ν_μ Interaction Systematics at T2K

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IOP Parallel Sessions - 30th March, 2010

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Outline of Talk

- Introduction

- Disappearance measurement at T2K:
  - Current world limits
  - Method and main source of background.

- Neutrino interaction systematics:
  - GENIE Monte Carlo generator
  - Event reweighting
  - Effect on oscillation measurement

- Constraining XSec systematics using near detector fits:
  - ND280 Tracker
  - CC1pi measurement
  - MC study of event rates

Very Brief Overview of Neutrino Oscillations

Mass and flavour eigenstates different:

- Mass eigenstates propagate at different speeds: $|\nu_1(t)\rangle = |\nu_1\rangle e^{i\vec{p}_1.\vec{x}-iE_1 t}$

- QM interference of flavour eigenstates --> Gives rise to neutrino oscillations.

Related by the PMNS matrix: $\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{\mathrm{MNS}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$

"Atmospheric" **"Beam/Reactor - whoever is first"** **"Solar"**

$$U_{\mathrm{MNS}} = \begin{pmatrix}1 & 0 & 0\\ 0 & +c_{23} & +s_{23}\\ 0 & -s_{23} & +c_{23}\end{pmatrix}\begin{pmatrix}+c_{13} & 0 & +s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & +c_{13}\end{pmatrix}\begin{pmatrix}+c_{12} & +s_{12} & 0\\ -s_{12} & +c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \approx \begin{pmatrix}0.8 & 0.5 & s_{13}e^{-i\delta}\\ 0.4 & 0.6 & 0.7\\ 0.4 & 0.6 & 0.7\end{pmatrix}$$

Open questions for current generation of experiments:

T2K aims to shed light on these.

- Is θ_{23} maximal? Look at $\nu_\mu \nrightarrow \nu_\mu$.
- Is θ_{13} non-zero? Look at sub-dominant $\nu_\mu \rightarrow \nu_e$.
- Is there CP violation? Future beam experiments depending on size of θ_{13}.
- Precise measurement of mass squared differences.

This talk focusses on measurement of θ_{23} and $|\Delta m^2_{23}|$

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Current Knowledge of Atmospheric Mixing Parameters

Survival probability given by:

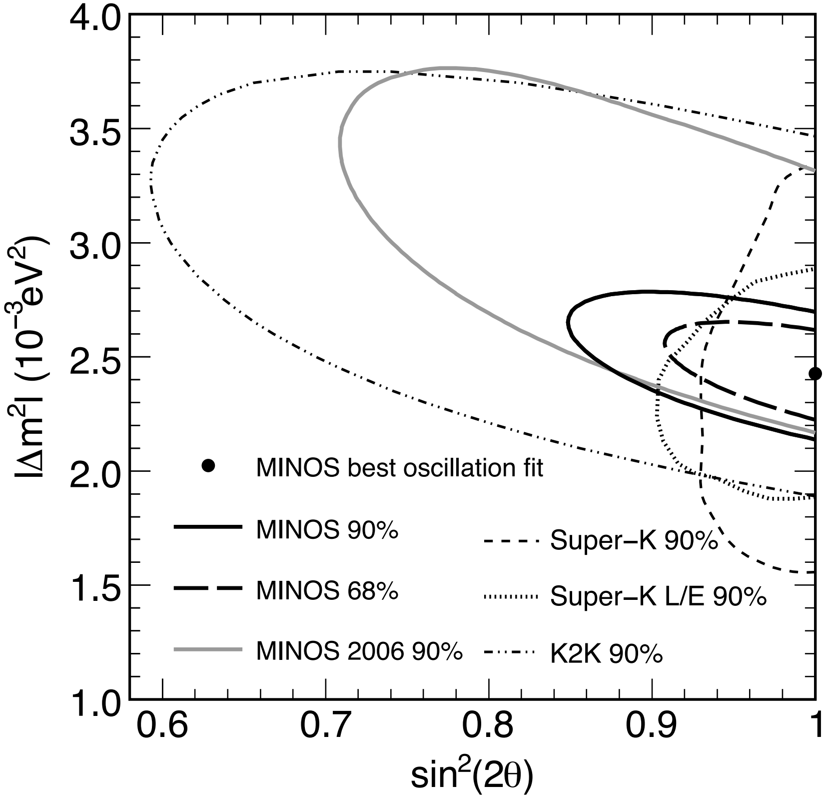
$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left[\frac{1.27\Delta m^2_{23}(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right]$$

Atmospheric
> 0.92 (90% CL)

Accelerator
(2.43+/-0.13)*10^{-3} (68% CL)

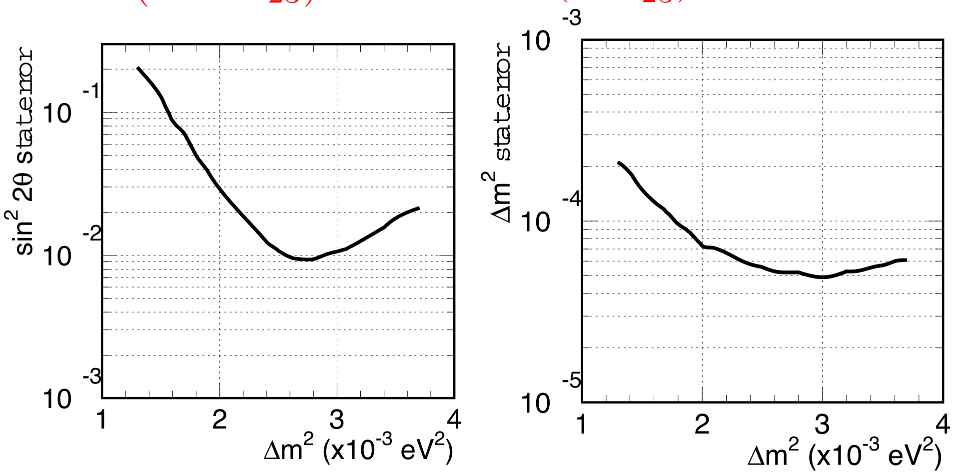
Compilation of world measurements:

Phys.Rev.Lett.101:131802,2008.



Expected sensitivity @ T2K after 5x10[21] POT:

$\delta(\sin^2 2\theta_{23}) \approx 0.01$ $\delta(\Delta m^2_{23}) < 10^{-4}eV^2$



* corresponds to ~ 3 years nominal running (see backups for details)

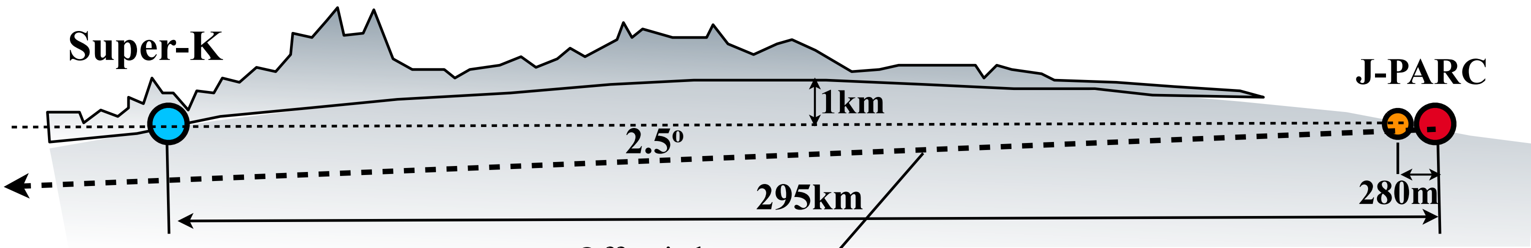
The Disappearance Measurement

Signal is anything that allows the species and energy of neutrino to be reconstructed. Extract oscillation parameters by comparing observed at SK with predicted and minimising w.r.t. oscillation parameters*.

$$\frac{dN_{\nu}^{obs}}{dE_{\nu}^{reco}}$$

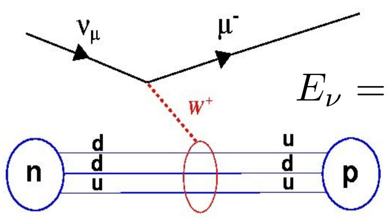
$$\frac{dN_{\nu}^{pred}(\sin^2\theta_{23}, \Delta m^2_{23})}{dE_{\nu}^{reco}}$$

Making this prediction is difficult. Requires many inputs - see next slide.



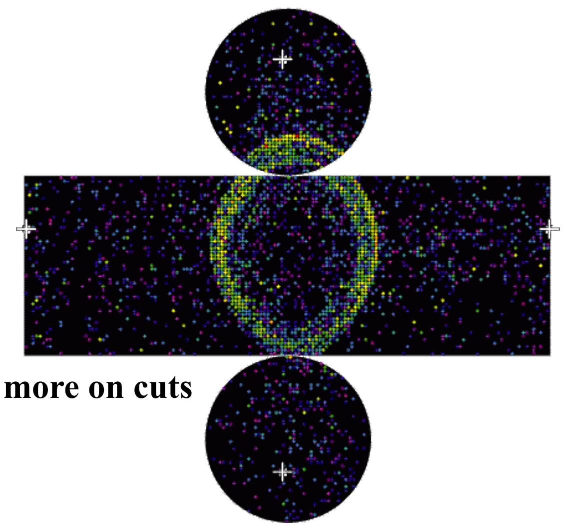
Off axis beam:
- Narrow energy spectrum
- Peak of spectrum --> oscillation maximum @ SK.

CCQE interactions are ideal candidate for signal:
- Reconstruct energy using only muon.
- 50% of CC events.



$$E_{\nu} = \frac{m_N E_{\mu} - m_{\mu}^2/2}{m_N - E_{\mu} + p_{\mu}\cos\theta_{\mu}}$$

At Super-K look for events with single clean ring (1Rμ-like):



See backup slides for more on cuts

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* And comparing to the NULL hypothesis.

Predicting what Passes the 1Rμ cut

True neutrino energy

$$\frac{dN_\nu^{pred}}{dE_\nu^{reco}} \propto \int dE_\nu \cdot \Phi^{SK}(E_\nu) \cdot \boxed{\sigma(E_\nu) \cdot \epsilon^{SK}_{1R_\mu}(E_\nu) \cdot p(E_\nu; E_\nu^{rec})}$$

Extrapolated from flux MC tuned using:

- NA61 data.
- Measurements at INGRID.
- Measurements at ND280.
- Simplest - use a Near/Far ratio.
- More involved - extrapolation matrices.

Detection efficiency for 1Rμ events:

- This is the sum over different types of event:

$$\sigma(E_\nu) \cdot \epsilon^{SK}_{1R_\mu}(E_\nu) = \sum_{i=1}^{N} \sigma_i \cdot \epsilon_i$$

Neutrino cross-sections:

- Use neutrino MC generators (GENIE, NEUT).
- Generators act as repository for world neutrino cross-section data.
- Have to link together many theoretical and phenomenological models to cover necessary kinematical range.

Probability of reconstructing an event with true energy E_ν as E_ν^{reco}

- For CCQE events this should b fairly well peaked around **E_ν**.
- For non-CC-QEL event which pass the **1Rμ** this will be asymmetric.

In practice use a chain of MC to evaluate the above.

Beam MC → Neutrino MC generator

Description of detector → Neutrino MC generator

Neutrino MC generator → Detector MC → Reconstruction/ Analysis cuts

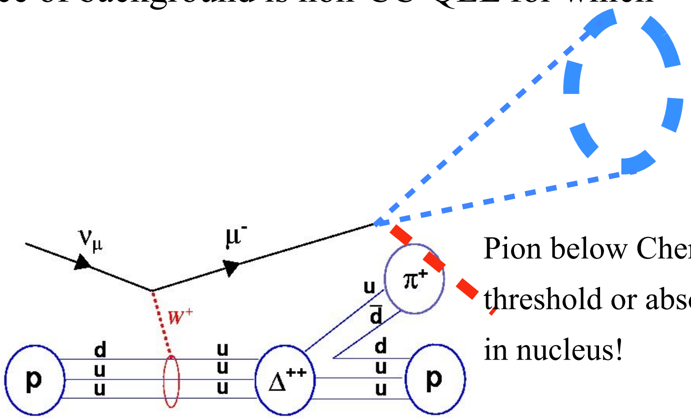
Computationally and logistically demanding! Size of data sets representing lifetime of experiment are prohibitive.

CC1π+ Background

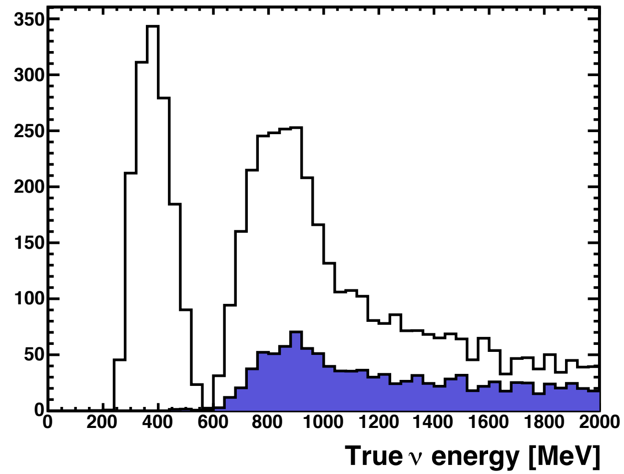
As mentioned before: At Super-K look for events with a single muon-like ring (**1Rμ**). Main source of background is non-CC-QEL for which only the muon is detected.

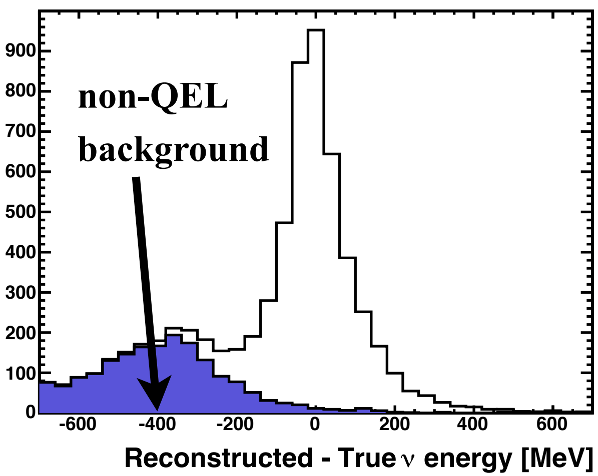
19% non-CC-QEL background:

- Mostly (~70%) from CC 1pi channel.
- Rest CC multi pi and NC 1pi channels.

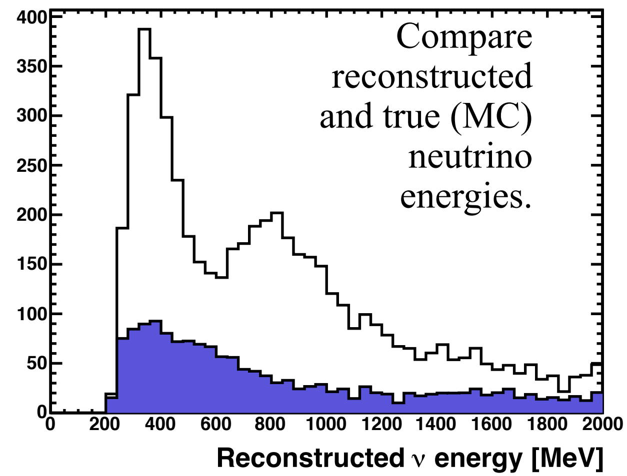


Pion below Cherenkov threshold or absorbed in nucleus!





Is background not because does not oscillate but because mis-reconstruct energy of higher energy neutrinos and fill in oscillation dip.



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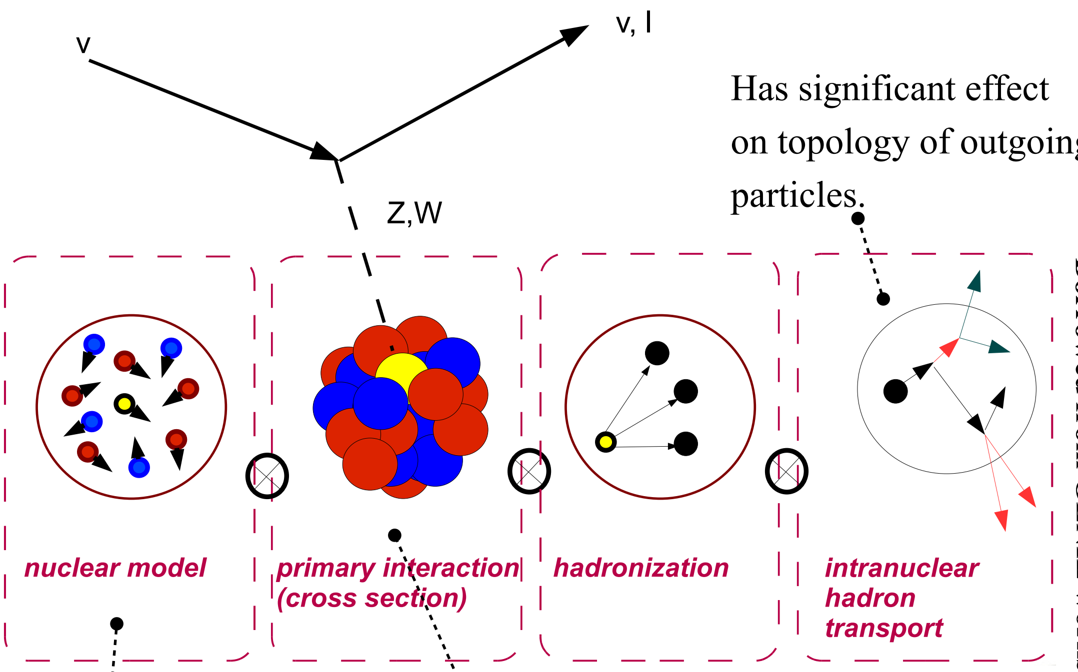
Simulating Neutrino Interactions

Can break up modelling of neutrino interactions into 4 pieces*:

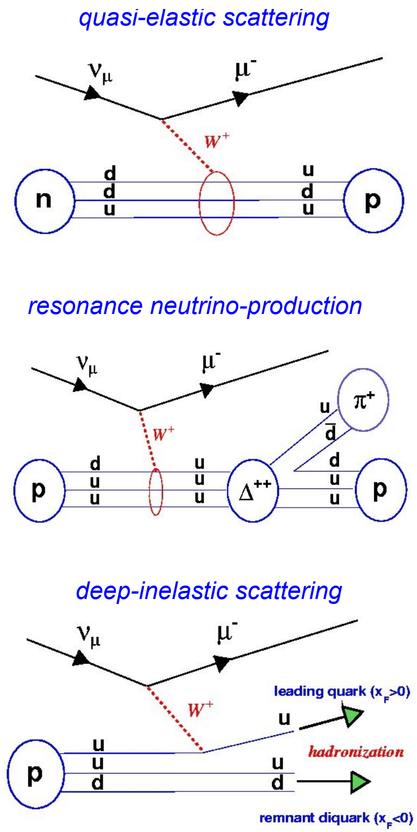


Has significant effect on topology of outgoing particles.

Effects cross-section and kinematics of outgoing particles.

Borrowed from GENIE workshop talk.

Dominant interaction modes at ~ 1GeV:



Get CC1π from sum of processes:

$$\sigma_{\nu N}^{\mathrm{tot}} = \sigma_{\nu N}^{\mathrm{(Q)ES}} \oplus \sigma_{\nu N}^{1\pi} \oplus \sigma_{\nu N}^{2\pi} \oplus \ldots \oplus \sigma_{\nu N}^{1K} \oplus \ldots \oplus \sigma_{\nu N}^{\mathrm{DIS}}$$

* A simplified picture.

GENIE Monte Carlo Generator

www.genie-mc.org

Generates **E**vents for **N**eutrino **I**nteraction **E**xperiments*:

- Developed by an international collaboration of neutrino interaction experts and used on many experiments**.
- Modern Object-Oriented Neutrino MC Generator:
  - Modular design.
  - Flexible to new experimental data and developments in theory.
- Combines many models to span a large kinematical range; Several MeV to several hundred GeV:
  - Maintains internal consistency and continuity.
- All neutrino flavours and all nuclear targets.
- Takes detailed flux simulations and generates events of detailed detector geometries.
- Can also operate in electron scattering mode - allows tuning and validation of models to electron scattering data.

Many, >100, configurable input physics parameters! + When added to the detector MC and the reconstruction stages the total production time is prohibitive. → Need to evaluate effect of uncertainties in the input parameters gives motivation for event reweighting.

* For full description of GENIE: **Nucl.Instrum.Meth.A614:87-104,2010**

** T2K, MINOS, NOvA, MINERvA, ArgoNEUT, MicroBooNE, INO

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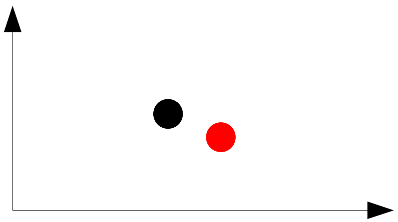
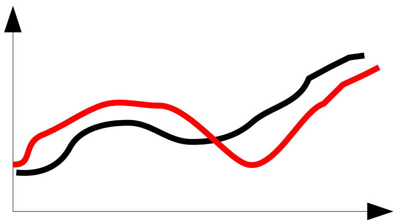
Event Reweighting

Motivation: To evaluate the effect of changes in input physics parameters without re-running time intensive MC.





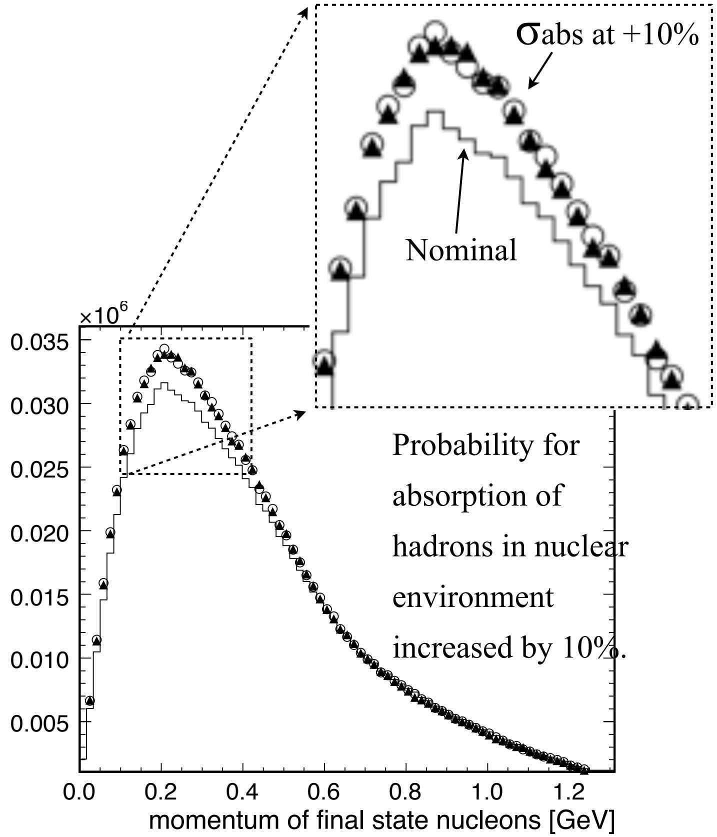
Extensive set of tools to do this are incorporated into GENIE - a thin interface is provided to link with T2K software. Currently can reweight parameters controlling:

- Cross-section models.
- Intranuclear hadron transport model.

Massive speed increase opens up lots of possibilities:

- Scan large volumes of input parameter space and evaluate systematic uncertainties.
- Use input parameters as free parameters in fits to data.

Validation: Compare reweighted (circle) with regenerated (triangle).



More info: http://th-www.if.uj.edu.pl/acta/vol40/pdf/v40p2613.pdf

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Oscillation Systematics Study

- Fit Mock Data

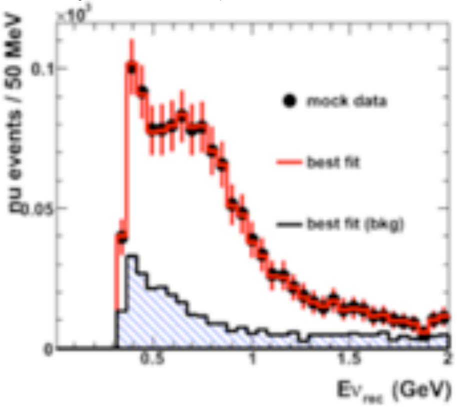
- Mock data were tweaked (reweighted)

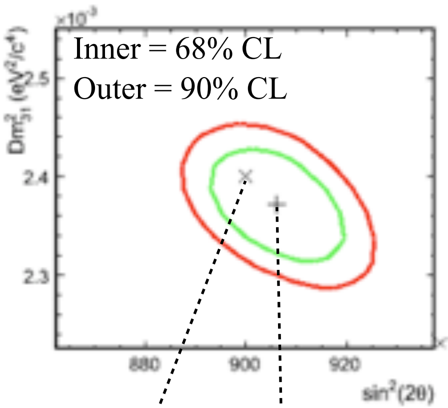
    - to account for a physics model change
    - modified:
        - Axial mass parameters for QEL and RES production, non-RES background scaling factors, hadron mean free paths, pion absorption fraction.

- Performed oscillation fit.

- Fit used the nominal MC (physicist unaware of nature's choice for the exact physics param value).

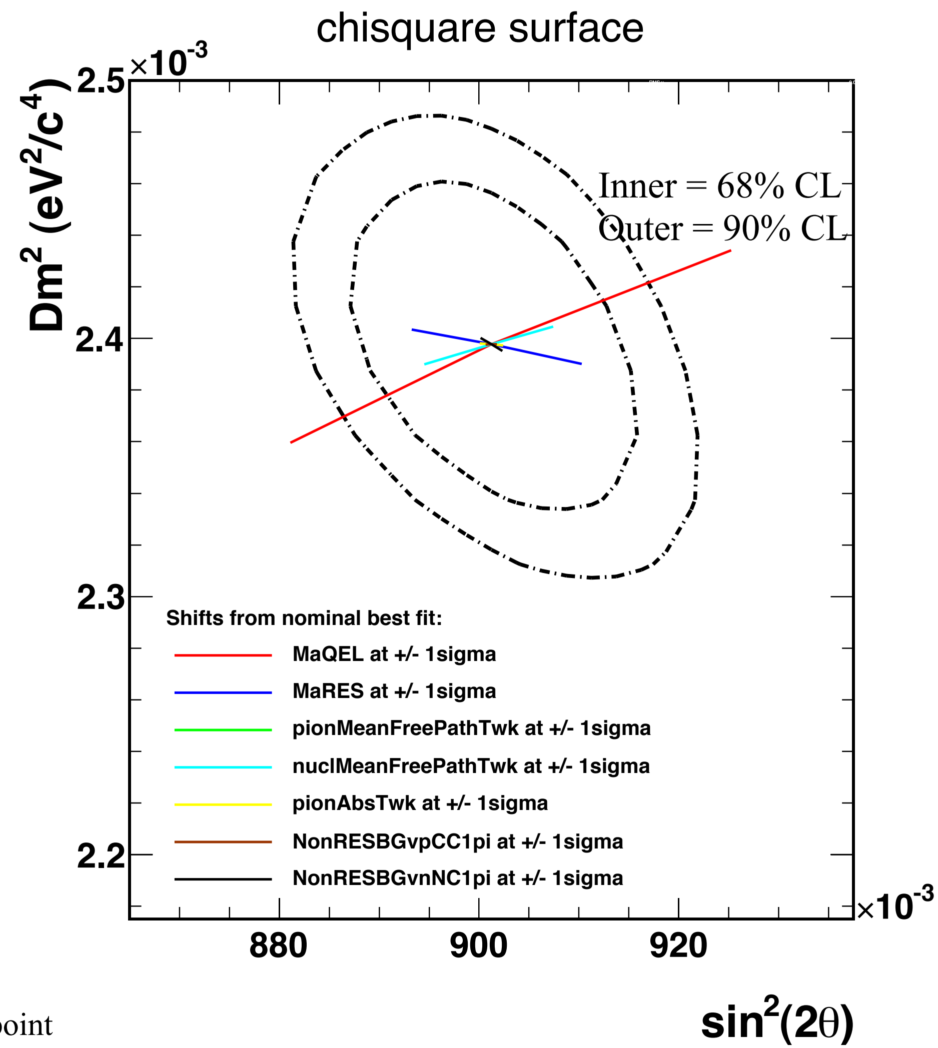
- Studied how the best fit point shifts (oscillation systematic).





Nominal best fit point

Shift in best fit point for tweaked MaRES by -20%



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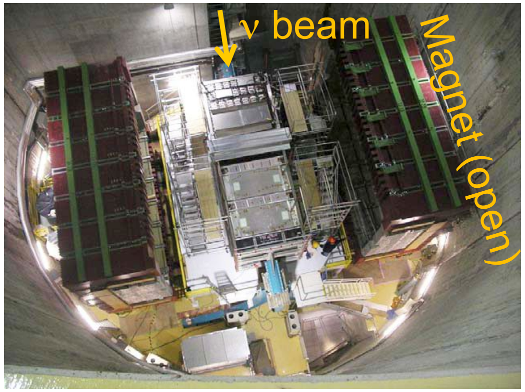
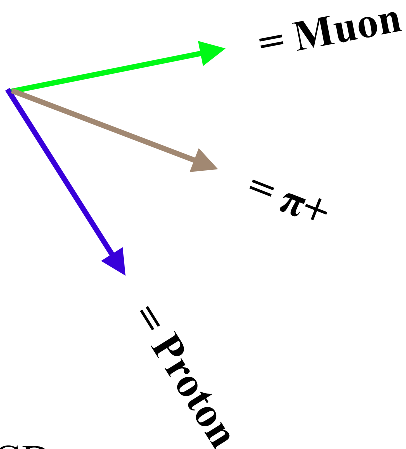
Constraining CC1π Background at ND280

Uncertainties in neutrino interaction models give rise to systematic uncertainties in oscillation measurement. Make cross-section measurement at ND280 to constrain systematics.

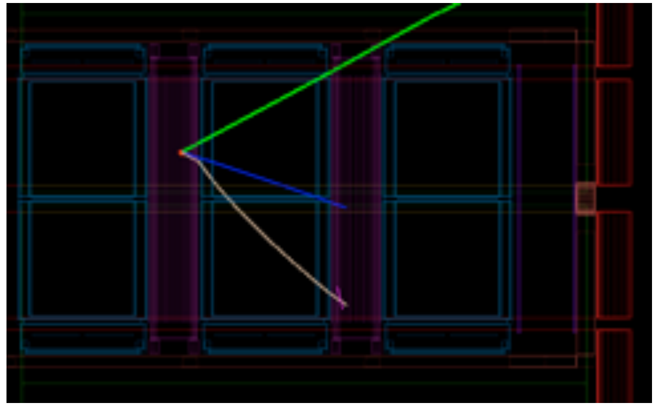
ND280 Tracker:



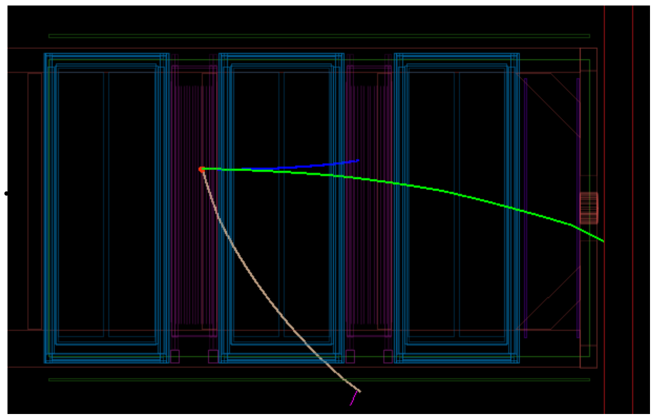
CC1π signature:

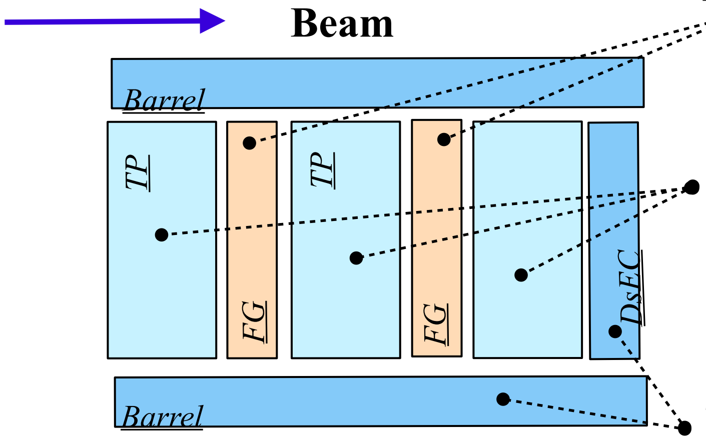


Top view of Tracker



Side view of Tracker





FGDs:
- Fiducial volumes.
- Vertex location.

TPCs:
- Momentum measurement..
- PID.
- Vertex location.

Tracker ECal:
- PID.
- Energy measurement.

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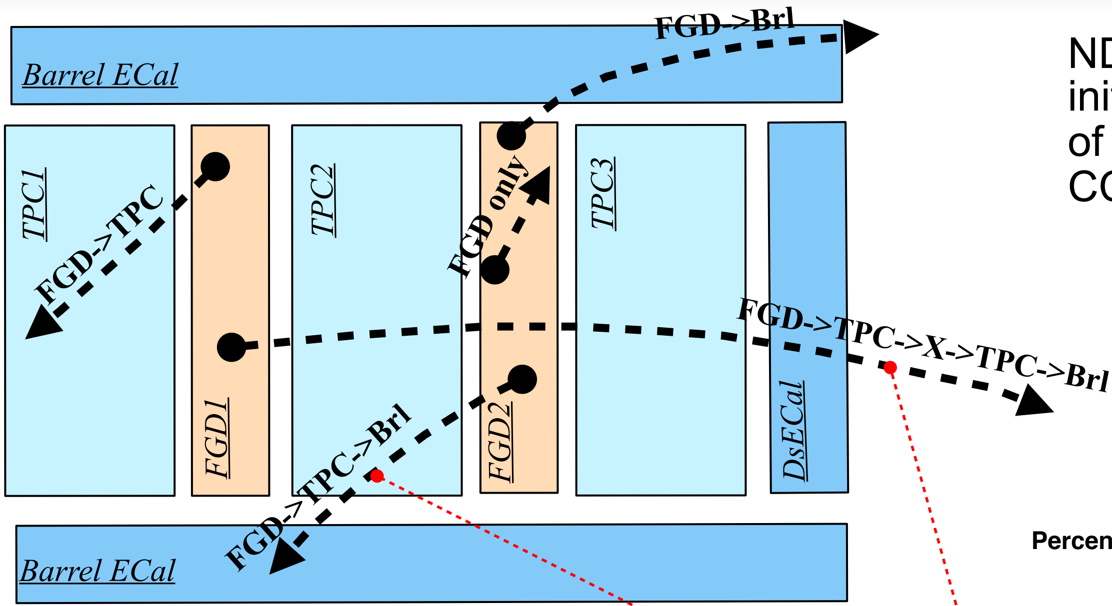
MC Study of Event Rates



ND280 is a complex detector: initially look at different types of detector topologies for CC1π measurement.

30 % both pion and muon have paths through a TPC.

~ 24,000 events for 1yr @ full intensity

Percentage of CC1π^+ events in FGDs for given detector paths

π detector path \ μ detector path	FGD only	FGD->Brl	FGD->TPC	FGD->TPC->Brl	FGD->TPC->X->TPC	FGD->TPC->X->TPC->Brl	kOther
kOther	0.01	0.02		0.01	0.00		0.01
FGD->TPC->X->TPC->Brl	0.09	0.09	0.02	0.26	0.19	0.05	0.02
FGD->TPC->X->TPC	0.33	0.39	0.18	0.96	0.78	0.11	0.03
FGD->TPC->Brl	2.58	1.96	4.09	4.76	3.31	0.54	0.11
FGD->TPC	3.43	2.97	6.88	5.45	1.94	0.36	0.16
FGD->Brl	1.49	1.99	2.07	1.53	1.05	0.21	0.20
FGD only	9.30	6.49	12.32	13.37	6.28	1.27	0.36

Initial thoughts:

- Significant statistics for events with both μ and π tracks going through TPC.
- Can recover events for which one track does not go through a TPC using the tracker ECal.
- Also a subset of events will have information on the proton track - detailed studies of kinematical dependencies of models.

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Summary

- Have ability to evaluate impact of many cross-section systematics on the oscillation measurement.

- $CC1\pi+$ is the dominant background for the disappearance measurement.

- In process of making cross-section measurement @ ND280 tracker:
  - High enough statistics to make very accurate measurements of $CC1\pi+$ channel.

- Utilise reweighting machinery in fits to constrain underlying physics parameters for processes that contribute to $CC1\pi+$ background.

BACKUPS

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Super-K Cuts

- Fiducial Volume Cut: Require reconstructed vertex is contained inside the fiducial. Removes difficult to reconstruct events close to wall.

- Fully Contained Cut: Put limit on hits in outer detector to make sure event did started inside detector.

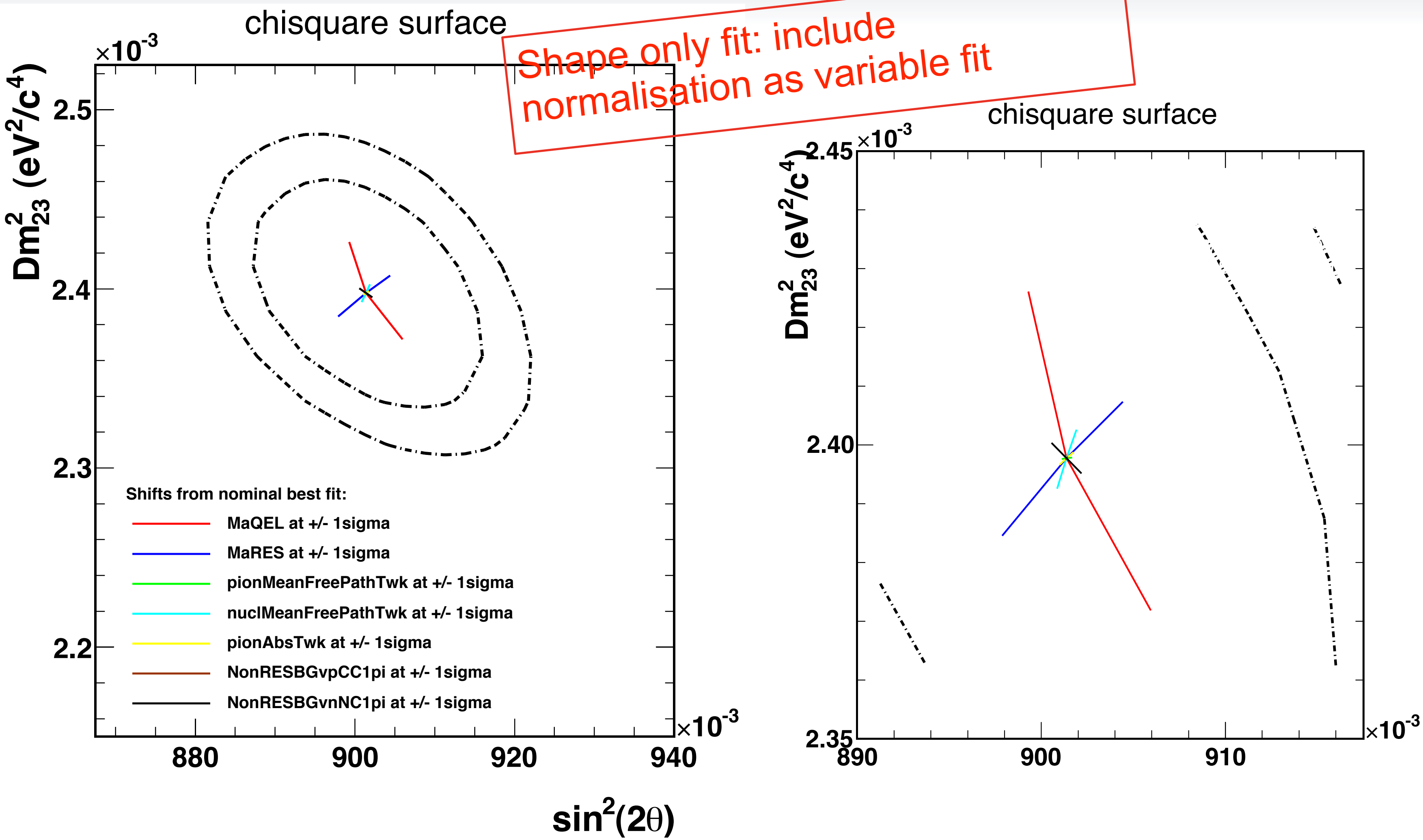
- Visible Energy Cut: visible energy in the inner detector (ID) is greater than 100 MeV/c . Removes noise and low energy events.

- Single ring cut: So dominantly select QEL events.

- Ring has to be muon-like.

Shape Only Fits

Shape only fit: include normalisation as variable fit



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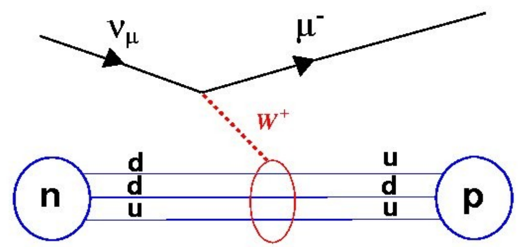
Process - Topology Breakdown

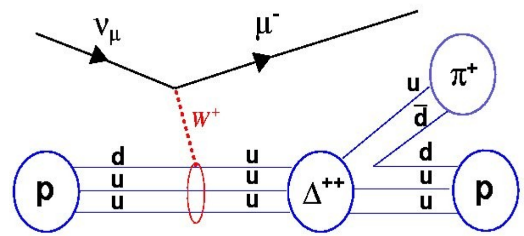
π topology	QEL	RES	DIS	COH	Other	Total
Total	51.65	28.03	19.36	0.72	0.24	
Multi πs		0.25	5.41		0.00	5.66
$1\pi^{+}+1\pi^{0}$	0.06	0.44	2.56		0.00	3.06
$1\pi^{-}+1\pi^{+}$		0.23	0.91		0.00	1.14
$1\pi^{-}+1\pi^{0}$		0.02	0.19		0.00	0.22
$2\pi^{+}$		0.07	0.78			0.85
$2\pi^{0}$		0.10	0.51		0.00	0.61
$2\pi^{-}$		0.00	0.03			0.03
$1\pi^{+}$	0.07	16.35	5.07	0.66	0.03	22.17
$1\pi^{0}$		4.26	2.35		0.02	6.63
$1\pi^{-}$		0.68	0.34	0.07	0.01	1.10
0π	51.52	5.64	1.20		0.17	58.53

Process

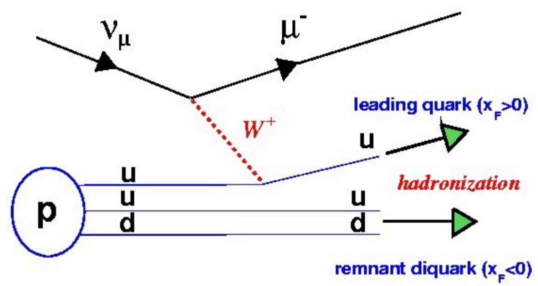
quasi-elastic scattering



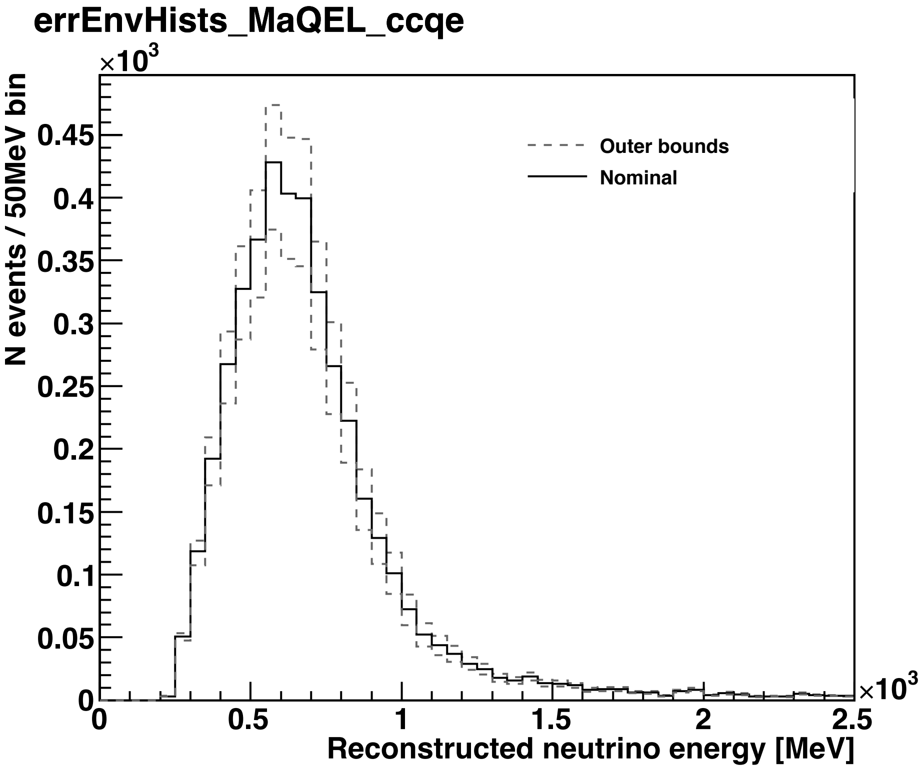
resonance neutrino-production

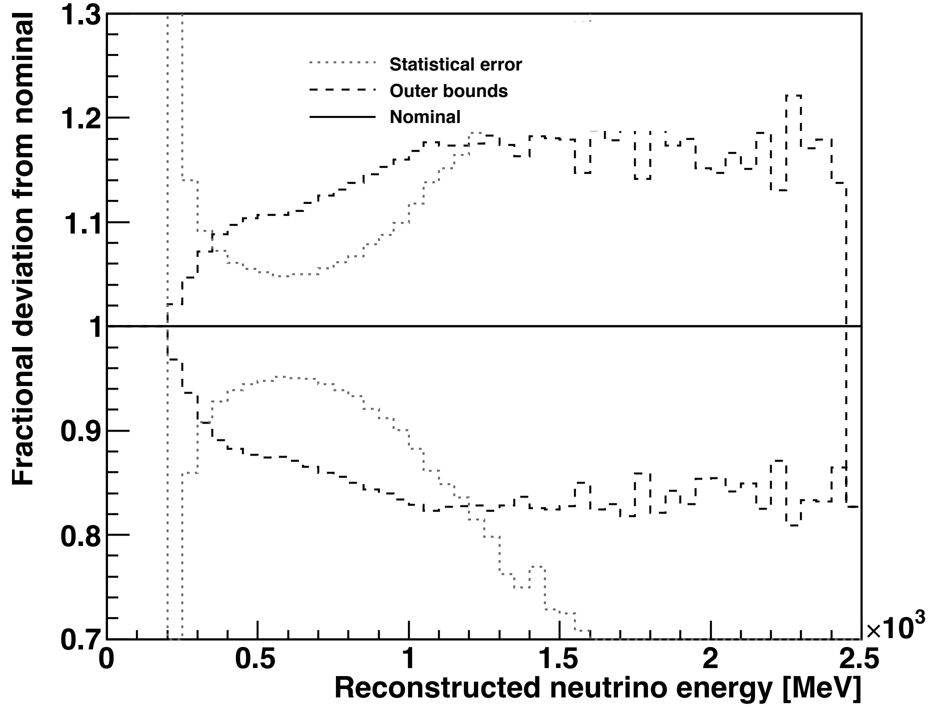


deep-inelastic scattering



SuperK CCQE Error Envelope: Tweaking QEL axial mass parameter by +/- 15%





All error envelope studies are for 5 years nominal running assuming ~ 1200 signal events/year.

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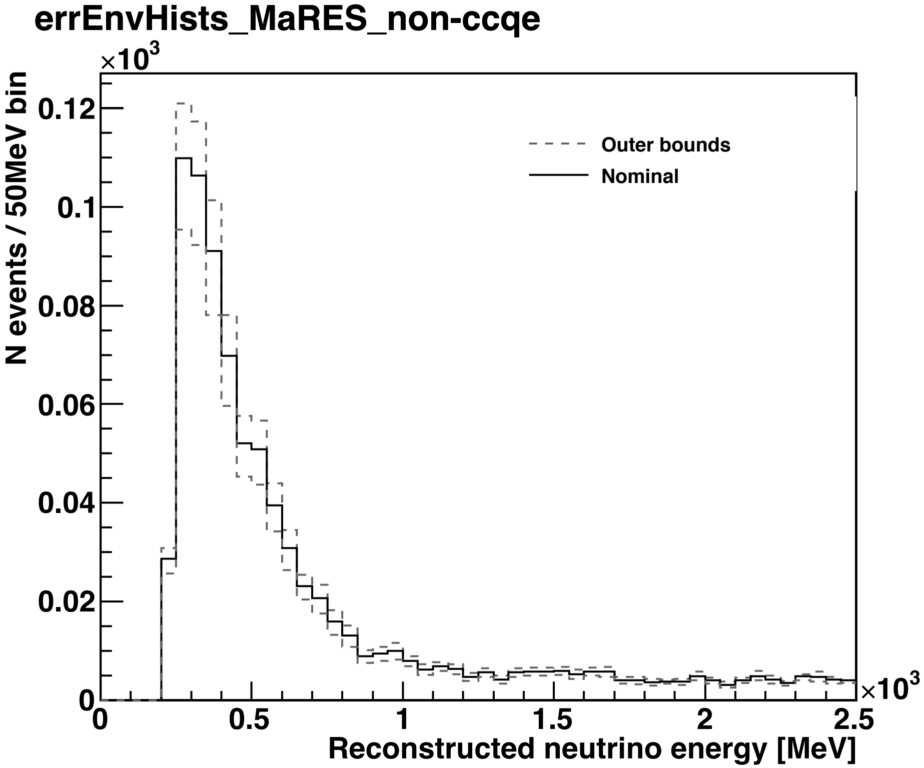
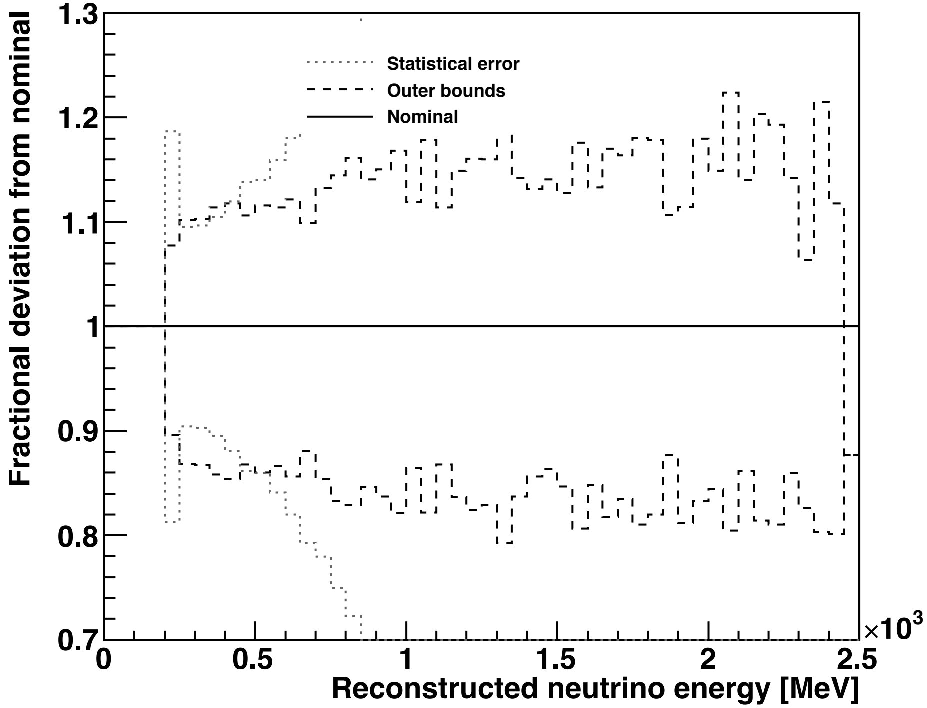
SuperK Non-CCQE Bkg Error Envelope: Tweaking RES axial mass parameter by +/- 20%





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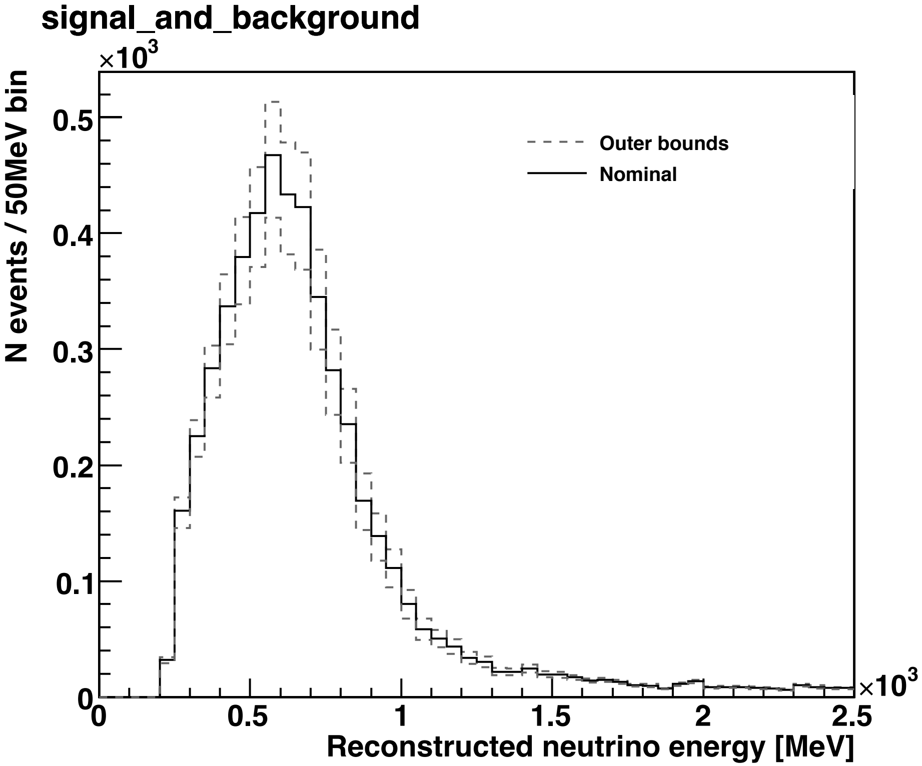
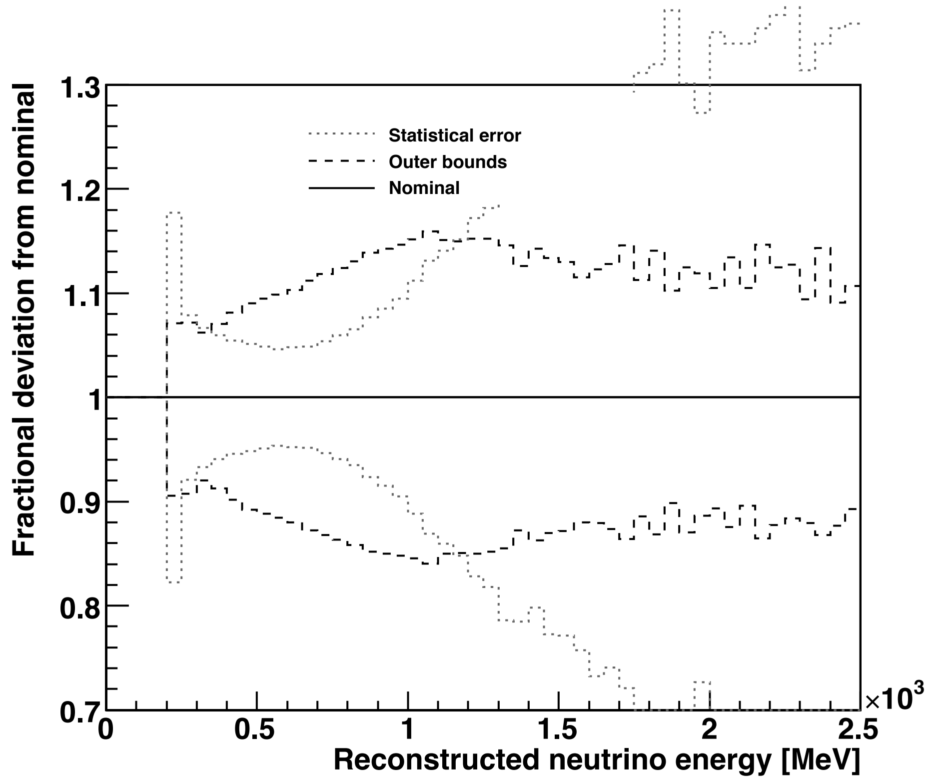
Error Envelope for events which pass FC1R cut: now include uncertainty on signal and background (add in quadrature)





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Including nuisance parameters in fit

[simplistic case: uncorrelated systematics]

Penalty terms

Systematic (nuisance)

Expected

Observed

$$\chi^2(\Delta m^2_{mn}, sin^2 2\theta_{mn}, \overbrace{a_0, a_1, ..., a_j}^{\text{Systematic (nuisance)}}) = \sum_{i=0}^{nbins} 2(e_i - o_i) + 2o_i ln(o_i/e_i) + \overbrace{\sum_{j=0}^{nsyst} \frac{(a_j - < a_j >)^2}{\sigma^2_{syst,j}}}^{\text{Penalty terms}}$$

Updates

Tweaks @ nominal MC

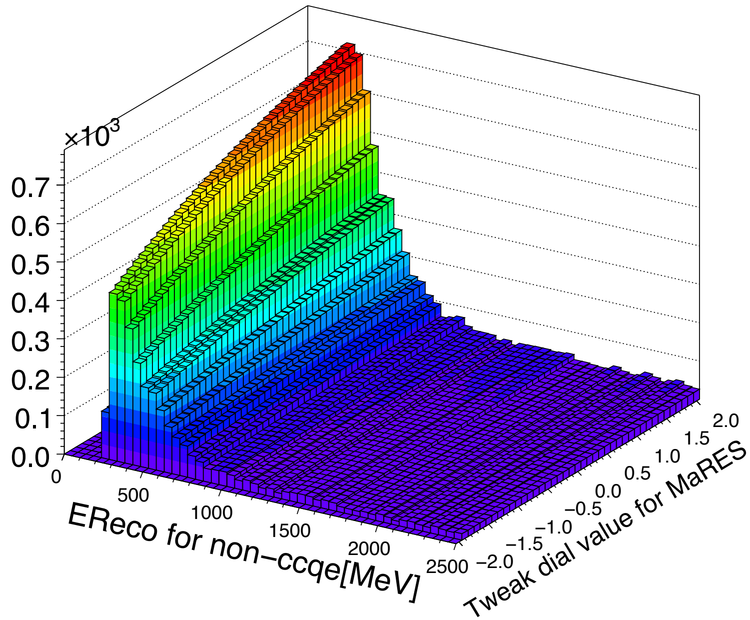
'Monte Carlo'

REWEIGHT

$$e_i = e_i(\Delta m^2_{mn}, sin^2 2\theta_{mn}, a_0, a_1, ..., a_j)$$

$$= (\prod_{j=1}^{nsyst} w_j) * e_i(\Delta m^2_{mn}, sin^2 2\theta_{mn}, < a_0 >, < a_1 >, ..., < a$$

Calculate gradients for optimised fitting techniques.



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