NEUTRINO 2024

XXXI International Conference on Neutrino Physics and Astrophysics
June 16-22, 2024 Milan, Italy

Theory of Neutrino Interactions

Luis Alvarez Ruso

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

EXCELENCIA
SEVERO
OCHOA

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT
DE VALÈNCIA

Financiado por
la Unión Europea
NextGenerationEU

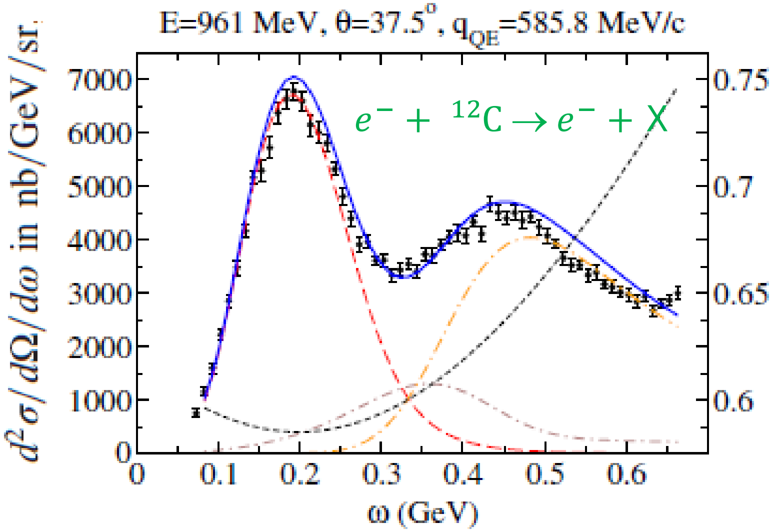
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Plan de Recuperación, Transformación y Resiliencia

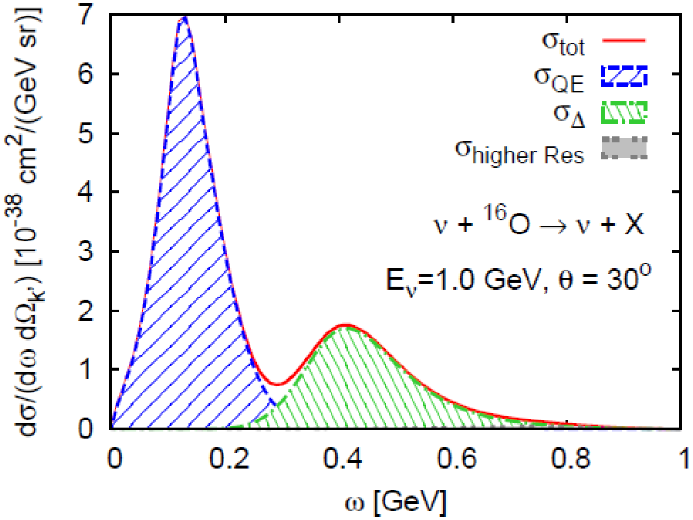
GENERALITAT VALENCIANA
Conselleria de Educación, Universidades y Empleo

GVANEXT
Fondos Next Generation en la Comunitat Valenciana

Overture



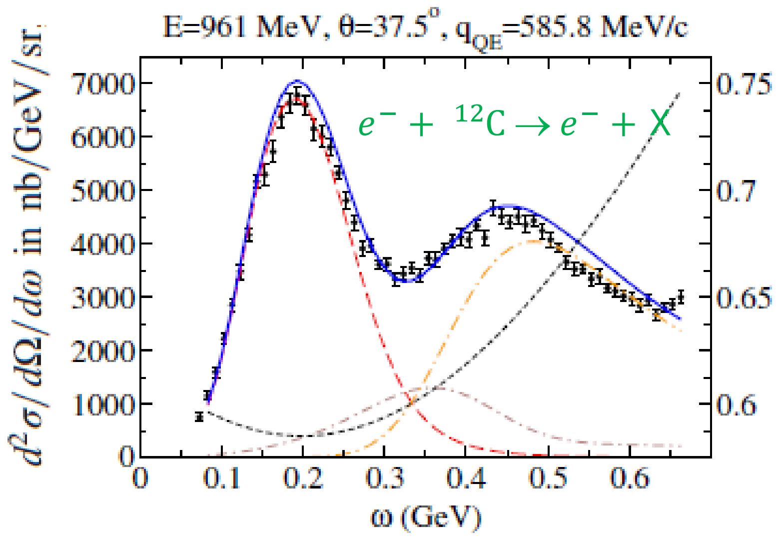
Megias et al., PRD 94 (2016)



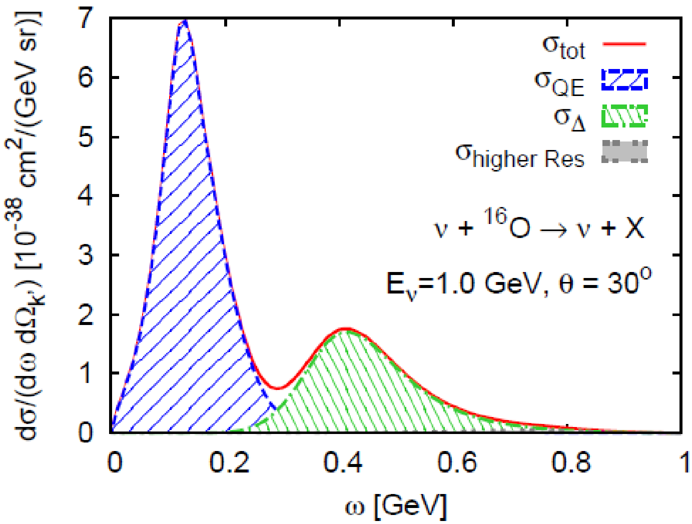
Leitner et al., PRC 79 (2009)

Overture

- Neutrino interactions are different:



Megias et al., PRD 94 (2016)

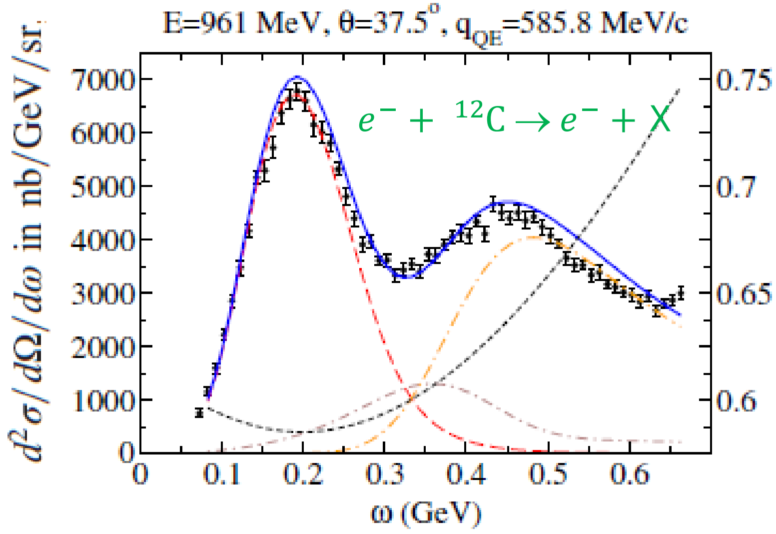


Leitner et al., PRC 79 (2009)

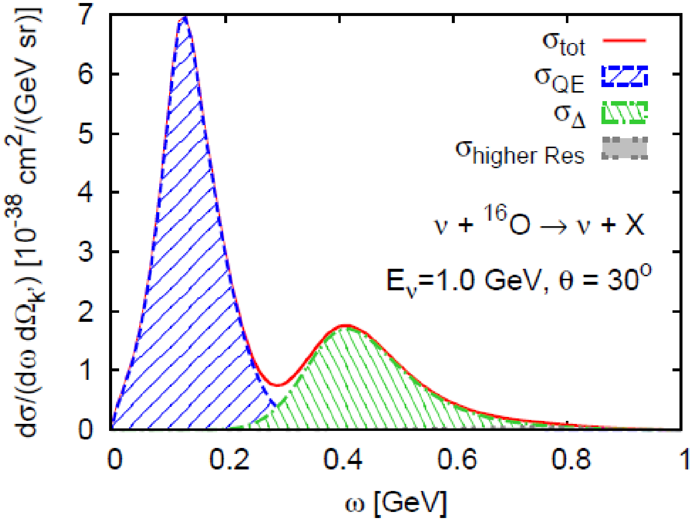
- Mediator mass ⇒ strength but also angular dependence
- Axial + Vector-Axial interference
- CC interactions change the quark flavor
- Different radiative corrections

Overture

- Neutrino interactions are different, but not so different…



Megias et al., PRD 94 (2016)

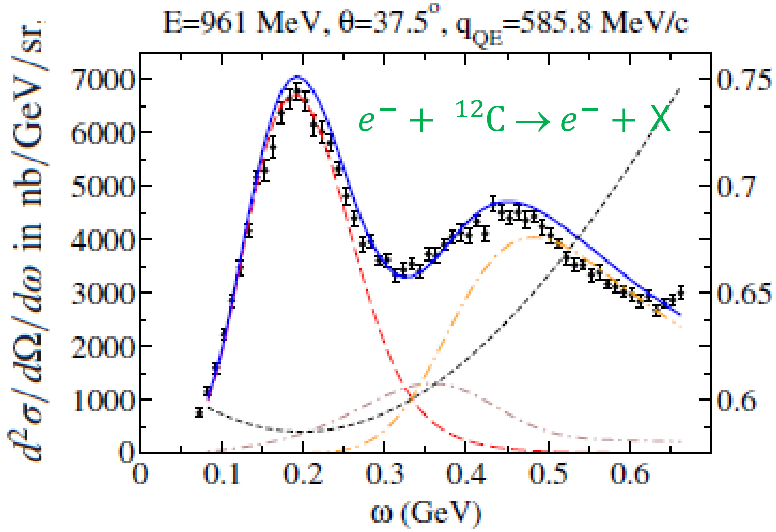


Leitner et al., PRC 79 (2009)

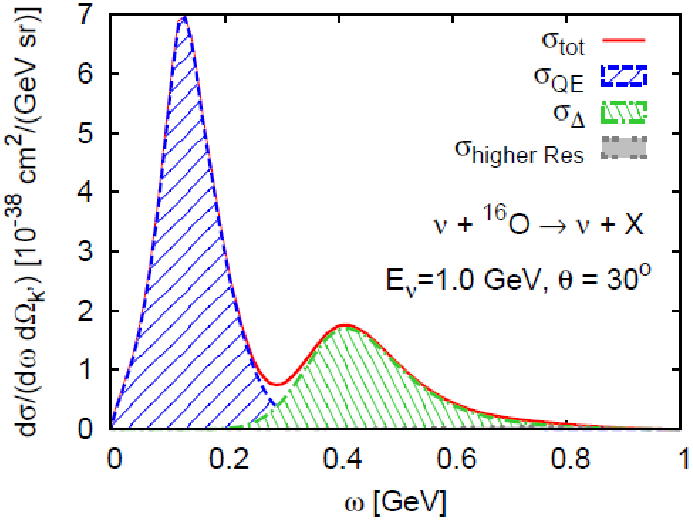
- Similarities reflect the underlying (approximate) symmetries of QCD
  - Isospin symmetry: electromagnetic processes ⇔ Vector current
  - Chiral symmetry: pion scattering ⇔ Axial current (at $Q^2 = 0$)

Overture

- Neutrino interactions are different, but not so different…

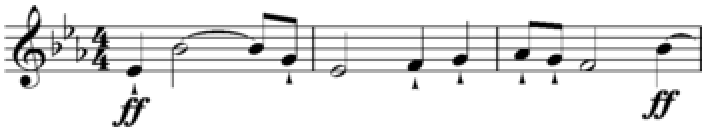


Megias et al., PRD 94 (2016)



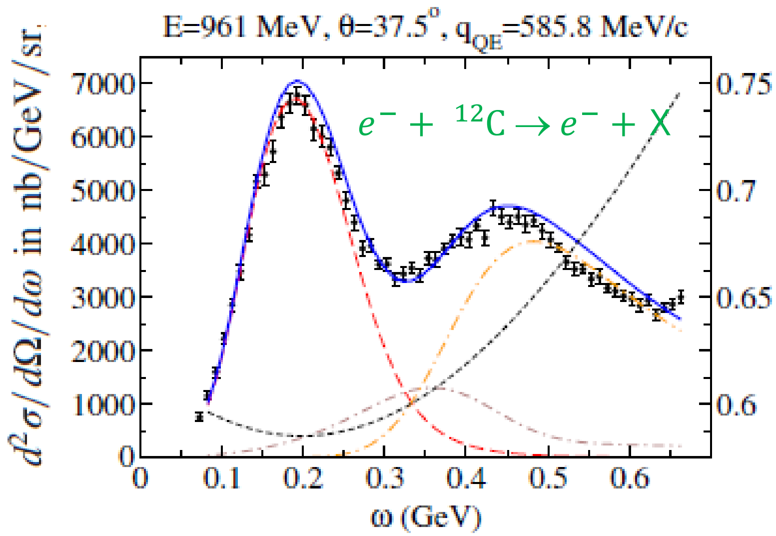
Leitner et al., PRC 79 (2009)

- Similarities reflect the underlying (approximate) symmetries of QCD
  - Isospin symmetry: electromagnetic processes ⇔ Vector current
  - Chiral symmetry: pion scattering ⇔ Axial current (at $Q^2 = 0$)

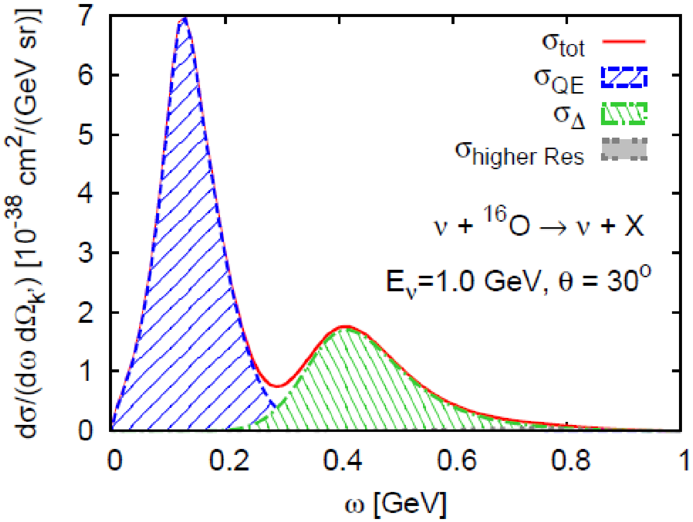


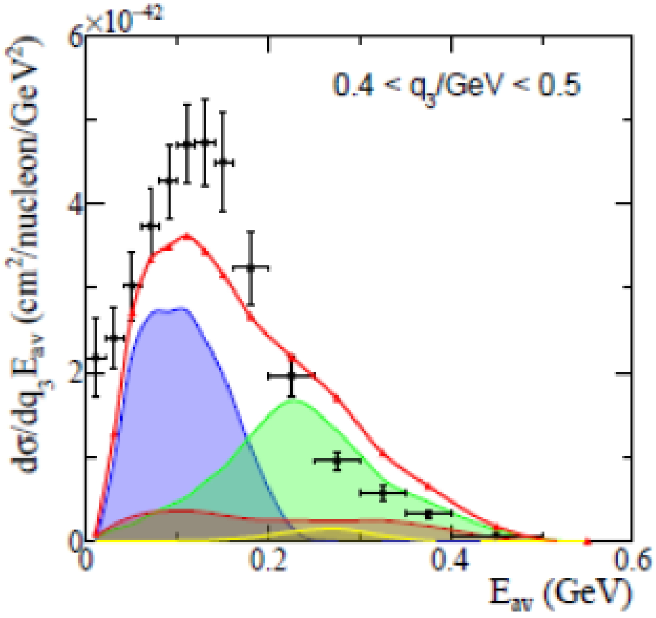
Overture

- Neutrino interactions are different, but not so different…



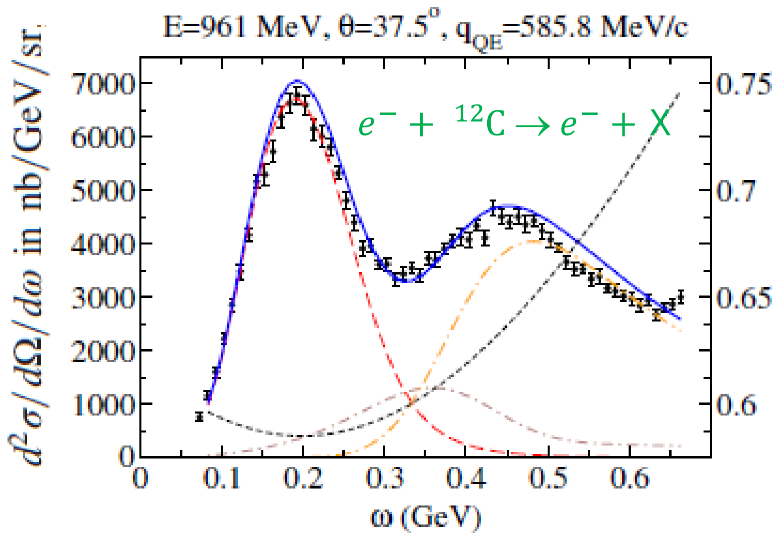
Megias et al., PRD 94 (2016)



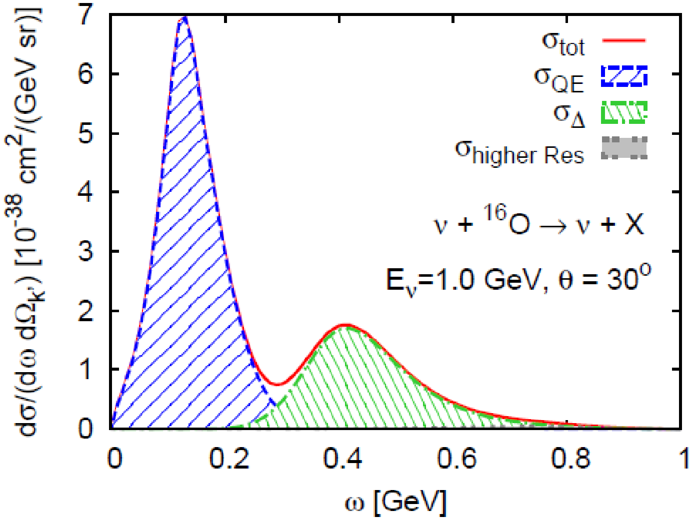


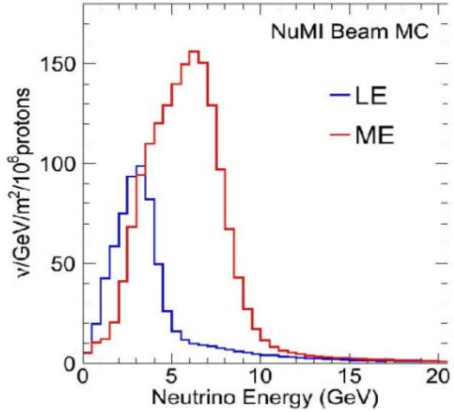
Overture

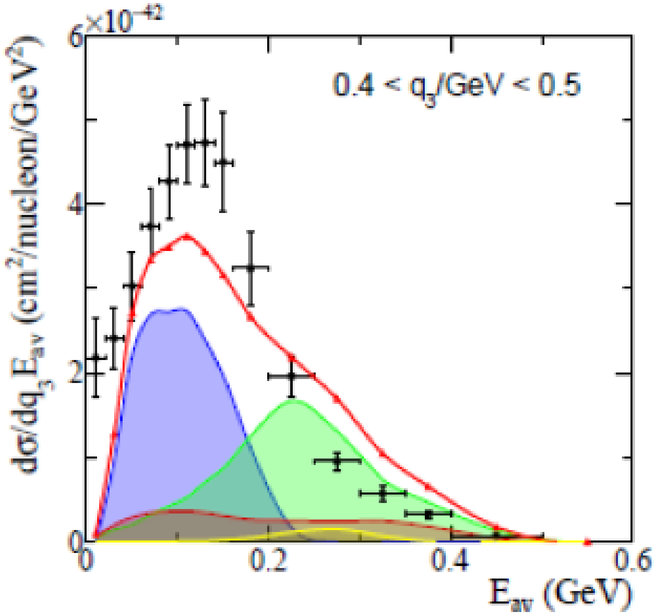
- Neutrino interactions are different, but not so different…



Megias et al., PRD 94 (2016)







Why ν interactions?

- They are crucial to achieve the precision goals of oscillation experiments

“uncertainties exceeding 1% for signal and 5% for backgrounds may result in substantial degradation of the sensitivity to CP violation and the mass hierarchy”
arXiv:1512.06148

- E_ν calorimetric determination
  - Detection thresholds
  - Neutrons

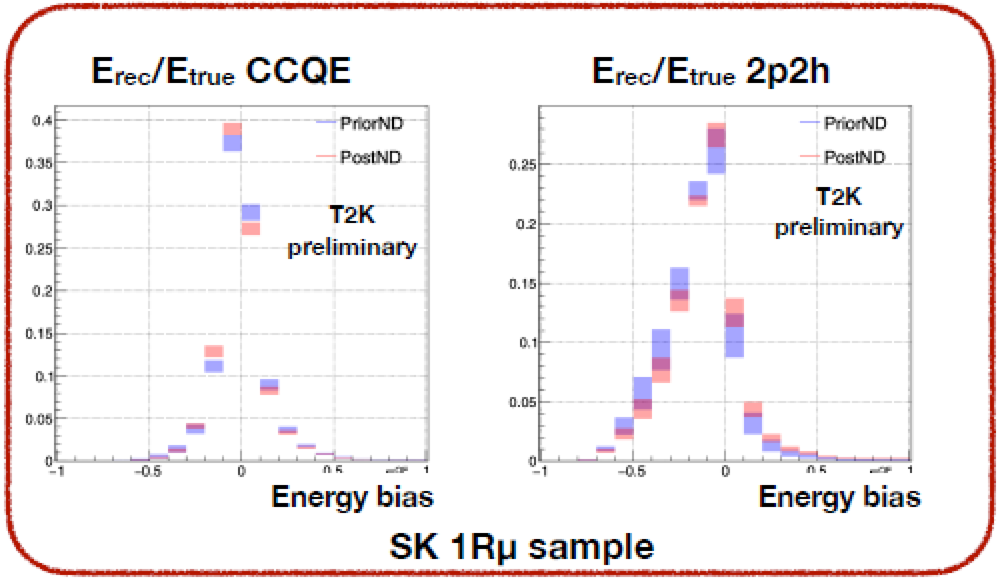
“For carbon, only 30–40% of the events reconstruct to within 5% of the real beam energy.”
Khachatryan et al., Nature 599 (2012)
J. Tena Vidal @ Neutrino 2024

Why ν interactions?

- They are crucial to achieve the precision goals of oscillation experiments

> “uncertainties exceeding 1% for signal and 5% for backgrounds may result in substantial degradation of the sensitivity to CP violation and the mass hierarchy”
> arXiv:1512.06148

- E_ν kinematic determination
  - QE-like mechanisms
    - π absorption
    - 2p2h



E_{rec}/E_{true} CCQE

E_{rec}/E_{true} 2p2h

SK 1Rμ sample

C. Giganti @ Neutrino 2024

Why ν interactions?

- They are crucial to achieve the precision goals of oscillation experiments

> “uncertainties exceeding 1% for signal and 5% for backgrounds may result in substantial degradation of the sensitivity to CP violation and the mass hierarchy”
> arXiv:1512.06148

  - E_ν determination
  - Backgrounds
    - E.g. e-like backgrounds from π^0 and photons

- Near detectors help reduce systematic errors

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

F. Sanchez

but cross section uncertainties do not cancel exactly in the ratio

- different geometry, acceptance, targets
- exposed to different fluxes with different flavor composition

Why ν 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

Neutrino scattering mismodeling in event generators can lead to **systematic errors** even if generators are tuned to the best (ND) data.

Why ν 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

Neutrino scattering mismodeling in event generators can lead to **systematic errors** even if generators are tuned to the best (ND) data.

- Clarification:
- For 0νββ (J. Menéndez @Neutrino2024), CEνNS (I. Nasteva, M. Green @Neutrino2024)
  - ground state and low-energy excited states
- For νA in the few-GeV region
  - q ~ 100s MeV
  - ground state
  - final state: hadron production/emission

Tool Box

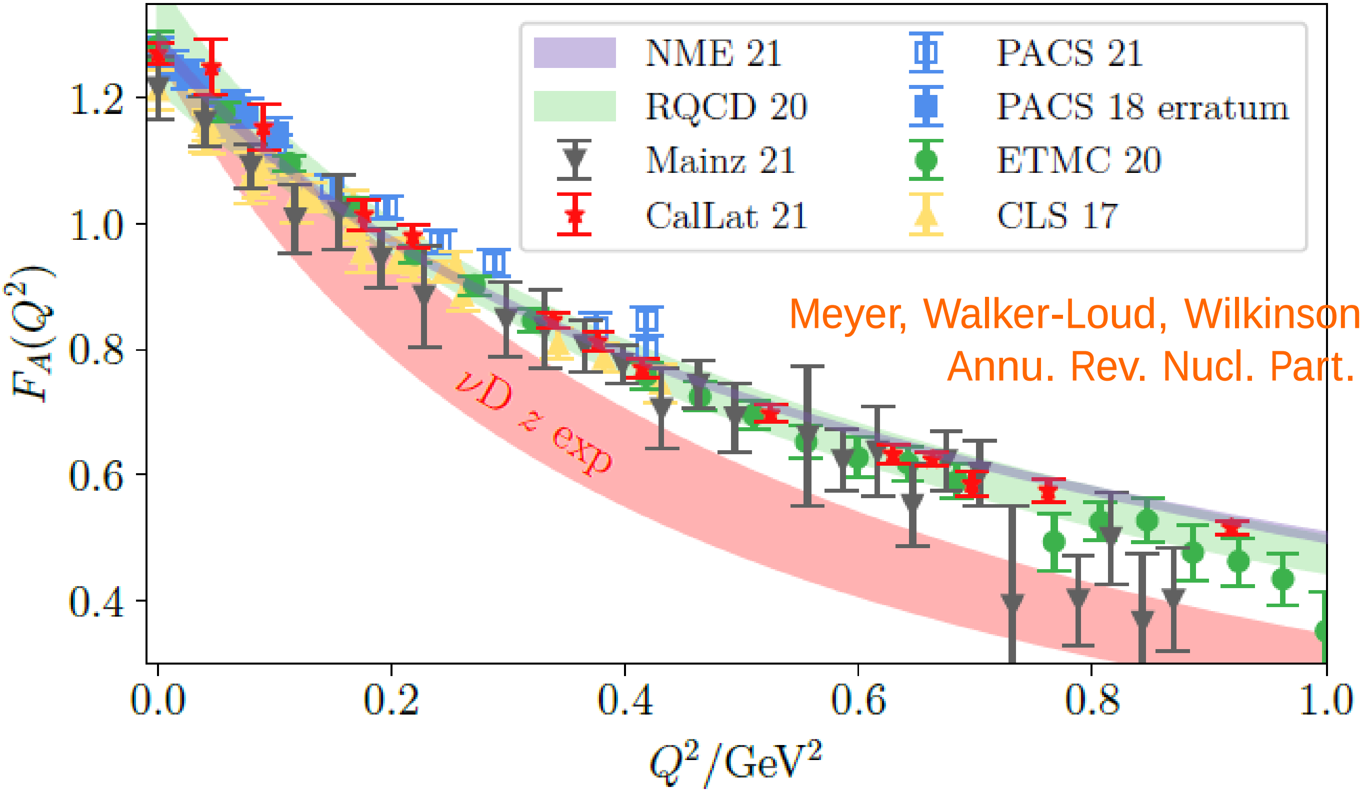
- **Lattice (and perturbative) QCD**
- **Effective Field Theory**
- **Phenomenological models**
- **Monte Carlo simulations**

Tool Box

- **Lattice QCD**
  - correlation functions in Euclidean time:
  - $\{a, L, m_q\} \rightarrow \{0, \infty, m_q(\text{phys})\} \Rightarrow$ matrix elements
  - numerically expensive
  - Axial nucleon and N-Res form factors & structure functions
    - Isospin symmetry $\Leftrightarrow$ Vector ones from electron scattering data
  - nonperturbative input for:

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

F_A: Exp. vs LQCD

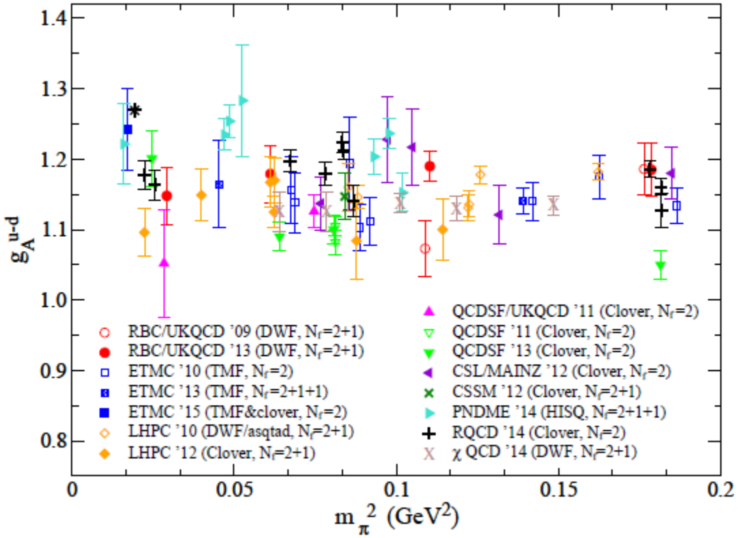


Meyer, Walker-Loud, Wilkinson,
Annu. Rev. Nucl. Part. Sci. 2022. 72:1–30

- How reliable are old bubble chamber experiments?
- Do LQCD present results still hide uncontrolled systematics?

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)

- 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)

Tool Box

- **Lattice QCD**
- **Effective Field Theory**
  - Low-energy approximation of QCD
  - DOF: π, N, $\Delta(1232)$; heavier DOF ⇒ LECs
  - Perturbative expansion (q/Λ_χ) ⇒ error estimate
- **Phenomenological models**
- **Monte Carlo simulations**

Tool Box

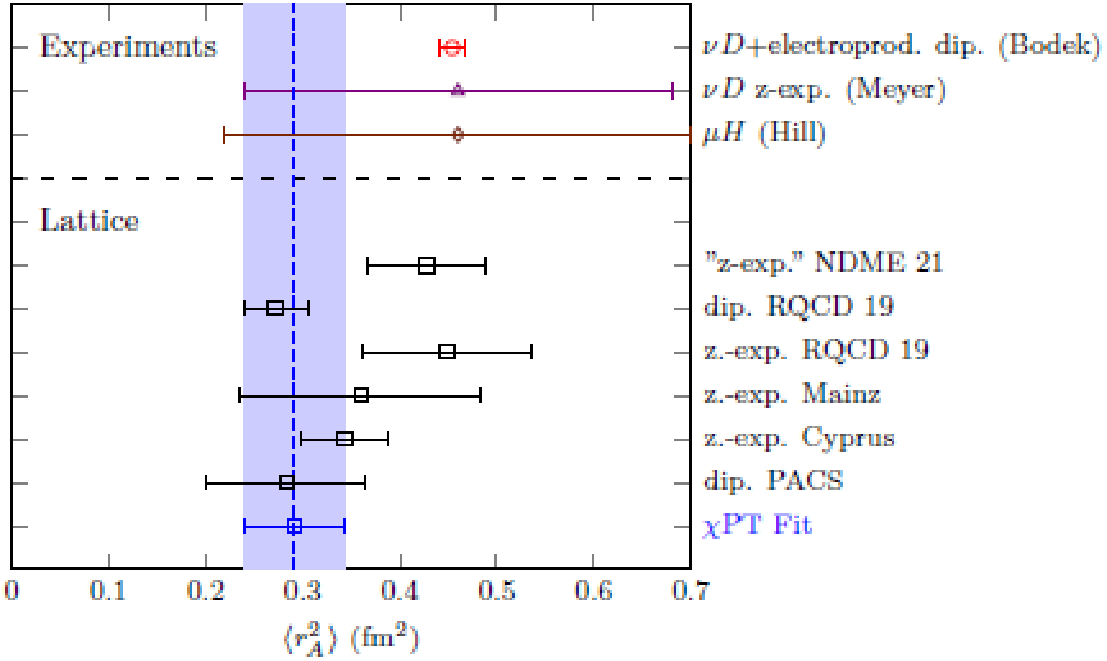
- **Lattice QCD**
- **Effective Field Theory**
  - Low-energy approximation of QCD
  - DOF: π, N, $\Delta(1232)$; heavier DOF ⇒ LECs
  - Perturbative expansion (q/Λ_χ) ⇒ error estimate
  - Light-quark (u,d,s) mass dependence of physical quantities
  - Limited to low momentum transfers: mainly benchmark for:
- **Phenomenological models**
- **Monte Carlo simulations**

F_A & LQCD

- 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

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

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

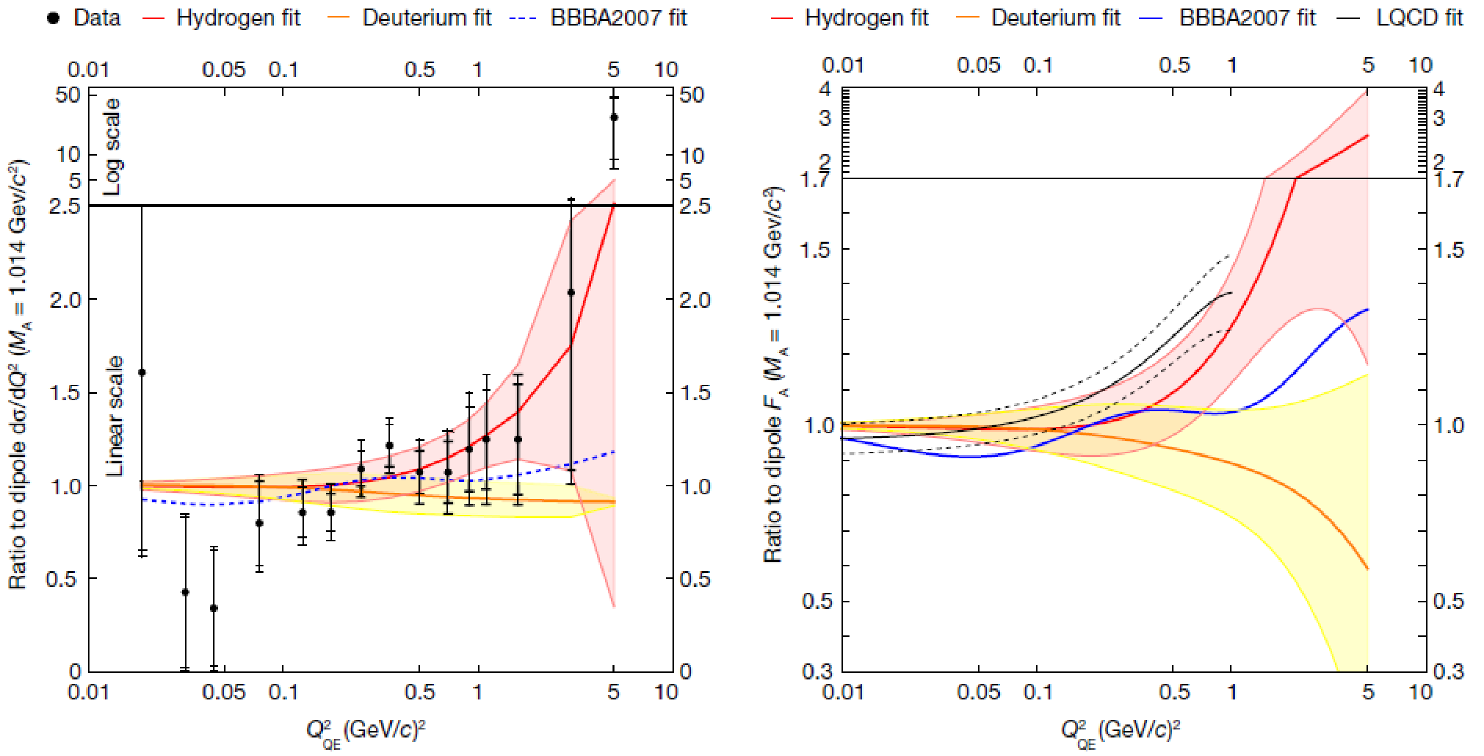


$\langle r_A^2\rangle = 0.291(52)$ fm^2 ⇔ $M_A = 1.27(11)$ GeV F. Alvarado, LAR

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

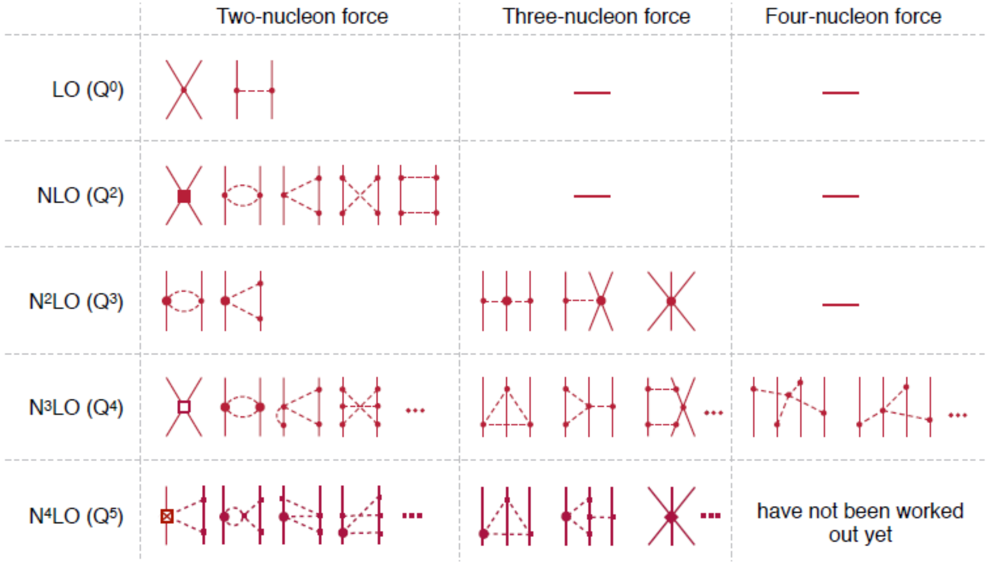
$\langle r_A^2 \rangle$ = 0.291(52) fm² ⇔ 0.53(25) fm² ⇐ r_A = **0.73(17) fm**

in tension with MINERvA

EFT for nuclear physics

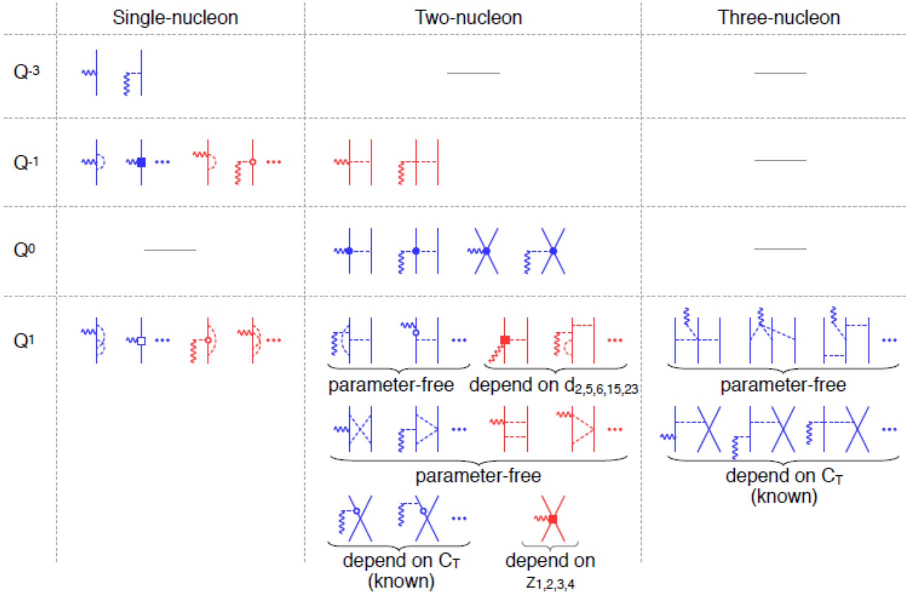
- EFT allow to calculate NN interactions and two-body currents consistently

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

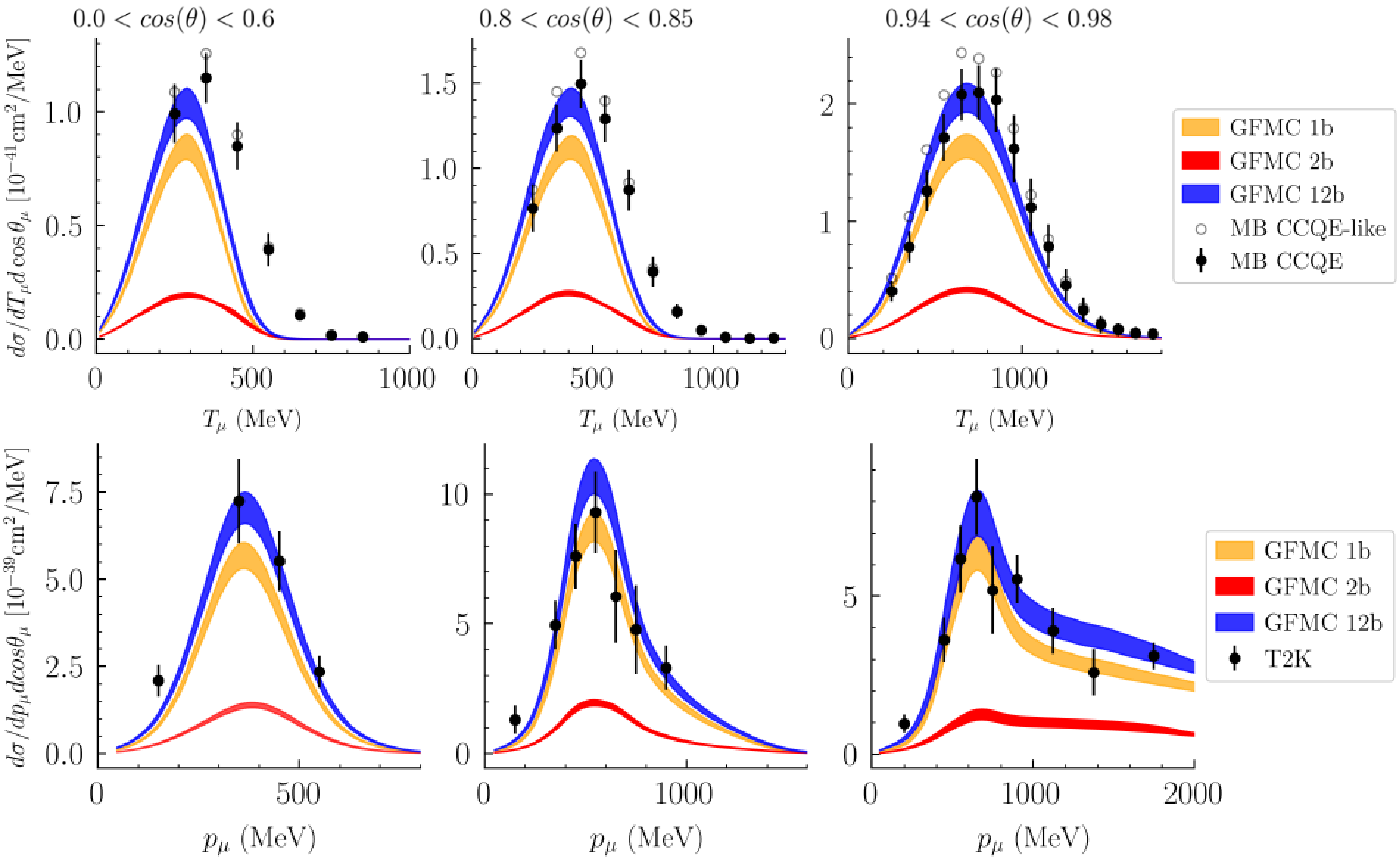
Ab initio

- LQCD computations of electroweak nuclear responses is out of reach
- 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

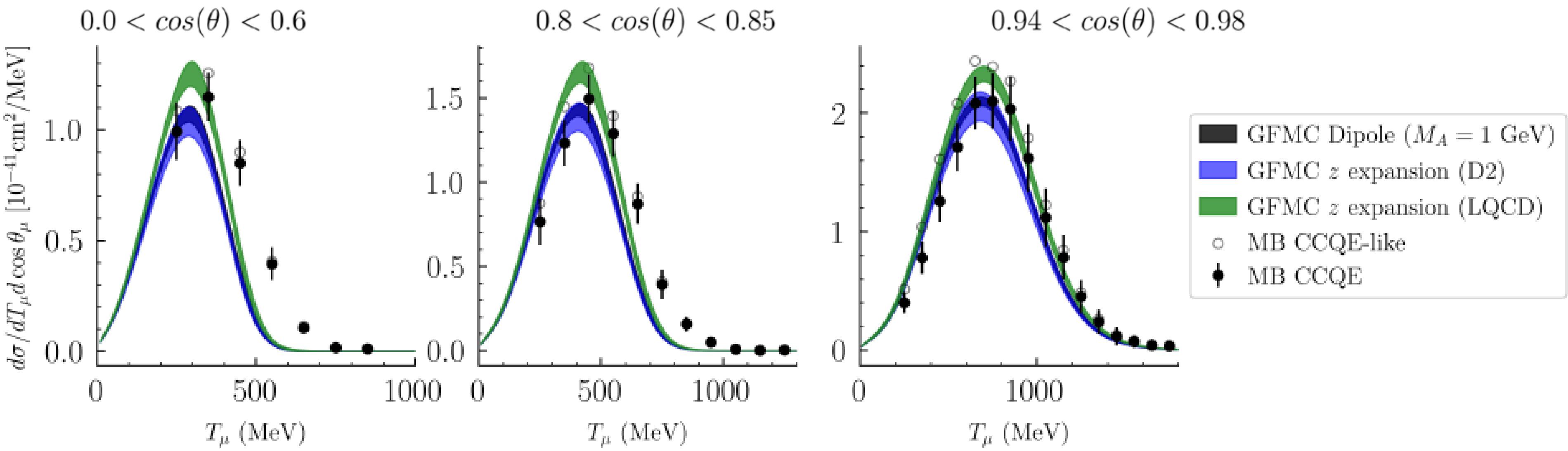
- Green's function MC

Simons et al., 2210.02455

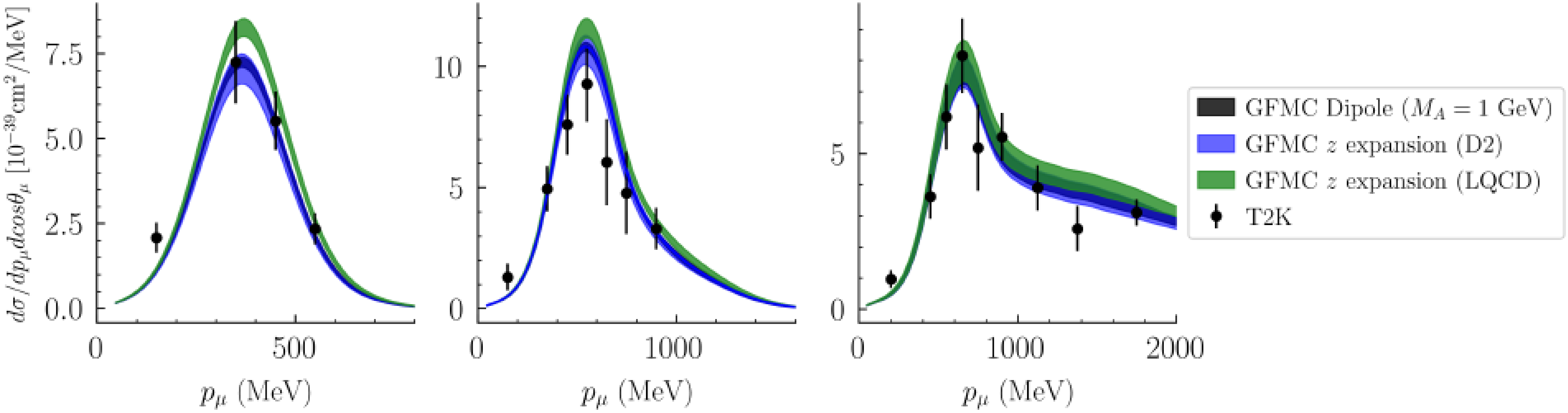


Ab initio

- Green's function MC   Simons et al., 2210.02455



LQCD leads to a 10-20% enhancement of the cross section

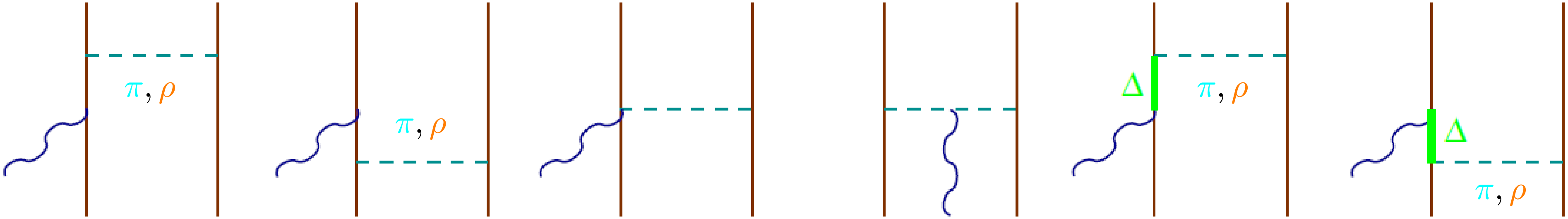


Tool Box

- **Lattice QCD**
- **Effective Field Theory**
- **Phenomenological models**
  - DOF: π, N, $\Delta(1232)$, heavier N*, Δ
  - (Should) match EFT close to threshold
  - Cover a broad kinematic range
  - Rely on (non-ν) data as input and/or validation
- **Monte Carlo simulations**

Pheno QE-like scattering

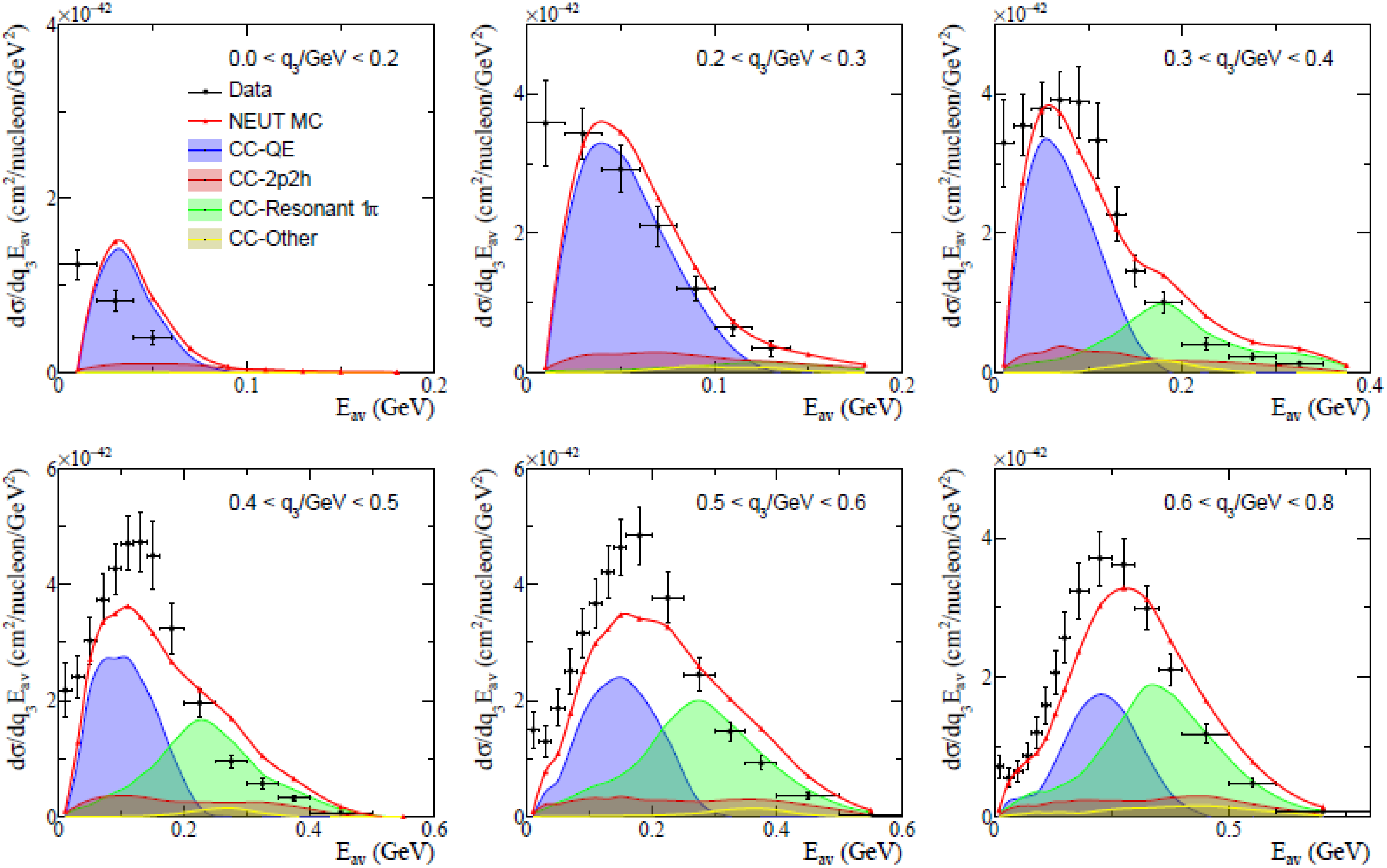
- Phenomenological 1- and 2-nucleon currents



- Different descriptions of initial state nucleons:
  - Global Fermi gas
  - Local Fermi gas
  - Mean field
  - Superscaling
  - Spectral functions
- can describe MiniBooNE and T2K 0π data
- Discrepancies found @ MINERvA & NOvA

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)
...

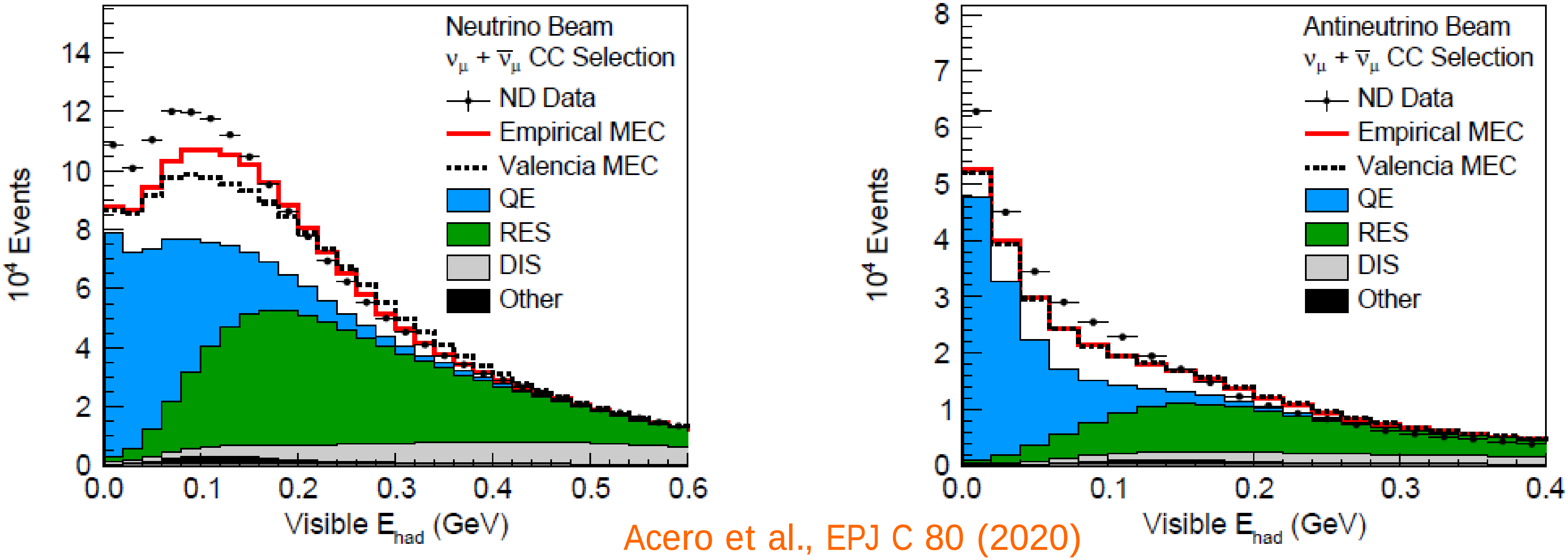
Pheno QE-like scattering



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

Pheno QE-like scattering

- Discrepancies found @ MINERvA & NOvA

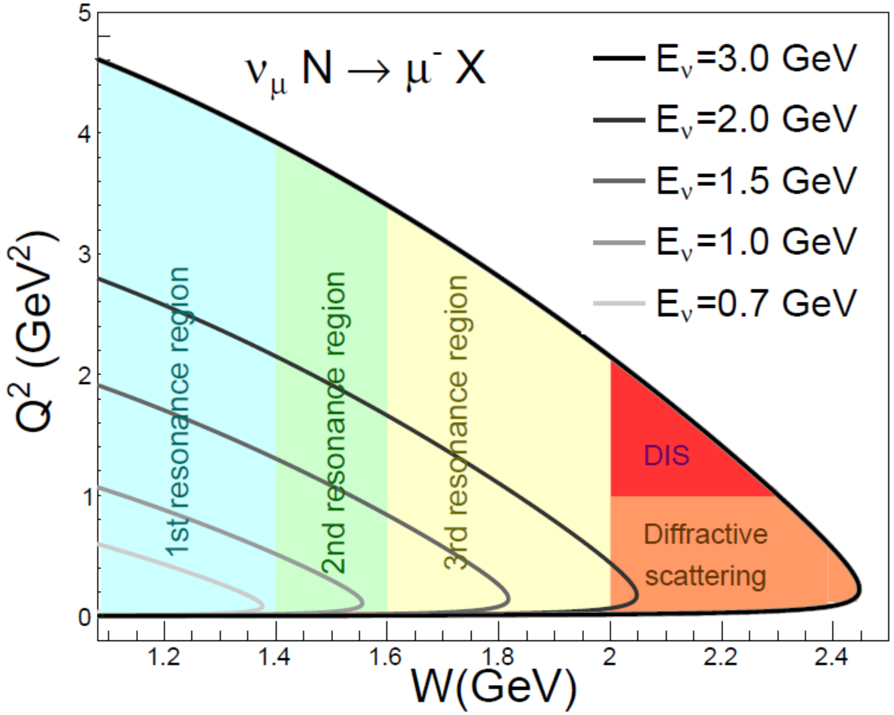


Acero et al., EPJ C 80 (2020)

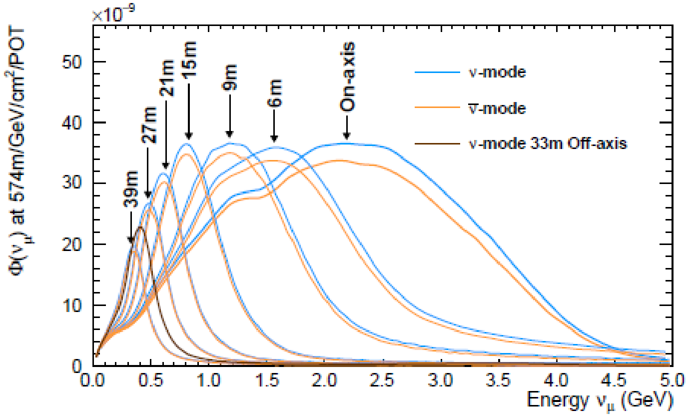
- Theoretical mismodeling or imperfect/inconsistent implementation in MC?
- Progress requires:
  - improvement in theory and generator implementation
  - (exclusive) data: several new results and comparisons to theory

M. Buizza Avanzini, A. Papadopoulou @ Neutrino 2024

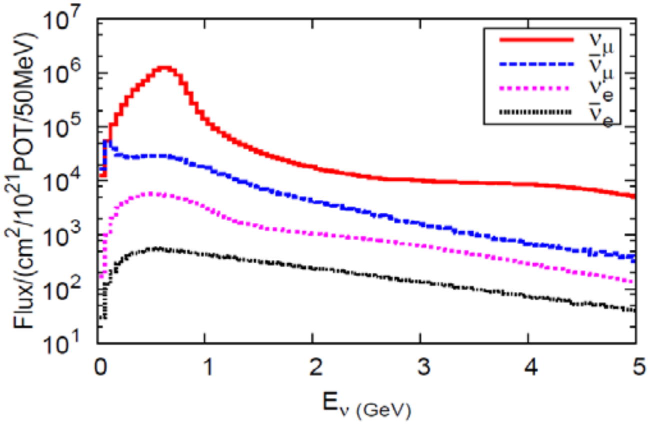
Inelastic scattering



LAR, M. Kabirnezhad



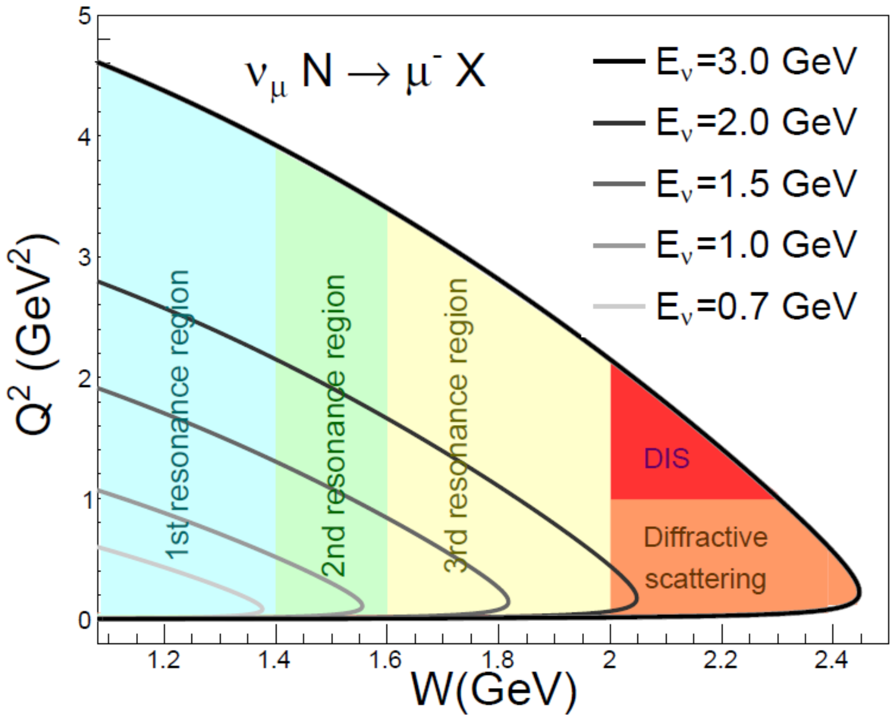
DUNE flux @ ND, 2002.03005



T2K flux @ ND

Inelastic scattering

LAR, M. Kabirnezhad



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

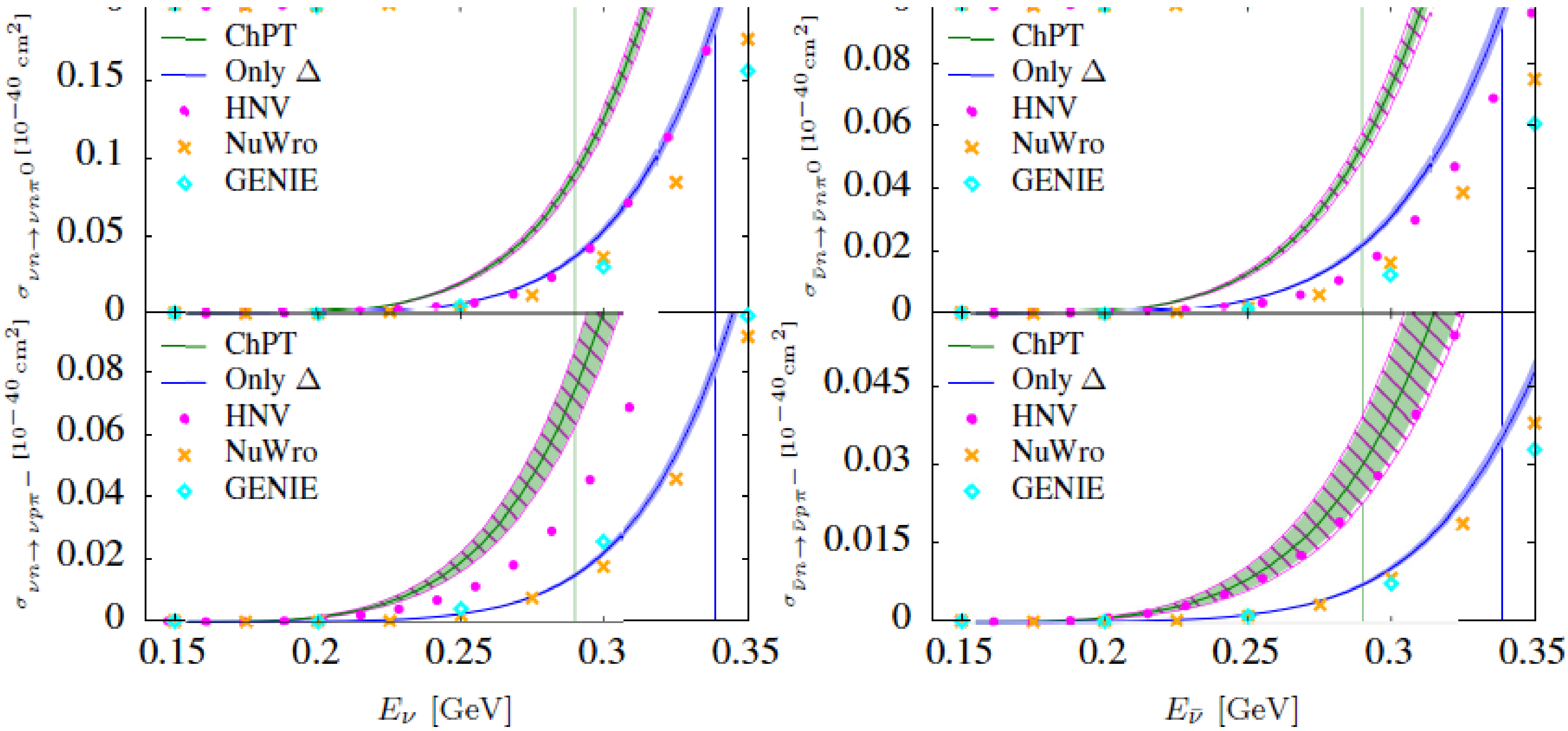
Weak pion production in EFT

- Chiral Perturbation Theory (low-energy EFT of QCD):
  Yao et al., PRD 98 (2018); PLB 794 (2019)
- Perturbative approach: power counting O(p^3), 1-loop unitarity
- LECs: 22 in total
  - information about remaining 3 could be obtained from new close-to-threshold measurements of ν-induced π production on protons

Weak pion production in EFT

- Benchmark for phenomenological models

Yao et al., PRD 98 (2018); PLB 794 (2019)



- Possible “standard candle” (with controlled errors) for flux monitoring

Pheno meson production models

- HNV: E. Hernandez, J. Nieves, M. Valverde, PRD 76 (2007); LAR et al, PRD 93 (2016); E. Hernandez, J. Nieves, PRD 95 (2017)
- DCC: S. X. Nakamura, H. Kamano, T. Sato, PRD 92 (2015)
- Hybrid: R. González-Jiménez et al., PRD 95 (2017)
- MK: M. Kabirnezhad, PRD 97 (2018); 102 (2020); 107 (2023)
  - DOF: π, N, Δ(1232), heavier N*, Δ
  - Match EFT close to threshold
  - Cover a broad kinematic range
  - Rely on (non-ν) data as input and/or validation

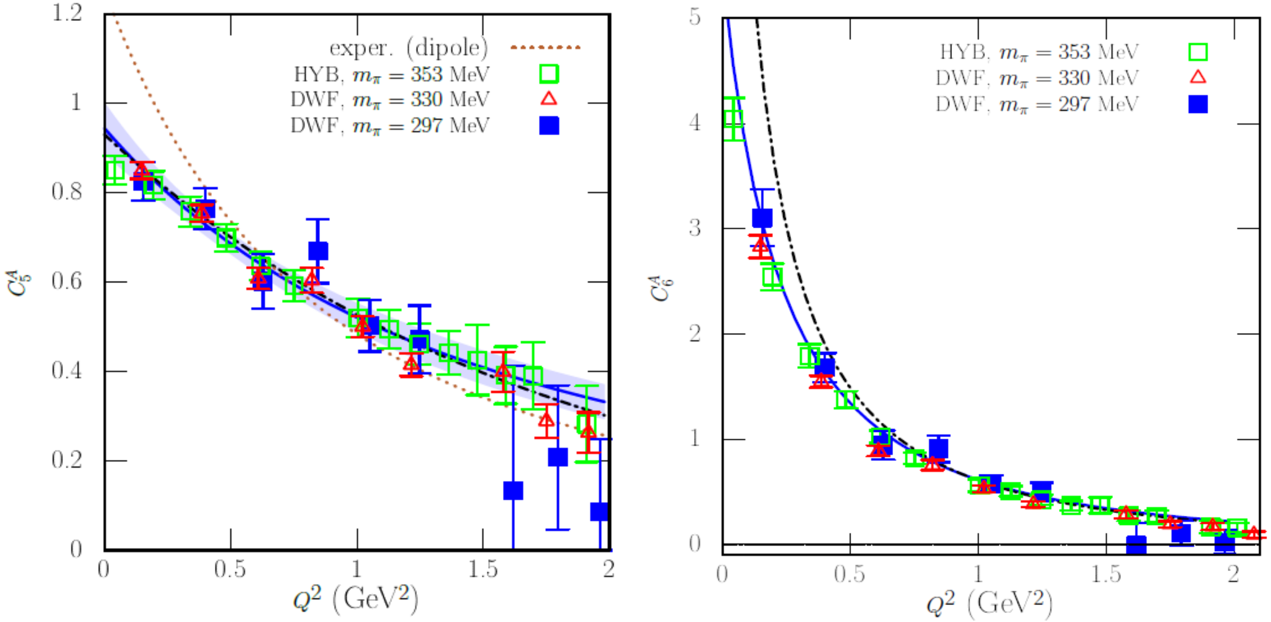
  - Vector current can be constrained with $\gamma N \to N \pi$, $e N \to e' N \pi$
  - Axial current at q² → 0 can be constrained with $\pi N \to N \pi$ (PCAC)

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

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

LQCD & meson production

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



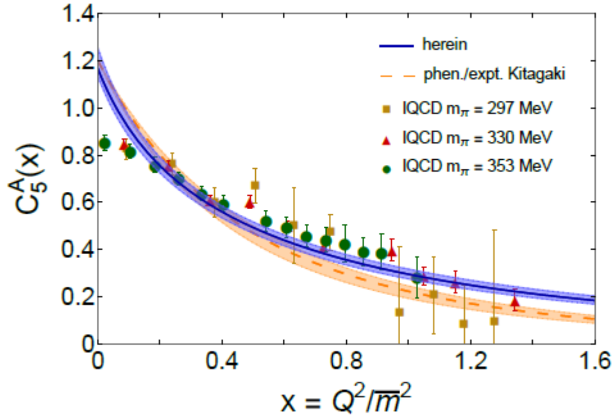
- Calculations of N-Δ,N-N* transition FF should become available in the next 5-10 years LAR et al., Snowmass 2021, 2203.09030
- Control systematic uncertainties is challenging

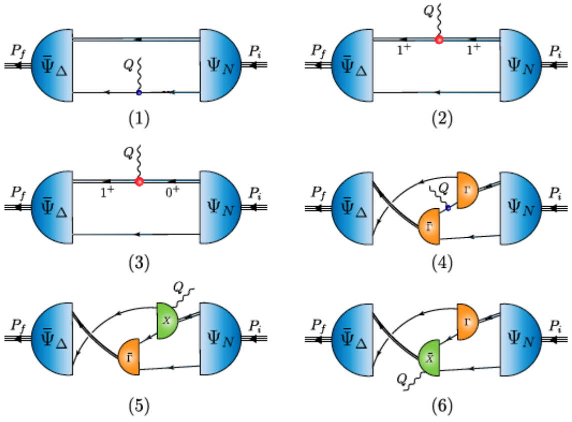
N-Δ(1232) axial transition matrix element:

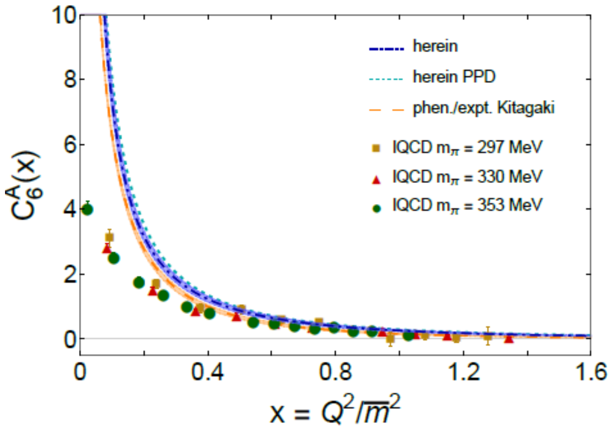
$$A^\mu = \bar{u}_\mu(p')\left[\frac{C_3^A}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{C_4^A}{M^2}(g^{\beta\mu}q\cdot p' - q^\beta p'^\mu) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2}q^\beta q^\mu\right]u(p)$$

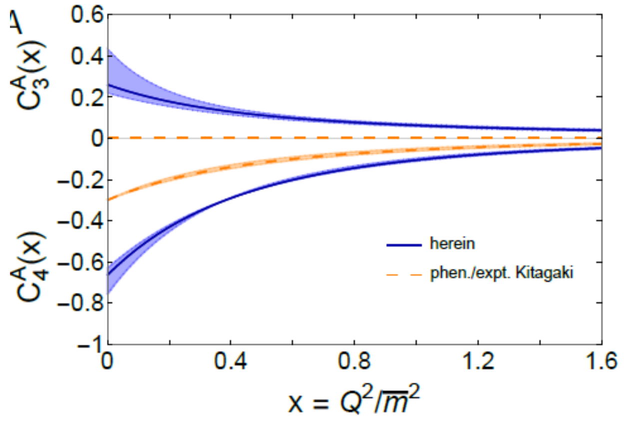
Continuum QCD & meson production

- Dyson-Schwinger + Fadeev eqs. for quarks. Chen, Fischer, Roberts, 2312.13724







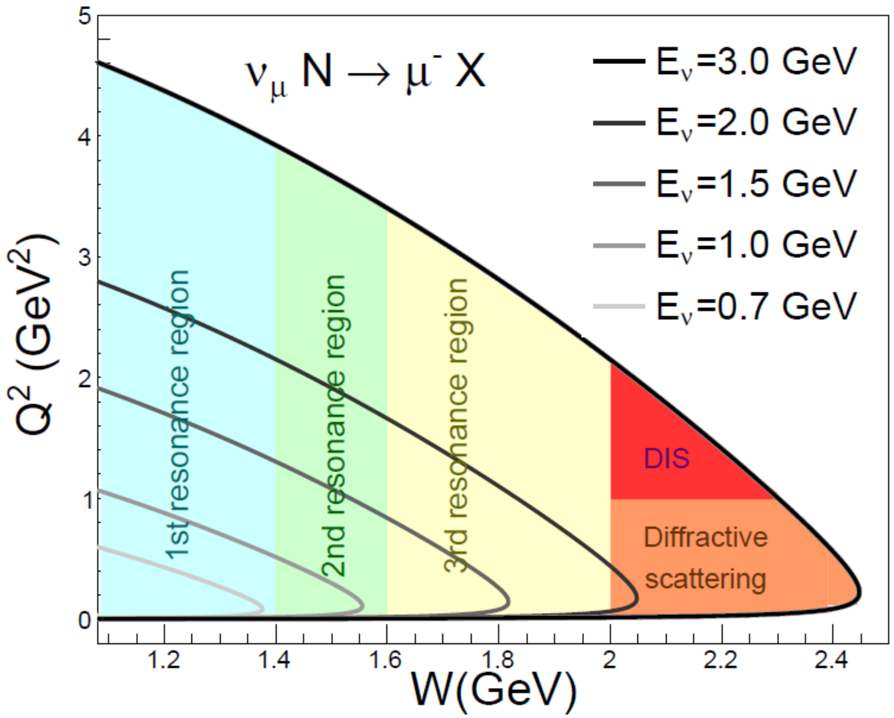


N-Δ(1232) axial transition matrix element:

$$A^\mu = \bar{u}_\mu(p') \left[\frac{C_3^A}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{C_4^A}{M^2}(g^{\beta\mu} q\cdot p' - q^\beta p'^\mu) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2} q^\beta q^\mu \right] u(p)$$

Inelastic scattering

LAR, M. Kabirnezhad



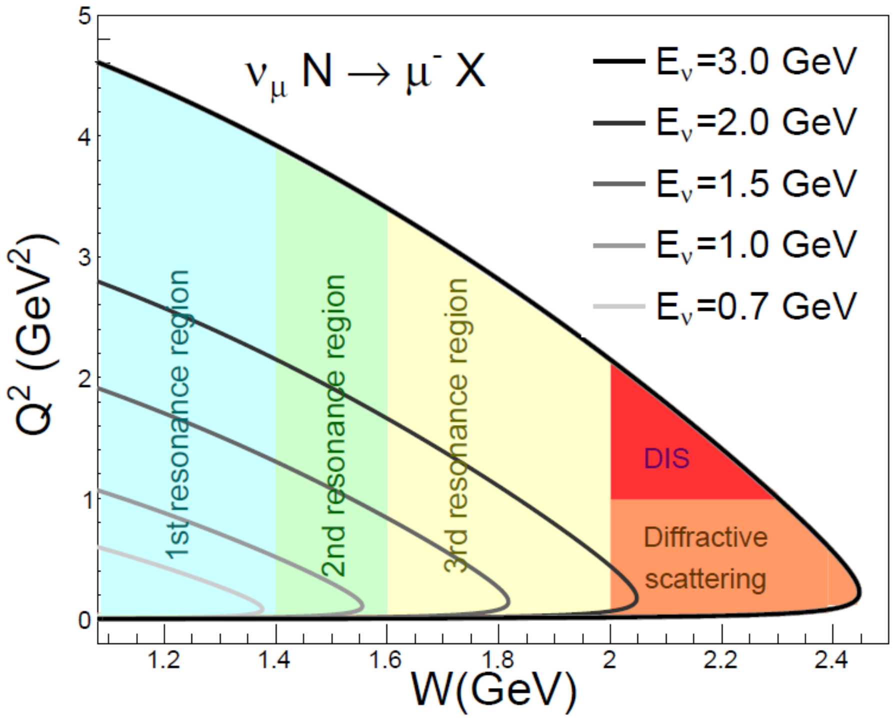
- Above the $\Delta(1232)$ peak: 1.3<W<2 GeV:
  - several overlapping resonances
  - non-trivial interference; coupled channels

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

- Different final states ⇒ different detector response

Inelastic scattering

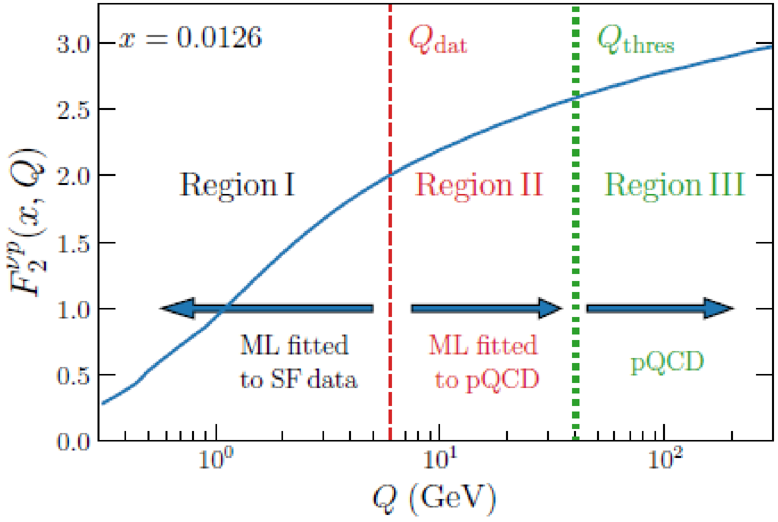
LAR, M. Kabirnezhad

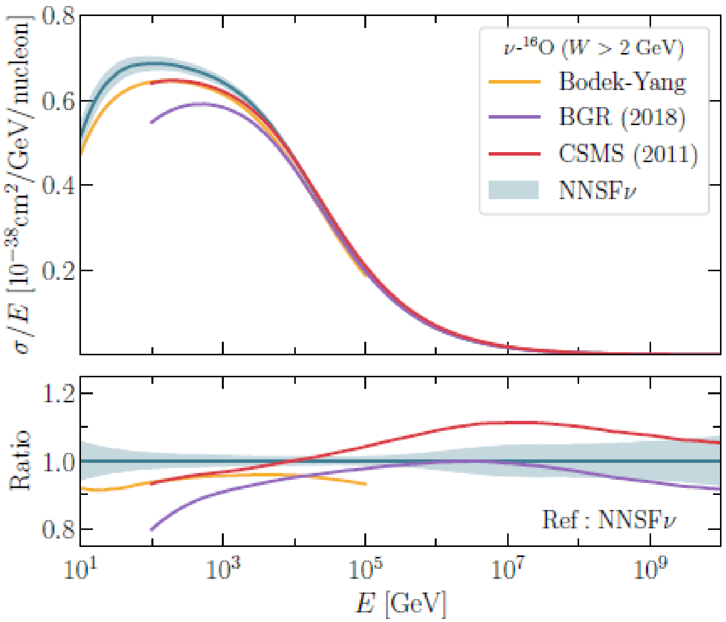


- Transition from RES to DIS:
  - More realistic description of RES
  - Deep inelastic scattering (DIS) → Shallow inelastic scattering (SIS)
    - Extend pQCD calculations → non-perturbative region

DIS → SIS

- Extend pQCD calculations → non-perturbative region
- Traditionally based on the now outdated Bodek-Yang model
- New approach NNSFν, Candido et al., JHEP 05 (2023)
  - Determination of inelastic structure functions
  - W > 2 GeV and various targets
  - Machine learning parametrization
  - Implements a high Q region (II) for matching to pQCD
  - 5-15% larger cross sections vs Bodek-Yang





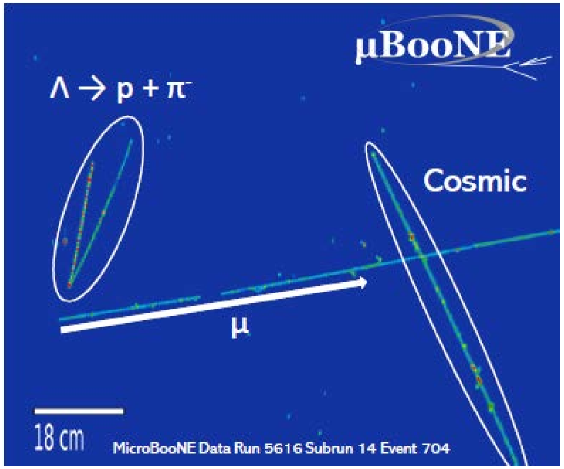
Rare processes

- Weak hyperon production
- ΔS = -1: $W^{-}u \rightarrow s$
- Cabibbo reduced ($V_{us} = 0.23$)
- Via Y→ π 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
- Mechanisms:
  - $\bar{\nu}\, N \rightarrow \mu^{+}\, Y$ (QE)
  - $\bar{\nu}\, N \rightarrow \mu^{+}\, Y\, \pi$ (inel)

- After accounting for detection thresholds:
- ~ 33% contribution from $\Lambda\pi$ (absent in MC)

	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

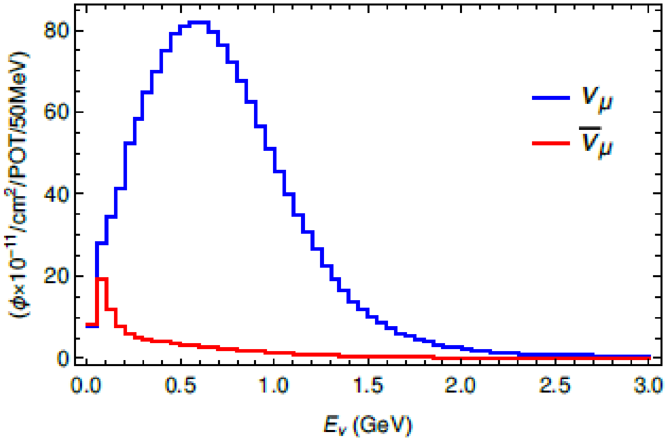
$\bar{\nu}\,\mathrm{Ar} \rightarrow \mu^{+}\,\Lambda\, X$

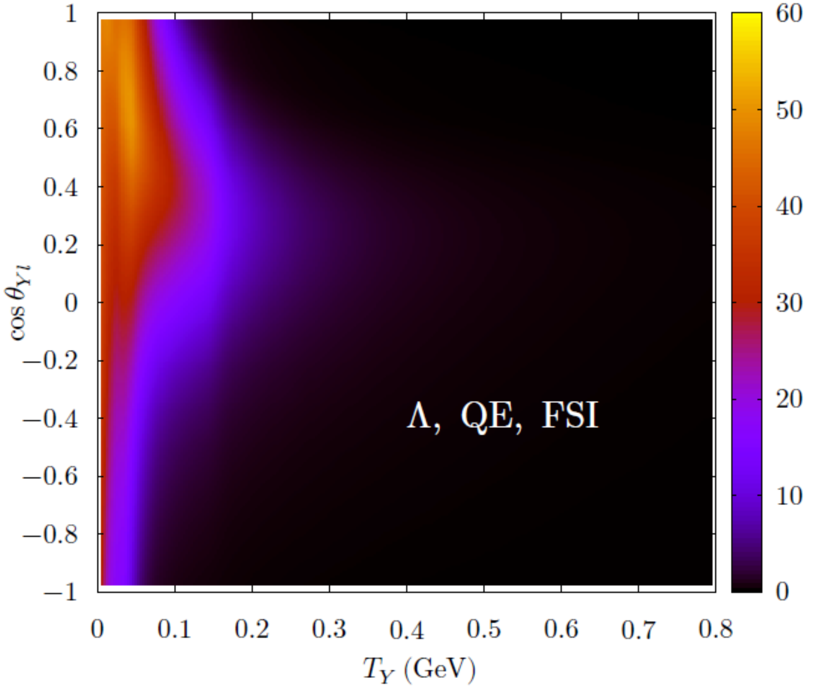


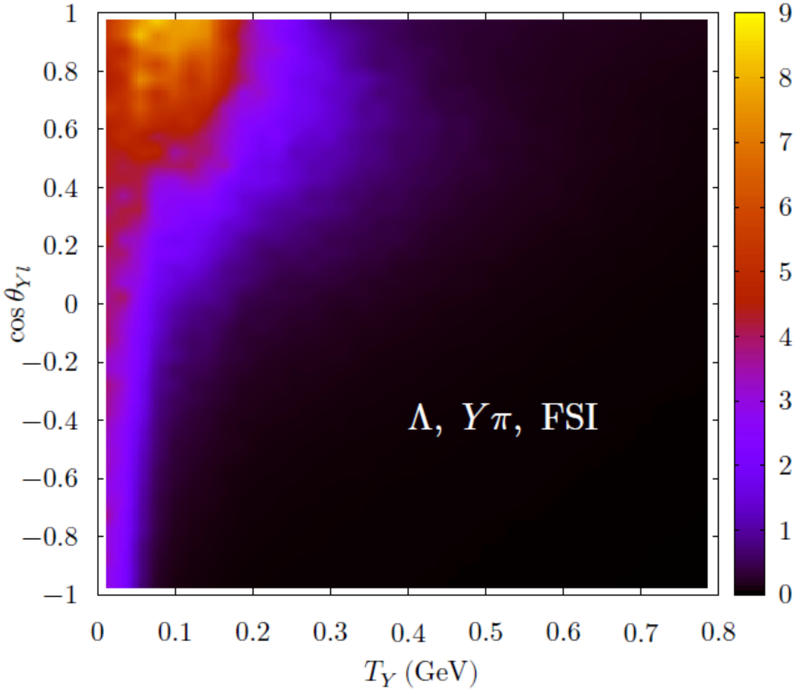
A. Papadopoulou @ Neutrino 2024
MicroBooNE, PRL 130 (2023)

Rare processes

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







Tool Box

- **Lattice (and perturbative) QCD**
- **Effective Field Theory**
- **Phenomenological models**
- **Monte Carlo simulations**
  - Connection between theory and experiment
  - Tool for experimental analysis
  - Provide a full description of the final hadronic state
    - Except for a few processes (single-nucleon knockout, Cohπ), QM treatment of final state interactions is unfeasible
    - $\Rightarrow$ semiclassical methods: intranuclear cascades and transport.

Monte Carlo simulations

- Usual suspects: NEUT, GENIE, NuWro, GiBUU
- Newcomers: ACHILLES, DarkNews

- Progress requires:
  - Implementation of new theoretical models
  - Test and validation with ν data
  - Test and validation with external data:
    - GENIE vs electron scattering data

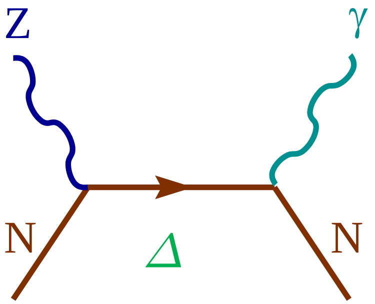
      Ankowski & Friedland, PRD 102 (2020), Khachatryan et al., Nature 599 (2012)
  - Internal consistency

Monte Carlo simulations

- Usual suspects: NEUT, GENIE, NuWro, GiBUU
- Newcomers: ACHILLES, DarkNews

- Progress requires:
  - Implementation of new theoretical models
  - Test and validation with ν data
  - Test and validation with external data:
    - GENIE vs electron scattering data

      Ankowski & Friedland, PRD 102 (2020), Khachatryan et al., Nature 599 (2012)
  - Internal consistency (positive long term consequences)
  - e.g. NC single γ searched at T2K, MicroBooNE(D. Caratelli @ Neutrino 2024)

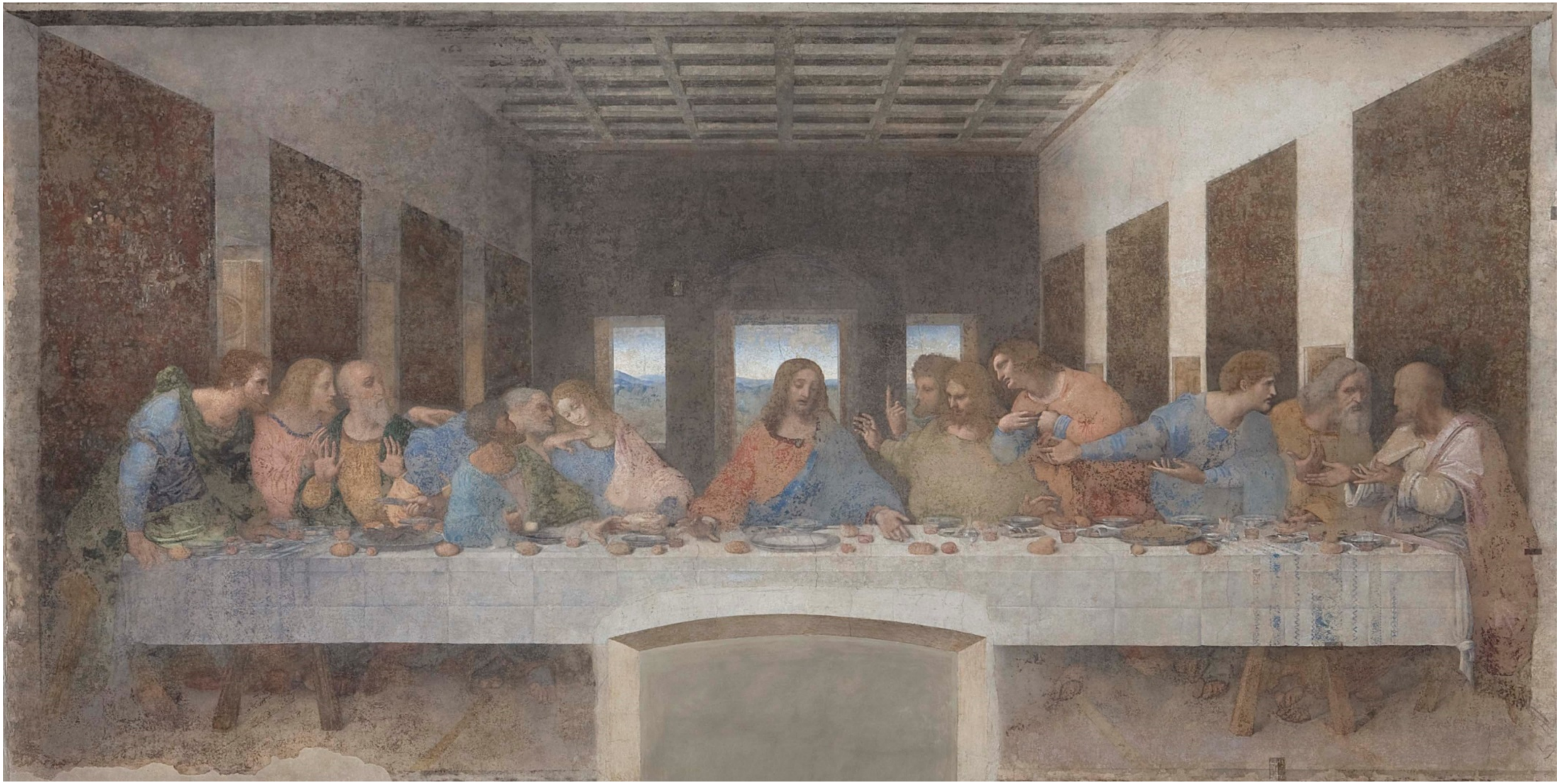


  - $\Delta \to N \gamma \Leftrightarrow$ vector part of $W N \to \Delta$ by isospin symmetry

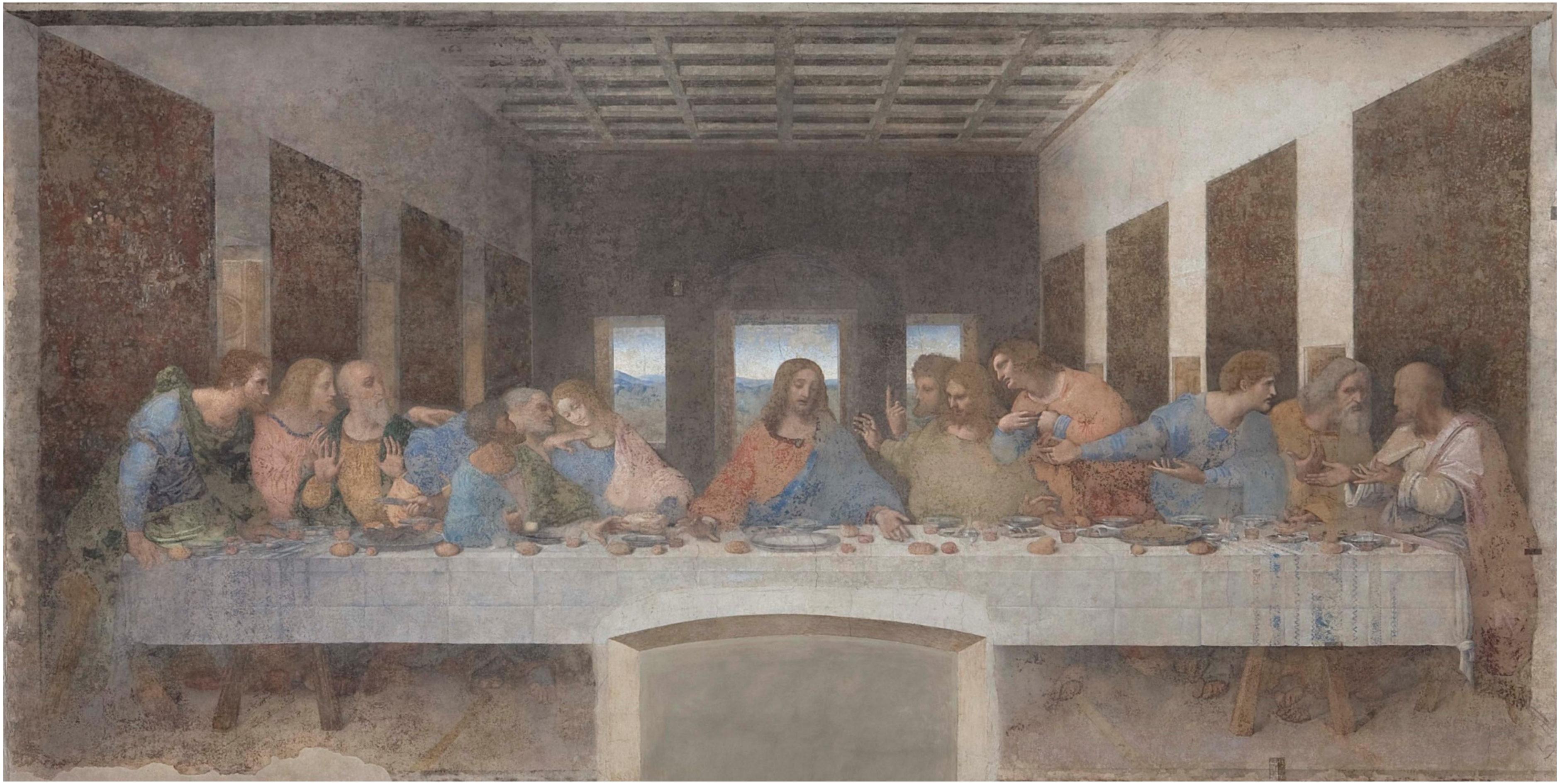
    $\Rightarrow \pi$ production

Finale

- Neutrino-interaction theory can critically contribute to the success of the experimental program.
- Ongoing progress:
  - **Lattice and perturbative QCD**
  - **Effective Field Theory**
  - **Phenomenological models**
  - **Monte Carlo simulations**
- In some cases, progress is hindered by the lack of high quality data on nucleons.



Data unblinding



Thank you