

Neutrino-Nucleon/Nucleus Interaction Measurements at the few-GeV Energy Scale: *Relevance, Present Status and Future Prospects*

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Science & Technology Facilities Council
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Outline

- What are we hoping to learn?
- Flagship LBL programme: Present and future
- Systematic error requirement for future LBL
- LBL oscillation analysis: Reliance on models
- Neutrino-nucleus interactions at the few-GeV energy range
- Modern experiments and recent measurements
- Illustrating our present understanding through two puzzles:
 - the "quasielastic puzzle"
 - the "single- π puzzle"
- Near-future experiments and measurements
- Summary

What are we hoping to learn?

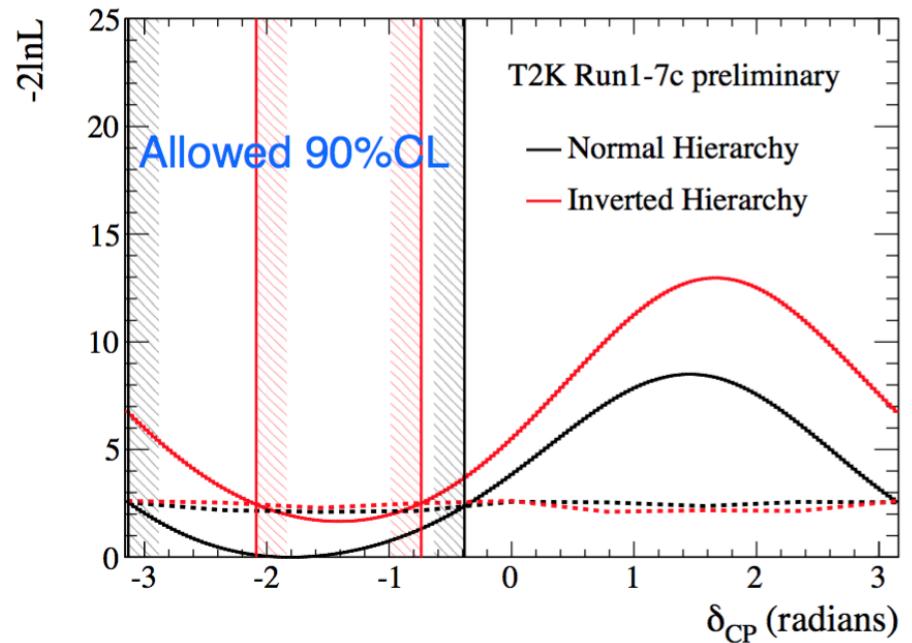
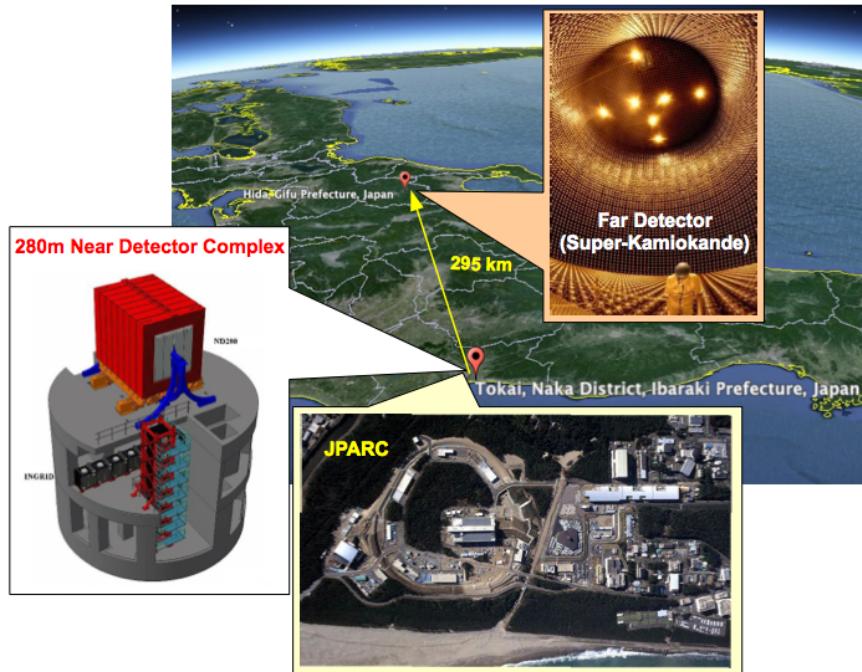
Study of neutrino masses and mixings the only known **window to new physics**.

Several key questions:

- **What is the neutrino mass generation mechanism?**
 - Could the neutrino be a Majorana particle?
 - Why are the masses so small?
- **What do neutrinos tell us about flavour?**
 - Nearly (exactly?) maximal mixing observed: ‘ μ ’ and ‘ τ ’ flavour interchangeable!
- **Does it provide a connection between quarks and leptons?**
 - Why the corresponding mixing matrices are so different?
- **What are the implications for the universe we live in?**
 - Baryon asymmetry of the universe: Leptogenesis requires CPV + Majorana mass
 - Dark matter: Sterile neutrino is a candidate.

Poor understanding of neutrino interactions **limits sensitivity to new physics!**

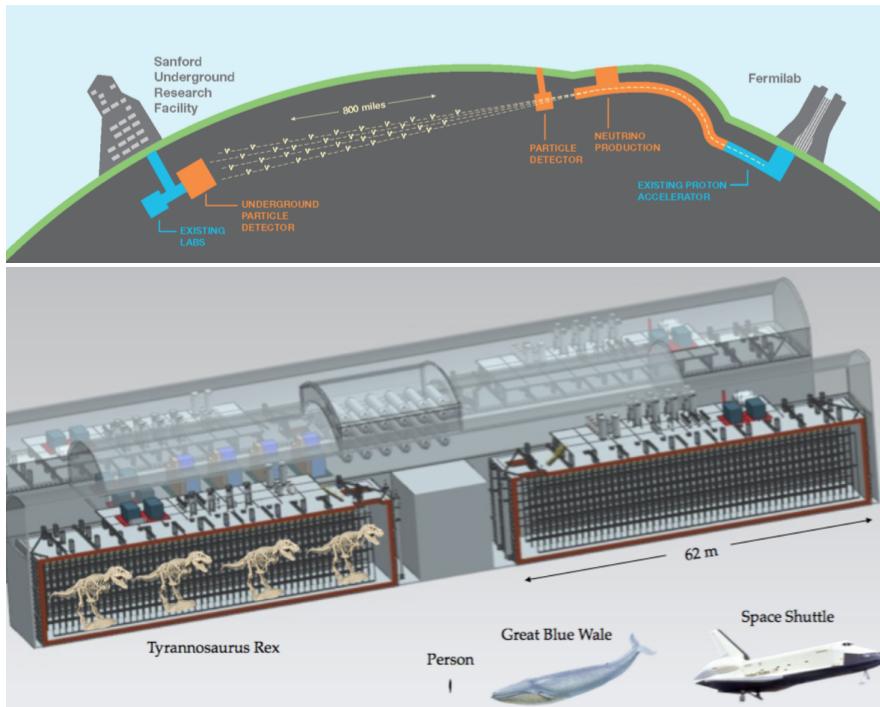
Flagship long-baseline oscillation programme: Present



- 7.57×10^{20} ν mode + 7.53×10^{20} $\bar{\nu}$ mode (20% of approved exposure)
- Observed 135 (66) 1-ring μ -like and 32 (4) 1-ring e-like events in ν ($\bar{\nu}$) mode
- 5% - 6% systematic uncertainty in the expected Far detector event rate
- **"Conserved CP' hypothesis excluded at 90% C.L."**
 - Best-fit: $\delta_{CP} = -1.885$, NH
 - $\delta_{CP} = 0$ is excluded at 2σ C.L., while $\delta_{CP} = \pi$ is excluded at 90% C.L.
 - Allowed 90% C.L. regions: $[-3.13, 0.39]$ (NH), $[-2.09, -0.74]$ (IH)

Similar results from NOvA

Flagship long-baseline oscillation programme: Future

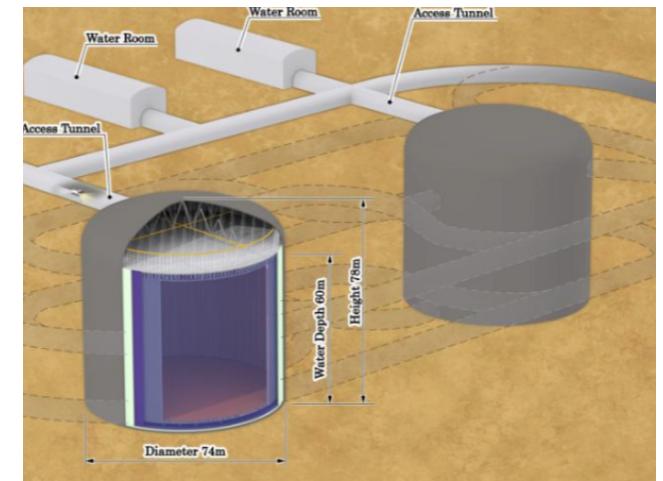


DUNE:

- New **wide-band** $\nu_\mu/\bar{\nu}_\mu$ beam at FNAL pointing towards SURF (**1300 km** away)
 - 1.2 MW protons from PIP-II by 2026.
 - Upgradeable to **2.4 MW by 2030!**
- **40-kt fiducial mass LAr TPC** located deep underground at SURF **4850-ft** level
 - first 10-kt module deployed in 2024!
- **High-resolution/fine-grained near detector**

HyperK:

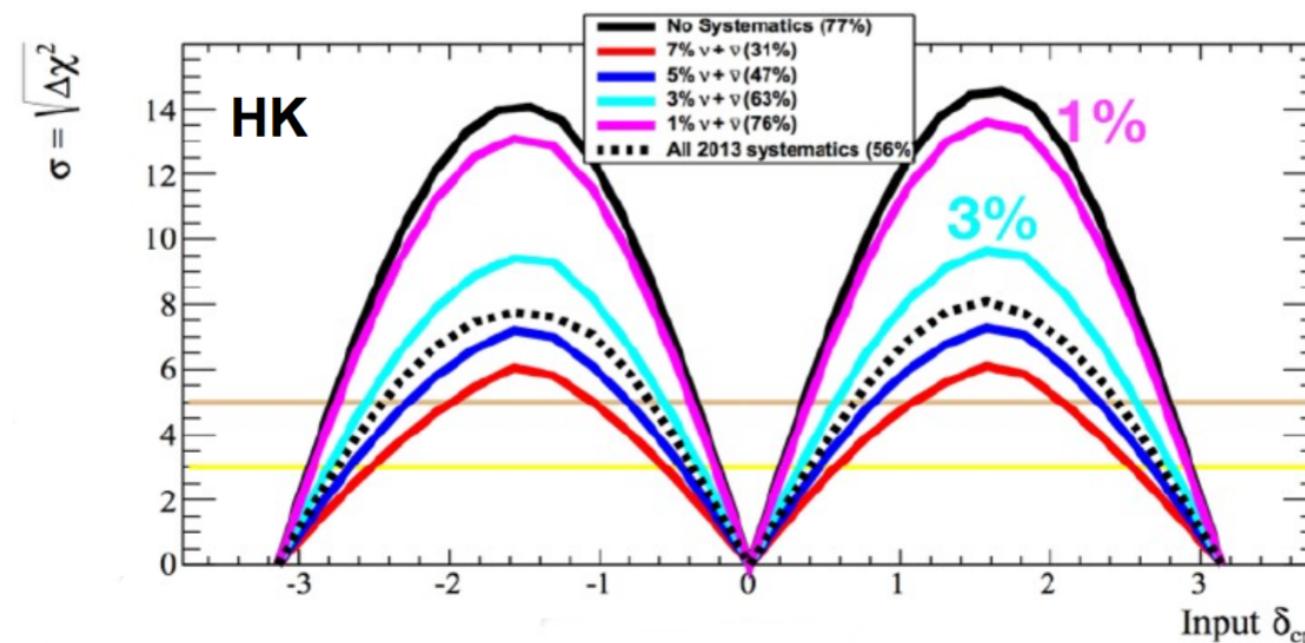
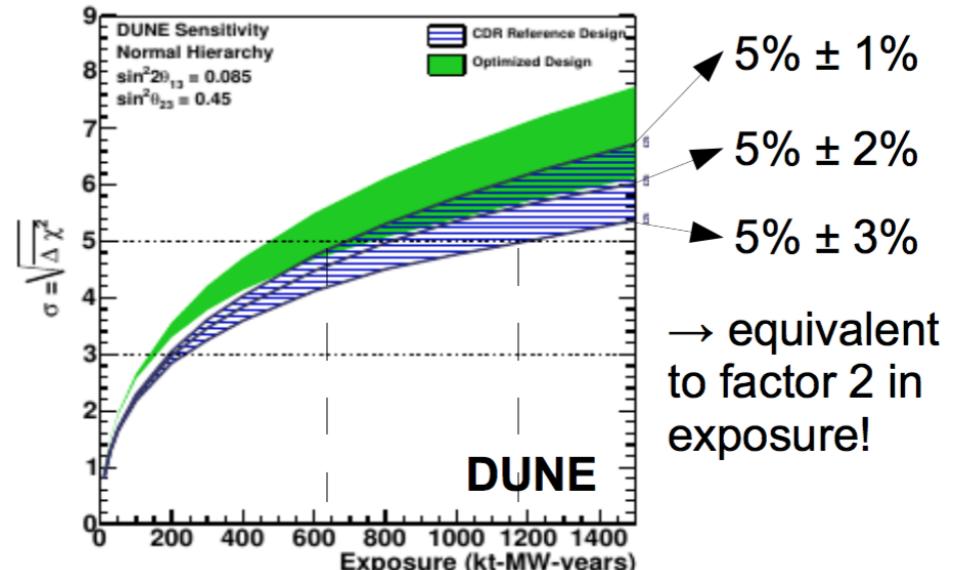
- Upgraded narrow-band $\nu_\mu/\bar{\nu}_\mu$ beam from the 30-GeV proton beam at J-PARC, reaching power of > 1.3 MW.
- Upgraded near detector at 280 m and new intermediate WCkv detector at 1-2 km to constrain systematics.
- New 0.52 Mt (0.38 Mton fiducial) WCkv detector, 2.5° off-axis, 295 km away, instrumented with 80k PMTs (40% photo-coverage)



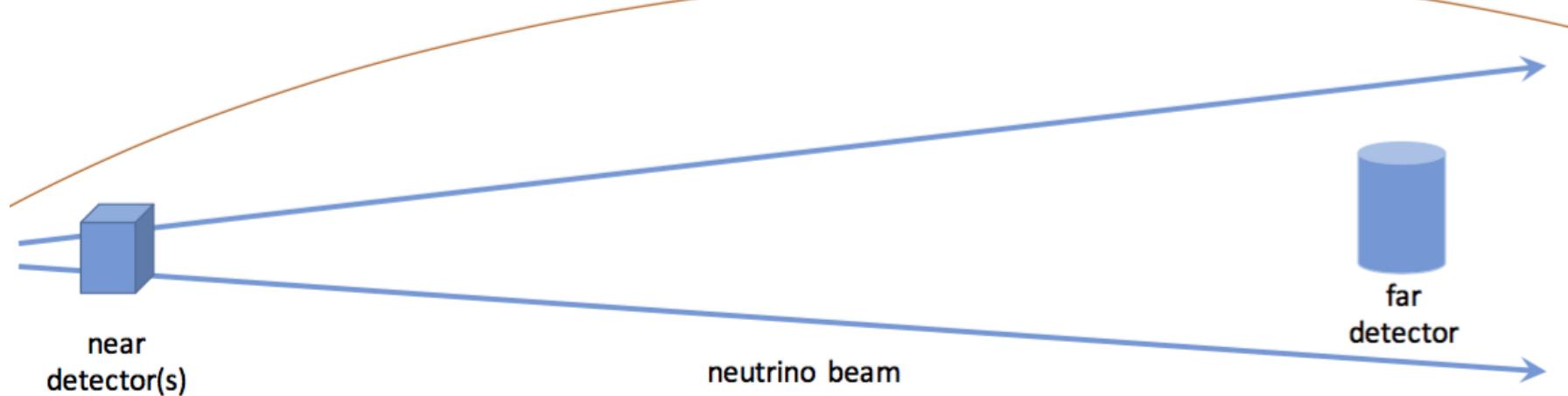
Controlling systematics

It is aimed that this new generation of LBL neutrino oscillation experiments (DUNE, HyperK) will be taking first beam data at 2026!!

Control of systematic uncertainties to 1% level is required.



Extrapolation from Near to Far Detector



Near to Far extrapolation:

- Provides data-driven estimate of unoscillated event rate at the Far detector.
- Influenced by uncertainties in the knowledge of flux and cross-sections.

Extrapolation from Near to Far Detector

The mantra of an LBL experiment is that reliance on models is limited by using 2 "functionally identical" detectors (Near and Far).

Very schematically, the event rate at the Far and Near detector is given by:

$$N_{\nu_\mu; \text{Far}}(E_\nu) \propto \epsilon_{\nu_\mu; \text{Far}}(E_\nu) \times \Phi_{\nu_\mu; \text{Far}}(E_\nu) \times \sigma_{\nu_\mu}(E_\nu, A) \times P_{\nu_\mu \rightarrow \nu_\mu}(E_\nu)$$

$$N_{\nu_\mu; \text{Near}}(E_\nu) \propto \epsilon_{\nu_\mu; \text{Near}}(E_\nu) \times \Phi_{\nu_\mu; \text{Near}}(E_\nu) \times \sigma_{\nu_\mu}(E_\nu, A)$$

Therefore, for functionally identical detectors ($\epsilon_{\nu_\mu; \text{Far}}(E_\nu) \approx \epsilon_{\nu_\mu; \text{Near}}(E_\nu)$) with a nuclear target of the same atomic mass A:

$$N_{\nu_\mu; \text{Far}}(E_\nu) \propto N_{\nu_\mu; \text{Near}}(E_\nu) \times \frac{\Phi_{\text{Far}}(E_\nu)}{\Phi_{\text{Near}}(E_\nu)} \times P_{\nu_\mu \rightarrow \nu_\mu}(E_\nu)$$

Cancelled detector efficiency and cross-section errors. Flux information enters in a ratio, so only the uncorrelated Far/Near uncertainty plays a role.

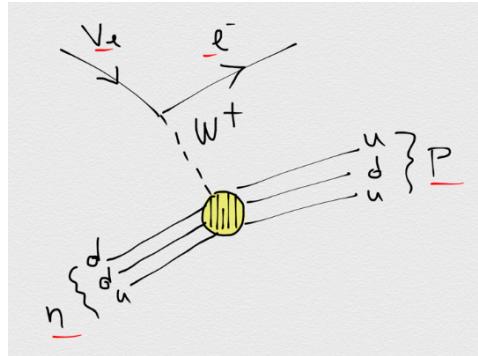
Reliance on models

In practise, the situation is **substantially more complicated**:

- There is no such thing as "functionally identical" detectors
 - Near detector closer to source and at shallower depth
 - Sees different and more substantial beam-related backgrounds
 - Sees a substantially different flux (line source vs point source)
 - High rate in the Near hall can necessitate different technology
 - Uncorrelated detector systematics between Near and Far detectors
 - Different acceptance from the Far (usually 4π) detector
 - Unconstrained part of the phase space at the Far detector
 - Different nuclear targets
 - Unconstrained nuclear effects at the Far detector
- The true neutrino energy is not known on an event-by-event basis
 - The true neutrino energy comes from a (usually broad) distribution
 - The mapping between the true and reconstructed energy is driven by detailed event characteristics (ID and momentum of all f/s particles)
 - Complex detector response/acceptance for each f/s.

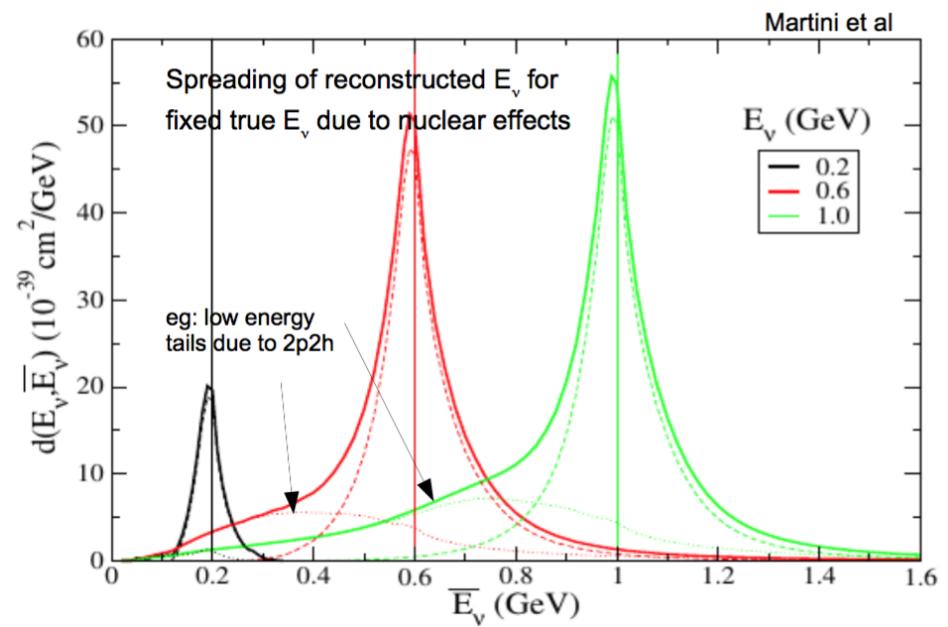
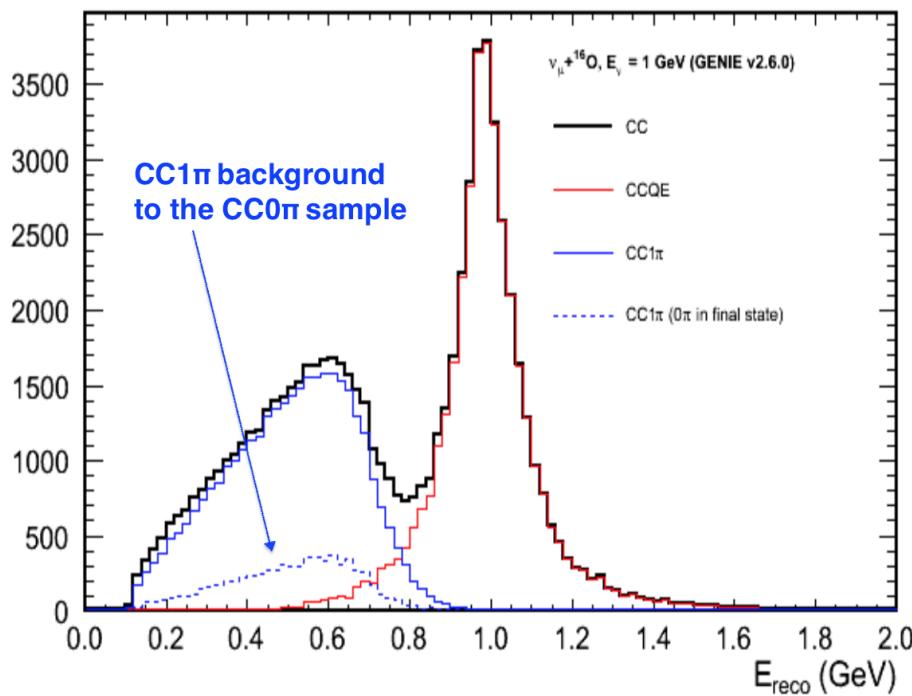
It is **impossible to avoid reliance on models**.

Reliance on models: Neutrino energy reconstruction

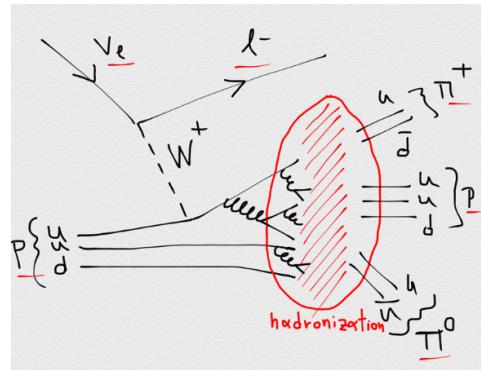


Reconstruction based on **2-body kinematics** for QE-enhanced samples

$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\ell^2 + 2(m_n - E_b)E_\ell}{2(m_n - E_b - E_\ell + p_\ell \cos\theta_\ell)}$$

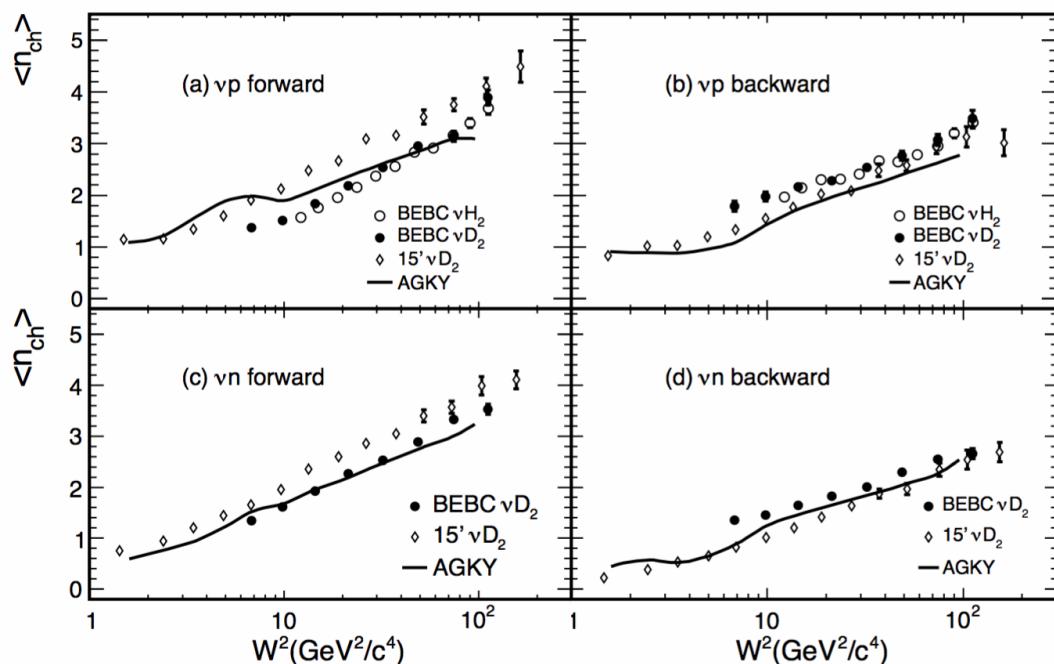


Reliance on models: Neutrino energy reconstruction

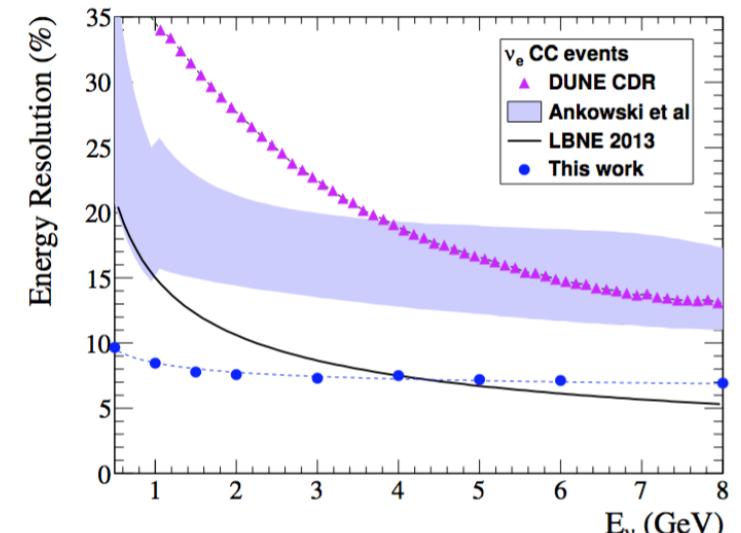


Calorimetric approach to energy reconstruction:

$$E_\nu = E_{\text{leptonic}} + E_{\text{hadronic}}$$



[Eur. Phys. J. C63:1-10, 2009]



[arXiv:1607.00293]

Neutrino MC Generators: A Theory/Experiment Interface

Model dependence encapsulated in comprehensive Neutrino MC Generators



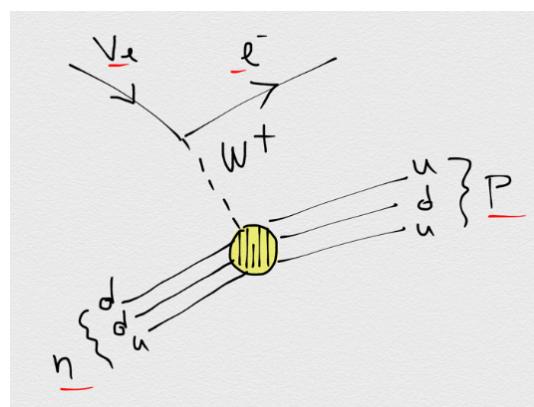
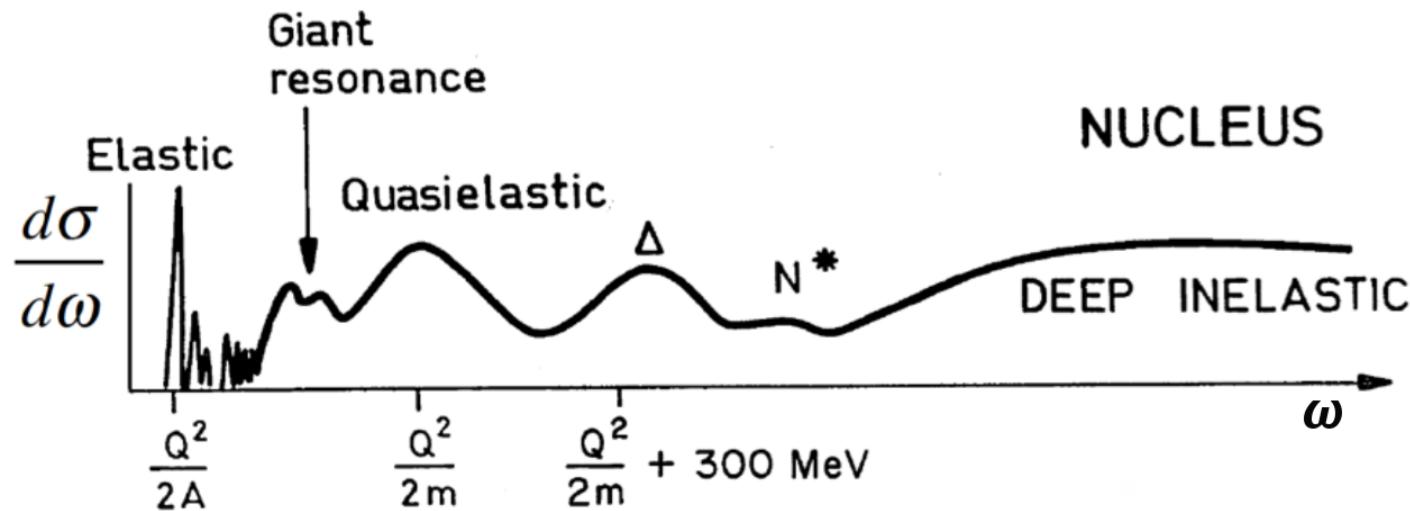
Neutrino MC Generators connect the true and observed event topologies and kinematics.

Every observable is a convolution of flux, interaction physics and detector effects. Neutrino MC Generators allow experimentalists to access, improve, validate, assess the uncertainty of and tune the *physics* models that drive the result of that convolution.

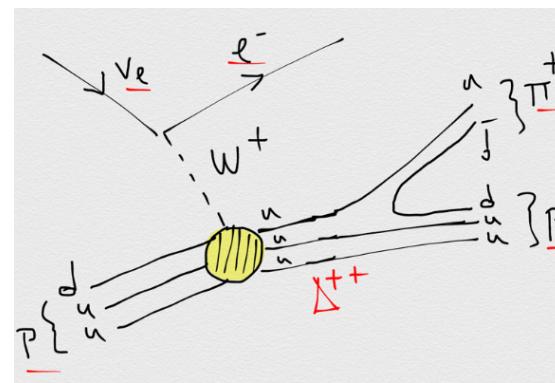
Several such MC Generators in use: **GENIE**, **NuWro**, **NEUT**

Scattering mechanisms at the few-GeV energy range

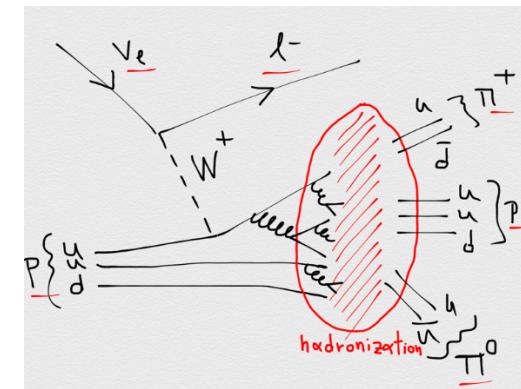
Broad energy range: Several scattering mechanisms are important.



QE



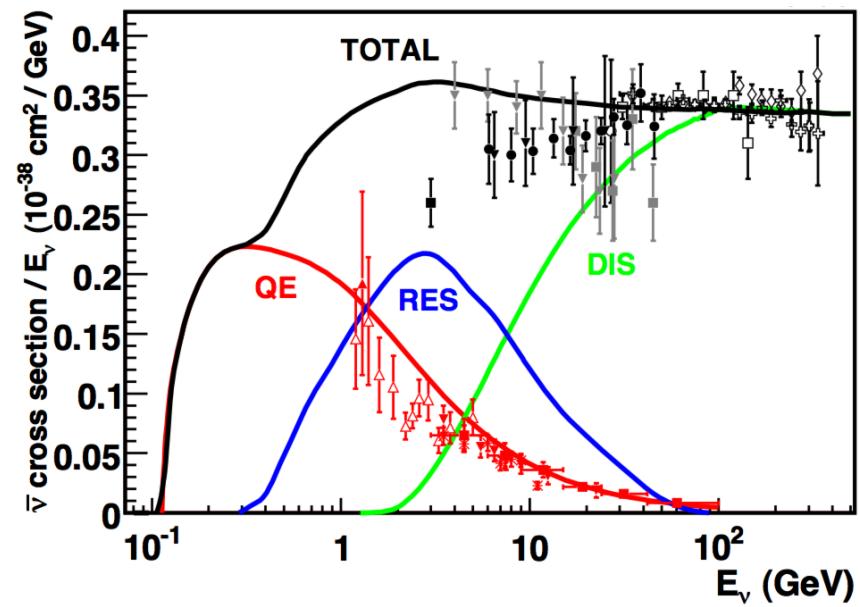
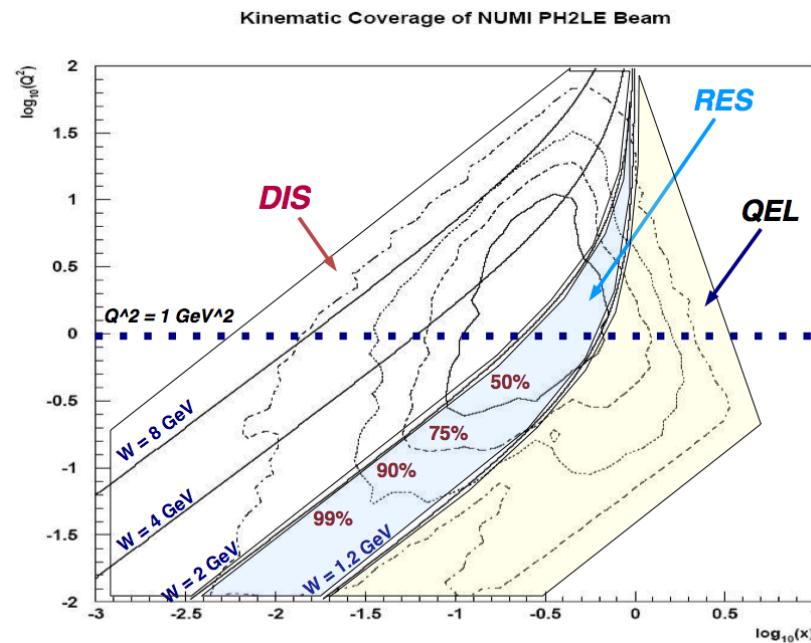
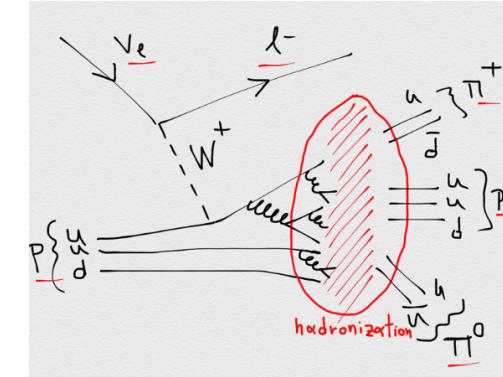
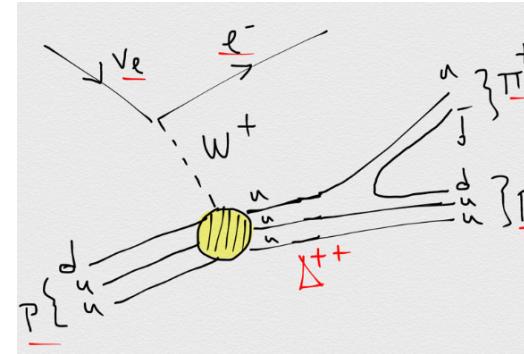
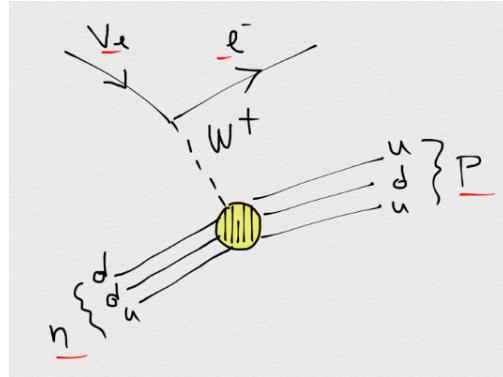
Δ



DIS

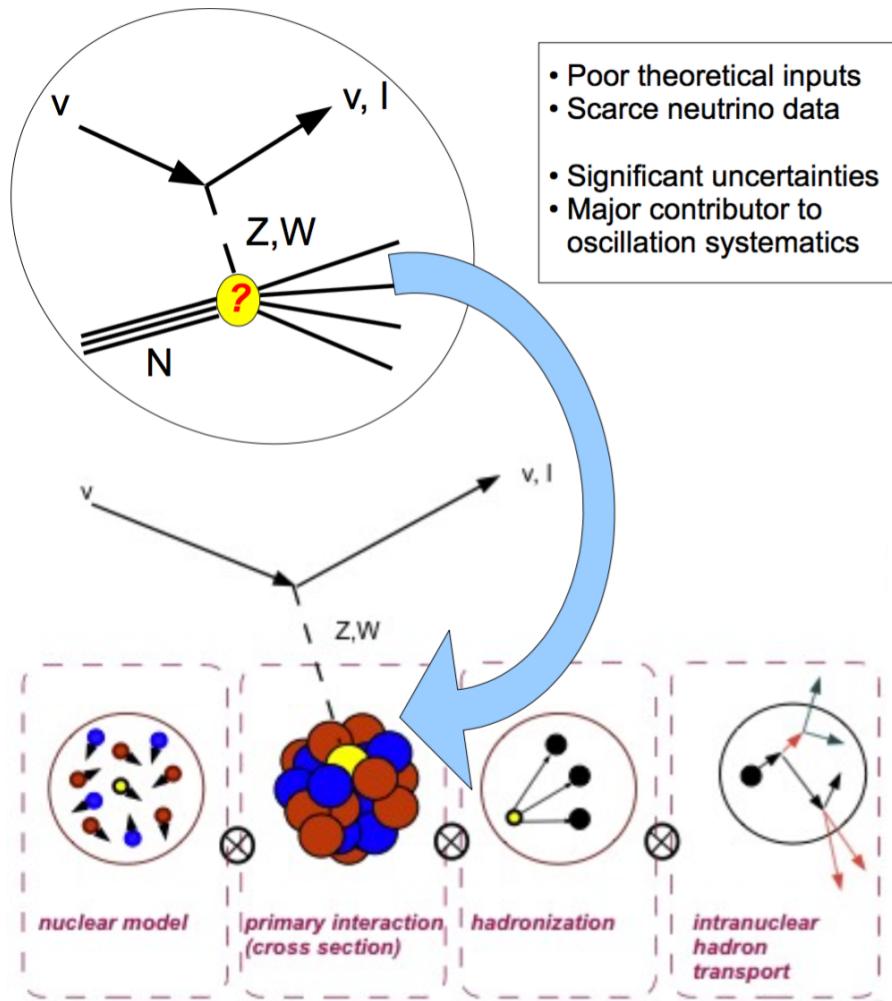
Scattering mechanisms at the few-GeV energy range

Broad energy range: Several scattering mechanisms are important.



Neutrino MC Generator factorization

Cross-section calculation at the **neutrino - nucleon level** a starting point.



The nucleon is not a simple object!

Process dynamics described by the invariant amplitude $|M|^2 = L_{\mu\nu} W^{\mu\nu}$
where:

$$W_{\mu\nu} = W_1 \delta_{\mu\nu} + W_2 p_\mu p_\nu + W_3 \epsilon_{\mu\nu\alpha\beta} p^\alpha p^\beta + \\ + W_4 q_\mu q_\nu + W_5 (p_\mu q_\nu + p_\nu q_\mu) + W_6 (p_\mu q_\nu - p_\nu q_\mu)$$

Issue: Knowledge of W_1, W_2, \dots in a kinematical regime that bridges the non-perturbative and perturbative pictures of the nucleon.

Neutrino-nucleus simulations by adding effects:

- the initial nuclear state dynamics
- hadronization
- intranuclear hadron transport

Key measurements needed

All **comprehensive models** to date are **primarily empirical ones**:

- Using theoretical inputs for simulating specific processes at specific parts of the kinematical phase space (where models are valid),
- but using empirical approaches to:
 - extrapolate in other kinematical regions, and
 - handle double-counting.
- Many built-in measurements (directly, or indirectly via tuning)
 - including several measurements from electron and hadron scattering off nucleons and nuclei

For validation and tuning, require key measurements:

- A dependence of cross-section and nuclear effects
- Differences between ν_e/ν_μ and $\bar{\nu}/\nu$
- Inclusive and low-multiplicity exclusive cross-sections in the **full kinematical space**, and correlations amongst samples.
- Low-multiplicity data subdivided by vertex activity to constrain nuclear effects, especially effects affecting energy reconstruction.
- CC and NC hadronic shower characteristics, affecting energy reconstruction and event ID.

Modern experiments and recent and measurements

Many experimental approaches and detection techniques (mineral oil Cerenkov, totally active solid or liquid scintillator, scintillator/steel sandwich, gas TPCs, liquid Argon TPCs, emulsion)

- **Booster neutrino beam**
 - MiniBooNE
 - SciBooNE
 - MicroBooNE
- **NuMI neutrino beam**
 - MINOS ND
 - ArgoNEUT
 - MINERvA
 - NOvA ND
- **J-PARC neutrino beam**
 - T2K INGRID on-axis ND
 - T2K ND280 off-axis ND
 - T60 emulsion experiment

Mainly measurements of:

- CC inclusive
- CC 0π
- CC $1\pi^+$
- CC $1\pi^0$
- CC coherent π^\pm
- NC elastic
- NC $1\pi^0$
- NC coherent $1\pi^0$

Note: Marked improvent in the analysis methodology, attempting to unfold experimental effects and limit model dependencies.

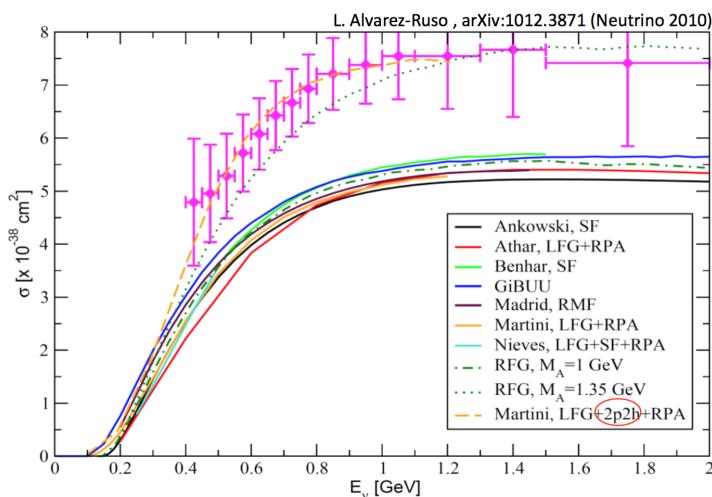
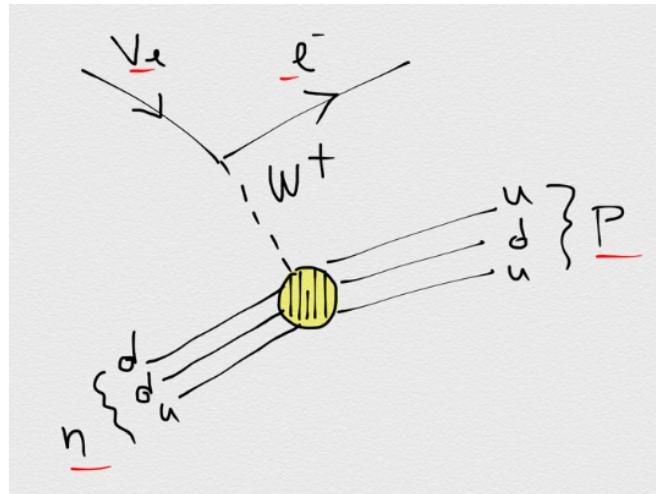
Present experimental status glimpsed through two puzzles:



- the "Quasielastic (QE) puzzle"
- the "Single-pion puzzle"

The QE puzzle

- QE: A **golden channel** for oscillation searches at T2K/HK.
- 2-body kinematics: E_ν reconstruction from lepton momentum/angle.



T2K 1-ring e-like candidates in ν mode:

	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$	Osc. ν_e	Osc. $\bar{\nu}_e$	Total
CCQE	0.056	2.129	0.001	0.088	15.875	0.099	18.249
CC1pi	0.016	0.348	0.000	0.027	1.688	0.017	2.096
CCcoherent	0.000	0.002	0.000	0.002	0.015	0.002	0.021
2p-2h	0.008	0.710	0.000	0.022	3.901	0.019	4.659
CCother	0.001	0.045	0.000	0.003	0.029	0.001	0.080
NC1pi0	0.524	0.012	0.017	0.001	N/A	N/A	0.553
NC1piPM	0.099	0.002	0.003	0.000	N/A	N/A	0.105
NCcoherent	0.174	0.004	0.018	0.001	N/A	N/A	0.197
NCother	0.126	0.005	0.008	0.001	N/A	N/A	0.139
NC1gamma	0.464	0.007	0.021	0.001	N/A	N/A	0.494
Total	1.469	3.264	0.069	0.145	21.508	0.138	26.594

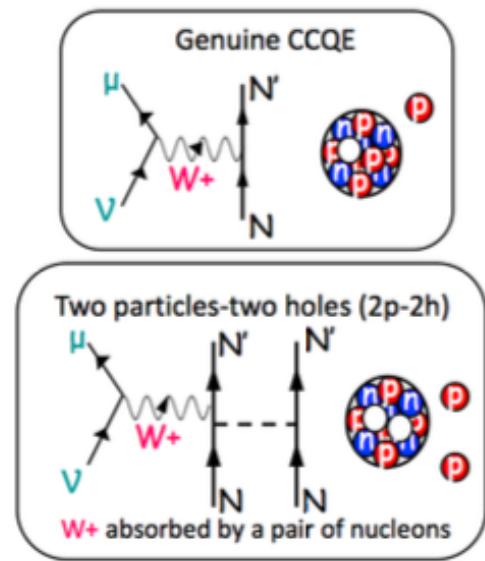
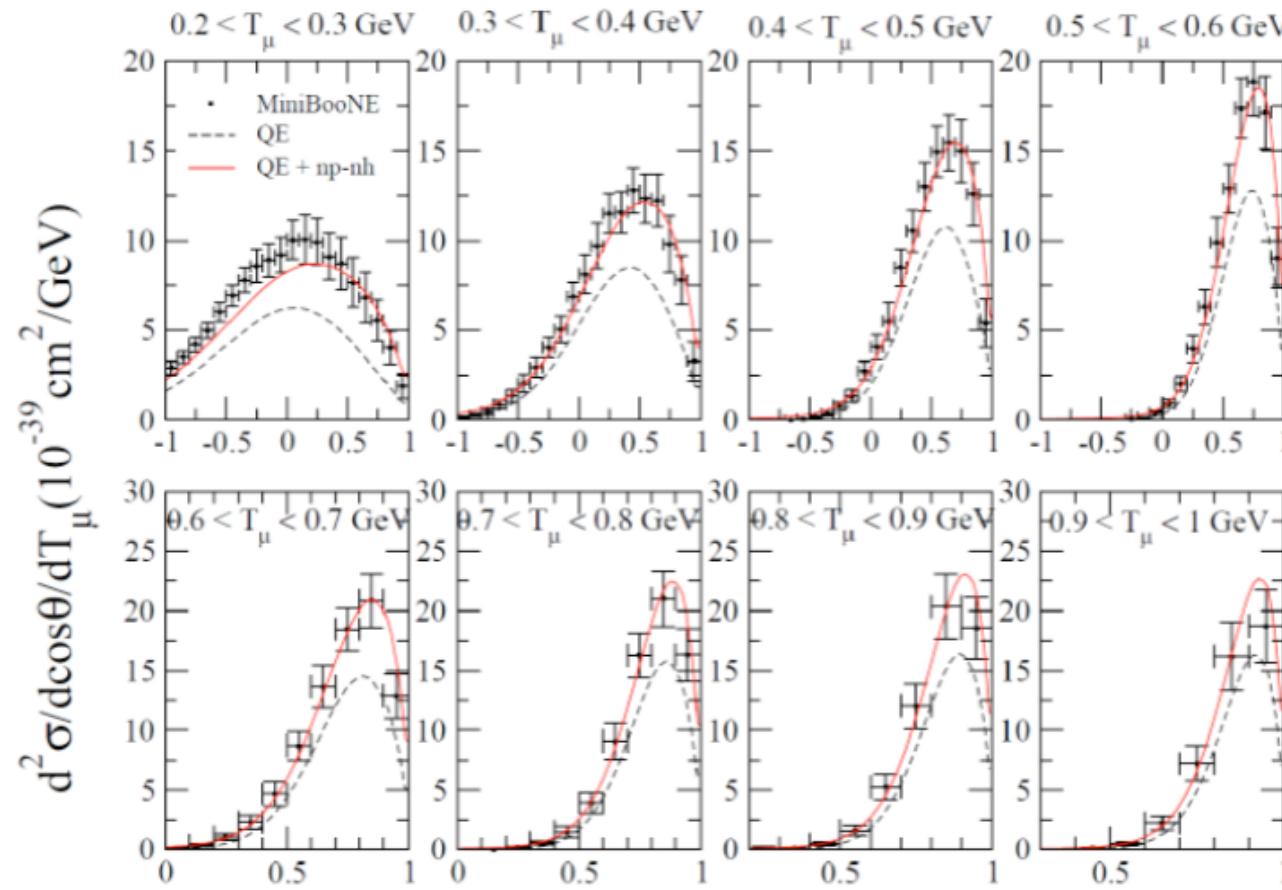
On single nucleons, this process is **theoretically understood and well constrained** by experimental information from

- electron scattering, neutron β decay, and
- ν experiments on Hydrogen/Deuterium.

Unable to describe nuclear QE-like data with models based on interactions on single nucleons alone.

The QE puzzle: Two-nucleon interactions

The observed discrepancy revealed the **importance of two-nucleon interactions**. This was further stressed by ab-initio calculations of nuclear response functions.



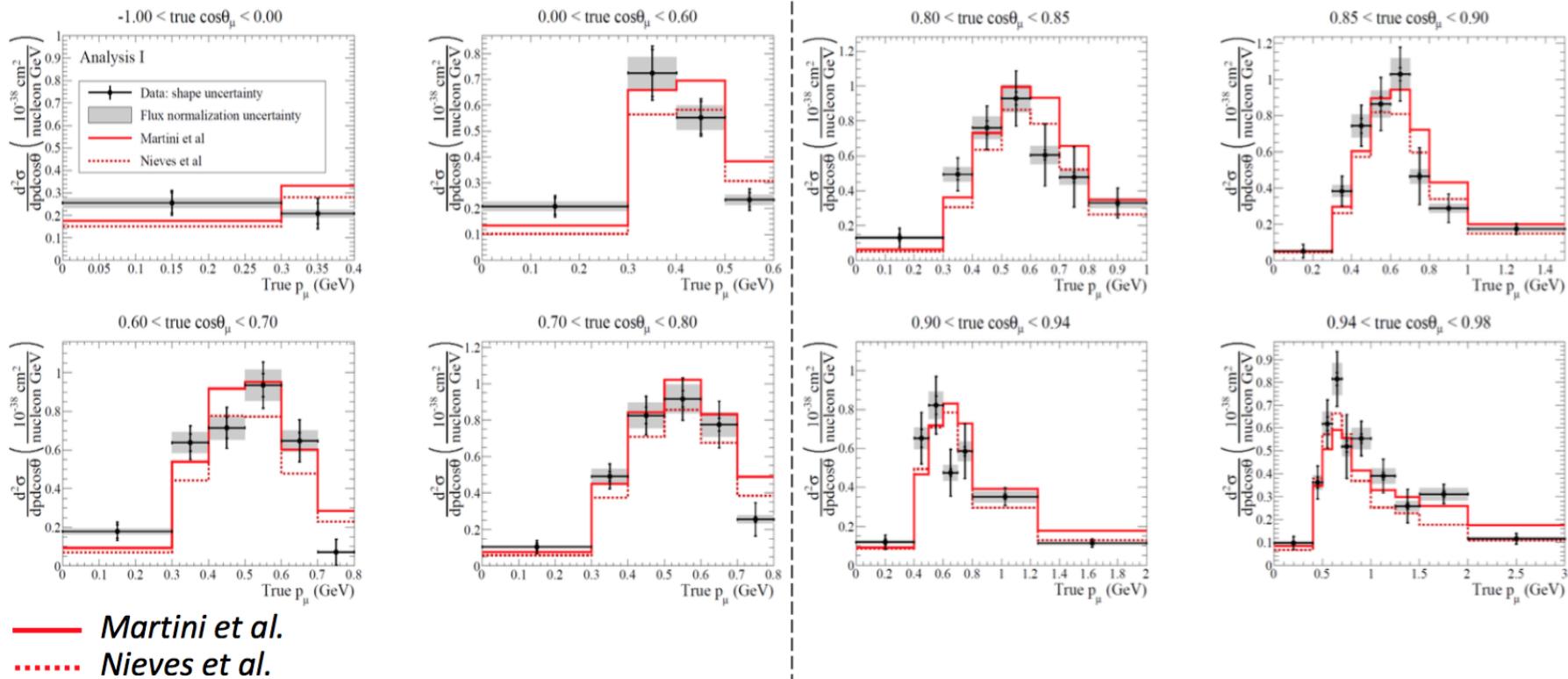
Meson exchange between
two bound nucleons
(e.g through virtual Δ or
contact term).

[Martini et al. PRC 84 055502 (2011)]; MiniBooNE data shown

The QE puzzle: Two-nucleon interactions

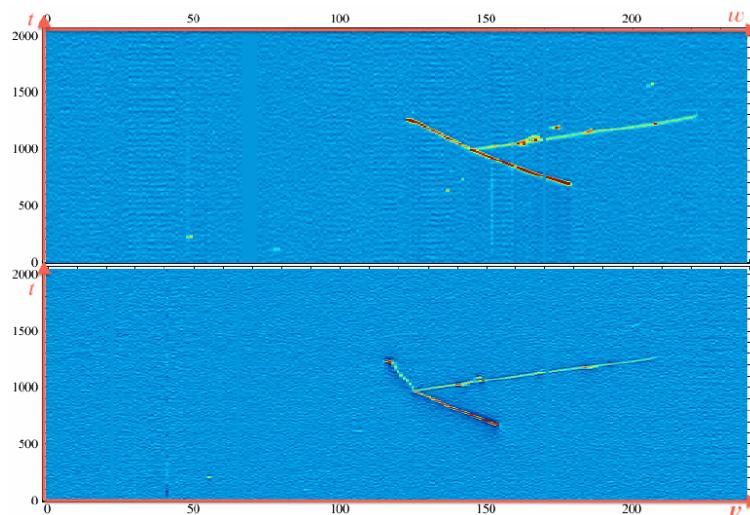
Recent CC0 π measurements from T2K in agreement with theoretical models including 2p2h.

T2K collaboration: Abe et al. Phys. Rev. D 93 11012 (2016)

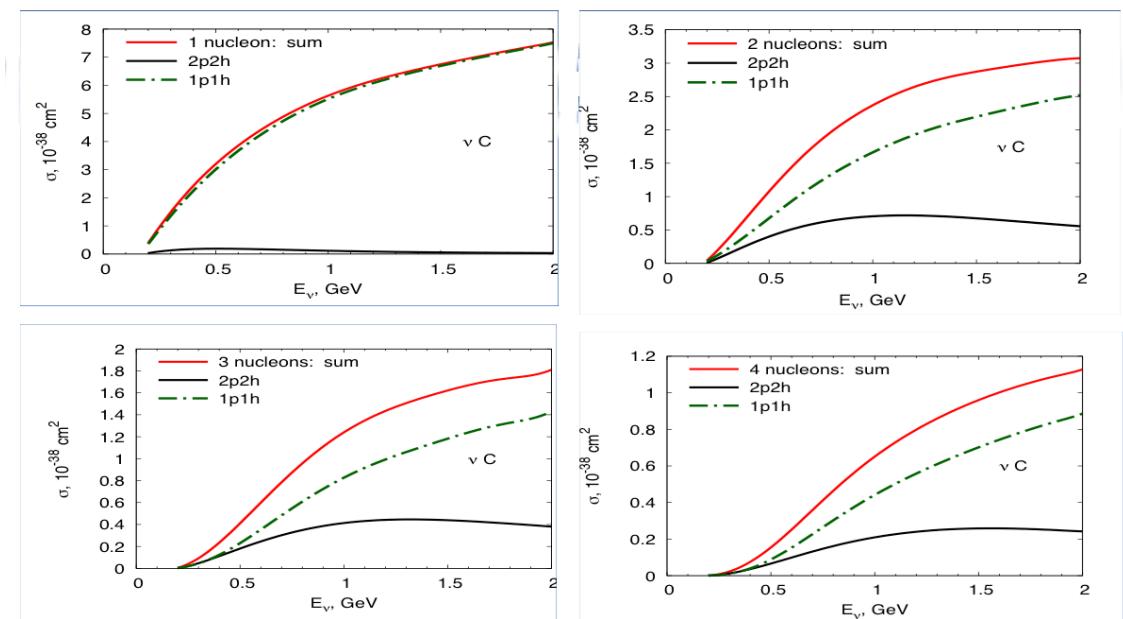


The QE puzzle: Identifying 2p2h events

- Characteristic events with 2 back-to-back f/s nucleons seen in ArgoNEUT.
- *"Avalanching shadows the initial reaction"* [U. Mosel]
- Future data from LarTPCs (or, better, gas TPCs) CC $\bar{\nu}\pi$ events subdivided based on nucleon multiplicity crucial for disentangling FSI and 2p2h effects.

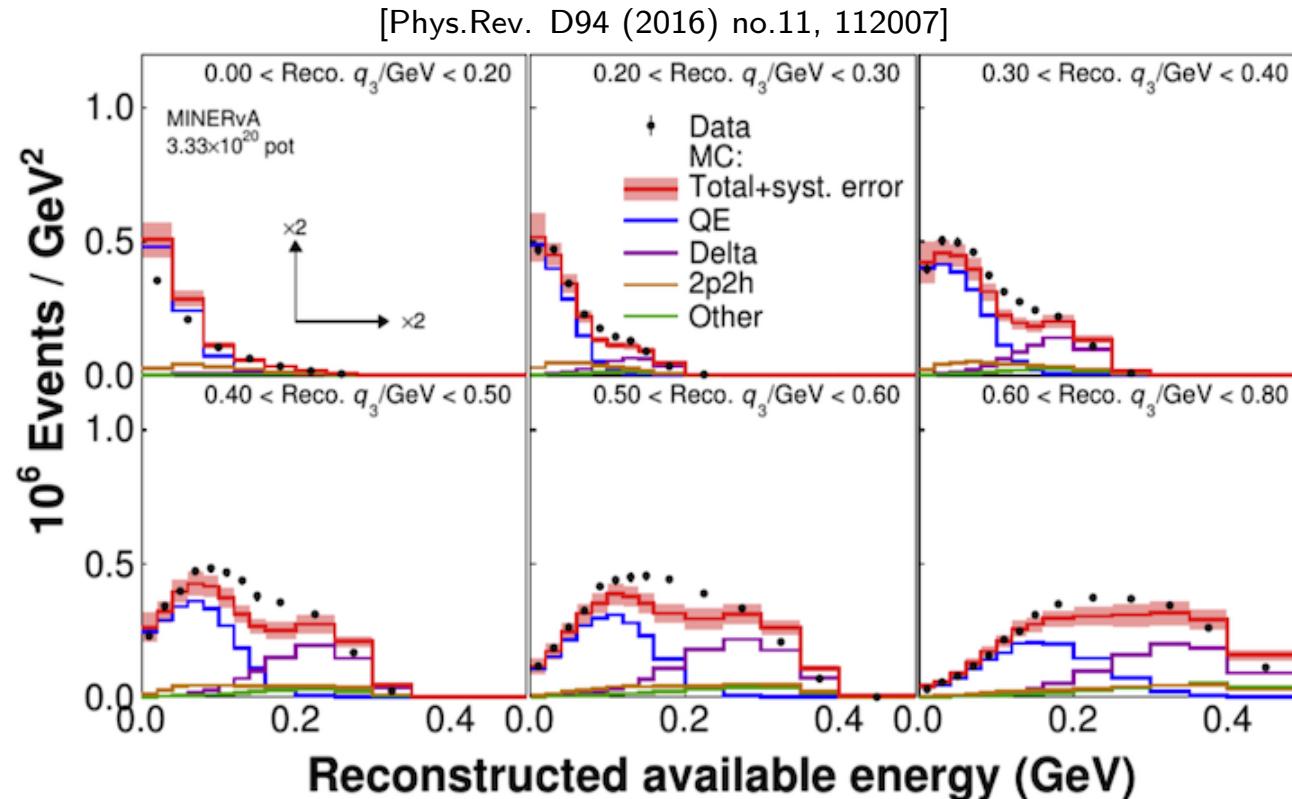


[Phys. Rev. D90 (2014) 1, 012008]



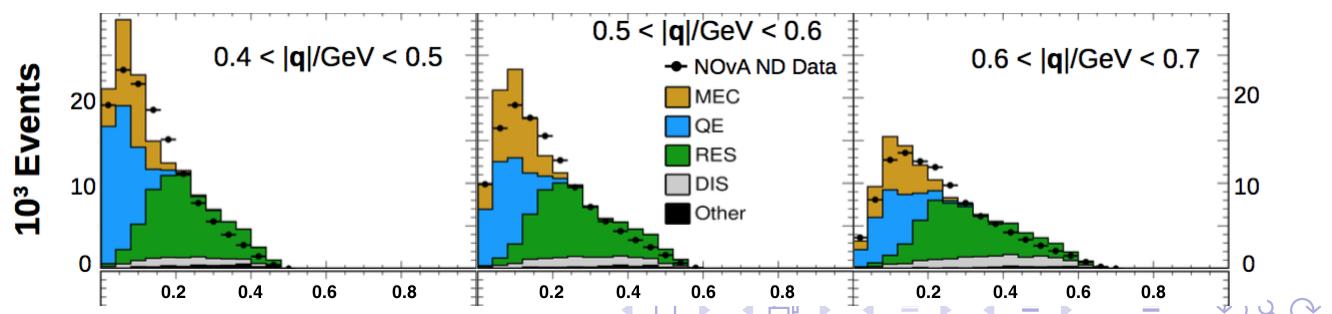
Ulrich Mosel

Resolving the QE puzzle: A new approach



New approach by MINERvA:
Inclusive ν_μ CC data in $(q_0, |\vec{q}_3|)$ space.
Exploiting the different kinematical dependency of each component to disentangle 2p2h.

Similar approach by NOvA.
[Phys.Rev. D93 (2016) no.7, 071101]

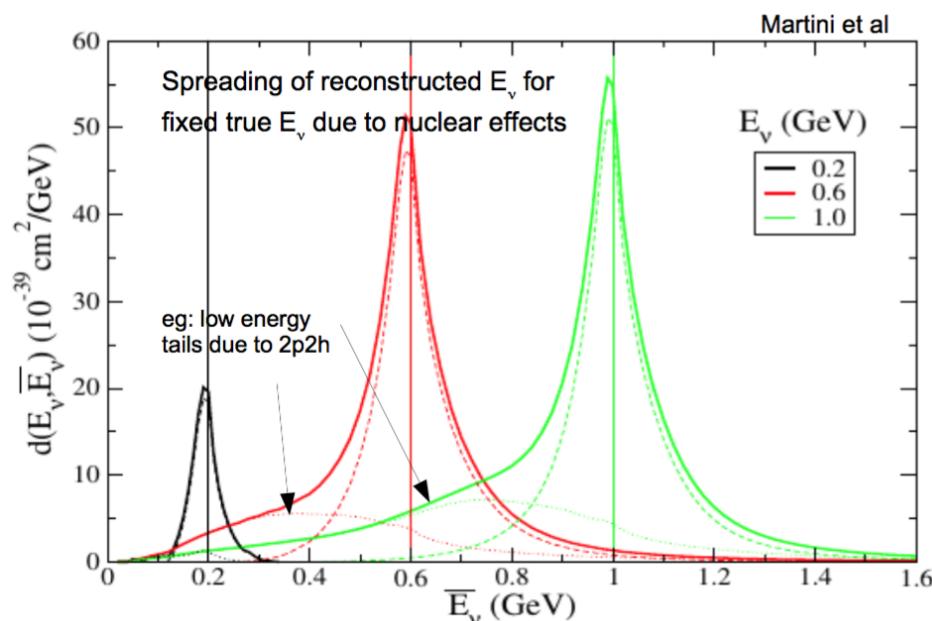


Resolving the QE puzzle: Why is this important?

Effective models (e.g. inflated axial mass) give reasonably good phenomenological description. Why is it important to understand the micro-physics?

Energy reconstruction

1p1h/2p2h mixture drives the mapping between true and reconstructed energy!



CP sensitivity

Large measured θ_{13} , yields large ν_e and $\bar{\nu}_e$ appearance rate, but smaller CP asymmetry (*). Appearance **signal systematics** important. Models predict differ in $\nu/\bar{\nu}$ 2p2h.

$$\begin{aligned} \frac{\partial^2 \sigma}{\partial \Omega \partial k'} &= \frac{G_F^2 \cos^2 \theta_c (\mathbf{k}')^2}{2 \pi^2} \cos^2 \frac{\theta}{2} \left[G_E^2 \left(\frac{q_\mu^2}{\mathbf{q}^2} \right)^2 R_{\tau}^{NN} \right. \\ &+ G_A^2 \frac{(M_\Delta - M_N)^2}{2 \mathbf{q}^2} \left. R_{\sigma\tau(L)} \right] \\ &+ \left(G_M^2 \frac{\omega^2}{\mathbf{q}^2} + G_A^2 \right) \left(-\frac{q_\mu^2}{\mathbf{q}^2} + 2 \tan^2 \frac{\theta}{2} \right) \left. R_{\sigma\tau(T)} \right] \\ &\pm 2 G_A G_M \frac{k + k'}{M_N} \tan^2 \frac{\theta}{2} \left. R_{\sigma\tau(T)} \right] \end{aligned}$$

M. Martini, M. Ericson, G. Chanfray, J. Marteau

Contribution to all terms in \mathcal{G}_+ and \mathcal{G}_-

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas et al.

J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly et al.

to all the terms

only to the C_3 term.

Relative role of 2p-2h for neutrinos and antineutrinos is different

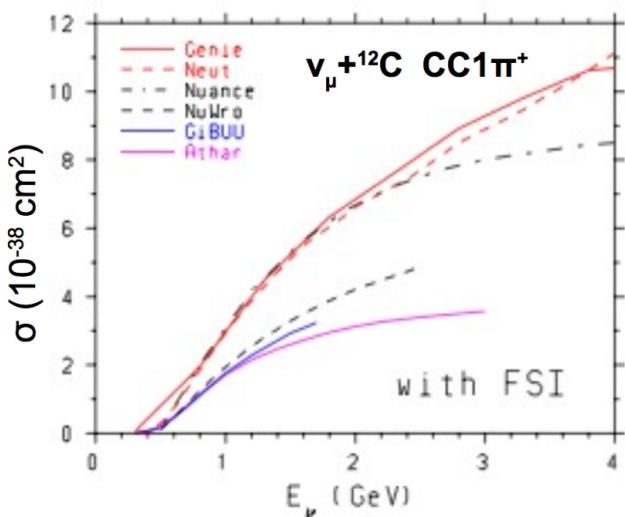
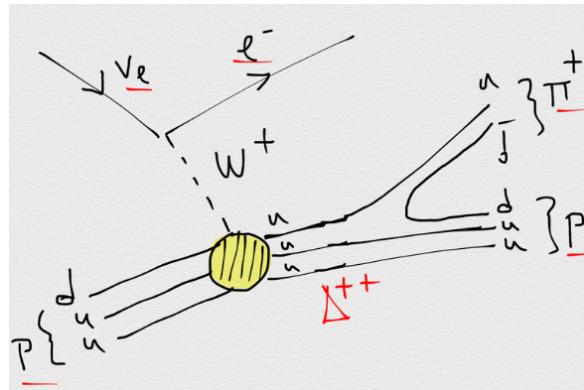
[Martini, INT 2013, Seattle]

$$(*) \quad A_{CP} \propto \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \sin \delta_{CP}$$

Single- π production

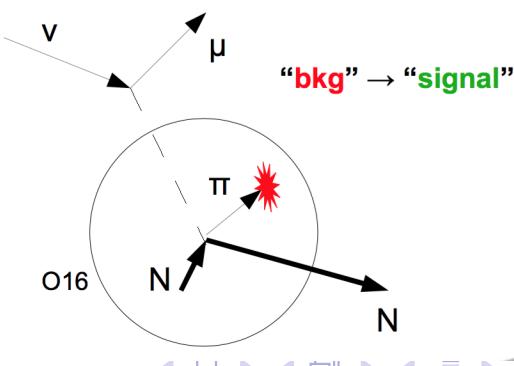
Dominant process in the region of transition from the non-perturbative to perturbative regime.
Important process for oscillation physics (both as a signal and background).

- In DUNE, resonance events contribute $\sim 30\%$ to the CC inclusive rate.
- In T2K/HyperK, single-pion events can mimic single-ring (QE-enhanced) signal events
- NC1 π^0 an important background for $\nu_e/\bar{\nu}_e$ appearance



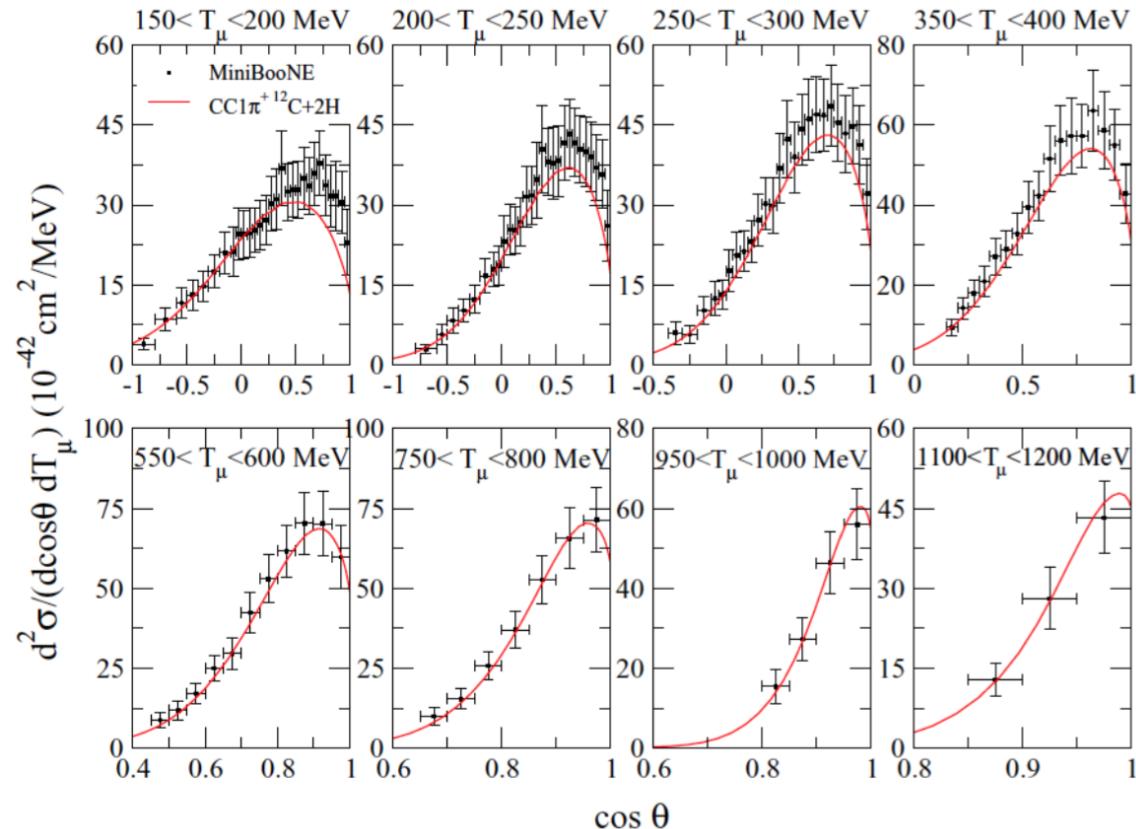
Number of T2K μ -like single-ring events to date
in the neutrino beam mode (FHC):

	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$	Osc. ν_e	Osc. $\bar{\nu}_e$	Total
CCQE	71.194	0.037	4.620	0.002	0.190	0.002	76.045
CC1pi	18.214	0.019	1.686	0.001	0.061	0.001	19.981
CCcoherent	0.351	0.000	0.086	0.000	0.001	0.000	0.438
MEC	20.442	0.011	0.910	0.000	0.045	0.000	21.408
CCother	8.340	0.009	0.533	0.001	0.002	0.000	8.885
NC1pi0	0.580	0.018	0.019	0.001	N/A	N/A	0.617
NC1piPM	4.253	0.096	0.153	0.009	N/A	N/A	4.511
NCcoherent	0.017	0.000	0.002	0.000	N/A	N/A	0.019
NCother	3.229	0.130	0.178	0.013	N/A	N/A	3.550
NC1gamma	0.004	0.000	0.000	0.000	N/A	N/A	0.004
Total	126.624	0.321	8.185	0.027	0.299	0.003	135.459



Single- π production

First recent (flux integrated double-differential) CC1 π^\pm (predominantly CC1 π^+) measurement was performed by MiniBooNE [Phys.Rev.D83, 052007 (2011)]

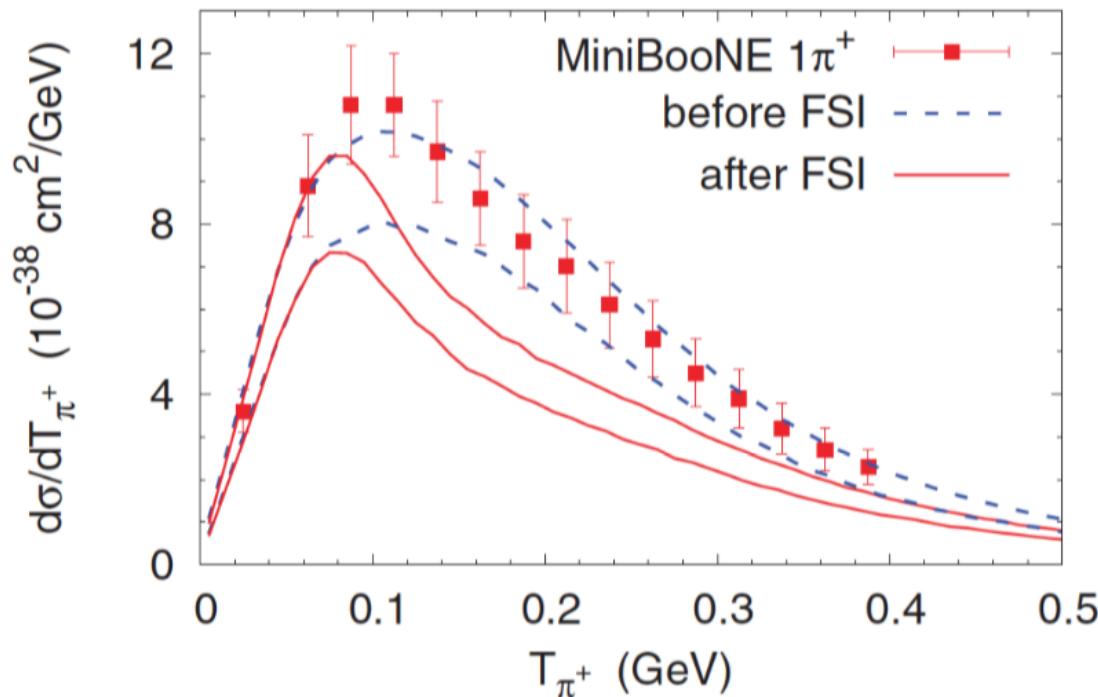


[Phys.Rev.C90,025501(2014)]

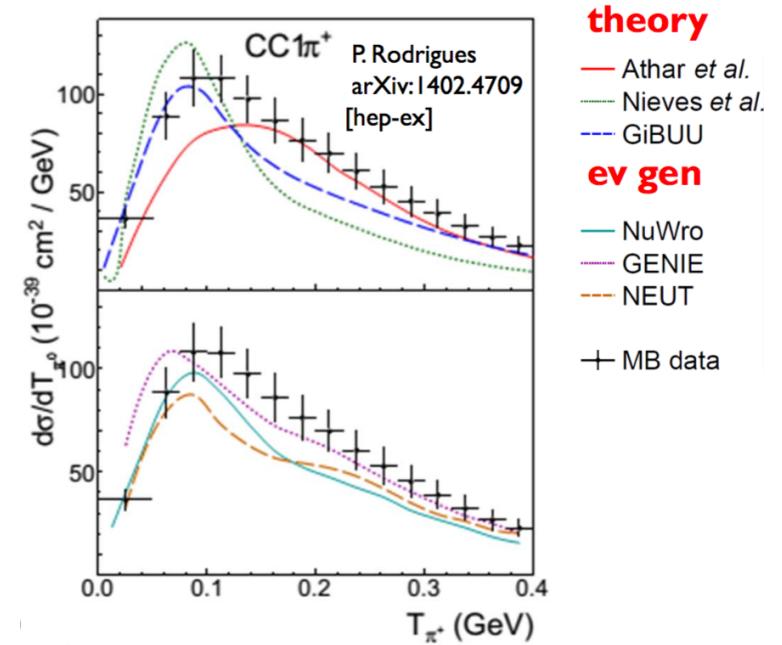
The single- π puzzle

But MiniBooNE data in terms of pion kinematics very hard to understand within any model.

Shape of MiniBooNE T_π distribution seems to prefer the absence of FSI effects!



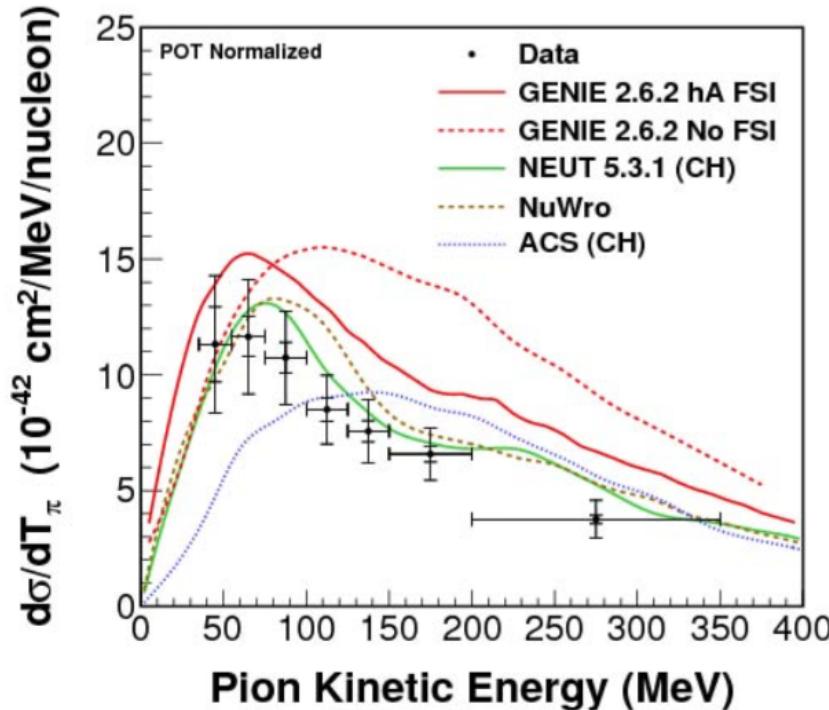
[Phys.Rev.C87, 014602 (2013)]



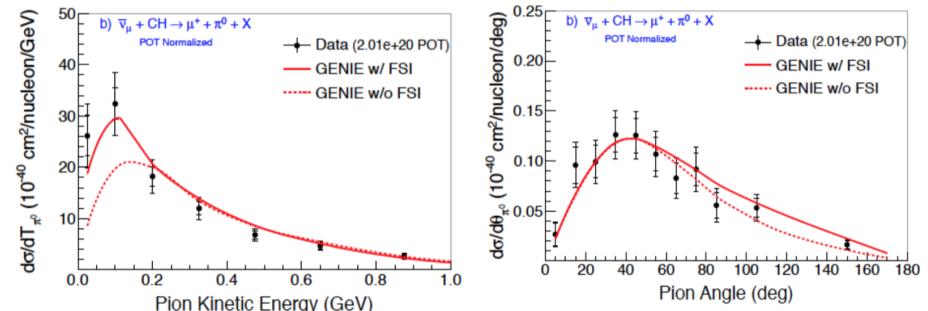
[arXiv:1402.4709 [hep-ex]]

The single- π puzzle

New neutrino CC1 π^+ and anti-neutrino CC1 π^0 measurements by MINERvA in CH, at higher energy than MiniBooNE.

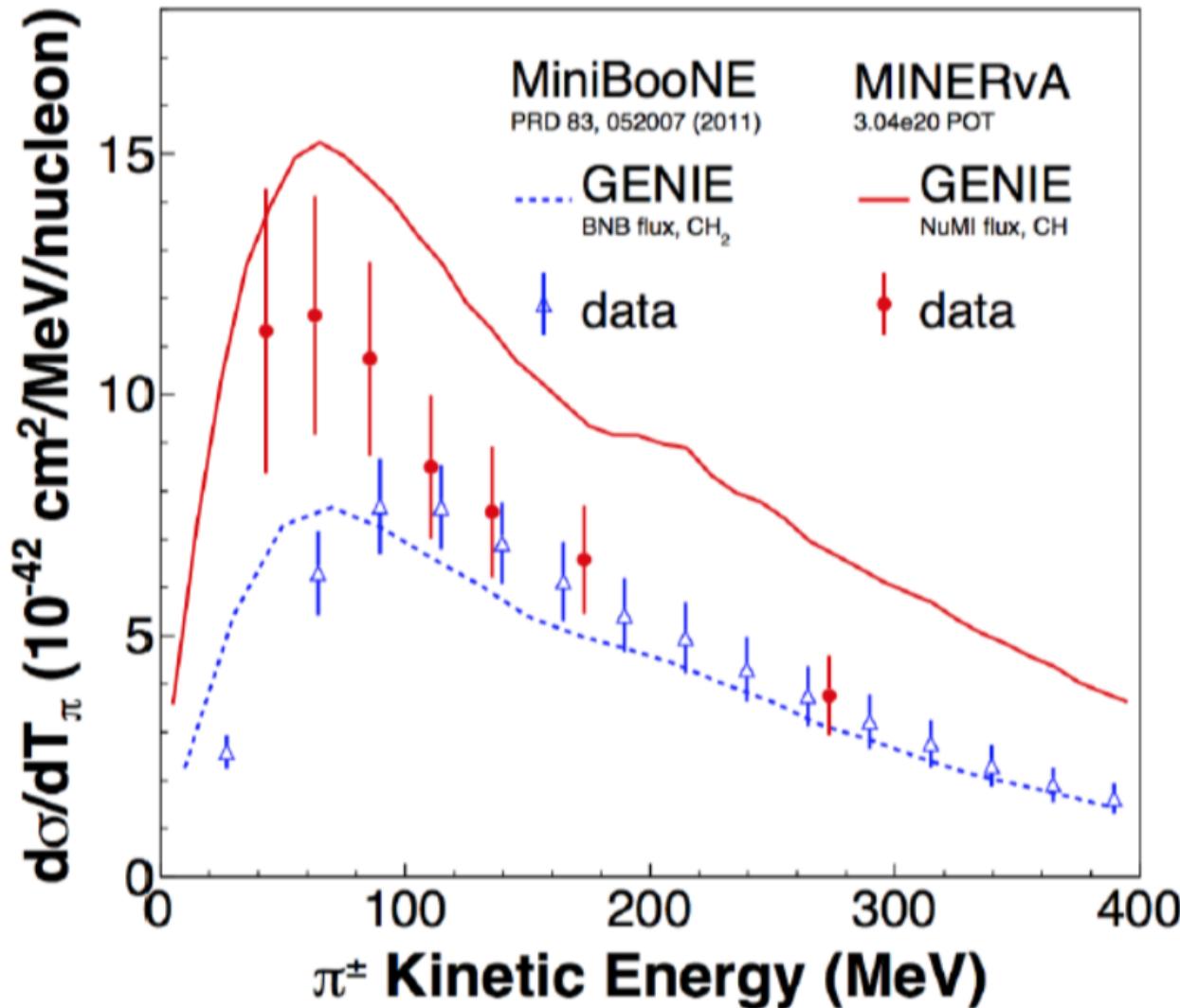


- Generator shape close to data
- As with MiniBooNE data, FSI strongly affects the prediction.
- Models with no FSI give wrong shape



[Phys.Rev.D92, 092008 (2015)]

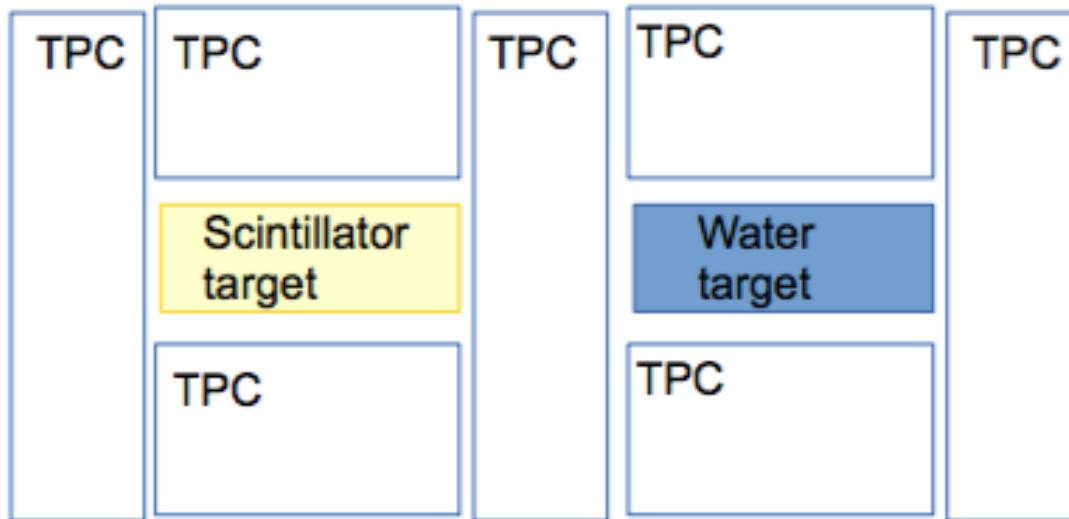
The single- π puzzle



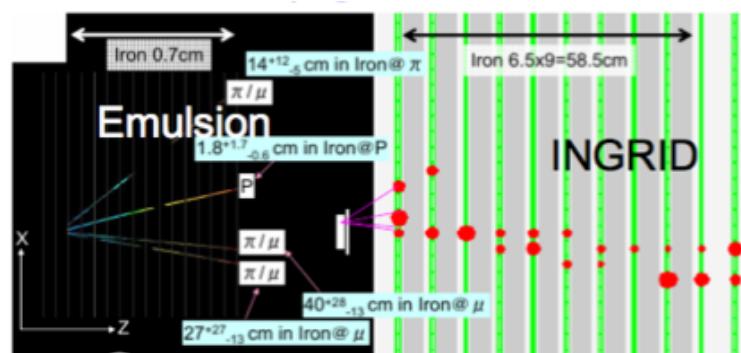
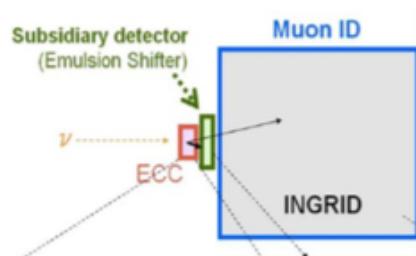
- Difficult to resolve the differences between MiniBooNE and MINERvA within our usual models.
- This tension between MiniBooNE and MINERvA data is not understood.

[Phys.Rev.D92, 092008 (2015)]

Near-future measurements @ the J-PARC beam

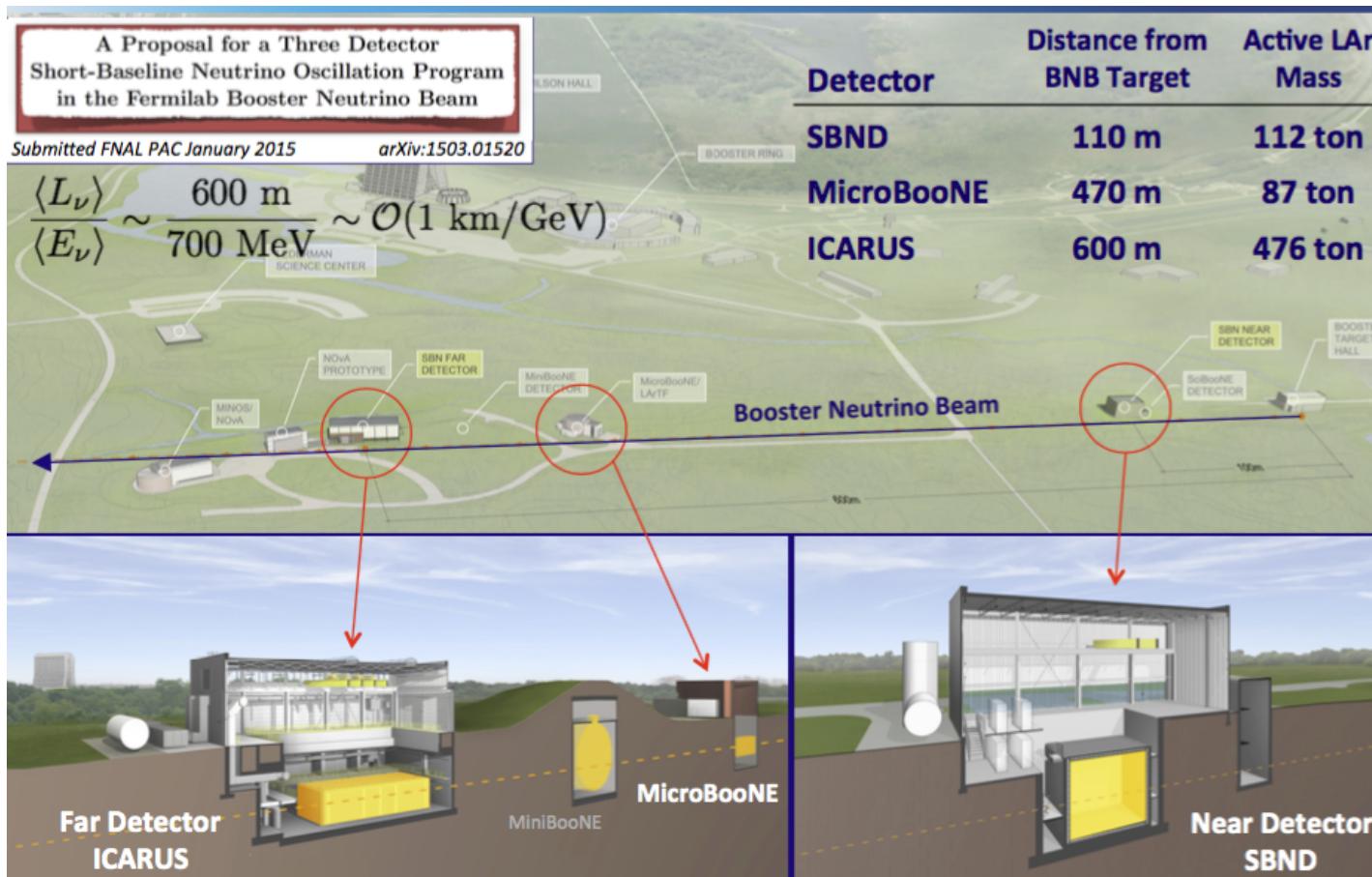


Upgraded Tracker at the T2K off-axis detector (ND280)
Horizontal targets surrounded by TPC
→ 4π acceptance + TOF between detectors to improve discrimination between forward μ^- and backward μ^+



Emulsion detector upstream of the T2K on-axis detector (INGRID)

Near-future measurements @ the Booster beam



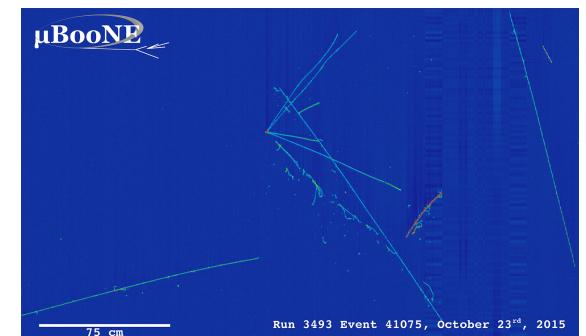
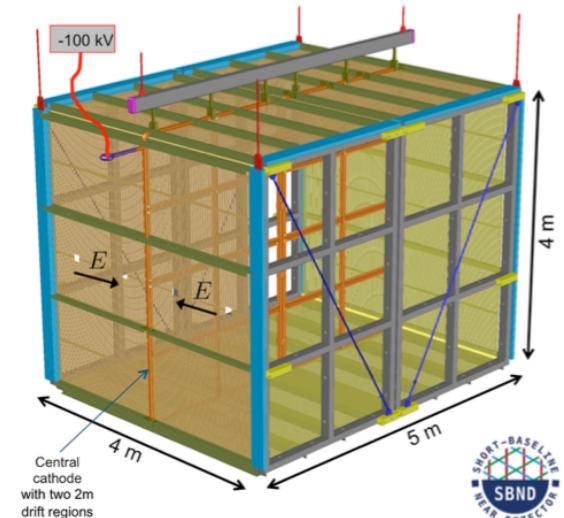
Physics data-taking: SBND: Early 2019, μ BooNE: now, ICARUS: 2018.

Near-future measurements @ the Booster beam

O(100 tonnes) liquid Argon TPCs with "bubble chamber"-like imaging capabilities: O(100k) - O(1M) event samples for key samples!

SBND event rates for an exposure of 6.6×10^{20} POT

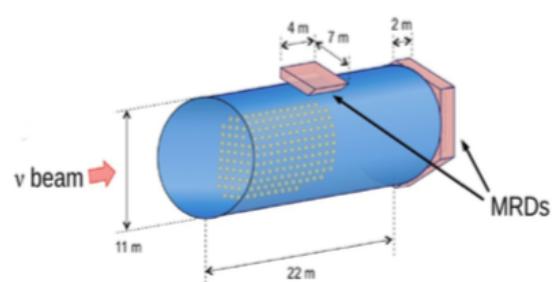
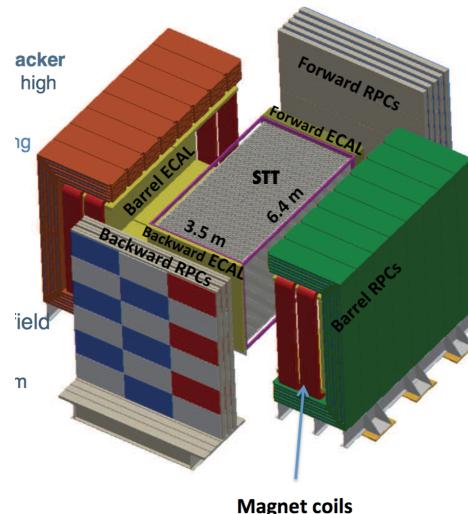
Process	No. Events	
<i>ν_μ Events (By Final State Topology)</i>		
CC Inclusive	5,212,690	
CC 0 π	$\nu_\mu N \rightarrow \mu + Np$ • $\nu_\mu N \rightarrow \mu + 0p$ • $\nu_\mu N \rightarrow \mu + 1p$ • $\nu_\mu N \rightarrow \mu + 2p$ • $\nu_\mu N \rightarrow \mu + \geq 3p$	3,551,830 793,153 2,027,830 359,496 371,347
CC 1 π^\pm	$\nu_\mu N \rightarrow \mu + \text{nucleons} + 1\pi^\pm$	1,161,610
CC $\geq 2\pi^\pm$	$\nu_\mu N \rightarrow \mu + \text{nucleons} + \geq 2\pi^\pm$	97,929
CC $\geq 1\pi^0$	$\nu_\mu N \rightarrow \mu + \text{nucleons} + \geq 1\pi^0$	497,963
<i>ν_e Events</i>		
CC Inclusive	36798	
NC Inclusive	14351	
Total ν_μ and ν_e Events	7,251,948	



Near detectors at future LBL experiments

Fine-Grained Tracker

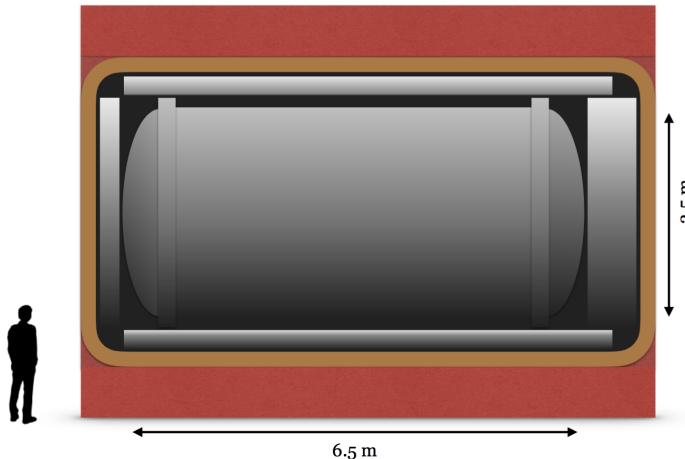
Active low-density straw-tube tracker in 0.4 T B field with embedded high pressure argon gas targets. Target mass ~ 7 tonnes. In 4π plastic scintillator ECAL.



(Note: Not in scale)

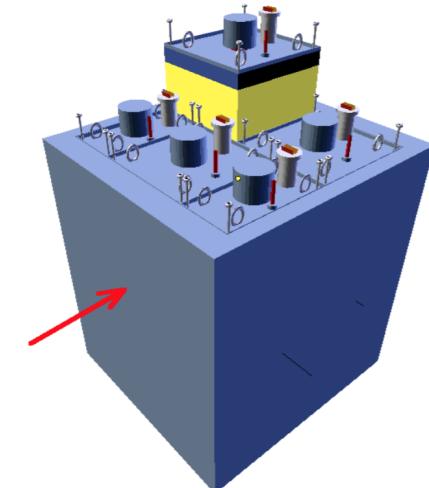
Gas Argon TPC

1 tonne of gas Argon at 10 bar pressure in a titanium alloy vessel. In a 0.4 T B field and surrounded by a 4π plastic scintillator ECAL.



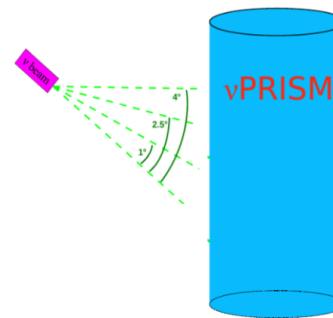
Liquid Argon TPC

Magnetized, modular LAr TPC sharing common cryostats. Shorter drift times and contained scintillation light in each module. Pixelated charge readout for 3-D reconstruction.



TITUS

Large water Cherenkov doped with Gadolinium and with side magnetized muon range detectors.



ν PRISM

Large and elongated water Cherenkov, combining measurements at many off-axis angles to understand the energy-dependence of the cross-section.

Summary (1/2)

- CP and MH sensitivity requirements for future LBL osc. experiments:
Systematic error reduction from the 5%-6% level to the 1% level.
- A detailed understanding of neutrino interaction is required!
- New ("model-independent") measurements for several key channels (CC inclusive, CC 0π , CC $1\pi^\pm$, CC $1\pi^0$, NC $1\pi^0$) at different energy ranges, using different detector technologies.
- **Several puzzles to understand.**

We are getting there:

- **Theory is improving rapidly** (but poor coverage in A / kinematics)
- Substantial effort by generator groups
 - embed improved theoretical inputs into extensive empirical models,
 - develop global tunes to further improve empirical models.

Summary (2/2)

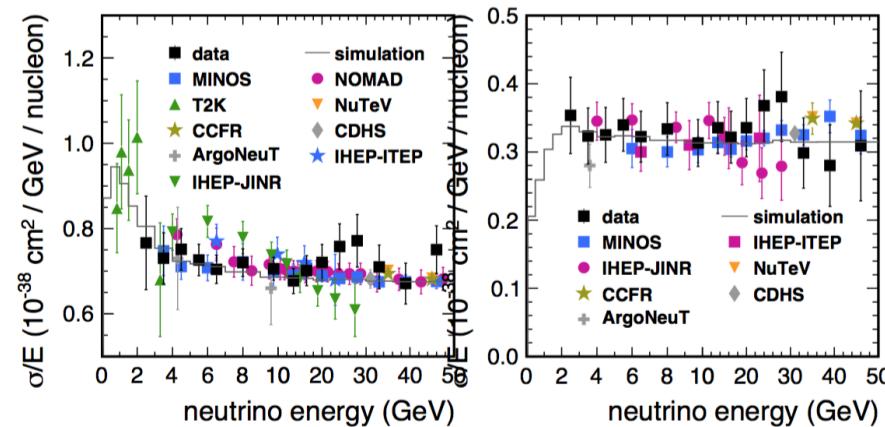
- Several **decisive new measurements** expected in the near future, in particular at the **Fermilab SBN programme**.
 - Closure in QE and single- π puzzles.
- No doubt, an array of puzzles (hopefully different ones) will be with us at the start of DUNE and HyperK data-taking in 2026 or so.
- Essential to build **highly-capable NDs for DUNE and HyperK!**
 - Currently being designed...
 - Crucial that they are over-designed, to offer the redundancy of information that may be needed to understand anomalies.



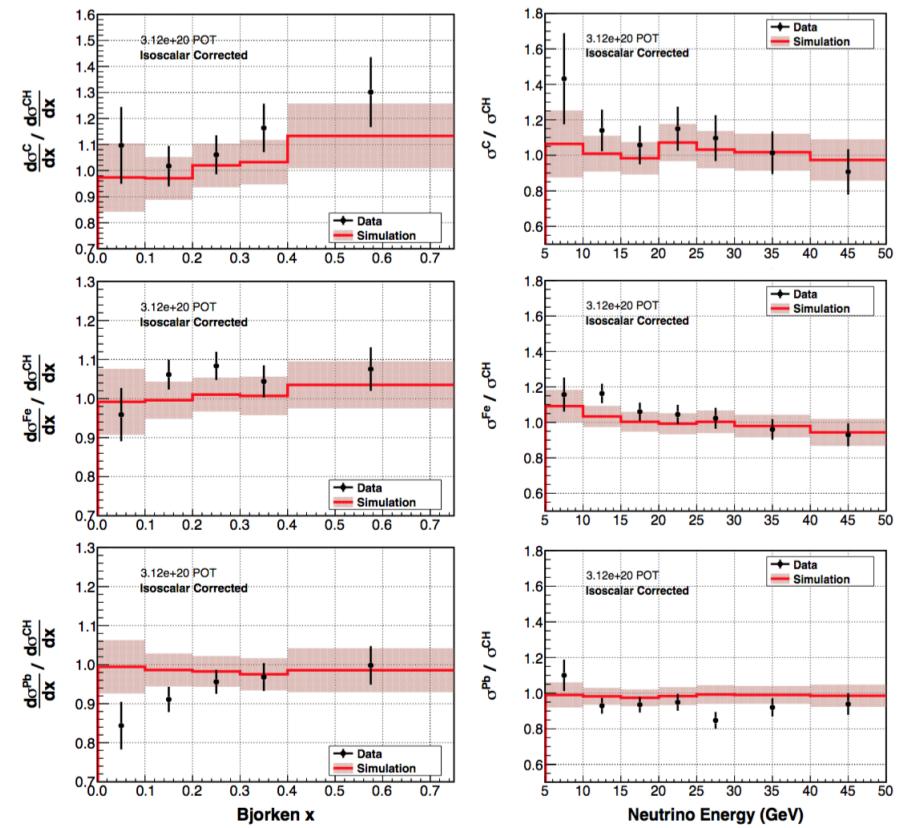
Way out: Need Hydrogen/Deuterium data to disentangle bare cross-section and nuclear/FSI effects!

Complementary slides

DIS



[Phys.Rev. D94 (2016) no.11, 112007]



[Phys.Rev. D93 (2016) no.7, 071101]