The Effect of Interaction Cross Section Systematics on the T2K ν_μ Disappearance Measurement

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IOP Parallel Sessions - 30th March, 2010

Imperial College London

Outline of Talk

- ν_μ 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 cross section systematics using near detector fits:
    - CC1π measurement at ND280, MC study of event rates.

Current Knowledge of Atmospheric Mixing Parameters

Survival probability given by:

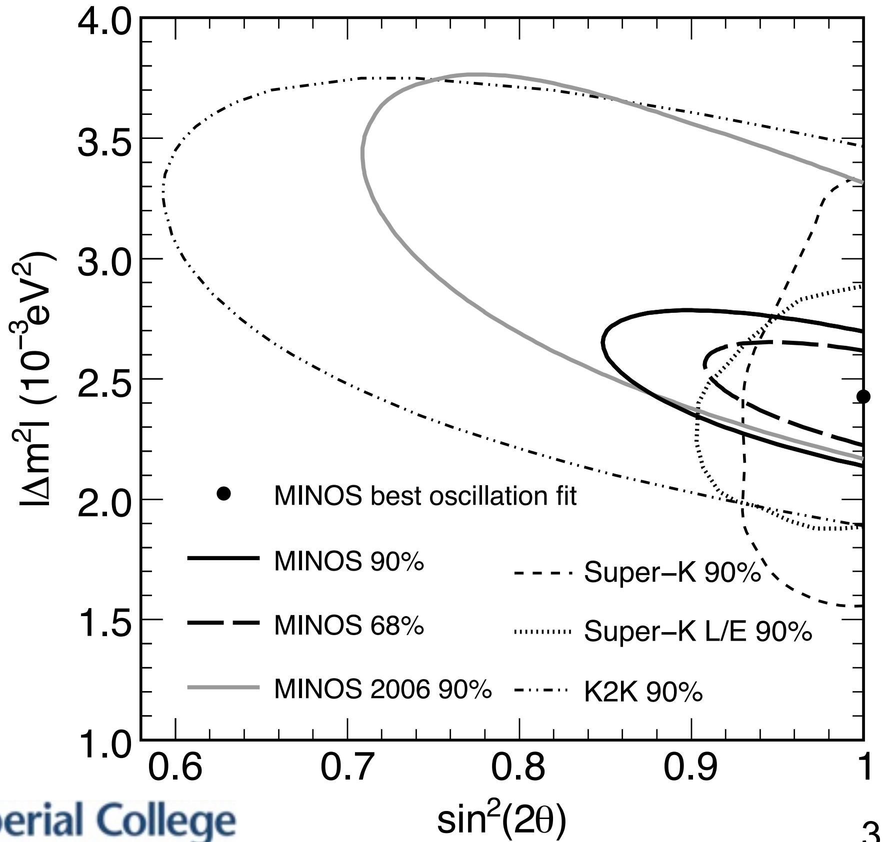
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left[\frac{1.27\Delta m^2_{23}(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right]$$

Atmospheric
> 0.92 (90% CL)

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

Compilation of world measurements:

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



Expected sensitivity at T2K after 5 years (nominal running):

$$\delta(\sin^2 2\theta_{23}) \approx 0.01$$

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

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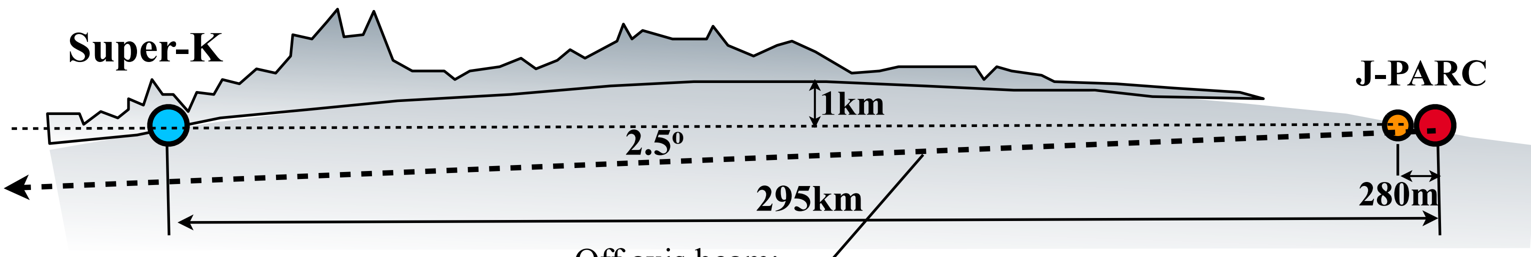
The ν_μ Disappearance Measurement

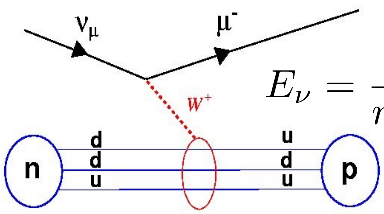
Signal = anything that allows the species and energy of neutrino to be reconstructed.
Compare expected with observed at Super-K to extract oscillation parameters.

$$\frac{dN_\nu^{obs}}{dE_\nu^{reco}} \qquad \frac{dN_\nu^{pred}(\sin^2\theta_{23}, \Delta m_{23}^2)}{dE_\nu^{reco}}$$



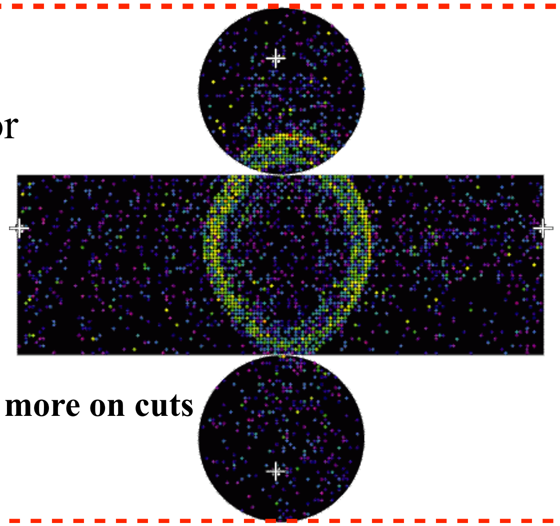
Off axis beam:
- Narrow energy spectrum
- Peak of spectrum --> oscillation maximum @ SK.

Charged current quasi-elastic (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 muon-like ring (**1Rμ-like**):



See backup slides for more on cuts

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Predicting what Passes the 1Rμ-like cut at Super-K

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

Prediction of flux at Super-K:
- Flux Monte Carlo
- NA61 data.
- Measurements at near detectors.

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 interface to 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 be 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

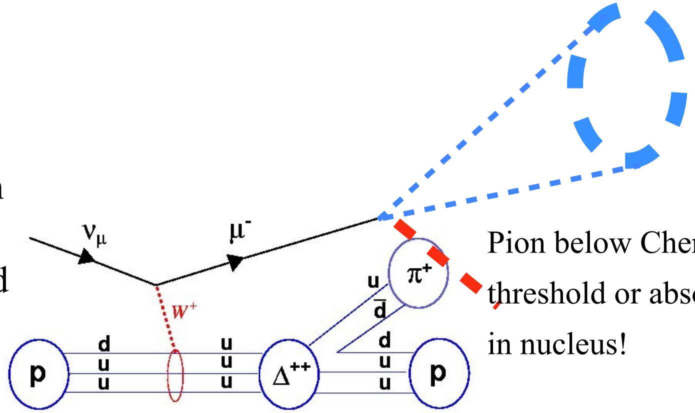
Computationally and logistically demanding! Size of data sets representing lifetime of experiment are prohibitive.

CC1π+ Background

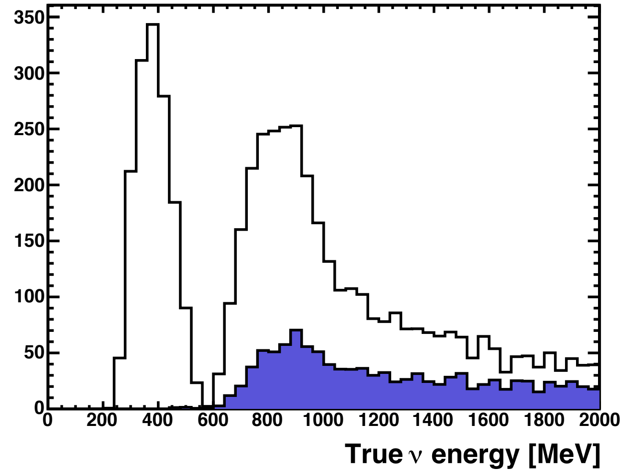
Main source of background is non-CC-QEL for which only the muon is detected.

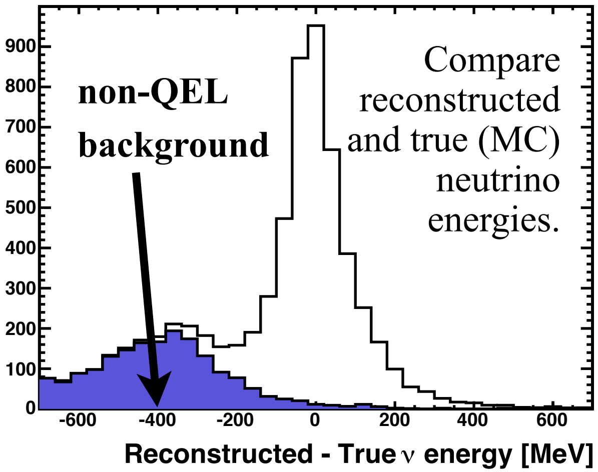
19% non-CC-QEL background:

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

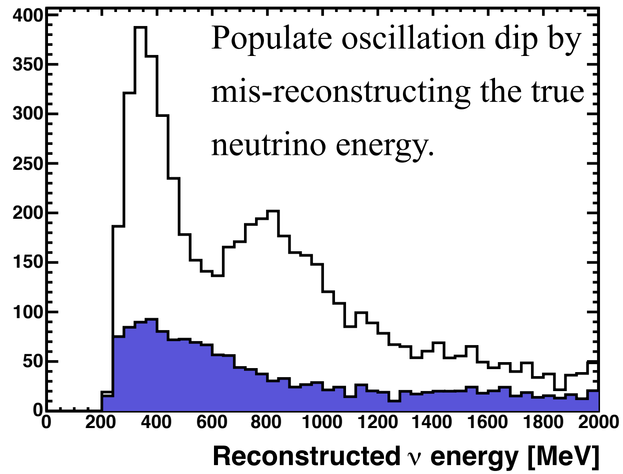


Pion below Cherenkov threshold or absorbed in nucleus!





Systematically mis-reconstruct neutrino energy for non-QEL background.

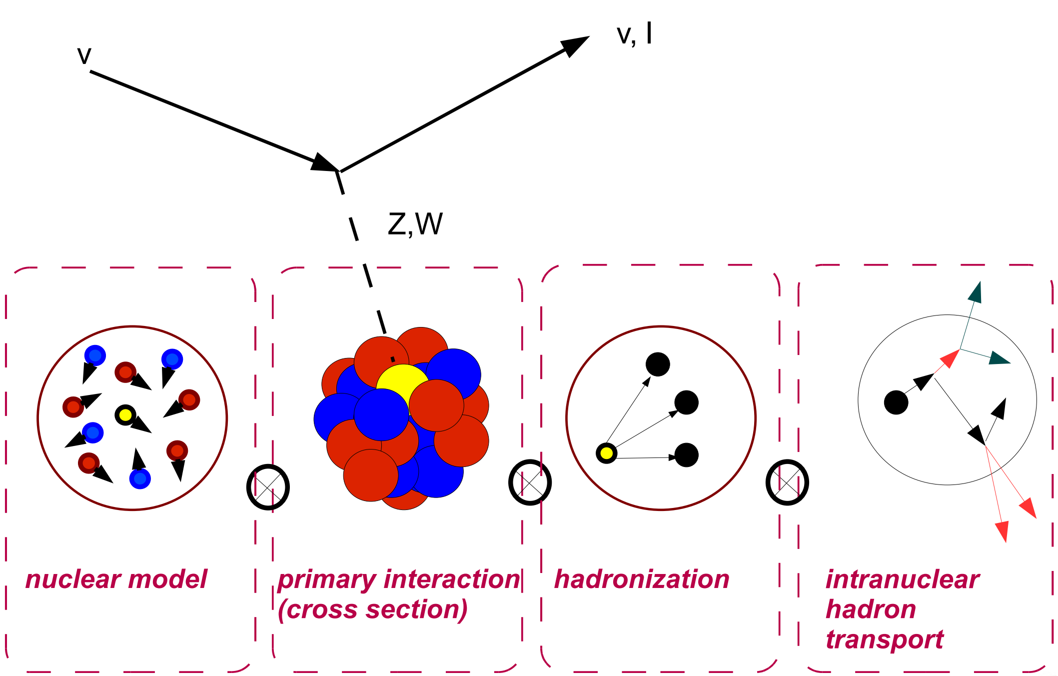


Simulating Neutrino Interactions

At ~1GeV cross-sections are poorly known:

- Lack of data.
- Inadequate theoretical models.
- Uncertainties of order 20%.

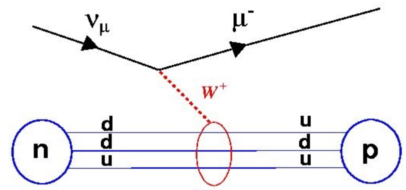
→ with sensitivity @ T2K this is now relevant



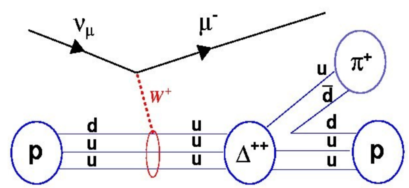
Borrowed from GENIE workshop talk.

Dominant interaction modes at ~ 1GeV:

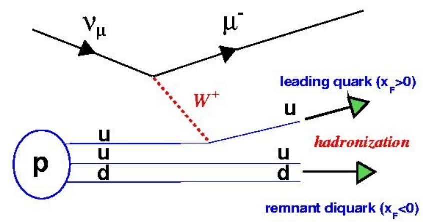
quasi-elastic scattering



resonance neutrino-production



deep-inelastic scattering



GENIE Monte Carlo Generator

www.genie-mc.org

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

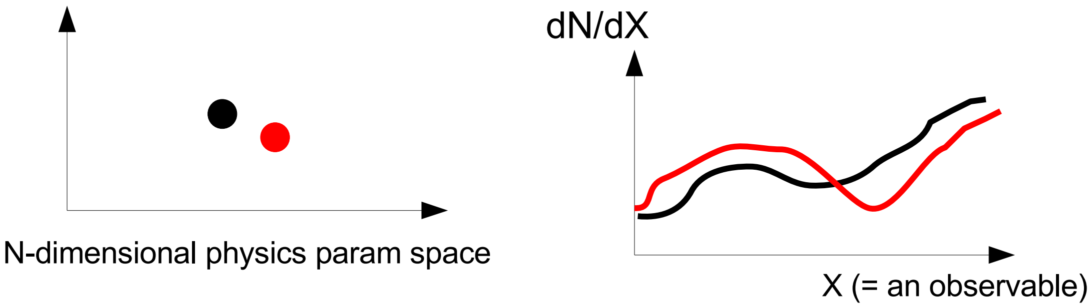
- Developed by an international collaboration of neutrino interaction experts and used on many experiments.
- Modern Object-Oriented Neutrino MC Generator:
  - Modular design.
  - Flexible to new experimental data and developments in theory.
- Combines many models to span a large kinematical range; Several MeV to several hundred GeV:
  - Maintains internal consistency and continuity.

Many, >100, configurable input physics parameters! + When added to the detector MC and the reconstruction stages the total production time is significant. → Fast simulation needed to evaluate changes in input parameters.

Full description of GENIE in: **Nucl.Instrum.Meth.A614:87-104,2010**

Event Reweighting

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



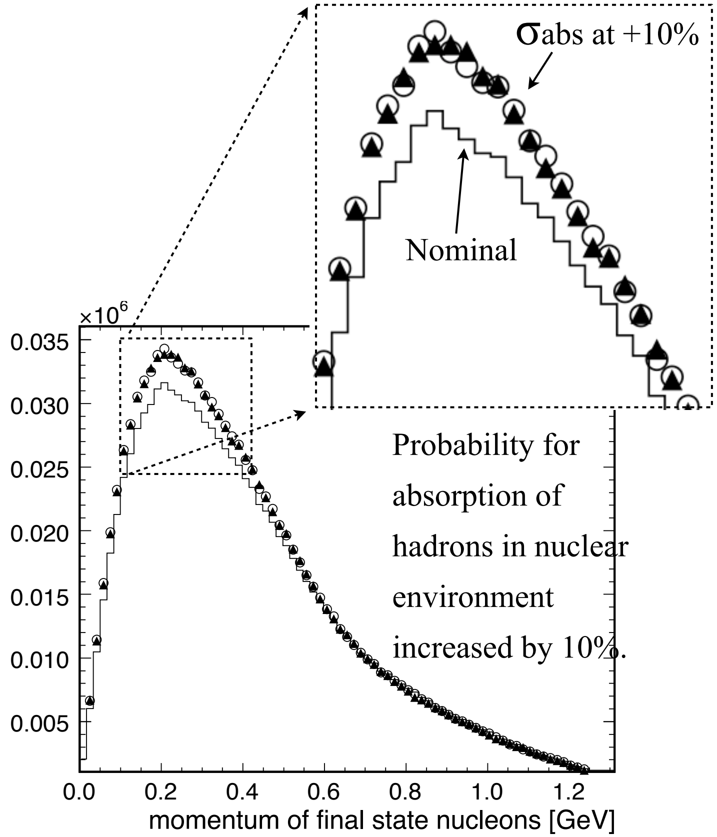
Can reweight parameters controlling:

- 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.

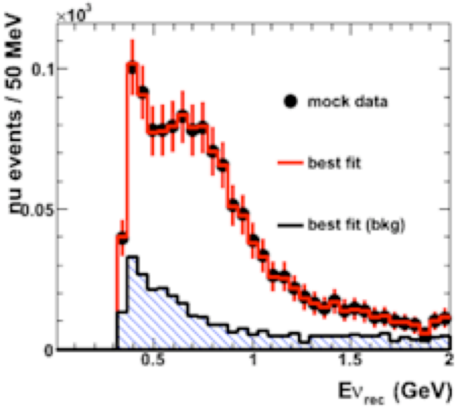
Validation: Compare reweighted (circle) with regenerated (triangle).

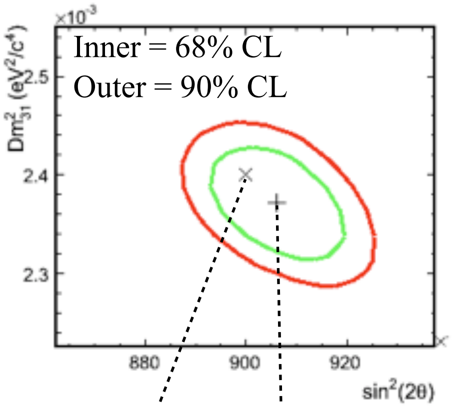


More info: http://th-www.if.uj.edu.pl/acta/vol40/pdf/v40p2613.pdf

Oscillation Systematics Study

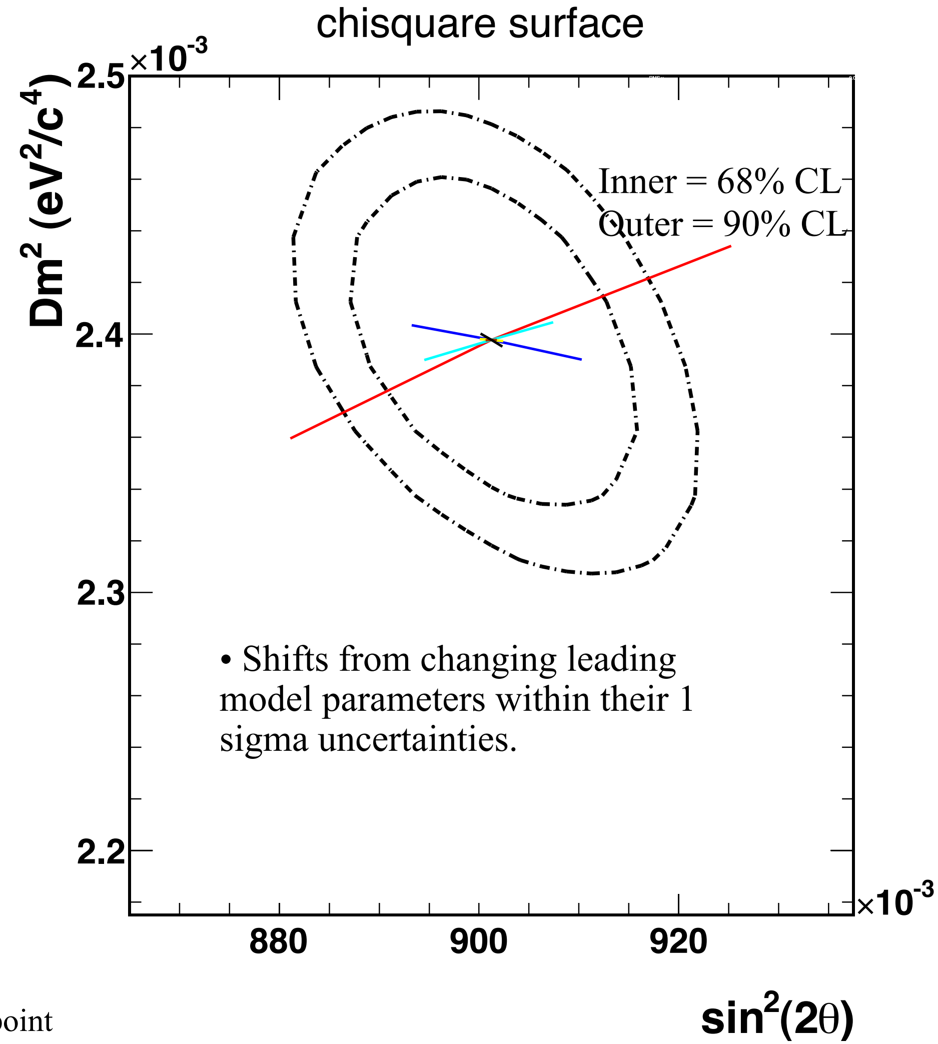
- Oscillation fit nominal mock data
- Mock data tweaked (reweighted) to account for a physics model change.
- Performed oscillation fit again.
  - Fit uses nominal MC as prediction.
- Studied how the best fit point shifts.





Nominal best fit point

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



- Shifts from changing leading model parameters within their 1 sigma uncertainties.

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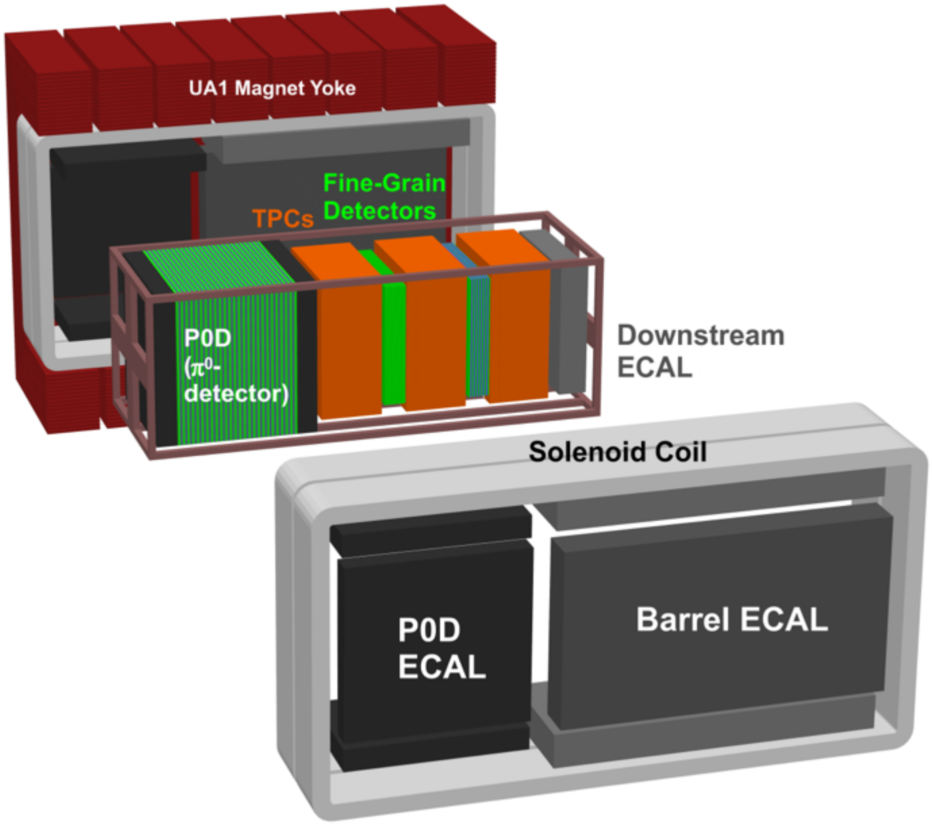
Constraining CC1π Background at ND280 (1)

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

ND280:



Fine Grain Detectors (FGDs):
- Fiducial volumes.
- Vertex location.

Time Projection Chambers (TPCs):
- Momentum measurement..
- PID.
- Vertex location.

Tracker ECal:
- PID.
- Energy measurement.

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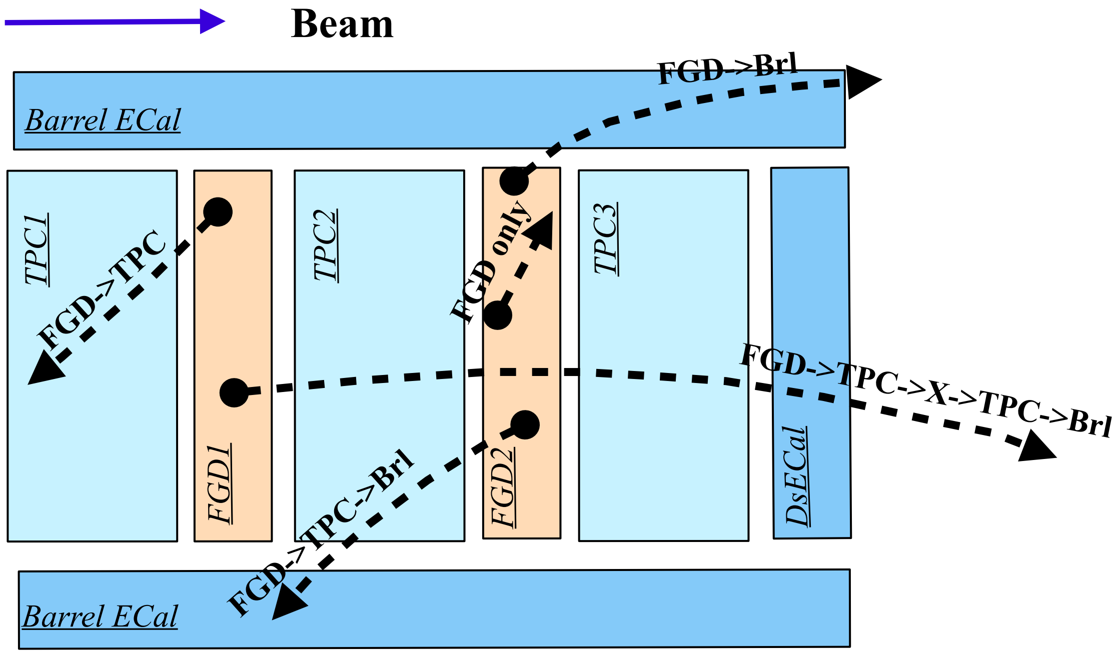
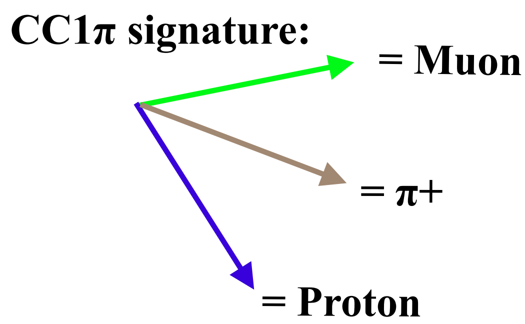
Constraining CC1π Background at ND280 (2)





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

~ 24,000 events for 1yr @ full intensity

Summary

- At T2K's sensitivity neutrino interaction systematics are important.
- CC1π+ is the dominant background for the disappearance measurement.
- Using measurement at ND280:
  - High enough statistics to make very accurate measurements of CC1π+ channel.
  - Use this to reduce interaction systematics.

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BACKUPS

Very Brief Overview of Neutrino Oscillations

Mass and flavour eigenstates different:

- Mass eigenstates propagate at different speeds: $|\,\nu_i(\vec{x},t)\rangle = |\,\nu_i\rangle e^{ip_i.\vec{x}-iE_i.t}$

- Quantum mechanical interference of flavour eigenstates $\longrightarrow$ Neutrino oscillations.

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

$s_{ij} = \sin\theta_{ij}$

$c_{ij} = \cos\theta_{ij}$

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

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

Open questions for current generation of experiments:

- Is θ_{23} maximal? Look at $\nu_\mu \nrightarrow \nu_\mu$. T2K
- Is θ_{13} non-zero? Look at sub-dominant $\nu_\mu \rightarrow \nu_e$. T2K
- Is there CP violation? Future beam experiments depending on size of θ_{13}.
- Precise measurement of mass squared differences. T2K

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.

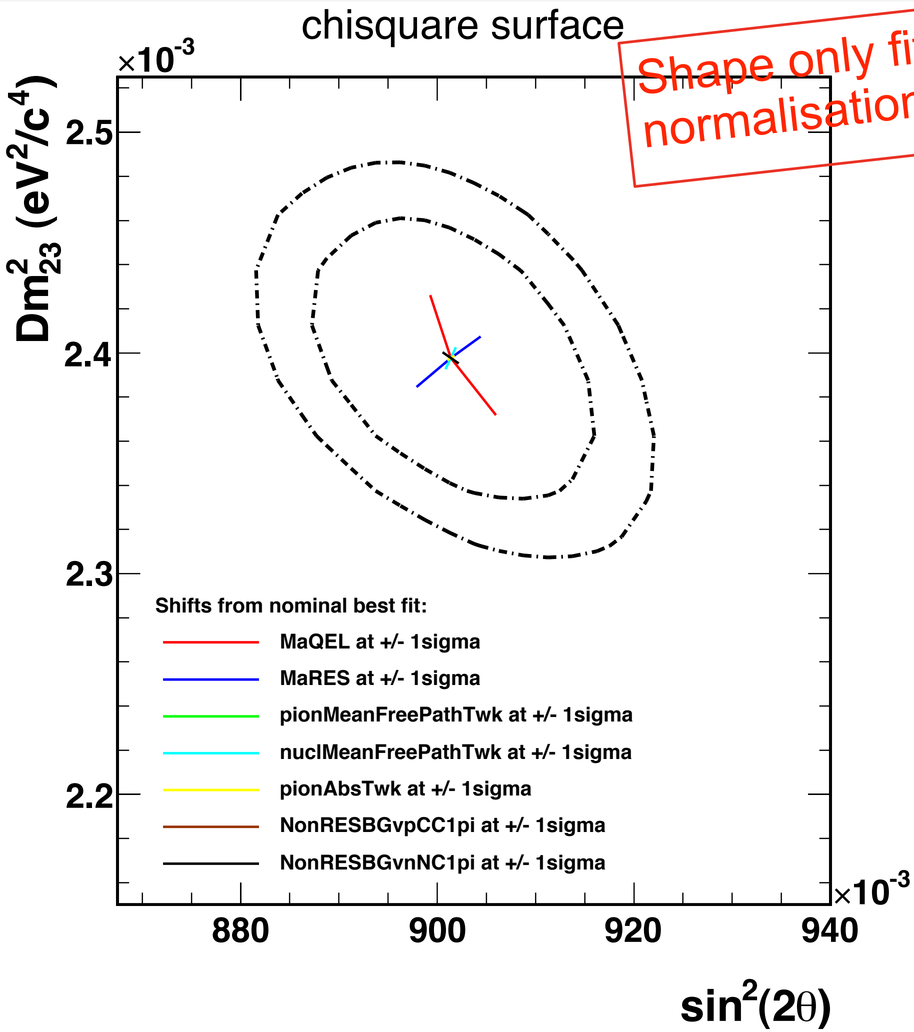
- Visible Energy Cut: visible energy in the inner detector (ID) is greater than 100 MeV/c . Removes noise and low energy events.

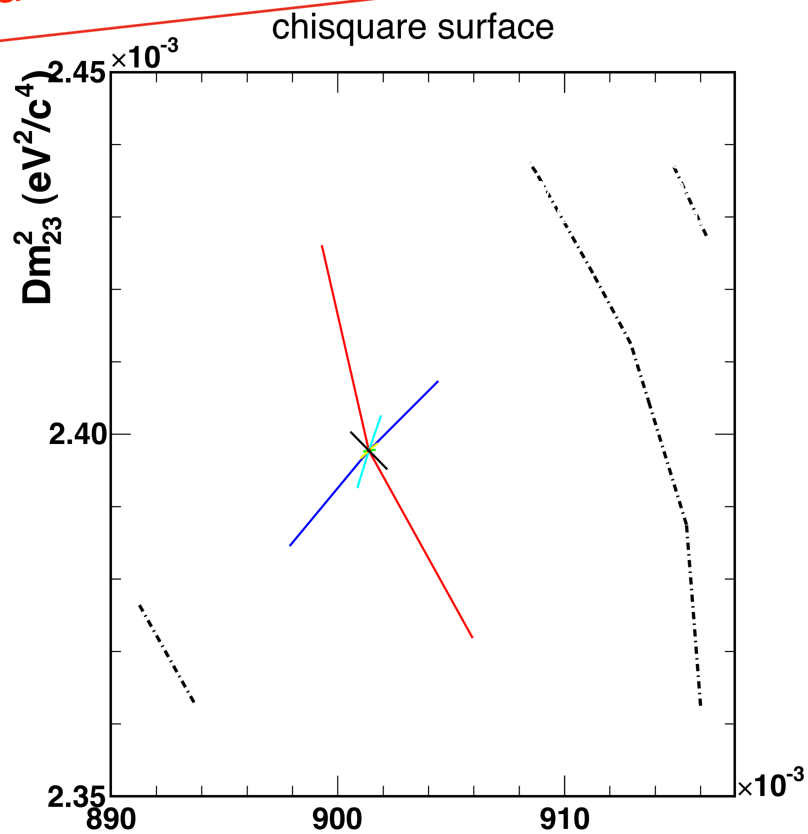
- Single ring cut: So dominantly select QEL events.

- Ring has to be muon-like.

Shape Only Fits

Shape only fit: include normalisation as variable fit





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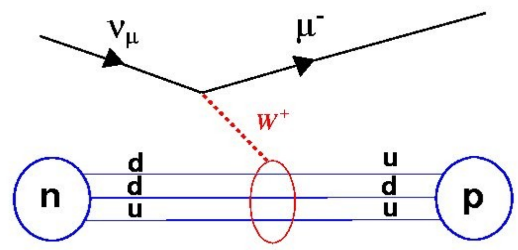
Process - Topology Breakdown

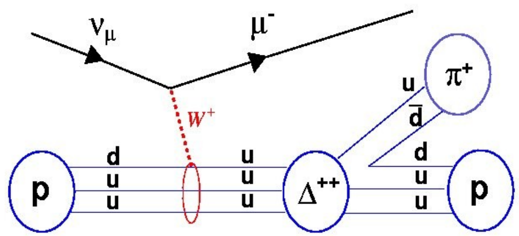
π topology	QEL	RES	DIS	COH	Other	Total
Total	51.65	28.03	19.36	0.72	0.24	
Multi πs		0.25	5.41		0.00	5.66
$1\pi^+ + 1\pi^0$	0.06	0.44	2.56		0.00	3.06
$1\pi^- + 1\pi^+$		0.23	0.91		0.00	1.14
$1\pi^- + 1\pi^0$		0.02	0.19		0.00	0.22
$2\pi^+$		0.07	0.78			0.85
$2\pi^0$		0.10	0.51		0.00	0.61
$2\pi^-$		0.00	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

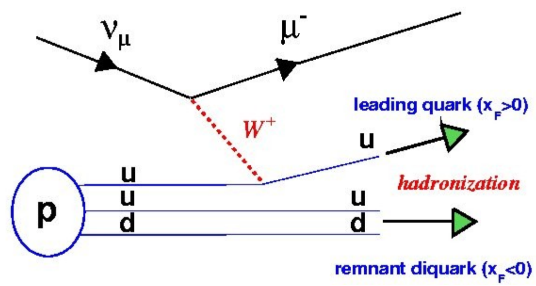
quasi-elastic scattering



resonance neutrino-production



deep-inelastic scattering



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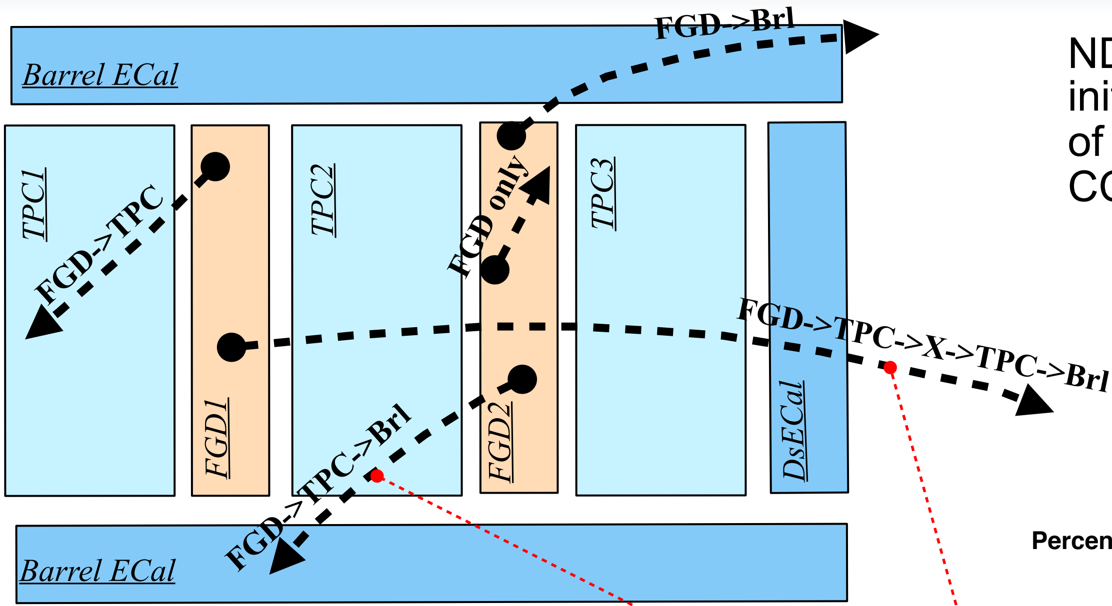
MC Study of Event Rates



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

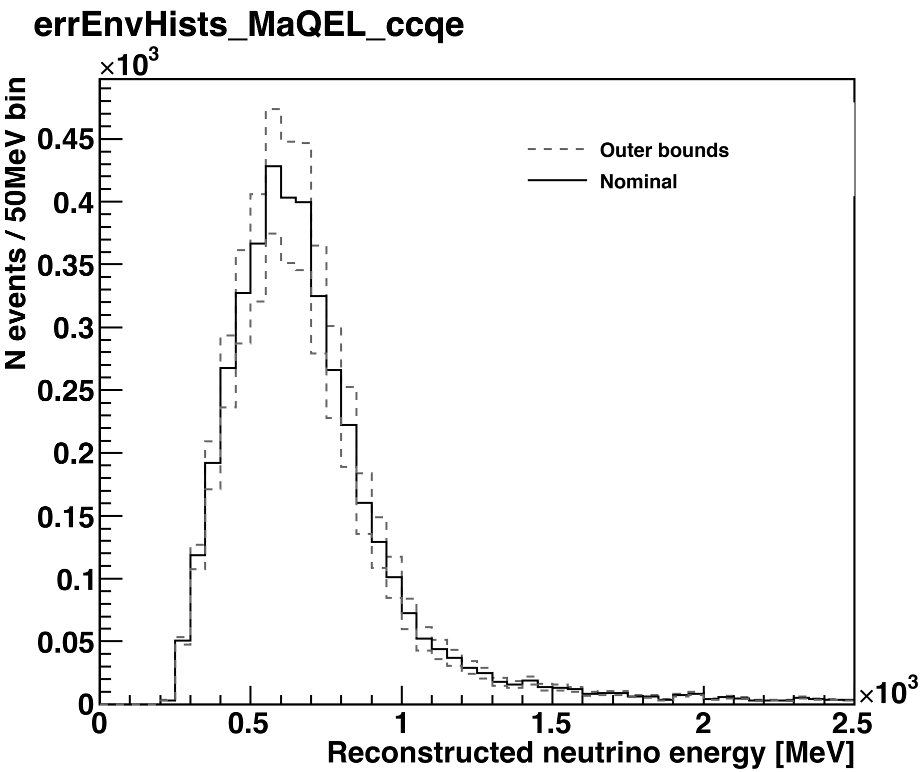
Percentage of CC1π^+ events in FGDs for given detector paths

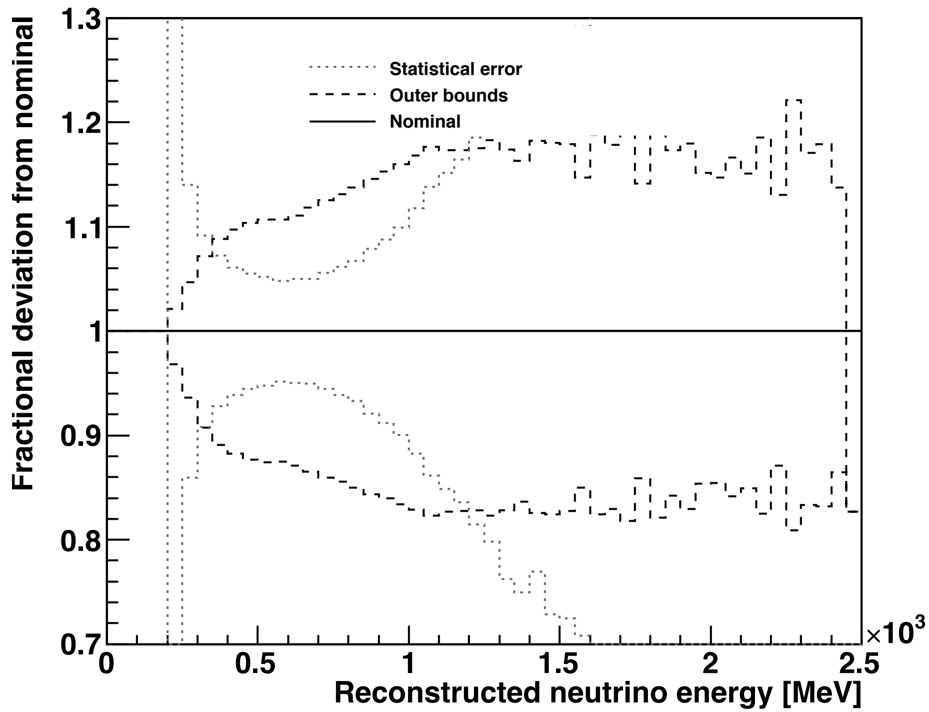
π detector path \ μ detector path	FGD only	FGD->Brl	FGD->TPC	FGD->TPC->Brl	FGD->TPC->X->TPC	FGD->TPC->X->TPC->Brl	kOther
kOther	0.01	0.02		0.01	0.00		0.01
FGD->TPC->X->TPC->Brl	0.09	0.09	0.02	0.26	0.19	0.05	0.02
FGD->TPC->X->TPC	0.33	0.39	0.18	0.96	0.78	0.11	0.03
FGD->TPC->Brl	2.58	1.96	4.09	4.76	3.31	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.

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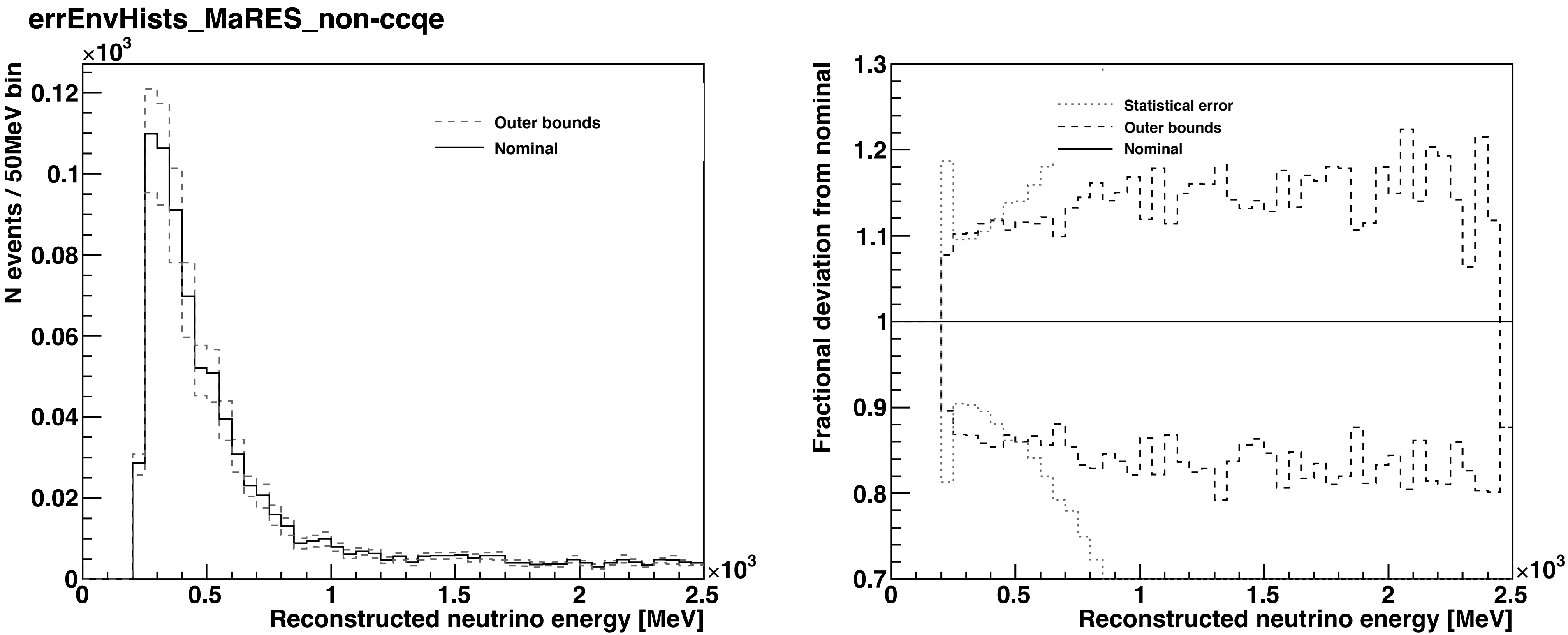
SuperK Non-CCQE Bkg Error Envelope: Tweaking RES axial mass parameter by +/- 20%



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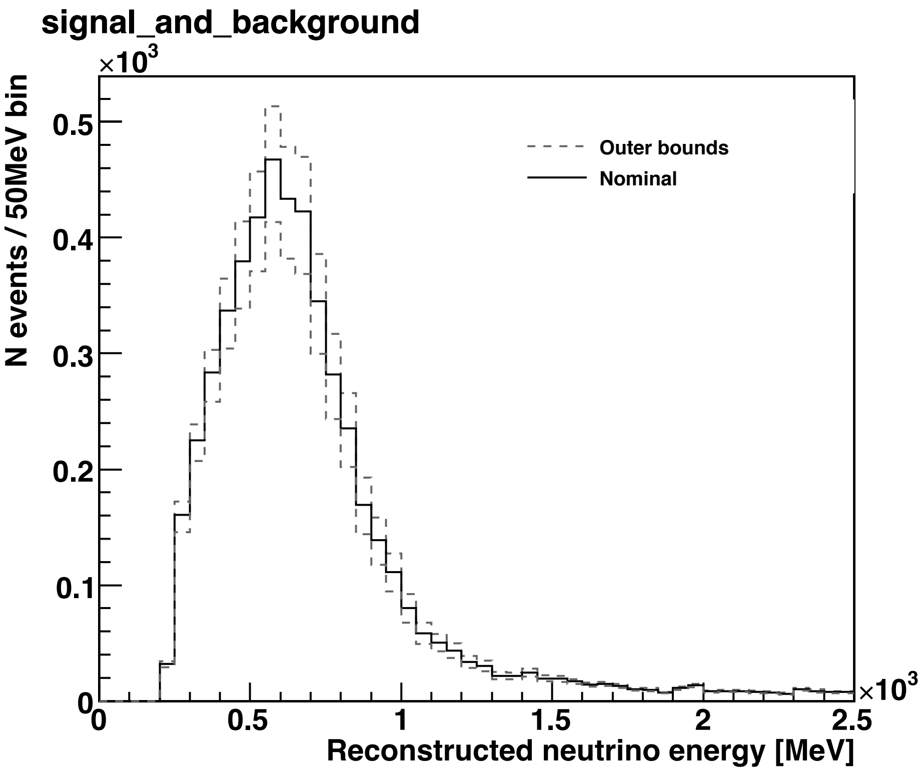
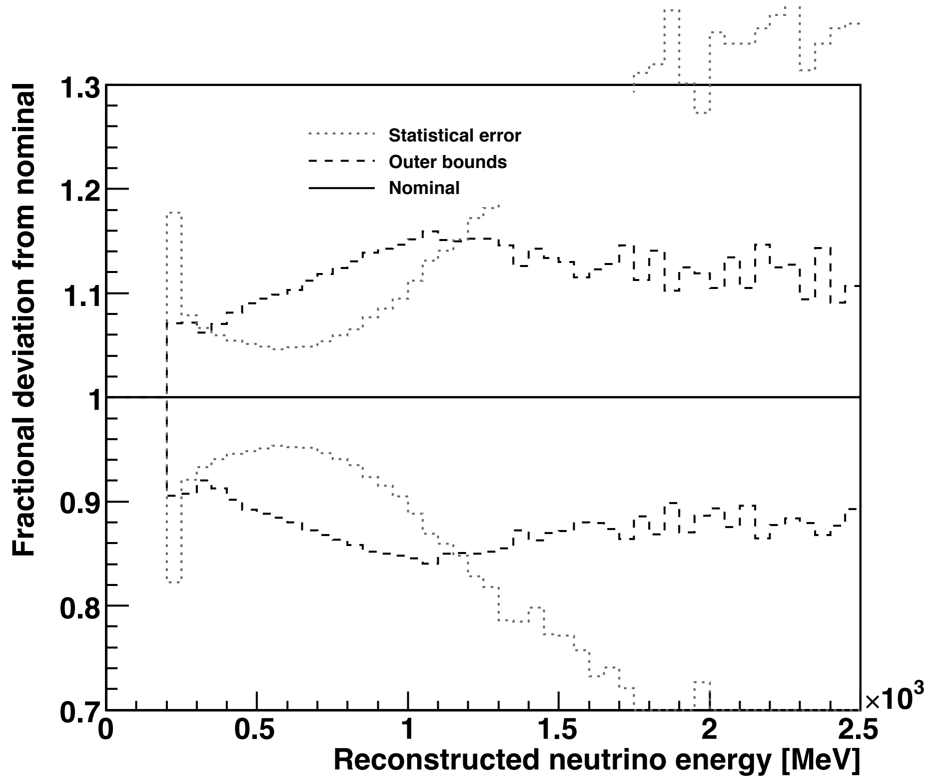
Error Envelope for events which pass FC1R cut: now include uncertainty on signal and background (add in quadrature)





Including Nuisance Parameters in Fit [simplistic case: uncorrelated systematics]

Systematic (nuisance) **E**xpected **O**bserved **Penalty terms**

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

Updates

'Monte Carlo'

REWEIGHT

Tweaks @ nominal MC

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

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

Calculate gradients for optimised fitting techniques.