Neutrino-Nucleus Interactions at few-GeV: *Relevance, Status and Impact on Oscillation Studies*

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Outline

- What are we hoping to learn?
- Neutrino-nucleus interactions at the few-GeV energy range
- LBL oscillation analysis: Reliance on models
- Illustrating our present understanding through two puzzles:
  - the "quasielastic puzzle"
  - the "single-π puzzle"
- Impact on LBL oscillation analyses.
- Summary

Neutrinos: What are we hoping to learn?

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

Several key questions:

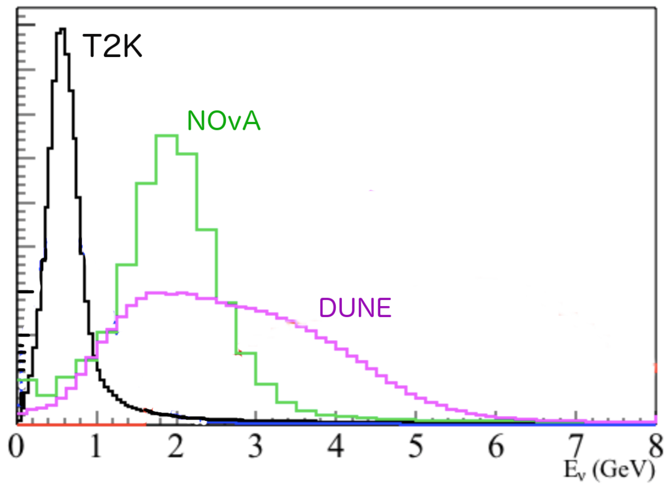
- **What is the neutrino mass generation mechanism?**
  - Could the neutrino be a Majorana particle?
  - Why are the masses so small?
- **What do neutrinos tell us about flavour?**
  - Nearly (exactly?) maximal mixing observed: 'μ' and 'τ' flavour interchangeable!
- **What is the connection between quarks 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.

Why few-GeV neutrino interactions?

Accelerator-based LBL oscillation experiments play a crucial role.

Maximize oscillation sensitivity at "atmospheric" squared mass splitting:

$$1.267\frac{|\Delta m^2_{32}|(eV^2/c^4)\cdot L(km)}{E_\nu(GeV)} = \frac{\pi}{2} \xrightarrow{|\Delta m^2_{32}|\approx 2.4\times 10^{-3} eV^2/c^4} E_\nu(GeV) = 0.002\cdot L(km)$$



	L (km)	E (GeV)
T2K	292	0.6
NOvA	810	1.6
DUNE	1300	2.6

At the few-GeV energy range:

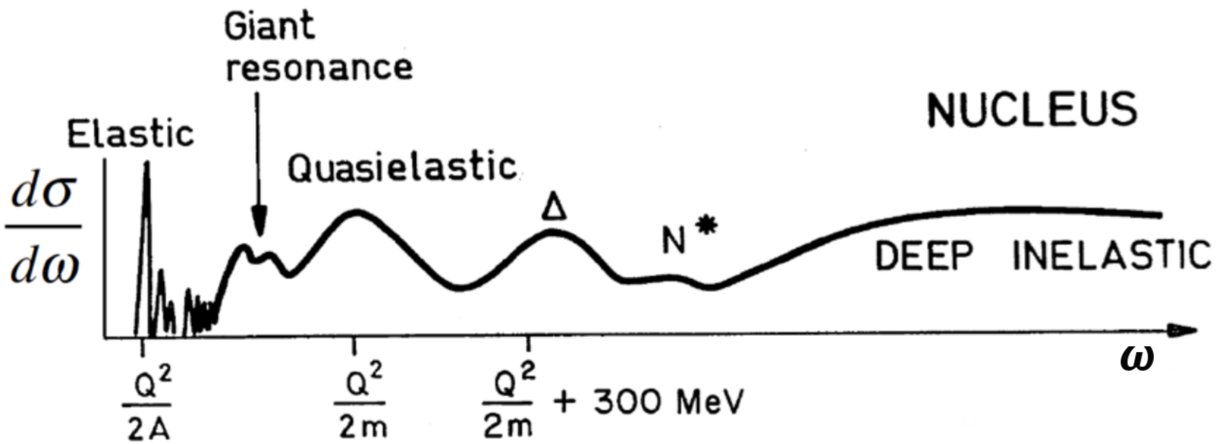
- Boundary between perturbative and non-perturbative regimes

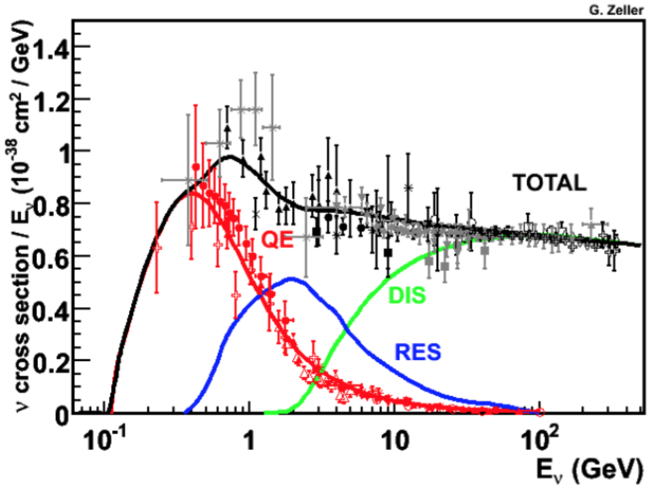
A further complication is the use of nuclear targets to boost statistics

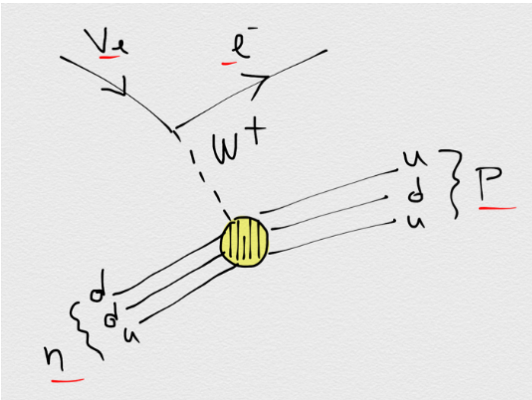
- In a kinematical regime where
  a) the impulse approximation is poor, and
  b) intranuclear hadron rescattering effects are substantial.

Scattering mechanisms at the few-GeV energy range

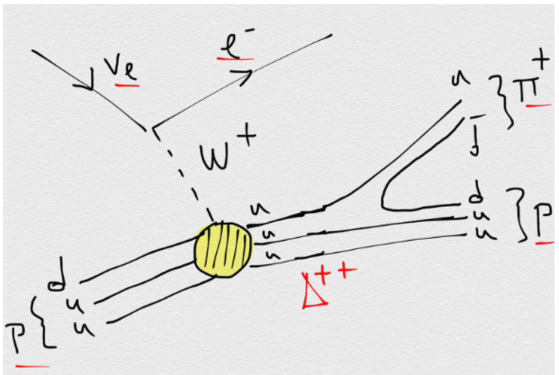
Broad energy range: Several scattering mechanisms are important.



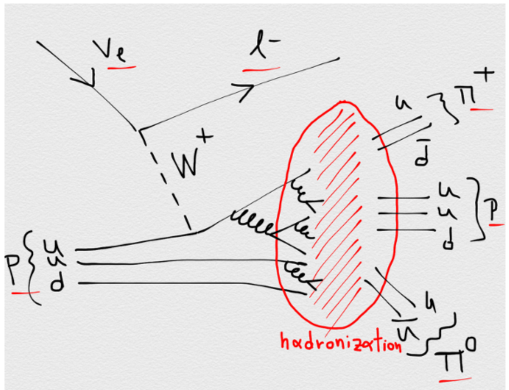




QE



Δ



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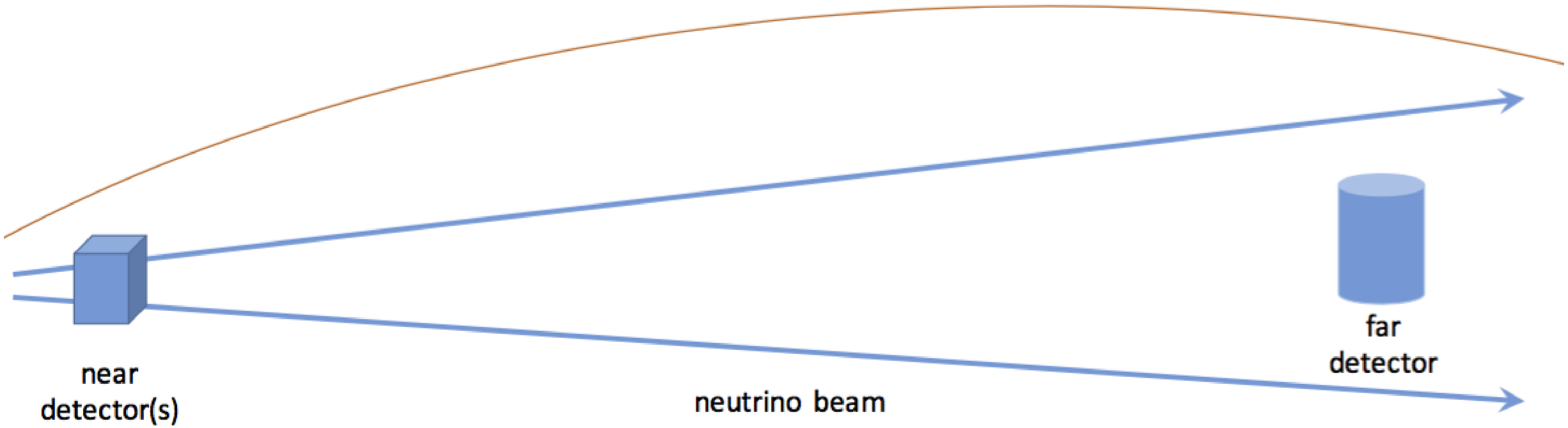
Extrapolation from Near to Far Detector

To mitigate the effect of (flux and interaction) uncertainties, we perform experiments with detectors at multiple baselines (Near and Far)



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:

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

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

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

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

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
    - Different beam-related backgrounds
    - Different flux (line source vs point source, oscillations!)
  - High rate in the Near hall can necessitate different technology
    - Uncorrelated detector systematics between Near and Far detectors
    - Different acceptance from the (usually 4π) Far detector
    - Different nuclear targets
- The true neutrino energy is not known on an event-by-event basis
  - The true neutrino energy comes from a 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.**

- But models not predictive enough

Reliance on models: ν_e and $\bar{\nu}_e$ cross-sections

- Large observed value of θ_{13} a **mixed blessing**
- **Large ν_e and $\bar{\nu}_e$ appearance rate**

$$P(\nu_\mu \to \nu_e) \simeq \boxed{\sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}}$$

Phys. Rev. D64 (2001) 053003

Leading term

CP violating $\quad - \alpha \sin\delta_{CP} \times \sin^2 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$

"+" for antineutrino

CP conserving $\quad \alpha \cos\delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$

$+ O(\alpha^2)$

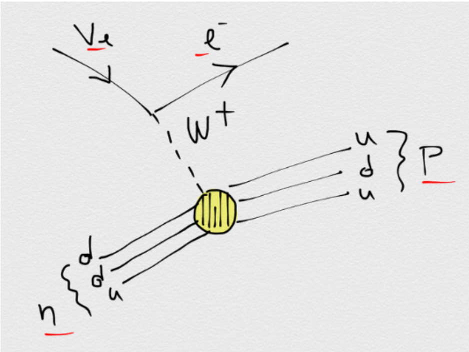
$$x = \frac{2\sqrt{(2)}G_F N_e E}{\Delta m^2_{31}} \quad \alpha = |\frac{\Delta m^2_{21}}{\Delta m^2_{31}}| \sim \frac{1}{30} \quad \Delta = \frac{\Delta m^2_{31} L}{4E}$$

- **But small CP asymmetry!**

$$A_{CP} \propto \frac{sin2\theta_{12}}{sin\theta_{13}} sin\delta_{CP}$$

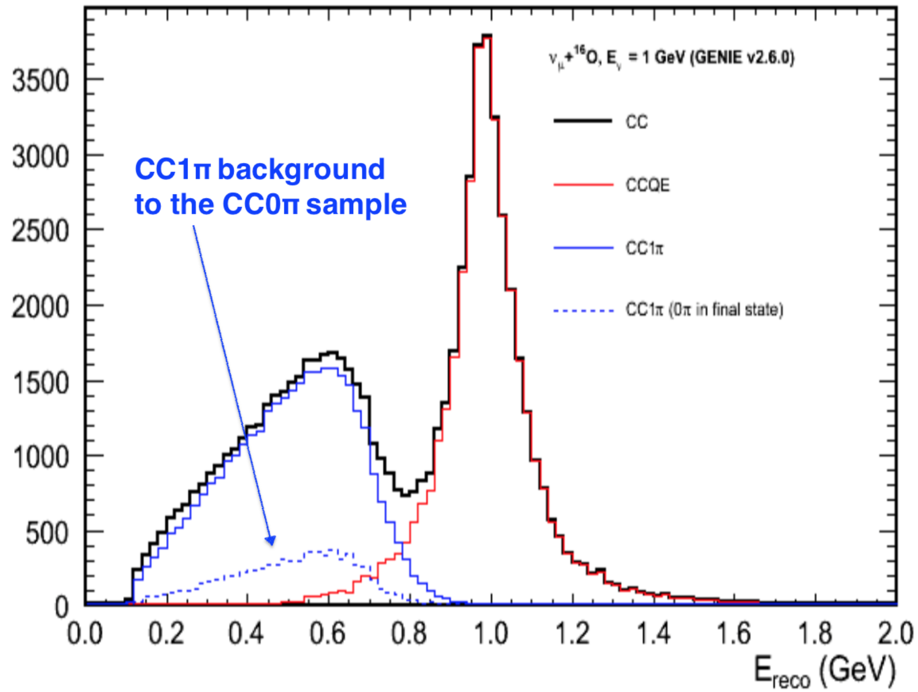
- **"Signal" systematics important**
  - Oscillation "signal" absent from NDs
  - Intrinsic ν_e contamination low and at different energy range

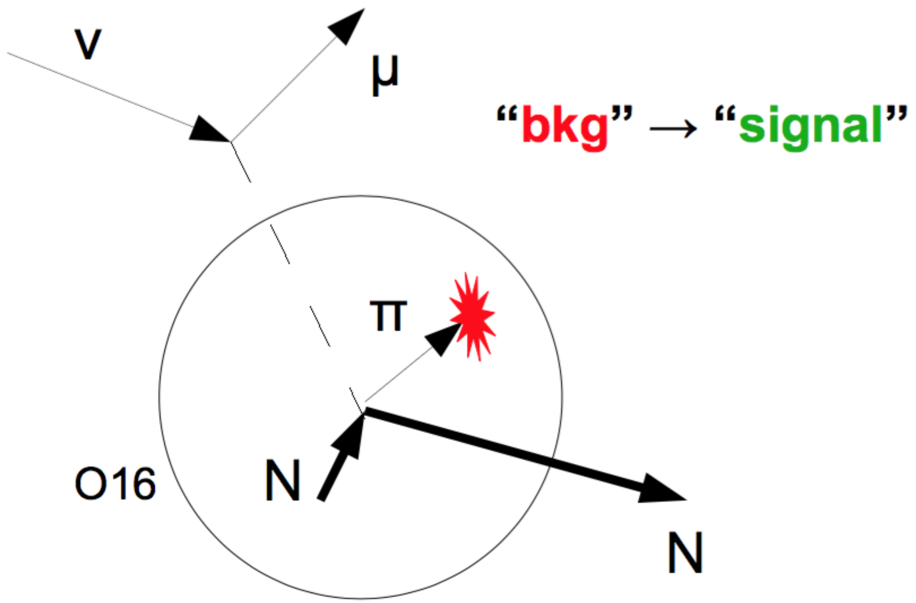
Reliance on models: Neutrino energy reconstruction



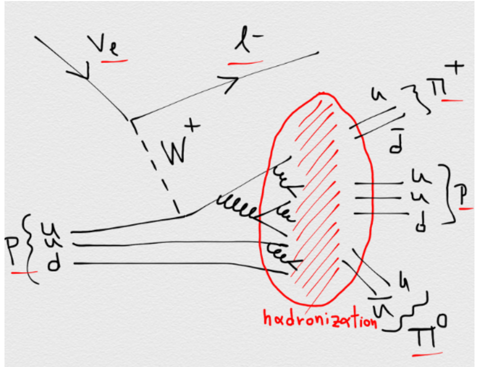
Reconstruction based on **2-body kinematics** for QE-enhanced samples

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



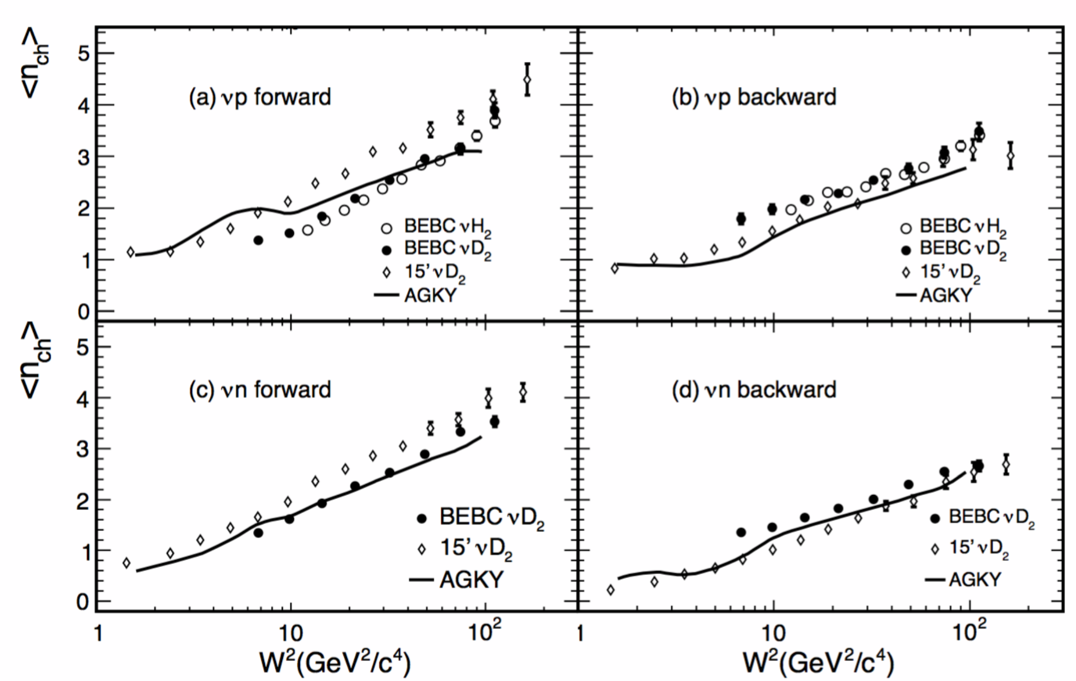


Reliance on models: Neutrino energy reconstruction

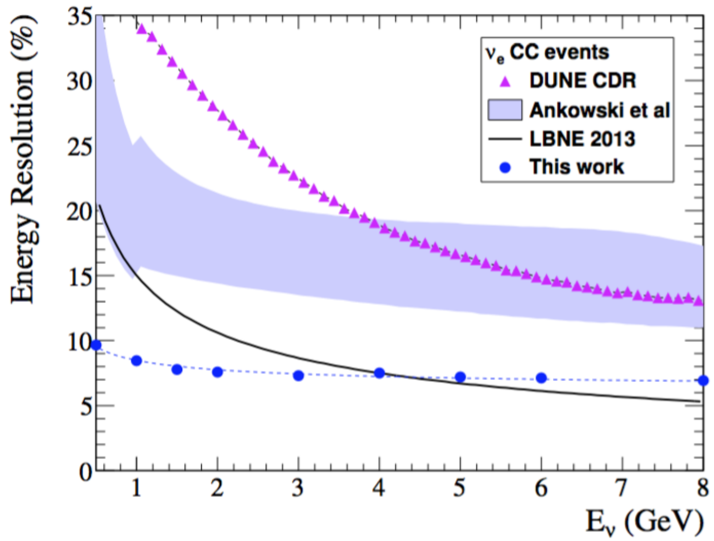


Calorimetric approach to energy reconstruction:

$$E_\nu = \color{red}{E_{leptonic}} + \color{green}{E_{hadronic}}$$



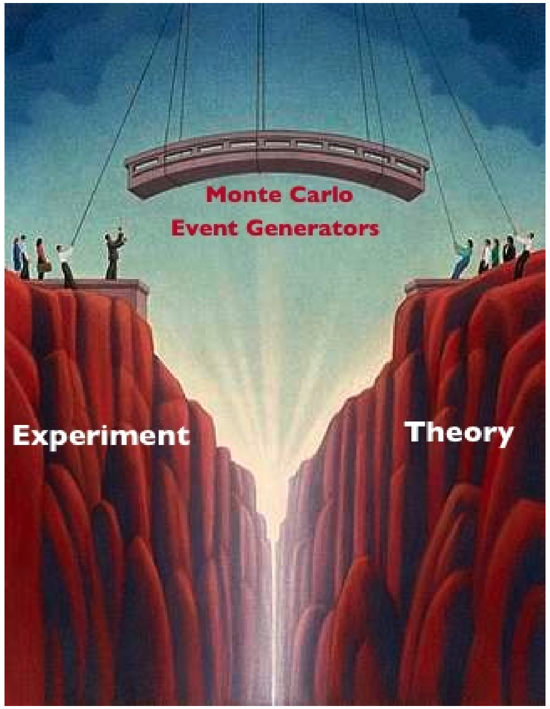
[Eur.Phys.J.C63:1-10,2009]



[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.

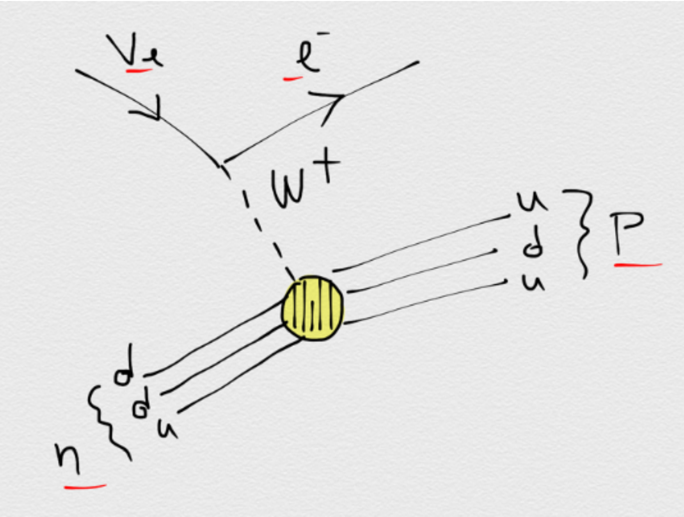
Every observable a convolution of flux, interaction physics and detector effects. Neutrino MC Generators allow experimentalists to access, improve, validate, assess the uncertainty of and tune the *physics* models that drive the result of that convolution.

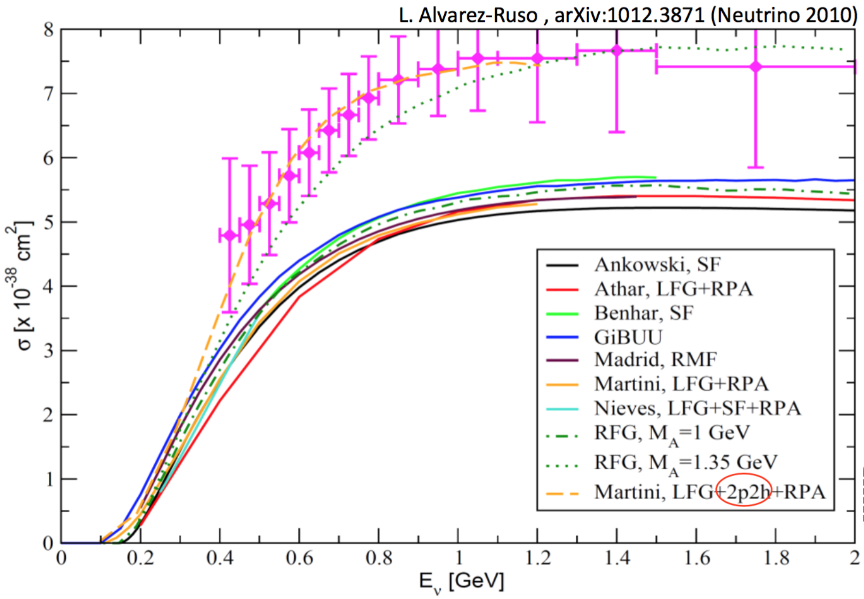
Only few such MCs exist and in wide-use: **GENIE**, **NuWro**, **NEUT**, **GiBUU**

Recent data have exposed MC weaknesses. Substantial effort underway to embed new and improved theory calculations, overhaul empirical models, characterise comprehensive models and perform global fits to data.

The QE puzzle

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





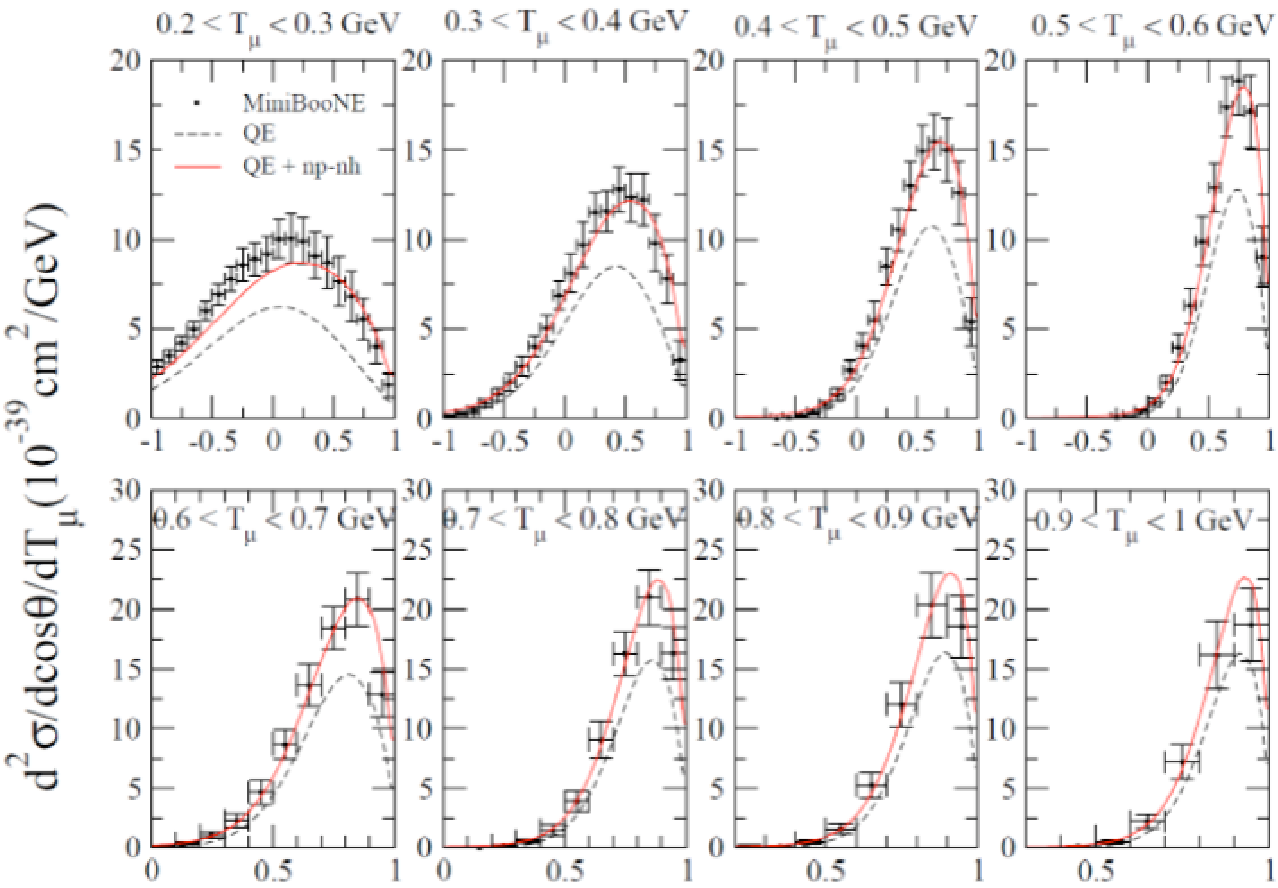
On single nucleons, the QE process is **theoretically understood and well constrained** by experimental information from

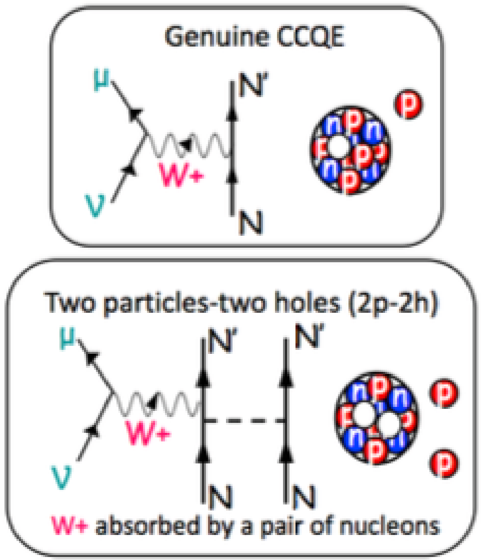
- electron scattering, neutron β decay, and
- ν experiments on Hydrogen/Deuterium.

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

The QE puzzle: Two-nucleon interactions

The observed dicrepancy 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

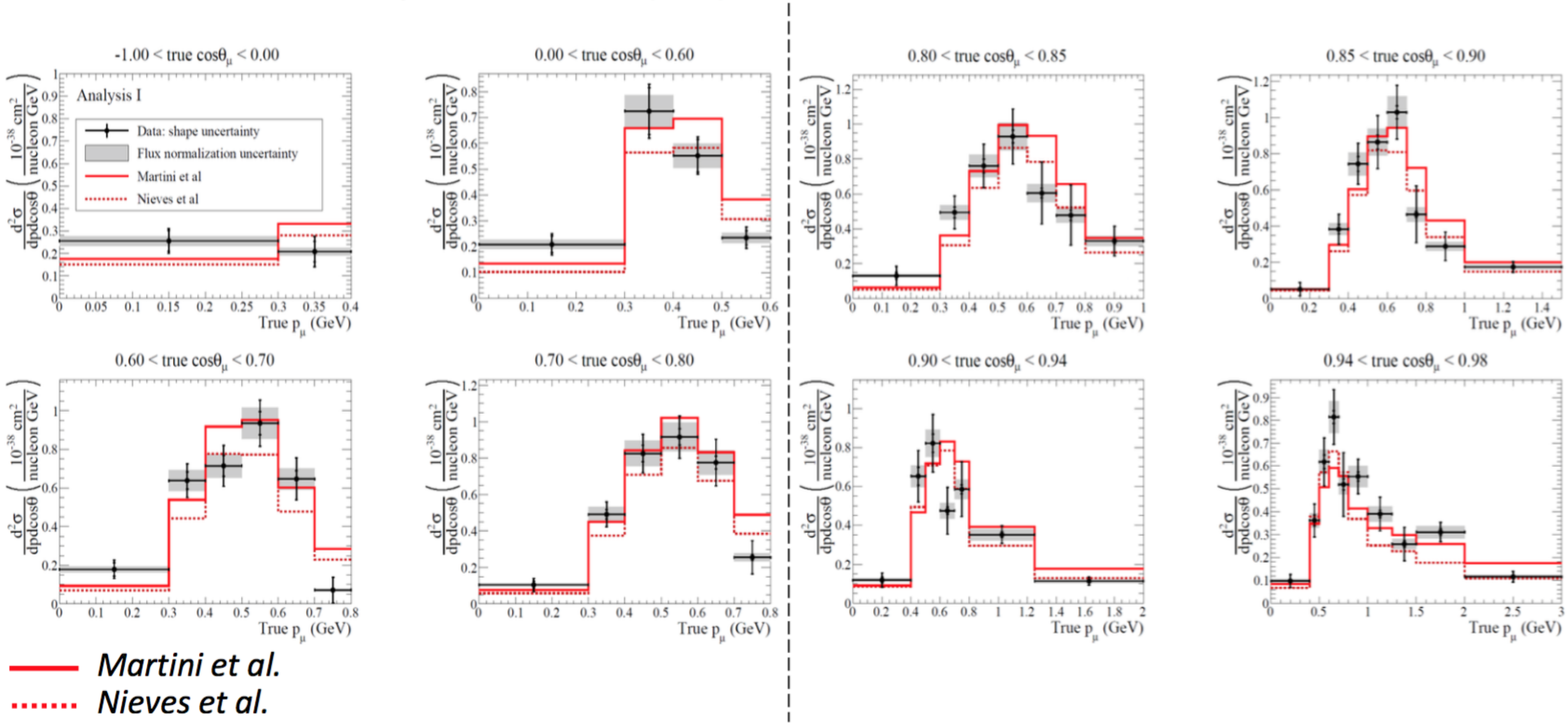
(e.g through virtual Δ or contact term).

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

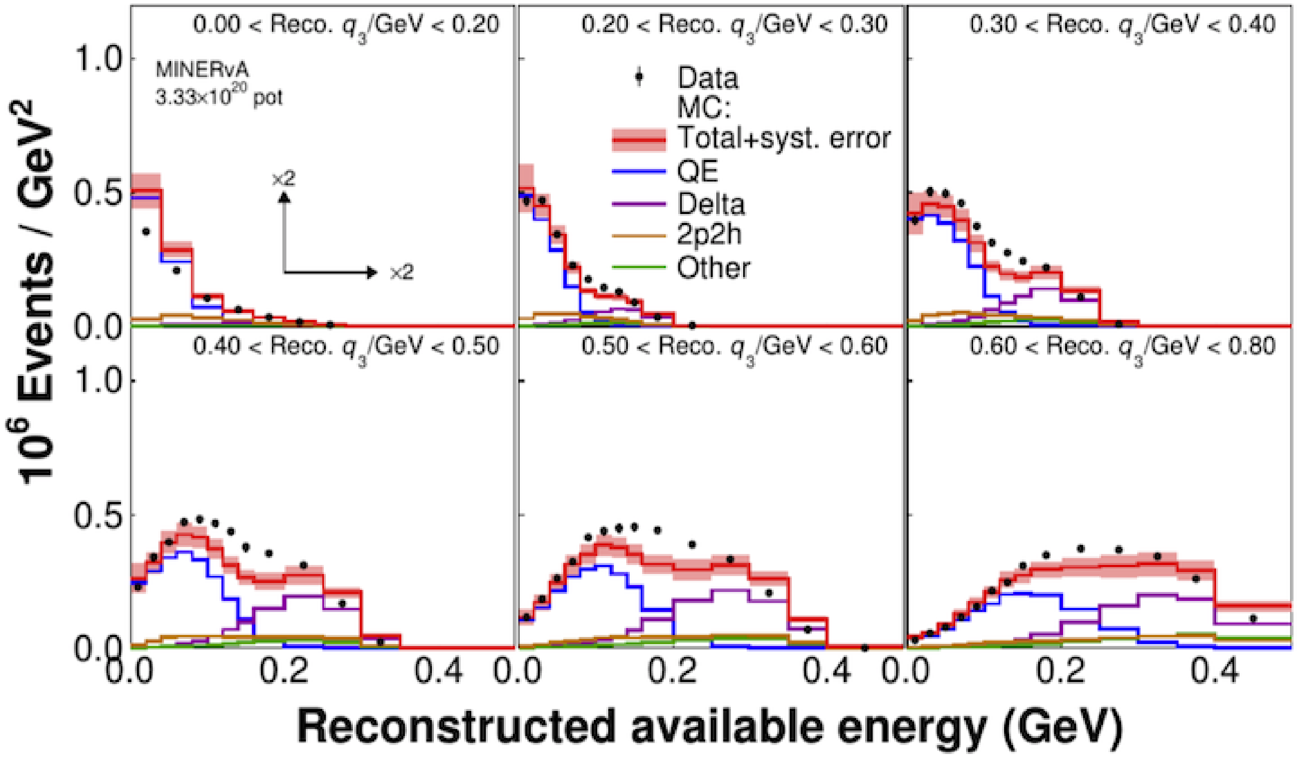
The QE puzzle: Two-nucleon interactions

Recent CC0π measurements from T2K in agreement with theoretical models including 2p2h.

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

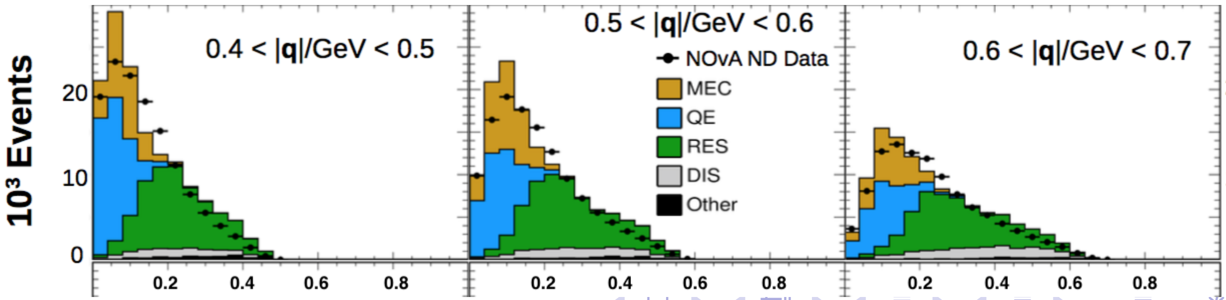


[Phys.Rev. D94 (2016) no.11, 112007]



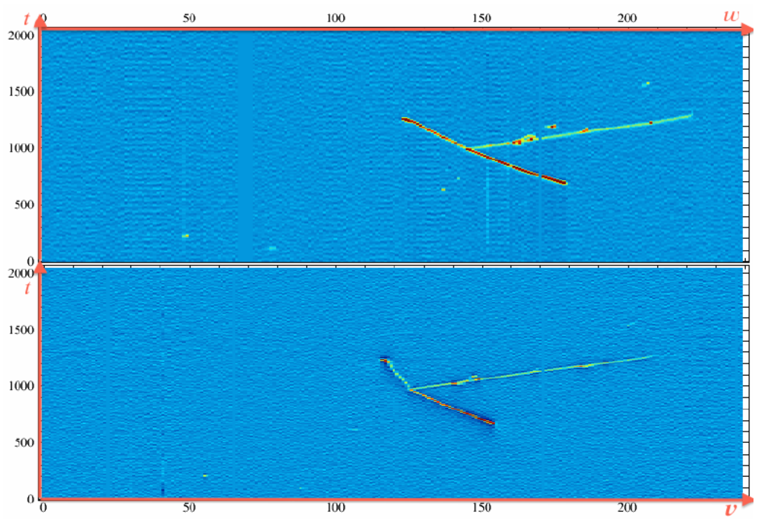
MINERvA **Inclusive** ν_μ **CC data in** $(q_0, |\vec{q_3}|)$**:**. Exploiting the different kinematical dependency of each component to disentangle 2p2h.

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

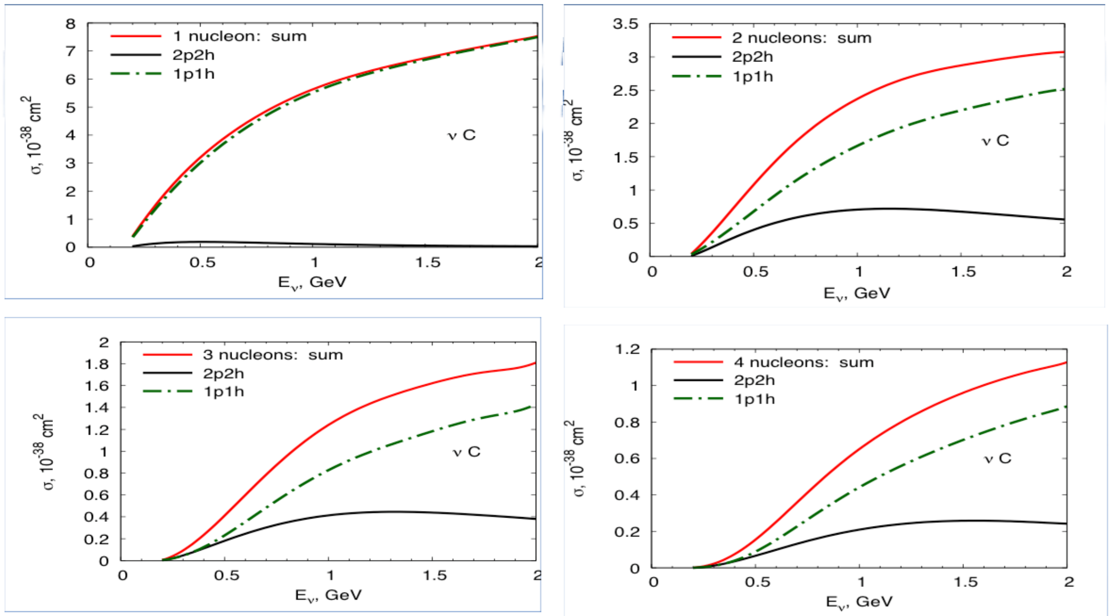


The QE puzzle: Towards a resolution

- 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) CC0π events subdivided based on nucleon multiplicity crucial for disentangling FSI and 2p2h effects.



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

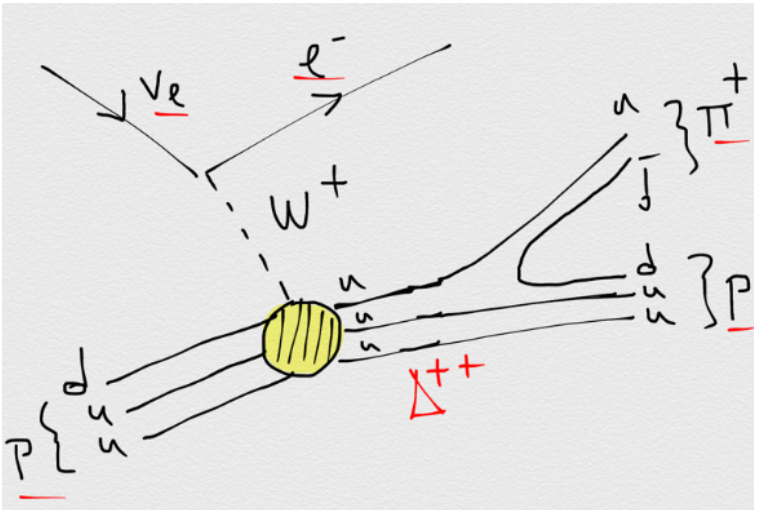


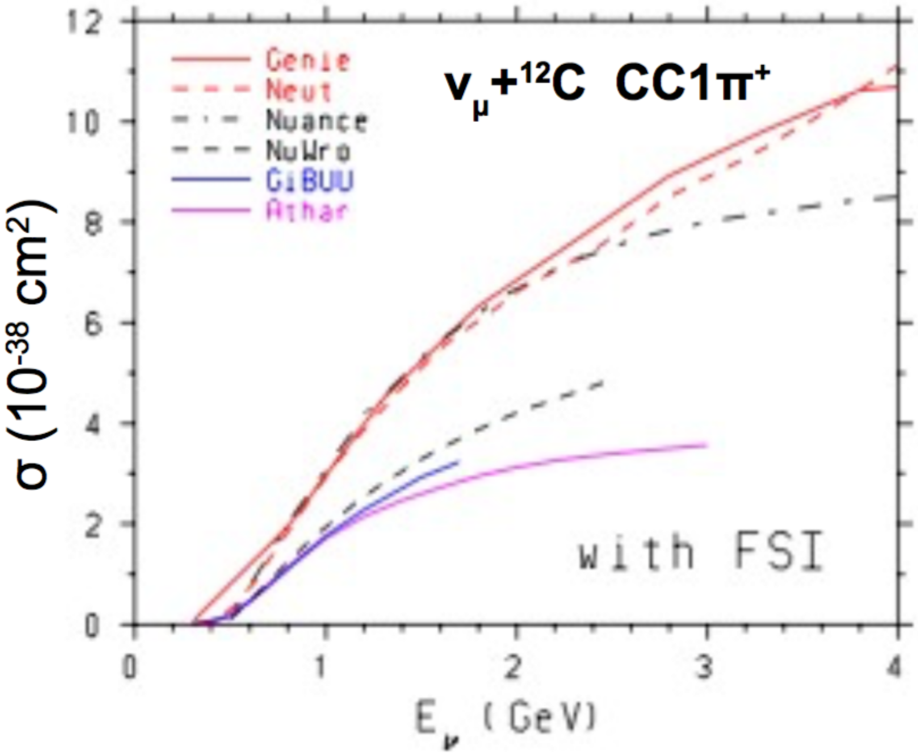
Ulrich Mosel

Single-π production

Important process for oscillation physics (both as a signal and background).

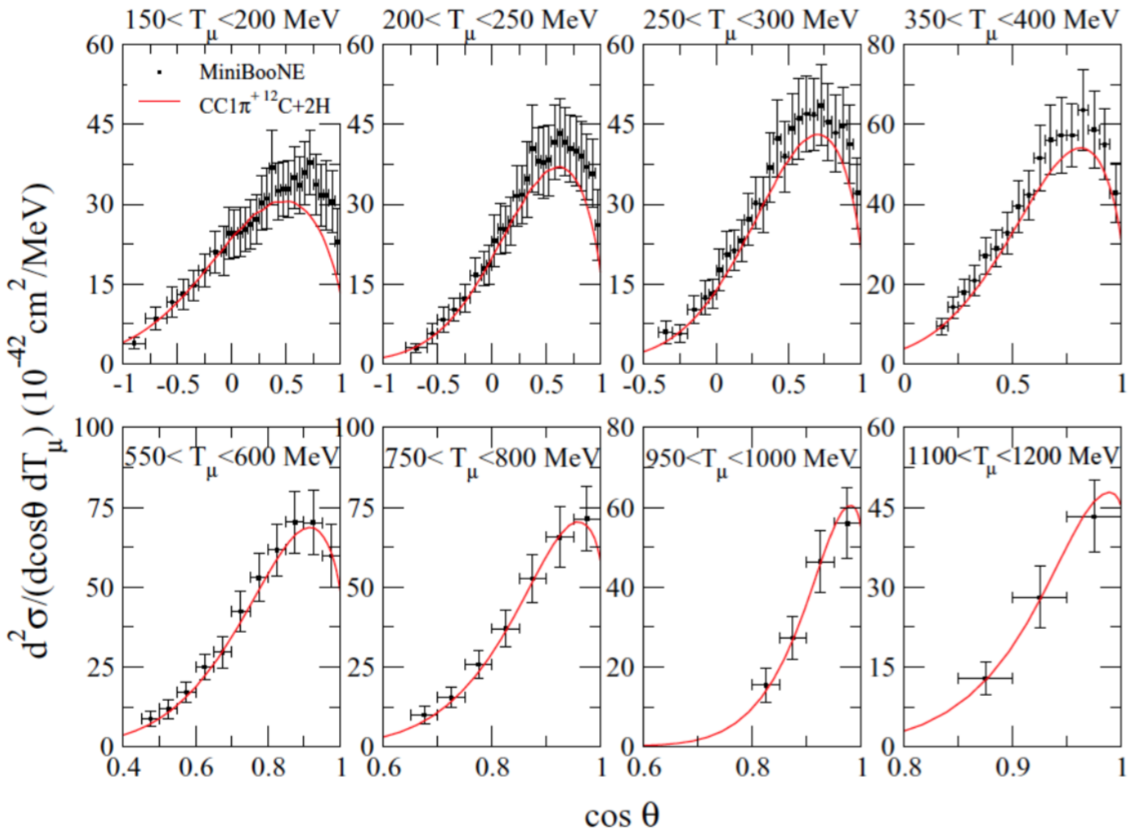
- In DUNE, resonance events cntribute $\sim$30% to the CC inclusive rate.
- In T2K(/HK), CC 1-pion events where the pion is absorbed in the nucleus (or not detected) can be classified as single-ring (QE-enhanced) signal events
- NC1π^0 an important background for $\nu_e/\bar{\nu}_e$ appearance





Single-π production

First recent (flux integrated double-differential) CC1$\pi^{\pm}$ (predominantly CC1π^{+}) measurement was performed by MiniBooNE [Phys.Rev.D83, 052007 (2011)]

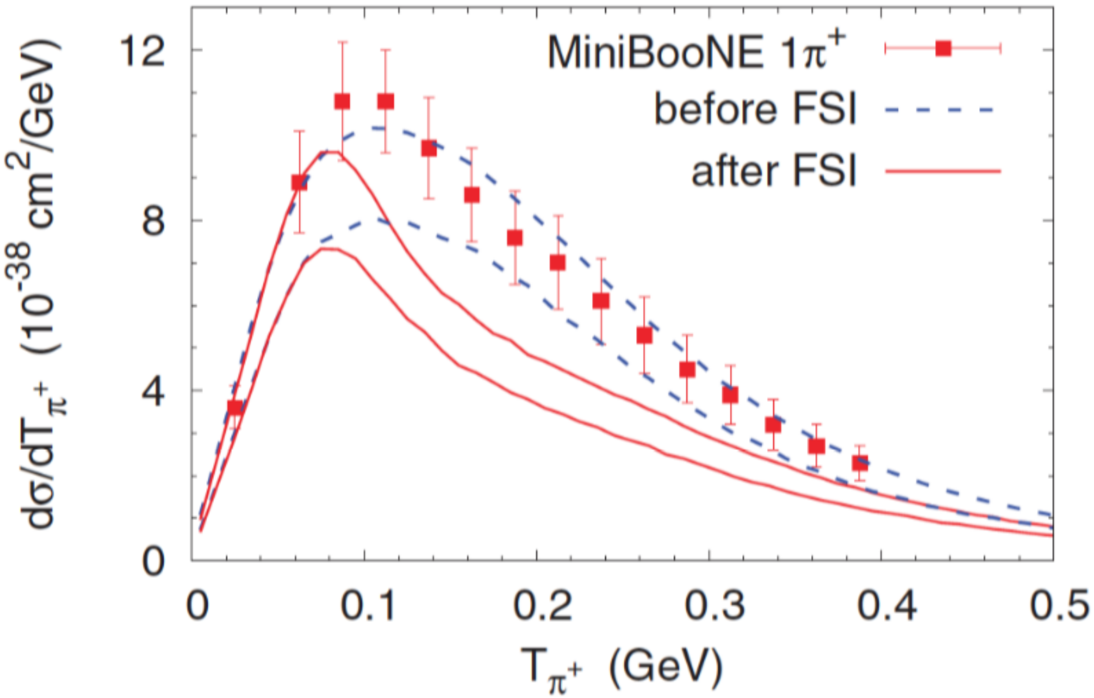


[Phys.Rev.C90,025501(2014)]

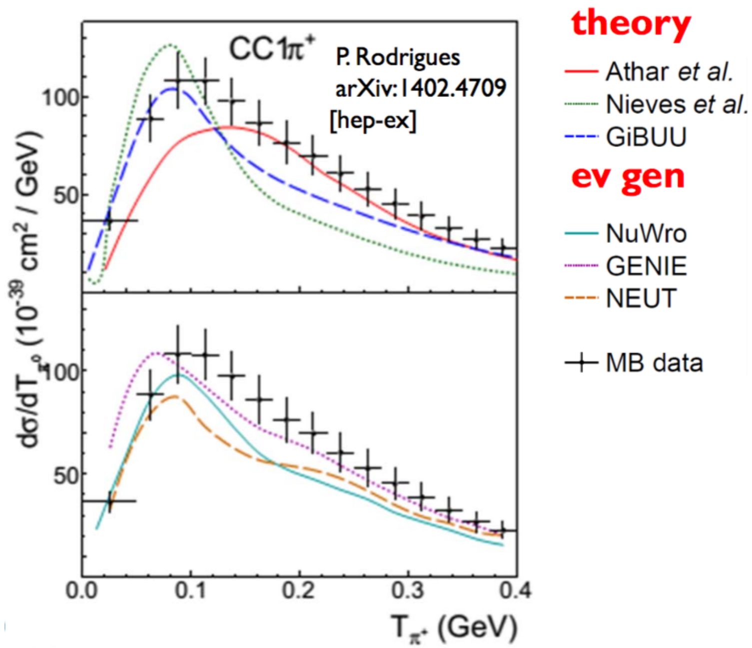
Differential cross-section in muon kinematics (muon kinetic energy T_μ and muon scattering angle θ_μ).

Reasonable agreement is obtained with several models.

But MiniBooNE data in terms of pion kinematics very hard to understand within any model. In particular, the shape of MiniBooNE T_π distribution seems to prefer the absence of FSI effects!

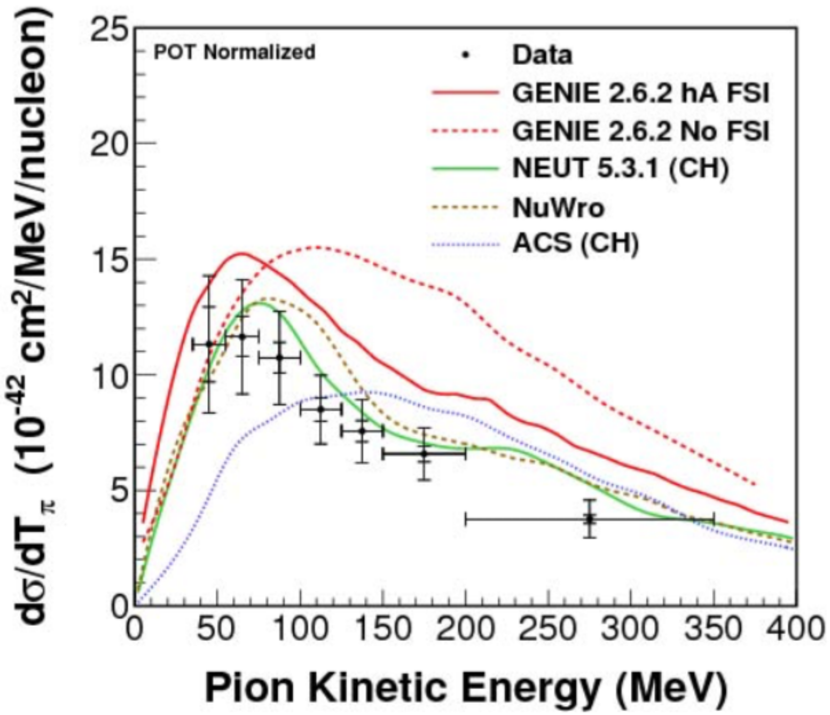


[Phys.Rev.C87, 014602 (2013)]



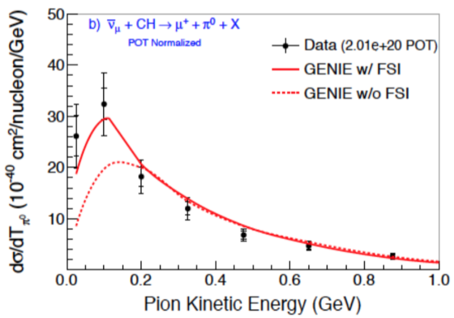
[arXiv:1402.4709 [hep-ex]]

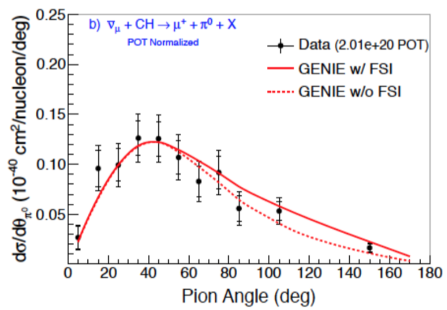
New neutrino CC1π^+ and anti-neutrino CC1π^0 measurements by MINERvA in CH, at higher energy than MiniBooNE.



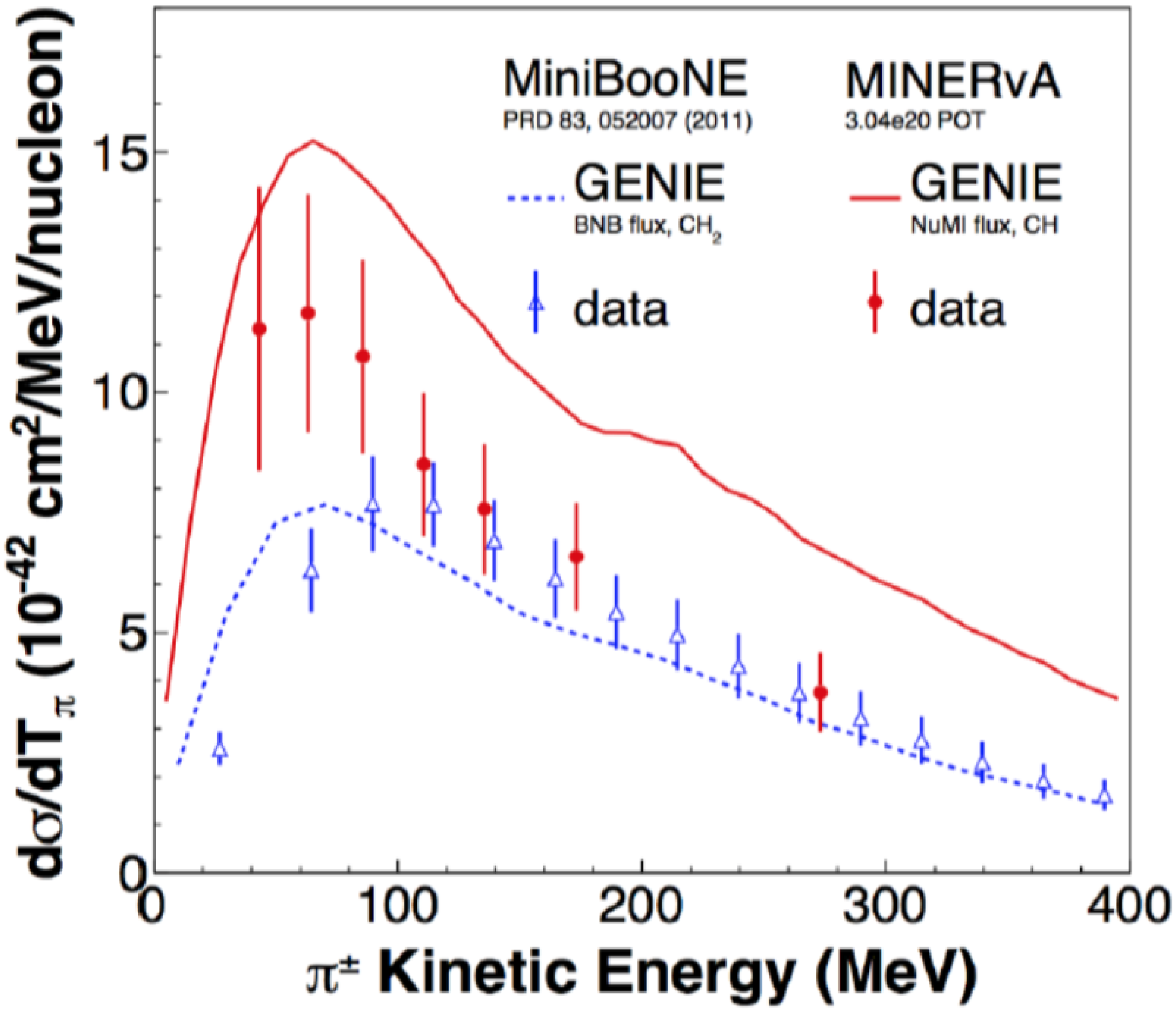
[Phys.Rev.D92, 092008 (2015)]

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





The single-π puzzle



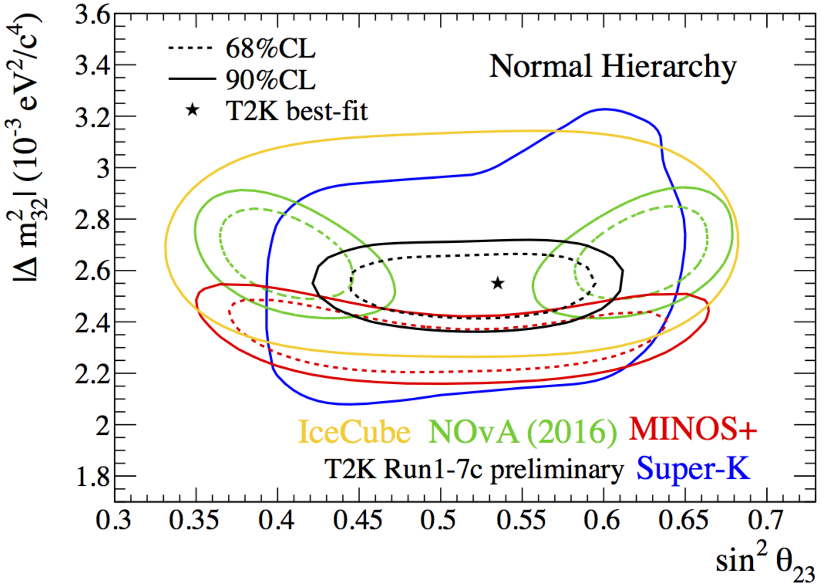
[Phys.Rev.D92, 092008 (2015)]

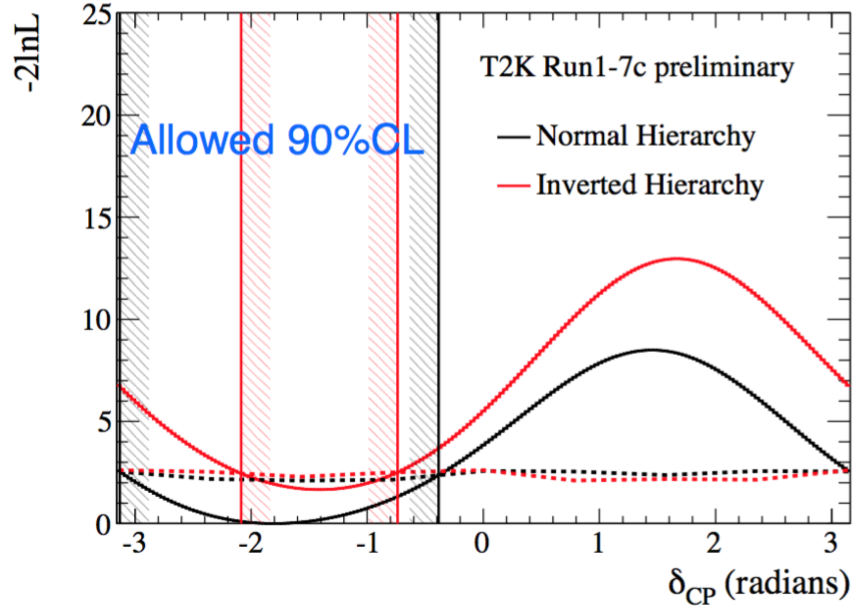
- Difficult to resolve the differences between MiniBooNE and MINERvA within our usual models.
- This tension between MiniBooNE and MINERvA data is not understood.

Neutrino-nucleus interaction effects in LBL

Recent T2K oscillation measurements (7.57×10^{20} POT ν + 7.53×10^{20} POT $\bar{\nu}$):

- **World-leading measurements of $\nu_\mu/\bar{\nu}_\mu$ disappearance parameters**
- **'Conserved CP' hypothesis excluded at 90% C.L.**
  - $\delta_{CP} = 0$ 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)
  - Best-fit: δ_{CP} = -1.885, NH
  - Using $sin^2 2\theta_{13} = 0.085 \pm 0.005$ [PDG2015]





Composition of T2K Far Detector analysis samples

ν-mode, 1-ring μ-like candidates

	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

- 56% CC QE
- 16% CC 2p-2h
- 15% CC 1π

ν-mode, 1-ring e-like candidates

	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

- 69% CC QE
- 18% CC 2p-2h
- 8% CC 1π

Effect of systematics on T2K Far Detector predictions

ν-mode, 1-ring μ-like candidates

Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	4.13%
SKDet only	3.86%
FSI+SI only	1.48%
Flux	3.60%
Flux (pre-fit)	7.63%
2p-2h (corr)	3.46%
2p-2h-bar (corr)	0.20%
NC other (uncorr)	0.78%
NC 1gamma (uncorr)	0.00%
XSec nue/numu (uncorr)	0.01%
XSec Tot (corr)	4.00%
XSec Tot	4.08%
XSec Tot (pre-fit)	7.73%
Flux+XSec (ND280 constrained)	2.79%
Flux+XSec (All)	2.90%
Flux+XSec+SKDet+FSI+SI	5.03%
Flux+XSec+SKDet+FSI+SI (pre-fit)	12.0%

ν-mode, 1-ring e-like candidates

Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	3.46%
SKDet only	2.39%
FSI+SI only	2.50%
Flux	3.64%
Flux (pre-fit)	8.94%
2p-2h (corr)	3.87%
2p-2h bar (corr)	0.05%
NC other (uncorr)	0.16%
NC 1gamma (uncorr)	1.44%
XSec nue/numu (uncorr)	2.65%
XSec Tot (corr)	4.13%
XSec Tot	5.12%
XSec Tot (pre-fit)	7.17%
Flux+XSec (ND280 constrained)	2.88%
Flux+XSec (All)	4.17%
Flux+XSec+SKDet+FSI+SI	5.41%
Flux+XSec+SKDet+FSI+SI (pre-fit)	11.9%

Effect of 1σ variations on the total number of events 1-ring μ-like and e-like events for neutrino mode given by all the systematic uncertainties, obtained by performing 10k toys MC.
The RMS of the distribution is assumed to be the 1σ uncertainty.
Using: $\delta_{CP} = -1.601$, $\theta_{23} = 0.528$ and Δm^2_{32} $(\Delta m^2_{13}) = 2.509 \times 10^{-3} eV^2/c^4$.
The global values from PDG 2016 are used as uncertainties on $\sin^2\theta_{13}$, $\sin^2\theta_{12}$ and Δm^2_{21}.

Dependence on cross-section model choices

Near detector data reduce dependence on interaction simulations.

To what extend?

Several studies were made using "alternative" models testing effect of:

- Spectral Function model
- Shape and strength of RPA correction
- Differences between Martini and Nieves 2p-2h
- Effect of 2p-2h models on lepton kinematics
- Differences between nominal and Nieves 1p-1h

Dependence on cross-section model choices

Maximum bias seen for any set of true oscillation parameters considered (Total expected exposure)

Fake data	Maximum absolute bias on parameter (σ)			
	Δm^2_{23}	$sin^2\theta_{23}$	$sin^2\theta_{13}$	δ_{CP}
SF	0.32	0.25	0.65	0.28
ERPA	0.00	0.08	0.00	0.15
Martini *2p-2h*	0.15	0.16	0.25	0.29
Martini *2p-2h* with $\bar{\nu}$ *2p-2h* parameter	0.31	0.10	0.43	2.43
with reactor constraint		0.09		0.12
PDD-like *2p-2h*	0.31	0.04	0.13	0.25
with reactor constraint		0.04		0.26
NonPDD-like *2p-2h*	0.63	0.21	0.27	0.16
with reactor constraint		0.30		0.15
Nieves-NEUT *1p-1h*	1.43	0.04	0.42	1.65
with reactor constraint		0.00		0.58
Nieves-NEUT *1p-1h* with ND280 error	0.95	0.04	0.42	1.78
with reactor constraint		0.09		0.68

Summary

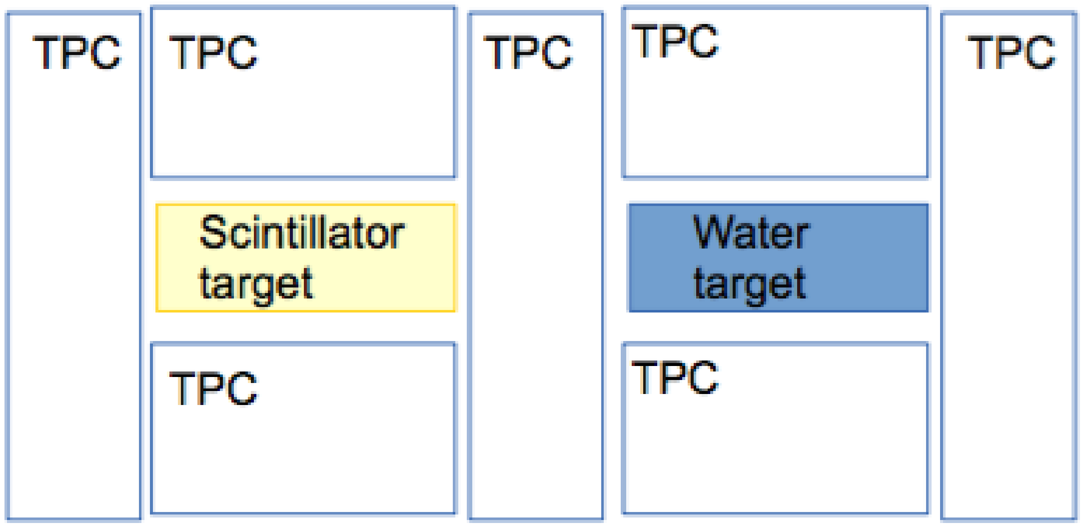
- A detailed understanding of neutrino-nucleus interactions at the GeV energy range is still missing! Several puzzles!
- 2-detector experiments have been successful in mitigating the effects.
- We're approaching a precision where this paradigm starts to crack!
- A detailed understanding of neutrino interaction physics is required!

Steady progress is happening:

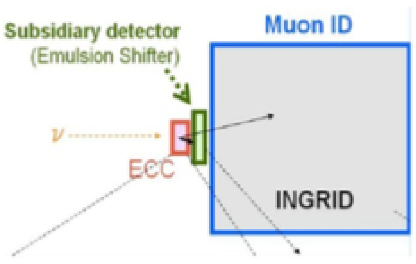
- Several recent measurements (+ many new ones expected at SBN)
- Theory is improving rapidly (but poor coverage in A / kinematics)
- Substantial effort to improve MC generators and produce global tunes
- Improvements of LBL analyses methods to further mitigate effects

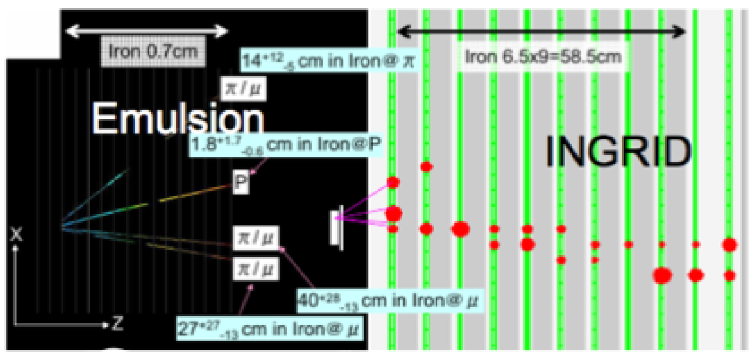
Complementary slides

Near-future measurements @ the J-PARC beam



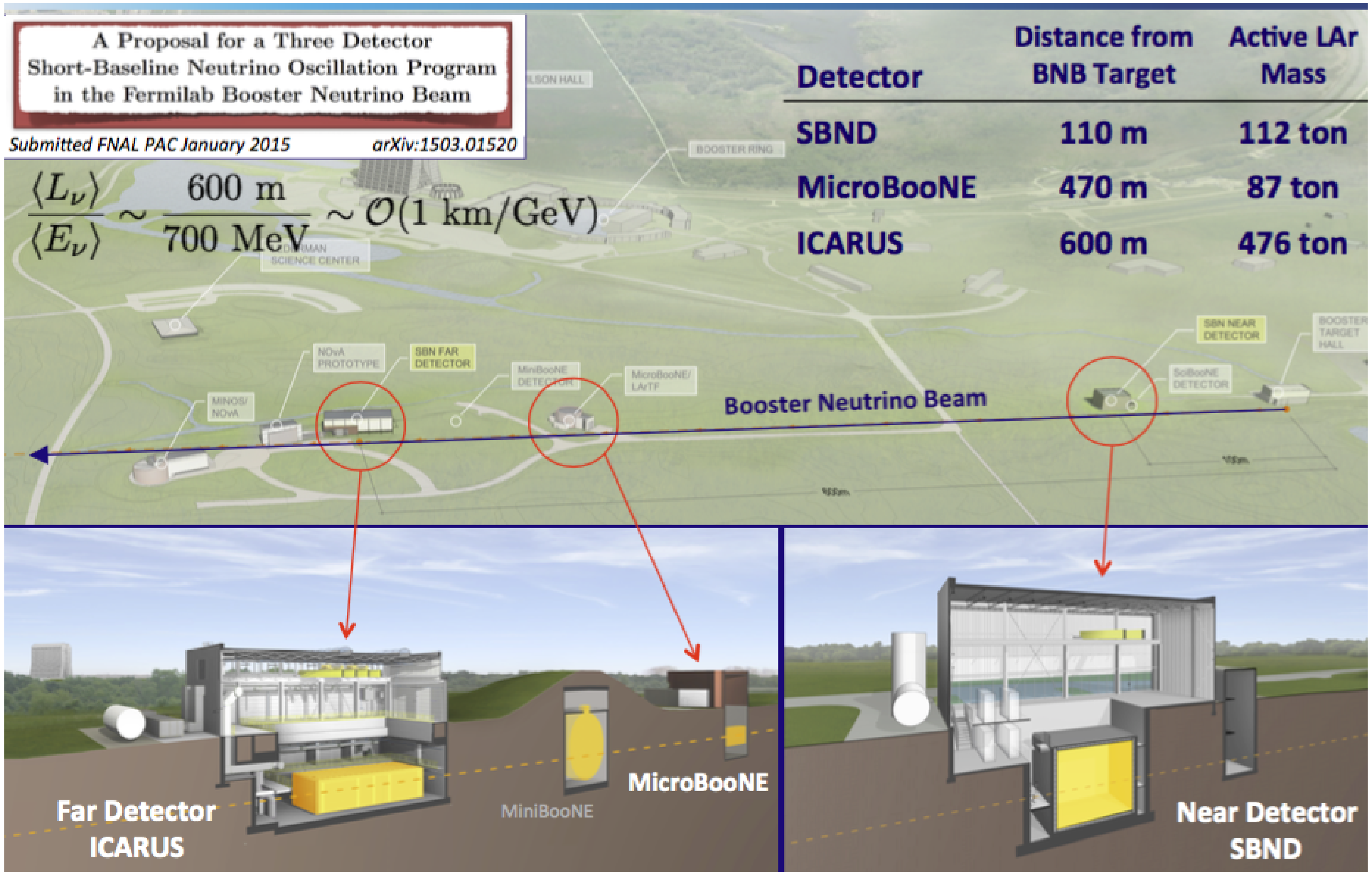
Upgraded Tracker at the T2K off-axis detector (ND280)
Horizontal targets surrounded by TPC $\rightarrow 4\pi$ acceptance + TOF between detectors to improve discrimination between forward μ^- and backward μ^+





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

Near-future measurements @ the Booster beam



Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

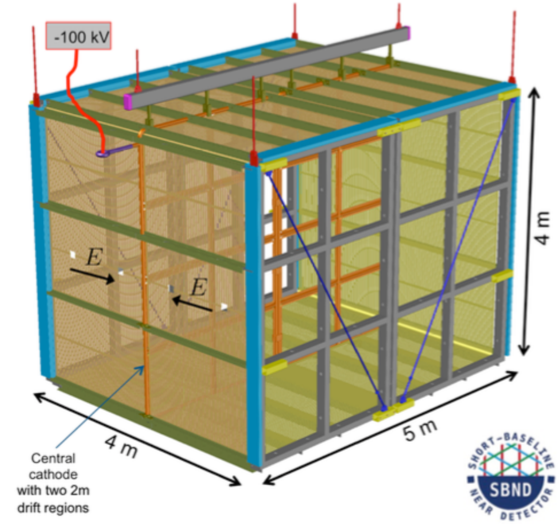
Physics data-taking: SBND: Early 2019, μBooNE: now, ICARUS: 2018.

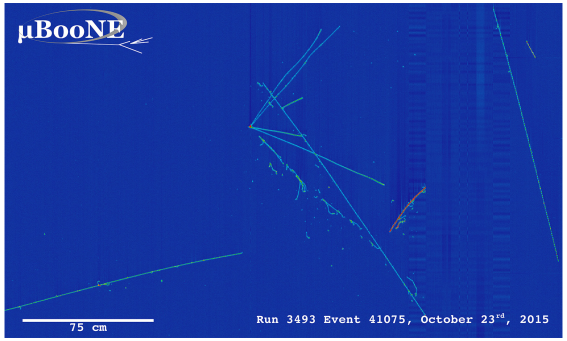
Near-future measurements @ the Booster beam

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 expore of 6.6×10^{20} POT

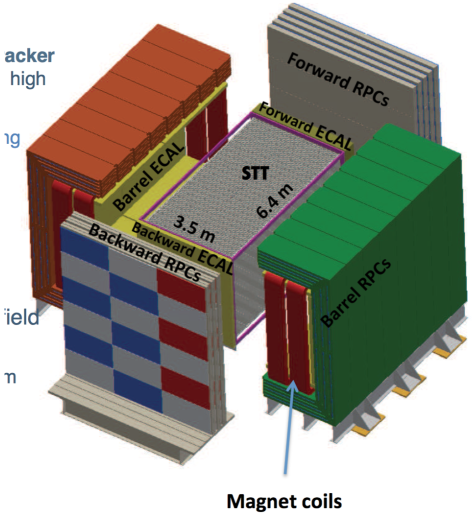
Process		No. Events
	ν_μ *Events (By Final State Topology)*	
CC Inclusive		5,212,690
CC 0 π	$\nu_\mu N \to \mu + Np$	3,551,830
	· $\nu_\mu N \to \mu + 0p$	793,153
	· $\nu_\mu N \to \mu + 1p$	2,027,830
	· $\nu_\mu N \to \mu + 2p$	359,496
	· $\nu_\mu N \to \mu + \geq 3p$	371,347
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ 1\pi^\pm$	1,161,610
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 2\pi^\pm$	97,929
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 1\pi^0$	497,963
NC Inclusive		1,988,110
NC 0 π	$\nu_\mu N \to$ nucleons	1,371,070
NC 1 $\pi^\pm$	$\nu_\mu N \to$ nucleons $+ 1\pi^\pm$	260,924
NC $\geq 2\pi^\pm$	$\nu_\mu N \to$ nucleons $+ \geq 2\pi^\pm$	31,940
NC $\geq 1\pi^0$	$\nu_\mu N \to$ nucleons $+ \geq 1\pi^0$	358,443
	ν_e *Events*	
CC Inclusive		36798
NC Inclusive		14351
Total ν_μ and ν_e Events		7,251,948





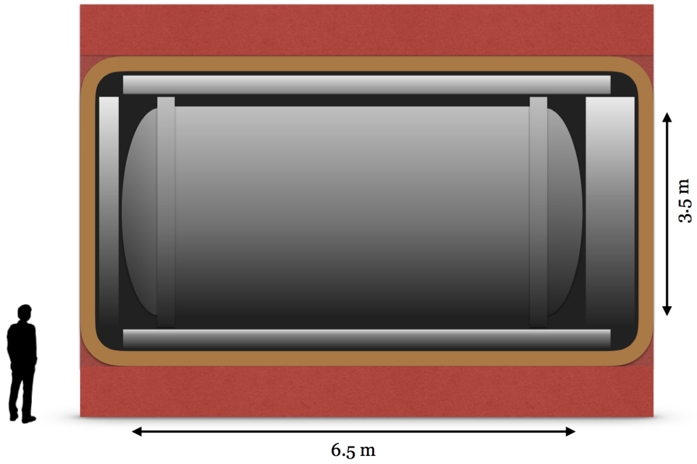
Fine-Grained Tracker

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



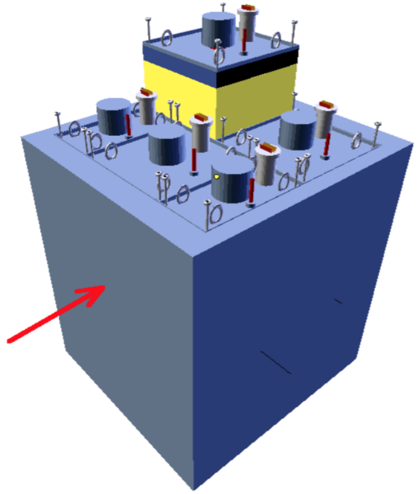
Gas Argon TPC

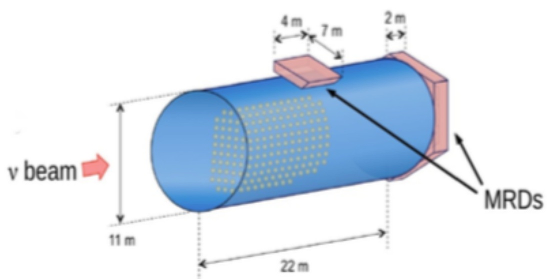
1 tonne of gas Argon at 10 bar pressure in a titanium alloy vessel. In a 0.4 T B field and surrounded by a 4π plastic scintillator ECAL.



Liquid Argon TPC

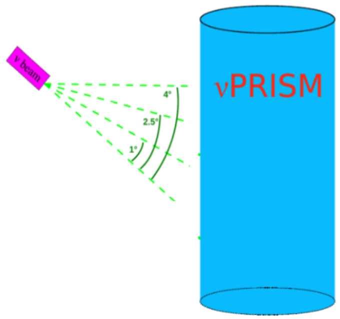
Magnetized, modular LAr TPC sharing common cryostats. Shorter drift times and contained scintillation light in each module. Pixelated charge readout for 3-D reconstruction.





TITUS

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



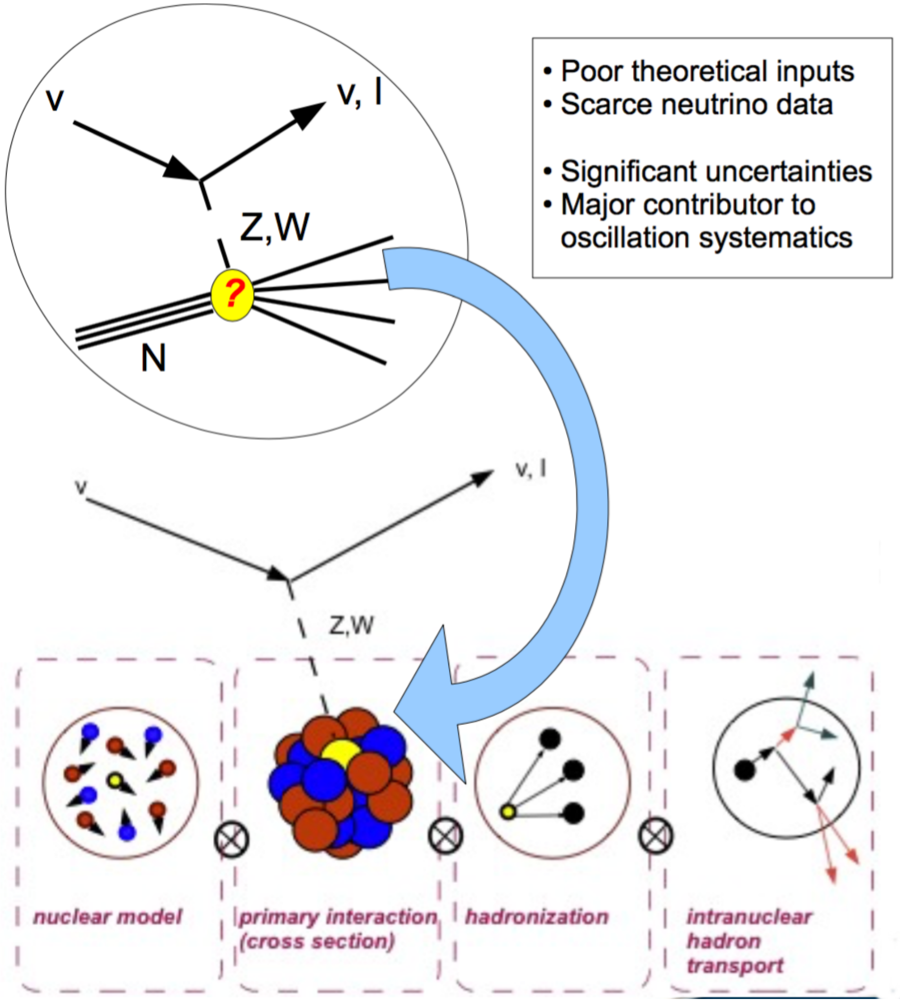
νPRISM

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

(Note: Not in scale)

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:

$$W_{\mu\nu} = W_1 \delta_{\mu\nu} + W_2 p_\mu p_\nu + W_3 \epsilon_{\mu\nu\alpha\beta} p^\alpha p^\beta +$$

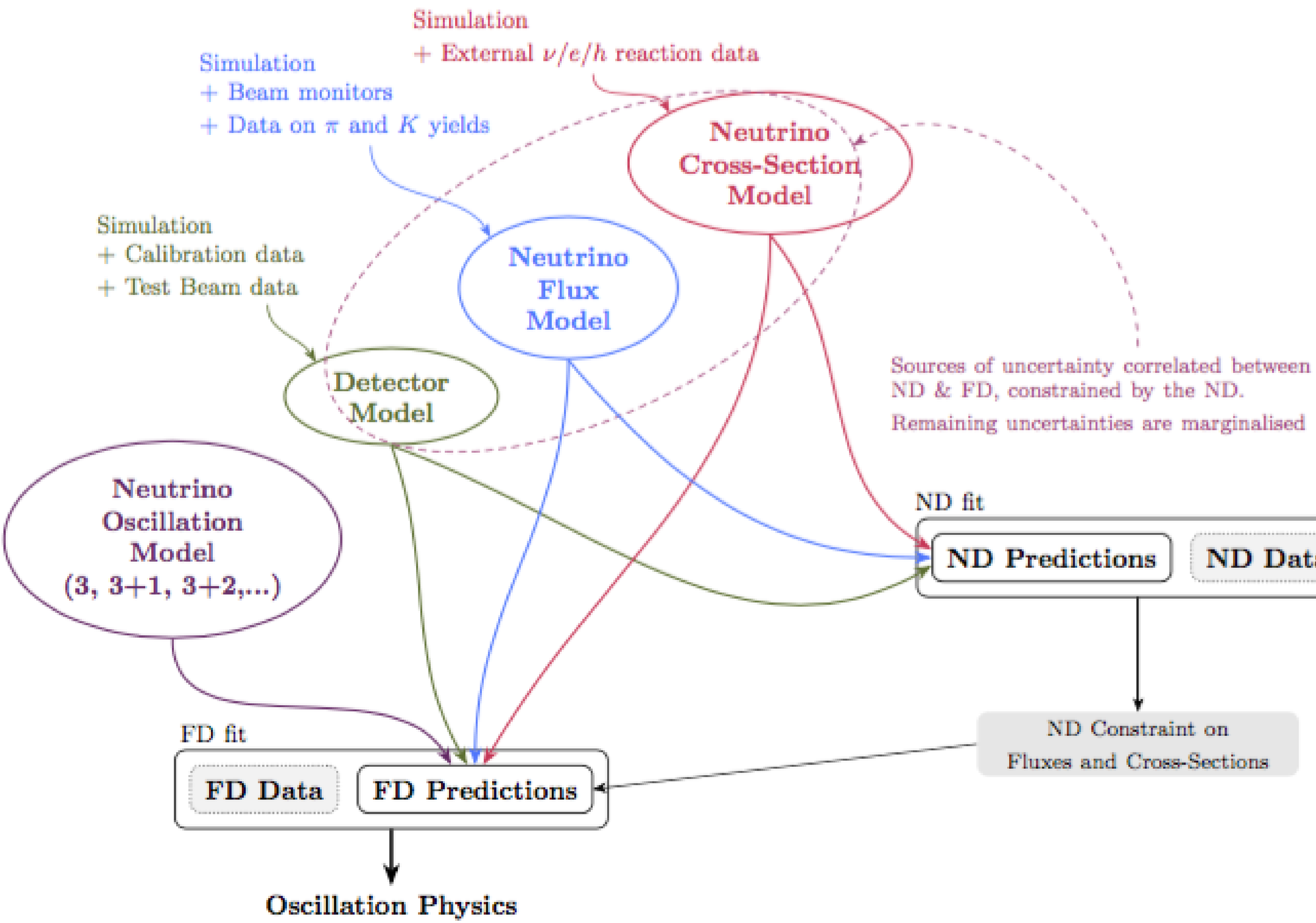
$$+ W_4 q_\mu q_\nu + W_5 (p_\mu q_\nu + p_\nu q_\mu) + W_6 (p_\mu q_\nu - p_\nu q_\mu)$$

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

Neutrino-nucleus simulations by adding effects:

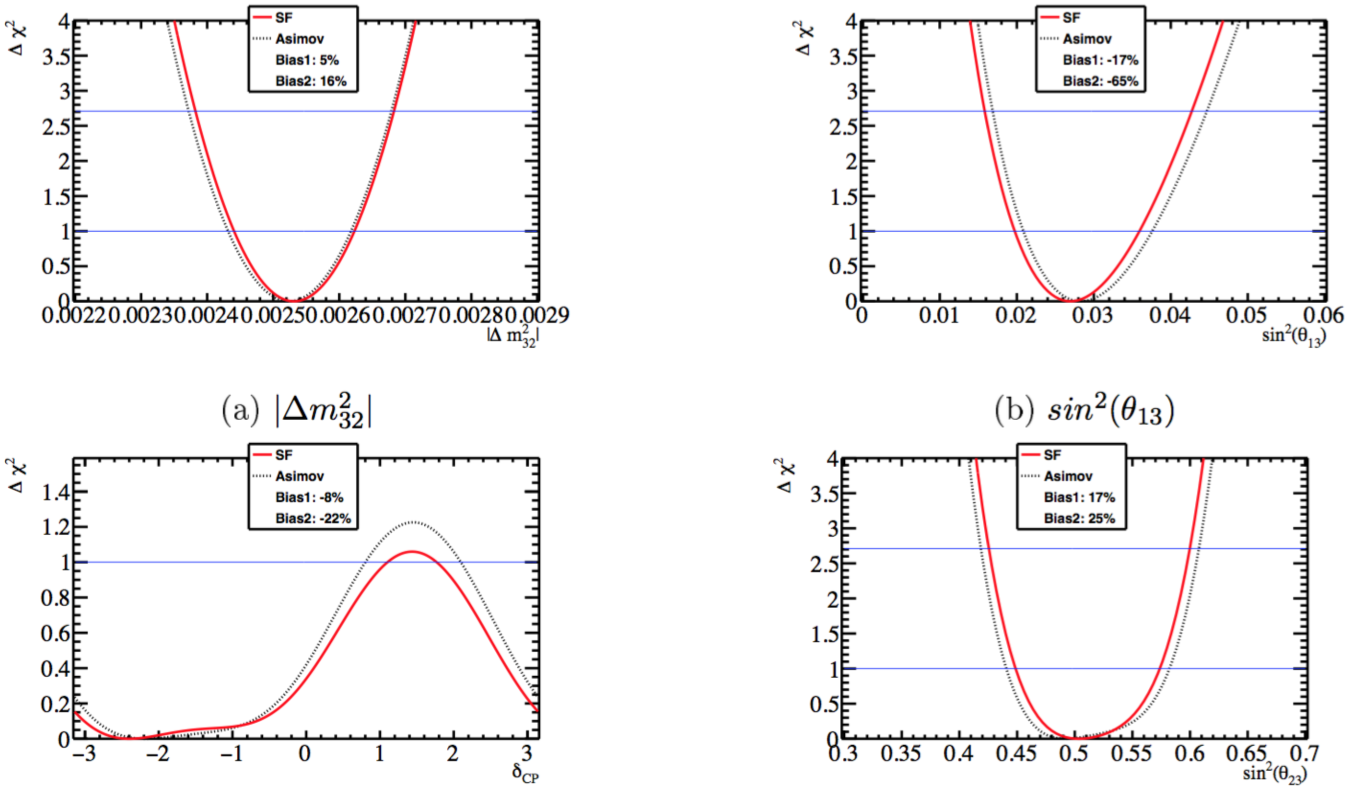
- the initial nuclear state dynamics
- hadronization
- intranuclear hadron transport

Oscillation analysis method



Dependence on cross-section model choices (example)

Effect of Spectral Function model:



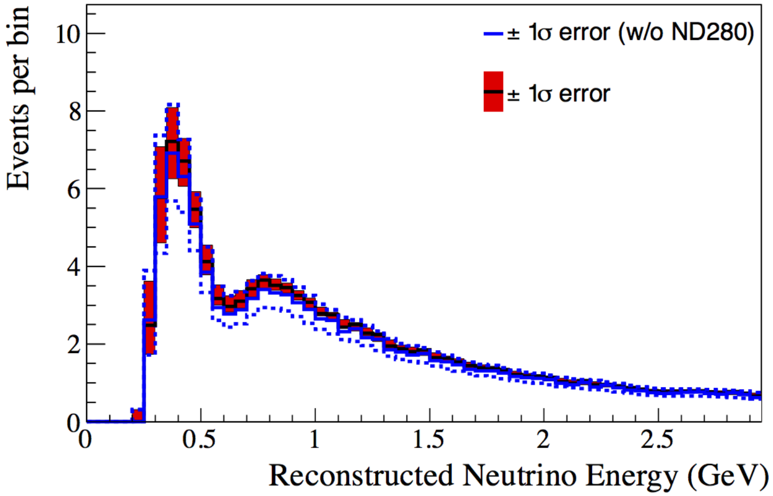
(a) $|\Delta m^2_{32}|$ (b) $sin^2(\theta_{13})$

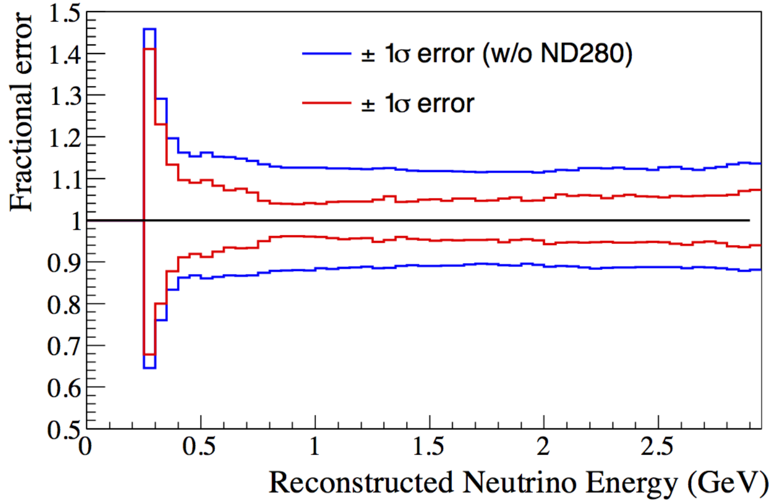
(c) δ_{cp} (d) $sin^2(\theta_{23})$

Using: $\delta_{CP} = -1.601$, $sin^2\theta_{23} = 0.528$, $sin^2\theta_{13} = 0.025$, $sin^2\theta_{12} = 0.306$, Δm^2_{32} $(\Delta m^2_{13}) = 2.509 \times 10^{-3} eV^2/c^4$, and $\Delta m^2_{31} = 7.5 \times 10^{-5} eV^2/c^4$.

Effect of systematics on T2K Far Detector predictions

ν-mode, 1-ring μ-like candidates





ν-mode, 1-ring e-like candidates