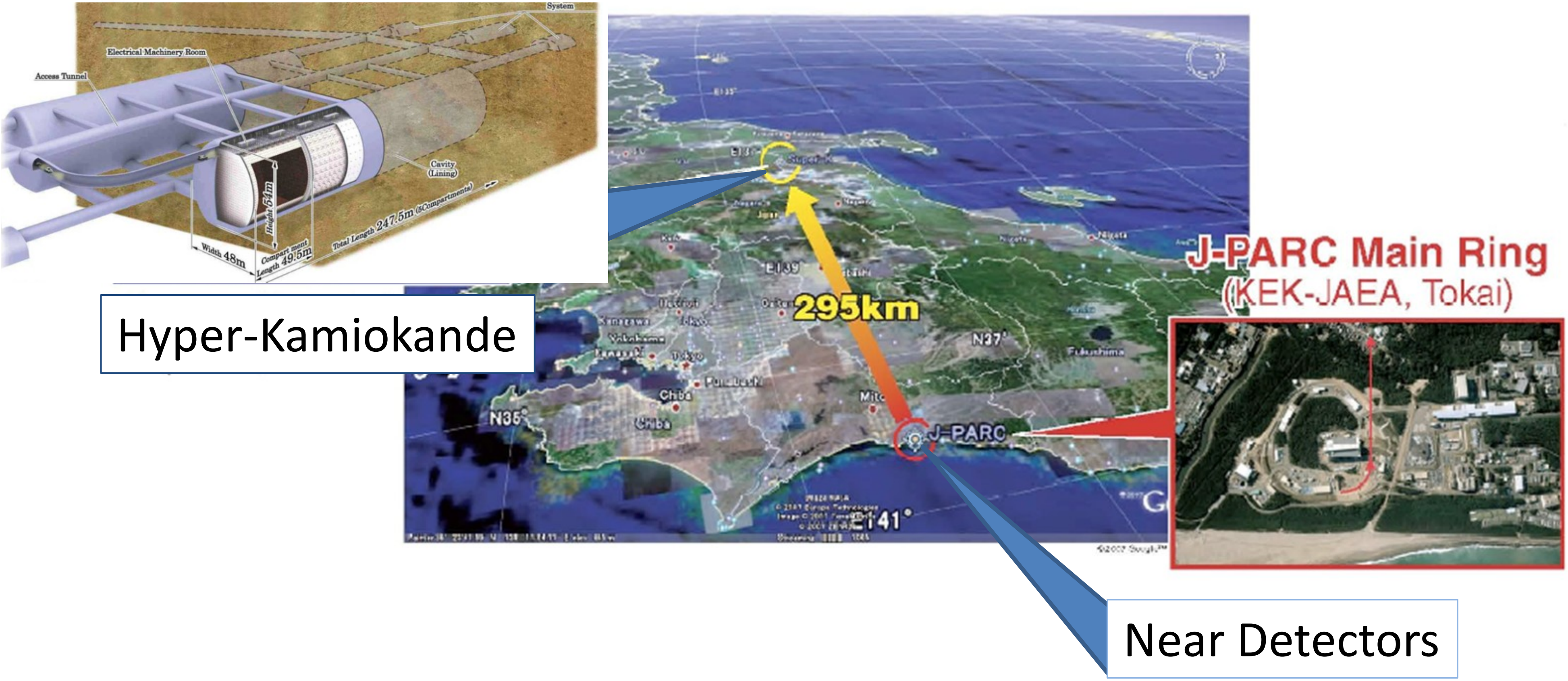

Near Detector Considerations

F. Di Lodovico (QMUL), D. Wark (STFC/Oxford) for the UK HK Community

Third Open Meeting for the Hyper-Kamiokande Project
Kavli IPMU, June 21-22 2013

Outline

- A reminder of the current ν_e analysis at T2K
  - Addressing current strategy and systematic errors

- Constraints from ND280
  - Beam
  - Neutrino interactions
    - A focus on the ~1GeV region
    - Multi-nucleon effects

- Systematic error reduction in the spectrum propagation to SK
  - 2KM WC

- Topology identification
  - LAr (Ne?)
  - ND280

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ν_e Appearance Analysis Strategy

Neutrino Flux Predictions

Neutrino Cross Section Predictions

ND280 CCQE and CCnQE Data Samples

Cross-check intrinsic ν_e component at ND280

Fit ND280 sample to tune ν_μ flux and CCQE, CC1π cross sections and reduce flux, cross section uncertainties

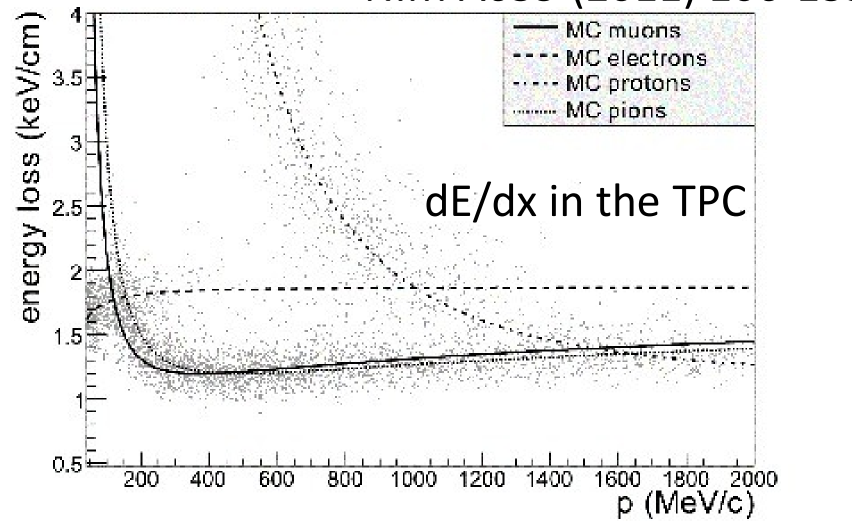
Apply rate correction to events at SK and fit to determine oscillation parameters.
ν_e appearance: θ_{13}; ν_μ disappearance : θ_{23}, Δm^2_{23}

Selecting CCν_μ interactions at ND280

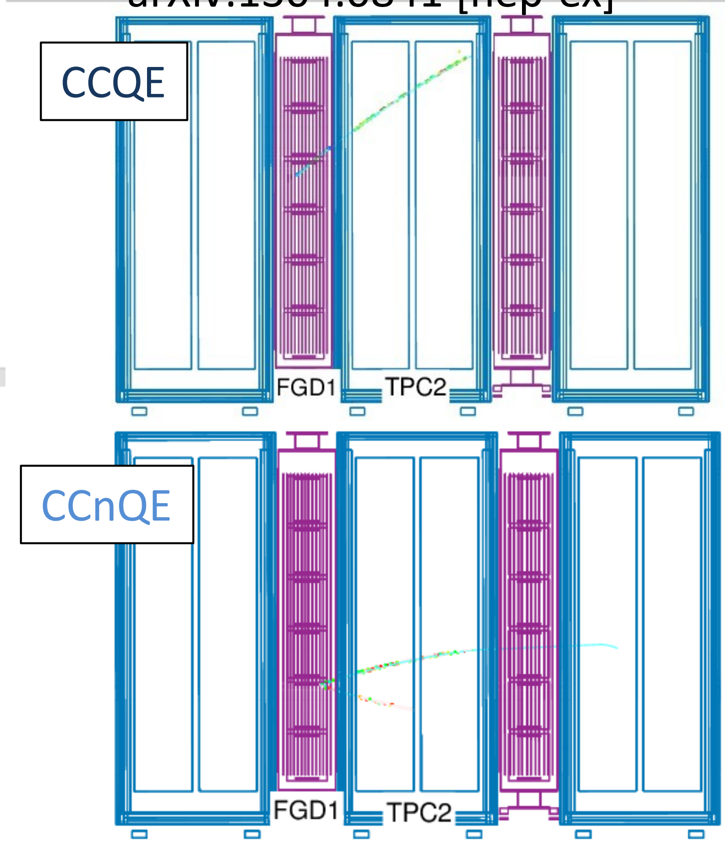
Measure un-oscillated ν_μ (CC) rate in ND280 tracker (current analysis):

- Neutrino interactions in FGD1 FV
- Veto events with TPC1 tracks
- Select highest momentum, negative curvature track as μ^- (TPC PID)
- Further separate sample into two categories:
  - CCQE-enhanced
    - 1 TPC-FGD matched track
    - No decay electron in FGD1
  - CCnQE-enhanced
    - All other CC inclusive
- The (P_μ, $\cos\theta_\mu$) spectrum used to constrain flux and xsection parameters used by SK

NIM A659 (2011) 106-135



arXiv:1304.0841 [hep-ex]



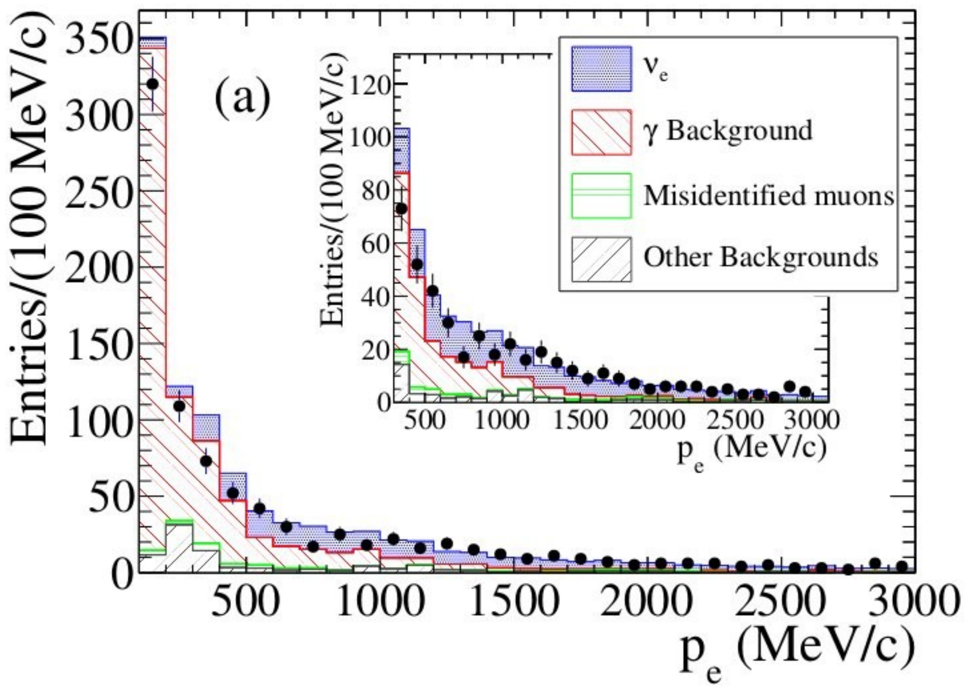
Intrinsic ν_e cross check

w/ Neil McCauley

Measure intrinsic ν_e (CC) rate in ND280 tracker (current analysis):

- Similar selection to CCν_μ
- Request an electron instead of a muon
- Use vertexes in the FGD2 as well to increase the statistics
- Use the ECAL to reject background reaching it.

arXiv:1304.0841 [hep-ex]



Selected events:

- ~80% ν_e are from kaon decays
- ~78% of the background is low energy electrons from γ conversion in the FGD, where γ come from π^0 from ν_μ interactions either in the FGD or in the surrounding material

Notes on near detector needs:

- at least as good PID as we have now
- reduction background from gamma rays

Overall Systematics Uncertainty at SK

After ND tuning , expect (8.2+3.3 =) 11.2 events with $\nu_\mu \rightarrow \nu_e$ oscillation, 3.3 without.

Signal ($\nu_\mu \rightarrow \nu_e$ osc)	#events
@$\sin^2 2\theta_{13}$=0.1, δCP=0	8.2

ν_e signal @ $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2,$\sin^2 2\theta_{23}=1.0$

Background	# events
Beam $\nu_e + \overline{\nu}_e$	1.7
CCν_μ	0.06
NCν_μ	1.2
Osc through θ_{12}	0.18
Total	3.3 ± 0.43 (syst)

arXiv:1304.0841 [hep-ex]

Uncertainties	ν_e bkgd	$\nu_e$sig+bkgd
ν flux + xsec (constrained by ND280)	±8.5%	±5.0%
ν Xsec (no constraint by ND280)	±5.9 %	±7.8 %
Far Detector	±6.6%	±3.0%
Total	±13.0%	±9.9%
No ND measurement	18.3± %	22.6± %

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Neutrino Interactions at ND and SK

arXiv:1304.0841 [hep-ex]

The flux parametrization variation is described by normalization parameters in bins of E_ν and flavour at a given detector.

The ND280 ν_μ and SK ν_μ flux predictions have large correlations: the ν_μ rate at the ND can constrain the unoscillated ν_μ interaction rate at the FD.

The SK ν_e flux at SK is also correlated with the ND280 ν_μ flux since they both originate from the $\pi \rightarrow \mu\, \nu_\mu$ decay

Propagated Neutrino Flux	Prior Value	Fitted Value
ν_μ 0.0-0.4 GeV	1.00±0.12	0.98±0.09
ν_μ 0.4-0.5 GeV	1.00±0.13	0.99±0.10
ν_μ 0.5-0.6 GeV	1.00±0.12	0.98±0.09
ν_μ 0.6-0.7 GeV	1.00±0.13	0.93±0.08
ν_μ 0.7-1.0 GeV	1.00±0.14	0.84±0.08
ν_μ 1.0-1.5 GeV	1.00±0.12	0.86±0.08
ν_μ 1.5-2.5 GeV	1.00±0.10	0.91±0.08
ν_μ 2.5-3.5 GeV	1.00±0.09	0.95±0.07
ν_μ 3.5-5.0 GeV	1.00±0.11	0.98±0.08
ν_μ 5.0-7.0 GeV	1.00±0.15	0.99±0.11
ν_μ >7.0 GeV	1.00±0.19	1.01±0.15

Similarly for the ν_e and the antiparticles

Neutrino Interactions at ND and SK

Interaction Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e Bgnd.
CCQE	76.6%	14.6%	85.8%	45.0%
CC1π	15.6%	29.3%	13.7%	13.9%
CC coh.	1.9%	4.2%	0.3%	0.7%
CC other	4.1%	37.0%	0.2%	0.7%
NC	1.5%	5.3%	-	39.7%

CCQE and **CC1π** are the largest interaction mode in ND, SK samples:

- Separation of CCQE and CCnQE ND samples gives additional power for fit to constrain cross section models
- Need to account for acceptance difference between ND (forward going selection) and SK (4π selection) for identical changes to cross section to correlate the two samples
- Compared external (MiniBooNE, SciBooNE…) neutrino-nucleon cross sections with neutrino interaction models

NC is the largest background at SK after the selection

Cross Section Parametrization

arXiv:1304.0841 [hep-ex]

Sub-set of parameters which are substantially constrained by the ND280 data-set and relevant to the event rate prediction at SK

Parameter	Prior Value	Fitted Value
M_A^{QE} (GeV)	1.21±0.45	1.33±0.20
M_A^{RES}(GeV)	1.16±0.11	1.15±0.10
CCQE norm 0-1.5 GeV	1.00±0.11	0.96±0.09
CC1π norm 0-2.5 GeV	1.63±0.43	1.61±0.29
CC1π^0 norm	1.19±0.43	1.19±0.40

Parameter value, uncertainty are determined from the MiniBooNE single pion samples

Parameter value, uncertainty are extrapolated to the SK sample

- M_A^{QE} and M_A^{RES} :modify Q^2 distribution of QE and resonant 1π cross sections
- Normalizations provide overall scaling independent of Q^2 on a particular interaction

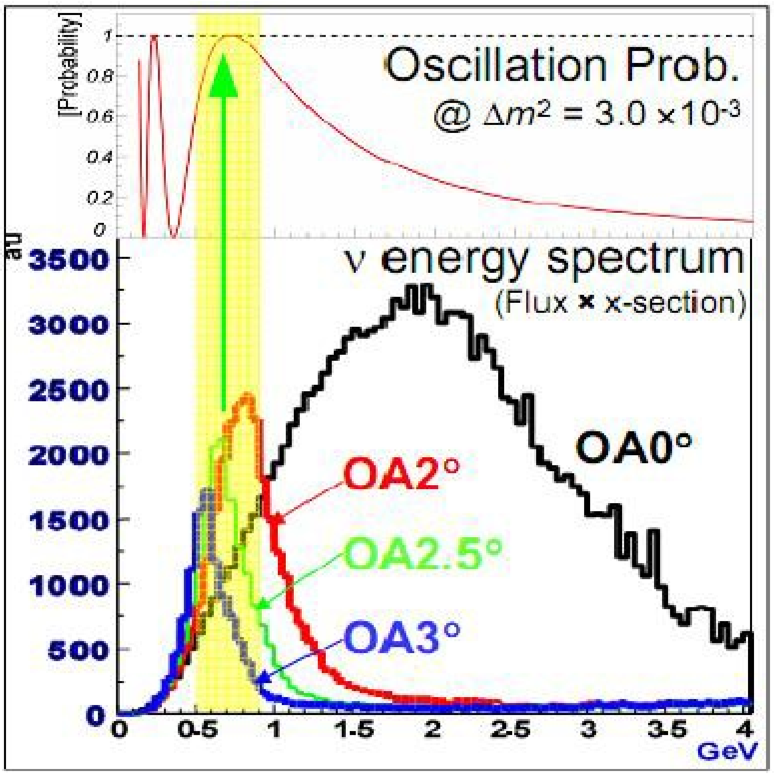
Apply cross section to observables at ND, SK using reweighting techniques

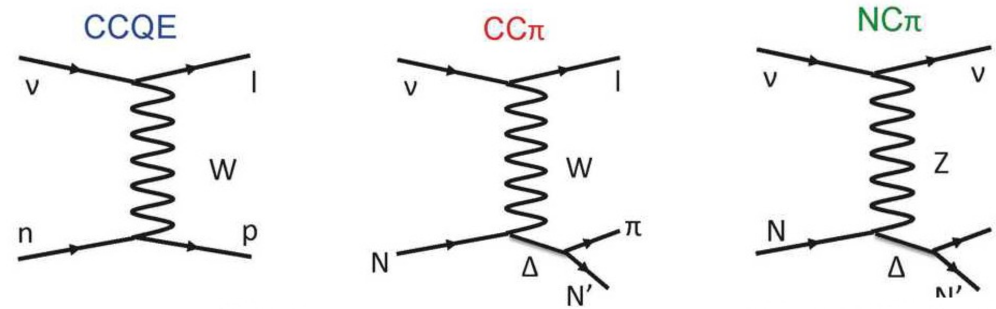
A focus on the ~1GeV region

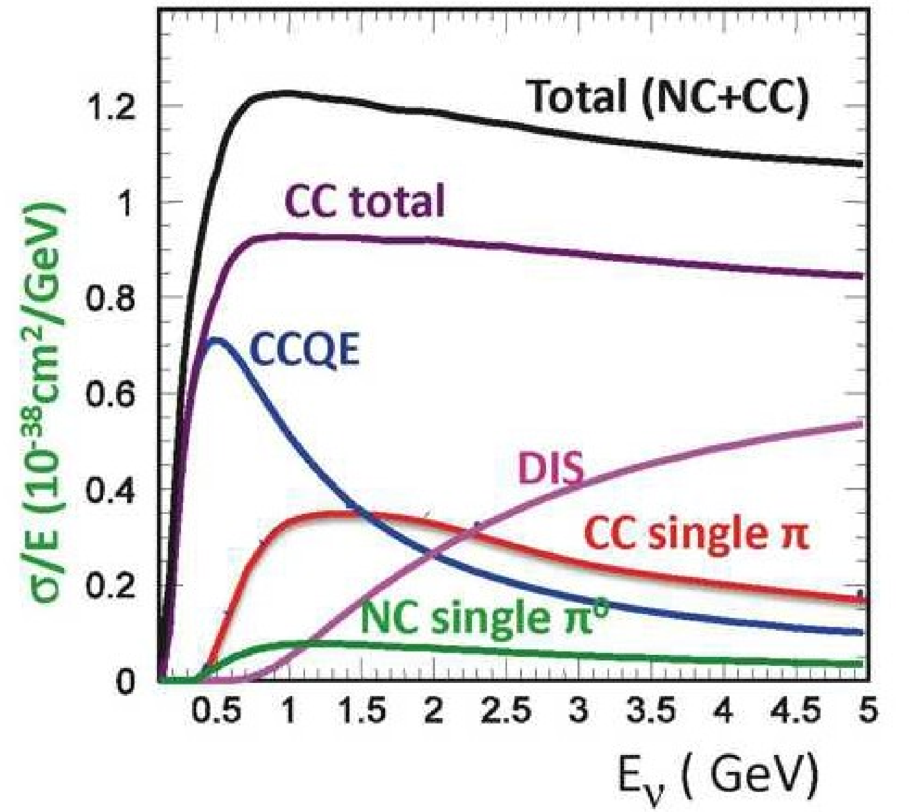
T2K flux around 0.5-1 GeV.

CC interactions dominated by CCQE

T2K Flux







Minor fraction of xsection at ~1GeV is purely leptonic - exactly known in the SM. Majority of interactions occur on bound states (nucleon, nuclei).

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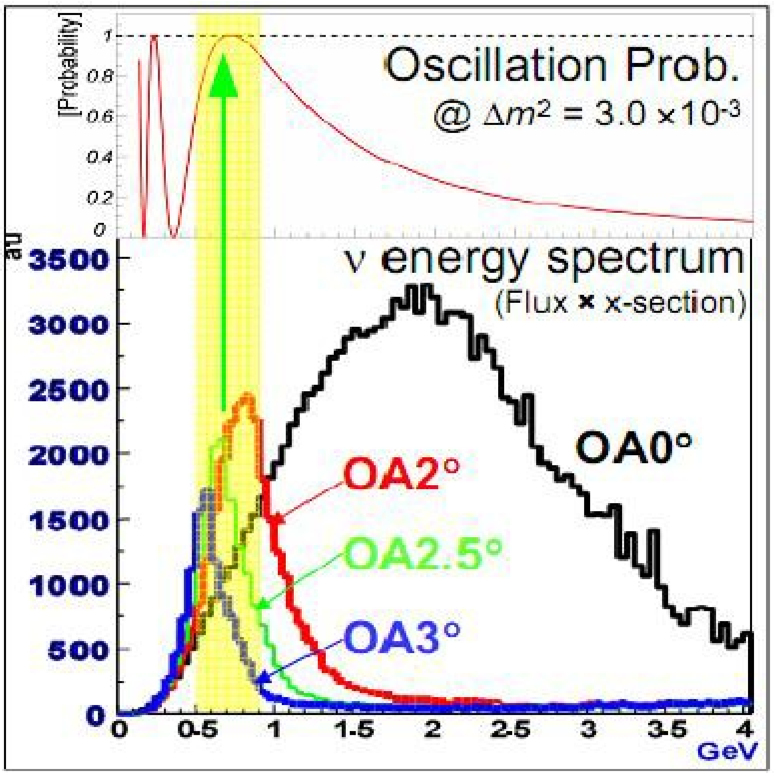

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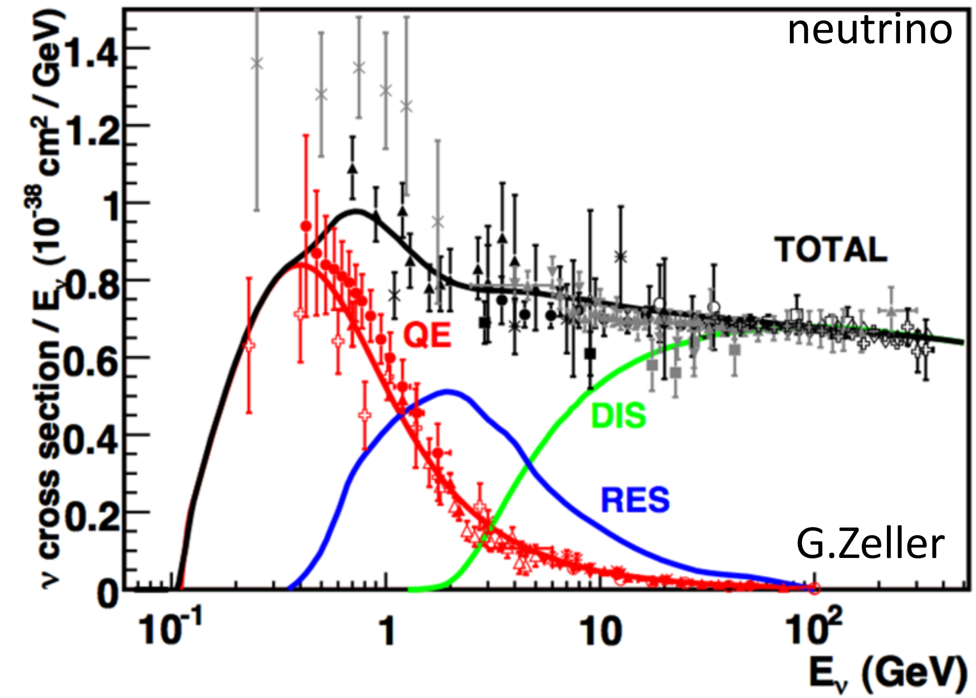
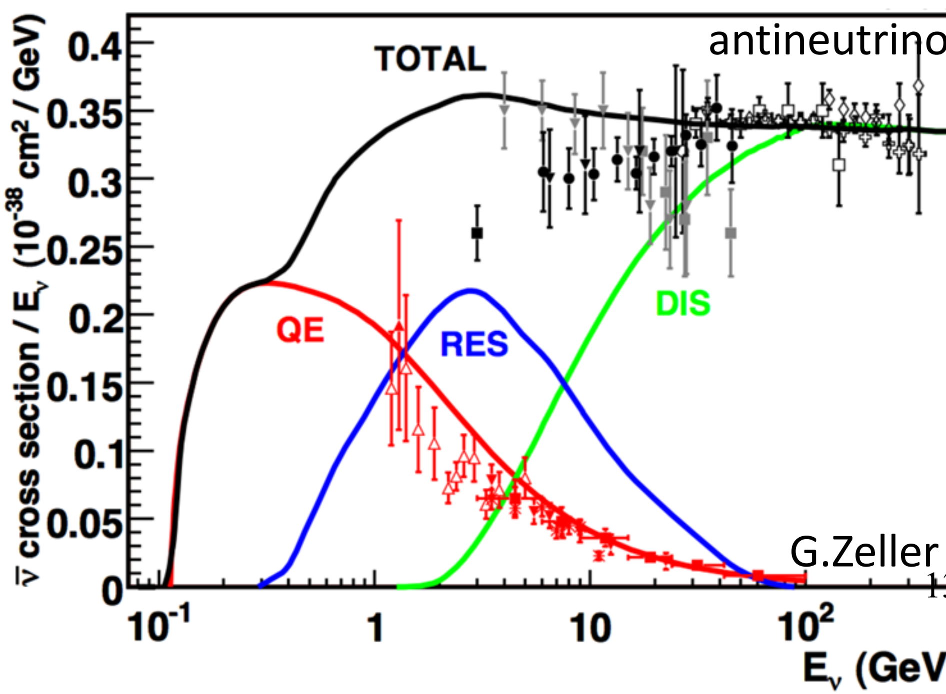
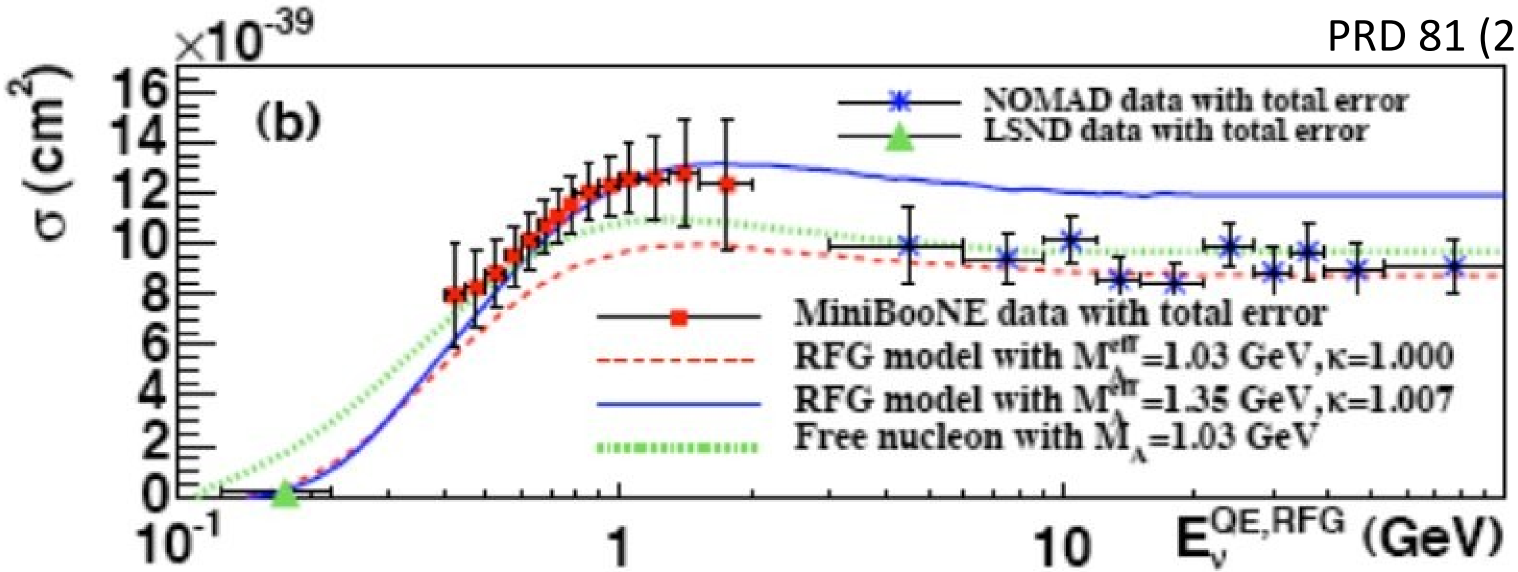




CCQE Measurements

- Turning point is the high statistics MiniBooNE CCQE double differential cross section measurement:

PRD 81 (2010) 092005



- Cross section energy dependence in C is inconsistent between NOMAD and MiniBooNE.
- Experiments use a different definition of CCQE than theorists

$\nu_\mu + n \rightarrow \mu + p$ (see Feynman diagram)

$\nu_\mu + X \rightarrow \mu + X' + 0\pi$ (MB)

$\nu_\mu + X \rightarrow \mu + X' + 0\pi$ + no vertex activity

$\nu_\mu + X \rightarrow \mu + X' + 0\pi + 0\gamma$ + no vertex activity

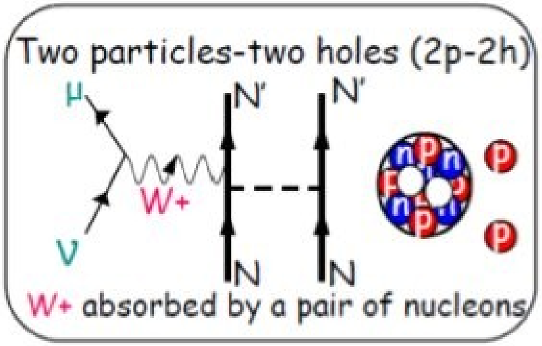
$\nu_\mu + X \rightarrow \mu + p + X' + 0\pi$ (NOMAD)

……

Based on what the experiments can observe

Introducing the Meson Exchange Current

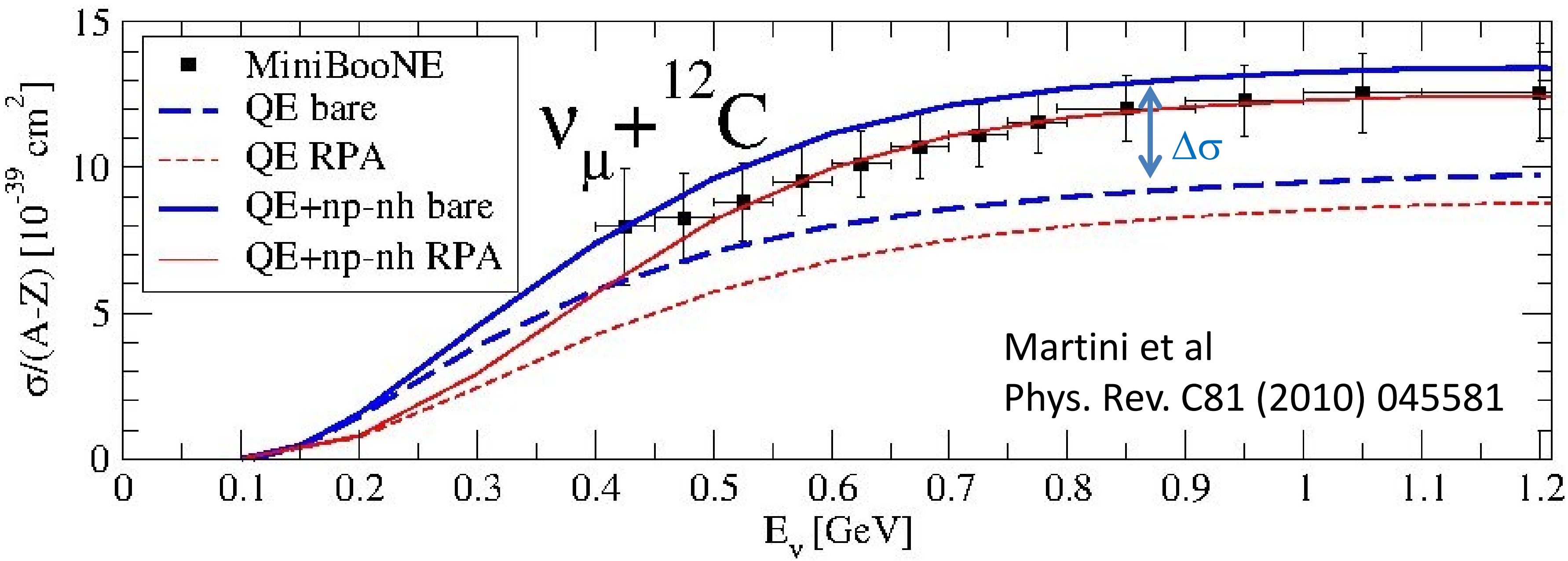
Plenty of models have arisen to explain MiniBooNE CCQE data
Most popular is np-nh or meson exchange currents (MEC)
Can calculate from diagrams:



Also include pion-less Δ decays in models

Models good up to ~1.5 GeV - No prediction for nucleon kinematics

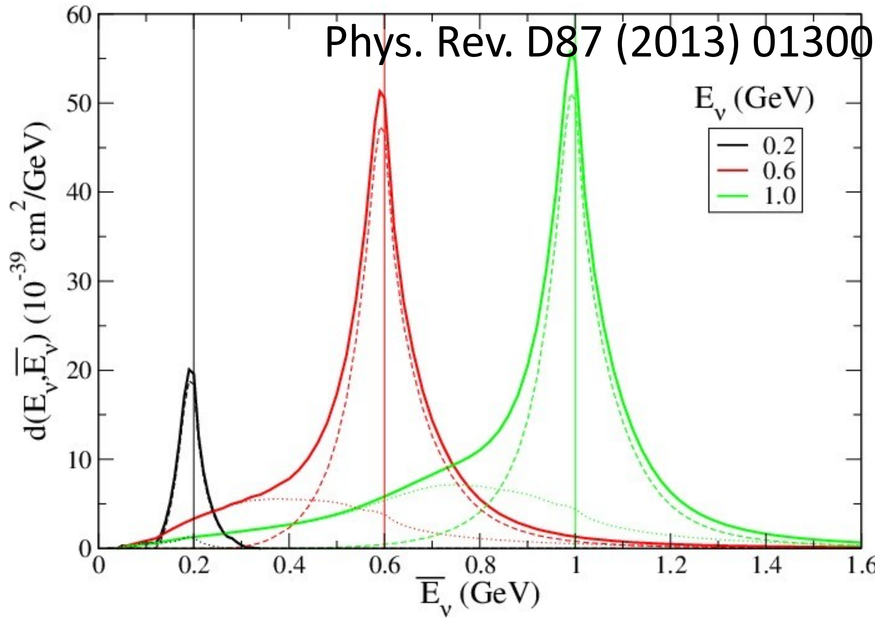
$\nu_\mu n \rightarrow \mu^- p + \nu_\mu(np)_{corr} \rightarrow \mu^- pp$



Reconstructed Energy Bias

- Not all the events (currently) reconstructed as CCQE are true CCQE, mainly due to multi-nucleon events.
- MEC events introduce a bias to the energy reconstruction.

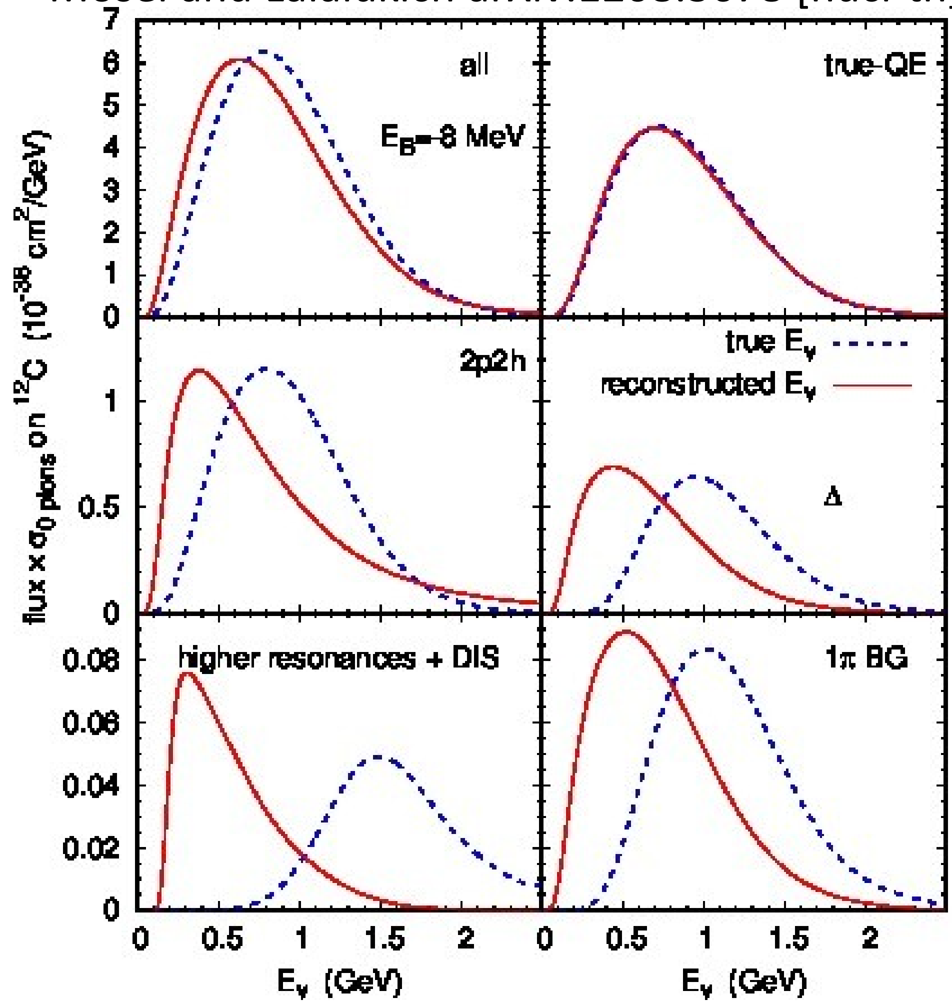
Martini et al
Phys. Rev. D87 (2013) 013009



To separate MEC from CCQE we need to analyze the final state nucleons.

Reconstructed neutrino energy bias in case not all the outgoing particles (nucleons, pions) are identified.

Mosel and Lalalukich arXiv:1208.3678 [nucl-th]



More references:
Nieves et al , Phys. Rev. D85 (2012) 113008
Nieves et al , arXiv:1304.1032 [hep-ph]

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  - ND280

Near Detectors

To reduce the errors at the FD we can concentrate on the following areas:

- Reduction of the differences between the ND and FD detectors:
  - Use same flux
  - Use same nucleus

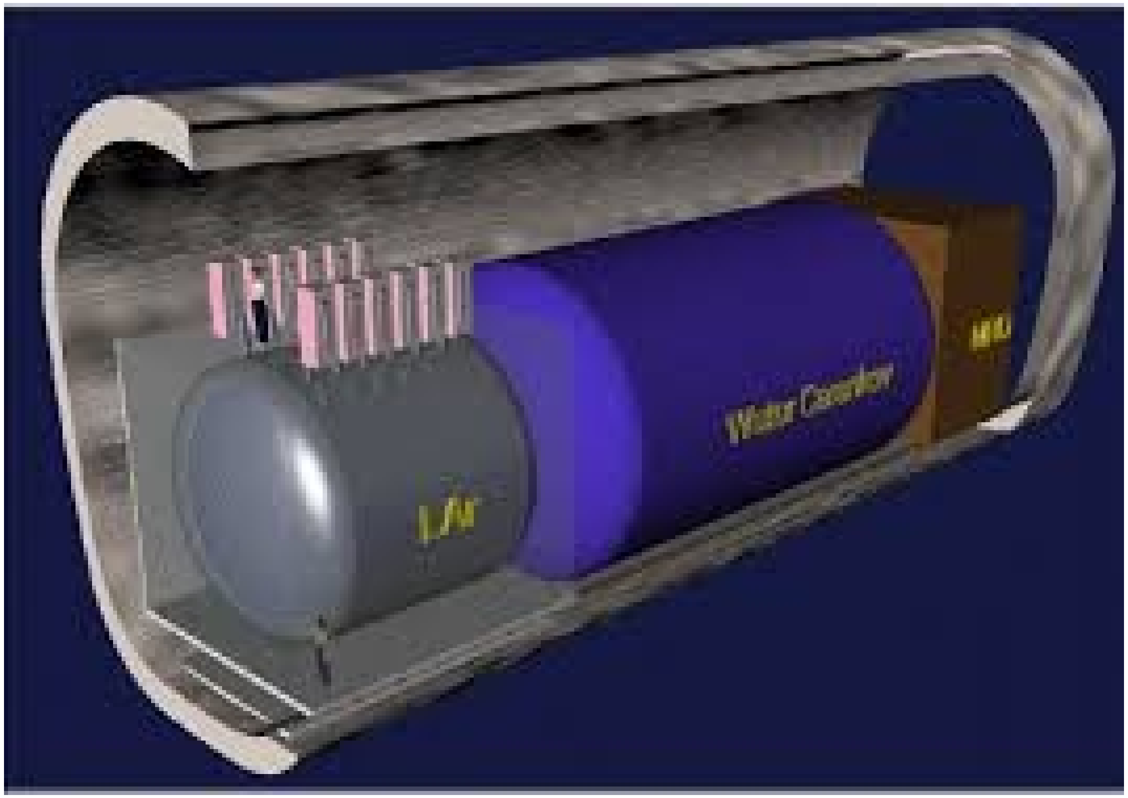
- Improve the knowledge of the cross sections at the ND
    - We need to measure both CC and NC cross sections
    - We need to be able to measure multi-nucleon final states.

- Improve the measurement of the intrinsic ν_e contamination

2KM (original proposal)

Original proposal for a 2KM detector for T2K in 2007

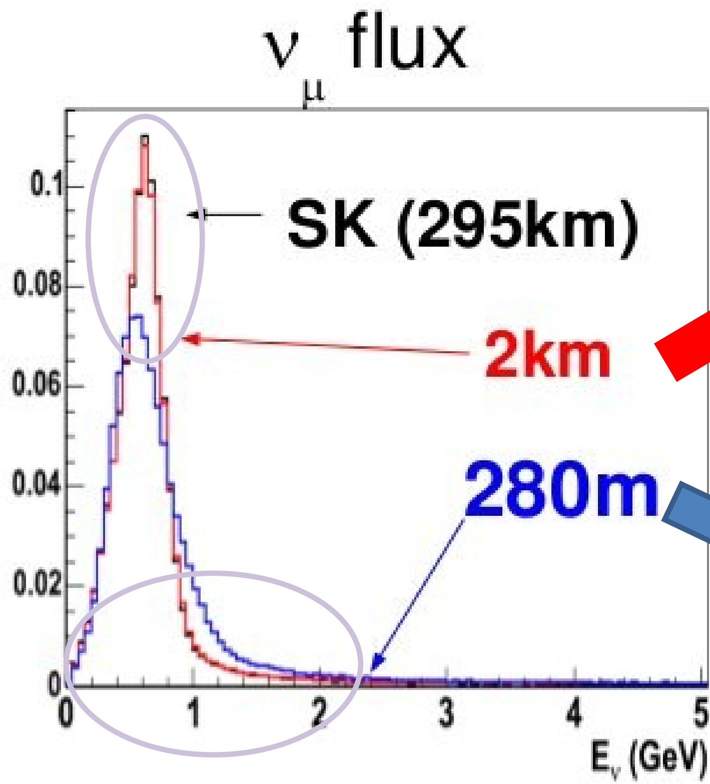
A letter of intent to extend T2K with a detector 2 km away from the JPARC neutrino source, June 2007

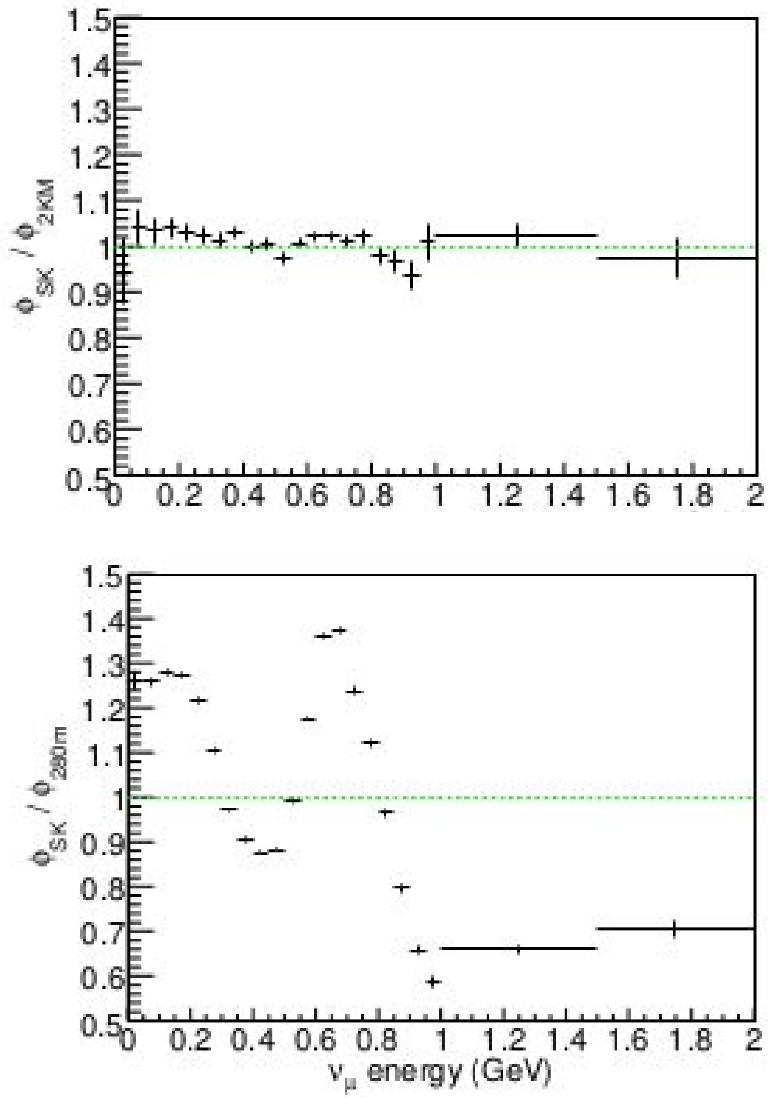


The 2007 proposal includes :

- 1kton Water Cherenkov Detector
- 100ton LAr detector
- Iron muon range

2KM Advantages for Flux





Plots from 2007 2KM Letter of Intent

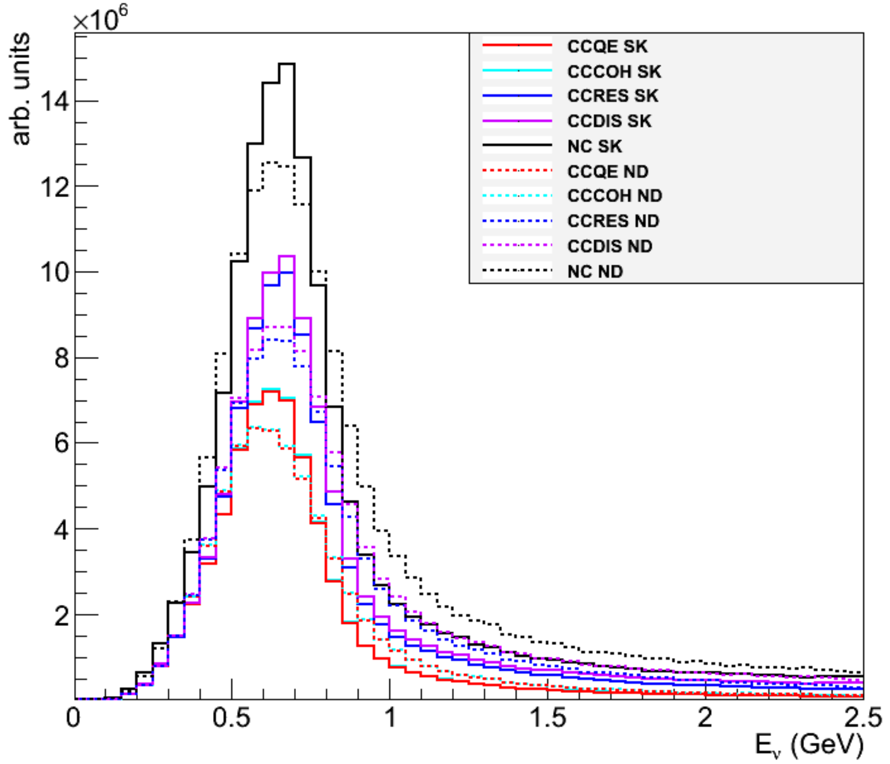
- At 280m: neutrino source not point-like, spectral differences with respect to SK
- Neutrino spectra at SK and 2KM are almost the same: ~same beam → energy spectrum
- To improve our current precision we need to improve our errors on the flux predictions

2KM Advantages for Neutrino Interactions

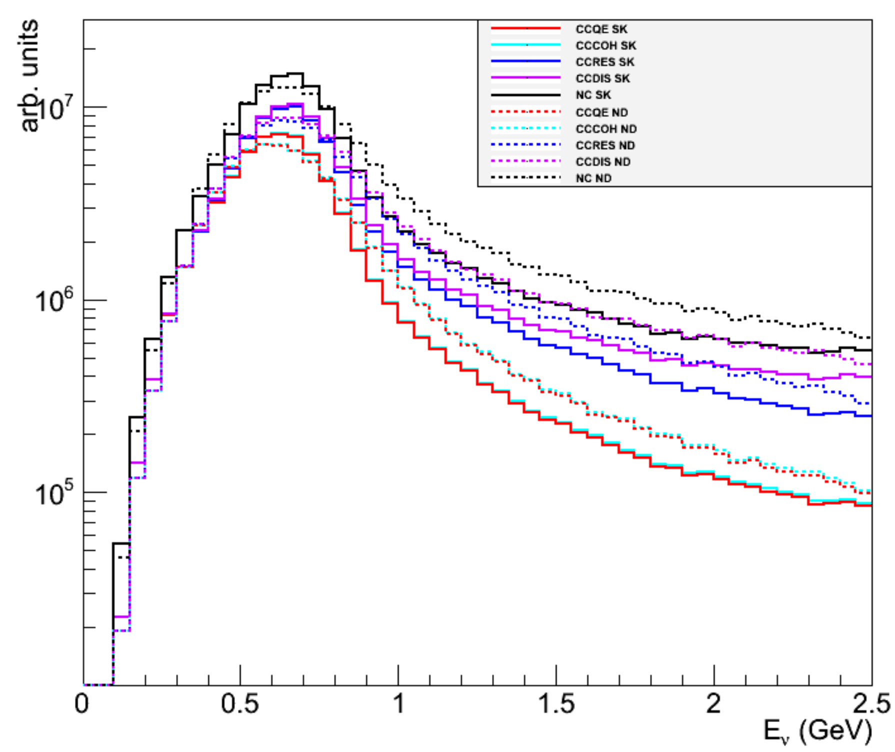
- Same nucleus at the 2KM and SK.
  - Same neutrino interaction cross sections
  - Same energy bias
- Neutrino energy tail ~20% smaller than at ND280
  - Less contribution from non-CCQE events to the neutrino energy

w/ Ryan Terri

ND280 and SK normalized to the same area:

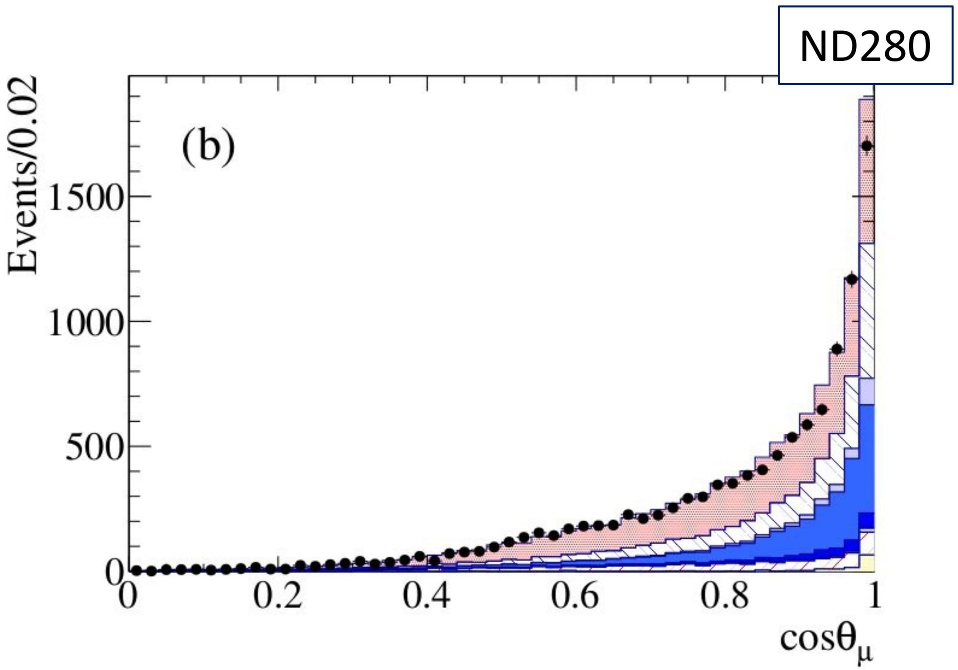


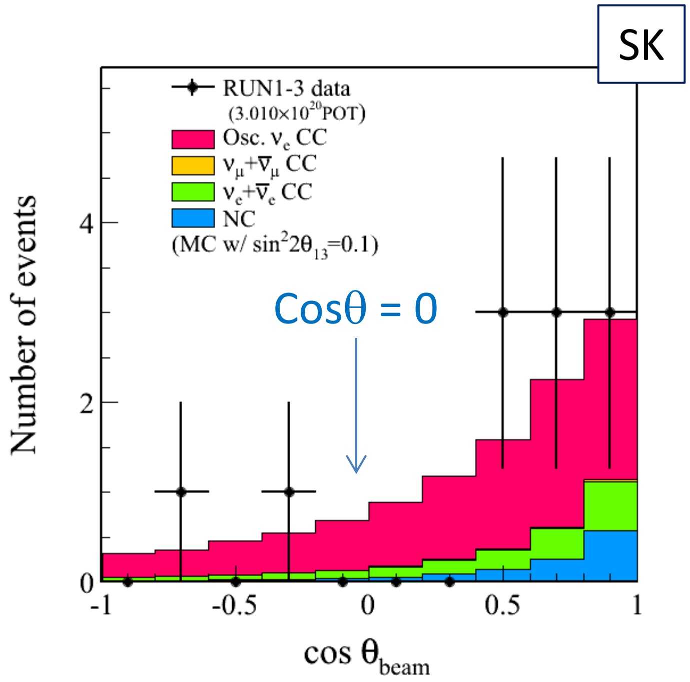
As left plot but logarithmic scale:



2KM Advantages

- Full 4π coverage for 2KM and SK detectors
  - ~20% of the SK events are backward.





- Measure rate of NC π^0 of NC single pion in water
- Much higher photocathode coverage → useful for systematics

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- Topology identification
  - LAr (Ne?)
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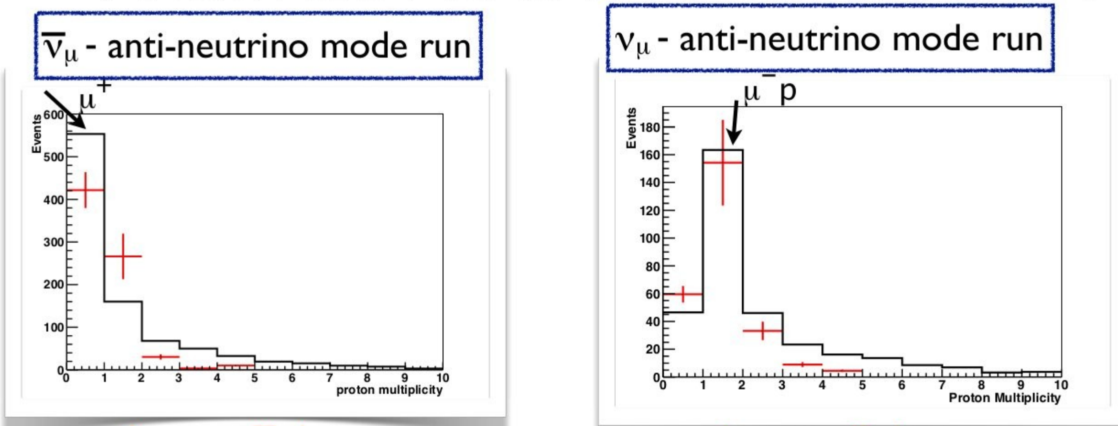
LAr Detector at 2KM

Main advantages of a LAr detector for HK are:

- Particles below Cherenkov threshold are visible, especially protons.
- Independent measure of off-axis flux and non-QE/QE event ratio.
- Exclusive measurement of NC and intrinsic electron neutrino background. Excellent PID will allow these to be separately measured.

ARGONEUT DATA-MC COMPARISON (II)



ArgoneuT data 727±68
Genie 925±15
Genie: 626 CCQE events
(+ 33% contribution from not CCQE)
NUANCE: 636 CCQE events

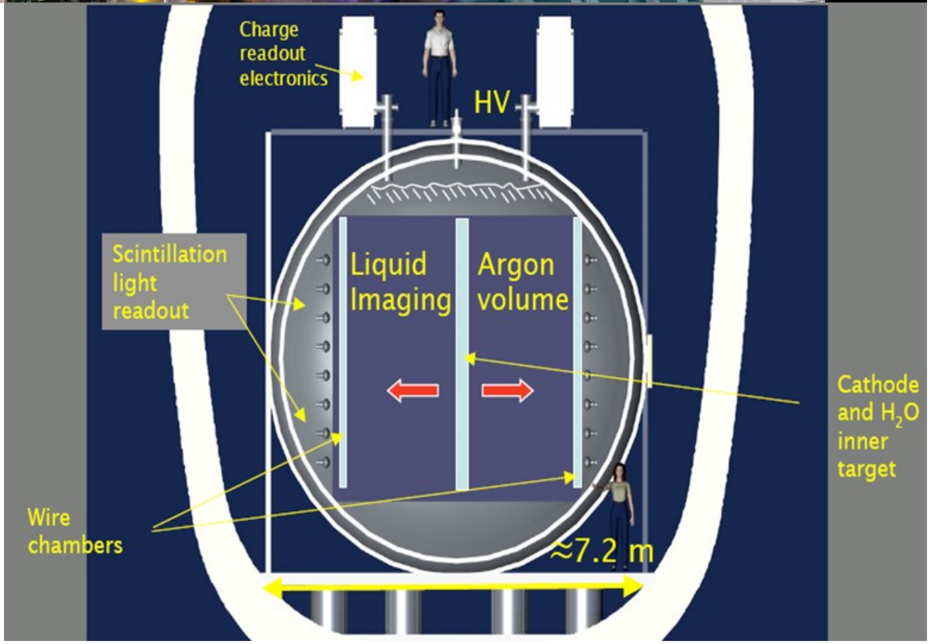
ArgoneuT data 260±34
Genie 337±9
Genie: 230 CCQE events
(+ 32% contribution from not CCQE)
NUANCE: 230 CCQE events

- Ratios among rates of different proton multiplicities in DATA don't agree with MC, in particular for $\bar{\nu}_\mu$
- MC agreement on total number of CCQE events
- Large (~30%) contribution from not CCQE events (FSI)

O.Palamara
NUINT2012

- Improve neutrino interaction understanding. It allows topology recognition with extraordinary sensitivity
- Many world-wide efforts in the LAr technology (test-beams and neutrino running)

LAr Detector at 2KM

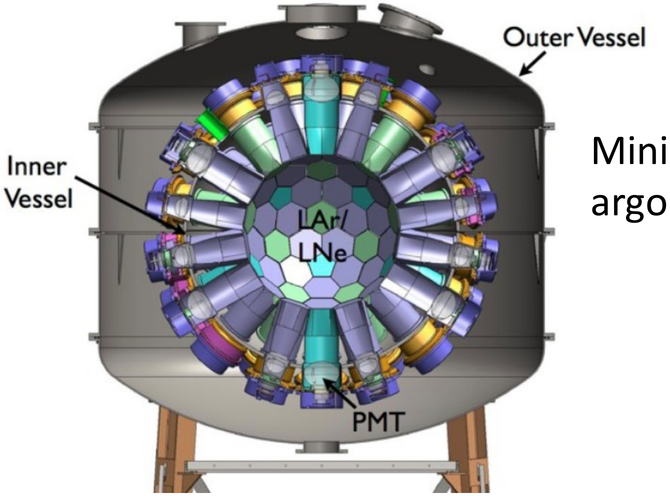


Note of caution for HK:

- Different nucleus than Oxygen, so one needs to properly rescale between them.
- A slab of frozen Oxygen in the middle of the detector was introduced in the original 2KM proposal to allow to directly measure the interactions in the two nuclei

- Some Dark Matter experiments, DEAP, CLEAN, miniCLEAN, are using both Ar and Neon. No further usage of Neon apart from DM, but we can look into it.

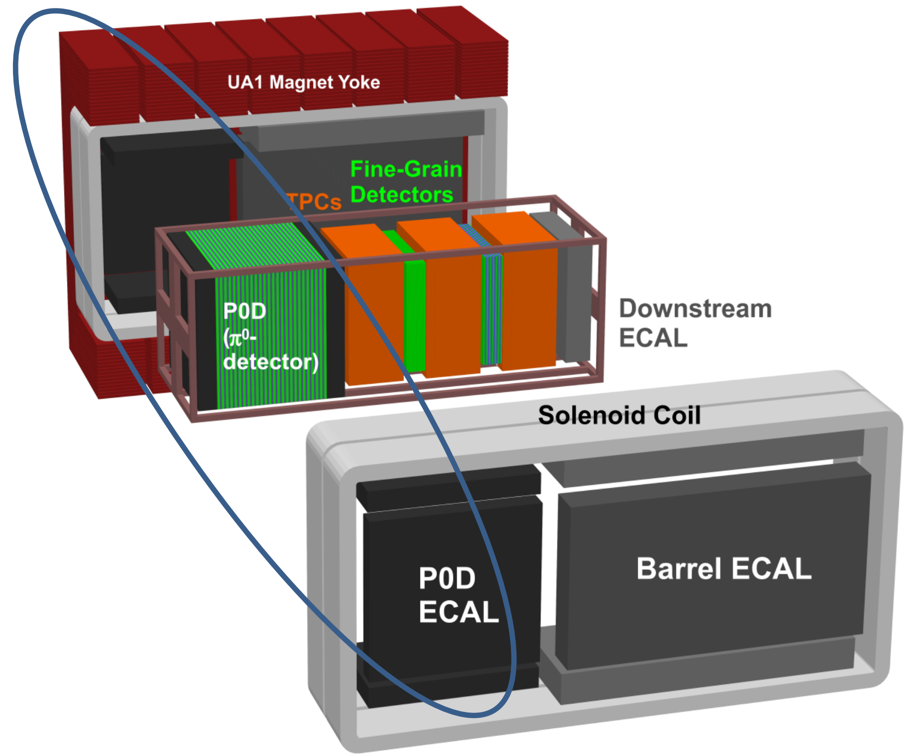
- Others?



MiniCLEAN-360: A liquid argon/neon dark matter.

The ND280 Detector

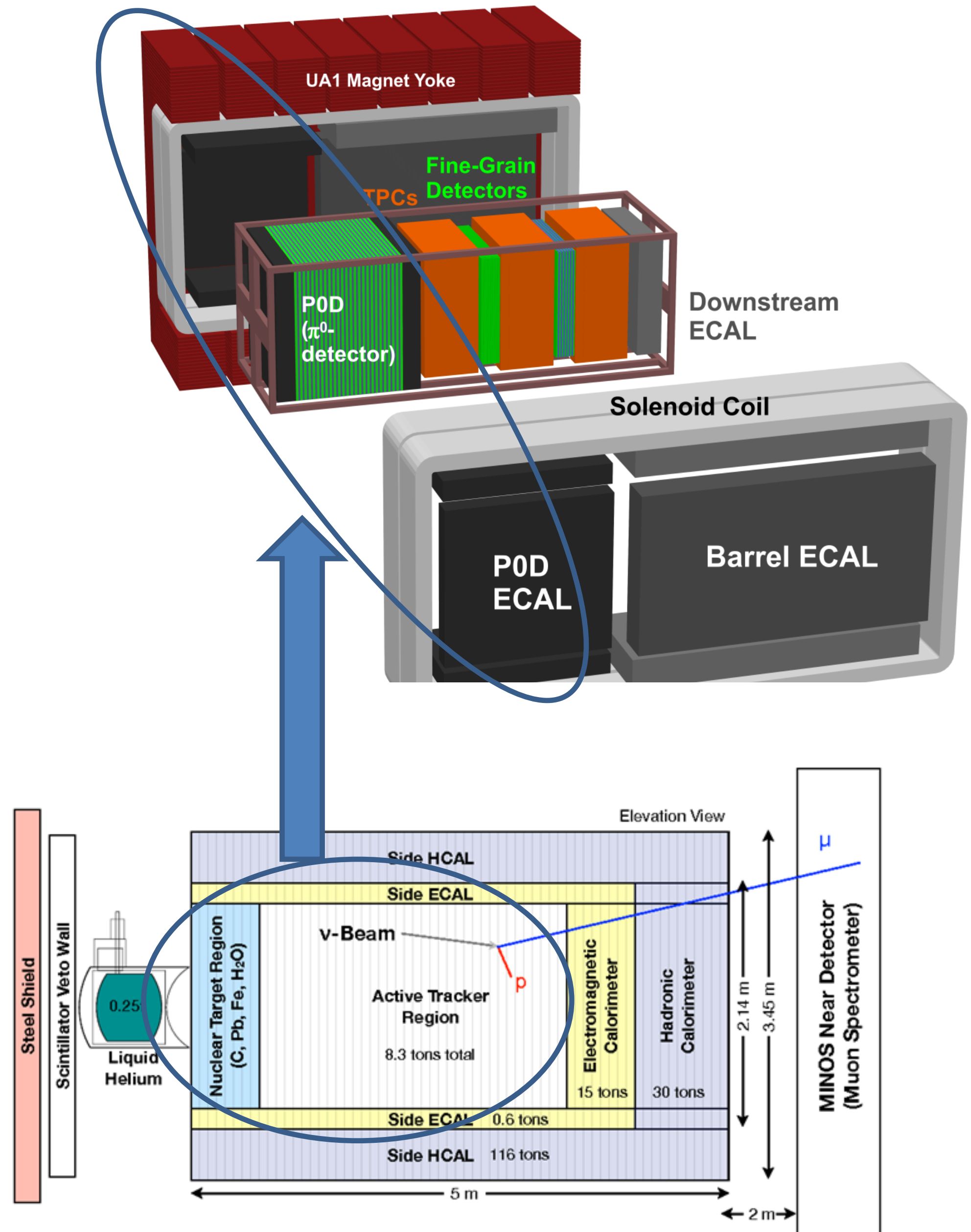
- We need a detector that can perform precise studies of neutrino-nucleon scattering.
- Recent requirement for measuring the cross section is to resolve multi-nucleon final states.
- The detector needs very good vertexing and ability to identify the produced particles in multi-particle final states, track low energy charged particles etc.



We can improve the ND280 detector using a finely-segmented scintillator-based up-stream tracking region.

The ND280 Detector

- Using scintillator strips instead of water → MINERvA-type detector
- A nuclear target region will allow to measure the interactions in Oxygen.
- The current detector can be adapted with scintillator instead of water planes in the P0D.
- Possibly use 3 different orientations of planes (XUV) → 3D reconstruction
- The P0D-ECAL can be replaced by a more segmented ECAL, similarly to Barrel or DSECAL.



MINERvA detector

The ND280 Detector Refurbishment List

w/ Roberto Sacco

The ND280 refurbishment is on top of any possible upgrade we aim to do.

- ND280 will be more than 13y old and will need to last for another decade at least.
- There are several aspects related to aging and spares (same technology may not be available anymore) that we need to address:
  - Electronics ageing:
    - Minimize the possible replacements. Some electronic cards may be impossible to replace unless we fully dis-assemble the detector. We can concentrate on the RMMs (Readout Merger Modules) only for upgrade/replacement, not TFBs (Trip-t Front End Boards).
  - MPPCs aging should be OK, but new technology and no experiment used them for long time. Extremely low failure rate so far.
  - MicroMega aging should be OK.
  - Scintillator/fiber aging:
    - To check light yield reduction. Studies from MINOs available.

Conclusion

- We can learn from current T2K experience how to design the ND.

- ND very important to reduce errors at the FD
  - Flux: using the ND280 flux to reweight the SK flux
  - Neutrino interactions: MEC effect is important

- Near Detectors for HK:
  - We can look (again) at the 2KM near detector
    - Very important for having the same flux as at HK
    - Systematics will partially cancel due to the usage of the same nucleus
  - Possible LAr (or other nuclei) will help in precisely measuring neutrino interaction and intrinsic ν_e beam background
  - Upgraded ND280 with a fully active up-stream detector to measure neutrino interaction with high precision.

Backup Slides

ν_e Appearance Analysis

$$N(\nu_e) = \Phi(E_\nu)\,\sigma(E_\nu)\,\epsilon\,P(\nu_\mu \rightarrow \nu_e)$$

Fit the observed rate to determine $\sin^2 2\theta_{13}$.

Also depends on

Neutrino Flux Prediction	Neutrino Cross Section Model	Far Detector Selection, Efficiency

We decrease the error on the ν_e rate, with the near detector;

$$N(\nu_\mu) = \Phi(E_\nu)\,\sigma(E_\nu)\,\epsilon$$

Neutrino Flux Prediction	Neutrino Cross Section Model	Near Detector Selection, Efficiency

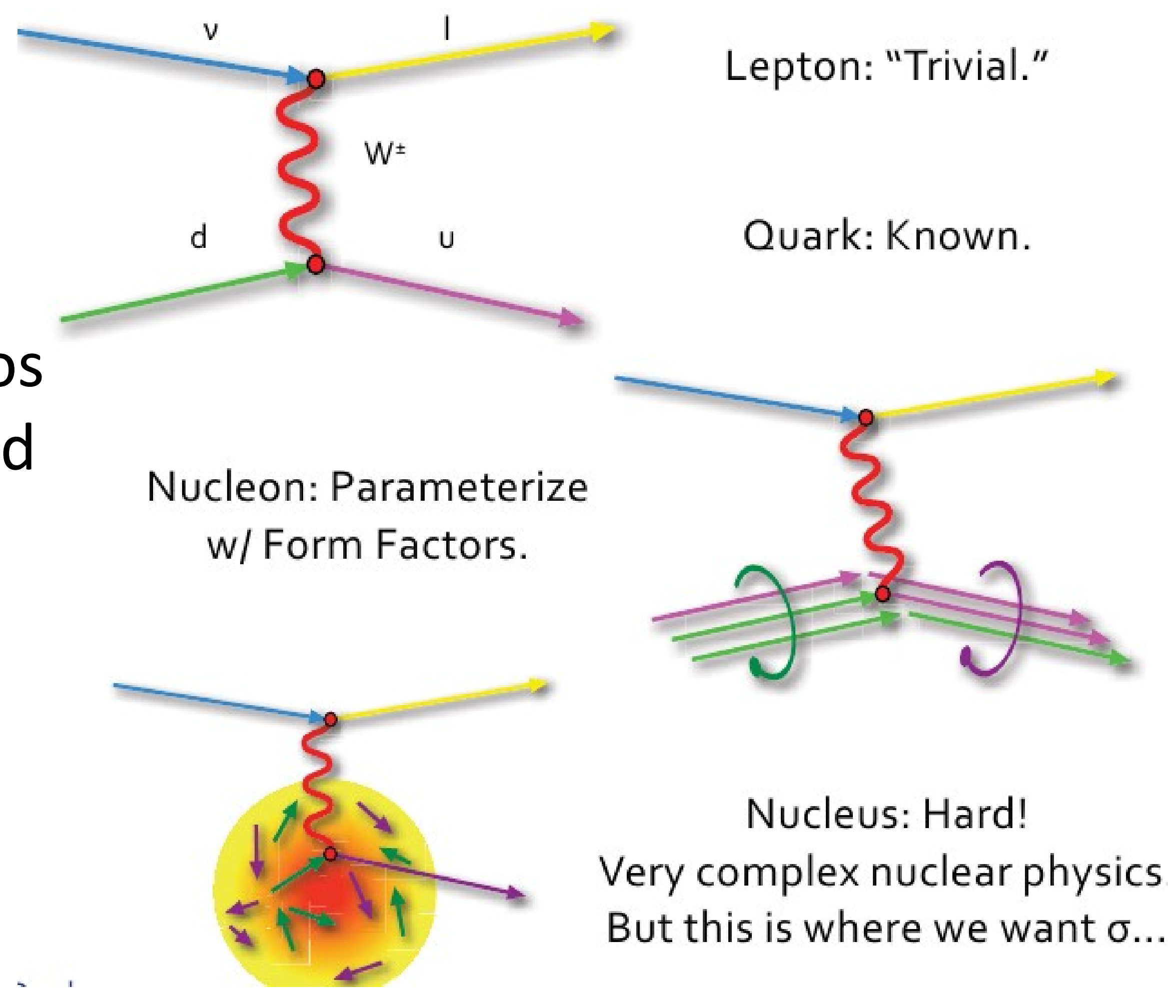
A focus on the ~1GeV region

Minor fraction of xsection at ~1GeV is purely leptonic - exactly known in the SM. Majority of interactions occur on bound states (nucleon, nuclei).

Until recently, assumed neutrinos interaction with individual bound nucleons (Impulse Approximation)

ν interaction is a two-step process: a primary interaction followed by final states interactions (FSI) effects: before leaving nucleus, hadrons undergo re-interaction

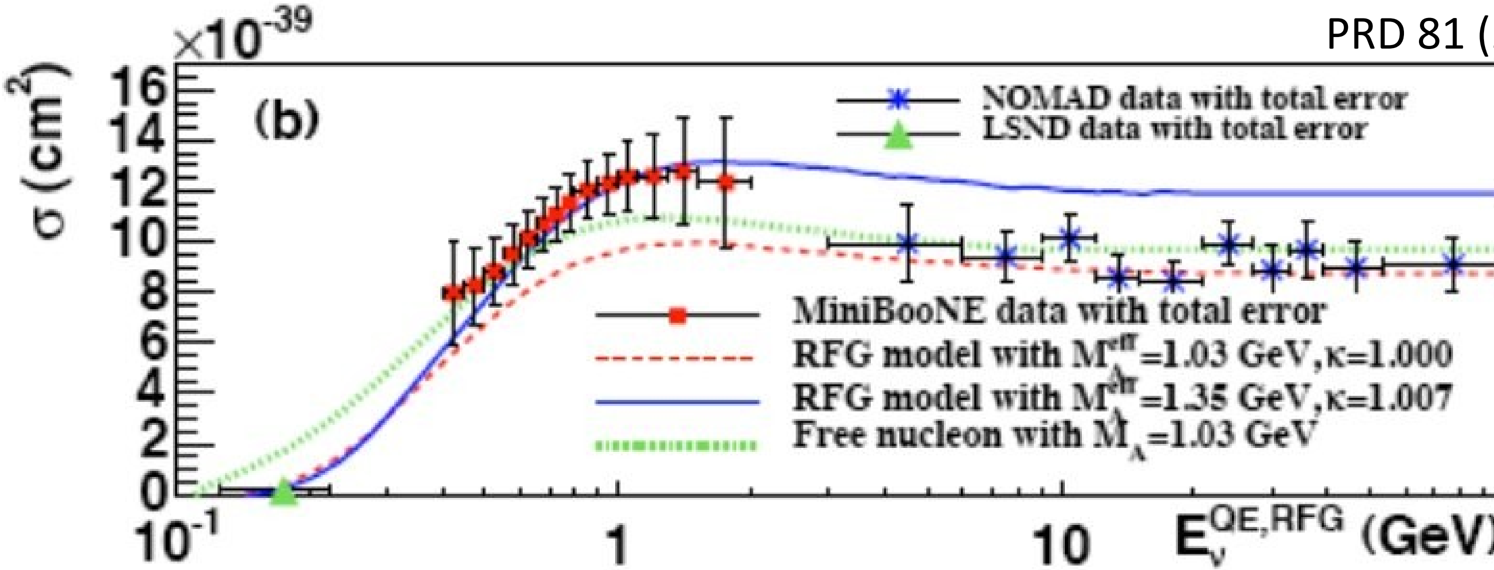
J.T.Sobczyk



CCQE Measurements

- Turning point is the high statistics MiniBooNE CCQE double differential cross section measurement:

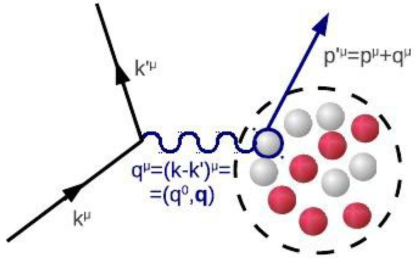
PRD 81 (2010) 092005



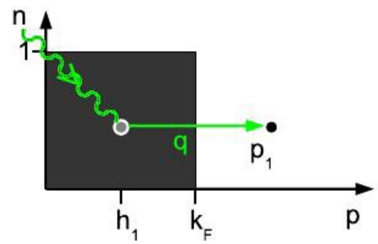
- Energy dependence of cross section of C is inconsistent between NOMAD and MiniBooNE.
- MiniBooNe measure μ 0π, NOMAD selects μ p
- Range of multinucleon models (extra process where neutrino interacts with more than a free nucleon) proposed:
  - Transverse enhancement to the cross section
  - Meson exchange current (MEC, simple Marteu process)
- Cross section also depends upon how nucleon is described within nuclear potential (nucleon is usually a relativistic gas model)

Introducing the Meson Exchange Current

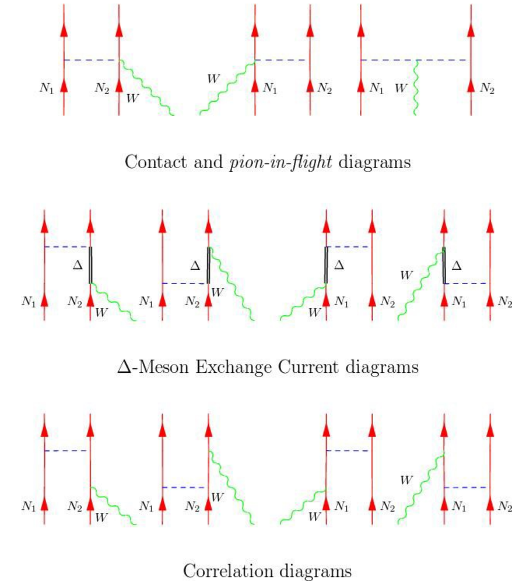
One body basic intuition:



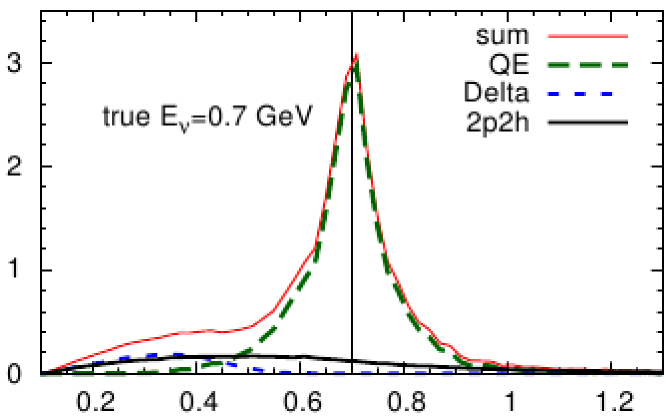
Fermi Gas: noninteracting nucleons, all states filled up to k_F



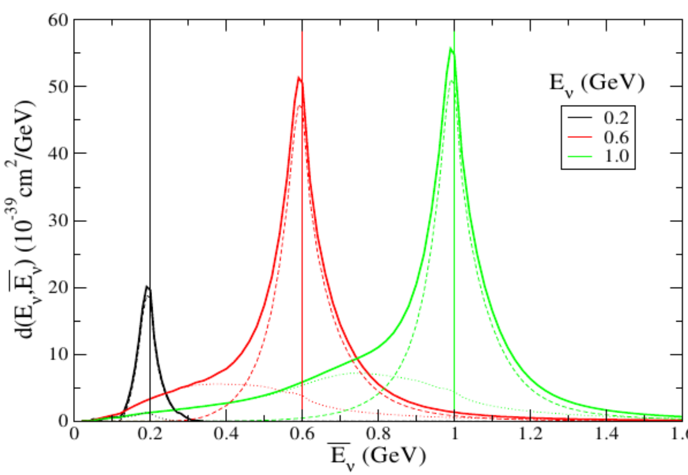
Two body basic intuition: think about more Feynman diagrams



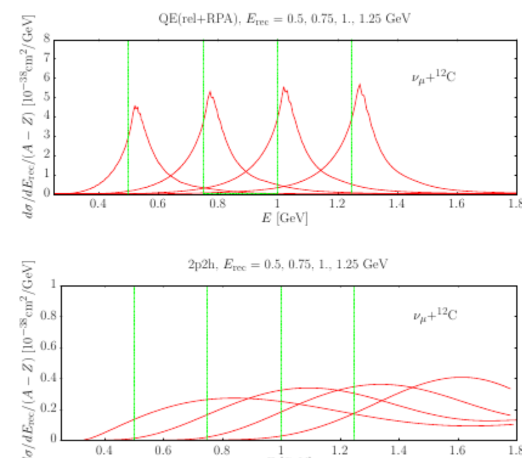
MEC events are suspected to introduce a strong bias to energy reconstruction:



Mosel and Lalalukich



Martini et al



Nieves and Sanchez

To separate MEC from CCQE analyze final state nucleons.