Inelastic scattering





DUNE flux @ ND, 2002.03005

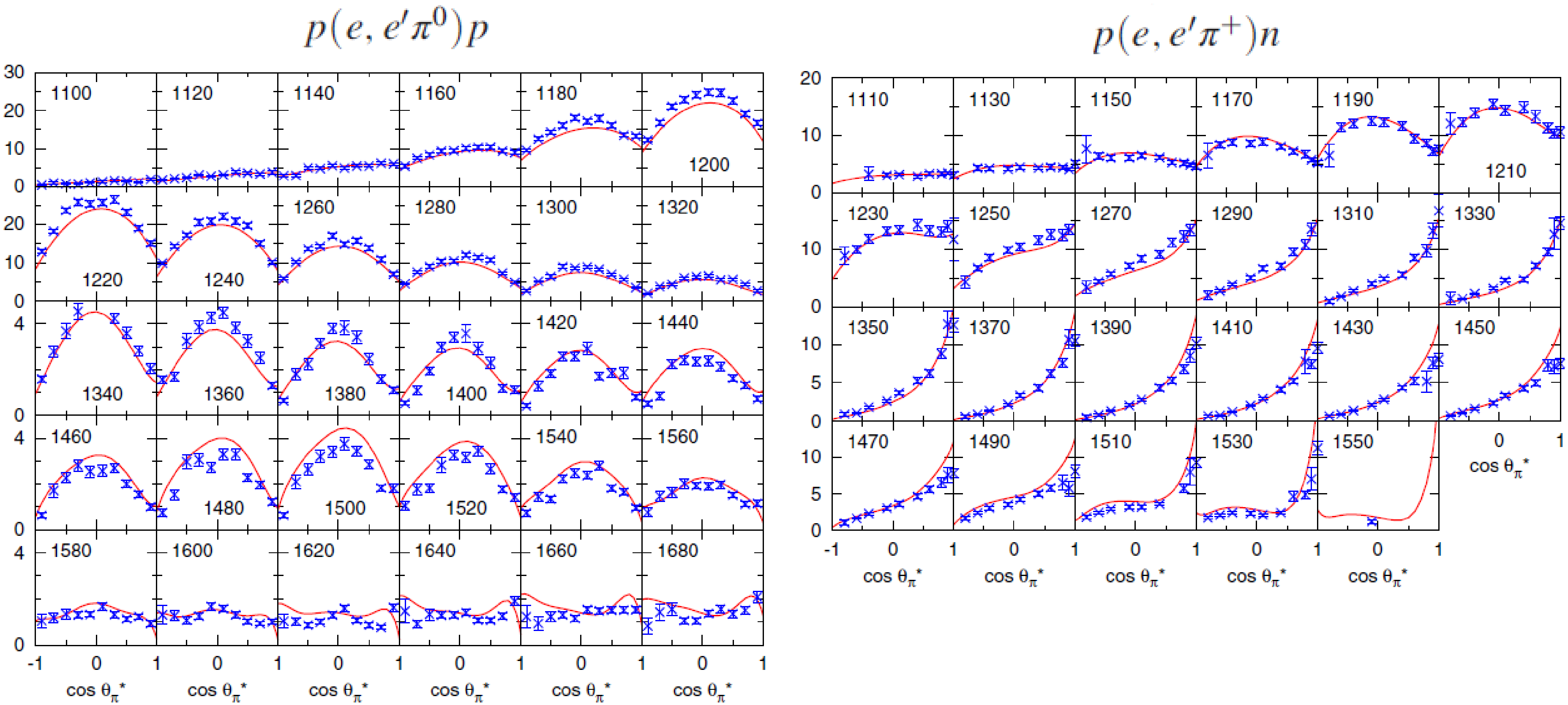
- Above the $\Delta(1232)$ peak: 1.3<W<2 GeV:
  - several overlapping resonances
  - non-trivial interference; coupled channels

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

- Different final states ⇒ different detector response

Pheno meson production models

- Rely on (non-ν) data as input and/or validation
  - Vector current can be constrained with $\gamma N \to N \pi$, $e N \to e' N \pi$



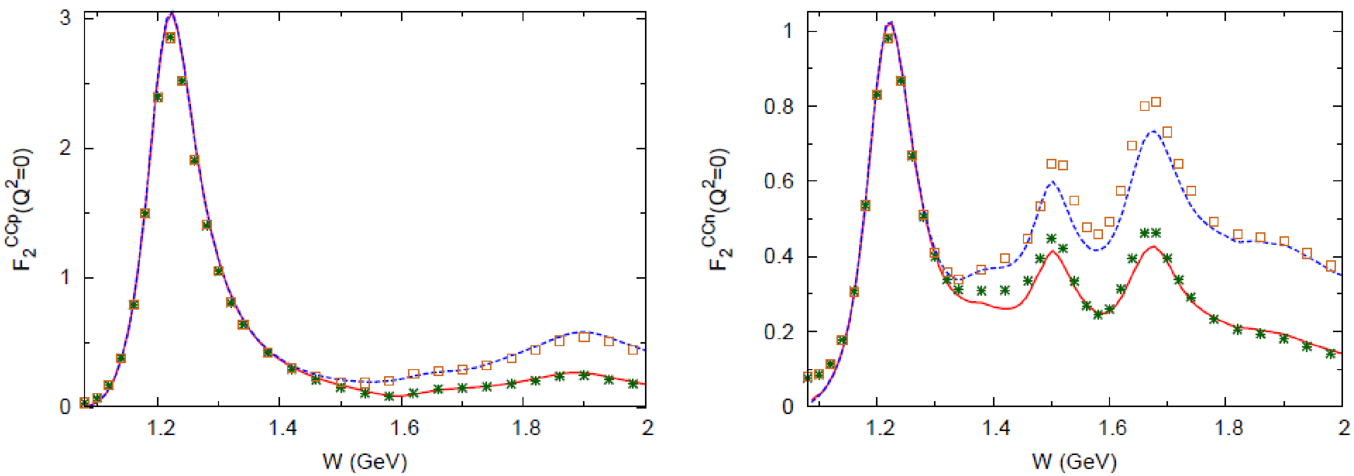
- e.g. Dynamical Coupled Channel (DCC) Model Nakamura et al., PRD92 (2015)

Pheno meson production models

- Rely on (non-ν) data as input and/or validation
  - Vector current can be constrained with $\gamma N \to N \pi$, $e N \to e' N \pi$
  - Axial current at $q^2 \to 0$ can be constrained with $\pi N \to N \pi$ (PCAC)

$$F_2(W, Q^2 = 0 \approx -m_\pi^2) \propto f_\pi^2 \sigma_{\pi N}(W)$$

$$\frac{d\sigma_{CC\pi}}{dE_l d\Omega_l}\Big|_{q^2=0} = \frac{G_F^2 V_{ud}^2}{2\pi^2} \frac{2 f_\pi^2}{\pi} \frac{E_l^2}{E_\nu - E_l} \sigma_{\pi N}$$



- e.g. Dynamical Coupled Channel (DCC) Model Nakamura et al., PRD92 (2015)

Pheno meson production models

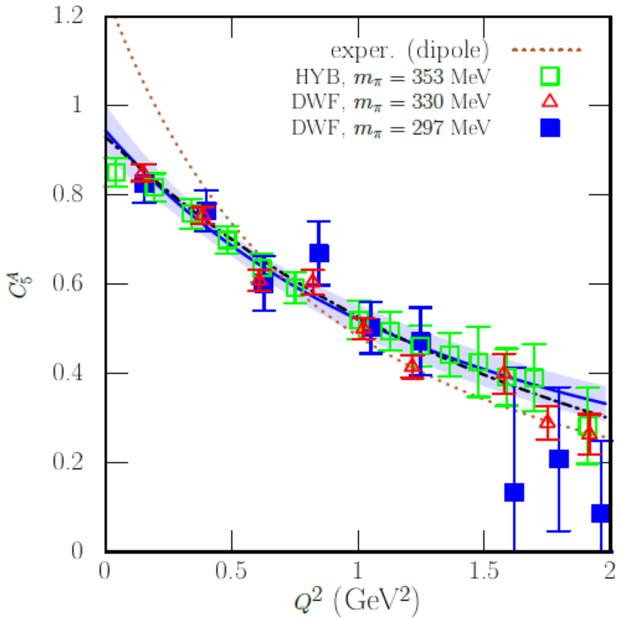
- Rely on (non-ν) data as input and/or validation
  - Vector current can be constrained with $\gamma N \to N \pi$, $e N \to e' N \pi$
  - Axial current at $q^2 \to 0$ can be constrained with $\pi N \to N \pi$ (PCAC)

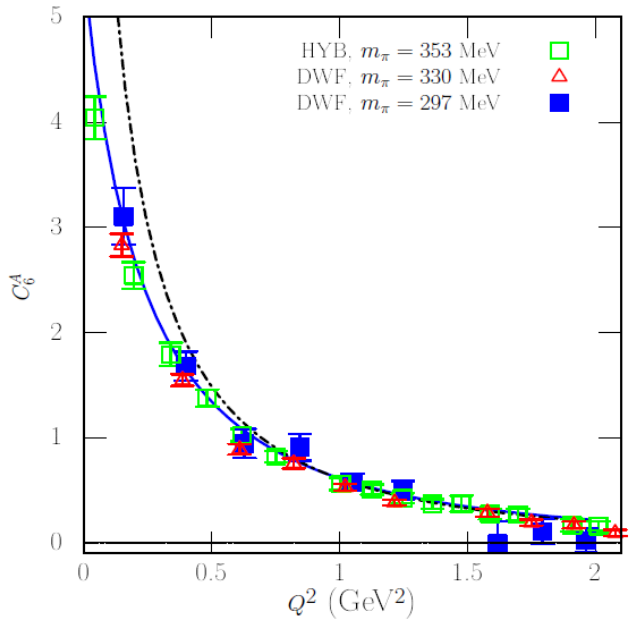
$$\left.\frac{d\sigma_{CC\pi}}{dE_l d\Omega_l}\right|_{q^2=0} = \frac{G_F^2 V_{ud}^2}{2\pi^2} \frac{2 f_\pi^2}{\pi} \frac{E_l^2}{E_\nu - E_l} \sigma_{\pi N}$$

  - Very limited information about the axial current at $q^2 \neq 0$
    - Some on N-Δ(1232) from ANL and BNL on $\nu_\mu d \to \mu^- \pi^+ p n$
    - Lattice QCD

LQCD & meson production

- Early N-Δ(1232) axial FF with heavy m_q Alexandrou et al.,PRD83 (2011)

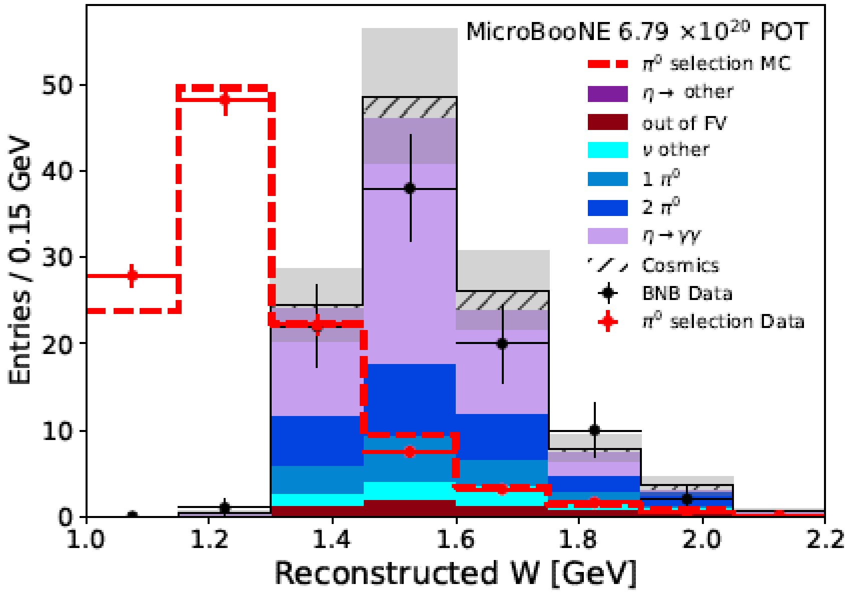


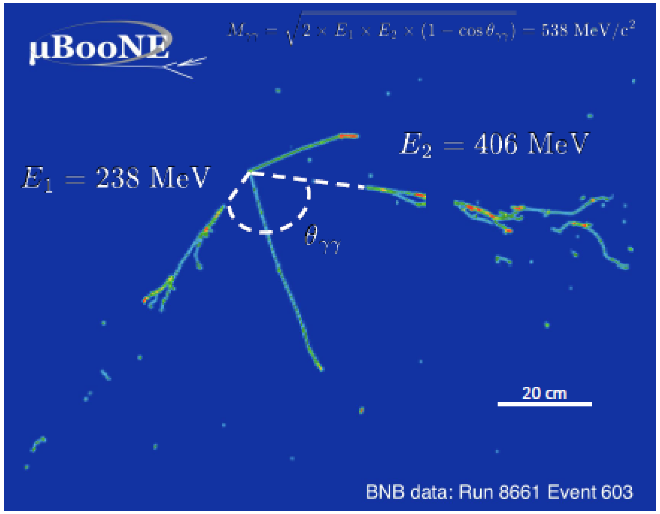


- Exploratory studies of N $\rightarrow$ Nπ axial matrix element
  Barca, Balli, Collins, PoS LATTICE2021 (2022) 359
- Calculations of N-Δ,N-N* transition FF should become available in the next 5-10 years LAR et al., Snowmass 2021, 2203.09030
- Control systematic uncertainties is challenging

Inelastic scattering on nuclei

- Measurement of $\nu\ \mathrm{Ar} \to l\ (\nu)\ \eta\ X$ @ MicroBooNE arXiv:2305.16249
- $\eta \to \gamma\ \gamma$

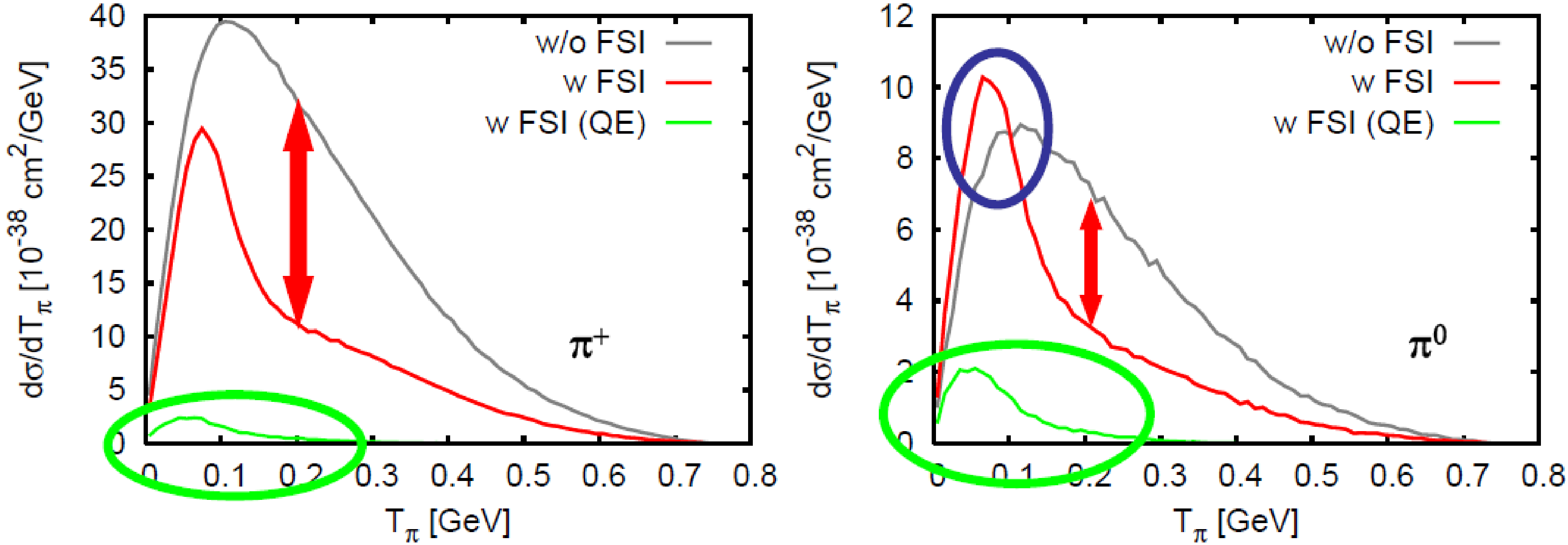




- Consistent with the expectation of N(1535) excitation → $N\ \eta$
- Much larger statistics expected @ SBND and DUNE
- However, in nuclei, the analysis is not straightforward:

Inelastic scattering on nuclei

- Final State Interactions alter the composition, energy and angular distribution of the final state.
  - Particularly for 100 -300 MeV pions...
    - scattering, charge exchange, absorption



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

Leitner, LAR, Mosel, PRC 73 (2006)

Inelastic scattering on nuclei

- Final State Interactions alter the composition, energy and angular distribution of the final state.
  - Particularly for 100 -300 MeV pions...
    - scattering, charge exchange, absorption
  - ... but not only:
    - nucleons
    - strangeness can be produced in secondary collisions:

      $\pi N \to K Y, \pi K Y, K \bar{K} N'$

      $N N \to K Y N$

      Lalakulich, Gallmeister, Mosel, PRC 86 (2012)
    - secondary η production: $\pi^+ n \to \eta p$

Weak hyperon production

- ΔS = -1: $W^- u \rightarrow s$
- Cabibbo reduced ($V_{us} = 0.23$)
- Quasielastic:
  - Lowest threshold: W ≥ 1.1 GeV ⇔ $\boldsymbol{E_v}$ ≥ 0.2 GeV
  - Y: $\bar{\nu}_l\, p \rightarrow l^+\, \Sigma^0 (\Lambda)$

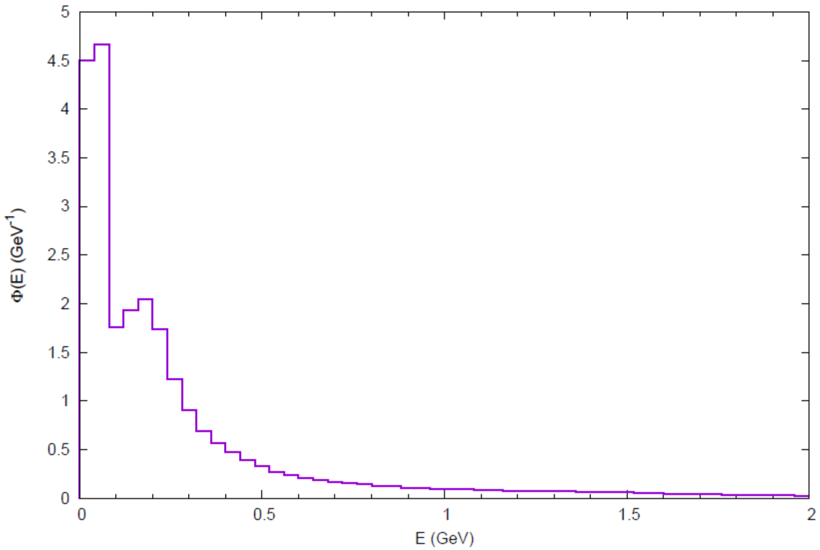
    $\bar{\nu}_l\, n \rightarrow l^+\, \Sigma^-$
- Inelastic:
  - Yπ: $\bar{\nu}_l\, p \rightarrow l^+\, \Sigma^0 (\Lambda)\, \pi^0$ $\quad \bar{\nu}_l\, n \rightarrow l^+\, \Sigma^0 (\Lambda)\, \pi^-$

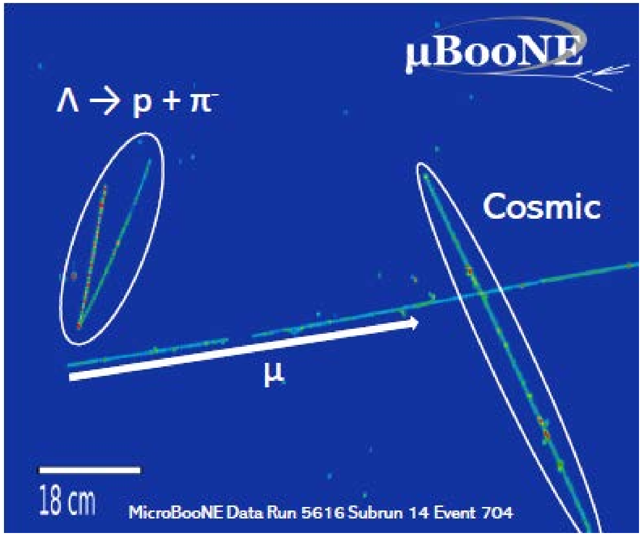
    $\bar{\nu}_l\, p \rightarrow l^+\, \Sigma^+\, \pi^-$ $\quad \bar{\nu}_l\, n \rightarrow l^+\, \Sigma^-\, \pi^0$

    $\bar{\nu}_l\, p \rightarrow l^+\, \Sigma^-\, \pi^+$
  - Higher threshold: W ≥ 1.3 GeV ⇔ $\boldsymbol{E_v}$ ≥ 0.4 GeV
  - can proceed through the excitation of Λ or Σ resonances
    - in particular: Σ^*(1385), Λ(1405)

MicroBooNE measurement

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



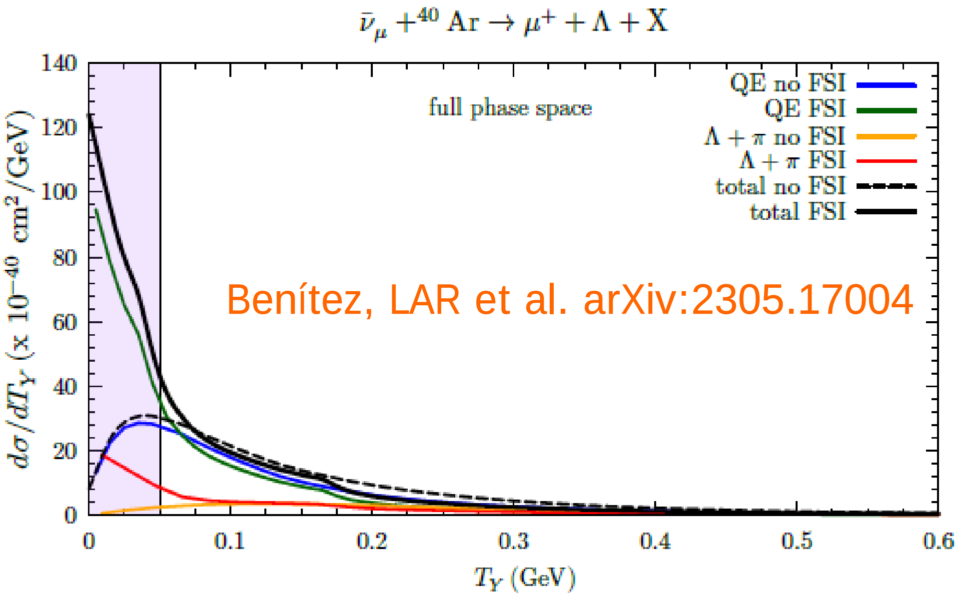


Area-normalized accumulated off-axis NUMI flux.
Courtesy of C. Thorpe.

- 5 events, but more to come...
- Phase-space restricted averaged cross section:

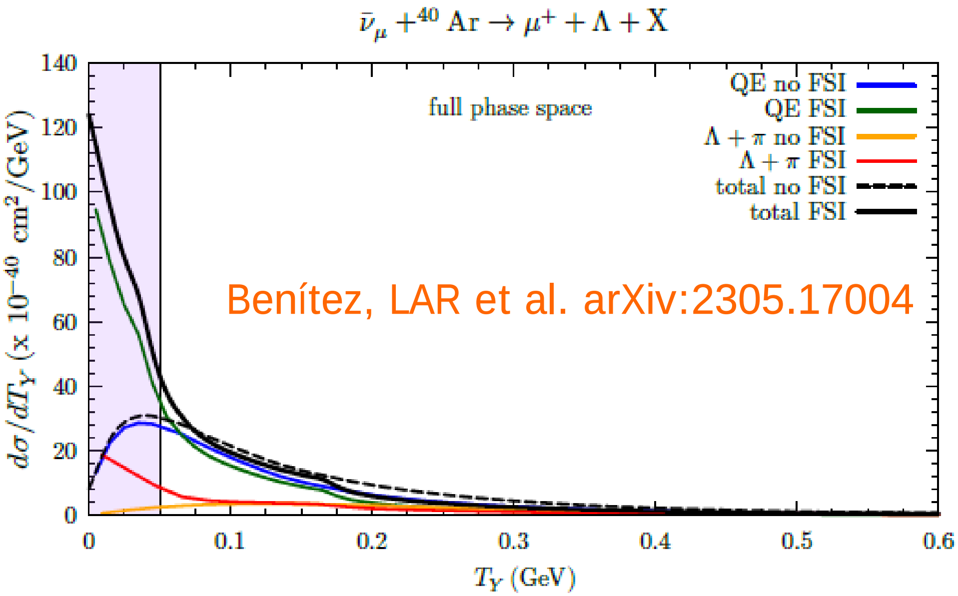
$$\sigma_* = 2.0^{+2.1}_{-1.6} \times 10^{-40}\ \mathrm{cm}^2/\mathrm{Ar}$$

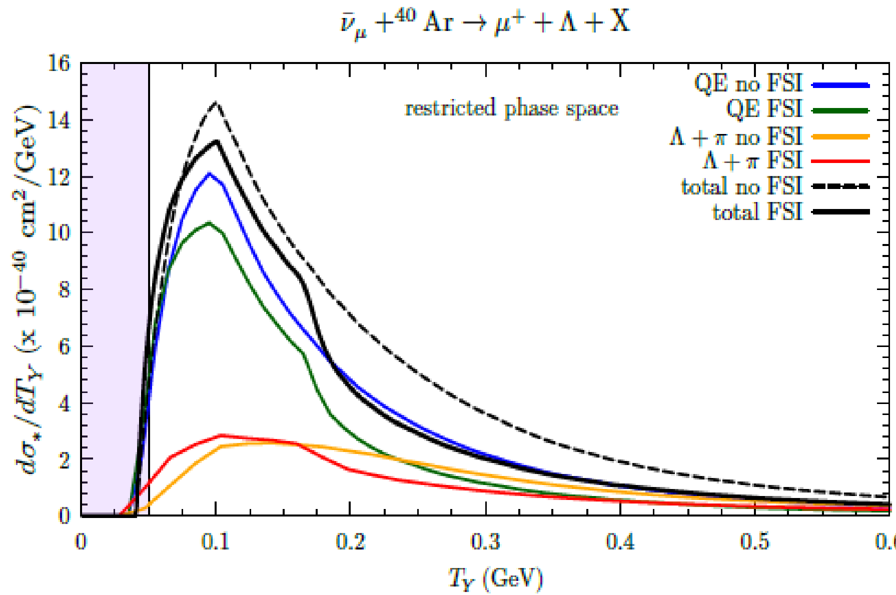
Comparison to MicroBooNE



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

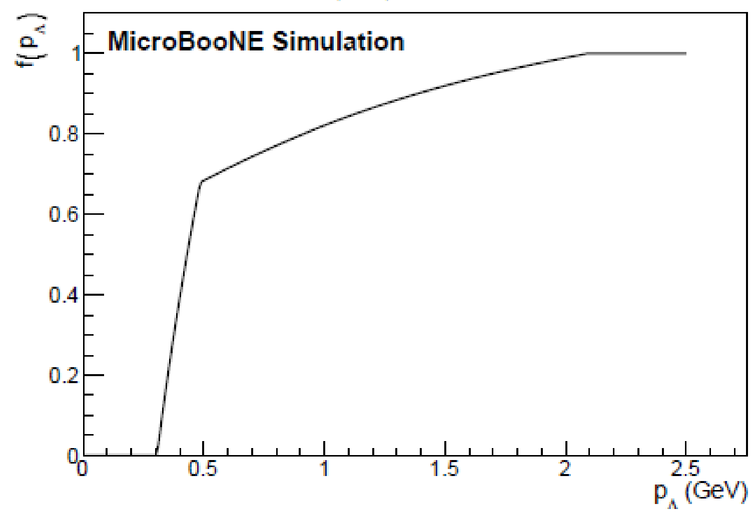
Comparison to MicroBooNE





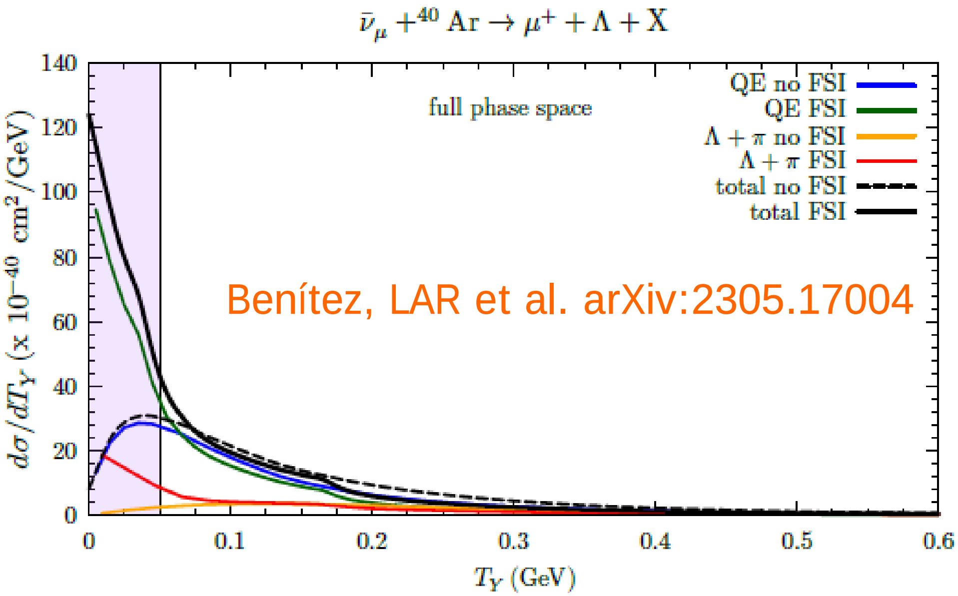
- After phase space restrictions:
- Large c. s. reduction; smaller impact of FSI
- ~ 33% contribution from $\Lambda\pi$

	σ_* $(\times 10^{40} cm^2/Ar)$
MicroBooNE	$2.0^{+2.1}_{-1.6}$
QE + $Y\pi$, full model	2.21
QE contr.	1.49
$Y\pi$ contr.	0.72

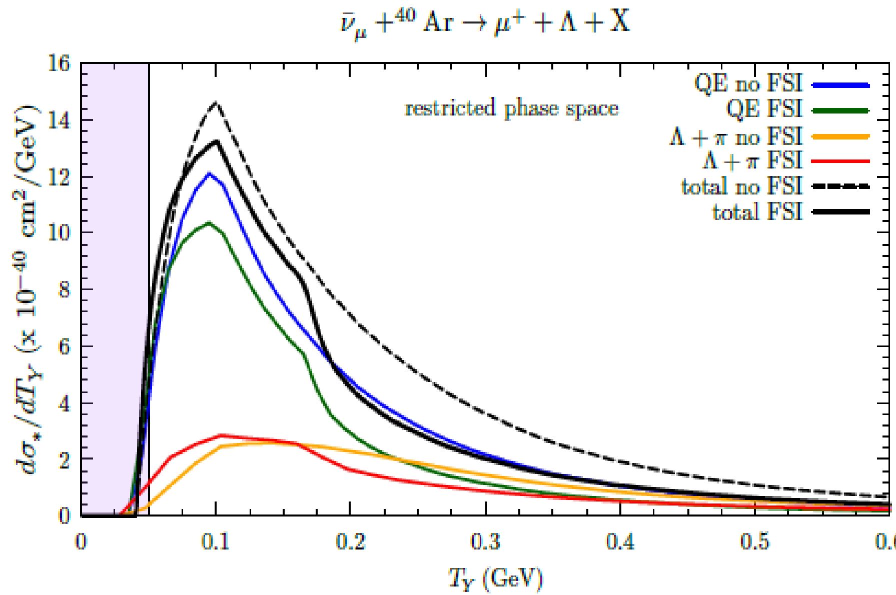


MicroBooNE, PRL 130 (2023)

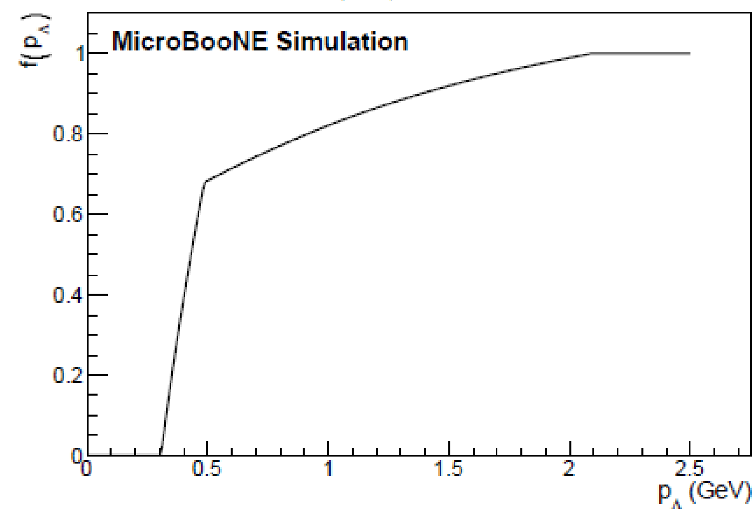
Comparison to MicroBooNE



Benítez, LAR et al. arXiv:2305.17004



- After phase space restrictions:
- Large c. s. reduction; smaller impact of FSI
- ~ 33% contribution from $\Lambda\pi$
- Opportunity for gaseous argon TPC such as NDGAr @ DUNE



MicroBooNE, PRL 130 (2023)

Interest

- K production by atmospheric ν is a potential background for $p \to \nu K^+$
- Via $Y \to \pi N$, Y are a source of low energy π in $\bar{\nu}$ scattering
- QE Y production could be used to constrain $\bar{\nu}$ contamination in ν beams
- YN form factors encode interesting information about:
  - 2nd class currents, T violation, SU(3) breaking corrections
- Inelastic processes can provide information about strange baryon resonances
  - Two-pole structure of the $\Lambda(1405)$ could be studied in $\bar{\nu}_l \, p \to l^+ \, \Lambda(1405) \to l^+ \, \Sigma \, \pi$

    without distortion due to K $\Lambda(1405)$ interactions in strong or em prod.
- Sensitivity to nuclear dynamics in the presence of strangeness
  - K-nucleus and Y nuclear potential
- $\Delta S = 1$: $W^+ \bar{u} \to \bar{s}$ and $\Delta S = -1$: $W^- u \to s$ are very different
  - Relevant for oscillations? Maybe not but insufficiently investigated

FCNC

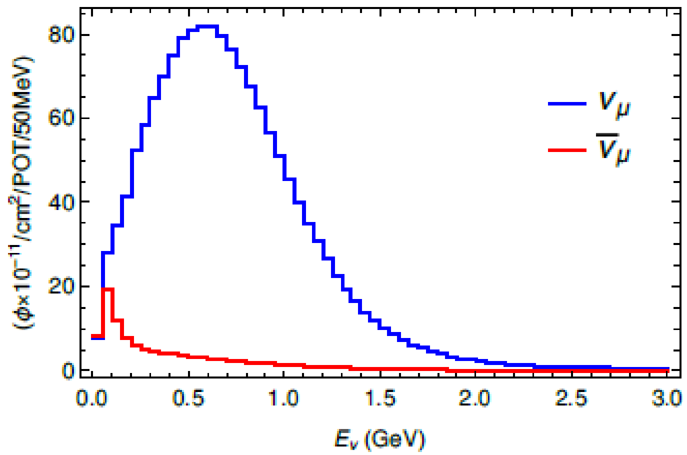
- Suppressed in the **SM**
- $d \to s$ using $$\begin{aligned} \nu_l\, n &\to \nu_l\, \Lambda \\ \nu_l\, p &\to \nu_l\, \Sigma^+ \end{aligned}$$
- Effective Hamiltonian:

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

  - Only left handed ν ; real $\epsilon_{V/A}$
  - Same matrix elements (up to isospin rotations) vs $W^- u \to s$
- Constraints from K decays: Geng, Martin Camalich, Shi, JHEP 02 (2022) 178
  - $K \to \pi\, \nu\bar{\nu}$ $\epsilon_V < 10^{-6} \approx 0$
  - $K \to \pi\pi\, \nu\bar{\nu}$ $|\epsilon_A| < 7 \times 10^{-3}$

FCNC searches with neutrinos

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



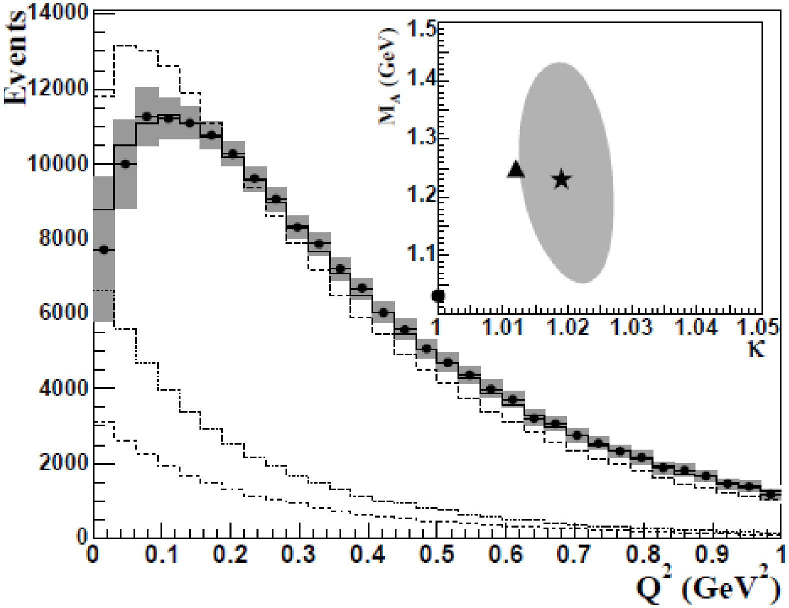
- $\dfrac{(n \to \Lambda)\text{ events}}{(p \to \Lambda)\text{ events}} \approx 466\, |\epsilon_A|^2 N_{CC\,\Lambda}$ (preliminary, without FSI)

- More than 1000 Λ are expected from $\bar{\nu}$
- With the upper bound $|\epsilon_A| < 7 \times 10^{-3}$ $\Rightarrow$ ~ (3×) 50 events

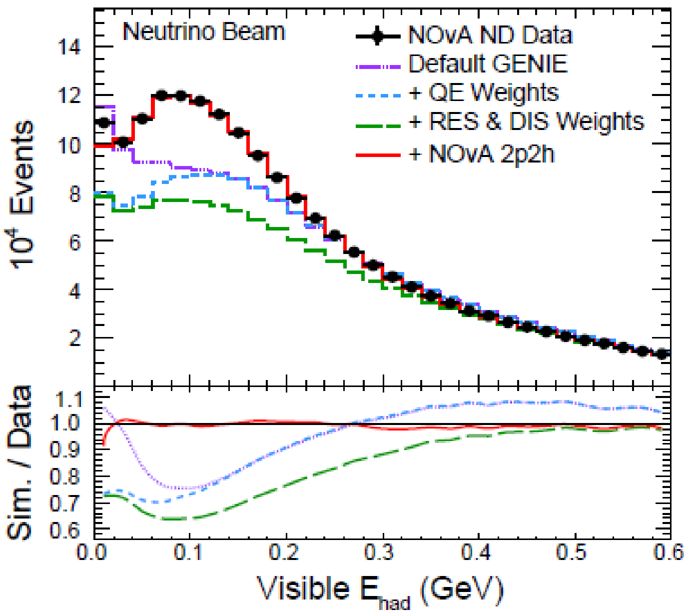
- At DUNE?
  - More possible final states: $\nu_l\, N \to \nu_l\, Y\,,\, Y\,\pi\,,\, N'\,\bar{K}\,,\, N'\,\bar{K}\,\pi$
  - More statistics (particularly with a gas TPC)
  - Background from $\nu_l\, N \to \nu_l\, Y\, K$

Summary

MiniBooNE

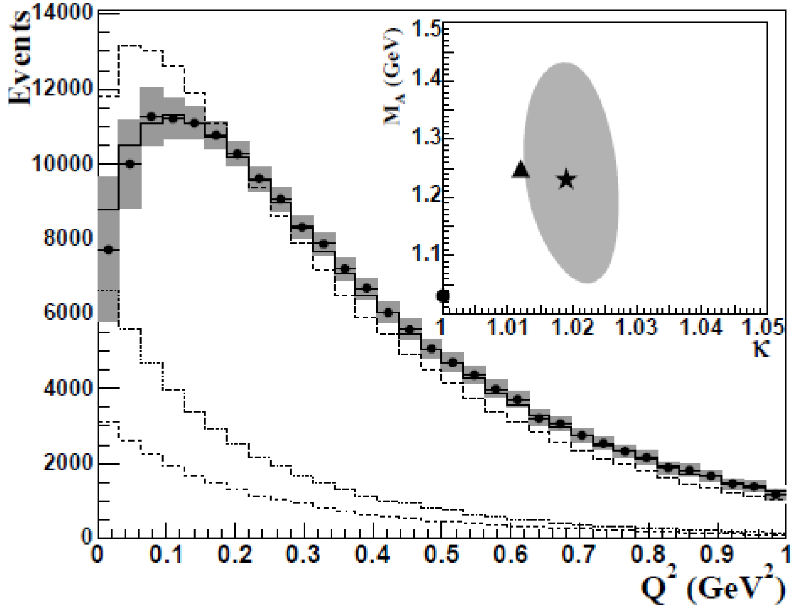


NOvA

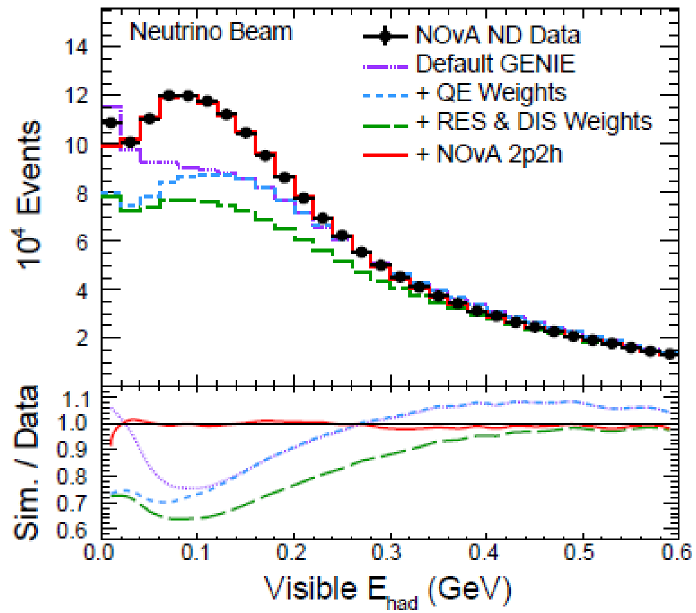


Summary

MiniBooNE



NOvA



- Don’t let this happen again with