IRN Neutrino

Highlights in Neutrino Interaction Physics

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

Introduction

- ν interactions
  - are crucial to achieve the precision goals of oscillation experiments

DEEP UNDERGROUND NEUTRINO EXPERIMENT

"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

- 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

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

Introduction

- ν interactions
  - are crucial to achieve the precision goals of oscillation experiments
  - probe the electroweak response of matter
  - have the potential to explore new physics:
    - generalized/non-standard interactions
    - exotic processes e.g. heavy-neutral lepton production

Theory Tool Box

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

Benefit from

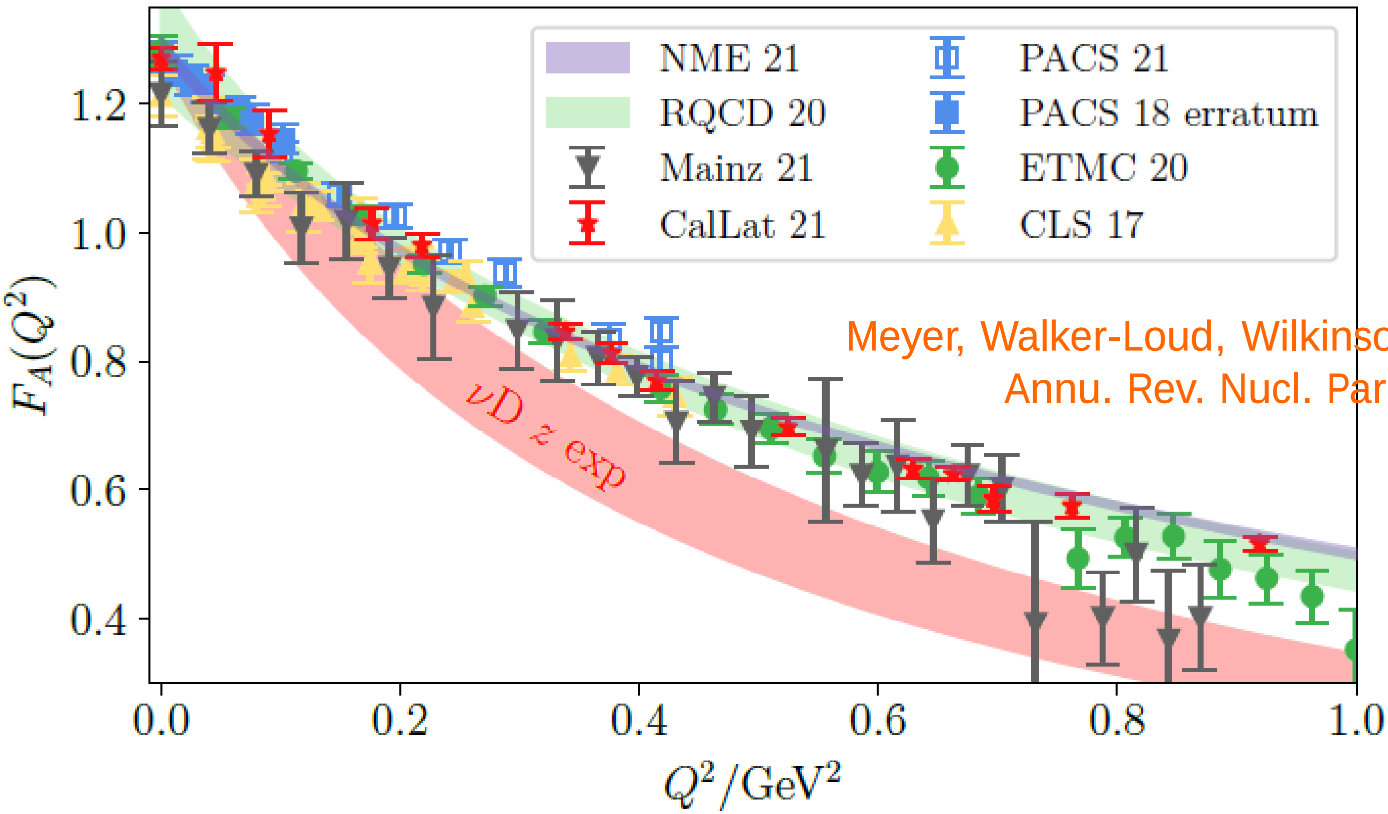
- new data: MINERvA, T2K, SK, NOvA, MicroBooNE, SBND, ...
- computer power and novel techniques

Lattice QCD

- Correlation functions in Euclidean time:
  - $\{a, L, m_q\} \rightarrow \{0, \infty, m_q(\text{phys})\} \Rightarrow$ matrix elements
  - improved algorithms for a careful treatment of excited state contamination
- Nonperturbative input for ν cross section calculations
  - nucleon and N-Res form factors & structure functions

F_A & LQCD

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



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

Effective Field Theory

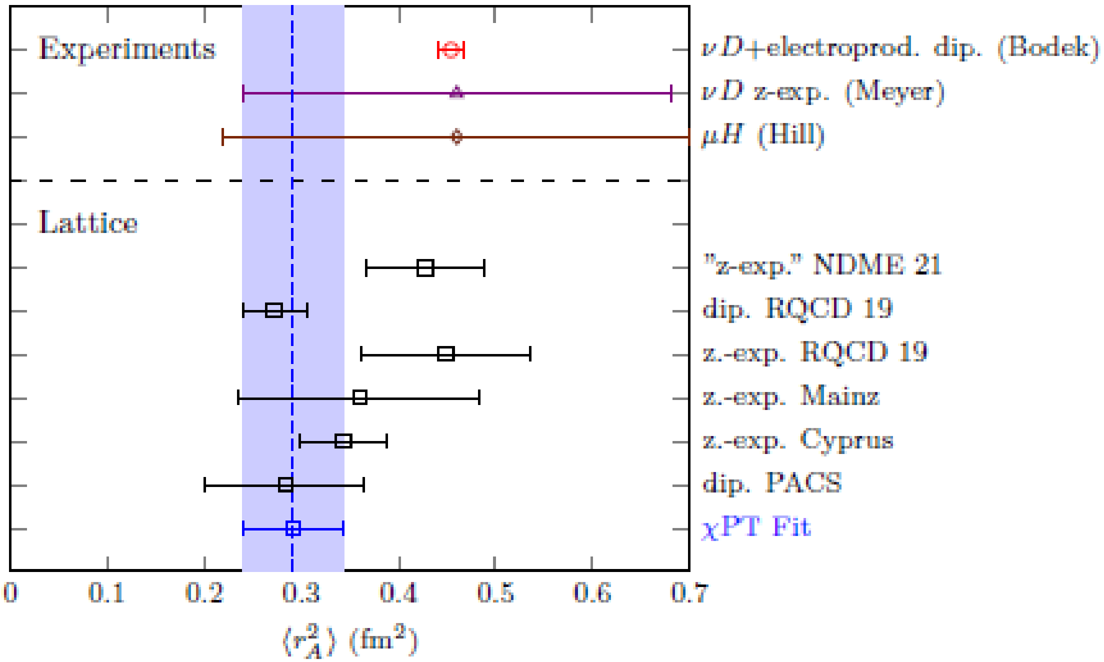
- Low-energy approximation of QCD
- DOF: π, N, Δ(1232); heavier DOF $\Rightarrow$ LECs
- Perturbative expansion (q/Λ_χ) $\Rightarrow$ error estimate
- Limited to low momentum transfer (q << $\Lambda_\chi \sim$ 0.7-1 GeV)
- Light-quark (u,d,s) mass dependence of physical quantities

F_A & LQCD

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

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

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

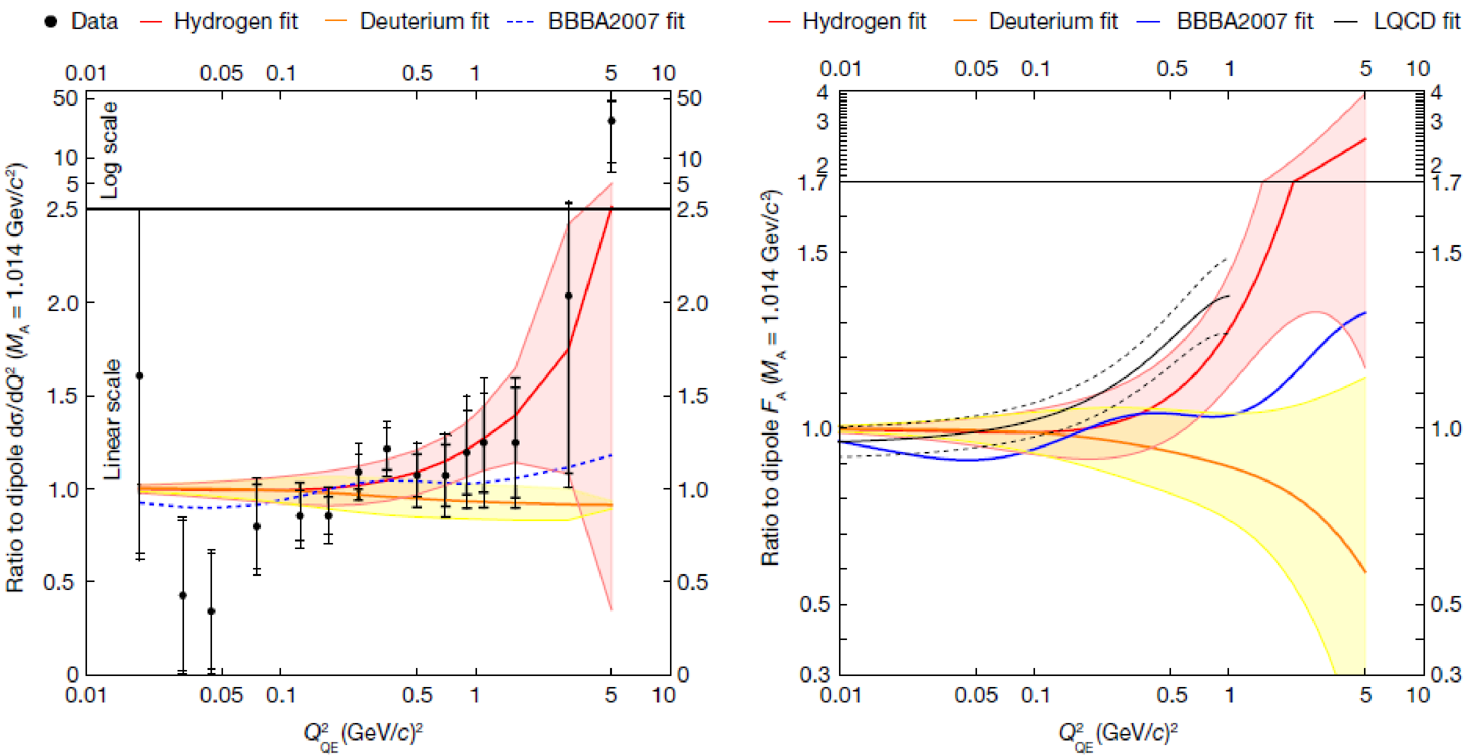


$\langle r_A^2 \rangle = 0.291(52)$ fm^2 ⇔ $M_A = 1.27(11)$ GeV F. Alvarado, LAR

in tension with empirical determinations from bubble-chamber exp.

F_A @ MINERvA

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



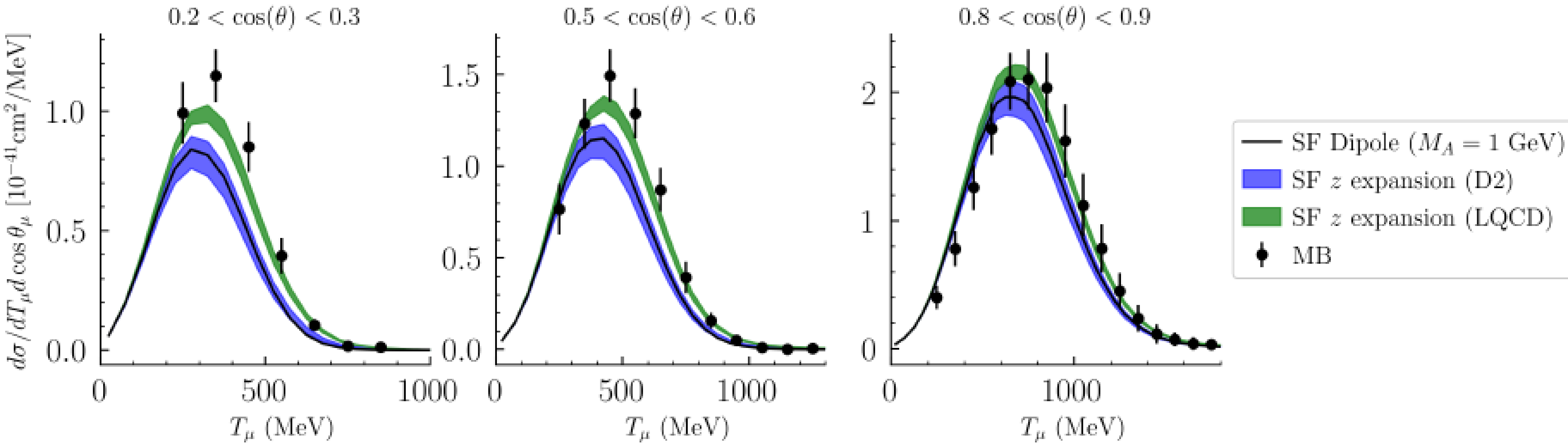
CHPT analysis of LQCD
F. Alvarado, LAR

$<r_A^2> = 0.291(52)$ fm² ⇔ 0.53(25) fm ⇐ **r_A = 0.73(17) fm**

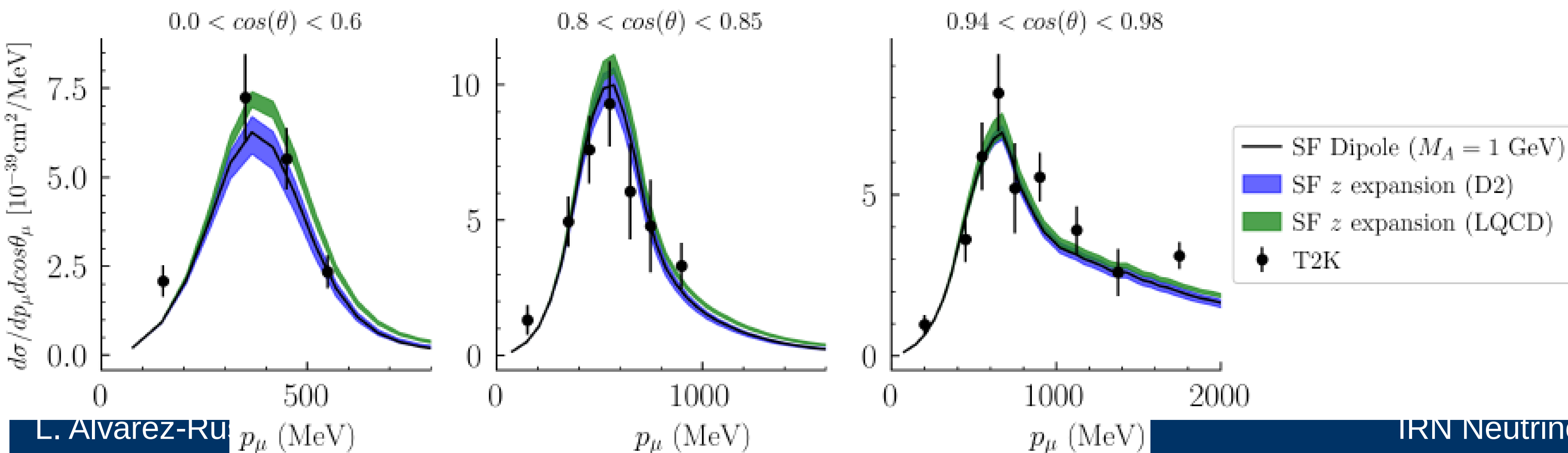
in tension with MINERvA

QE-like scattering

- Spectral Function Simons et al., 2210.02455

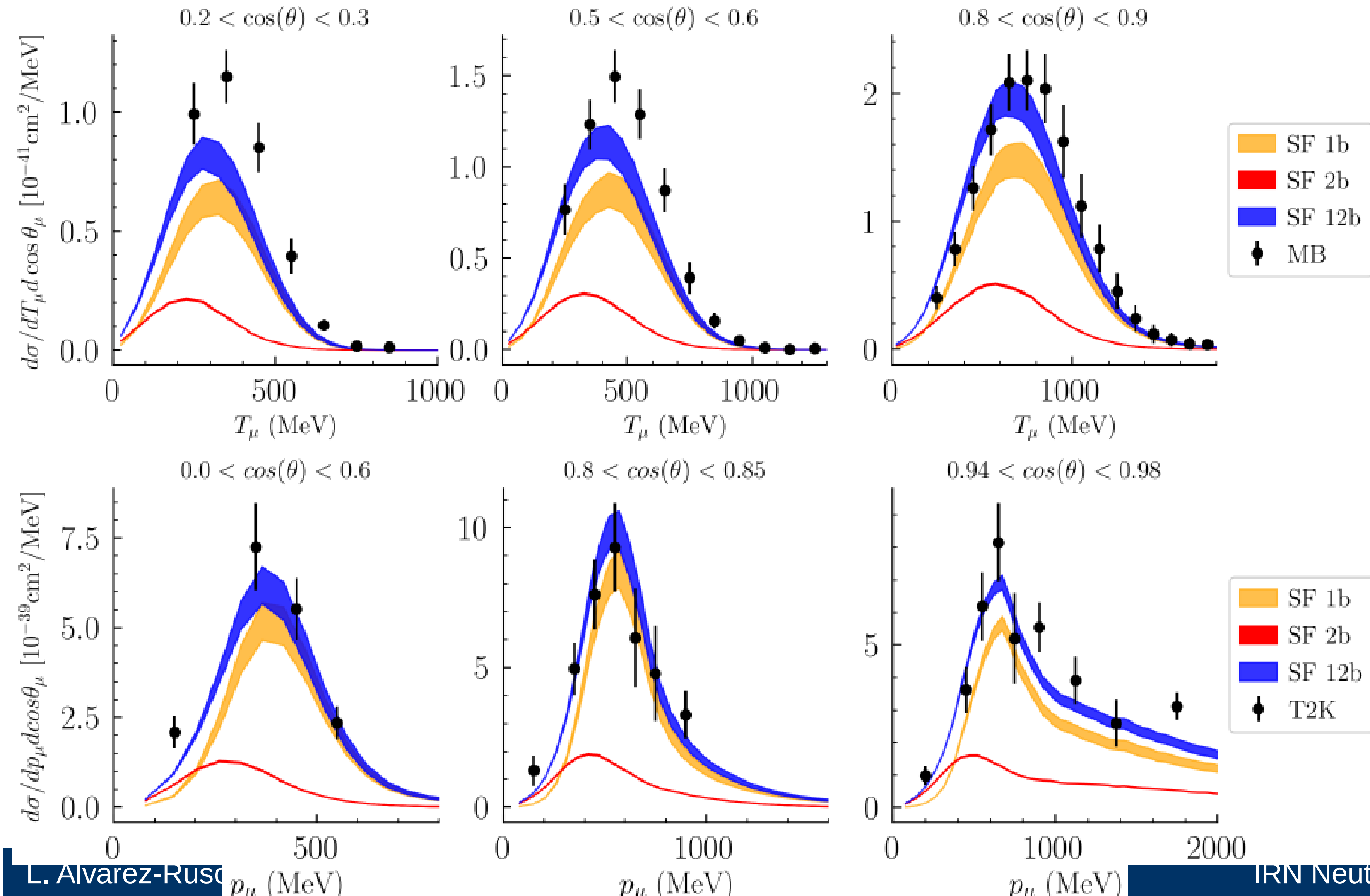


LQCD leads to a 10-20% enhancement of the cross section



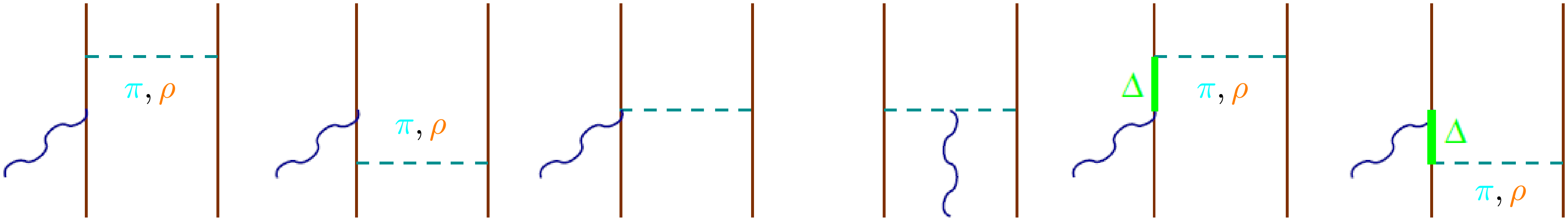
QE-like scattering

- Spectral Function Simons et al., 2210.02455



Pheno models for QE-like scattering

- Phenomenological 1- and 2-nucleon currents



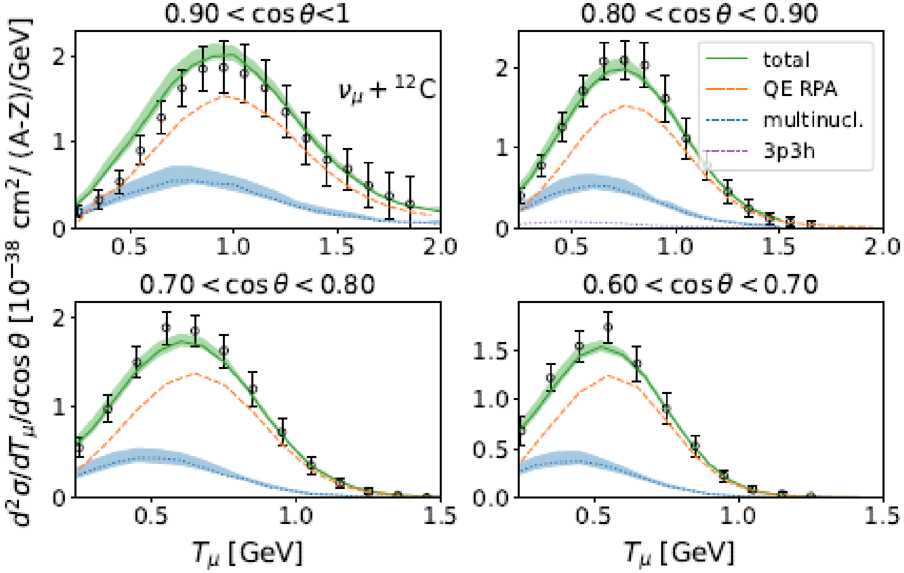
- Different descriptions of initial state nucleons:
  - Global Fermi gas
  - Local Fermi gas
  - Mean field
  - Superscaling
  - Spectral functions

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)
...

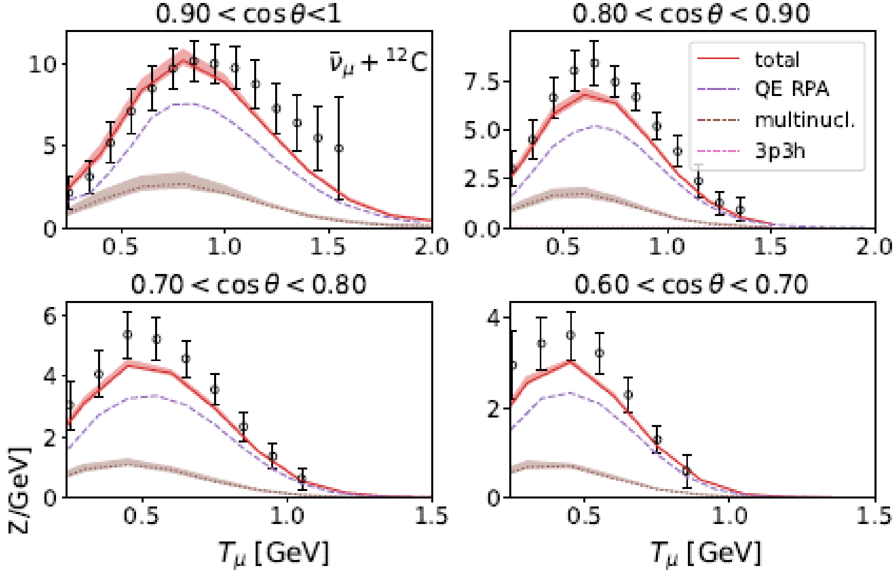
Pheno models for QE-like scattering

- Improvements in the Valencia/Nieves 2p2h model
  Sobczyk, Nieves, PRC 111 (2025)
  - Consistent treatment of the nucleon in-medium selfenergy
  - 20-40% higher cross sections
  - Comparison to MiniBooNE:

ν_μ

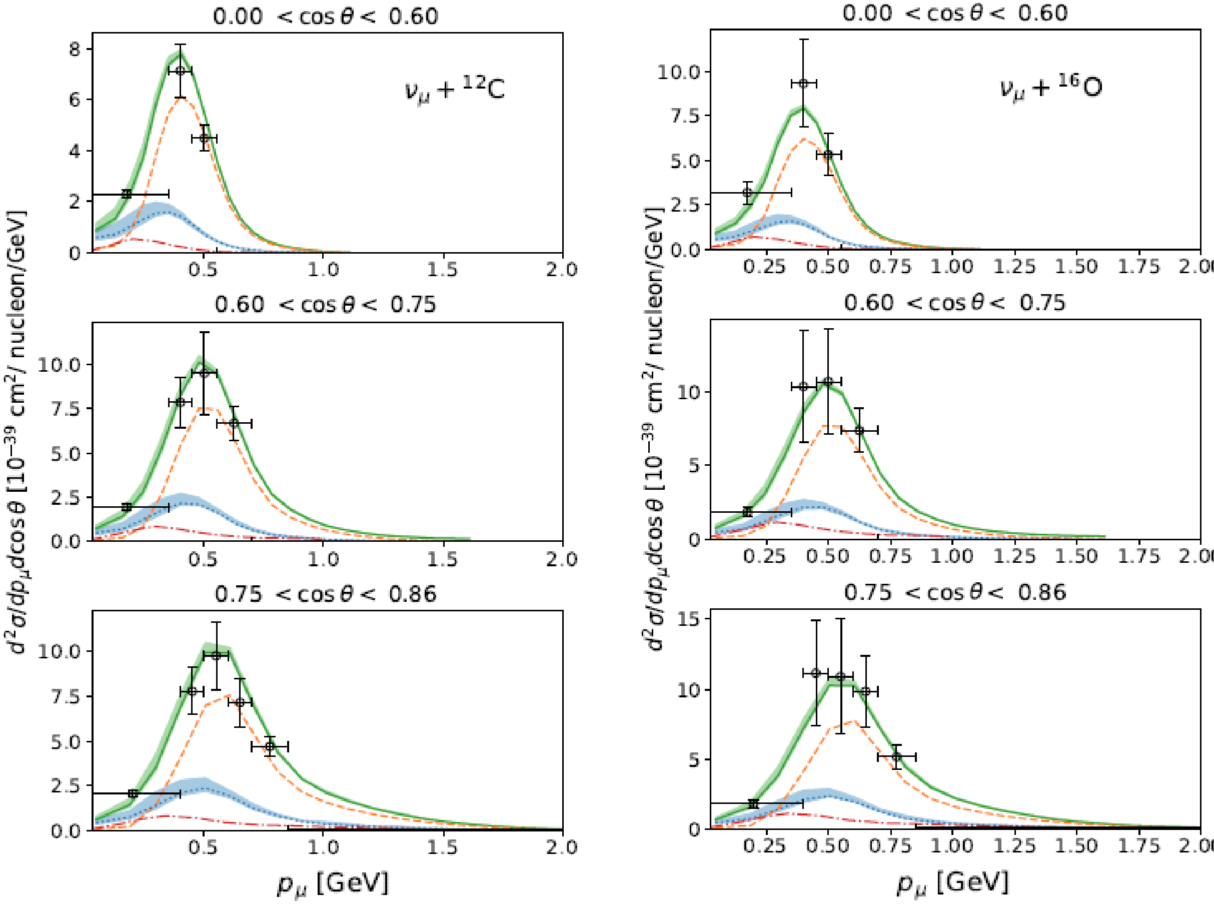


$\bar{\nu}_\mu$



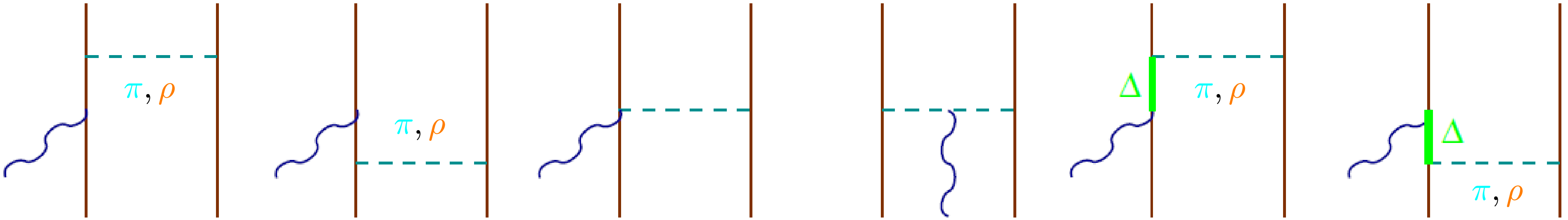
Pheno models for QE-like scattering

- Improvements in the Valencia/Nieves 2p2h model
  Sobczyk, Nieves, PRC111 (2025)
  - Consistent treatment of the nucleon in-medium selfenergy
  - 20-40% higher cross sections
  - Comparison to T2K:



Pheno models for QE-like scattering

- Phenomenological 1- and 2-nucleon currents

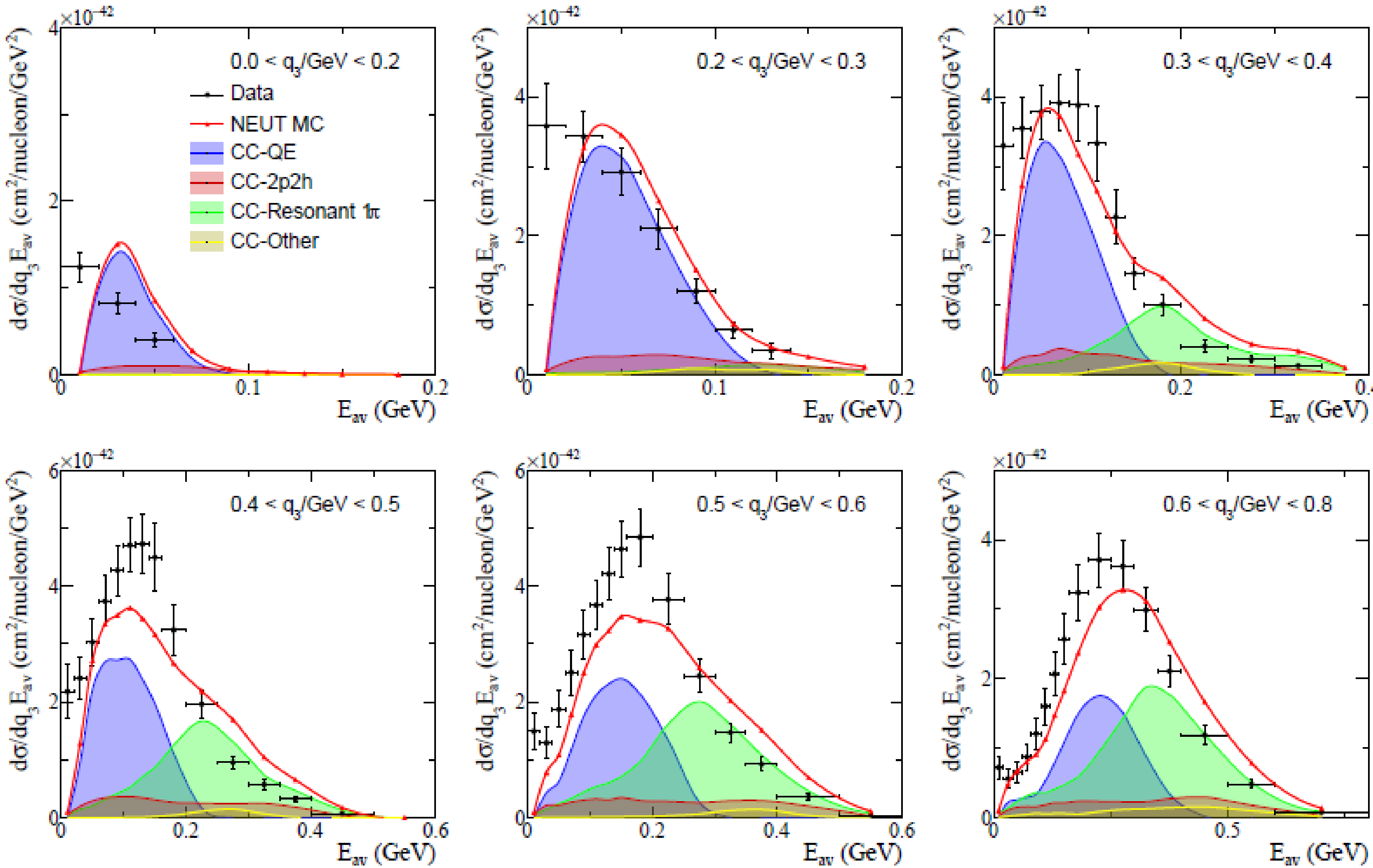


- Different descriptions of initial state nucleons:
  - Global Fermi gas
  - Local Fermi gas
  - Mean field
  - Superscaling
  - Spectral functions

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)
- strong model dependence (particularly in the 2p2h part)
- Discrepancies found @ MINERvA & NOvA

Pheno models for QE-like scattering

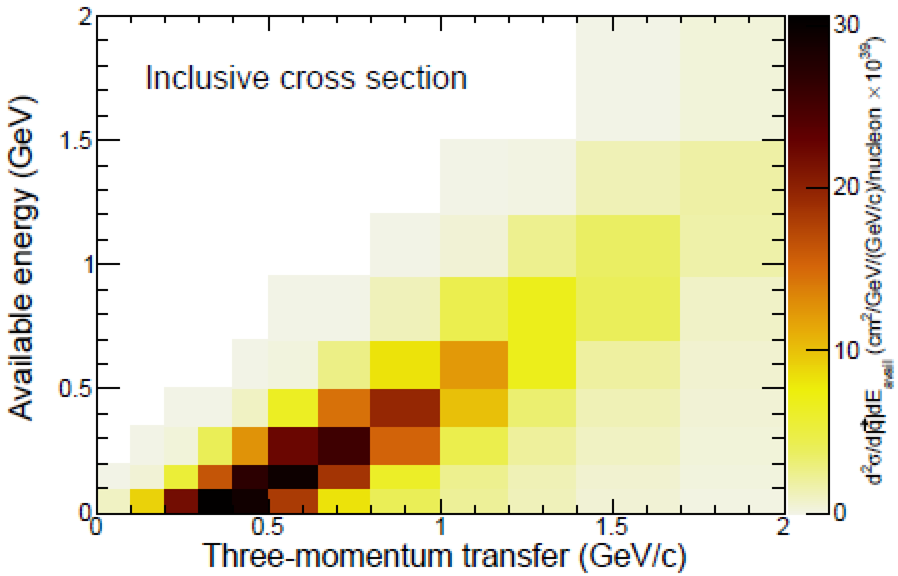


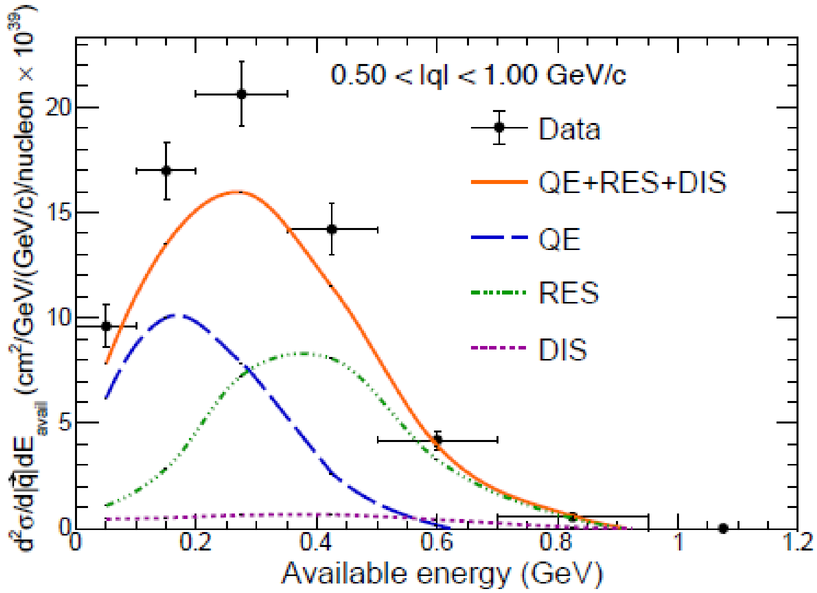
MINERvA inclusive CC data [Rodrigues et al. PRL (2016) vs T2K ref. model (NEUT)]

P. Stowell, PhD disertation (2019)

Pheno models for QE-like scattering

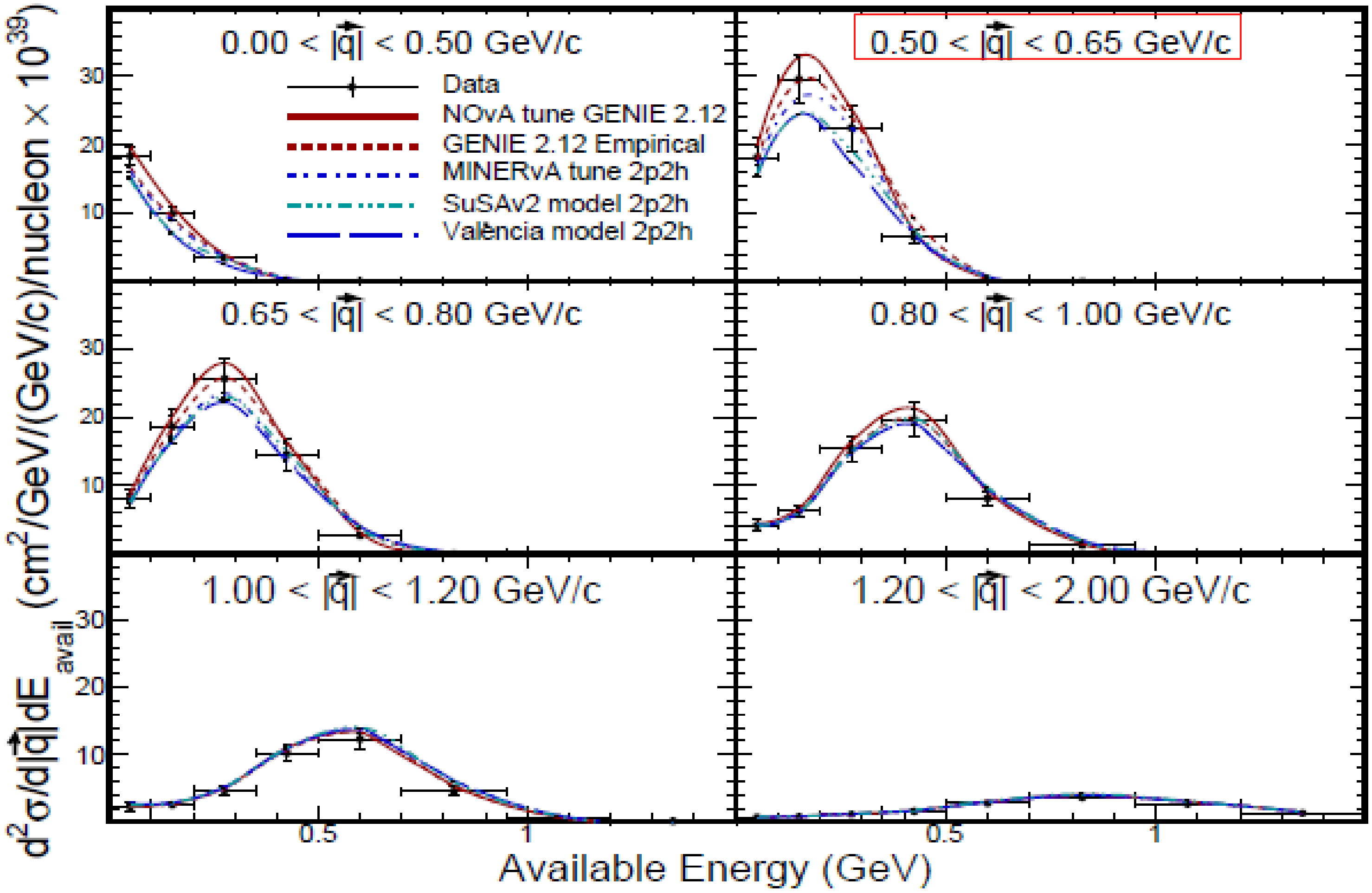
- NOvA Acero et al., PRD 111 (2025)





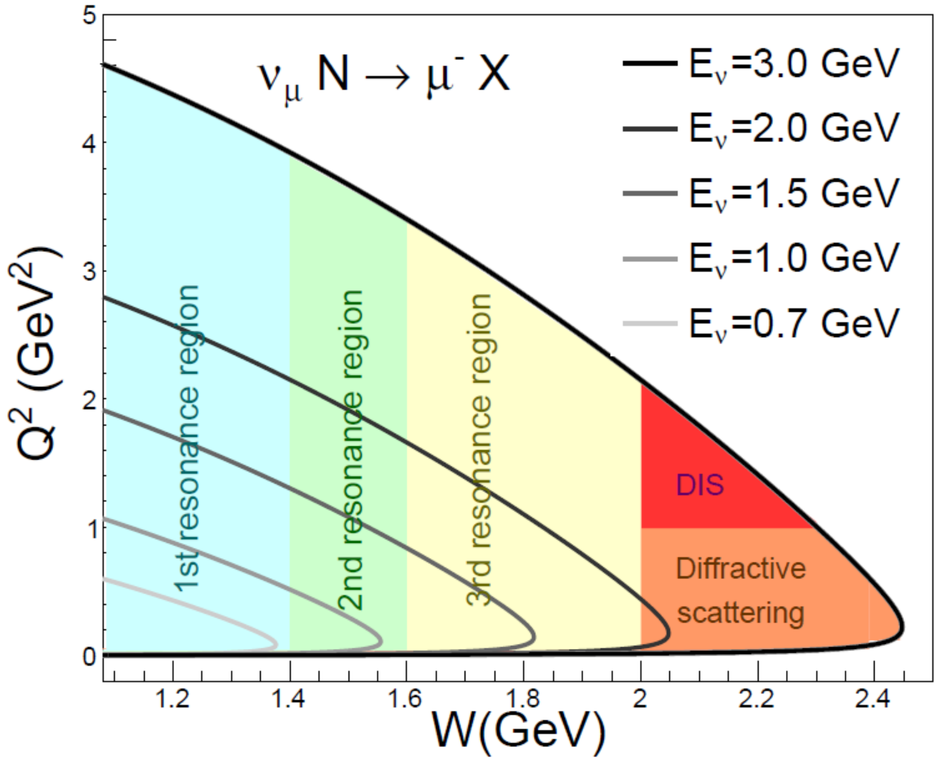
Pheno models for QE-like scattering

- NOvA Acero et al., PRD 111 (2025)



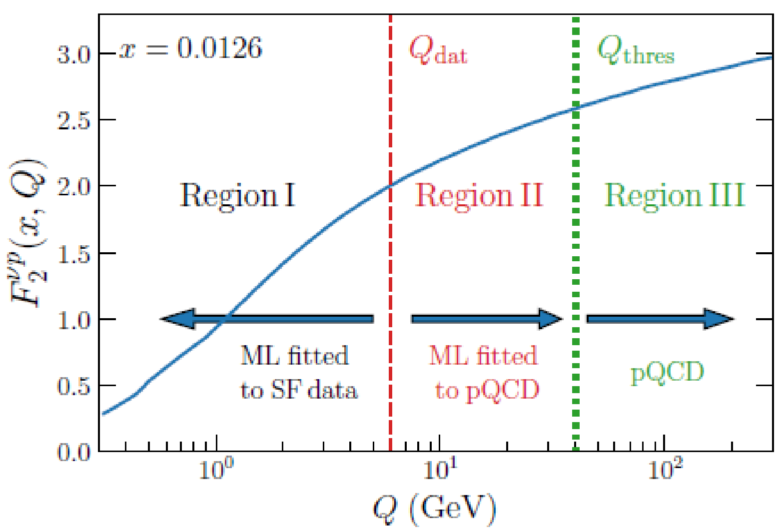
Inelastic scattering

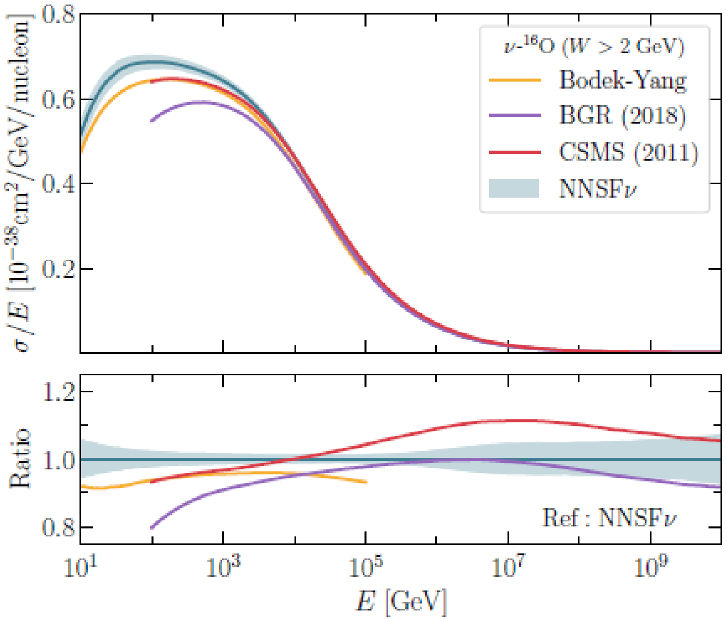
LAR, M. Kabirnezhad



Inelastic scattering

- Extend pQCD calculations → non-perturbative region
- 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 now outdated Bodek-Yang



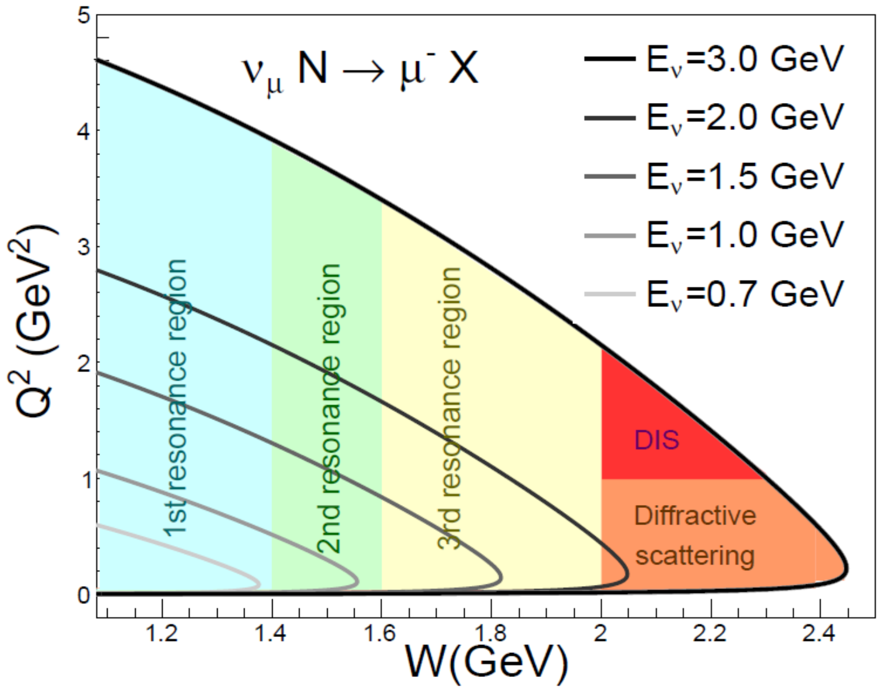


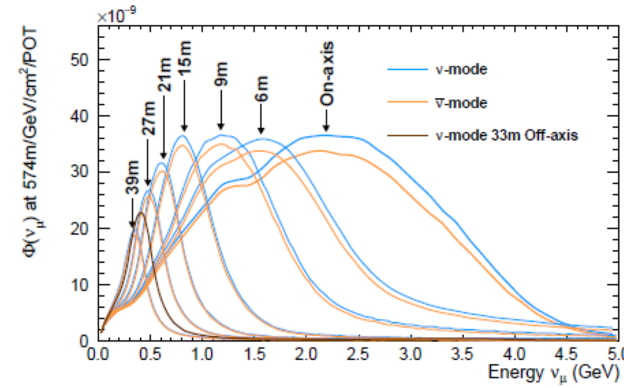
Inelastic scattering

- Extend pQCD calculations → non-perturbative region
- 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 now outdated Bodek-Yang
- Exclusive channels are not predicted...

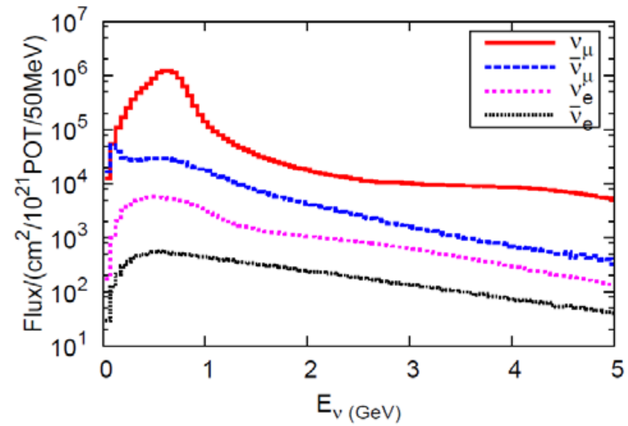
Inelastic scattering

LAR, M. Kabirnezhad





DUNE flux @ ND, 2002.03005



T2K flux @ ND

- 1π production: dominated by $\Delta(1232)$ excitation
- Above the $\Delta(1232)$ peak: 1.3<W<2 GeV:
  - several overlapping resonances
  - non-trivial interference; coupled channels

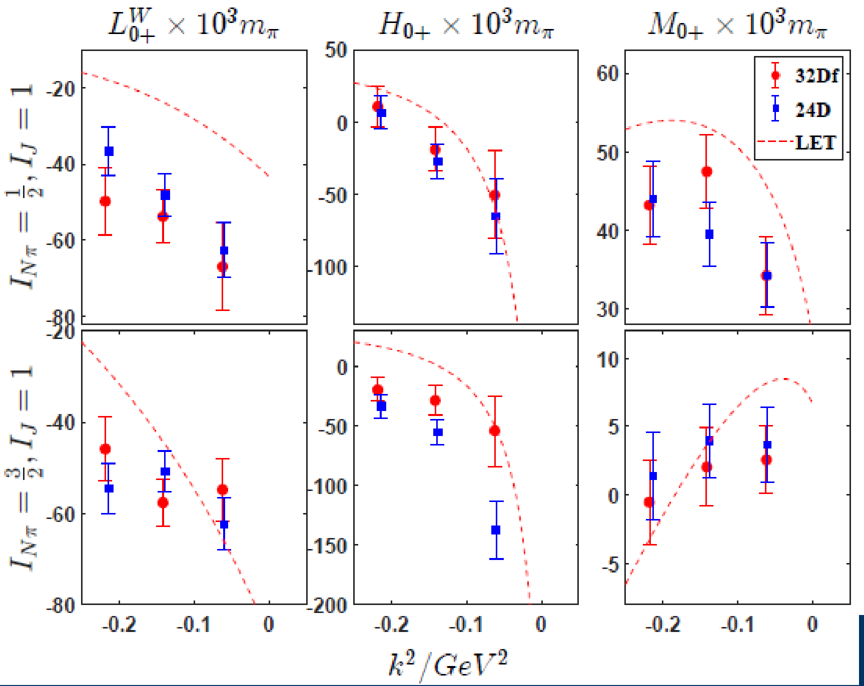
$$\nu_l\, N \to l\, N'\, \pi\pi$$
$$\nu_l\, N \to l\, N'\, \eta$$
$$\nu_l\, N \to l\, \Lambda(\Sigma)\, \bar{K}$$

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
  - 19 can be extracted from external (non-ν) processes: $\pi N \to N \pi$, $\gamma^* N \to N \pi$
  - 3 require new measurements of ν-induced π production on protons

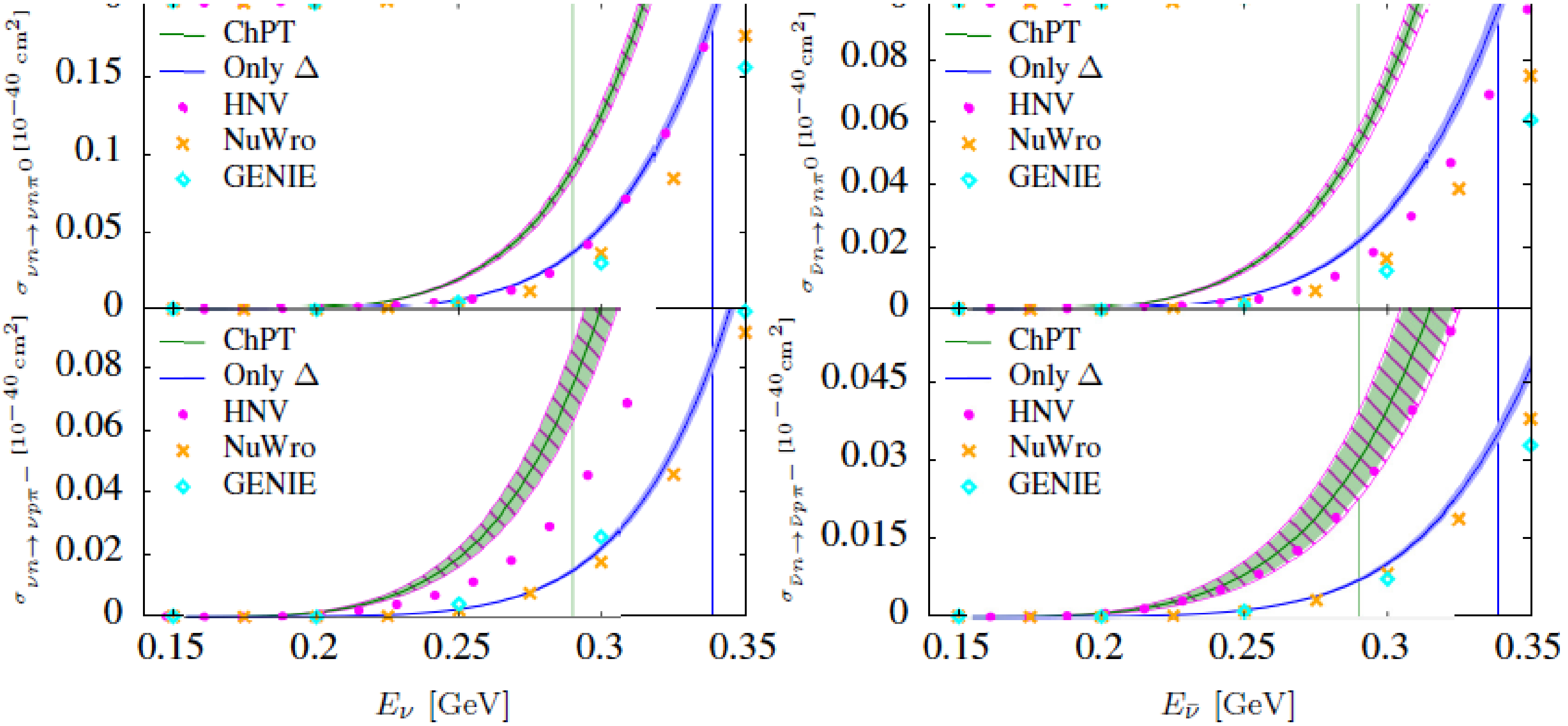
Weak pion production in EFT

- 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
  - 19 can be extracted from external (non-ν) processes: $\pi N \to N\pi$, $\gamma^* N \to N \pi$
  - 3 require new measurements of ν-induced π production on protons
- First LQCD study of EW π production: $\gamma^* N \to N \pi$ $W^*, Z^* N \to N \pi$
  Gao et al., PRL 134 (2025)



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
- Kinematically limited: q << Λ_χ ~ 0.7-1 GeV
- Benchmark for phenomenological models



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, $\Delta(1232)$, 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 q$^2 \to 0$ can be constrained with $\pi N \to N\pi$ (PCAC)

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

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

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

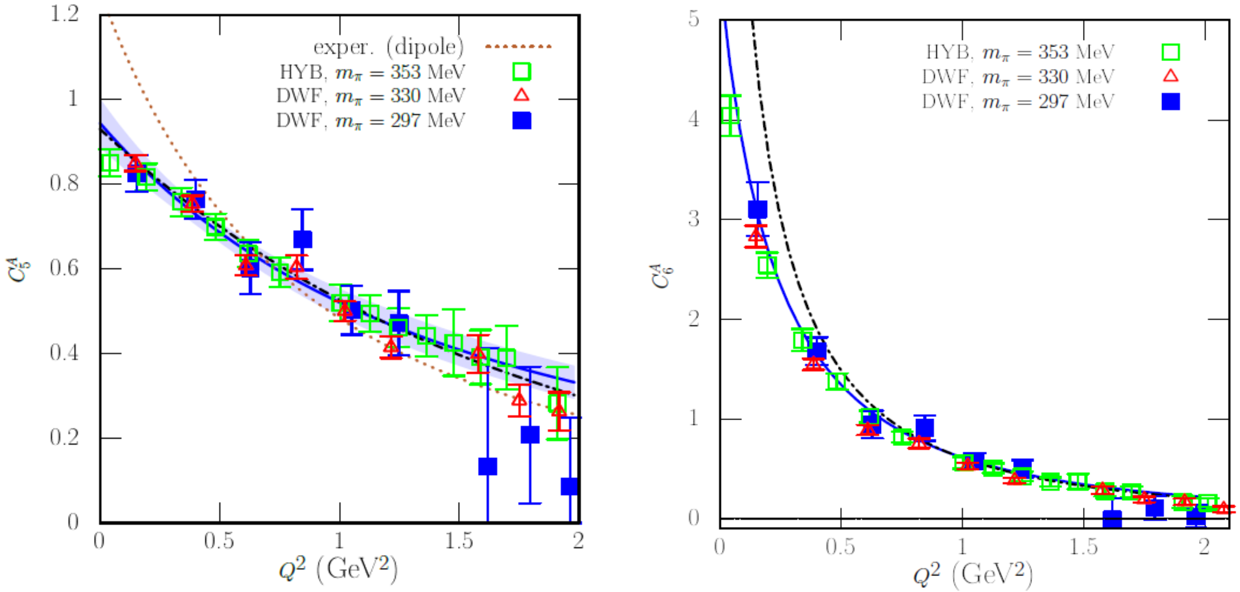
  - Vector current can be constrained with $\gamma N \to N \pi$, $e N \to e' N \pi$
  - Axial current at $q^2 \to 0$ can be constrained with $\pi N \to N\pi$ (PCAC)

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

  - **Very limited information about the axial current at $q^2 \neq 0$**
    - Progress is hindered by the lack of data on nucleons

LQCD & meson production

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



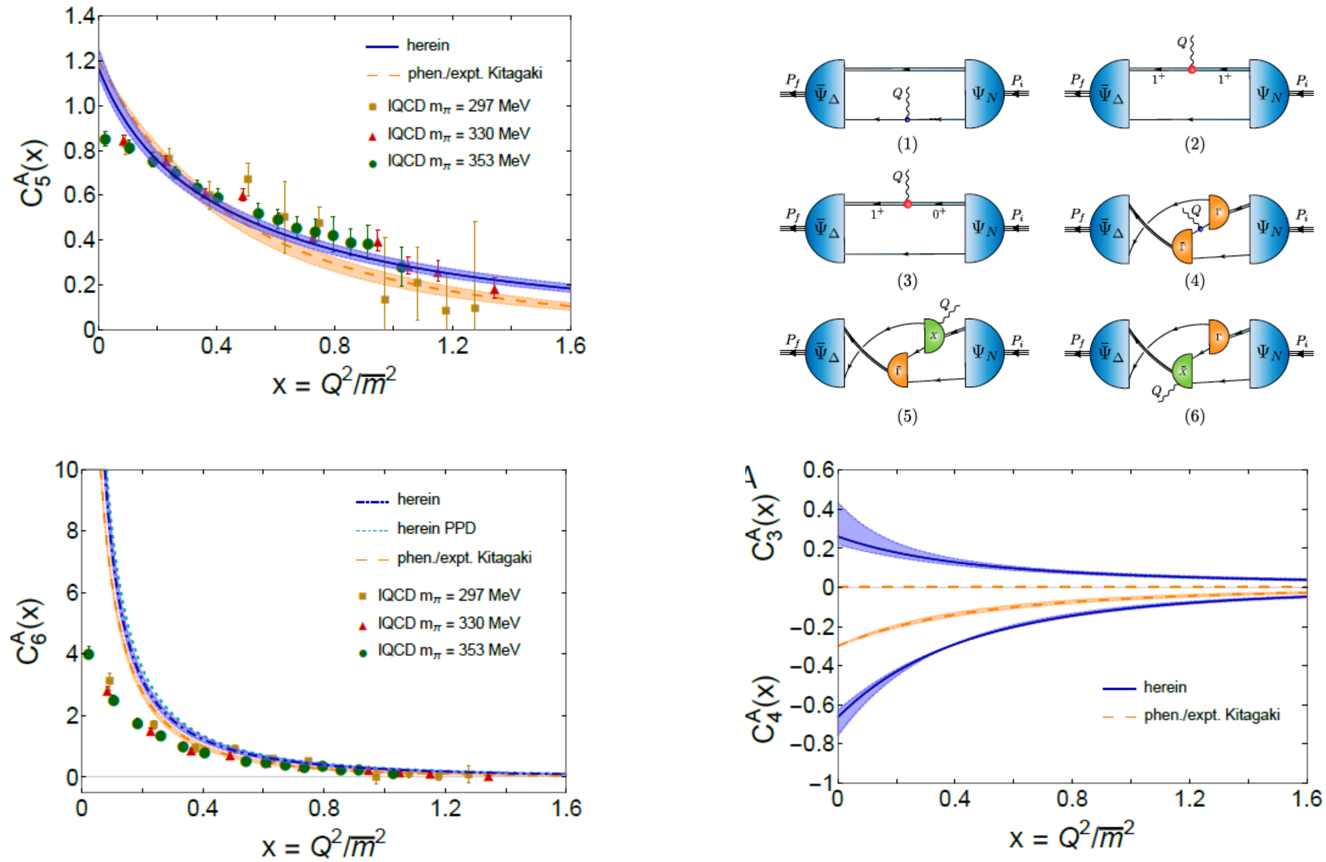
- Calculations of N-Δ,N-N* transition FF should become available in the next 5-10 years LAR et al., Snowmass 2021, 2203.09030
- Control systematic uncertainties is challenging

N-$\Delta(1232)$ 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+Faddeev eqs. for quarks. Chen,Fischer,Roberts, PRL133(2024)

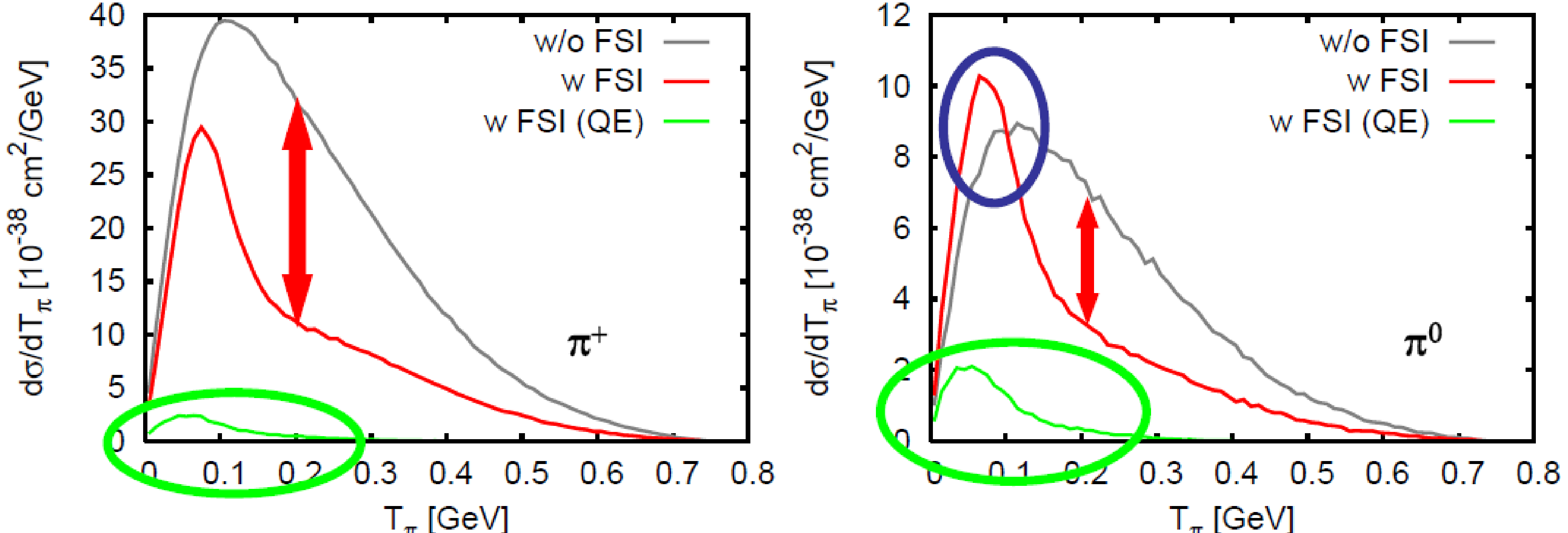


N-Δ(1232) axial transition matrix element:

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

Inelastic scattering 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)

  - Except for a few processes (single-nucleon knockout, Cohπ), QM treatment of final state interactions is unfeasible
    - $\Rightarrow$ semiclassical methods: intranuclear cascades and transport
      - Rely on meson-nucleus scattering data as input and/or validation

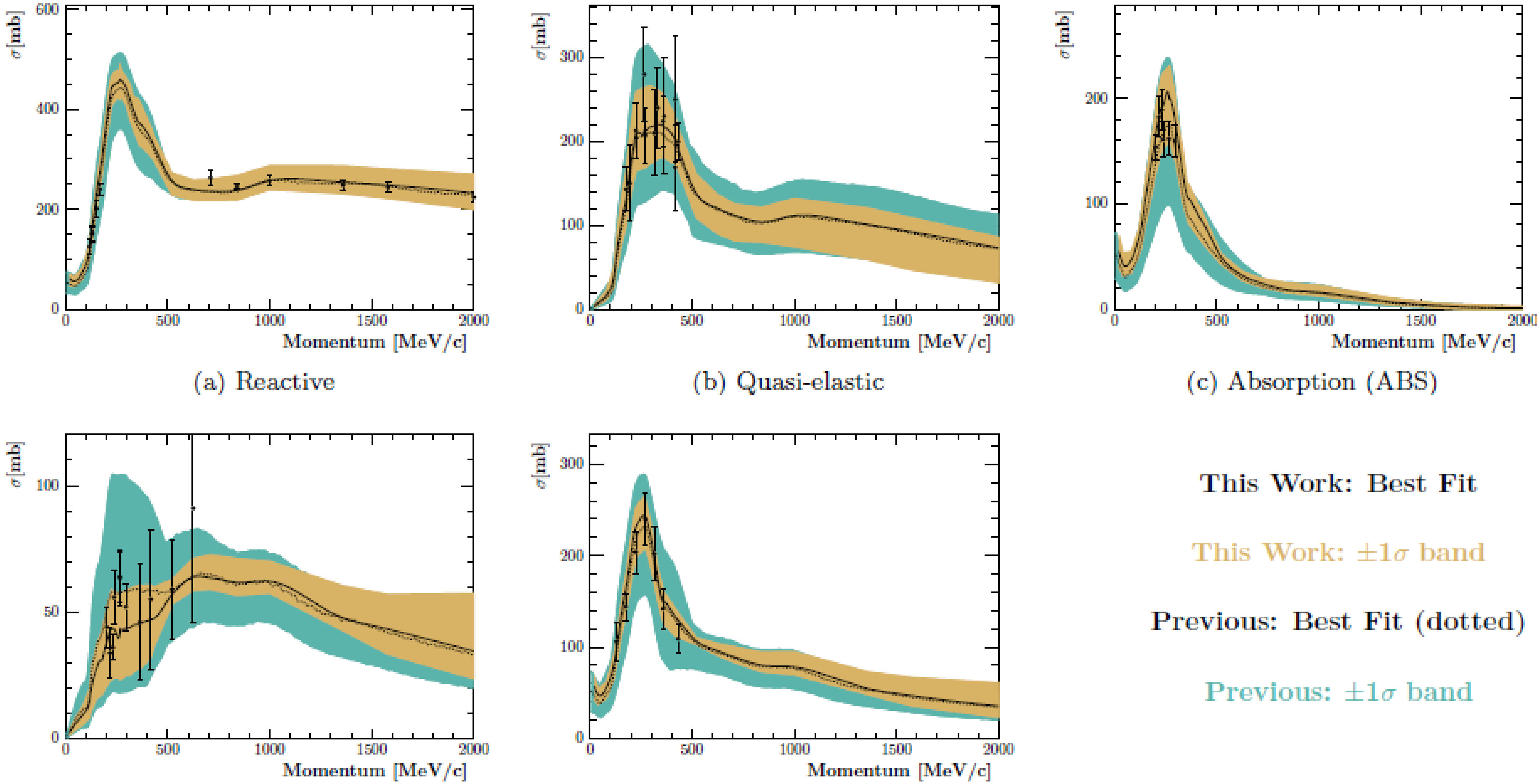
Final State Interactions

- NEUT intranuclear cascade improved by fitting a large π-nucleus data set
  Pinzon Guerra et al., PRD 99 (2019)

Reference	Polarity	Targets	p_π [MeV/c]	Channel(s)
B. W. Allardyce *et al.* [26]	$\pi^\pm$	^{12}C, ^{27}Al, ^{207}Pb	710-2000	REAC
A. Saunders *et al.* [27]	$\pi^\pm$	^{12}C, ^{27}Al	116-149	REAC
C. J. Gelderloos *et al.* [28]	π^-	^{12}C, ^{27}Al, ^{63}Cu, ^{207}Pb	531-615	REAC
F. Binon *et al.* [29]	π^-	^{12}C	219-395	REAC
O. Meirav *et al.* [30]	$\pi^\pm$	^{12}C, ^{16}O	128-169	REAC
C. H. Q. Ingram [31]	π^+	^{16}O	211-353	QE
S. M. Levenson *et al.* [32]	π^+	^{12}C	194-416	QE
M. K. Jones *et al.* [33]	π^+	^{12}C, ^{208}Pb	363-624	QE, CX
D. Ashery *et al.* [34]	$\pi^\pm$	^{12}C, ^{27}Al, ^{56}Fe	175-432	QE, ABS+CX
H. Hilscher *et al.* [35]	π^-	^{12}C	156	CX
T. J. Bowles [36]	π^+	^{16}O	128-194	CX
D. Ashery *et al.* [37]	$\pi^\pm$	^{12}C, ^{16}O, ^{207}Pb	265	CX
K. Nakai *et al.* [38]	$\pi^\pm$	^{27}Al, ^{63}Cu	83-395	ABS
E. Bellotti *et al.* [39]	π^+	^{12}C	230	ABS
E. Bellotti *et al.* [40]	π^+	^{12}C	230	CX
I. Navon *et al.* [41]	π^+	^{12}C, ^{56}Fe	128	ABS+CX
R. H. Miller *et al.* [42]	π^-	^{12}C, ^{207}Pb	254	ABS+CX
E. S. Pinzon Guerra *et al.* [43]	π^+	^{12}C	206-295	ABS, CX

Final State Interactions

- NEUT intranuclear cascade improved by fitting a large π-nucleus data set
  Pinzon Guerra et al., PRD 99 (2019)



(a) Reactive
(b) Quasi-elastic
(c) Absorption (ABS)
(d) Charge exchange (CX)
(e) ABS+CX

ν interactions and BSM physics

- Generalized ν interactions

$$\mathcal{L}_{\rm WEFT} \supset -\frac{2V_{jk}}{v^2}\Big\{[1+\epsilon_L^{jk}]_{\alpha\beta}(\bar{u}^j\gamma^\mu P_L d^k)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) + [\epsilon_R^{jk}]_{\alpha\beta}(\bar{u}^j\gamma^\mu P_R d^k)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)$$
$$+\frac{1}{2}[\epsilon_S^{jk}]_{\alpha\beta}(\bar{u}^j d^k)(\bar{\ell}_\alpha P_L\nu_\beta) - \frac{1}{2}[\epsilon_P^{jk}]_{\alpha\beta}(\bar{u}^j\gamma_5 d^k)(\bar{\ell}_\alpha P_L\nu_\beta)$$
$$+\frac{1}{4}[\epsilon_T^{jk}]_{\alpha\beta}(\bar{u}^j\sigma^{\mu\nu}P_L d^k)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\Big\}.$$

$$v \equiv (\sqrt{2}G_F)^{-1/2}$$

Falkowski et al., JHEP 10 (2021)

- Non-standard ν interactions

$$\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}G_F\epsilon_{ij}^{fX}\bar{\nu}^i\gamma_\mu P_L\nu^j\bar{f}\gamma^\mu P_X f \qquad P_{X=L,R} = (1\mp\gamma_5)/2$$

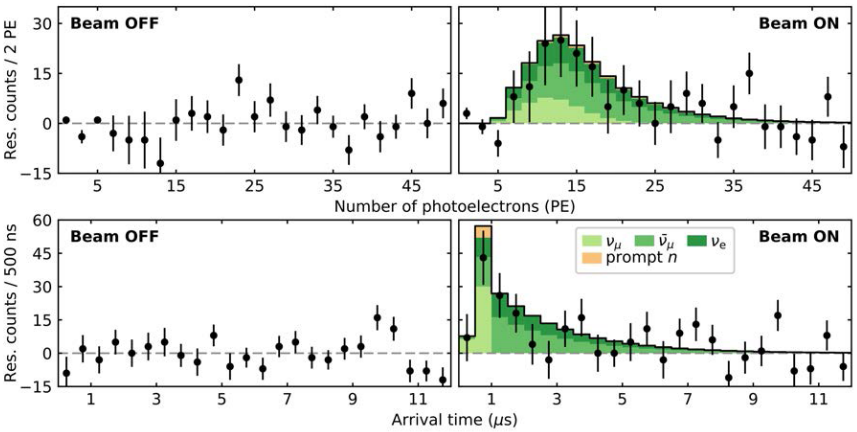
can be (potentially) accessed in:

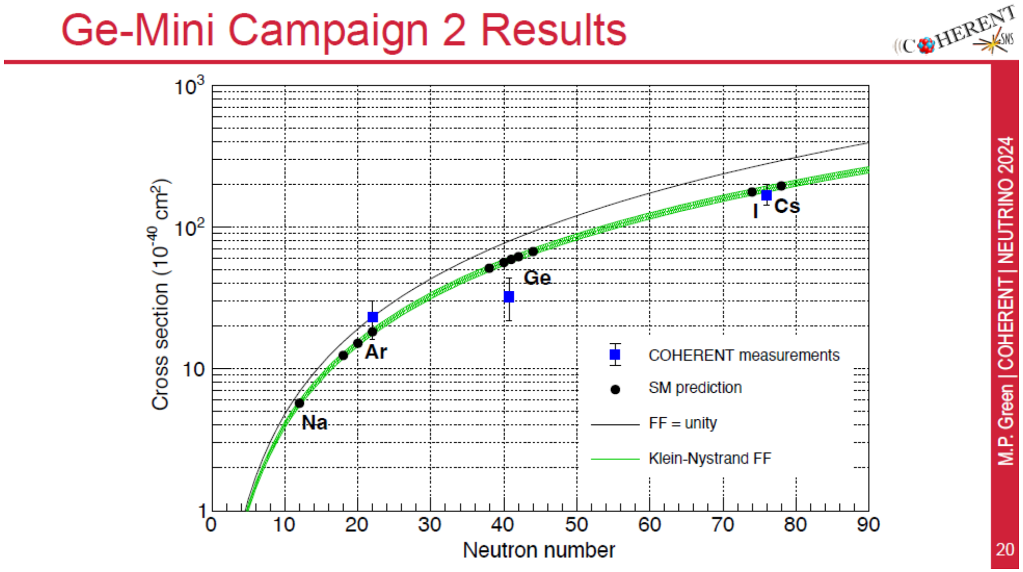
- τ, β, (heavy) hadron semi-leptonic decays
- Oscillations (matter effects)
- Cosmology ($N_{\rm eff}$)
- ν scattering (@ detection):
  - DIS
  - ν-e
  - CEνNS

CEνNS

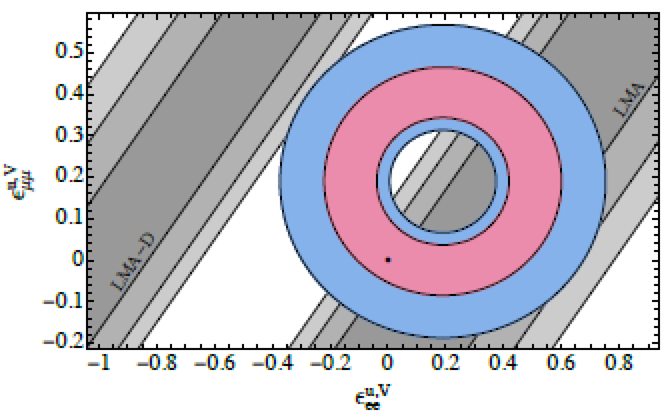
$$\frac{d\sigma}{dT} = \frac{G_F^2}{(2\pi)} \frac{\left[Z(1-4\sin^2\theta_W) - N\right]^2}{4} F^2(-2MT) M \left[2 - \frac{MT}{k_0^2}\left(1 - 2\frac{k_0}{M}\right)\right]$$

- Coherent Science 357 (2017)





- Strong constrains to the LMA-Dark degeneracy of oscillation data



Coloma et al., PRD 96 (2017)

New Physics in ν interactions

- ν-nucleus QE scattering: Kopp, Rocco,Tabrizi, JHEP 08 (2024)
  - main uncertainties at the nucleon level
- ν-nucleon scattering
  - confronting (future) new data with predictions (using LQCD as input)
- Using MINERvA $\bar{\nu}_\mu \, p \to \mu^+ \, n$ data, Cai et al., Nature 614 (2023), new confidence intervals for tensor and scalar interactions have been obtained Tomalak et al., PLB 854 (2024)

$$T_{\bar{\nu}_\ell p \to \ell^+ n} = T^{m_\ell = 0}_{\bar{\nu}_\ell p \to \ell^+ n} + \sqrt{2} \mathrm{G_F} V^\star_{ud} \frac{m_\ell}{M} \left[\frac{\bar{f}_T}{4} \bar{\nu}_\ell \sigma^{\mu\nu} \mathrm{P_R} \ell^+ \, \bar{n} \sigma_{\mu\nu} p - \bar{\nu}_\ell \mathrm{P_R} \ell^+ \, \bar{n} \left(\bar{f}_3 + \bar{f}_P \gamma_5 - \frac{\bar{f}_R}{4} \frac{\gamma^\mu P_\mu}{M} \gamma_5 \right) p \right]$$

$$\bar{f}^j_i \left(\nu, Q^2\right) = \frac{\mathfrak{Re} \bar{f}^j_i (0) + i \mathfrak{Im} \bar{f}^j_i (0)}{\left(1 + \frac{Q^2}{\Lambda^2}\right)^2}$$

	$\mathfrak{Re} \bar{f}_3$	$\mathfrak{Re} \bar{f}_T$	$\mathfrak{Re} \bar{f}_{A3}$	$\mathfrak{Re} \bar{f}_R$
$\bar{\nu} p$ scattering	$88.4^{+33.5}_{-58.0}$	$-0.5^{+5.0}_{-4.8}$	$-1.0^{+0.4}_{-0.3}$ & $1.0^{+0.3}_{-0.4}$	$-80.1^{+40.6}_{-26.0}$
beta decay	0.0 ± 1.8 [72]	-9.3 ± 10.3 [73]	0.0 ± 0.075 [66]	

	$\mathfrak{Im} \bar{f}_3$	$\mathfrak{Im} \bar{f}_T$	$\lvert\mathfrak{Im} \bar{f}_{A3}\rvert$	$\lvert\mathfrak{Im} \bar{f}_R\rvert$
$\bar{\nu} p$ scattering	$-82.1^{+34.6}_{-23.8}$ & $82.1^{+23.8}_{-34.6}$	0.0 ± 4.9	$1.00^{+0.29}_{-0.43}$	$69.9^{+20.9}_{-30.9}$
beta decay	13.0 ± 54.0 [73]	-1.9 ± 15.4 [73]		

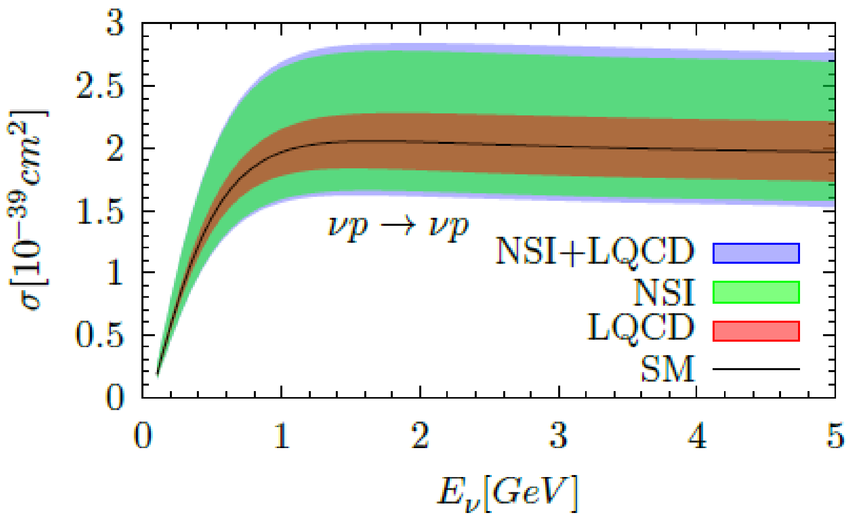
New Physics in ν interactions

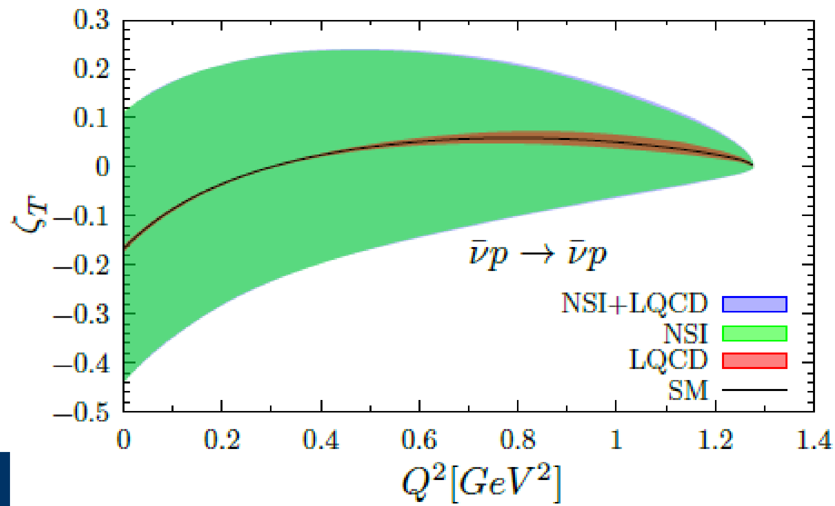
- ν-nucleon scattering
  - confronting (future) new data with predictions (using LQCD as input)
- NCE scattering $\nu/\bar{\nu}\, N \to \nu/\bar{\nu}\, N$ in presence of NSI, Ilma et al., PRD (2025)

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

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

  - Requires the flavor decomposition of F_A (u,d,s quarks)
    - Available from LQCD: Alexandrou et al., PRD 104 (2021)





Flavor Changing Neutral Currents

- Eg. $d \to s$
- Suppressed in the **SM**
- Effective Hamiltonian:

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

  - Only left handed ν
  - Lepton flavor diagonal
  - Real $\epsilon_{V,A}$ (CP violation not considered)

- Constraints from K decays: Geng, Martin Camalich, Shi, JHEP 02 (2022) 178
  - Based on upper limits for branching ratios from KOTO and NA62
  - $K \to \pi \nu\bar{\nu}$ $\epsilon_V < 10^{-6} \approx 0$
  - $K \to \pi\pi \nu\bar{\nu}$ $|\epsilon_A| < 7.6 \times 10^{-3}$ ($\times \sqrt{3}$ if only 1ν flavor contributes)

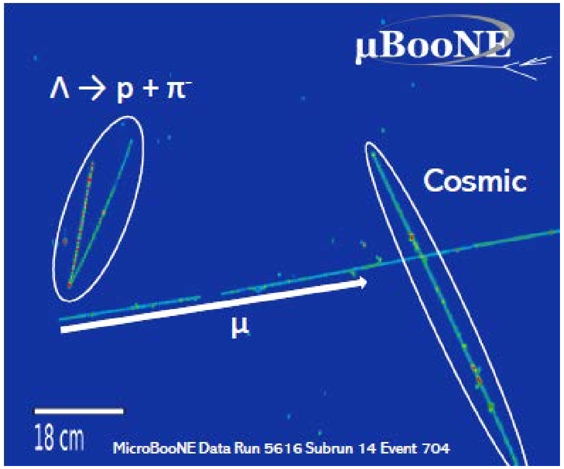
Weak hyperon production

- ΔS = -1: $W^- u \to s$
- 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:
  - $\bar{\nu}\, N \to \mu^+\, Y$ (QE)
  - $\bar{\nu}\, N \to \mu^+\, Y\, \pi$ (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

Benitez et al. PRD 109 (2024)

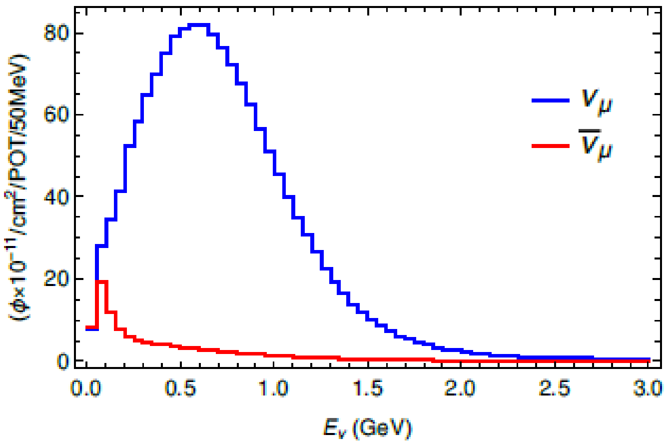
$\bar{\nu}\, \mathrm{Ar} \to \mu^+\, \Lambda\, X$

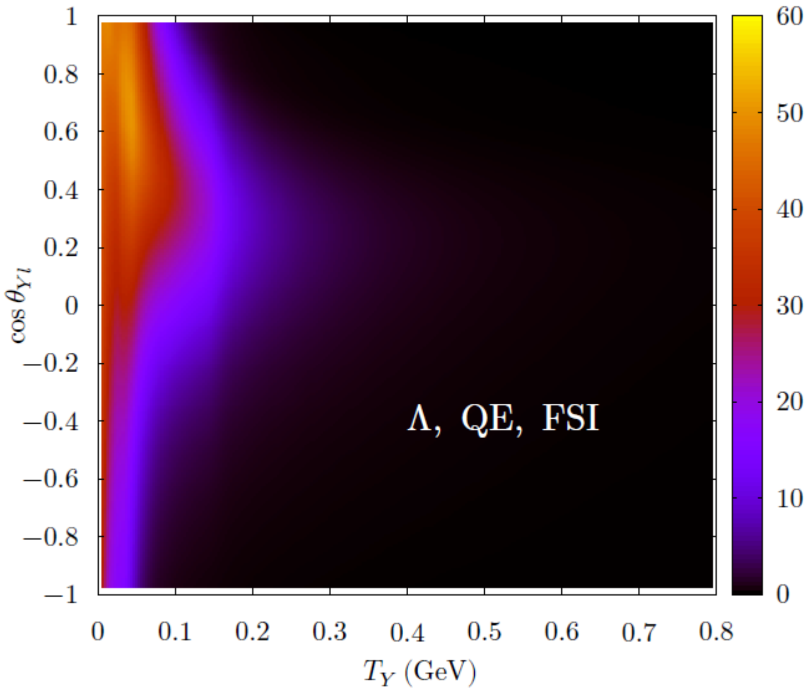


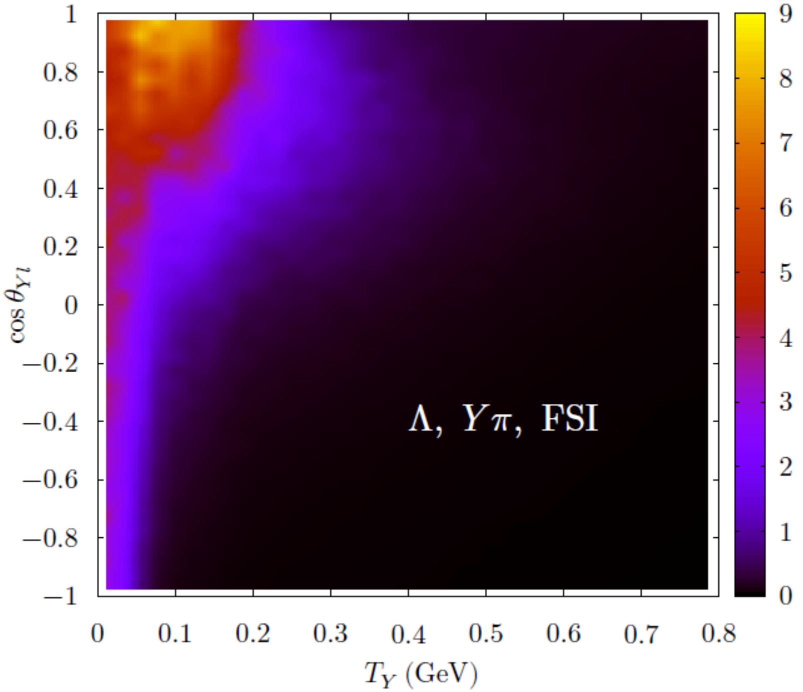
MicroBooNE, PRL 130 (2023)

Weak hyperon production

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

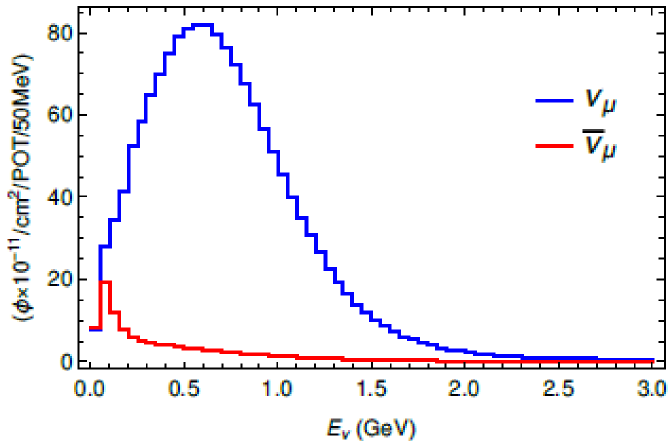






FCNC searches with neutrinos

- At SBND
- $d \to s$ using $$\nu_l\, n \;\to\; \nu_l\, \Sigma_0(\Lambda)$$ $$\nu_l\, p \;\to\; \nu_l\, \Sigma^+$$



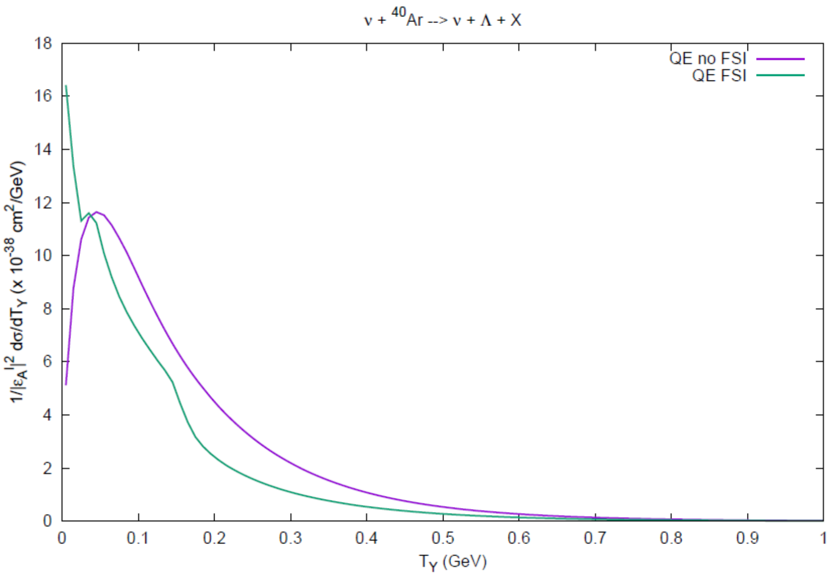
- Same matrix elements (up to isospin rotations) as in $W^- u \to s$

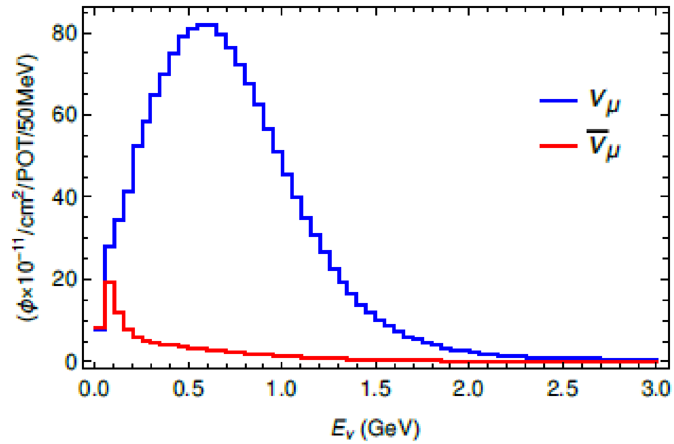
$$\langle \Lambda | \bar{s}\gamma^\mu(\gamma_5) d | n \rangle = \langle \Lambda | \bar{s}\gamma^\mu(\gamma_5) u | p \rangle$$
$$\langle \Sigma^0 | \bar{s}\gamma^\mu(\gamma_5) d | n \rangle = -\langle \Sigma^0 | \bar{s}\gamma^\mu(\gamma_5) u | p \rangle$$
$$\langle \Sigma^+ | \bar{s}\gamma^\mu(\gamma_5) d | p \rangle = \langle \Sigma^- | \bar{s}\gamma^\mu(\gamma_5) u | n \rangle$$

FCNC searches with neutrinos

- At SBND
- $d \to s$ using

$$\nu_l \, n \rightarrow \nu_l \, \Sigma_0(\Lambda)$$
$$\nu_l \, p \rightarrow \nu_l \, \Sigma^+$$





- (Preliminary) upper bounds:

N_Λ FCNC	No Thr.	μBooNE Thr.	SBND Thr.
QE	35 – 45	8 – 10	25 – 35

(× 3 if only ν_μ contributes)

Summary

- Neutrino-interaction modeling 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.
- Some processes have the potential to discover/constrain NSI and exotics