Title: Impact of neutrino interaction uncertainties

Date: Jun 13, 2017 11:30 AM

URL: http://pirsa.org/17060009

Abstract:

Why are neutrino interactions important for neutrino physics?

Radiative Corrections at the Intensity Frontier of Particle Physics

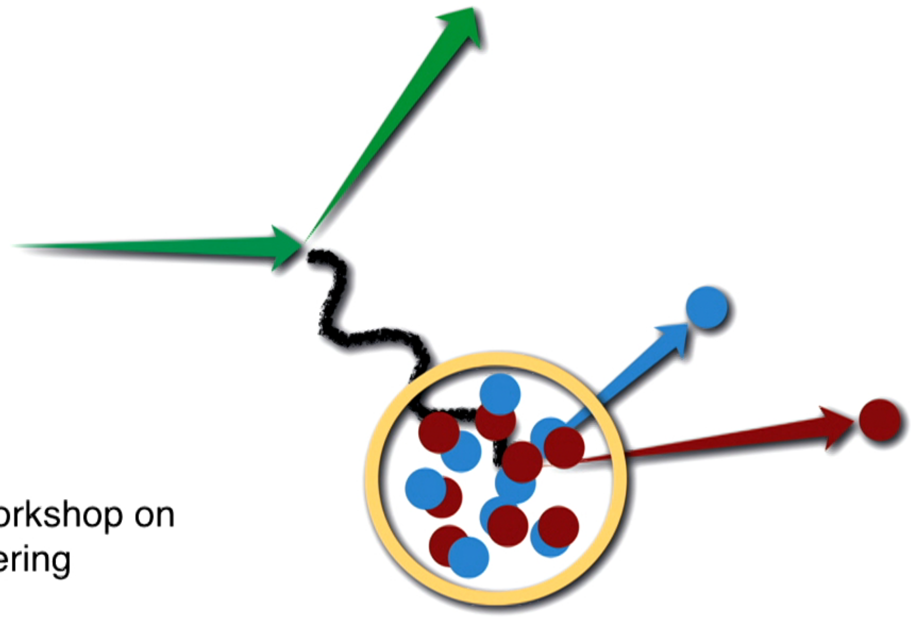
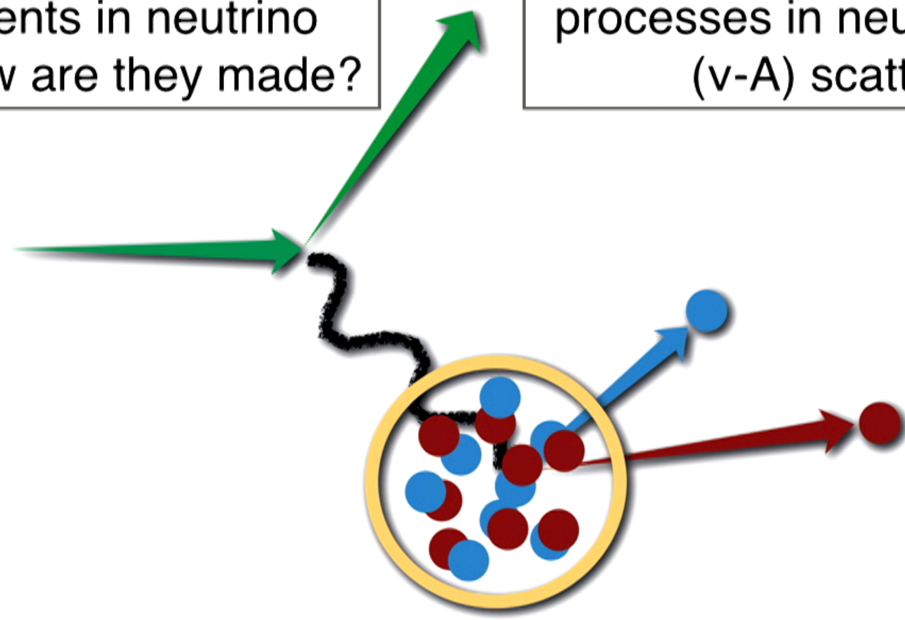


Image from workshop on neutrino scattering (NuInt2014)

Kendall Mahn
Michigan State University

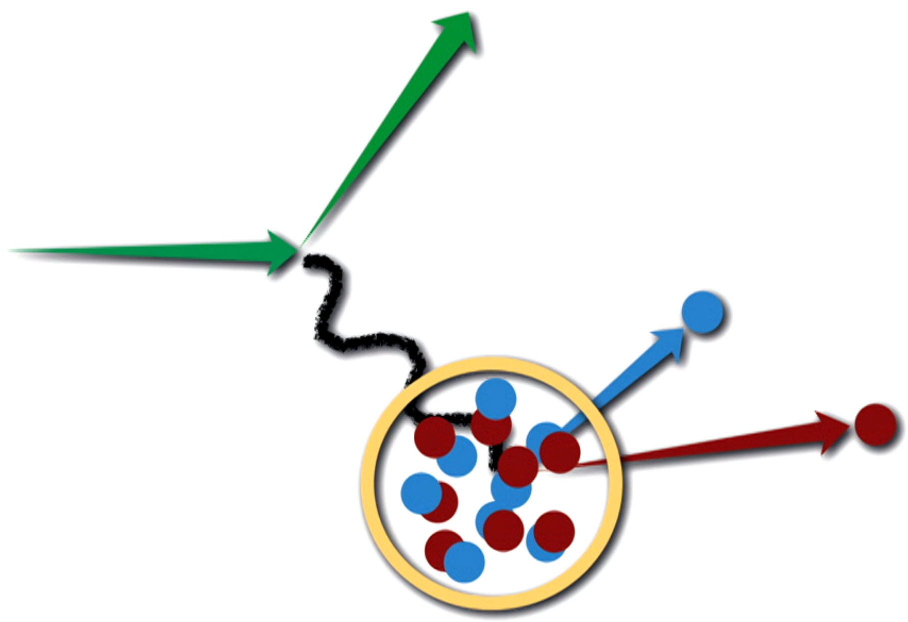
What are the interesting measurements in neutrino physics? How are they made?

What are the relevant processes in neutrino nuclear (ν-A) scattering?



Why is ν-A scattering important to neutrino oscillation and cross section expt's?

Neutrino oscillation



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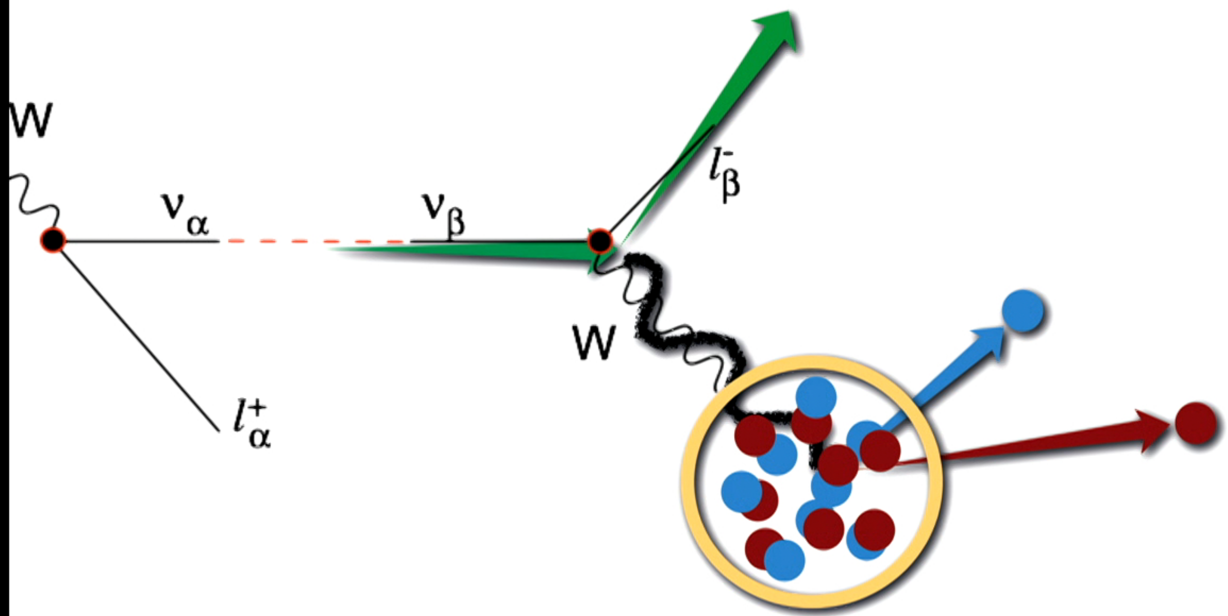

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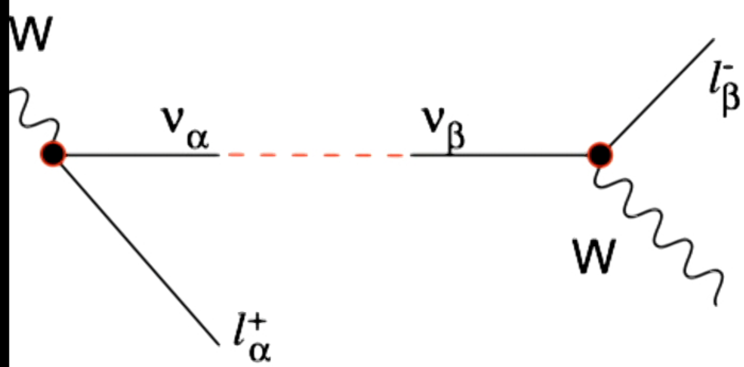
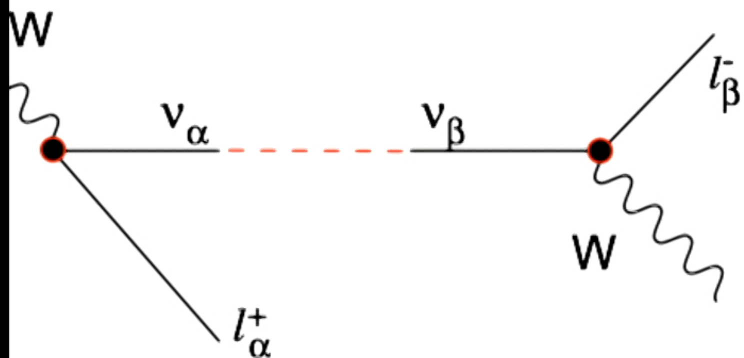


- Interference between mass and flavor eigenstates
- Appearance (beta != alpha) or disappearance (beta = alpha)

Neutrino oscillation



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Interference between mass and flavor eigenstates
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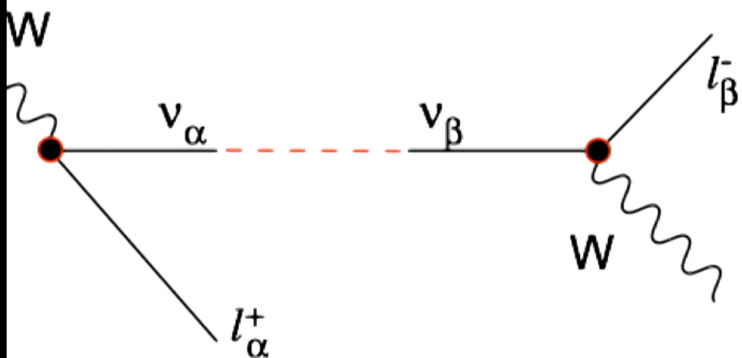
Neutrino oscillation

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}\left[U_{\beta i}U^{*}_{\alpha i}U^{*}_{\beta j}U_{\alpha j}\right]\sin^{2}\left(\frac{1.27\Delta m^{2}_{ij}L}{E}\right) + 2\sum_{i>j}\mathrm{Im}\left[U_{\beta i}U^{*}_{\alpha i}U^{*}_{\beta j}U_{\alpha j}\right]\sin\left(\frac{2.54\Delta m^{2}_{ij}L}{E}\right)$$



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Neutrino oscillation

- Three rotation angles (θ_{12}, θ_{13}, θ_{23})
  - θ_{12}: solar and reactor experiments
  - θ_{13}: reactor and long-baseline (accelerator) experiments
  - θ_{23}: long-baseline and atmospheric experiments
- One complex phase δ_{CP}
  - additional phases if neutrinos are "Majorana", not measured in oscillation experiments

Standard factorization of U

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$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

Standard factorization of U

Current knowledge and open questions

Parameter	best-fit	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99)
		((0.83 – 1.99))

Known: separation of solar
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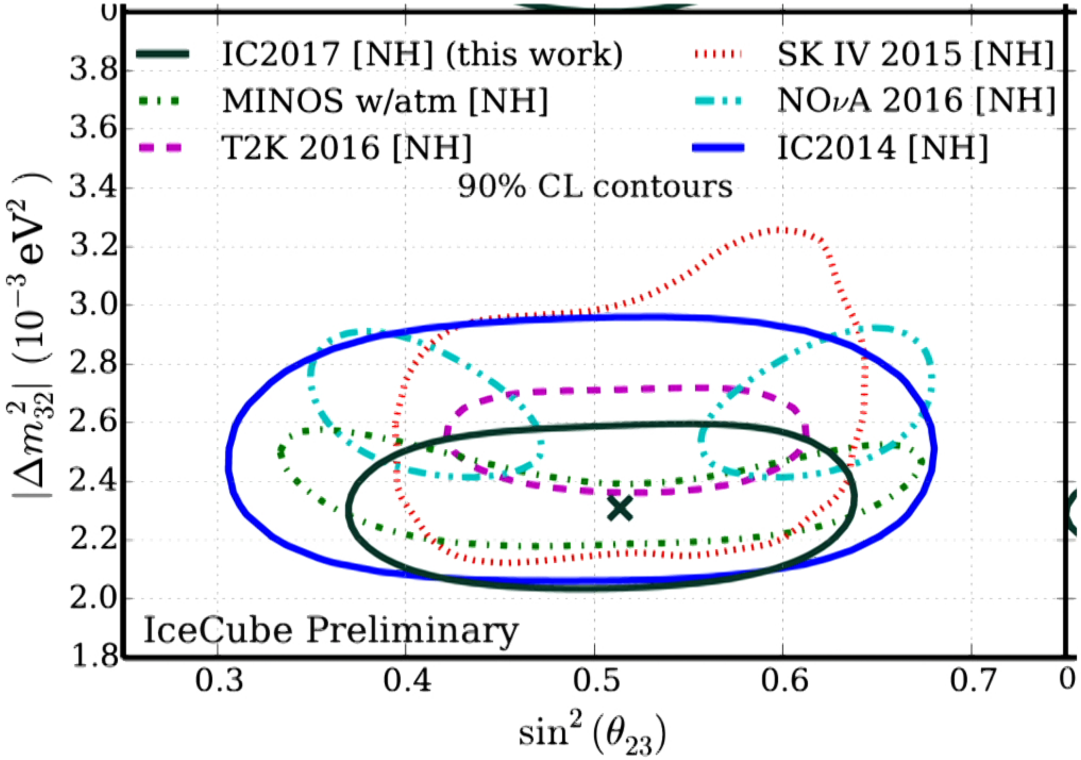
Known: separation of solar and atmospheric splittings

Unknown: ordering of mass splittings (mass hierarchy)

Is there CP violation?

Current knowledge and open questions



The experiments

Current generation:

Accelerator-based: Tokai-to-Kamioka (T2K), NOvA

Atmospheric: IceCube, Super-Kamiokande

Reactor: Daya Bay, RENO, Double Chooz

Future:

Accelerator-based (+ atmospheric): DUNE, Hyper-Kamiokande

Atmospheric: PINGU

Reactor: JUNO

Oscillation probabilities

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2 \Delta m^2_{31}\frac{L}{4E}$$

- Precision measurement of $2\theta_{23}$ and Δm^2_{31}
- CPT tests with antineutrino mode ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)

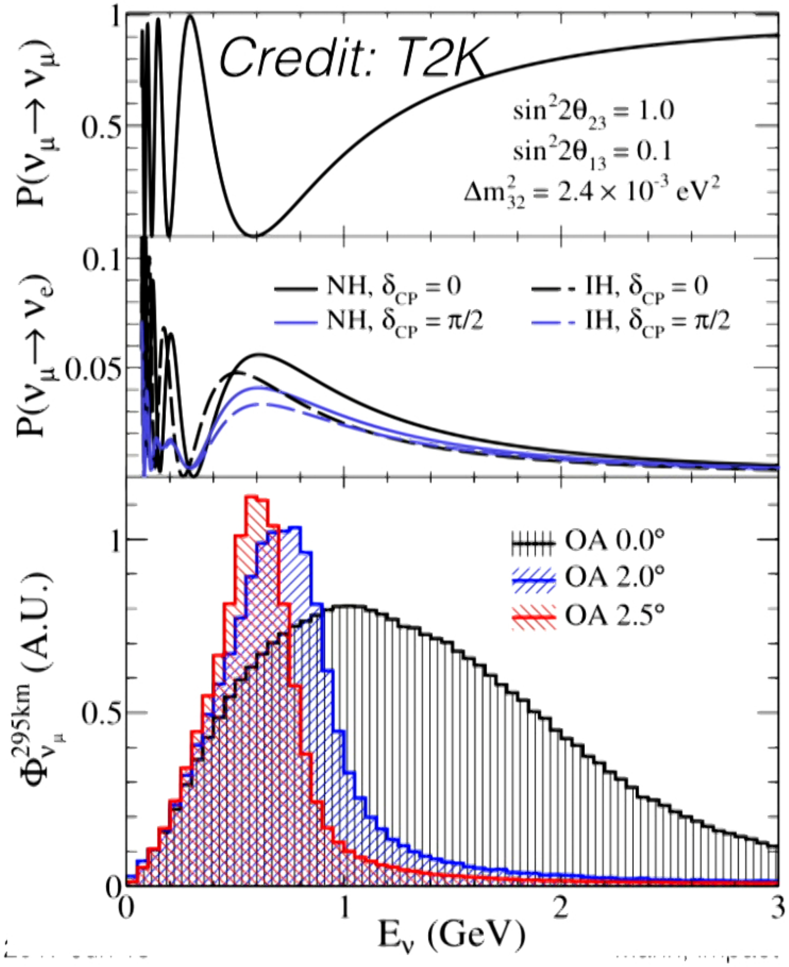
$$\begin{aligned} P(\nu_\mu \to \nu_e) \sim\ & \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\ & -\alpha\sin\delta \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\alpha\cos\delta \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\mathcal{O}(\alpha^2) \end{aligned}$$

$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

M. Freund, Phys.Rev. D64 (2001) 053003

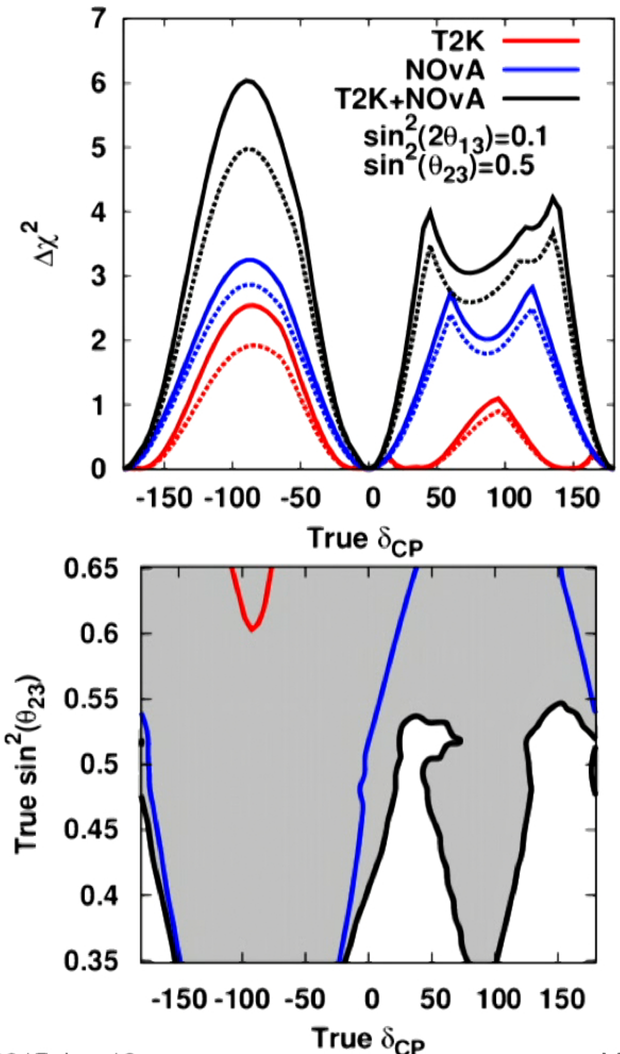
- $\sin^2 2\theta_{13}$ dependence of leading term
- θ_{23} dependence of leading term: "octant" dependence (θ_{23}=/>/<45°?)
- CP odd phase δ: asymmetry of probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if sin δ ≠ 0
- Matter effect through x: $\nu_e(\bar{\nu}_e)$ enhanced in normal (inverted) hierarchy

Details of oscillation experiments



Interdependence of different effects in oscillation probability

- Combined analysis of neutrino and antineutrino data, appearance and disappearance samples
- But, fluxes are different for neutrino vs. antineutrino sources



Prog Theor Exp Phys (2015) 2015 (4): 043C01

- Combinations of different baselines/energies give enhanced physics reach

Aside: What do we know about CP violation?
Slides from Tanaka, Neutrino 2016

- Observe
  - more ν_e candidates than predicted
  - fewer $\bar{\nu}_e$ candidates than predicted

  in the case of NH, δ_{CP} = -π/2 that induces the largest asymmetry

observed vs. expected number of ν_e and ν_e candidates

		EXPECTED (NH, $\sin^2\Theta_{23}$=0.528)			
	OBS.	δ_{CP}=-π/2	δ_{CP}=0	δ_{CP}=+π/2	δ_{CP}=π
ν_e	**32**	27.0	22.7	18.5	22.7
$\bar{\nu}_e$	**4**	6.0	6.9	7.7	6.8

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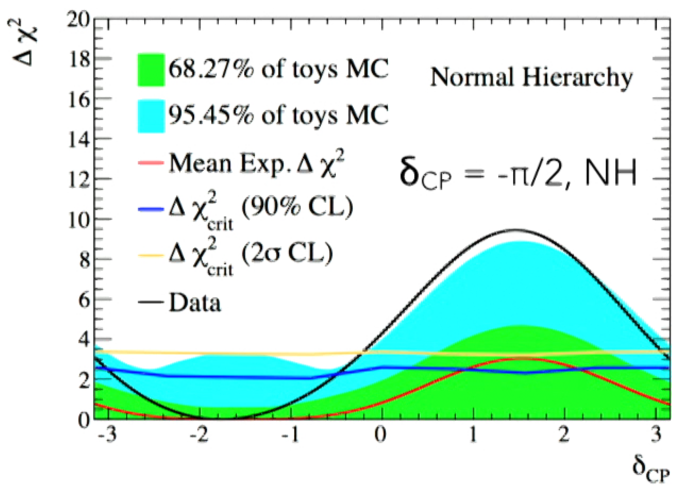
ν_e	32	27.0	22.7	18.5	22.7
$\bar{\nu}_e$	4	6.0	6.9	7.7	6.8



- Toy MC run to assess probability of outcome given a set of "true" parameters
- Below: fraction where δ_{CP} =0 excluded at 90% or 2 σ CL for NH, δ_{CP} = -π/2, 0

	TRUE PARAMETERS δ_{CP}=-π/2, NH	δ_{CP}=0, NH
90%	0.187	0.102
2 σ	0.089	0.047

Aside: What do we know about CP violation?

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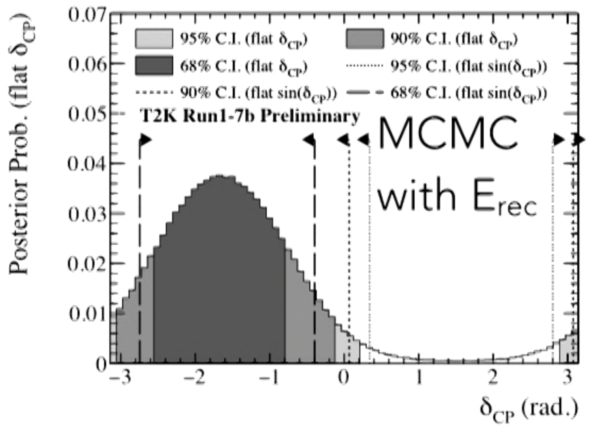

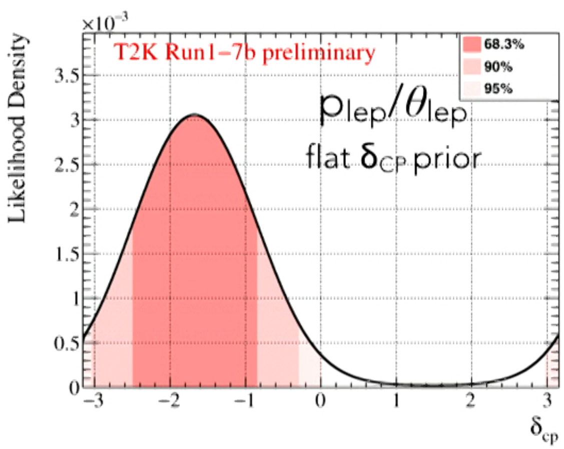

- Left: posterior probability distribution in δ_{CP} marginalizing over all other parameters
  - negligible dependence on priors except for δ_{CP}
    - (flat in δ_{CP} vs. $\sin \delta_{CP}$)

Aside: What do we know about CP violation?
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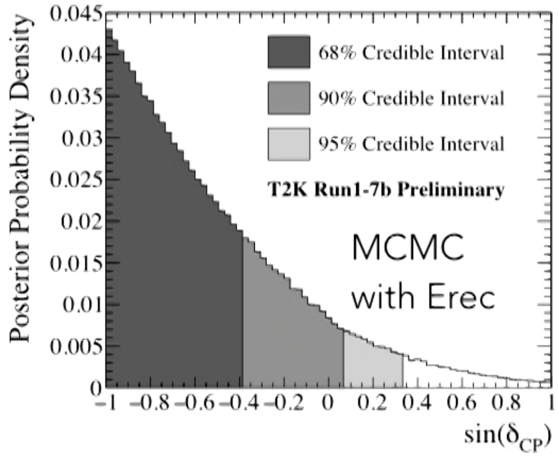

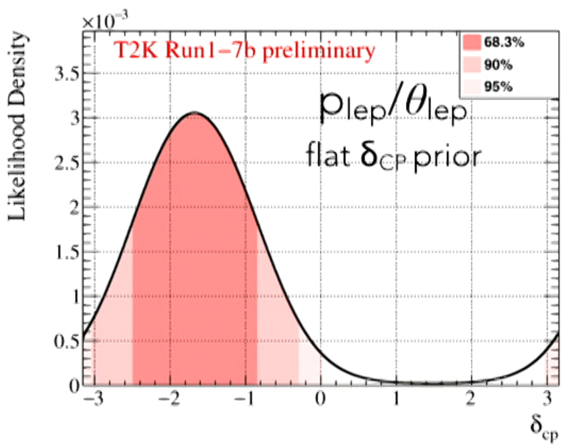

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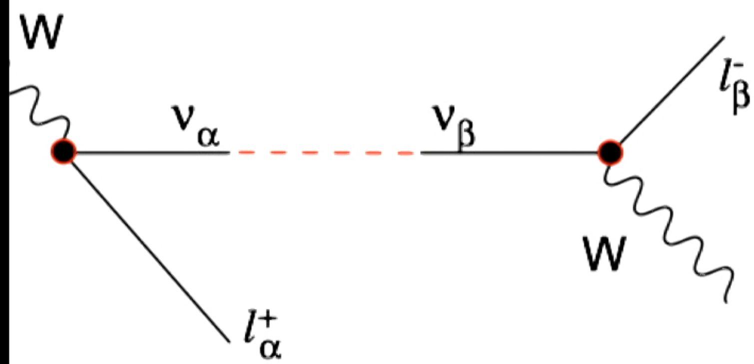
Aside: What do we know about CP violation?
Slides from Tanaka, Neutrino 2016

- Posterior probability distributions for θ_{23} octant and hierarchy with MCMC analysis
  - mild preference for $\theta_{23} > \pi/4$ and normal hierarchy

	NH	IH	SUM
$\sin^2\theta_{23} \leq 0.5$	0.218	0.072	0.290
$\sin^2\theta_{23} > 0.5$	0.529	0.181	0.710
SUM	0.747	0.253	1.000

What about non-standard effects?

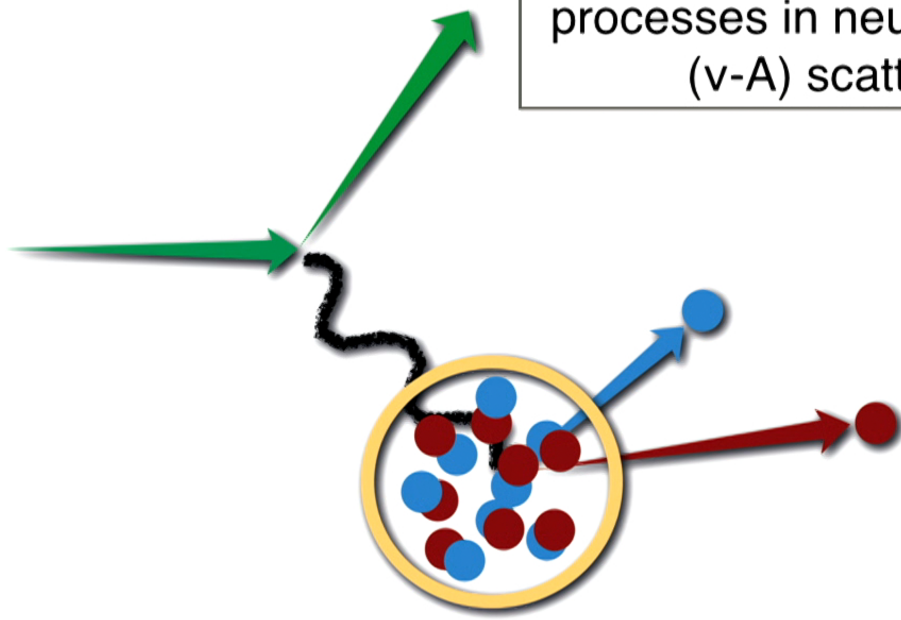
See Andre's talk



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & \cdots & U_{eN} \\ U_{\mu 1} & U_{\mu 2} & \cdots & U_{\mu N} \\ U_{\tau 1} & U_{\tau 1} & \cdots & U_{\mu N} \\ \vdots & \vdots & \ddots & \vdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_N \end{pmatrix}$$

- Light sterile neutrinos: anomalous appearance or disappearance through sterile. Similar setup to "standard oscillation" except shorter distances
  - Short baseline neutrino program at Fermilab
  - Long baseline neutral current disappearance
- Non-Standard Interactions (at source, or detector via matter effects), often constrained by charged lepton data
- Tests of unitarity of mixing matrix

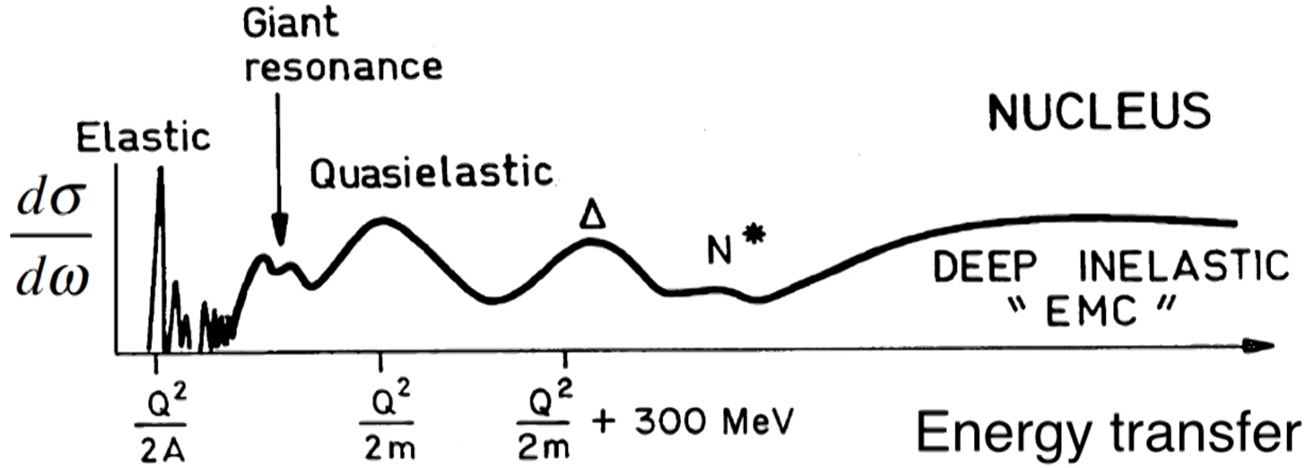
What are the relevant processes in neutrino nuclear (ν-A) scattering?



For these details and more, (Neutrino Scattering Theory Experiment Collaboration (NuSTEC) White Paper:
https://arxiv.org/abs/1706.03621
Subscribe to newsletter (backups)

Processes in Neutrino Scattering

B Foris, and C N Papanicolas, Electron Scattering and Nuclear Structure



- Reactor energies: cross section well known
- Need charged current (CC) interactions to detect flavor
- Neutral current (NC) also relevant (backgrounds, non-standard oscillation)

Processes in Neutrino Scattering

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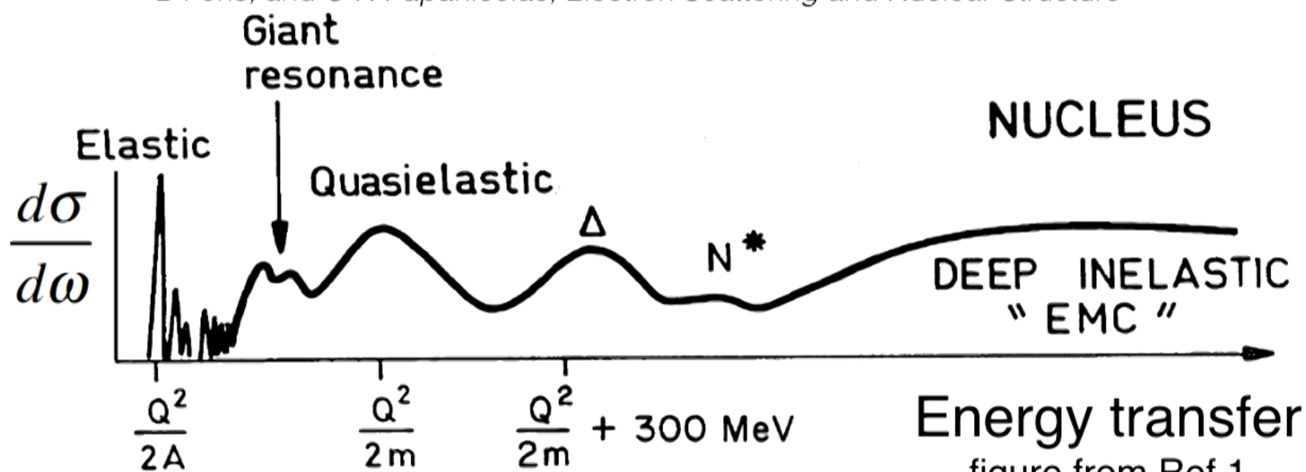
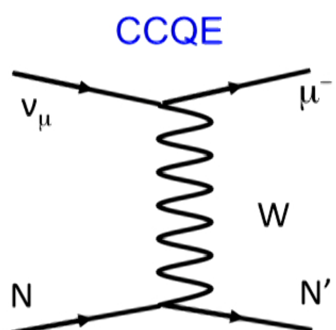


figure from Ref 1

- Charged Current Quasi Elastic (CCQE) and multinucleon processes (2p2h)



Observable

neutrino (anti)

- muon or electron (+)
- proton (neutron)

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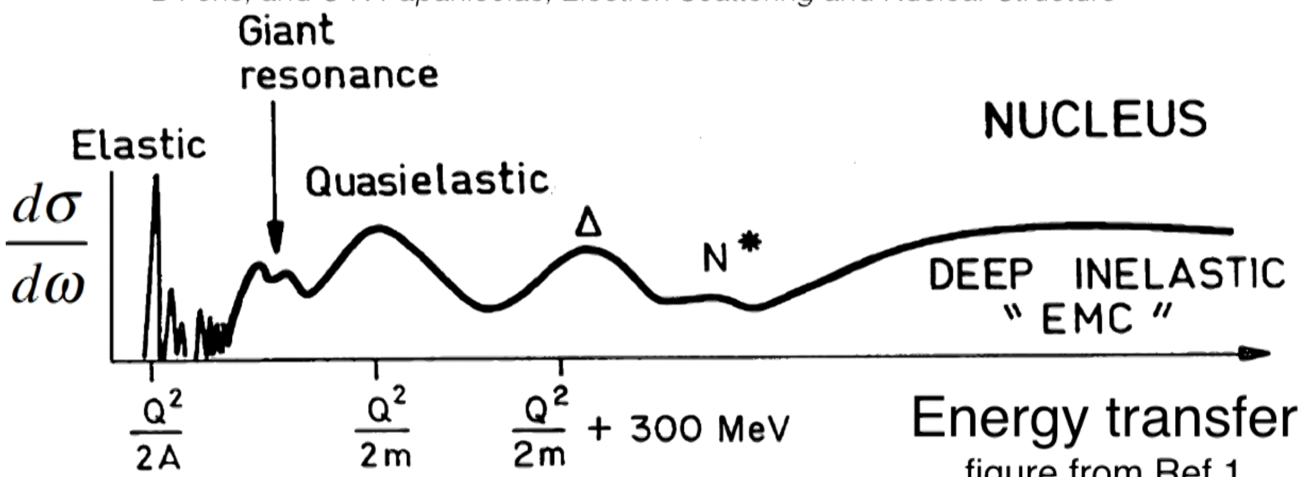

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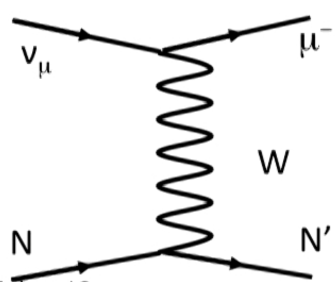
CCQE



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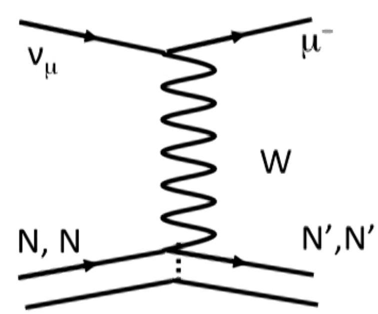

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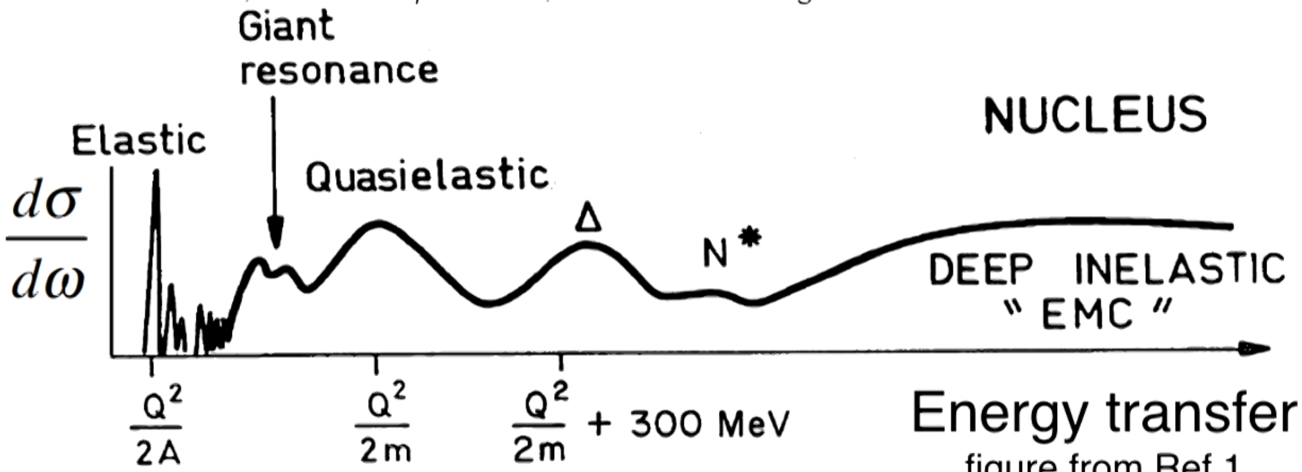
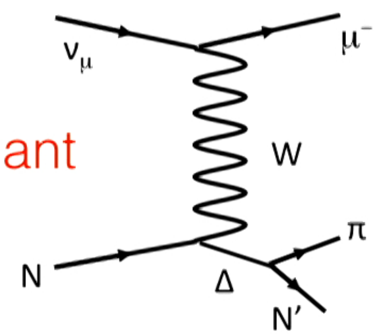


figure from Ref 1

- Production of pions, $CC1\pi^{+/0/-}$ and $NC1\pi^{+/0/-}$

CCπ

resonant



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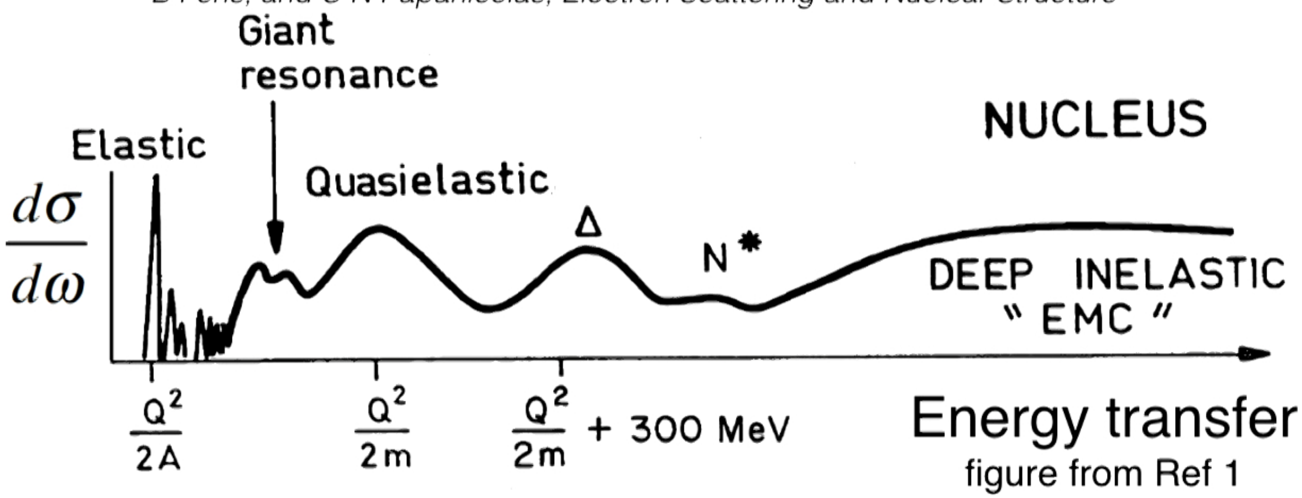

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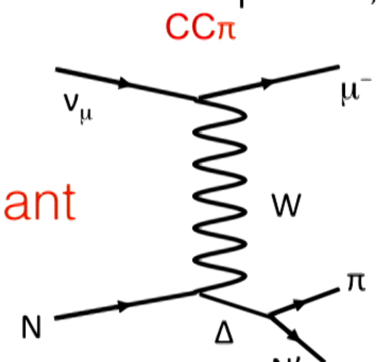
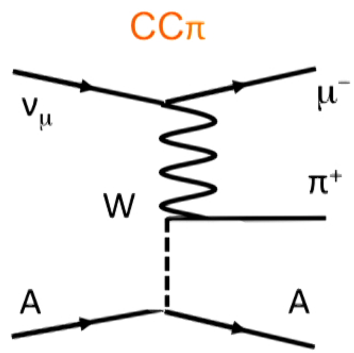
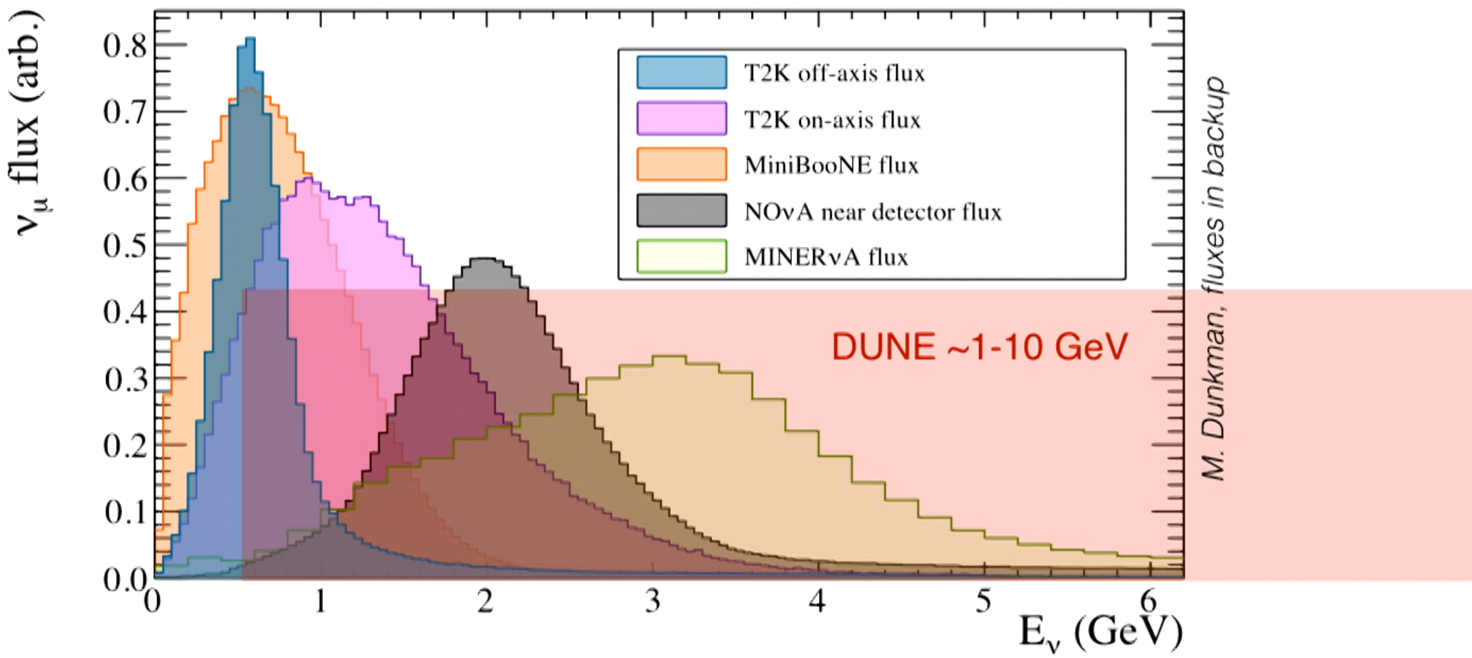


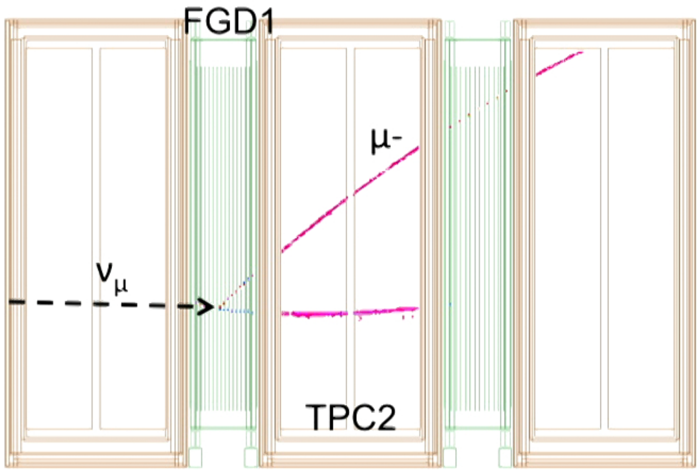


Neutrino Sources and Nuclear Effects



- Neutrino decay-in-flight beams are **not mono-energetic**
  - Spread of beam is larger than nuclear effects
- **Nuclear target** needed for experimental statistical sample size

Nuclear effects: process vs. topology



T2K experiment example

- CC0π "topology": 1 muon, no pion
- Includes CCQE, 2p2h, CC1π (pion absorbed in nucleus)

An overly generic oscillation analysis

$$N_{\mathrm{FD}}^{\alpha\to\beta}(\boldsymbol{p}_{\mathrm{reco}}) = \sum \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma_\beta^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}}; \boldsymbol{p}_{\mathrm{reco}})$$

Rate is a combination of:

- Flux
- Oscillation probability
- All processes which contribute to the topology
- Efficiency
- Relationship (R) between inferred and true energy of the process from kinematics

An overly generic oscillation analysis

$$N_{\mathrm{FD}}^{\alpha\to\beta}(\boldsymbol{p}_{\mathrm{reco}}) = \sum \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma_\beta^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}};\boldsymbol{p}_{\mathrm{reco}})$$

$$N_{\mathrm{ND}}^{\alpha}(\boldsymbol{p}_{\mathrm{reco}}) = \sum \phi_\alpha(E_{\mathrm{true}}) \times \sigma_\alpha^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}};\boldsymbol{p}_{\mathrm{reco}})$$

Near detector provides event rate (constrains flux, cross section and (some) of the detector response). Inherent difficulties:

1. Energy dependance enters in integral over energy due to P
2. ν_e appearance (but ND measures ν_μ rate)
3. Not pure flavor beam (neutrino and antineutrino contributions)
4. Wide flux spectrum (not possible to isolate cross section processes)
5. Small differences in flux and detector response of ND and FD
6. Correct association between true and reconstructed variables

The problem

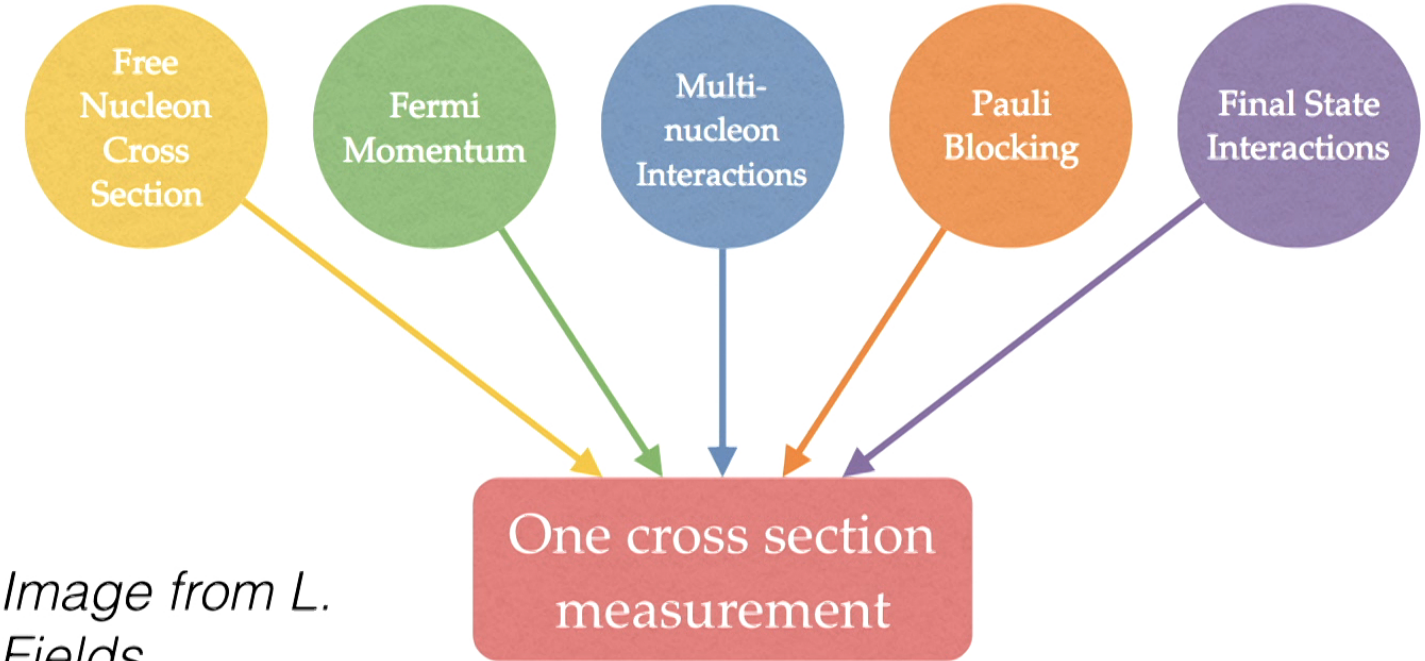
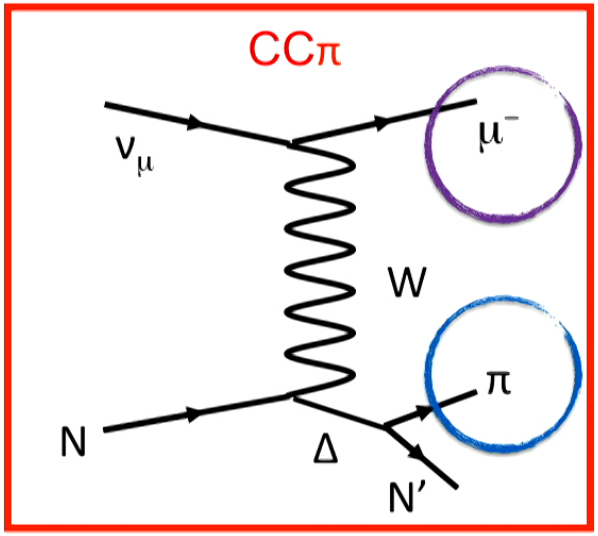


Image from L. Fields

- Measurements are sensitive to multiple physics effects on signal and background processes

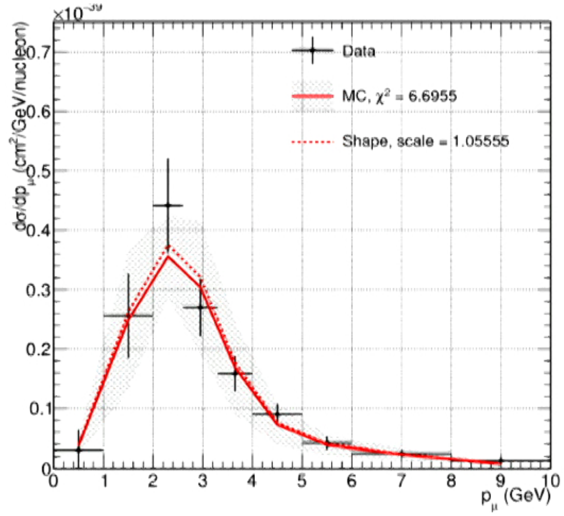
Example: Single Pion Production Puzzles

- Important background (and signal) process for oscillation (non-standard) physics
- **Challenge to model!**
  - non-resonant backgrounds?
  - pion re-interaction (final state interaction) model?
  - Busted single nucleon model?
- Example from NUISANCE software framework in references thanks to C. Wilkinson - *work in progress*
- *Related work in Gabe's talk*



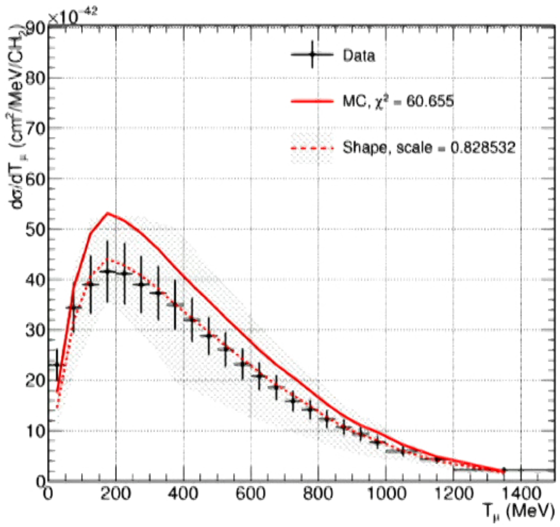
Single Pion Production Puzzles

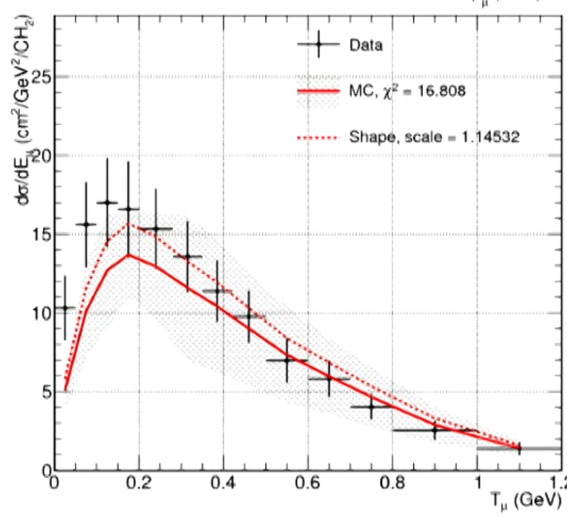
- **Reasonable agreement in outgoing muon spectrum**
- Terrible agreement in outgoing pion spectrum
- Model development essential



MIN $\bar{\nu}_\mu$-CH CC1π^0
PRD 94 (2016) 052005

MB ν_μ-CH$_2$ CC1π^+
PRD 83 (2011) 052007





MB ν_μ-CH$_2$ CC1π^0
PRD 83 (2011) 052009

TENSIONS2016 Workshop

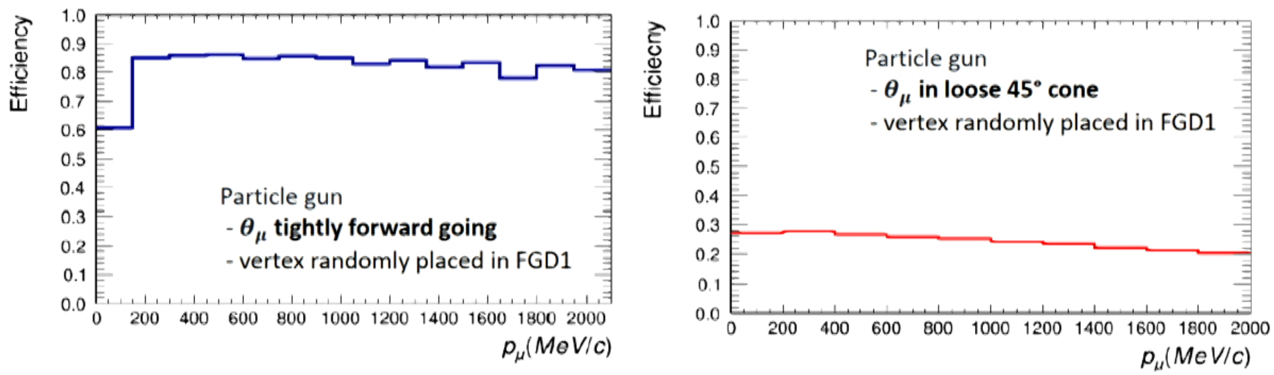
Inability to reconcile MiniBooNE, MINERvA QE-like, and single pion measurements within a single model (“data tensions”)

- T2K attempts to fit [QE: PRD93 no.7, 072010 (2016)]
- Single pion pain

Motivated a workshop (writeup underway) to understand:

- Differences in signal definition? Selection? Extraction?
- **Role of efficiency in cross section measurements**

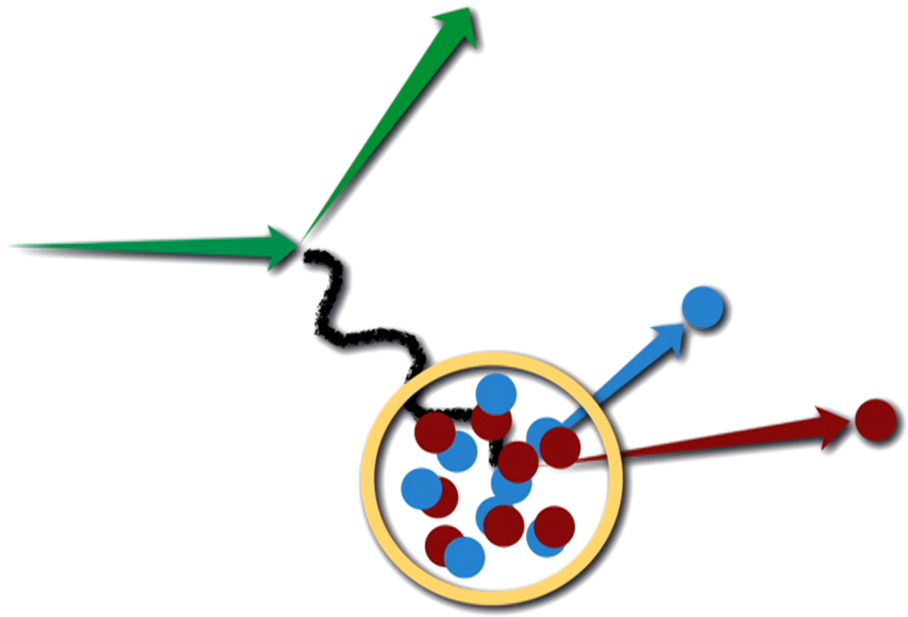
- **Example 1** – want to measure p_μ for single muons using TPC.
  - The efficiency is very dependent on the underlying θ_μ distribution.
  - The underlying θ_μ distribution depends on the neutrino scattering model



Credit: S. Dolan, T2K-XSEC workshop and State of Nu-tion speaker

Need correct angular and momentum distributions for signal/background processes!

- Getting latest models (and appropriate uncertainty) into software to use



Why is ν-A scattering important to neutrino oscillation and cross section expt's?

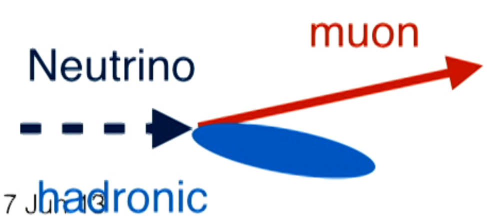
Impact of alternate models on oscillation physics

Why is ν-A important for oscillation expts?

- Oscillation depends on energy
  - Estimate from hadronic and/or leptonic information

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)} \qquad E_\nu = E_\mu + \sum E_{hadronic}$$

- Nuclear effects bias true and estimated neutrino energy



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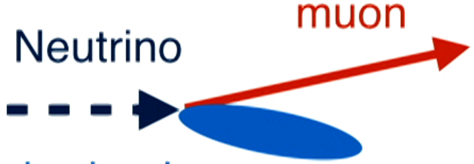

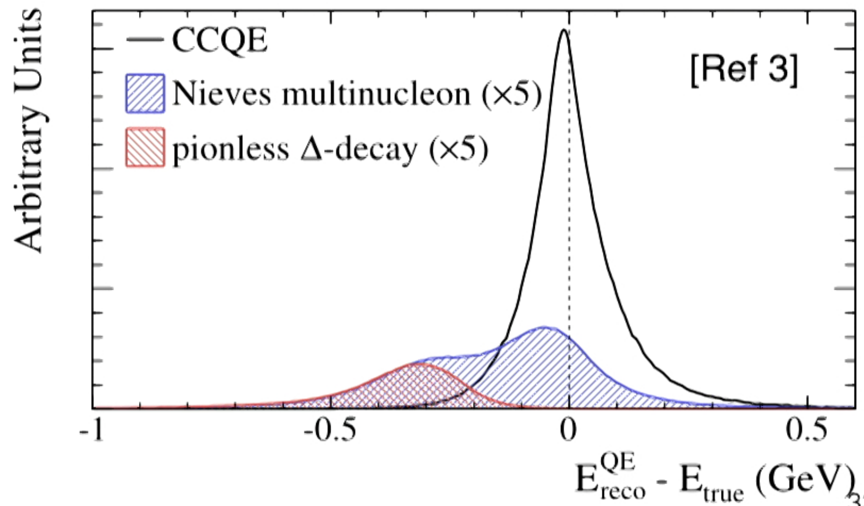

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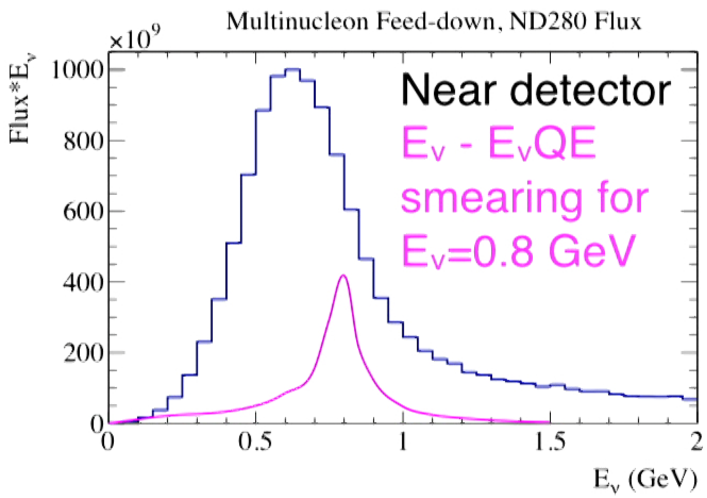
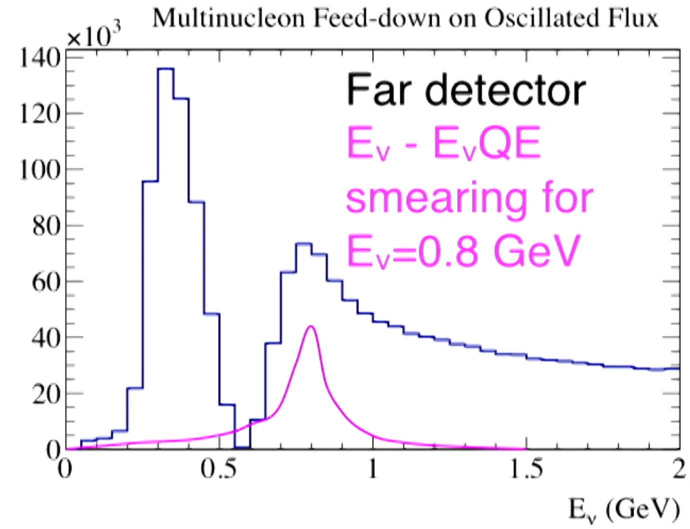




$$ND(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{ND}$$

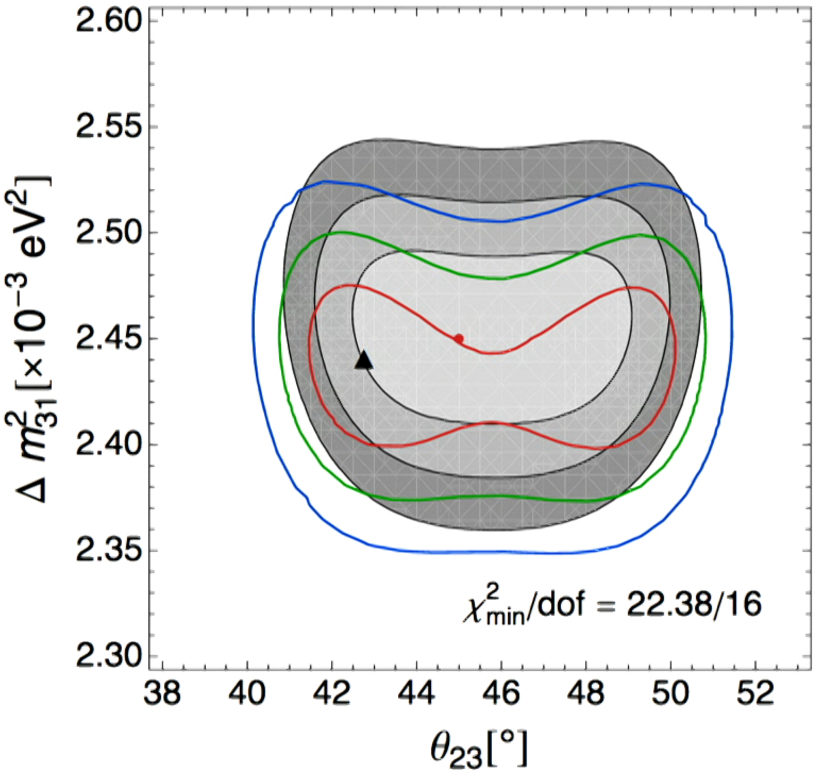
$$FD(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{FD} \times P(\nu_\mu \rightarrow \nu_e)$$

- Even with a near detector, **critical reliance on model**
  - QE method assumptions: 2p2h feed-down to oscillation peak from [Ref 4]
  - Hadronic method assumptions: particle multiplicity, detection threshold

Effect of ν-A on oscillation physics

- **Model choice determines:**
- Size of effect on oscillation physics
- Parameterization of the ν-A uncertainties

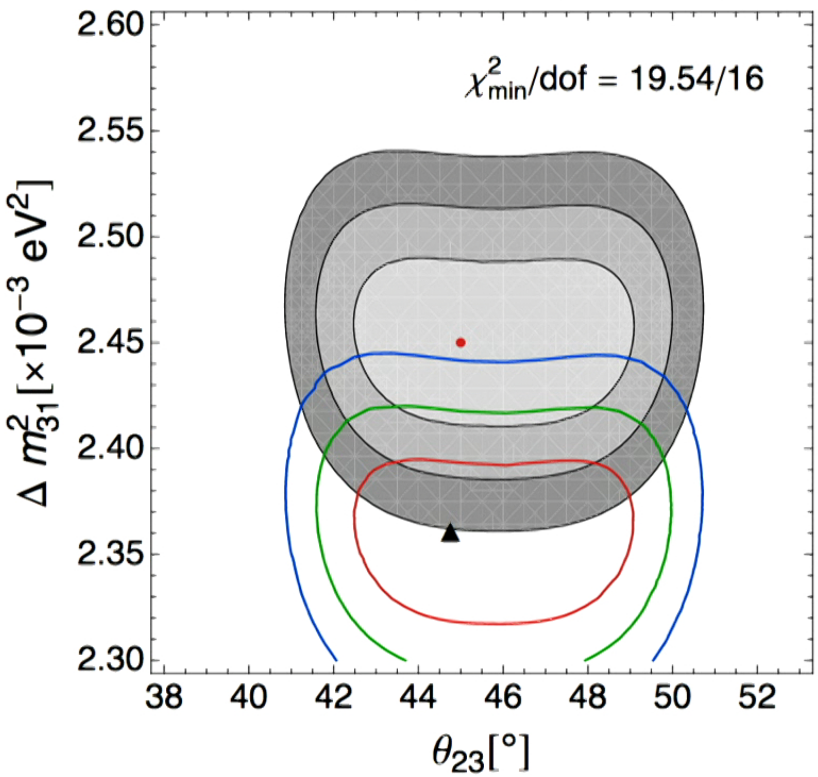
P. Coloma et al, PRD 89, 073015 (2014)



Effect of ν-A on oscillation physics

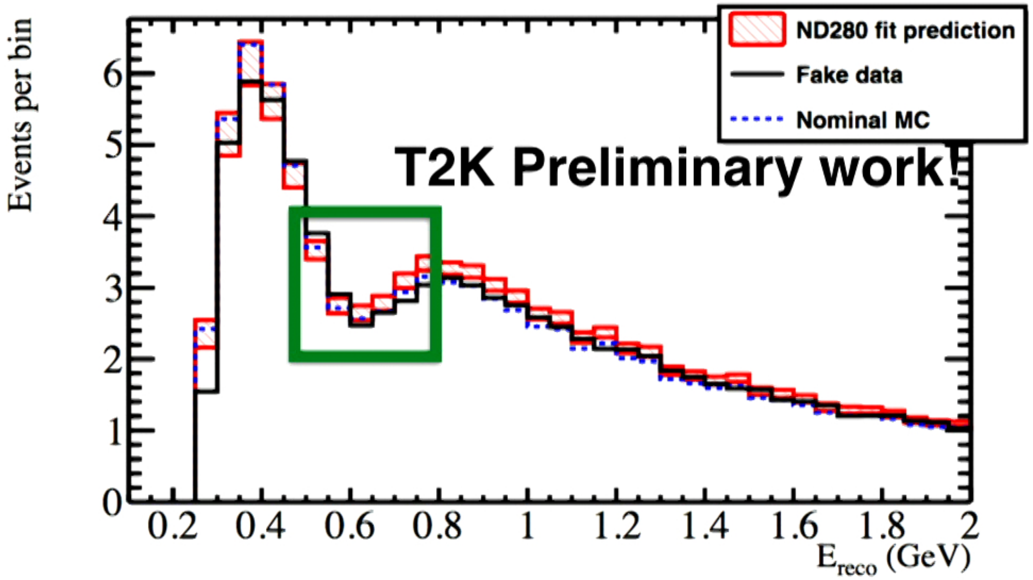
- **Model choice determines:**
- Size of effect on oscillation physics
- Parameterization of the ν-A uncertainties
- Which oscillation parameter(s) are affected
- Which method (QE or calormetric) is used

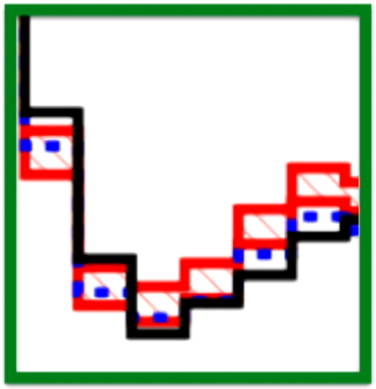
P. Coloma et al, PRD 89, 073015 (2014)



An example of the pitfalls

- Take a QE model of interest (full simulation or likely, smeared simulation)
- Run entire T2K oscillation analysis chain (fit ND, propagate uncertainties, fit neutrino, antineutrino samples) and evaluate effect on oscillation parameters





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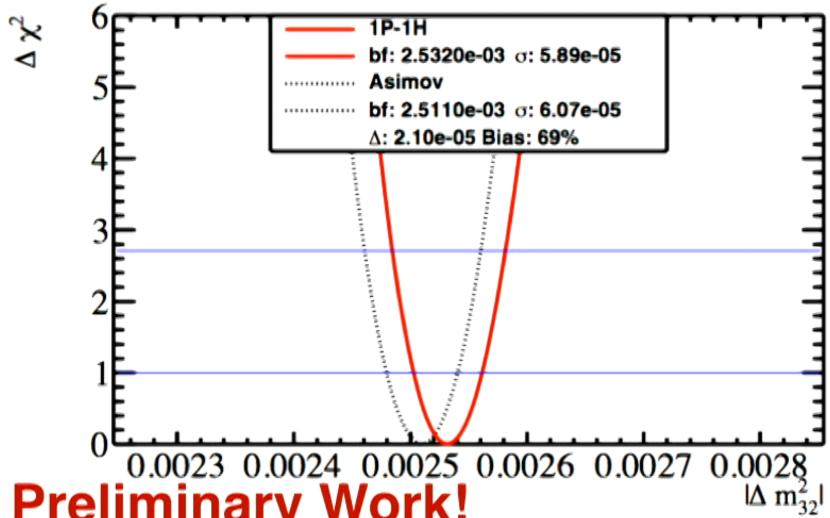
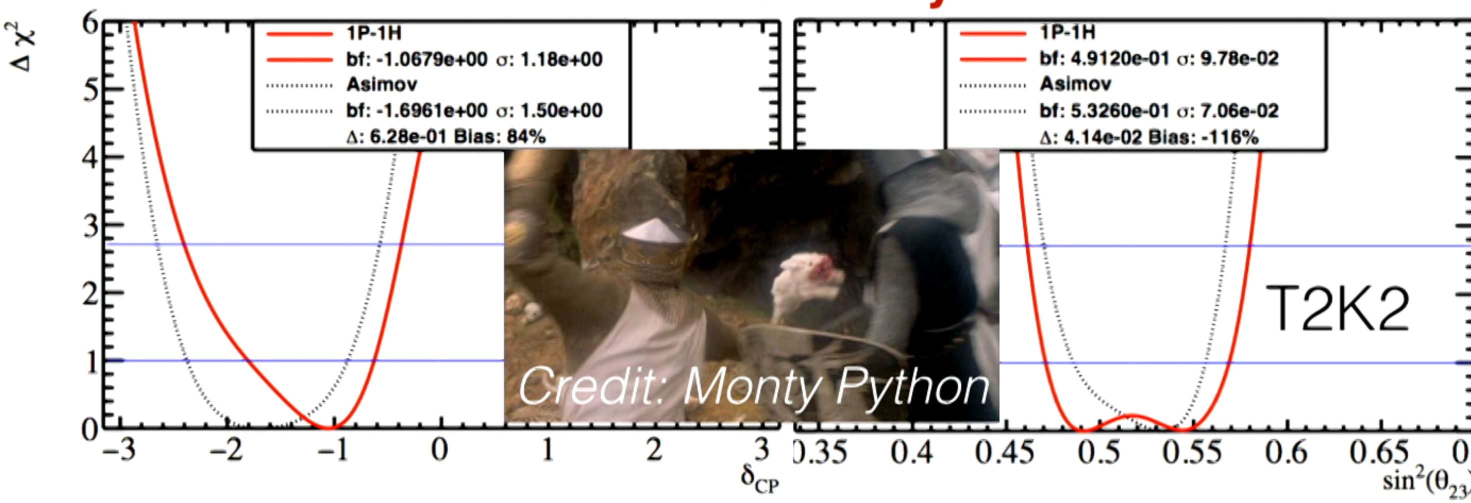
An example of the pitfalls

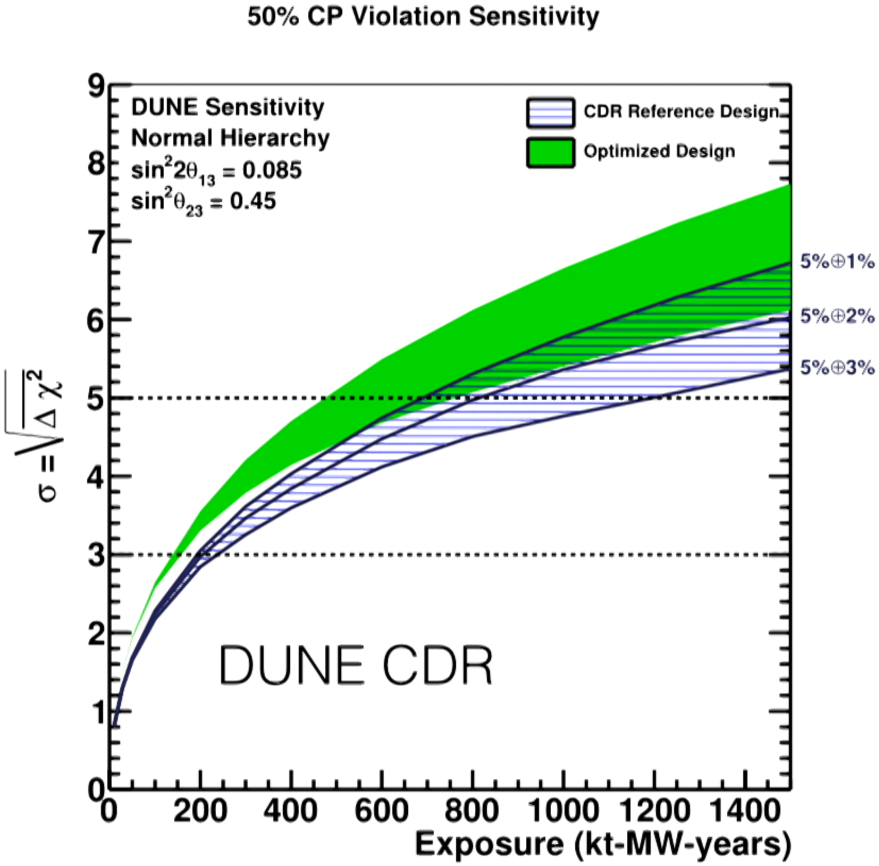
- For an extended run of T2K, significant bias possible.
- Creation of multiple minima
- We mustn't run away!



T2K Preliminary Work!

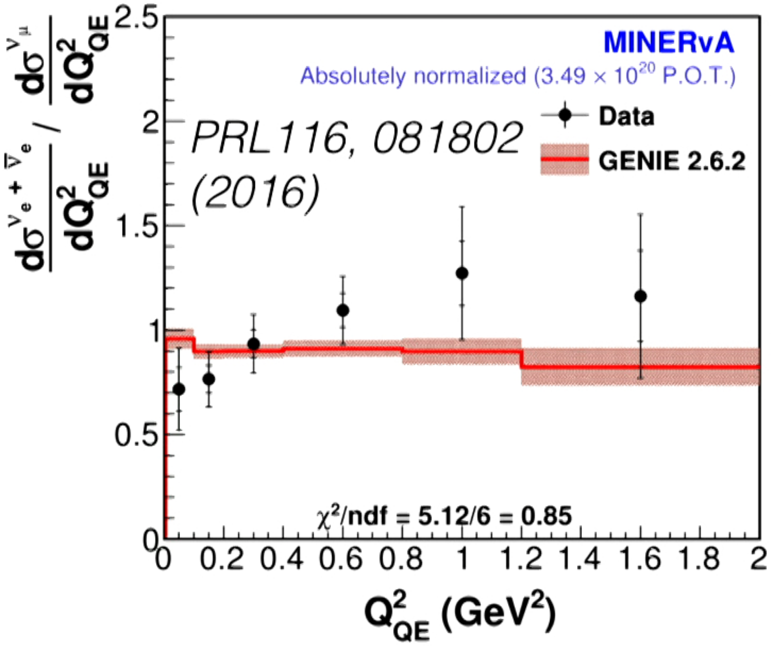


How well do we need to know ν-A?



	ν_e	$\bar{\nu}_e$
T2K 2017 PRL	5.4% (>3.9%)	6.2% (>4.1%)
NOvA 2016 PRL	17.6% (14.0%)	-

Known challenge: electron neutrino cross sections

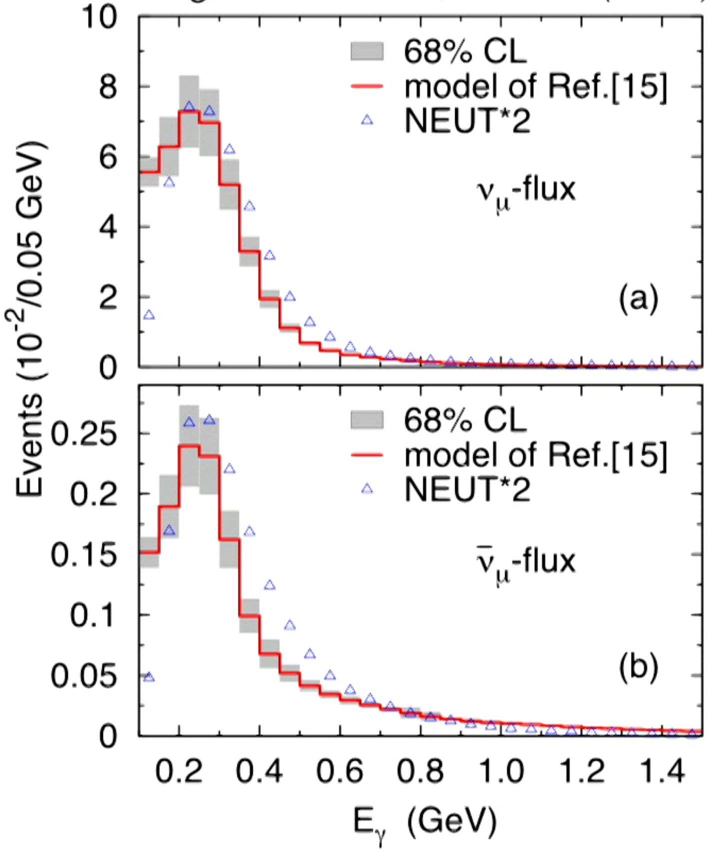


- Measurements from MINERvA, NOvA, T2K of ν_e interactions
- Sets scale of different ν_e/ν_μ nuclear effects of <15-30%

- Tough measurement: small sample size, separation from backgrounds.
- Effects are ~few percent. **Please help calculate!**

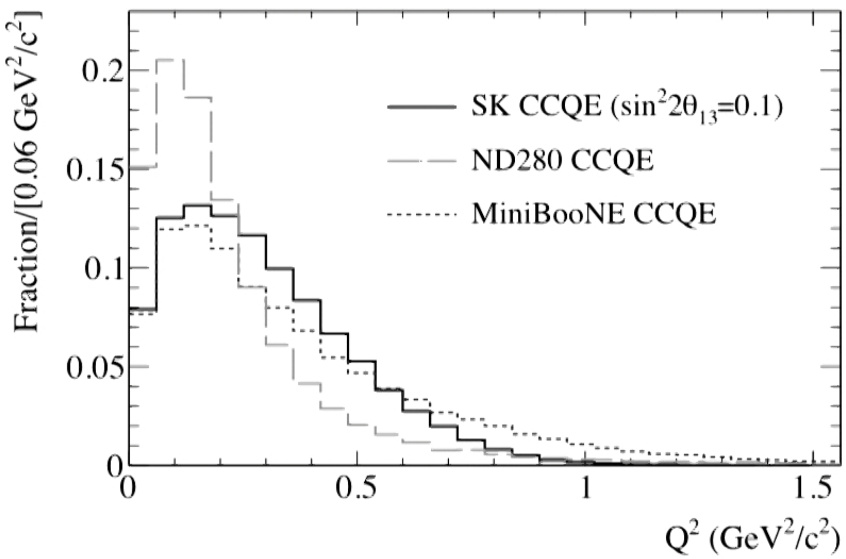
Known challenge: neutral current processes

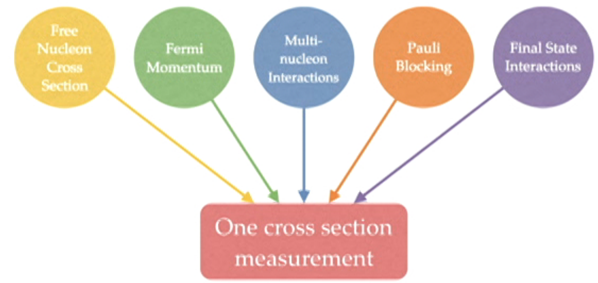
Wang et al PRD 92, 053005 (2015)



- NC single photon processes ($\Delta \rightarrow N\gamma$) are small (1% of event rate) but difficult to distinguish from signal. Also, photonuclear absorption of 1 photon from NC π^0 production.
- Measurements are challenging (like ν_e) though in principle shared with ND
- **Help:** Are there any anomalous contributions? Differences between antineutrino production rates?

Impact of single nucleon form factors





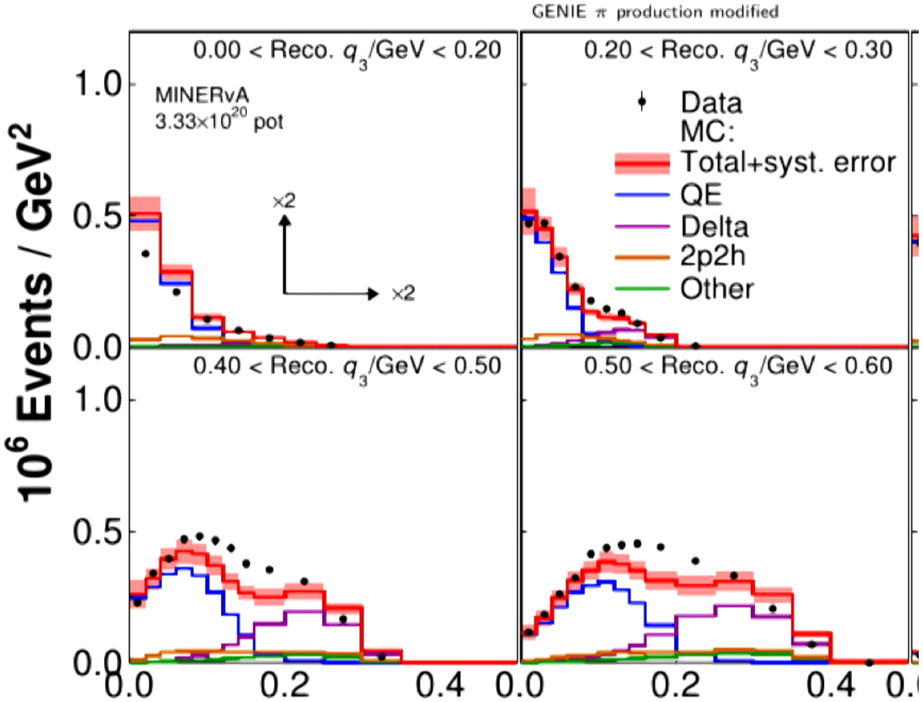
Reliance in T2K analysis on parametrization extrapolation from low to high Q^2

- Testing this now in T2K analyses. How important is this?

Complicated by other processes measured by ND

Novel MINERvA Test of Nuclear Effects

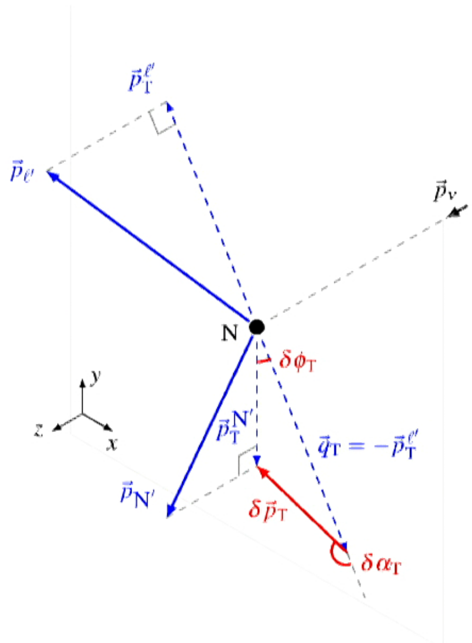
Phys. Rev. Lett. 116, 071802 (2016), plot from NuInt2016

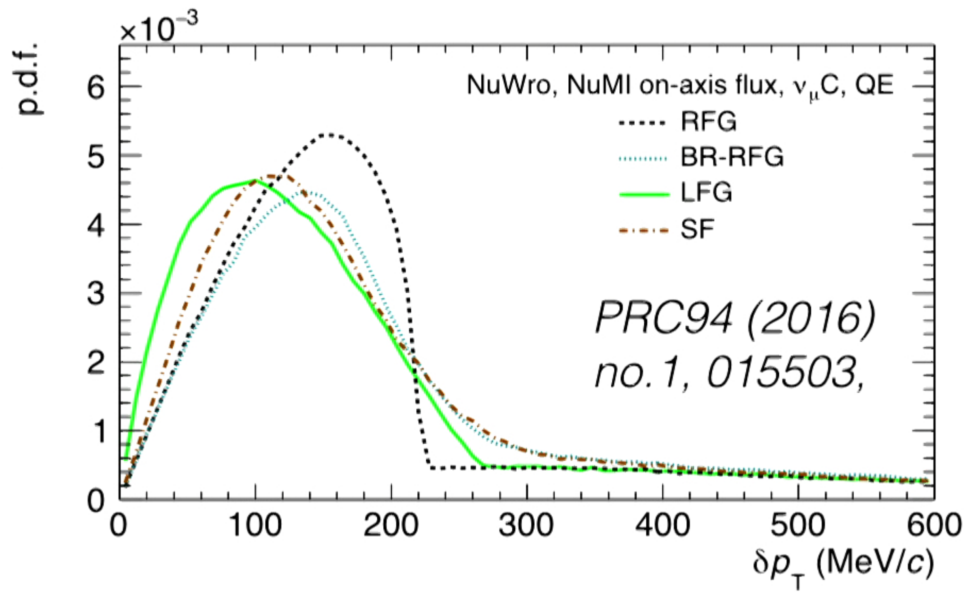


Similar analysis soon from NOvA

- CC inclusive selection, use estimate of available energy from all charged particle tracks (proton, pion, muon)
- 2p2h model not “enough”: **new experimental way to test model**

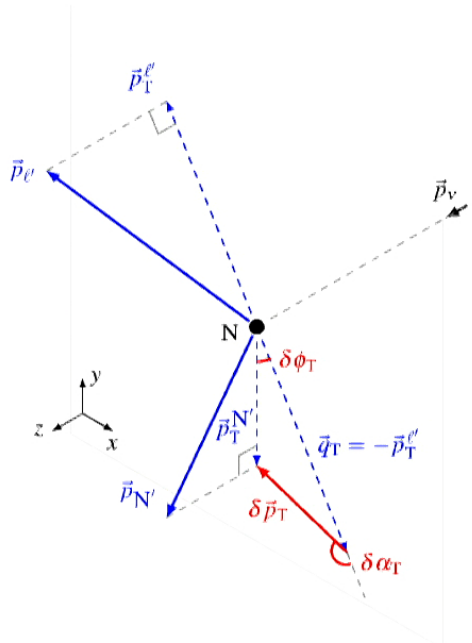
Novel approach: Transversity

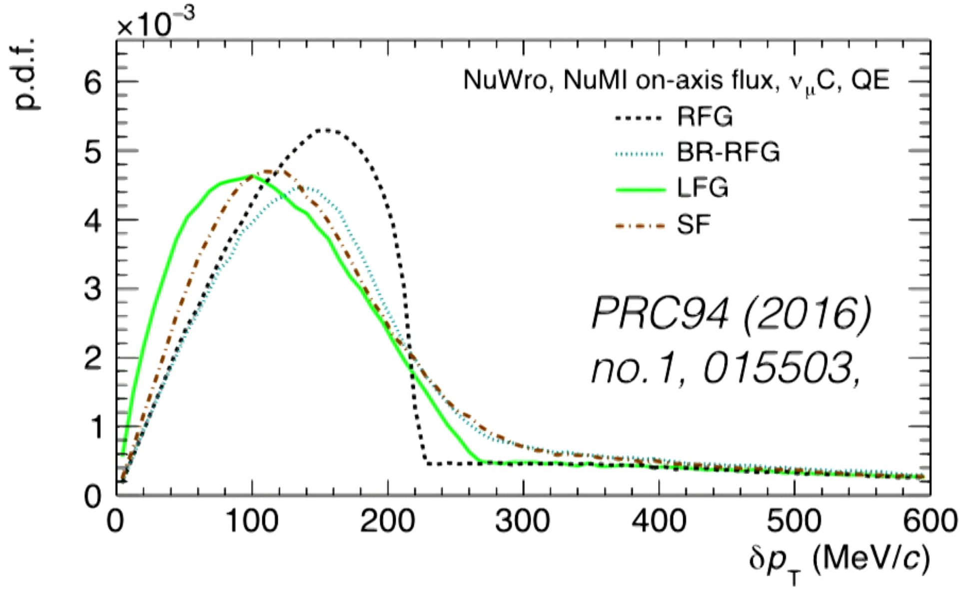




- Kinematic variables relative to the beam direction are sensitive to nuclear effects

Novel approach: Transversity

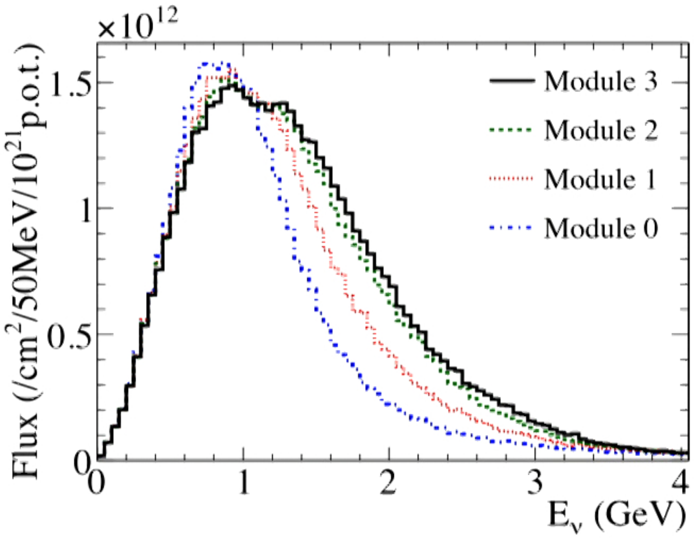




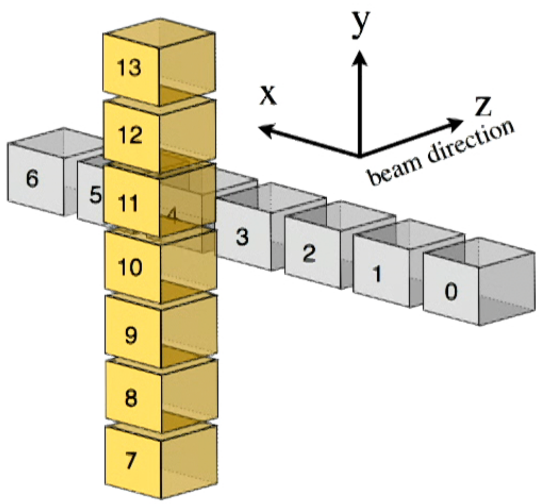
- Kinematic variables relative to the beam direction are sensitive to nuclear effects

- **Challenges:** Requires robust modeling of final state particle composition multiplicity and kinematics => Semi-inclusive or better theory. Care with uncertainties of neutrino source direction

Novel: use of flux techniques

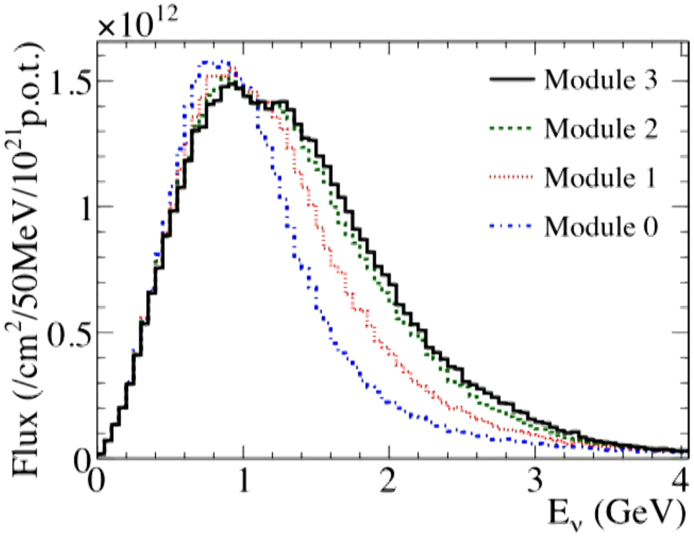


Phys. Rev. D 93, 072002 (2016)

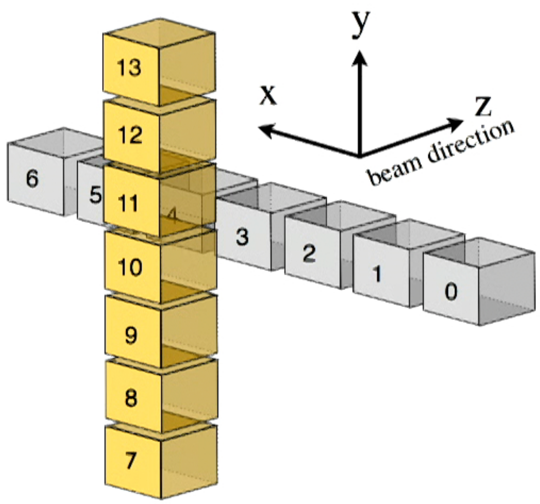


- Flux changes across on-axis T2K detector due to off-axis effect

Novel: use of flux techniques

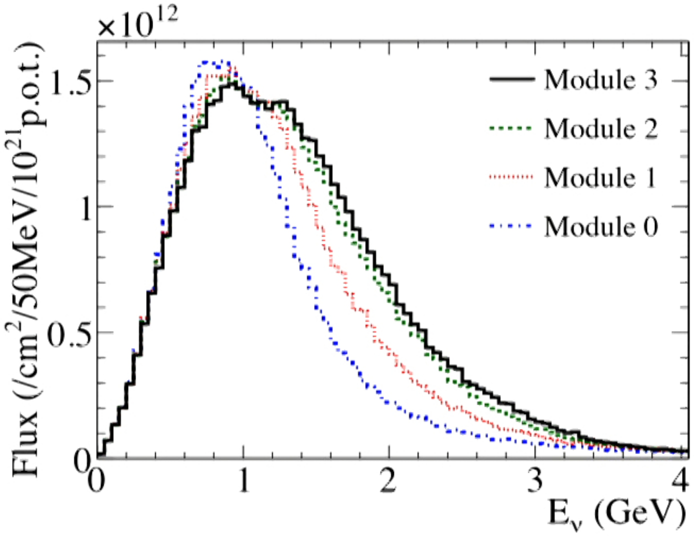


Phys. Rev. D 93, 072002 (2016)

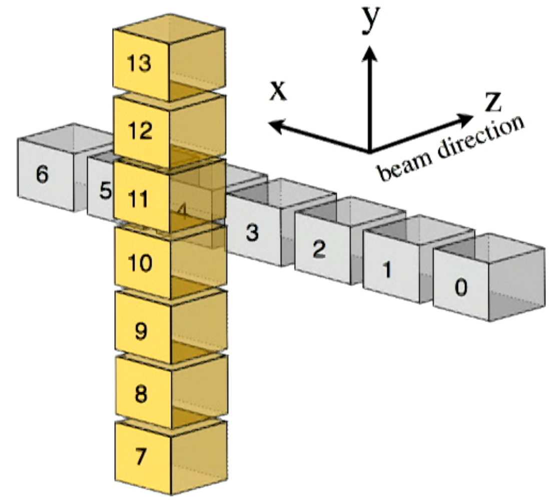


- Flux changes across on-axis T2K detector due to off-axis effect
- Compare nearby detectors to infer cross section using known flux properties

Novel: use of flux techniques

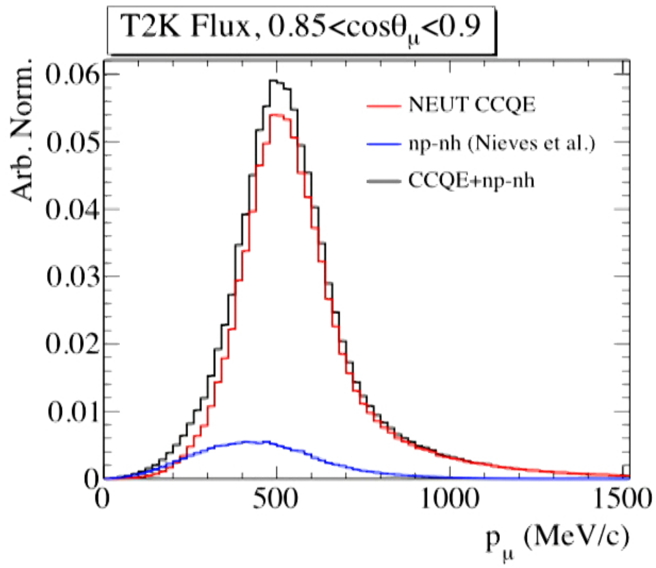


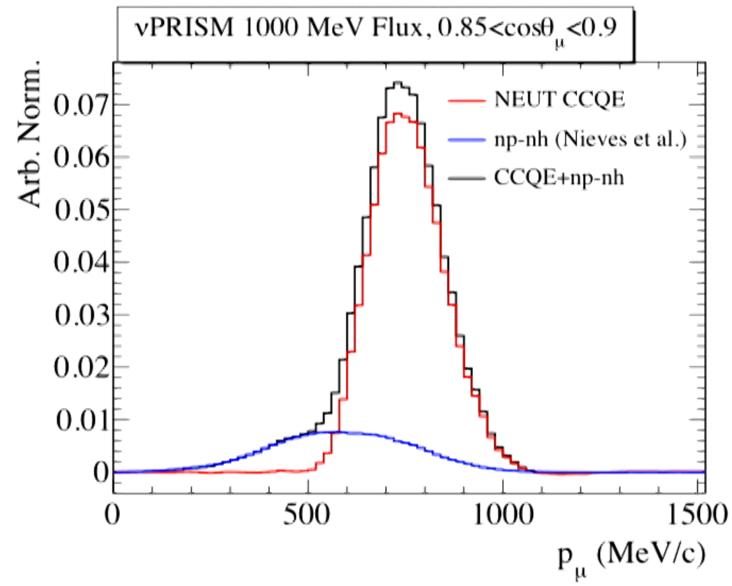
Phys. Rev. D 93, 072002 (2016)



- Flux changes across on-axis T2K detector due to off-axis effect
- Compare nearby detectors to infer cross section using known flux properties
  - Similar to breaking cross section-flux interplay with nu-e scattering

Novel: use of flux techniques





νPRISM

- Probe of nuclear effects from data at multiple positions in beam
- First phase: ~1% statistical uncertainty on electron neutrino cross section
    - Dominant uncertainty for Hyper-Kamiokande experiment (3%)

Summary

- Exciting era of precision in oscillation programs comes at the price of lots of work. Nuclear effects in neutrino interactions are important for the current and future oscillation physics program.
- Help welcome in robust model building:
    - Tools to exchange theory/determine what effects are significant
    - Single nucleon knowledge (lQCD/z-expansion). Would nuclear effects change this?
    - Leveraging nu-e scattering
    - Differences between electron and muon neutrinos
    - Rare but irritating backgrounds (NC photon production)