NOW 2022
Neutrino Oscillation Workshop

Neutrino Cross Sections for future Oscillation Experiments

Luis Alvarez Ruso

IFIC
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Introduction

- Electroweak interactions open a doorway to fundamental properties of strong interacting matter
- ν cross sections are crucial to achieve the precision goals of oscillation experiments
- 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
  - **more realistic and efficent future projections**
- Neutrino scattering mismodeling in event generators can lead to **systematic errors** even if tuned to the best (ND) data.

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

THE EUROPEAN PHYSICAL JOURNAL C

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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-

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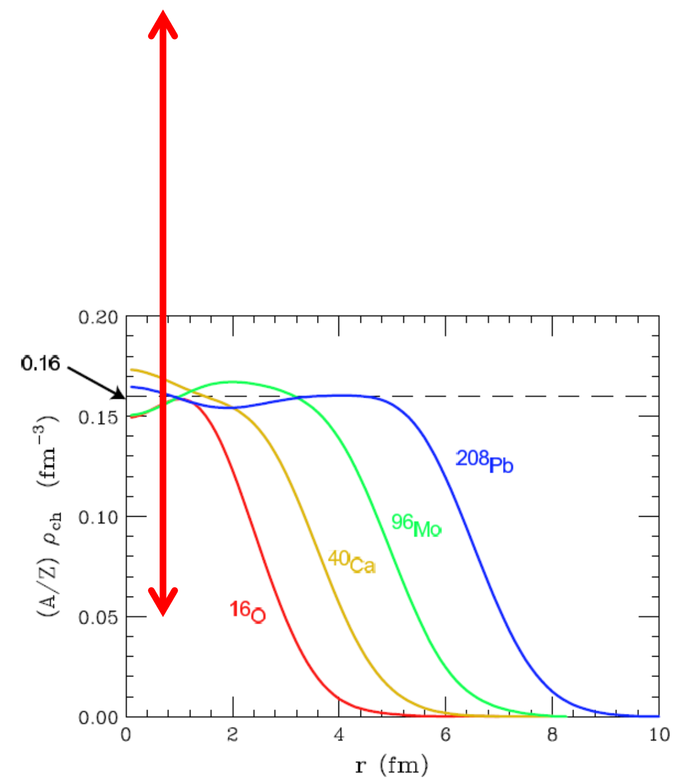
M_A^{QE}, Axial mass for CCQE	$^{+0.25}_{-0.15}$ GeV
QE FF, CCQE vector form factor shape	N/A
p_F Fermi surface momentum for Pauli blocking	±30%
Low W	
M_A^{RES}, Axial mass for CC resonance	±0.05 GeV
M_V^{RES} Vector mass for CC resonance	±10%

$$\rho \sim p_F^3$$

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

- The 30% p_F uncertainty masks the interaction model deficiencies



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1 Introduction

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

- The 30% p_F uncertainty masks the interaction model deficiencies
- This can hide systematic errors but also interesting physics
- A more efficient management of the resources may be possible

Tool Box

- **Lattice QCD**
- **Effective Field Theory**
- **Phenomenological models**
- **Monte Carlo simulations**

Tool Box

- **Lattice QCD**

A. Meyer @ NDNN workshop (2021)

  - correlation functions in Euclidean time: e.g. $\langle \mathcal{O}_1(t)\mathcal{O}_2(0)\rangle = \sum_n \langle 0|\mathcal{O}_1|n\rangle\langle n|\mathcal{O}_2|0\rangle e^{-E_n t}$
  - $\{a, L, m_q\} \to \{0, \infty, m_q(\text{phys})\}$ $\Rightarrow$ matrix elements, e.g. $\langle N|J_\mu|N\rangle$
  - numerically expensive
  - nonperturbative input for:
- **Effective Field Theory**
- **Phenomenological models**
- **Monte Carlo simulations**

Tool Box

- **Lattice QCD**
  - correlation functions in Euclidean time
  - $\{a,L,m_q\} \to \{0,\infty, m_q(\text{phys})\} \Rightarrow$ matrix elements
  - numerically expensive
  - nonperturbative input for:
- **Effective Field Theory**
  - Low-energy approximation of QCD
  - DOF: π, N, $\Delta(1232)$; heavier DOF $\Rightarrow$ LECs
  - Perturbative expansion $(q/\Lambda_\chi) \Rightarrow$ error estimate
  - Light-quark (u,d,s) mass dependence of physical quantities
  - Limited to low momentum transfers: mainly benchmark for:
- **Phenomenological models**
- **Monte Carlo simulations**

Tool Box

- **Lattice and perturbative QCD**
  - correlation functions in Euclidean time
  - $\{a, L, m_q\} \to \{0, \infty, m_q(\text{phys})\} \Rightarrow$ matrix elements
  - numerically expensive
  - nonperturbative input for:
- **Effective Field Theory**

} **synergy**

  - Low-energy approximation of QCD
  - DOF: π, N, Δ(1232); heavier DOF $\Rightarrow$ LECs
  - Perturbative expansion $(q/\Lambda_\chi) \Rightarrow$ error estimate
  - **Light-quark (u,d,s) mass dependence of physical quantities**
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Nucleon axial form factor

- Fundamental nucleon property

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

$$q = k - k' = p' - p$$

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

$$Q^2 = -q^2 > 0$$

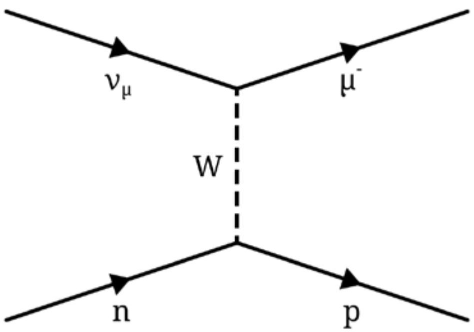
- Main source of uncertainty for QE scattering on nucleons:

$$\text{CCQE}: \nu(k) + n(p) \rightarrow l^-(k') + p(p')$$

$$\bar{\nu}(k) + p(p) \rightarrow l^+(k') + n(p')$$

$$\text{NCE}: \nu(k) + N(p) \rightarrow \nu(k') + N(p')$$

$$\bar{\nu}(k) + N(p) \rightarrow \bar{\nu}(k') + N(p')$$



  - Largest contribution at T2K, MicroBooNE
  - Used for kinematic E_ν reconstruction

- Input in models of non-resonant inelastic reactions (meson production) and two-nucleon currents

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

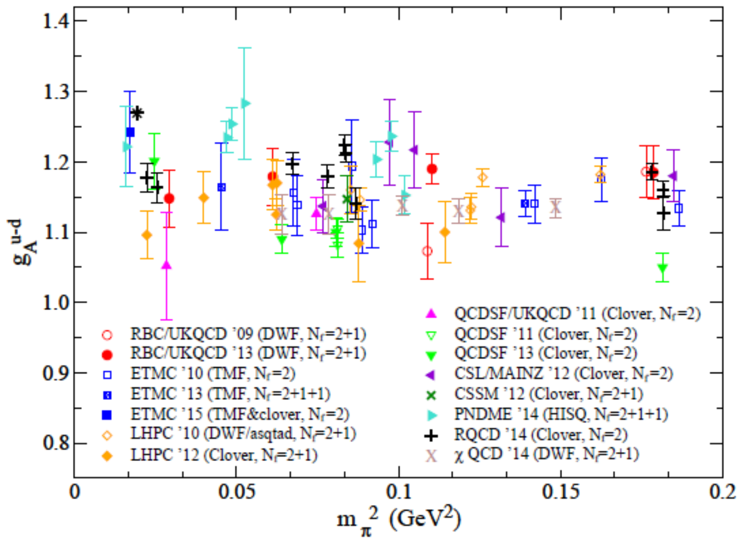
$$F_A(q^2) = g_A \left[1 + \frac{1}{6}\langle r_A^2\rangle q^2 + \mathcal{O}(q^4)\right]$$

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

  - Lattice QCD

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)

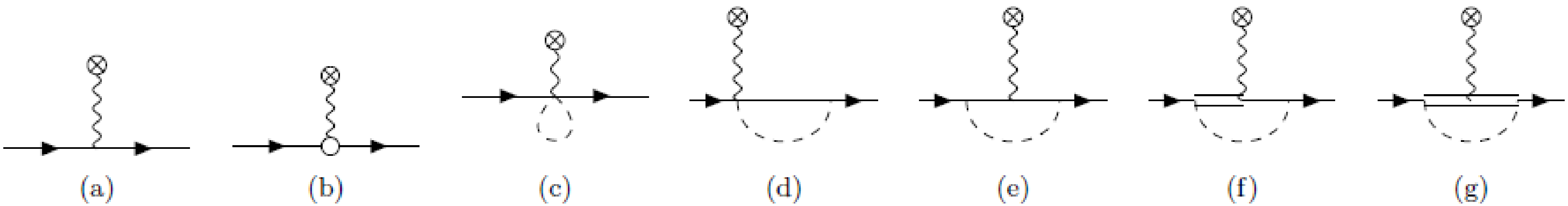
F_A & LQCD

- 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

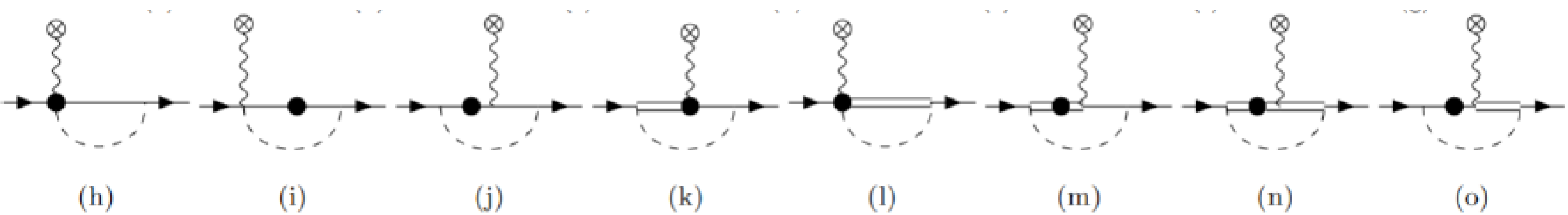
$$F_A(Q^2, M_\pi^2) = g + 4 d_{16} M_\pi^2 + d_{22} Q^2 + F_A^{(\text{loops})} + F_A^{(wf)}$$

- Up to O(p[3]) Yao, LAR, Vicente Vacas, PRD 96 (2017)

$$\delta = m_\Delta - m_N \sim \mathcal{O}(p)$$



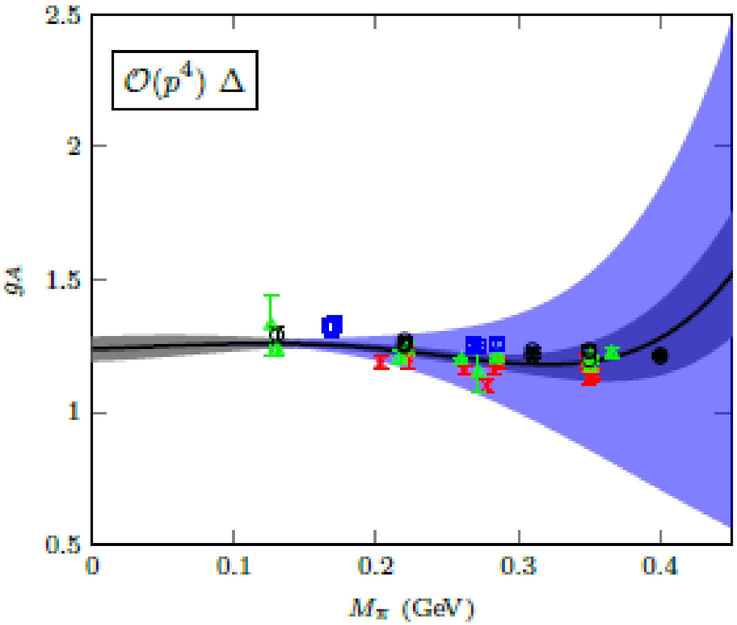
- Up to O(p[4]) Alvarado, LAR, PRD 105 (2022); work in progress



- Differences between O(p[3]) and O(p[4]) are considerable (at larger M_π) and provide a measure of the systematic error arising from the truncation of the perturbative expansion.

g_A & LQCD

- Differences between $O(p^3)$ and $O(p^4)$ are considerable (at larger M_π) and provide a measure of the systematic error arising from the truncation of the perturbative expansion.
  - Best seen for $g_A(M_\pi)$ Alvarado, LAR, PRD 105 (2022)



$$\chi^2 = \sum_i \frac{\left(g_A(M_\pi^i, a_i) - g_A^i\right)^2}{(\Delta g_A^i)^2} + \chi^2_{\rm prior}$$

$$(\Delta g_A^i)^2 = (\Delta g_{A \rm LQCD}^i)^2 + (\Delta g_{A\chi}(M_\pi^i))^2$$

FLAG 2021 Flavour Lattice Averaging Group

- **g_A = 1.2600(120)** vs $g_A = 1.2754(13)_{exp}(2)_{RC}$ vs g_A = 1.2460(280)
- $d_{16} = -0.88 \pm 0.88\ \mathrm{GeV}^{-2} \leftarrow M_\pi$ dependence of long range nuclear forces

F_A & LQCD

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

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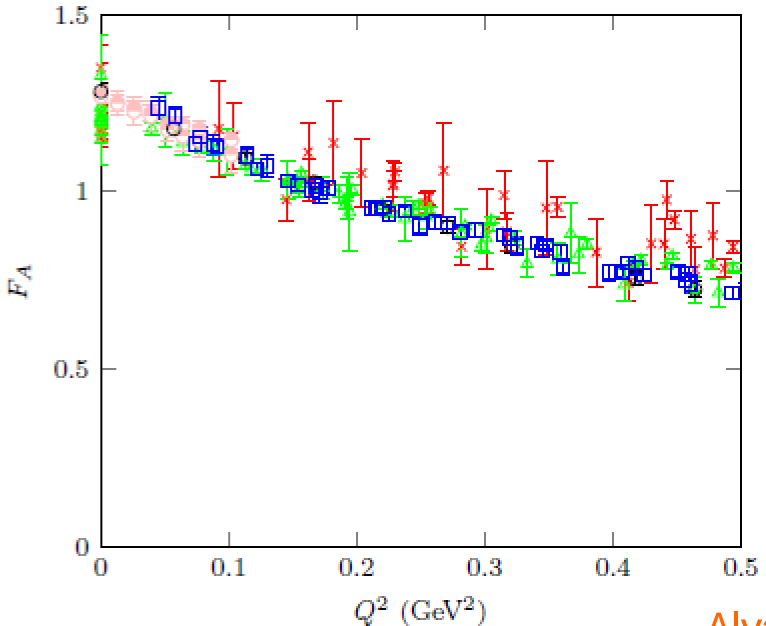
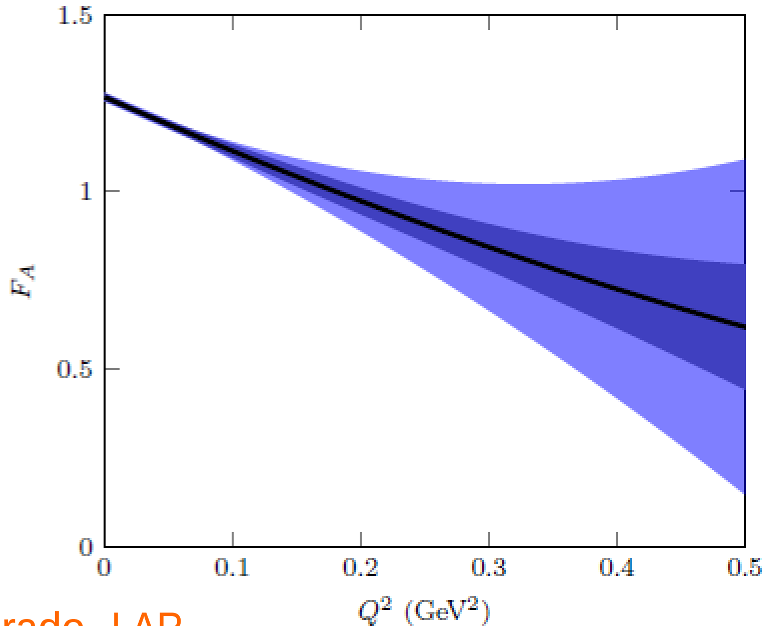
M_π < 400 MeV



M_π physical



Alvarado, LAR

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

Axial radius & LQCD

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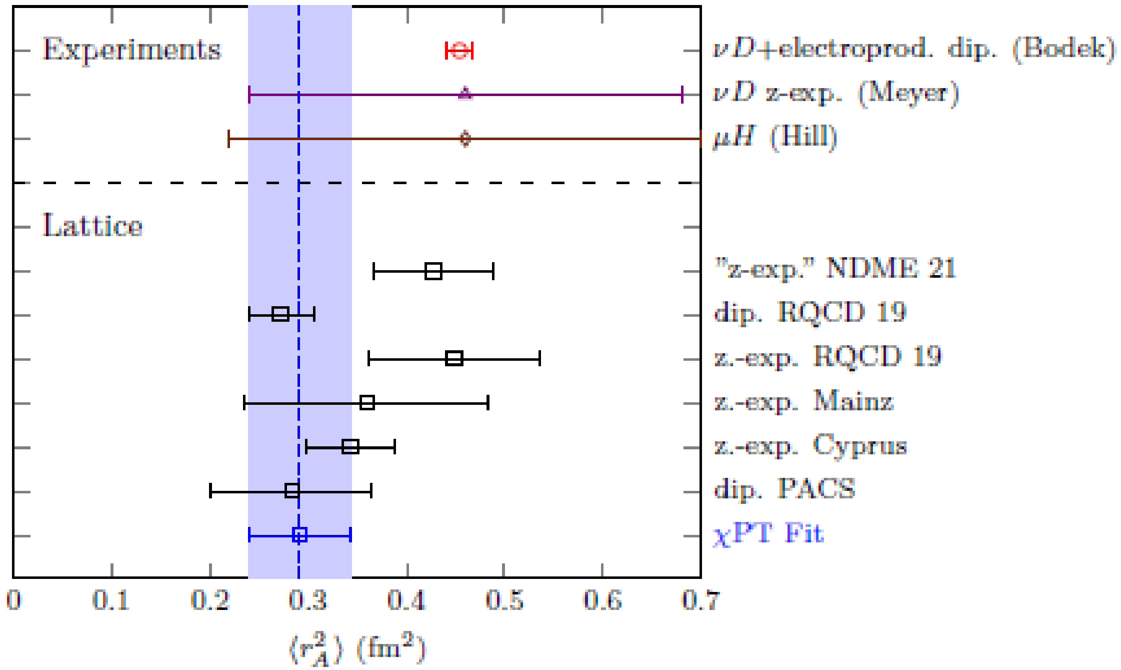
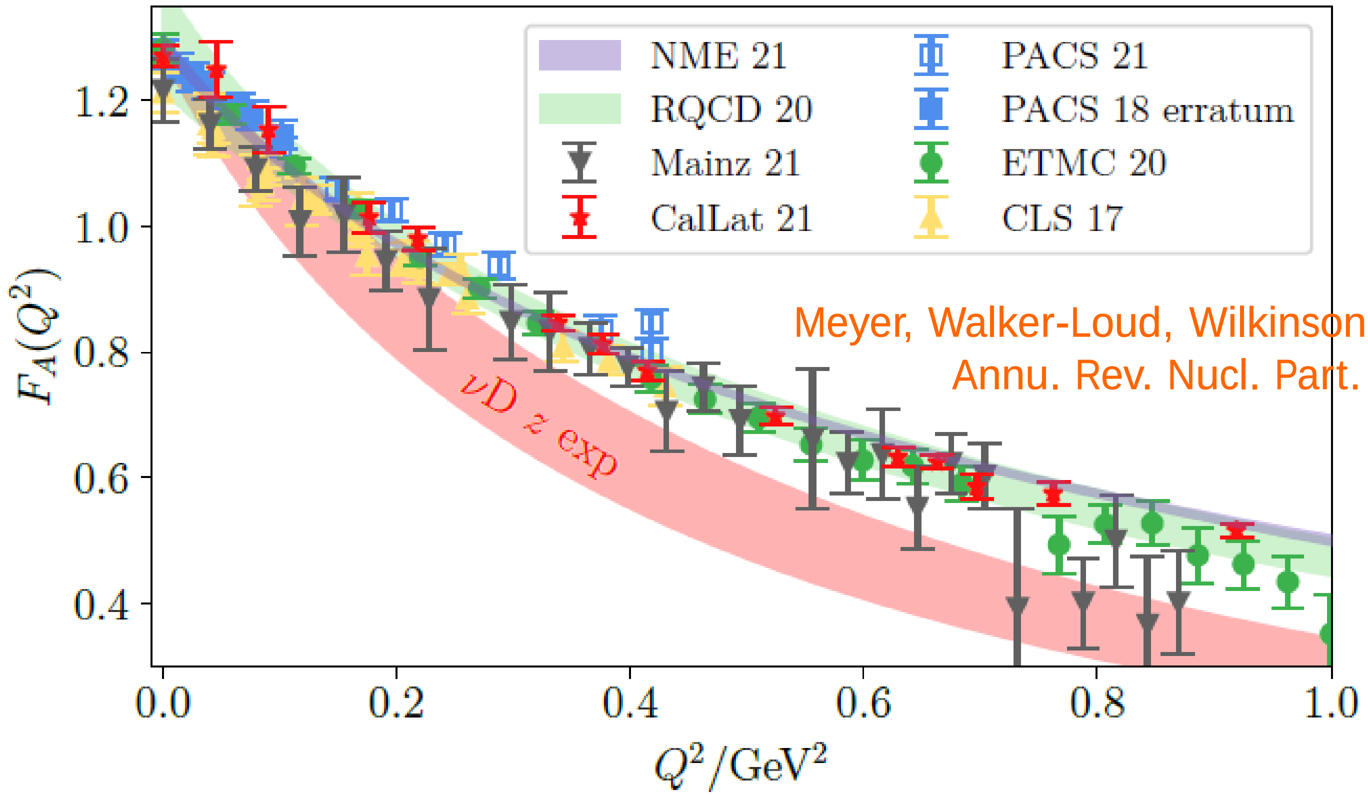


$\langle r_A^2\rangle = 0.291(52)\ \mathrm{fm}^2 \Leftrightarrow M_A = 1.27(11)$ GeV

In tension with empirical determinations

Alvarado, LAR

F_A: Exp. vs LQCD



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

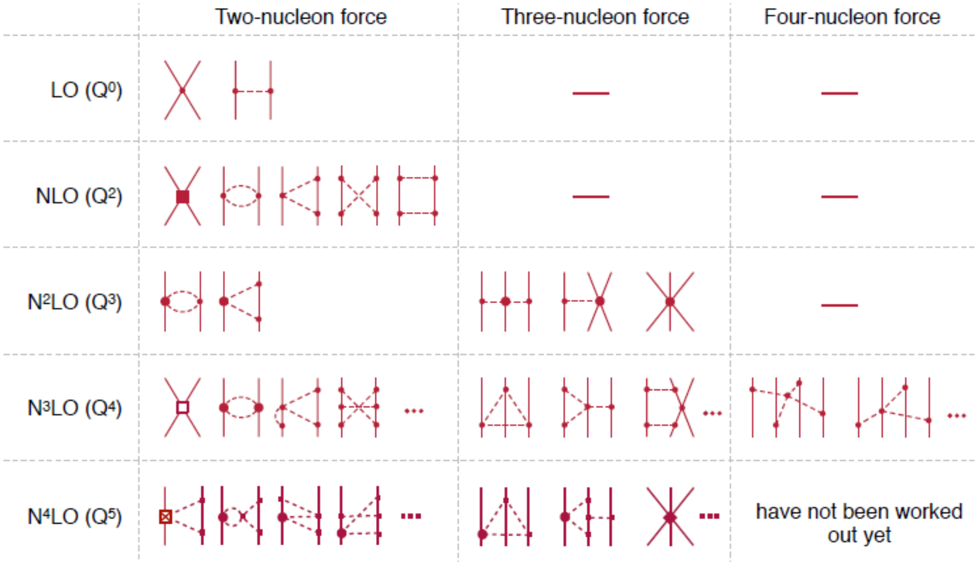
- How reliable are old bubble chamber experiments?
- Do LQCD present results still hide uncontrolled systematics?
  - Most systematics (extrapolation to the continuum and to physical quark masses, ...) expected to be controlled to <2% and excited-state contamination to <5% in 5 years

LAR et al., Snowmass 2021, 2203.09030

EFT for nuclear physics

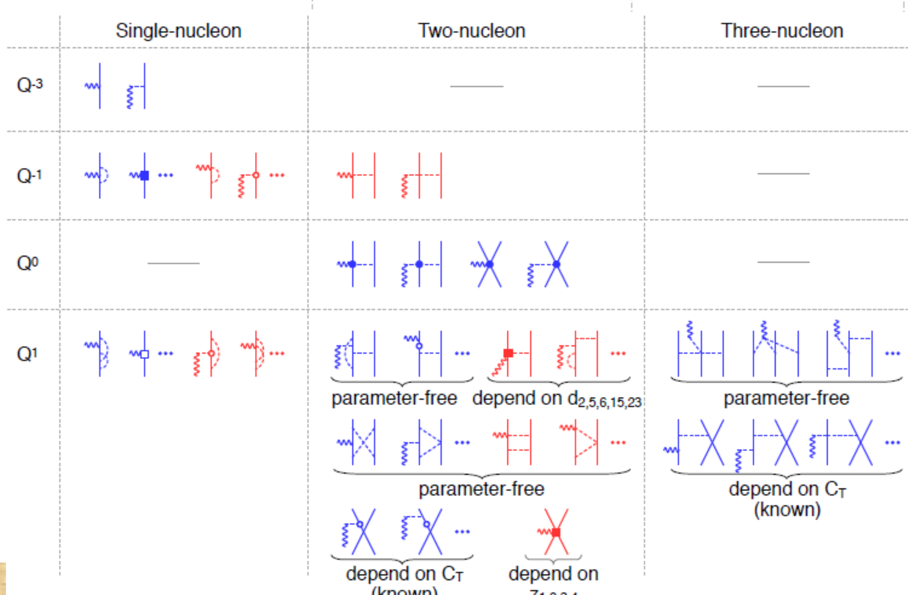
- EFT allow to calculate NN interactions and two-body currents consistently

Epelbaum, 1908.09349



Approaches:
Baroni et al., PRC93 (2016)
Krebs et al, Ann.Phys.378 (2017)

Chiral expansion of nuclear forces

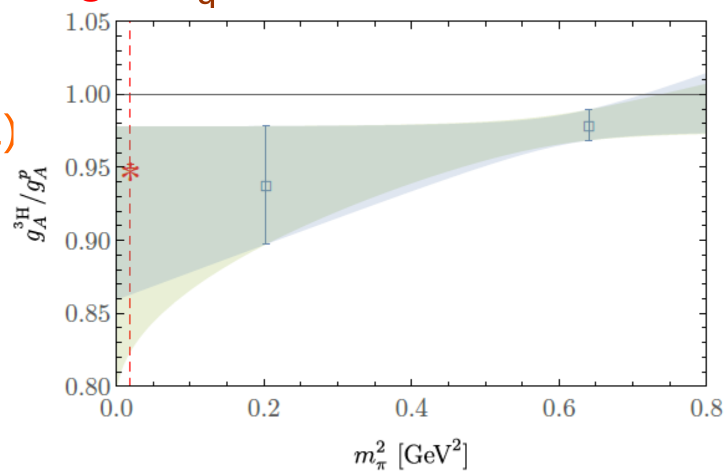


Chiral expansion of the nuclear axial current

LECs ⇐ experiment & Lattice QCD

LQCD for nuclear physics

- Nonperturbative input:
- Single-nucleon currents in nuclei:
  - LECs ⇒ EFT
  - Nucleon form factors ⇒ pheno. models
- Two/few-nucleon currents?
  - Pioneering studies of matrix elements at high m_q:
    - $\langle pp|A_\mu^+|d\rangle$ Savage et al., PRL 119 (2017)
    - $\langle {}^3\mathrm{He}|A_\mu^+|{}^3\mathrm{H}\rangle$ Parreño et al., PRD 103 (2021)



  - LQCD results with control over excited states, ∼physical m_q, robust {a,L} → {0,∞} extrapolations: 5-10 years
    LAR et al., Snowmass 2021, 2203.09030
- LQCD computations of electroweak nuclear responses is out of reach

Ab initio

- Green's function MC
  - Nuclear response function in Euclidean time
  - DOF: π, N but **no** $\Delta(1232)$
  - Nonrelativistic 1- and 2-body currents
  - Nonrelativistic NN + NNN phenomenological Hamiltonian (AV18)
  - Computationally expensive: light nuclei < ^{12}C
  - Lovato et al.: semi-inclusive ν-nucleus scattering in the QE region

Ab initio

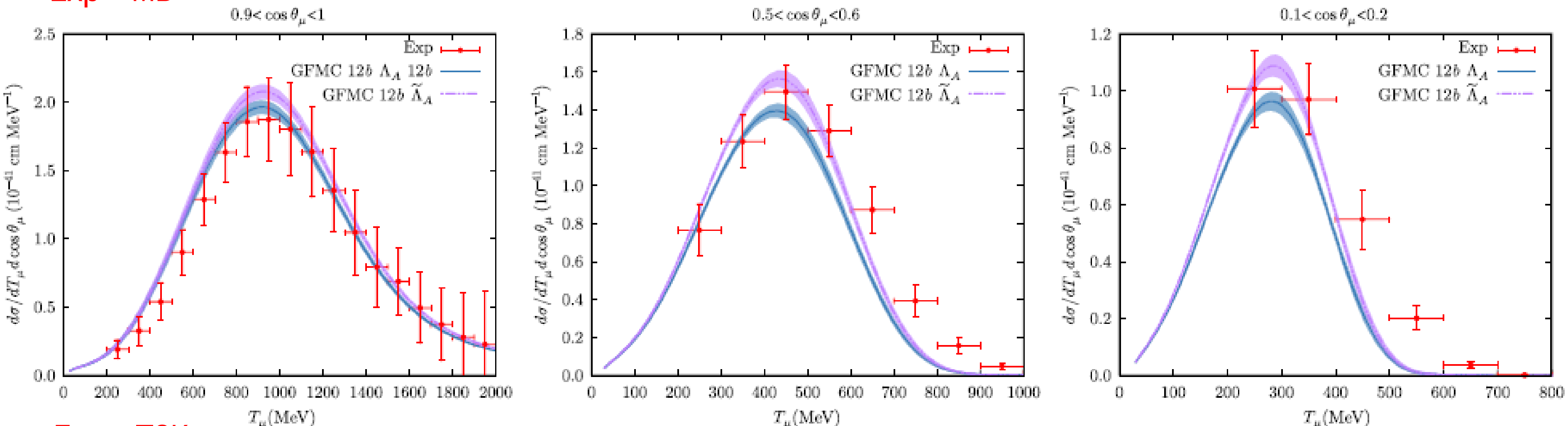
- Green's function MC

Lovato et al., PRX 10(2020)

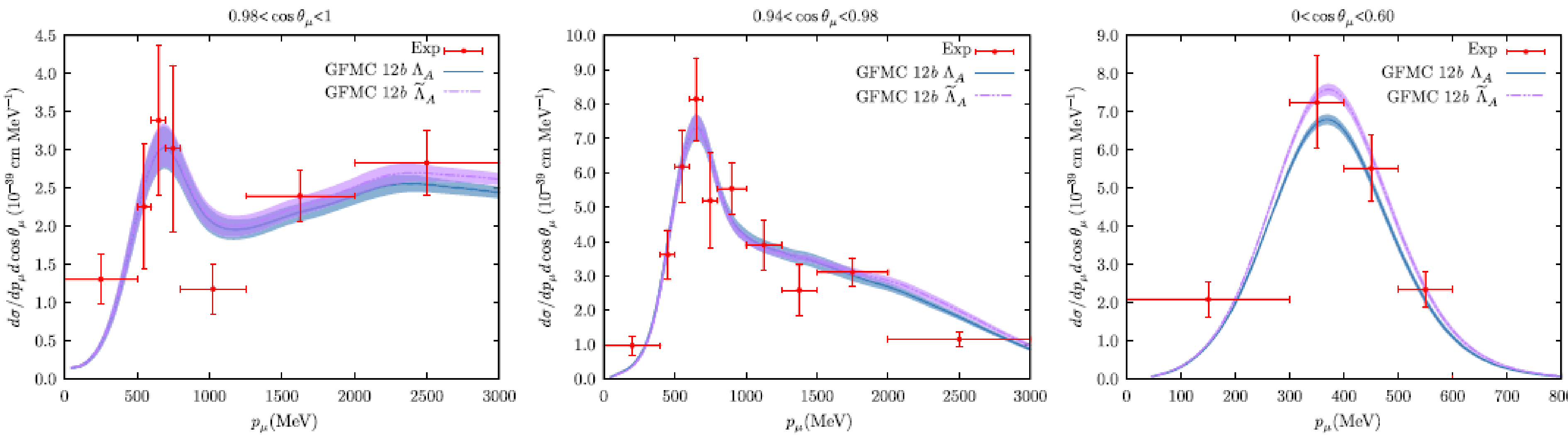
$\Lambda_A \equiv M_A$= 1 GeV

$\widetilde{\Lambda}_A \equiv M_A$=1.15 GeV

Exp= MB

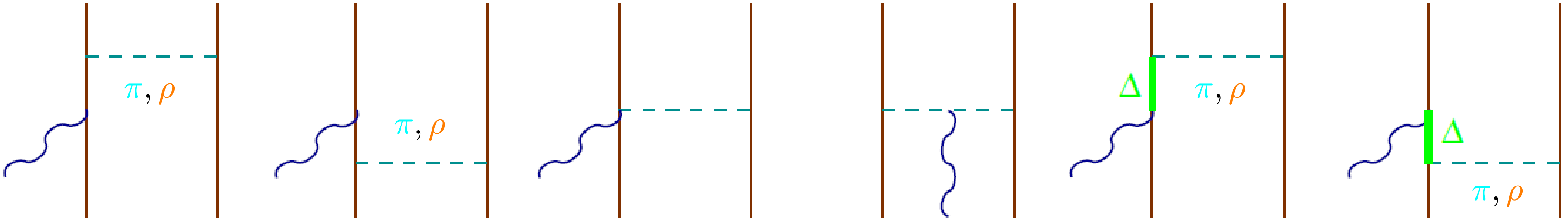


Exp= T2K



Phenomenological models

- Phenomenological 1- and 2-nucleon currents

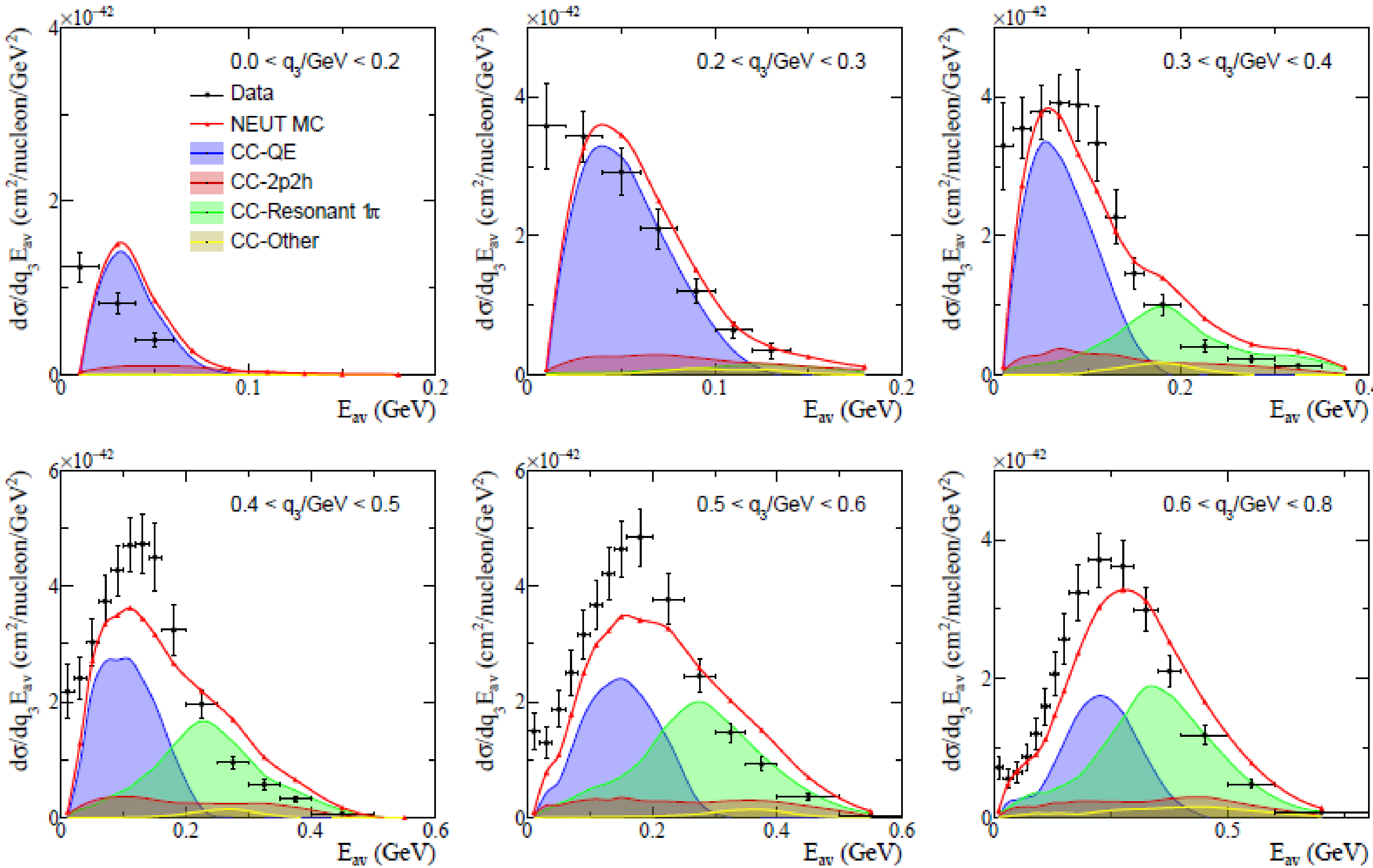


- Different descriptions of initial state nucleons:
  - Global Fermi gas
  - Local Fermi gas
  - Mean field
  - Superscaling
  - Spectral functions

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

Pheno models for QE-like scattering



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

Pheno models for QE-like scattering

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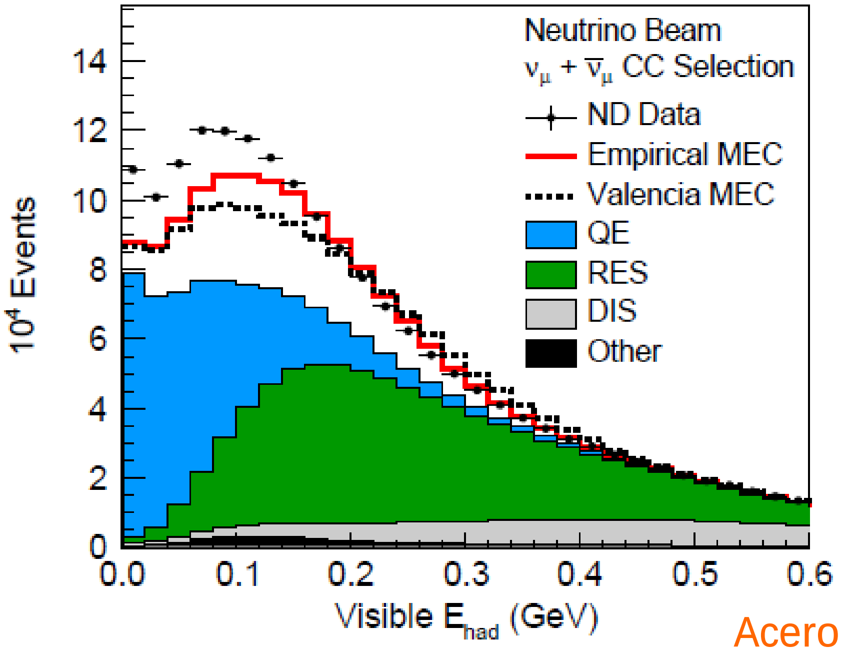
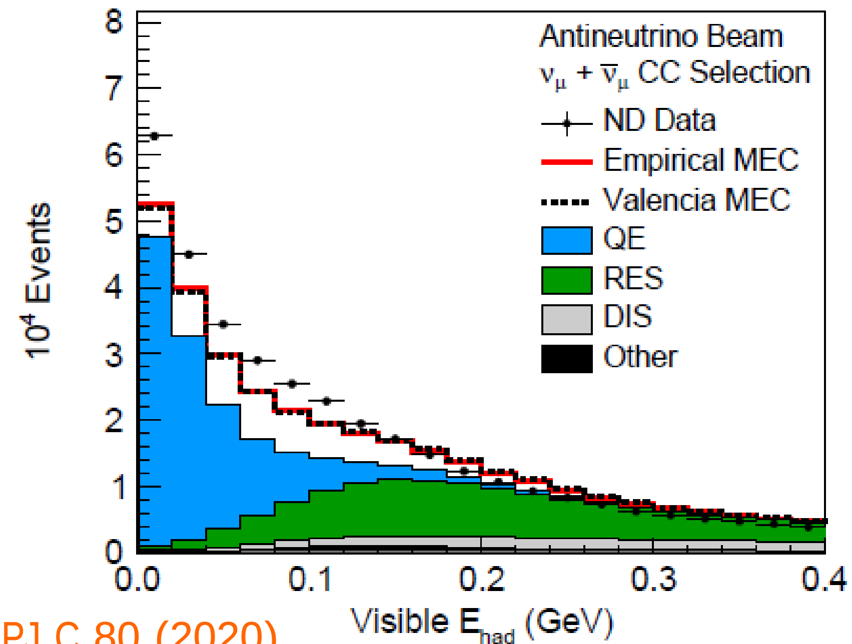


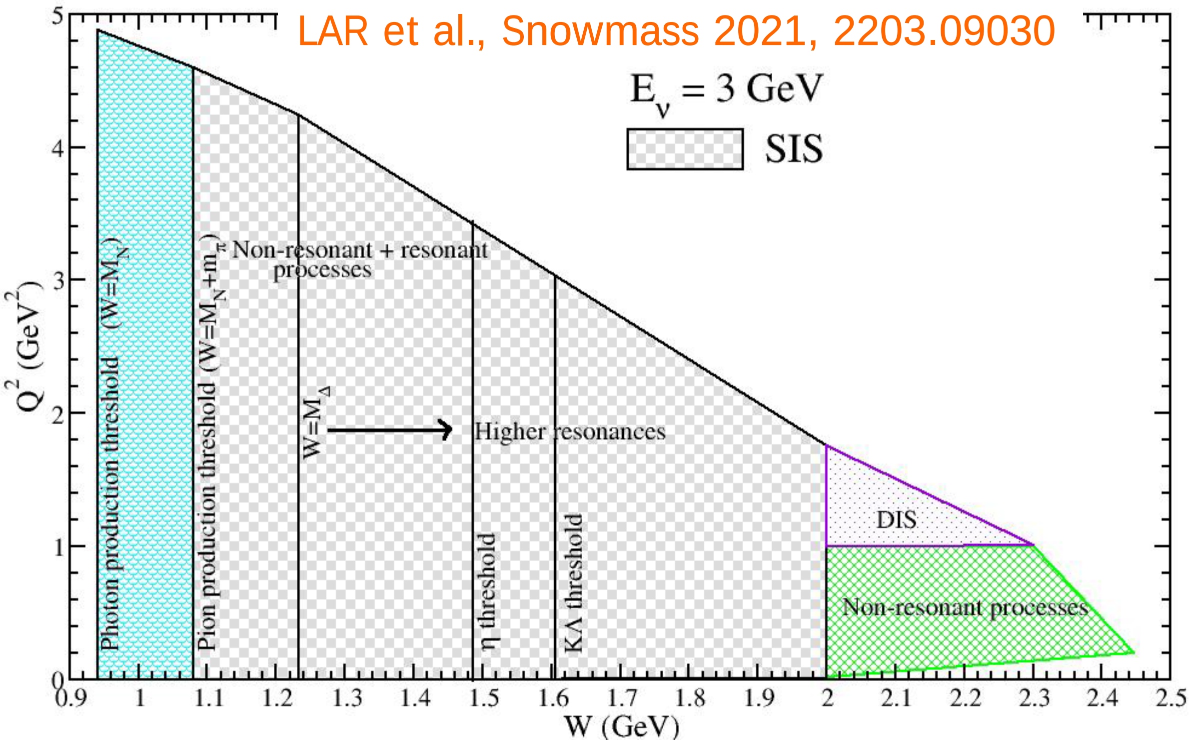


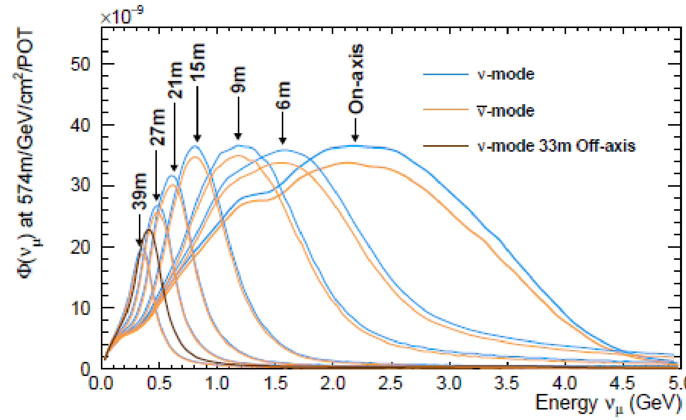
Acero et al., EPJ C 80 (2020)

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

Inelastic scattering

LAR et al., Snowmass 2021, 2203.09030

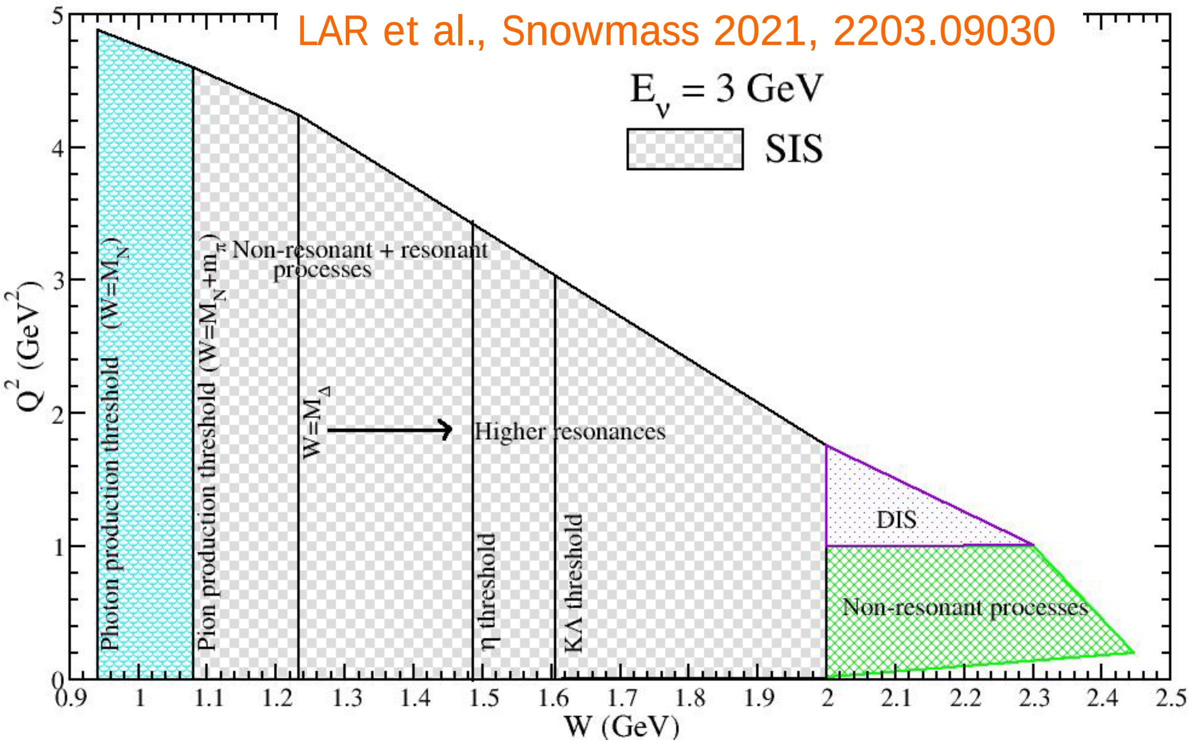




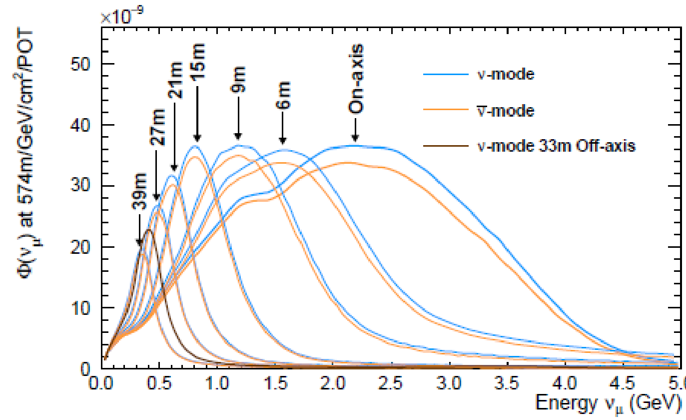
DUNE flux @ ND, 2002.03005

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

Inelastic scattering



LAR et al., Snowmass 2021, 2203.09030

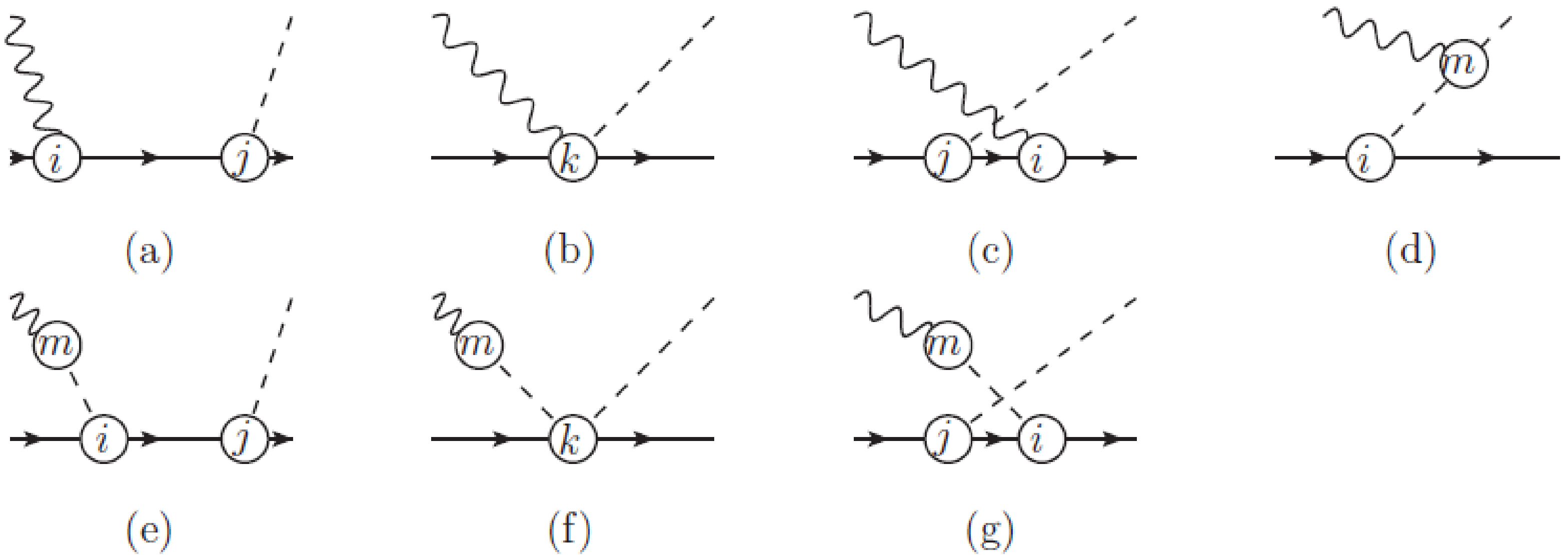


DUNE flux @ ND, 2002.03005

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

Weak pion production in ChPT

- First study in ChPT: Yao et al., PRD 98 (2018); PLB 794 (2019)
- Part of a comprehensive study of $\pi N \to N\pi$, $\gamma^* N \to N \pi$, $W^*, Z^* N \to N \pi$, ...
- EOMS, explicit $\Delta(1232)$, $O(p^3)$
- δ-counting: $\delta = m_\Delta - m_N \sim O(p^{1/2})$ $\Rightarrow$ $D = 4L + \sum_k kV^{(k)} - 2I_\pi - I_N - \frac{1}{2} I_\Delta$
  - applicable at threshold: $p/\delta \approx \delta/\Lambda$
- A different counting at the $\Delta(1232)$ peak is also possible



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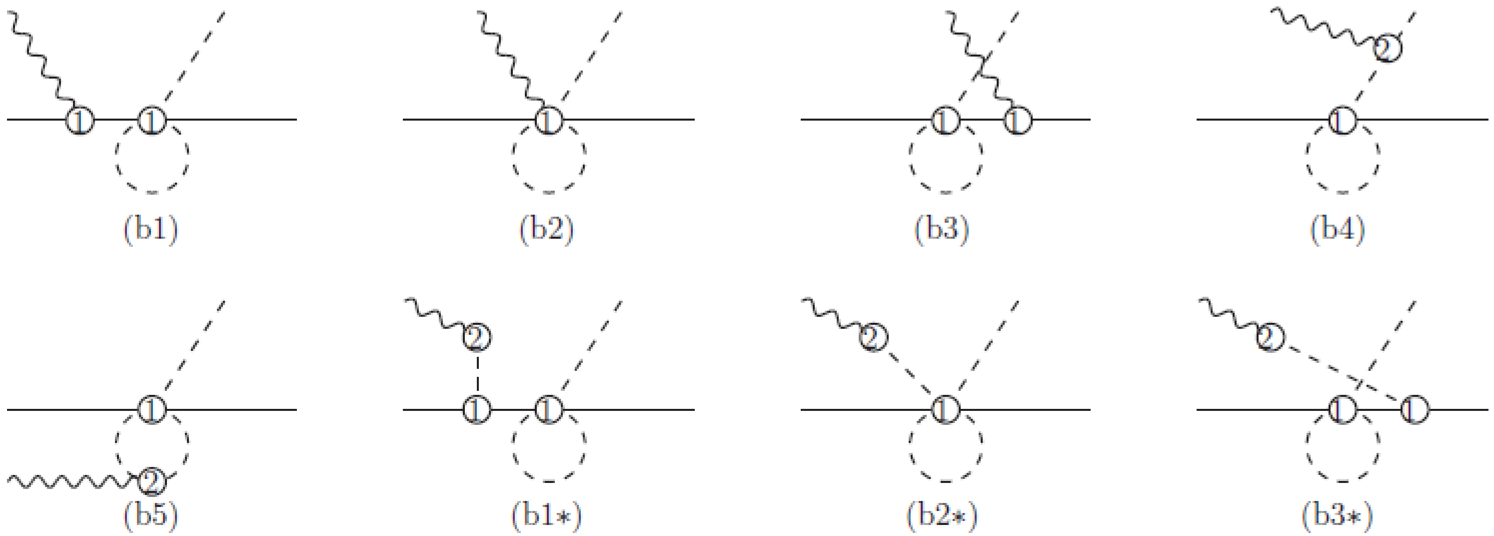
- δ-counting: δ = $m_\Delta - m_N \sim O(p^{1/2})$
  - Examples of loop terms:



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- EOMS, explicit $\Delta(1232)$, $O(p^3)$
- δ-counting: $\delta = m_\Delta - m_N \sim O(p^{1/2})$

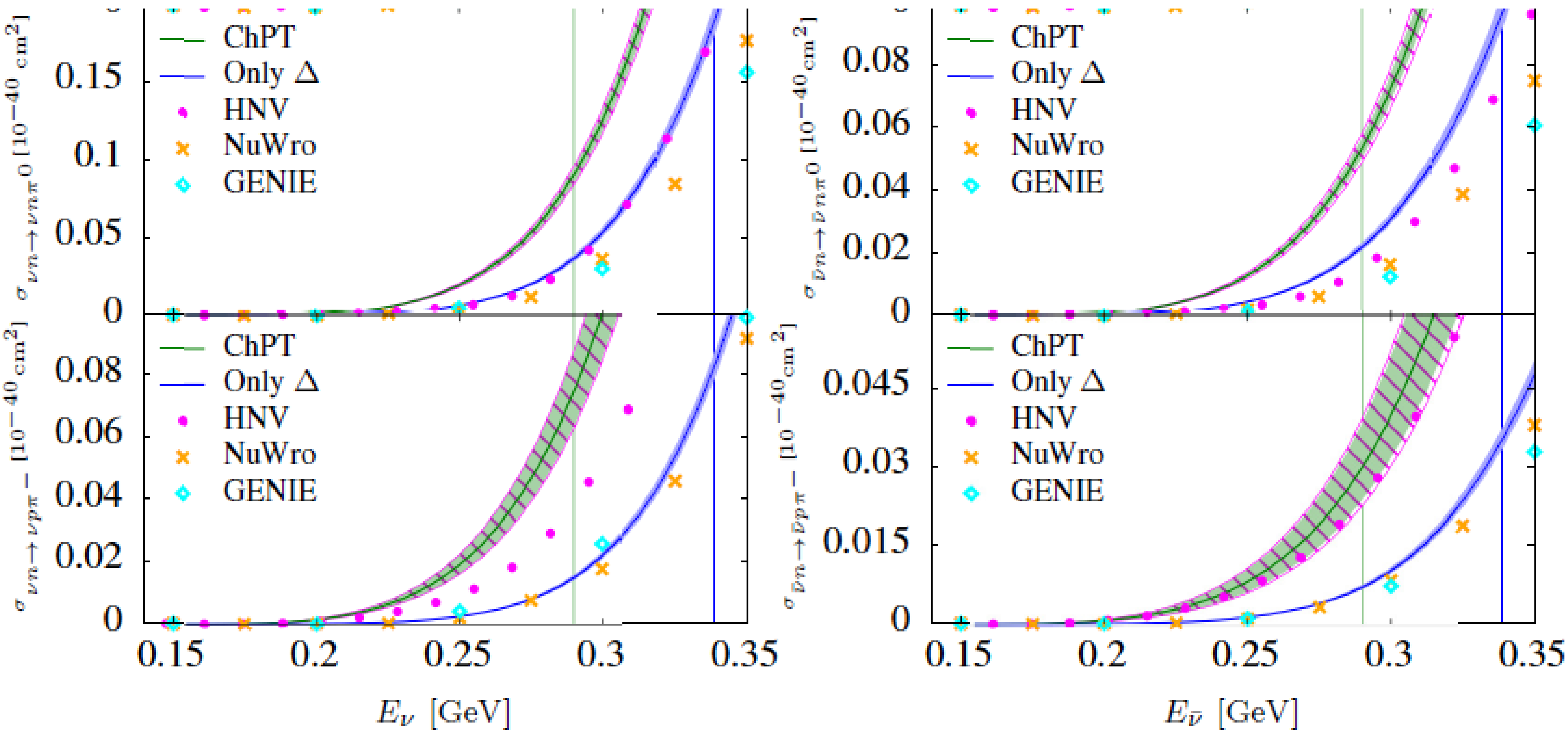
- LECs : 22 in total
  - 7 unknown:
    - 4 can be extracted from pion photo and electro-production

      Guerrero Navarro, Vicente Vacas, PRD 102 (2020)
    - information about remaining 3 could be obtained from new close-to-threshold measurements of ν-induced π production on protons

- Benchmark for phenomenological models

Weak pion production in ChPT

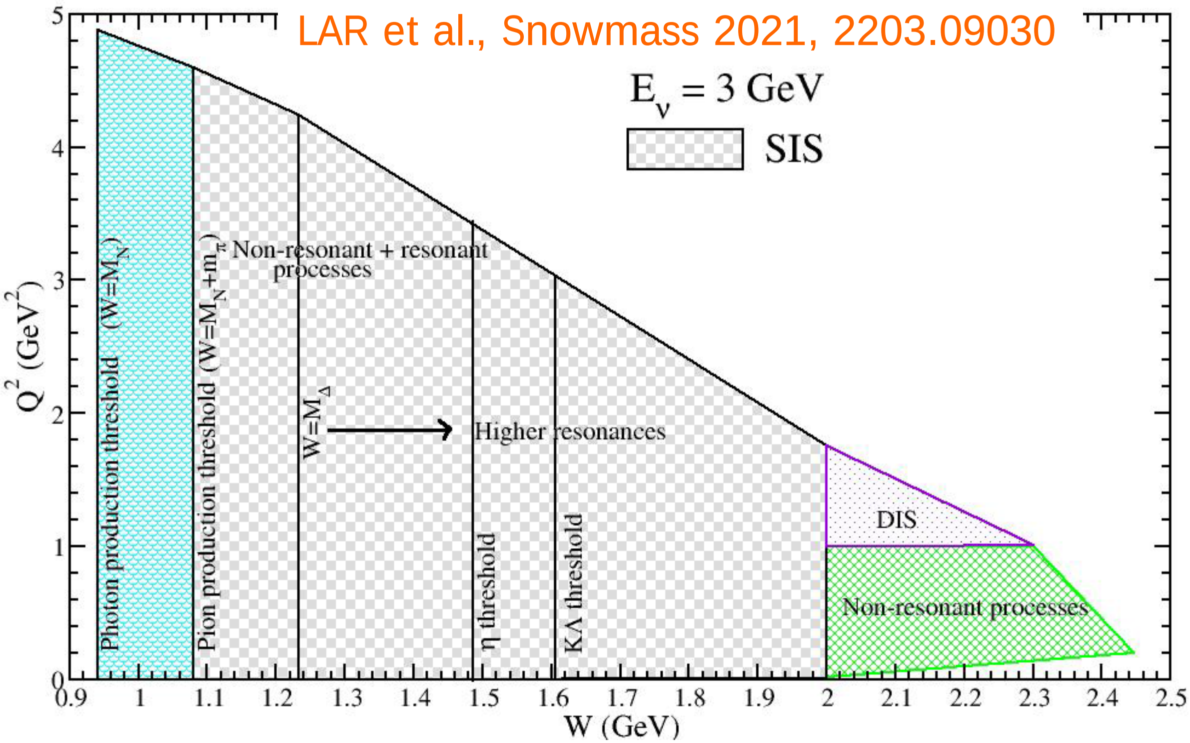
- First study in ChPT: Yao et al., PRD 98 (2018); PLB 794 (2019)
- Benchmark for phenomenological models

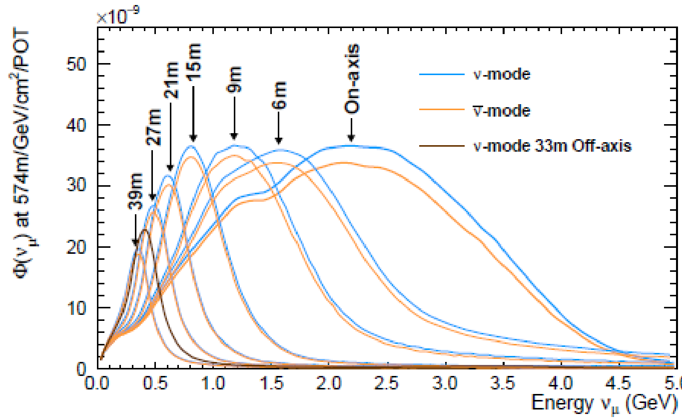


Weak pion production in ChPT

- "Standard candle" for flux monitoring
  - "Solid Hydrogen" concept at the Straw Tube Tracker (STT) as part of the System for on-Axis Neutrino Detection (SAND) at the DUNE near-detector complex
    - extraction of CC pion production data on H by subtracting measurements on graphite (pure C) from those on a CH_2 plastic
      Duyang, Guo, Mishra, R. Petti, PLB 795 (2019)
    - Flux determination: using ChPT to have controlled errors
      LAR, R. Petti, work in progress

Inelastic scattering





DUNE flux @ ND, 2002.03005

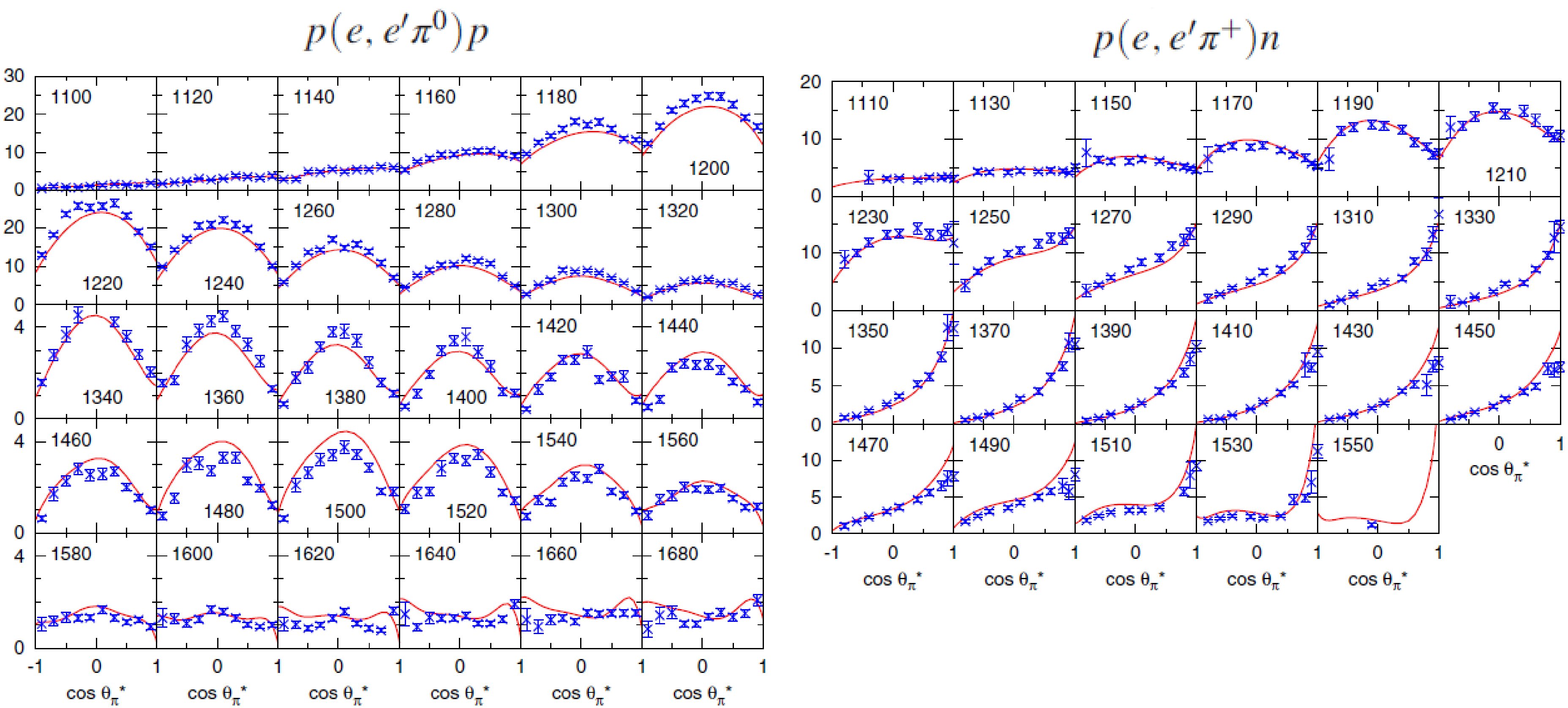
- Above the $\Delta(1232)$ peak: 1.3<W<2 GeV:
  - several overlapping resonances
  - non-trivial interference; coupled channels

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

- Different final states $\Rightarrow$ 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)

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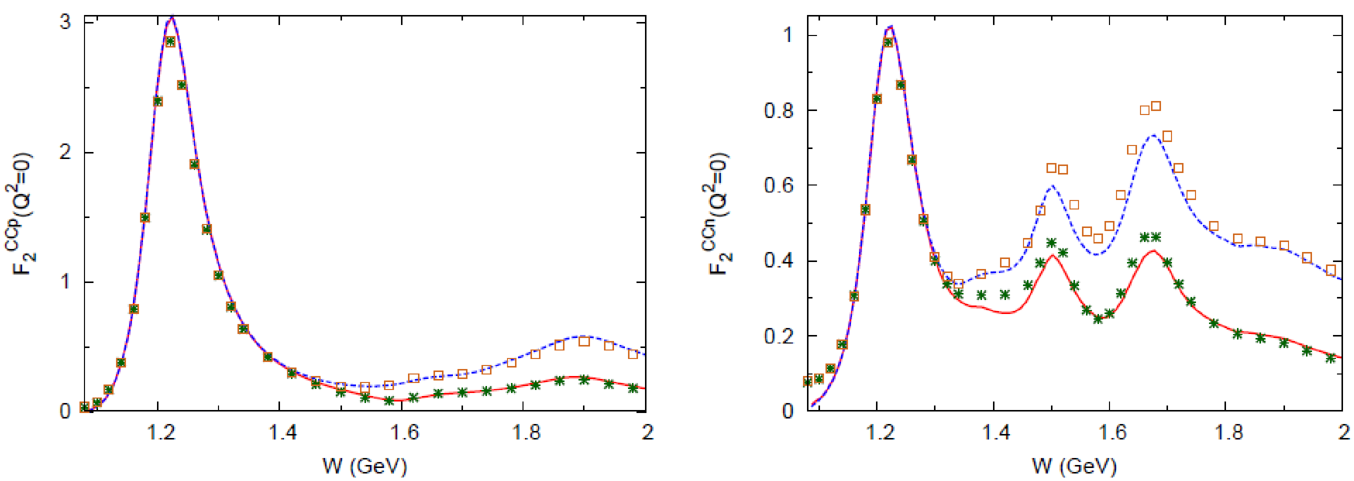
$$F_2(W, Q^2 = 0 \approx -m_\pi^2) \propto f_\pi^2 \, \sigma_{\pi N}(W)$$

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



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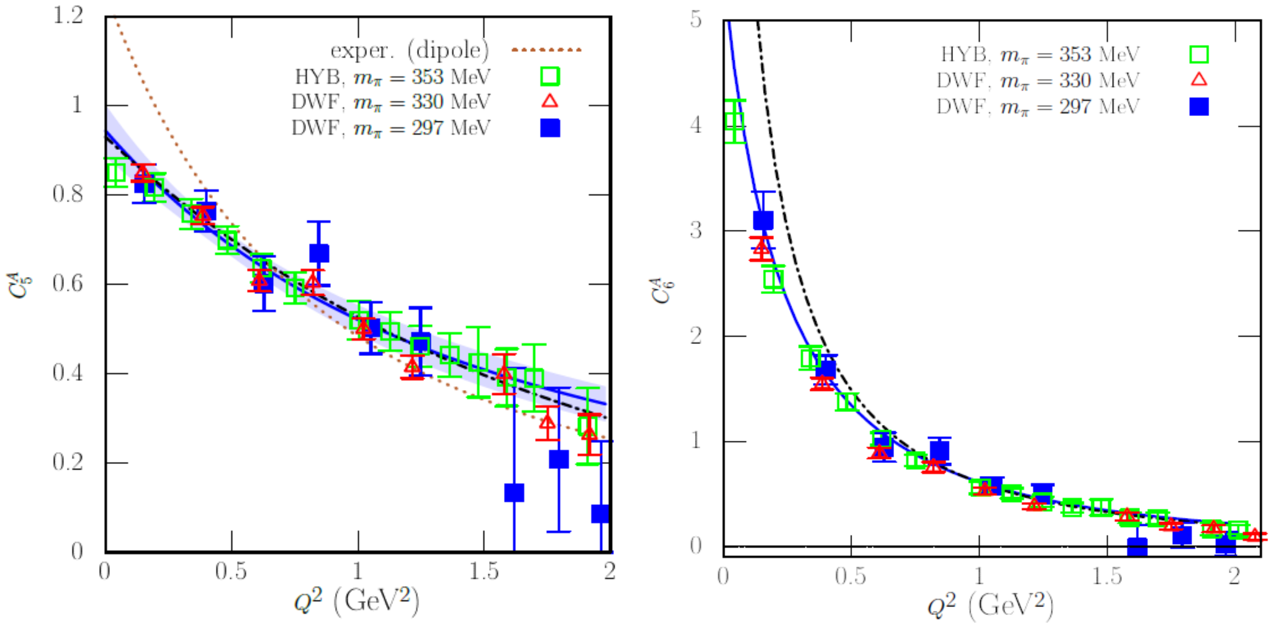
  - Very limited information about the axial current at $q^2 \neq 0$
    - Some on N-Δ(1232) from ANL and BNL on $\nu_\mu\, d \to \mu^- \pi^+ p\, n$
    - Lattice QCD

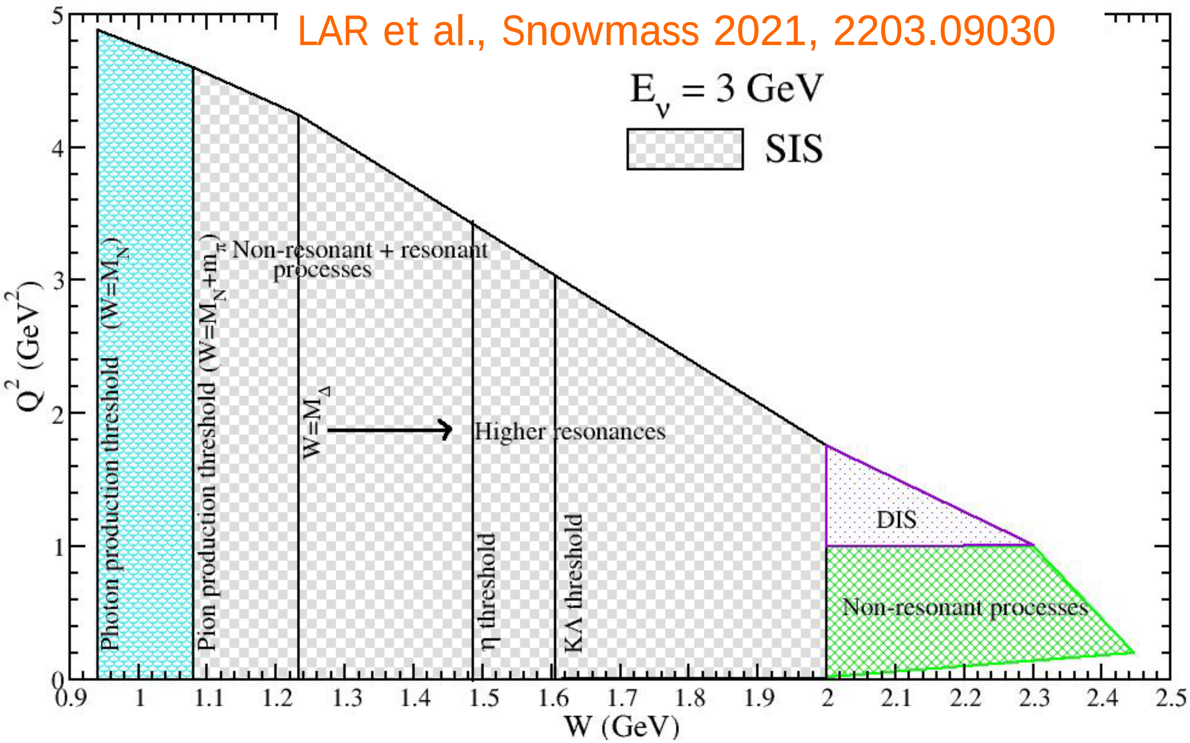
LQCD & meson production

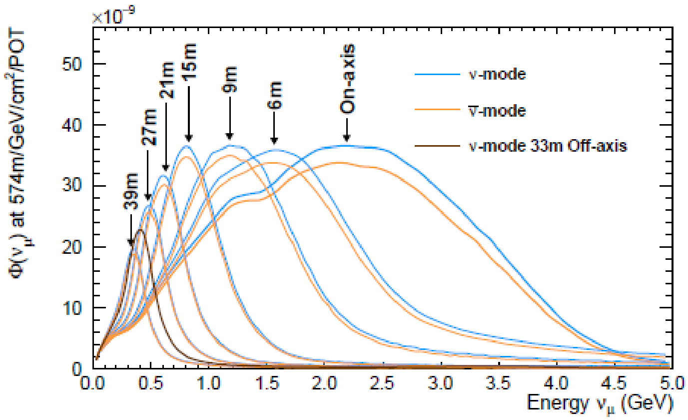
- Early N-Δ(1232) axial FF with heavy m_q Alexandrou et al.,PRD83 (2011)



- 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

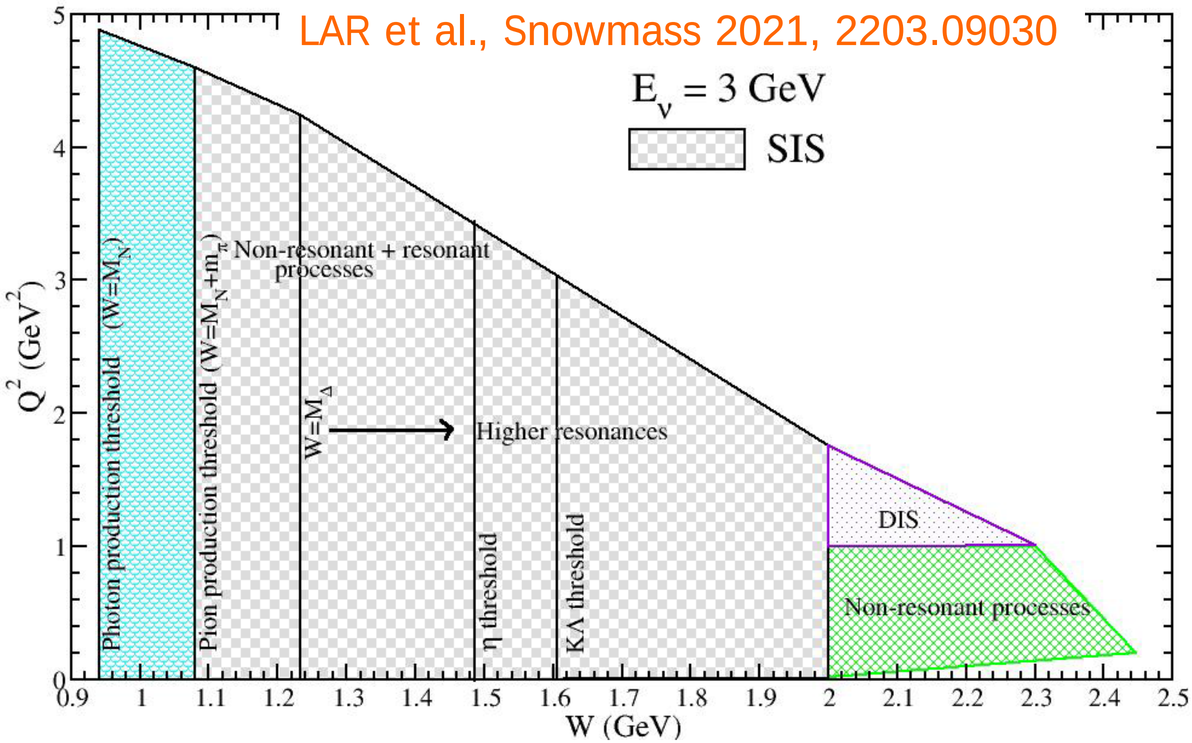


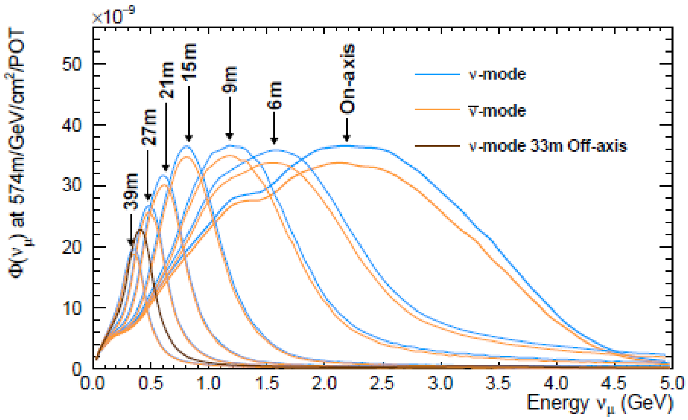


DUNE flux @ ND, 2002.03005

- Transition from RES to DIS:
- Traditional approach in MC generators:
  - pdf empirically extrapolated from the DIS region to lower W and Q2
    Bodek & Yang
    - Motivated by duality arguments
    - The specific particle content of the final state is not predicted

Inelastic scattering





DUNE flux @ ND, 2002.03005

- Transition from RES to DIS:
  - More realistic description of RES
  - Higher twists
- Progress in this direction is hindered by the lack of experimental information about the axial current for inelastic processes on nucleons

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)

Inelastic scattering on nuclei

- Except for a few processes (single-nucleon knockout, Cohπ, Cohγ, ...), QM treatment of FSI is unfeasible $\Rightarrow$ semiclassical methods: intranuclear cascades and transport.
  - Usual suspects: NEUT, GENIE, NuWro, GiBUU
  - Newcomers:
    - A CHIcagoLand Lepton Event Simulator (ACHILLES) Isaacson et al., 2205.06378
      - event generator for lepton-nucleus scattering
      - spectral function + intranuclear cascade (with a mean-field potential)
      - validated with e-^{12}C data (both inclusive and exclusive)
      - still limited to one-body QE scattering
    - DarkNews Abdullahi et al., 2207.04137
      - MC generator for beyond-SM neutrino-nucleus scattering
      - dilepton and single-photon events
      - production and decay of heavy neutral leptons via vector, scalar mediators and transition magnetic moments: candidates to explain the MiniBooNE excess

Summary

- Systematic errors in oscillation experiments are expensive: neutrino-interaction theory can critically contribute to the success of the experimental program (and benefit from it).
- Ongoing progress:
  - **Lattice and perturbative QCD**
  - **Effective Field Theory**
  - **Phenomenological models**
  - **Monte Carlo simulations**
- Some studies suffer from the lack of high quality data on elementary targets
- These efforts should have an (in)direct impact on the event generators used in planning, running and analyzing oscillations experiments.