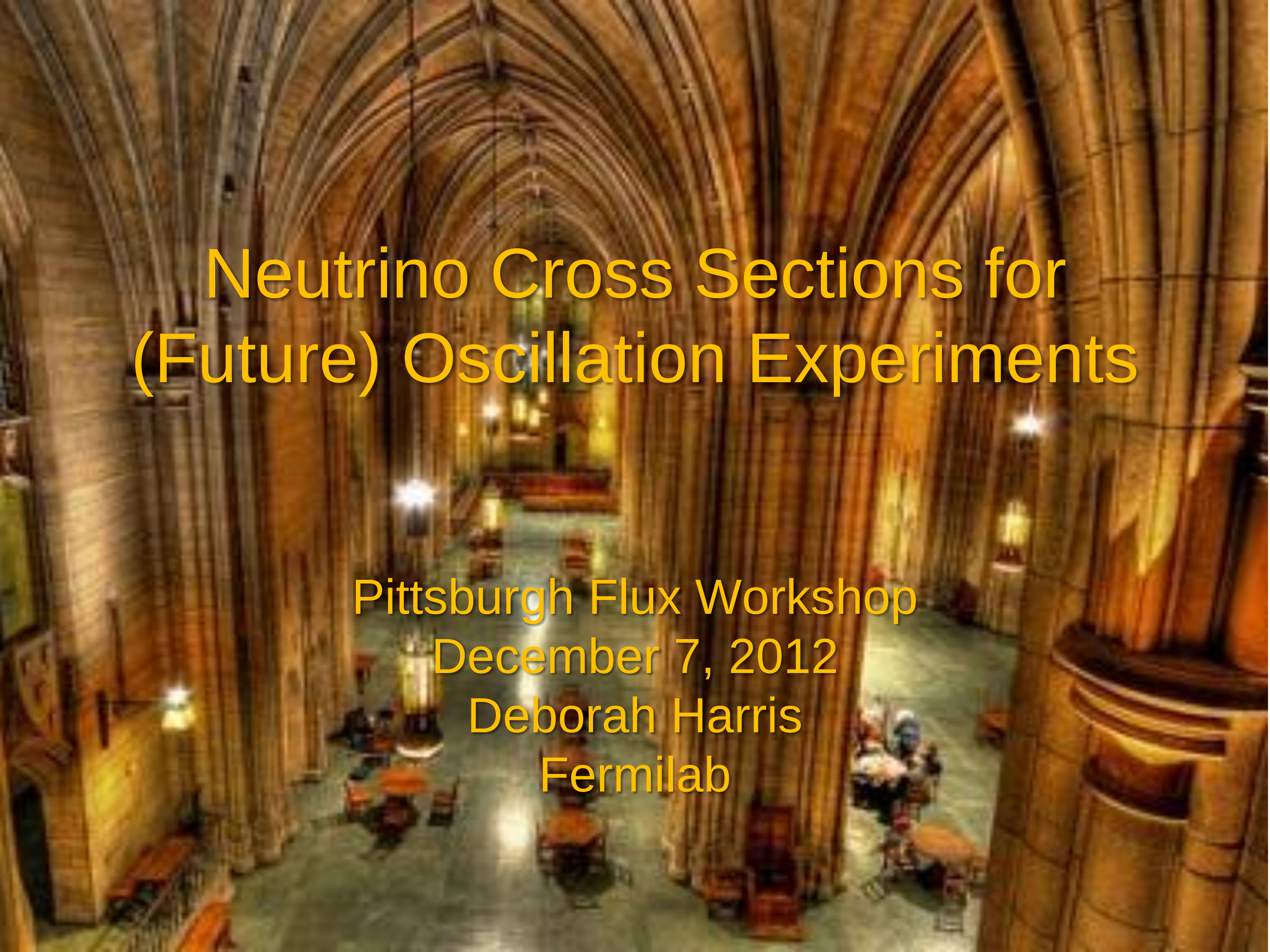
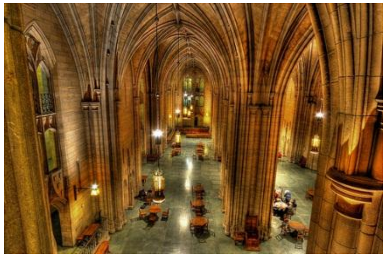


Neutrino Cross Sections for (Future) Oscillation Experiments

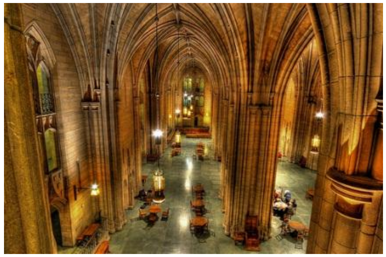
Pittsburgh Flux Workshop
December 7, 2012
Deborah Harris
Fermilab

Outline

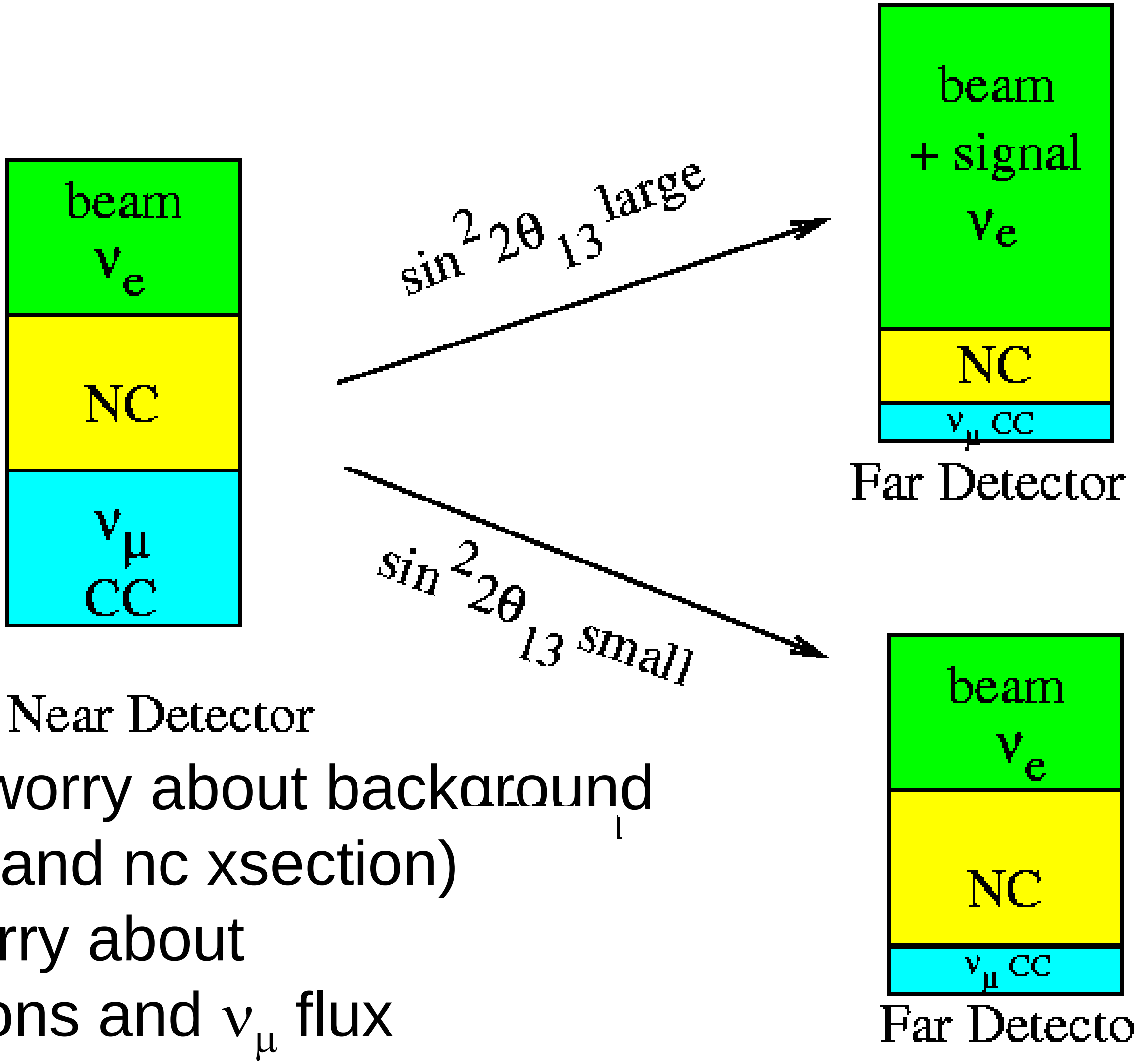


- Simple Toy model of why Cross Sections Matter (2004)
- 2 Case Studies: T2K and NOvA (2012)
- What about the next generations?
- Not covered: nuclear effects (see Jorge’s talk tomorrow)
- Conclusion: we need better ways to measure fluxes if
  - We are ever going to measure cross sections
  - We are ever going to measure CP violation!

ν_e Appearance analysis, circa 2004

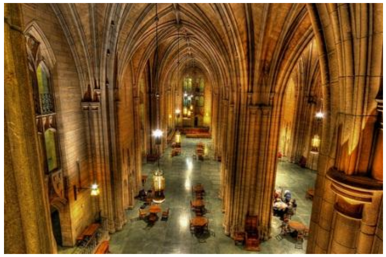


Event Samples
are different
Near to far, so
Uncertainties
In cross sections
Won't cancel



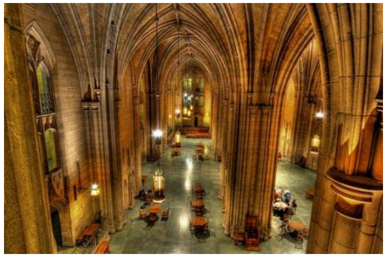
If signal is small, worry about background prediction (ν_e flux and nc xsection)
If signal is big, worry about signal cross sections and ν_μ flux

ν_e Backgrounds by process



- Neutral Currents
  - Should scale like total neutrino flux (ν_μ flux)
  - Dominant background processes at 2GeV:
    - NC coherent
    - resonant pi0 production
- ν_μ Charged Currents
  - Are present in near detector, but NOT in far
  - Dominant processes that give background at 2GeV
    - Deep inelastic scattering
- Intrinsic beam ν_e events
  - Present in near detector, mostly in far also
  - Average “baseline” ratio different than ν_μ
  - Dominant processes: Quasi-elastic and Resonance events

Event samples near and far

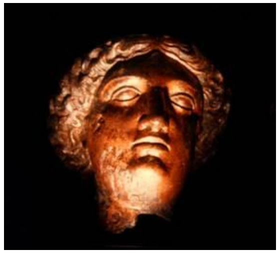


- Study is for a totally active scintillator detector in off axis beam centered on 2GeV neutrino beam
- Any similarities between this and NOVA are purely coincidental…
- Statistics shown are for 5 year run in neutrino mode only
- Although this study was from a long time ago, you can see that the processes for each background are very different

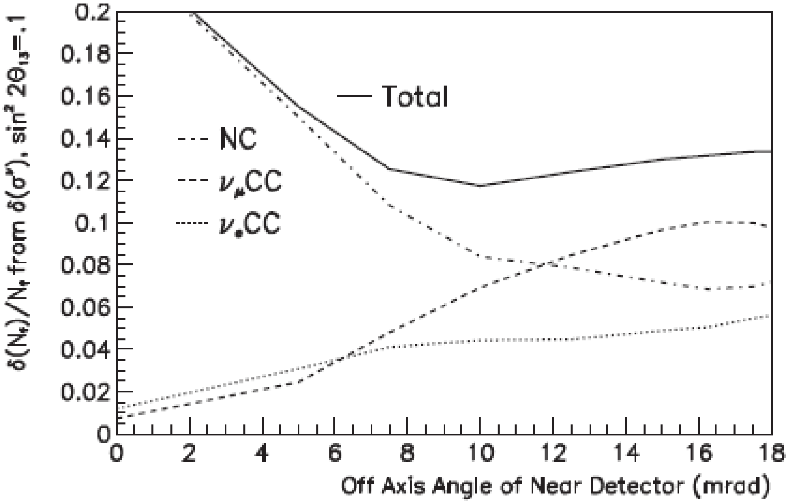
Process	**Events**	QE	RES	COH	DIS
$\delta\sigma/\sigma$		20%	40%	100%	20%
Signal ν_e **$\sin^2 2\theta_{13}=0.1$**	**175**	55%	35%	n/i	10%
NC	**15.4**	0	50%	20%	30%
ν_μCC	**3.6**	0	65%	n/i	35%
Beam ν_e	**19.1**	50%	40%	n/i	10%

arXiv:hep-ex/0410005v1

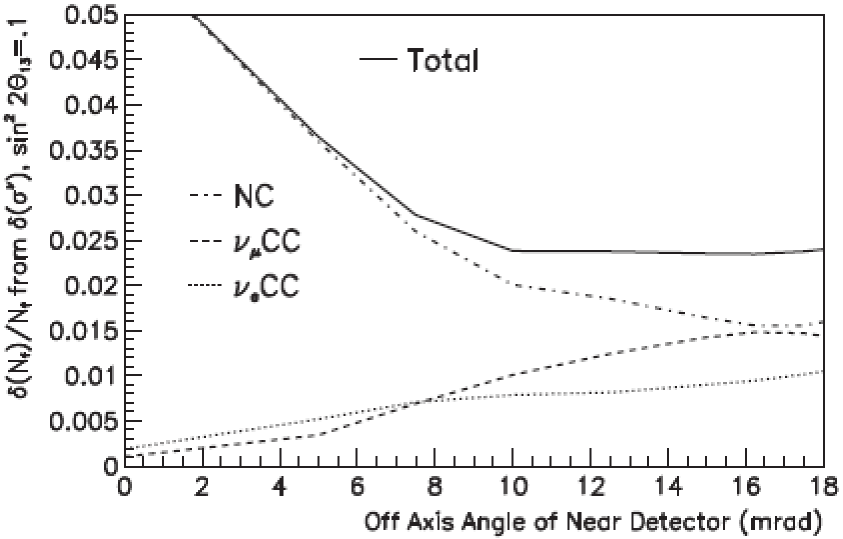
How much do cross section errors cancel near to far? (circa 2004)



- **Toy analysis**: start with old NOvA detector simulation, which had same ν_e/NC ratio, mostly QE & RES signal events accepted, more ν_μCC/NC accepted
- Near detector backgrounds have ~3 times higher $\nu_\mu$cc!
- Assume if identical ND, can only measure 1 background number: hard to distinguish between different sources



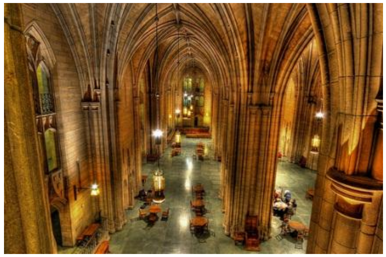
Assume that now, σ's known at:
ΔQE = 20%, ΔRES = 40% (CC, NC)
ΔDIS = 20%, $\Delta\mathrm{COH}_{Fe}$ = 100%



Assume in the next few years, σ's known at:
ΔQE = 5%, ΔRES = 5, 10% (CC, NC)
ΔDIS = 5%, $\Delta\mathrm{COH}_{Fe}$ = 20%

arXiv:hep-ex/0410005v1

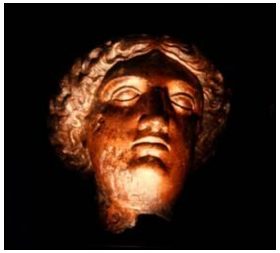
Caveat Emptor



Assume in the next few years, σ's known at:
$\Delta QE = 5\%$, $\Delta RES = 5, 10\%$ (CC, NC)
$\Delta DIS = 5\%$, $\Delta COH_{Fe} = 20\%$

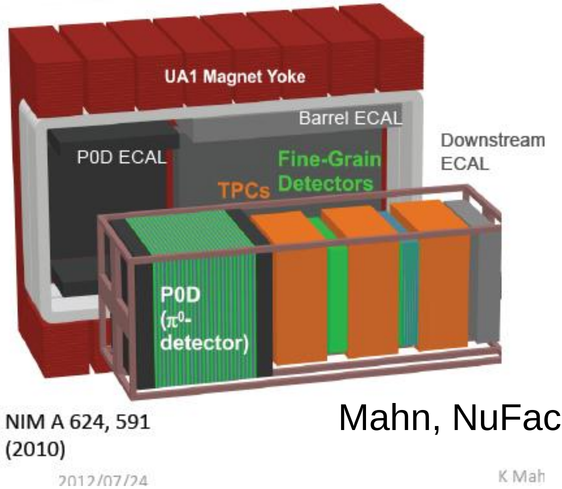
- This assumption about how well cross sections can be known implies something about how well FLUXes will be known!
- Above statement assumes <5% absolute flux uncertainty (at MINERvA, for example)
- ~~Don't trust people who say things like this~~
- Trust but verify…

Fast Forward 8 years…



T2K Experiment

- 700MeV ν_μ off axis beam, 295km
- Far detector: Water Cerenkov
- Near Detector Suite at 280m
  - Off Axis Detector
    - Scintillator with water targets
    - POD for EM final states
    - TPC's for good particle ID
    - All in Magnetic Field
  - On Axis Detector
    - Steel and tracker in a grid to see neutrino beam center

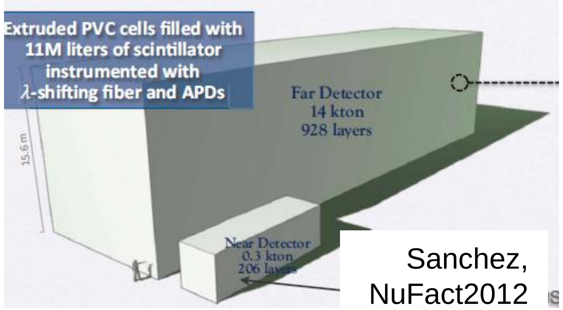


NIM A 624, 591 (2010)

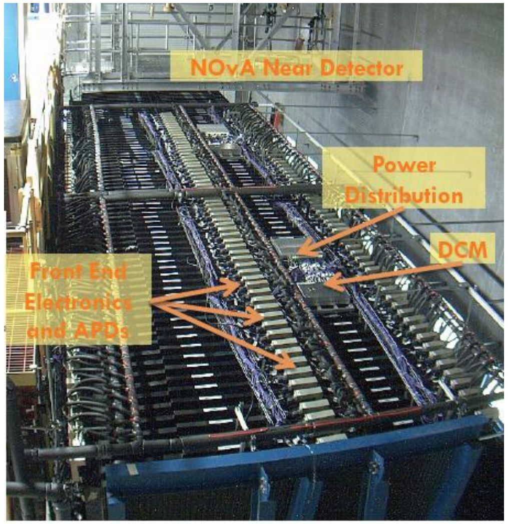
Mahn, NuFact2012

NOvA Experiment

- 2GeV ν_μ off axis beam, 810km
- Far detector: Totally Active Segmented Liquid Scintillator
- Near Detector at ~800m
  - 2m by 3m wide
  - Steel muon range stack at the end
  - Same segmentation as Far Detector

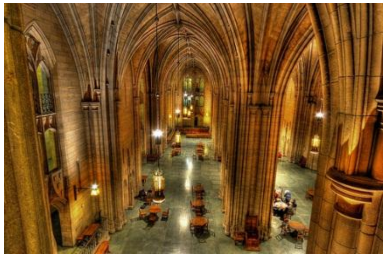


Sanchez, NuFact2012



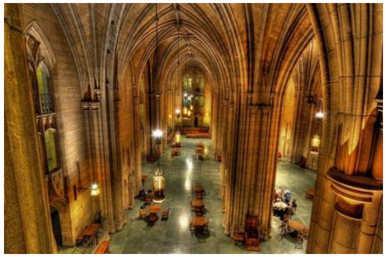
Vahle, 2010 FNAL PAC

What do you learn from a Near Detector

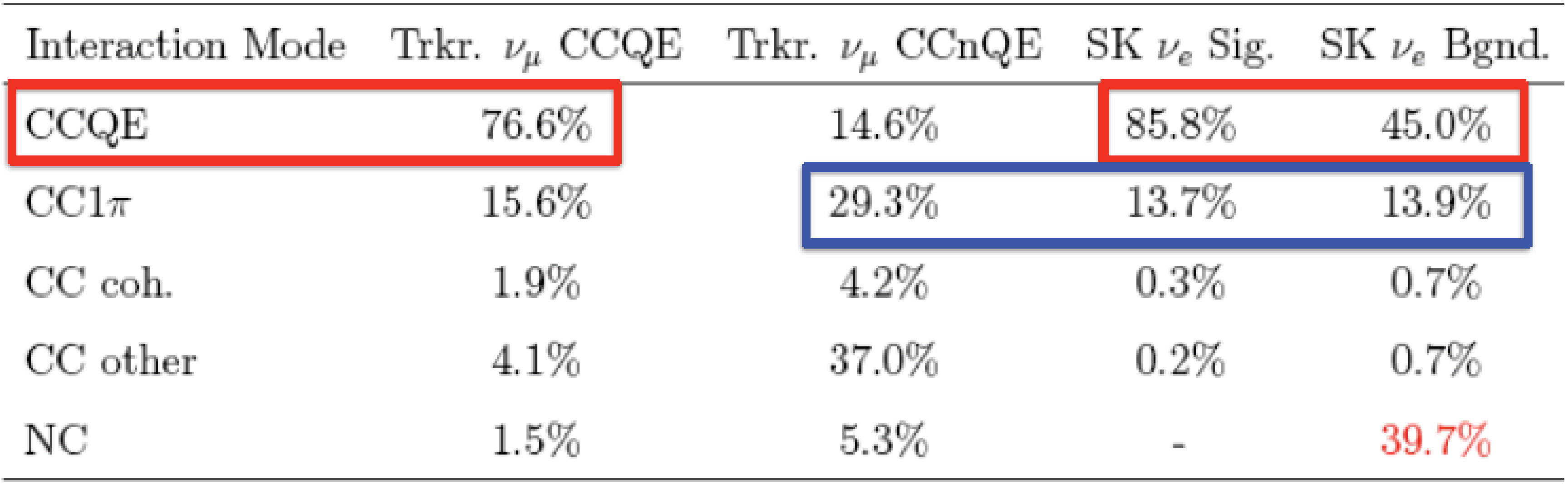


- Both T2K and NOvA plan to constrain individual contributions to Far Detector background from near Detector measurements
- T2K has the advantage of some data...and a first ν_e oscillation result
- NOvA techniques are (currently) based on experience with MINOS ν_e oscillation search
- If you do separate different backgrounds in a near detector, then FD uncertainties may depend more on flux differences between the two, and how well you know them
- Following slides provide examples from T2K and NOvA
  - T2K: slides from Kendall Mahn, NuFact 2012
  - NOvA: slides from Mayly Sanchez, NuFact 2012

T2K: Near/Far Detector Event Samples

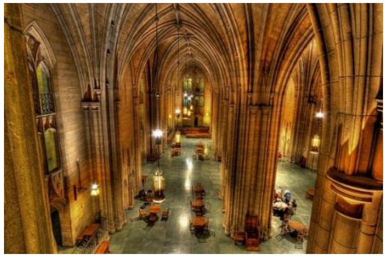


- Fraction of events vs process in different event samples
- At the far detector, the fraction of QE events is very different if it’s ν_e signal or background

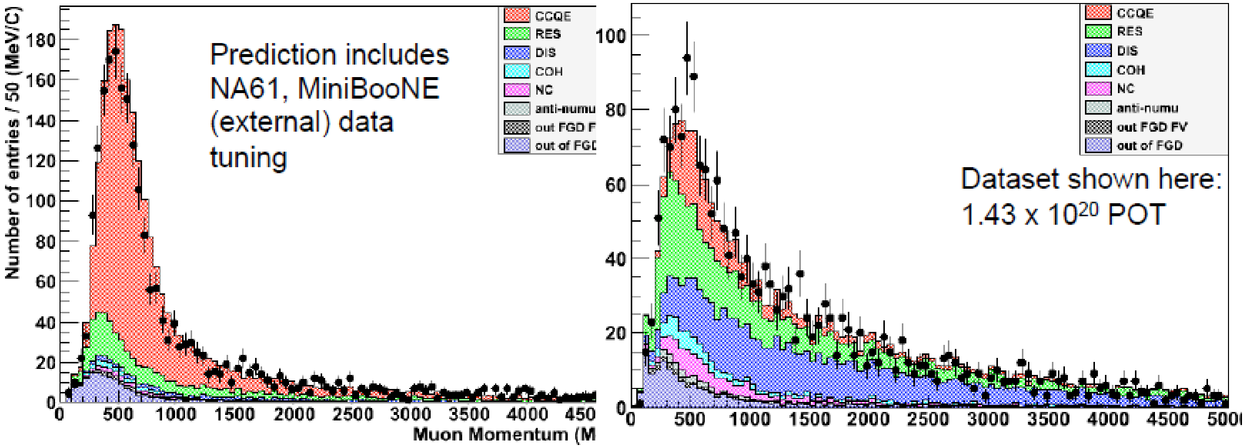


Interaction Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e Bgnd.
CCQE	76.6%	14.6%	85.8%	45.0%
CC1π	15.6%	29.3%	13.7%	13.9%
CC coh.	1.9%	4.2%	0.3%	0.7%
CC other	4.1%	37.0%	0.2%	0.7%
NC	1.5%	5.3%	-	39.7%

T2K: Near Detector Constraints on signal and background processes



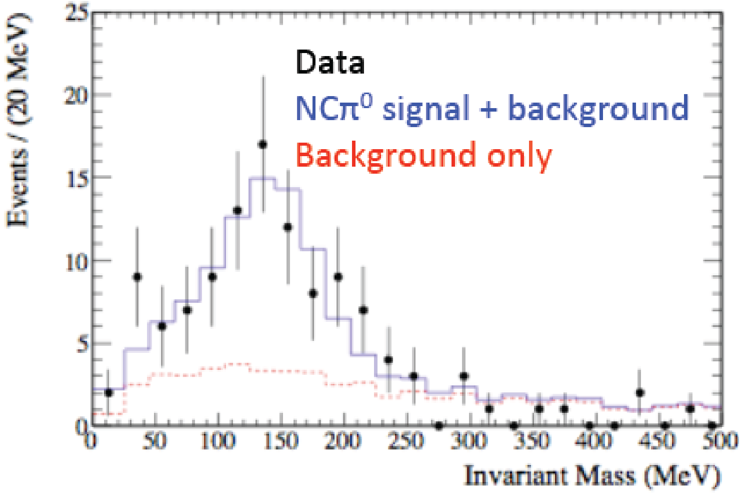
- CCQE/CCnQE:
  - Acceptance is different between ND and SK (forward muons in ND mostly)
  - need external data to get higher angles (MiniBooNE)
  - What ND calls CCQE and CCnQE may be different from what SK calls CCQE (acceptance for pions and extra protons very different)
- CC1π
  - Look for NC π^0's in POD



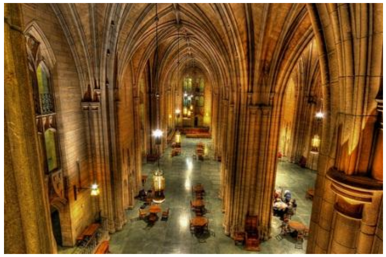
Prediction includes NA61, MiniBooNE (external) data tuning

Dataset shown here: 1.43 x 10^{20} POT

Separate sample into two subsamples, CCQE enhanced and CCnQE enhanced

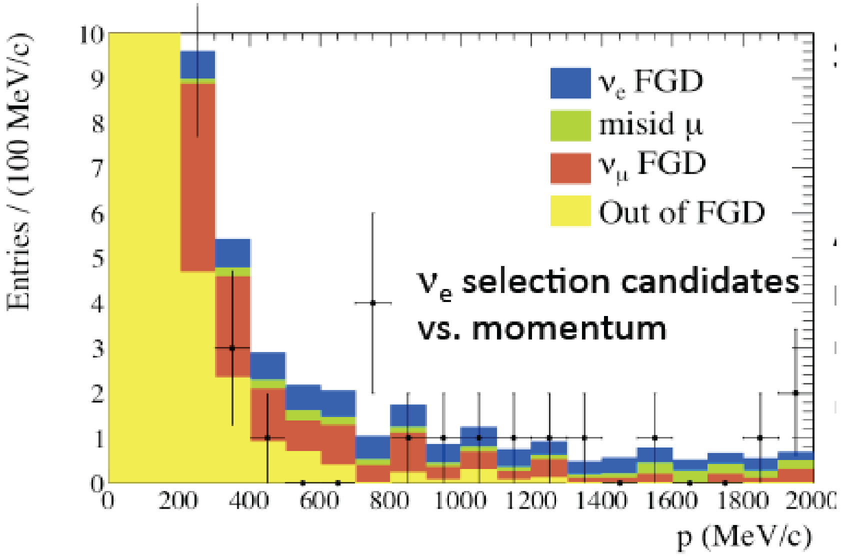


- Target: ND selection is C, SK is O
  - C-O model dependent uncertainties included

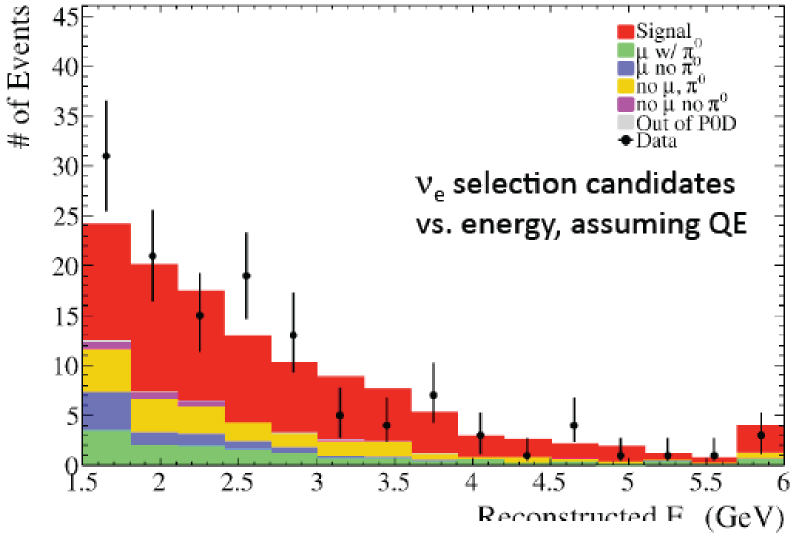


T2K intrinsic ν_e Constraints

- Two detectors, two techniques:
  TPC events, and POD events



ν_e selection candidates vs. momentum



ν_e selection candidates vs. energy, assuming QE

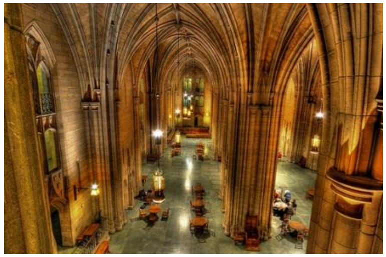
$N(\nu_e)/N(\nu_\mu) = R(e{:}\mu) = 1.0\% \pm 0.7\%$ (statistics) $\pm 0.3\%$ (systematics)
$R(e{:}\mu, \text{data}) / R(e{:}\mu, \text{MC}) = 0.6 \pm 0.4$ (statistics) ± 0.2 (systematics)

Signal region energies, high backgrounds

data-bkrd(MC)/sig(MC)= R

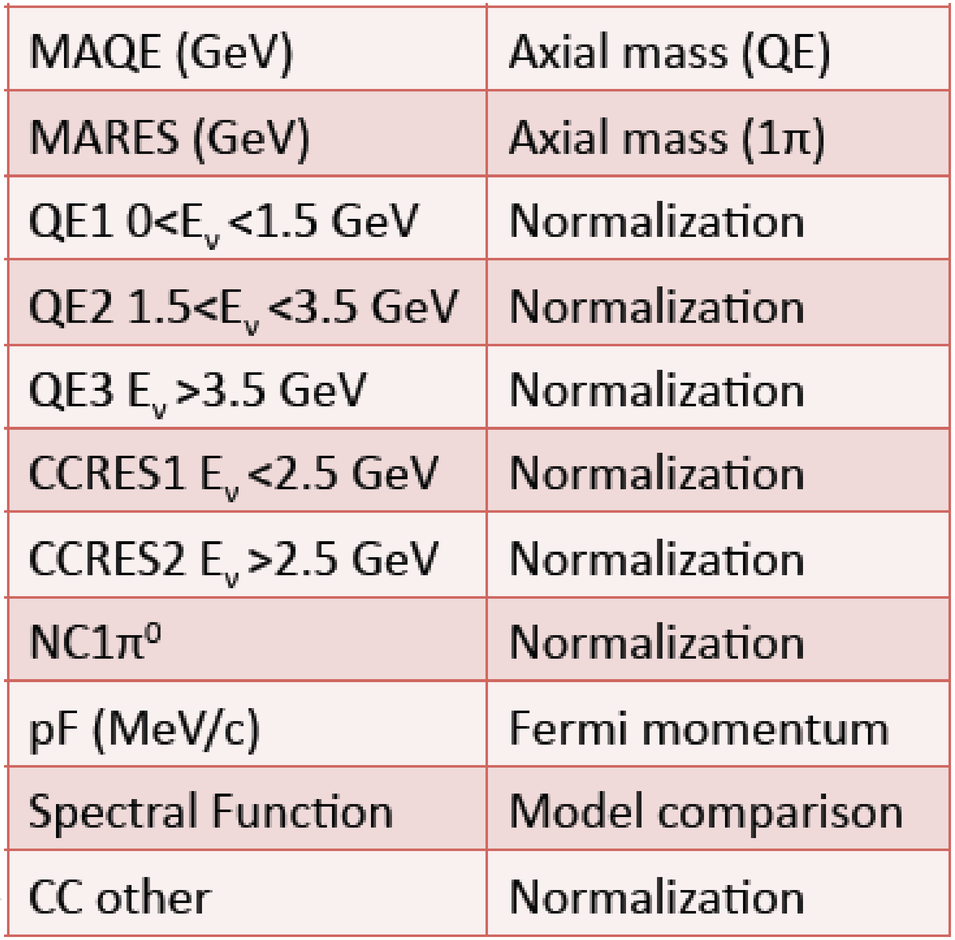
$R = 1.19 \pm 0.15$(statistics) ± 0.26 (systematics)

Lower backgrounds but above signal energy



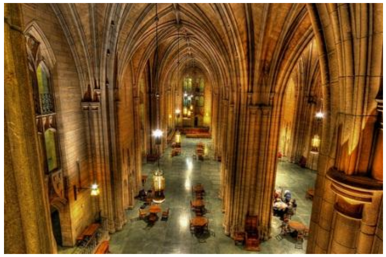
T2K: Near Detector Fit Technique

- Put all the near detector and external data into a fitter, and allow following parameters to vary:
(See A. Marino's talk!)

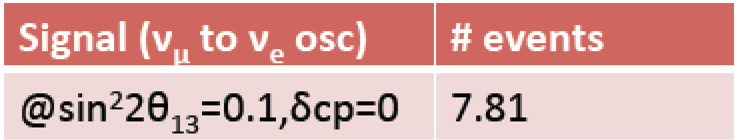


MAQE (GeV)	Axial mass (QE)
MARES (GeV)	Axial mass (1π)
QE1 $0<E_\nu<1.5$ GeV	Normalization
QE2 $1.5<E_\nu<3.5$ GeV	Normalization
QE3 $E_\nu>3.5$ GeV	Normalization
CCRES1 $E_\nu<2.5$ GeV	Normalization
CCRES2 $E_\nu>2.5$ GeV	Normalization
NC1π^0	Normalization
pF (MeV/c)	Fermi momentum
Spectral Function	Model comparison
CC other	Normalization

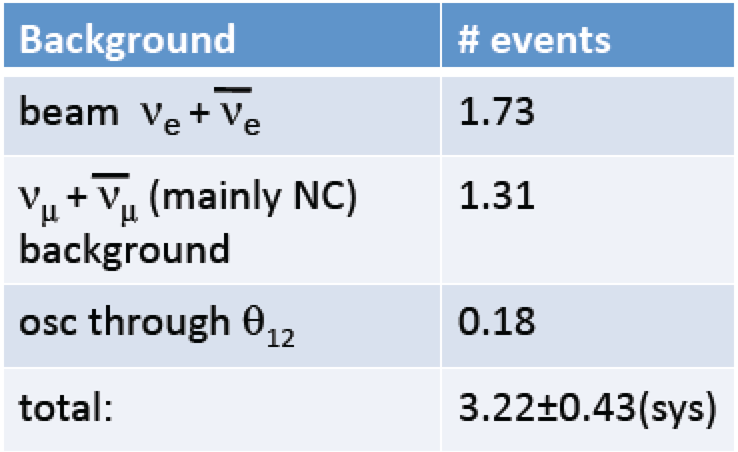
T2K: Fit results and Uncertainties



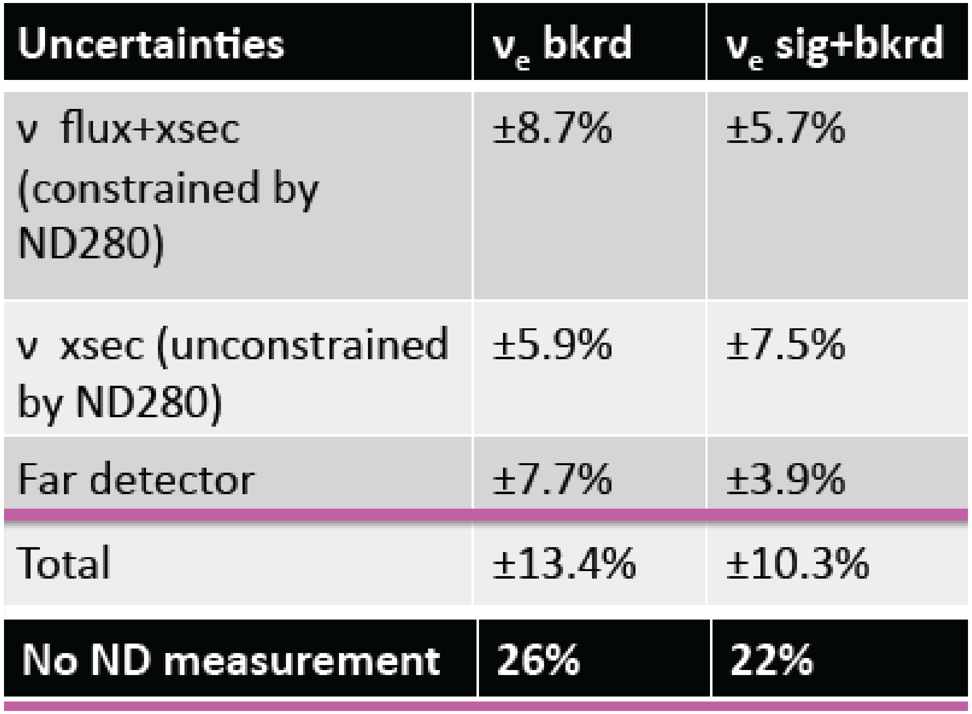
- Fit allows many things to vary, not just cross sections



Signal (ν_μ to ν_e osc)	# events
@$\sin^2 2\theta_{13}=0.1, \delta cp=0$	7.81

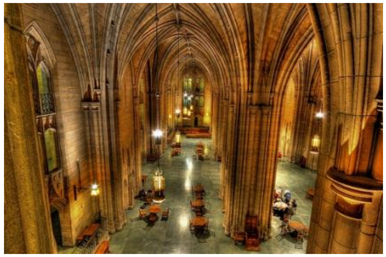


Background	# events
beam $\nu_e+\overline{\nu}_e$	1.73
$\nu_\mu+\overline{\nu}_\mu$ (mainly NC) background	1.31
osc through θ_{12}	0.18
total:	3.22±0.43(sys)



Uncertainties	ν_e bkrd	ν_e sig+bkrd
ν flux+xsec (constrained by ND280)	±8.7%	±5.7%
ν xsec (unconstrained by ND280)	±5.9%	±7.5%
Far detector	±7.7%	±3.9%
Total	±13.4%	±10.3%
No ND measurement	26%	22%

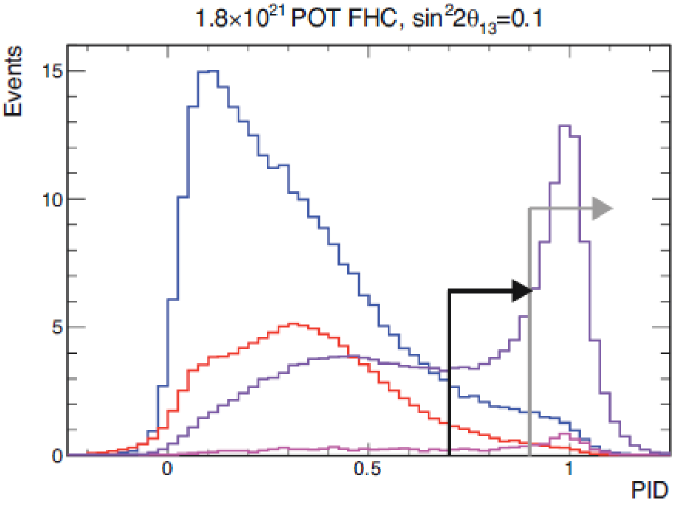
NOvA: Event Samples

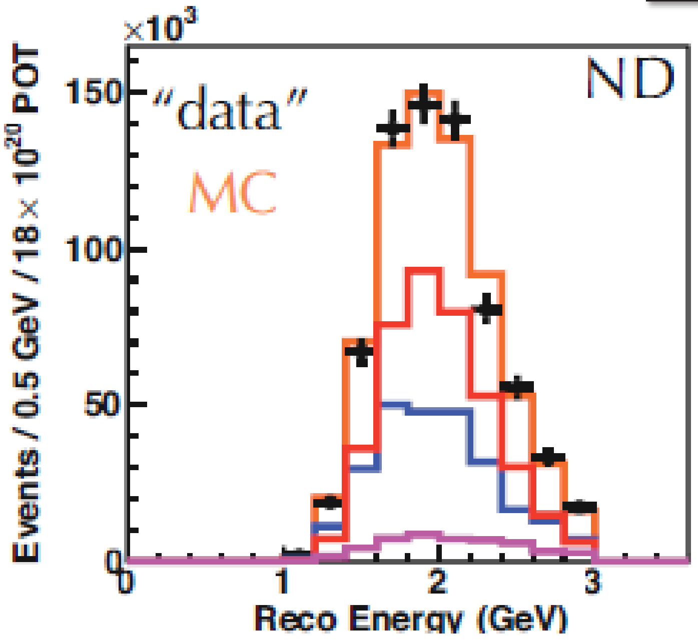


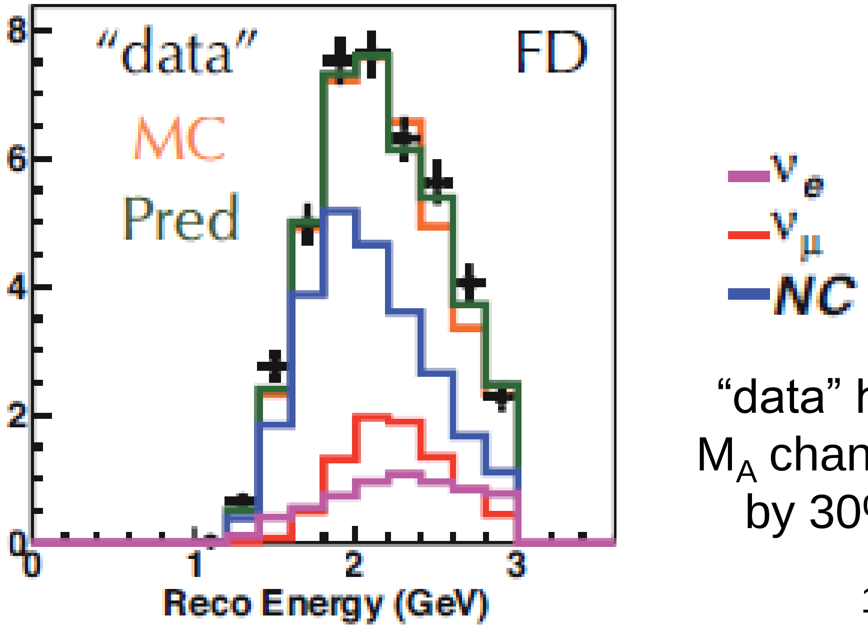
- NOvA has developed particle ID algorithm based on libraries (similar to MINOS technique)
- Plots below are after a PID cut

3 yr + 3 yr

beam = ν	ν	$\bar{\nu}$
NC	19	10
ν_μ CC	5	<1
ν_e CC	8	5
tot. BG	32	15
$\nu_\mu \to \nu_e$	68	32

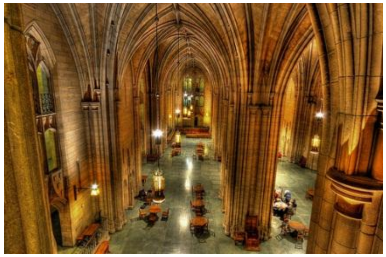




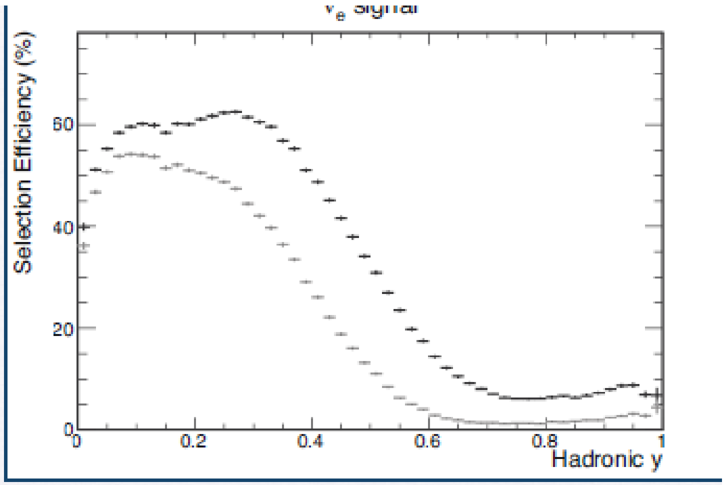


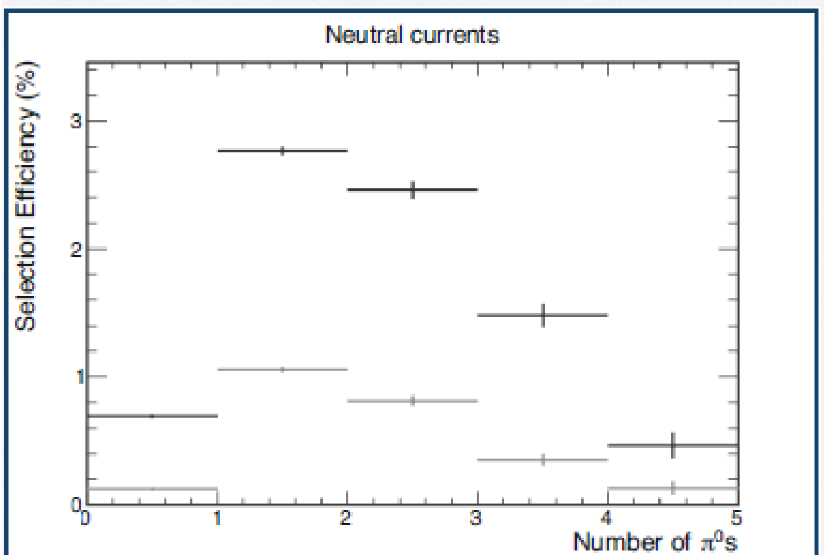
"data" has M_A changed by 30%

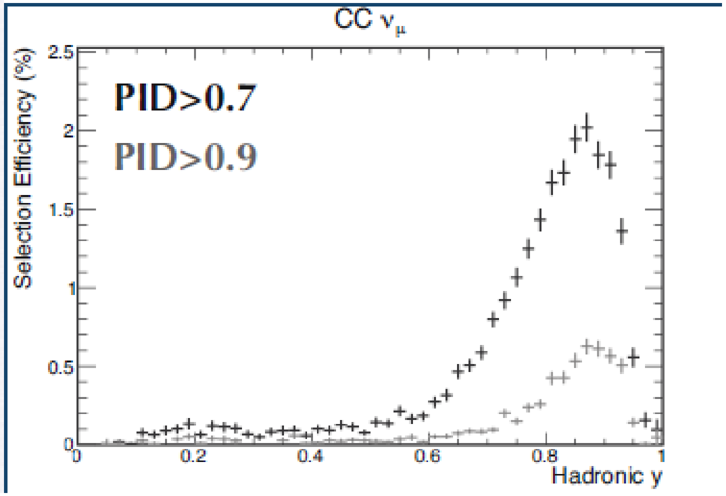
Accepted Events in NOvA



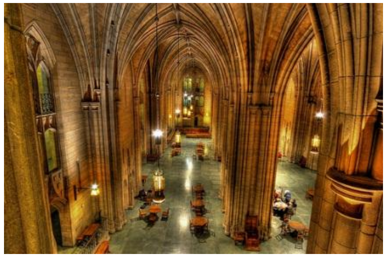
- Low y ν_e signal events are accepted in far detector
- High y NC and ν_μ CC events are accepted
- Single pion and multi-pion events are important NC backgrounds

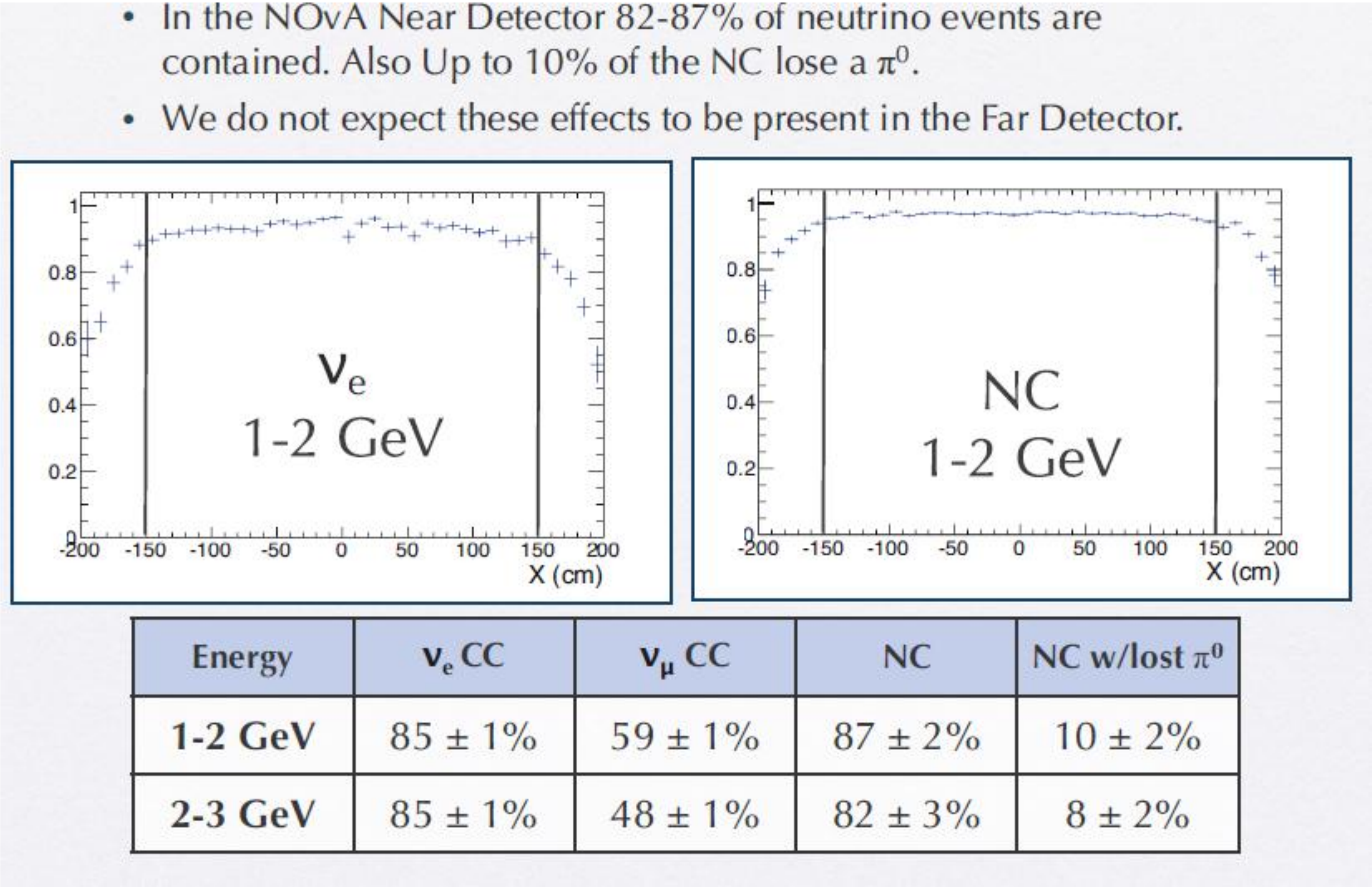






Differences in acceptance

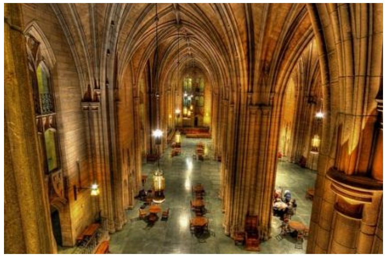




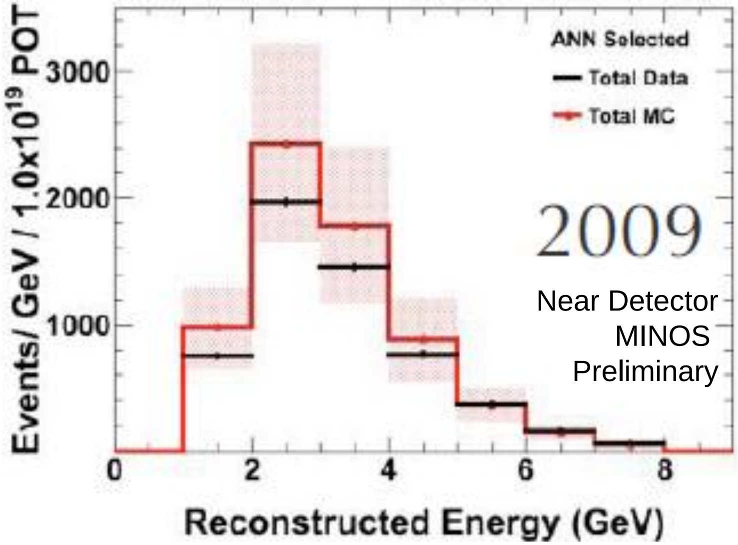
- In the NOvA Near Detector 82-87% of neutrino events are contained. Also Up to 10% of the NC lose a π^0.
- We do not expect these effects to be present in the Far Detector.

Energy	ν_e CC	ν_μ CC	NC	NC w/lost π^0
1-2 GeV	85 ± 1%	59 ± 1%	87 ± 2%	10 ± 2%
2-3 GeV	85 ± 1%	48 ± 1%	82 ± 3%	8 ± 2%

NC/CC ν_μ Background Constraint

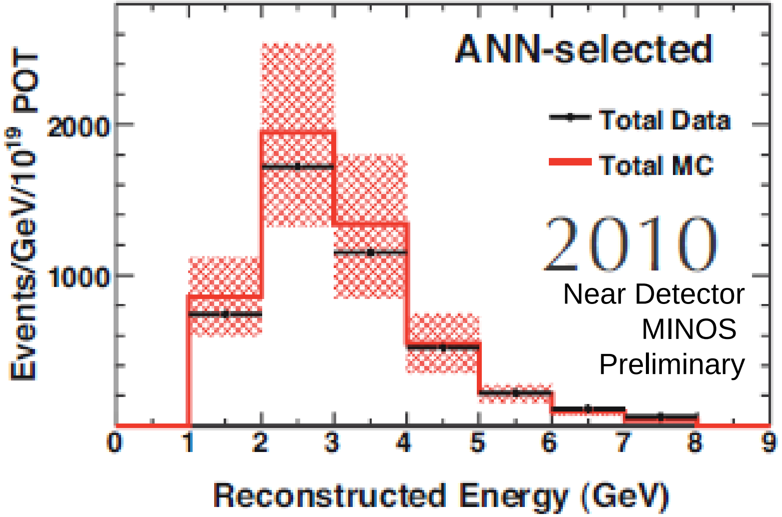


- Expect to use technique a la MINOS to study hadronic showers in ND
- Tuned hadronic model to external data and to CC events with muon track removed



2009

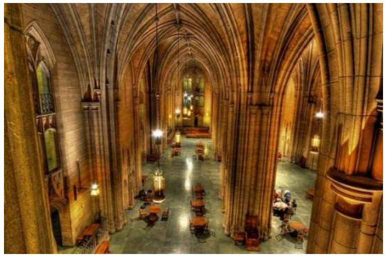
Near Detector
MINOS
Preliminary



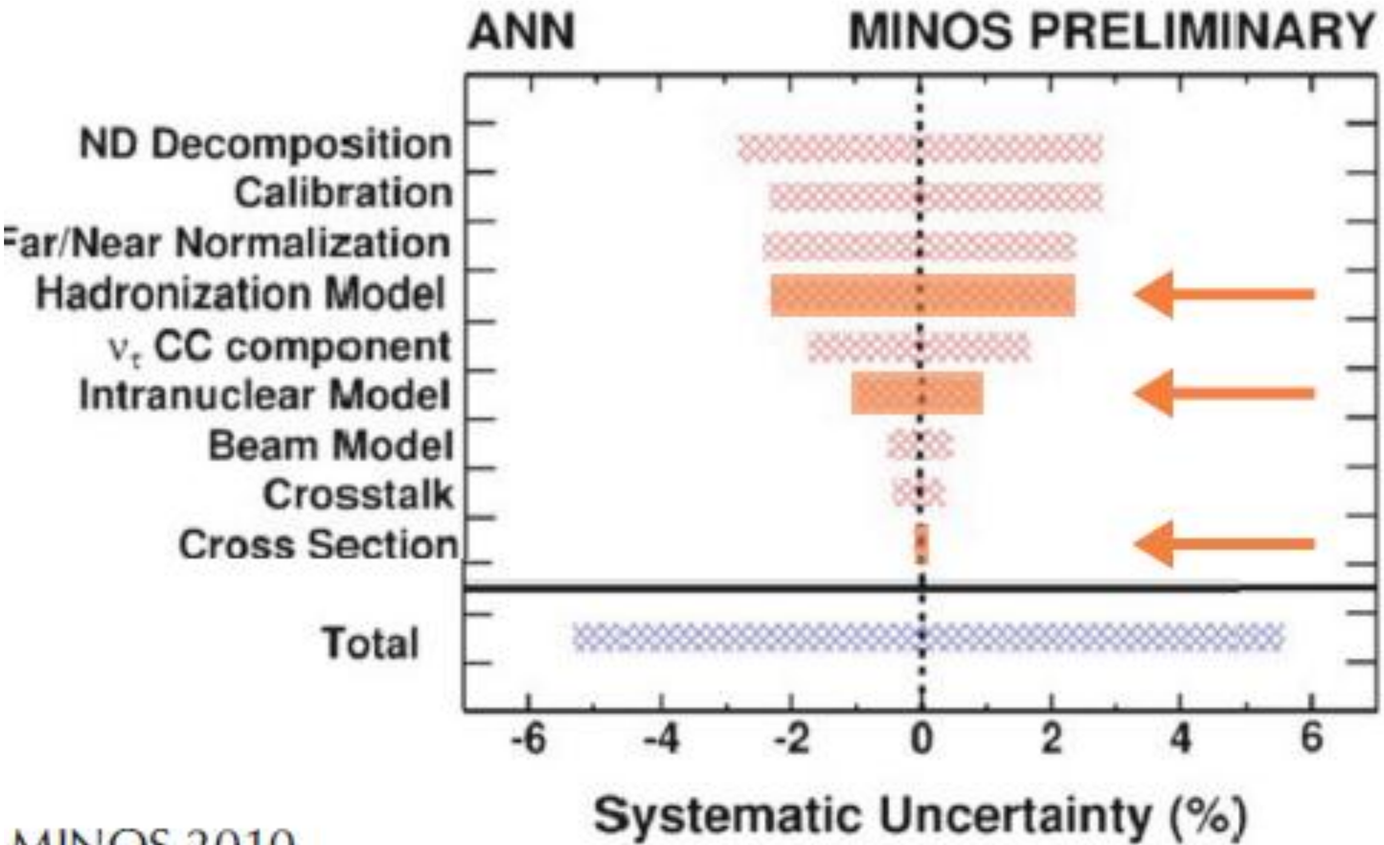
2010

Near Detector
MINOS
Preliminary

MINOS Systematic Errors



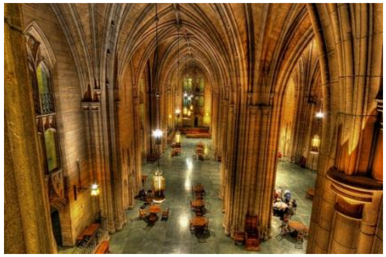
- To study systematics in MINOS, changed various parameters MC one at a time
- Used changed Near/Far extrapolation on original MC set to see how prediction changed

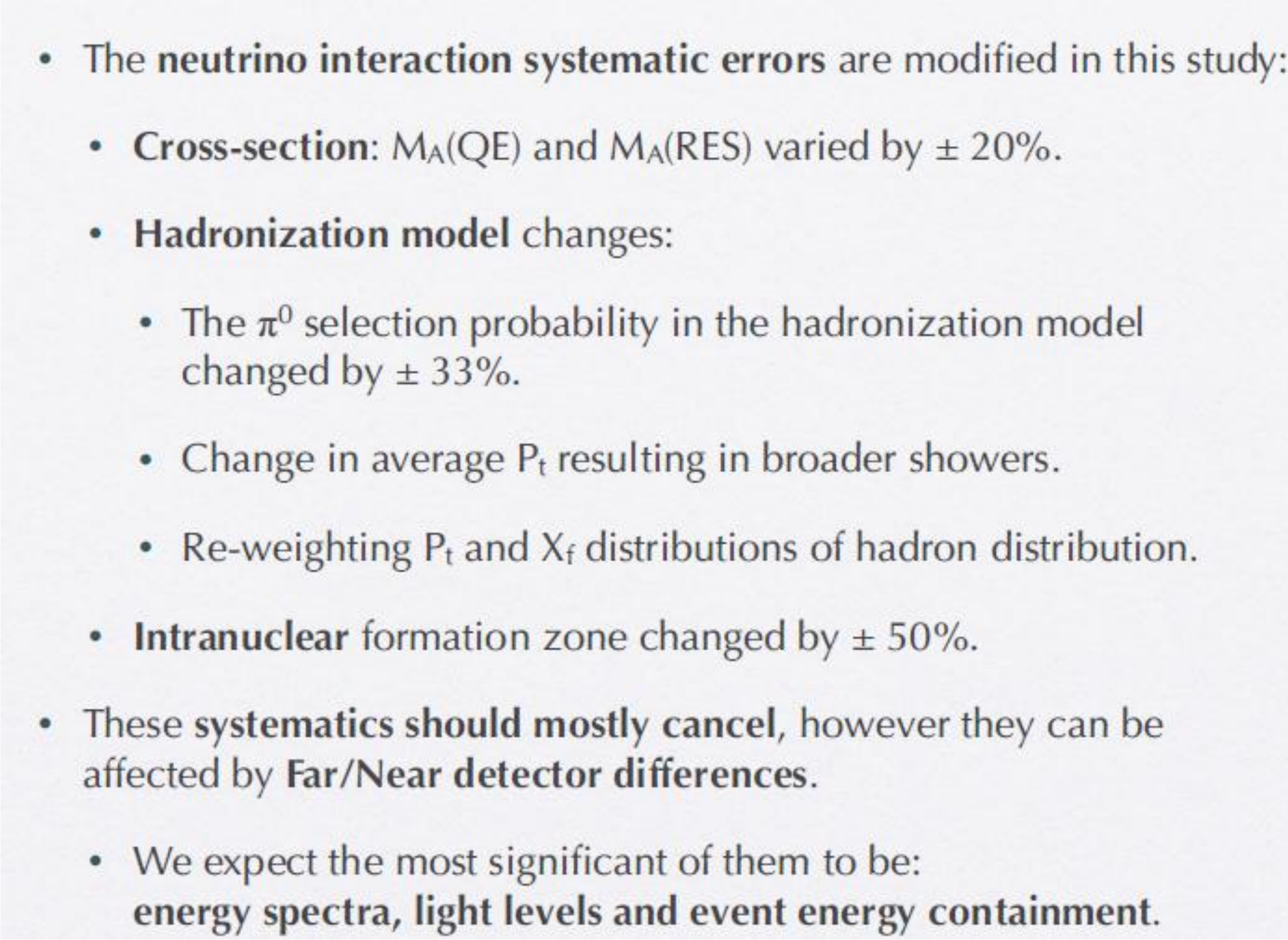


MINOS 2010

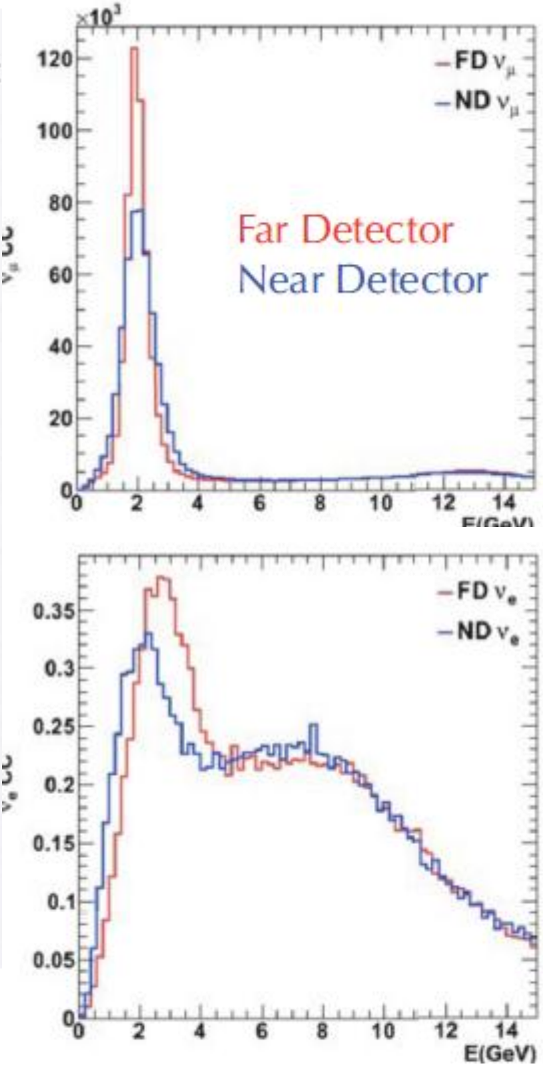
Note: in MINOS, Near and Far samples dominated by NC

Systematic error study in NOvA

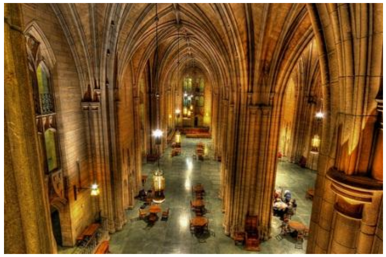


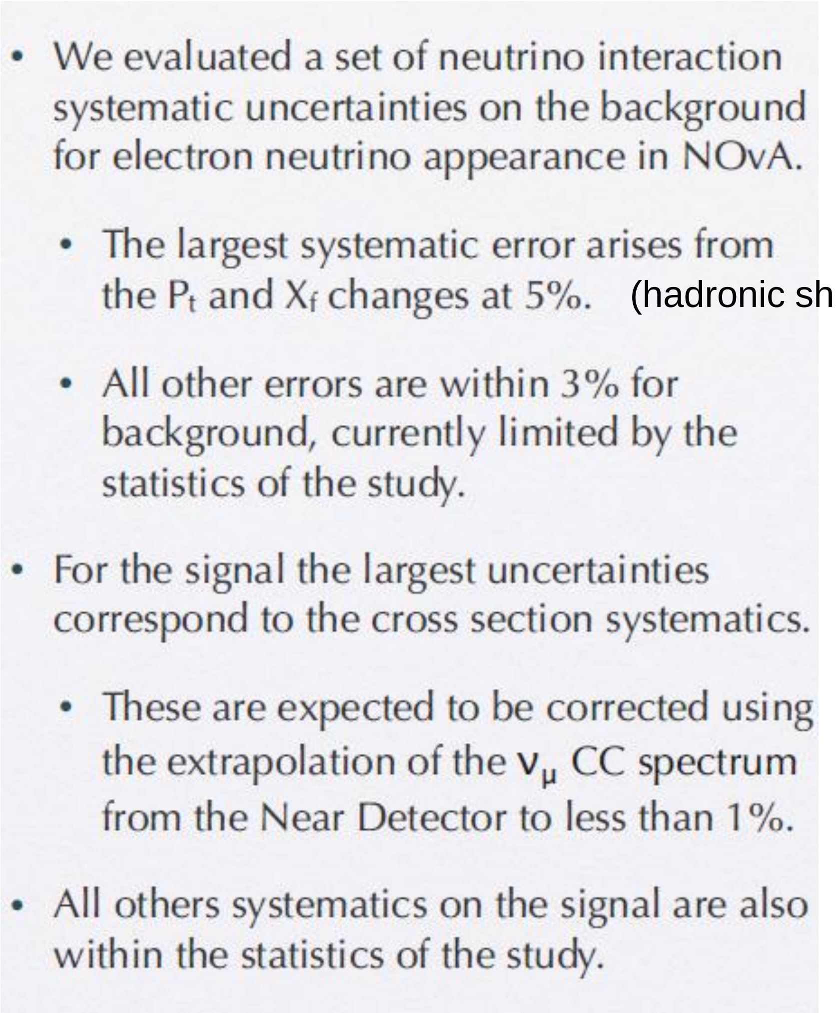


- The **neutrino interaction systematic errors** are modified in this study:
  - **Cross-section**: M_A(QE) and M_A(RES) varied by ± 20%.
  - **Hadronization model** changes:
    - The π^0 selection probability in the hadronization model changed by ± 33%.
    - Change in average P_t resulting in broader showers.
    - Re-weighting P_t and X_f distributions of hadron distribution.
  - **Intranuclear** formation zone changed by ± 50%.
- These **systematics should mostly cancel**, however they can be affected by **Far/Near detector differences**.
  - We expect the most significant of them to be: **energy spectra, light levels and event energy containment.**

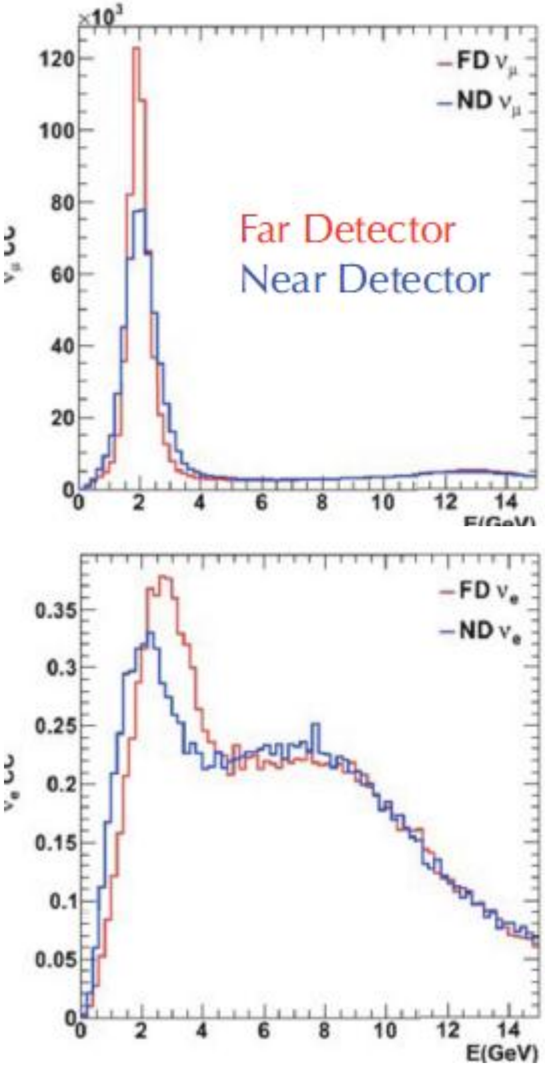


NOvA Preliminary estimate

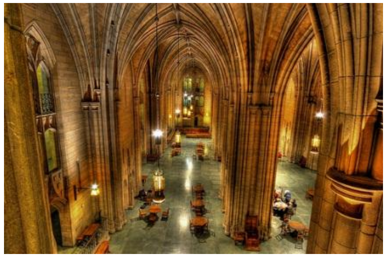




- We evaluated a set of neutrino interaction systematic uncertainties on the background for electron neutrino appearance in NOvA.
  - The largest systematic error arises from the P_t and X_f changes at 5%. (hadronic shower model)
  - All other errors are within 3% for background, currently limited by the statistics of the study.
- For the signal the largest uncertainties correspond to the cross section systematics.
  - These are expected to be corrected using the extrapolation of the ν_μ CC spectrum from the Near Detector to less than 1%.
- All others systematics on the signal are also within the statistics of the study.

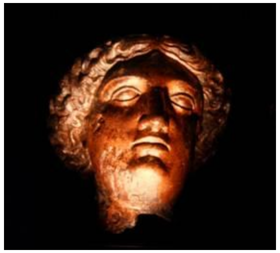


Comparison

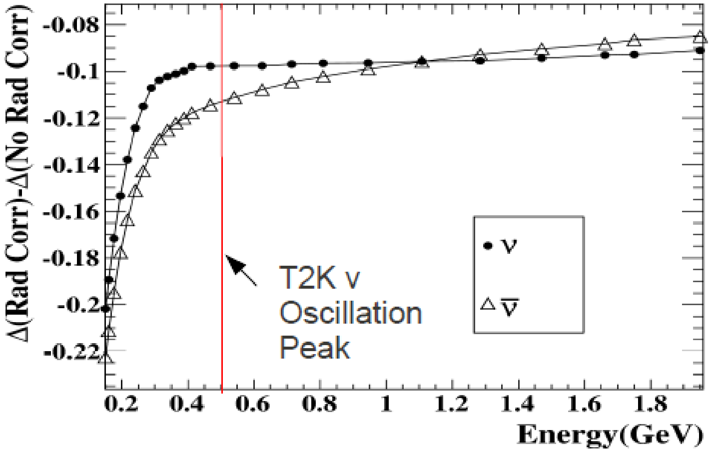


Experiment	**T2K (data through 6/2012)**	**NOvA (3 years of ν running)**	**Toy MC**
Background Composition (intrinsic ν_e to ν_μ /NC&CC)	1.73/1.31	8/24	19/19
Signal ν_e events (predicted, $\sin^2\theta_{13}=0.1$)	7.81	68	175
Near Detector Strategy	Multi-purpose, forward acceptance, High resolution	"Functionally identical" but much smaller, steel muon range stack in back	Assume identical
Systematic error on Background	7.7%	5% hadron shower model, 3% others	8% "now"/ 1.5% "later"
Systematic error estimated on signal	3.9%	Expect <1% using ν_μ CC	12% "now" / 2.5% "later"

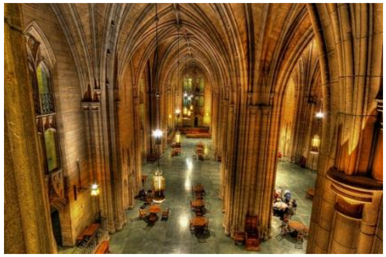
Sensitivities versus ν_e/ν_μ cross section ratio



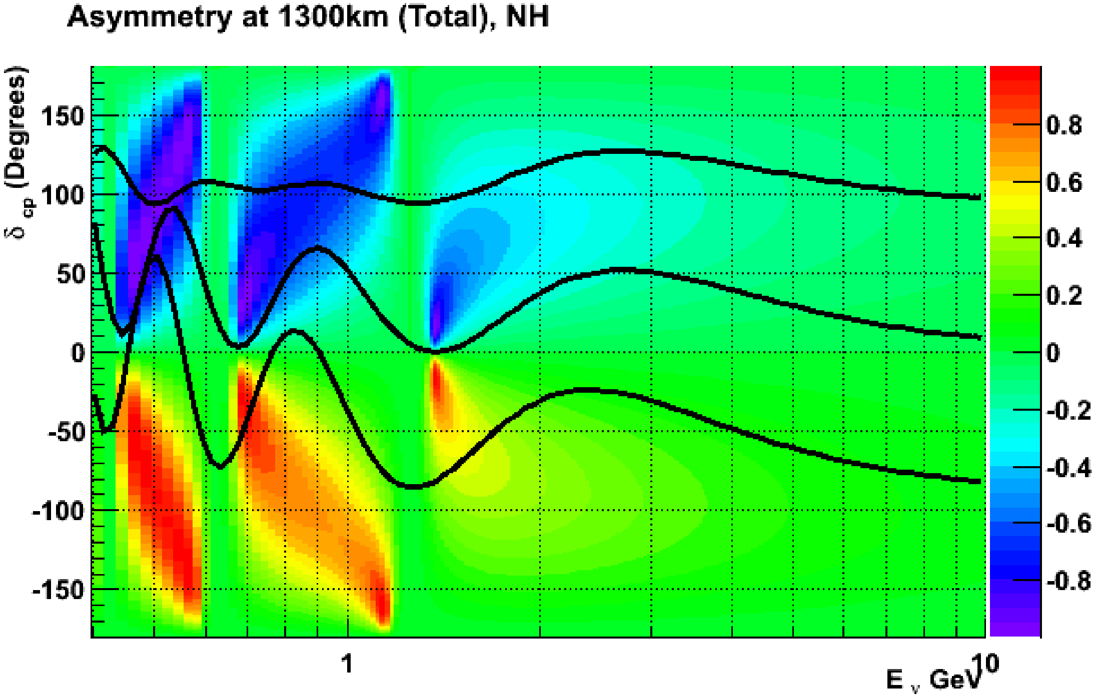
- Should not assume that once you know ν_μ CC cross sections that the ν_e CC cross sections are known to the same level of precision, especially <1GeV!
- See M. Day's talk at NuFact 2012
  (or M. Day & K.S. McFarland, *Phys.Rev.* ***D****86 (2012)*)
- Long list of effects need to be incorporated
  - Kinematic Limits
  - Axial Form Factor Contributions
  - Pseudoscalar Form Factor Contributions
    - Pole mass uncertainty
    - Goldberger-Treiman Violation
  - Second Class Current Contributions
    - Vector and Axial Form Factors
  - Radiative Corrections



Trying to understand next steps

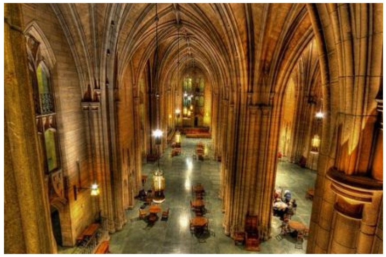


- Want to understand what cross sections will be important for next generations
- Flux?
- Cross sections?
- Large Θ_{13} means looking for small differences

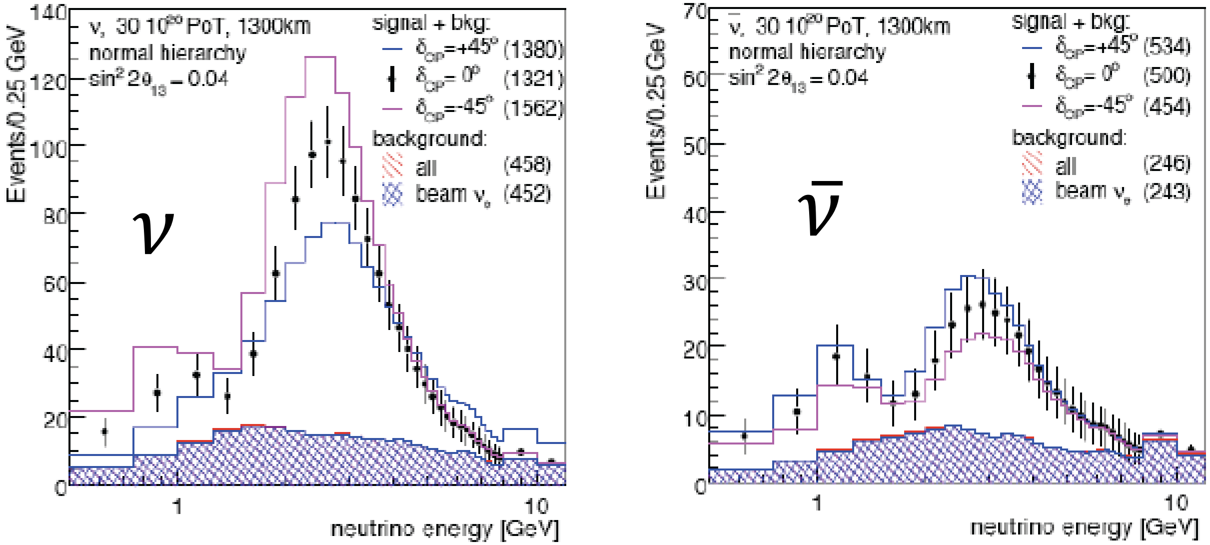


- Plot at left shows LARGEST asymmetry vs δ_{CP} and ν Energy for LBNE (from M. Bishai, plot is w/o matter effects, matter effects will make this harder in one mode, easier in another)

Cross sections that matter in the next generation

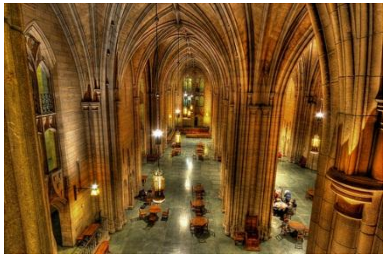


- T2HK: Water Cerenkov, expect similar backgrounds as T2K: (NC, ν_μ CC, beam ν_e)
- LBNE/LBNO: Liquid Argon
  - – Historically, predict that the backgrounds are dominated by beam ν_e's, because of excellent e/γ discrimination



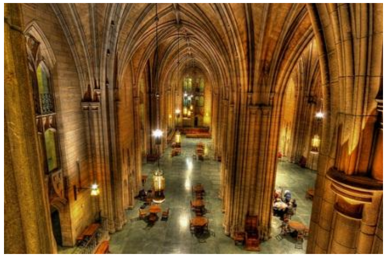
arXiv:0705.4396

What cross sections matter if all backgrounds are ν_e's?

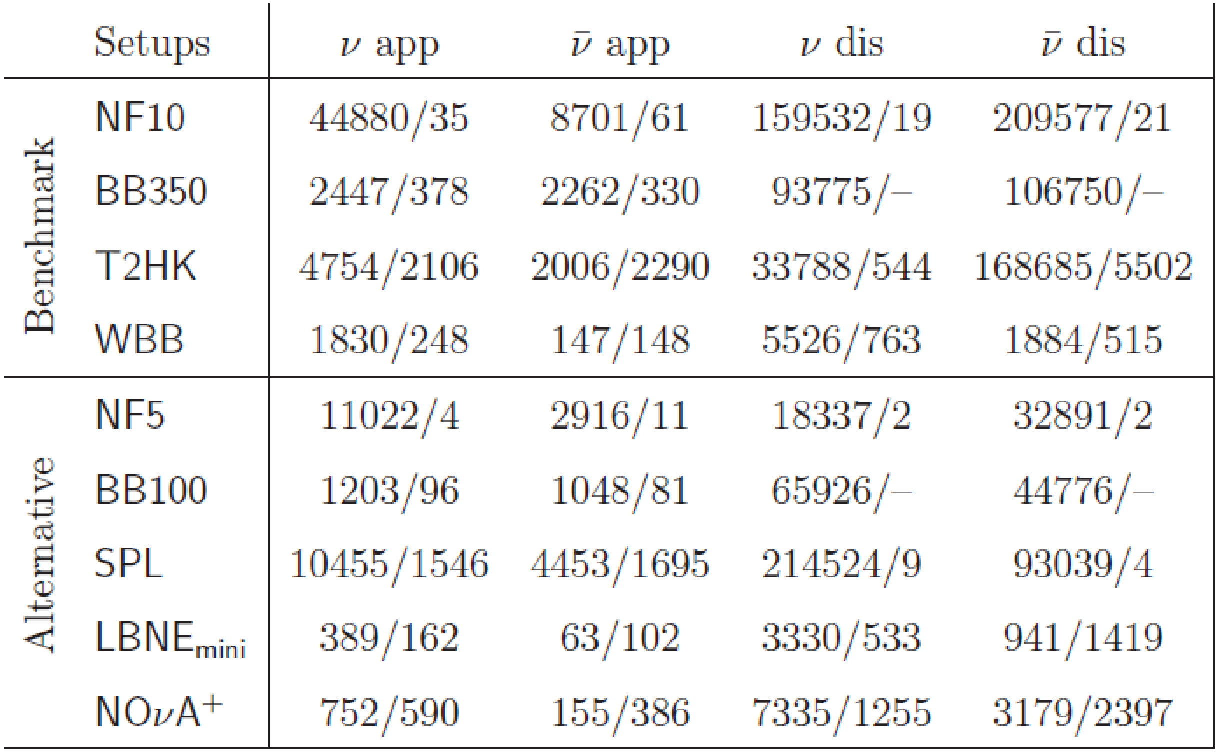


- Signal Cross sections matter (QE, Resonance)
  - Will also need acceptance over broad range of angles, not just small muon and electron angles
  - Which means that flux predictions for the cross section experiments matter a lot
- Flux predictions of the oscillation experiment beamline matter that much more
  - ν_μ flux matters for denominator in probability
  - ν_e flux matters for background subtraction
    - Would be nice in particular to measure ν_e cross sections in ND with a near detector…
    - Other idea around for dedicated ν_e cross section measurement: NUSTORM

Sneak Preview: many new ideas for next step



- Signal / background is very different depending on what future facility you have in mind
- See P. Coloma, P. Huber, J. Kopp, W. Winter, “Systematic uncertainties in long-baseline neutrino oscillations for large θ_{13}”, arXiv: 1209.5973 [hep-ph]



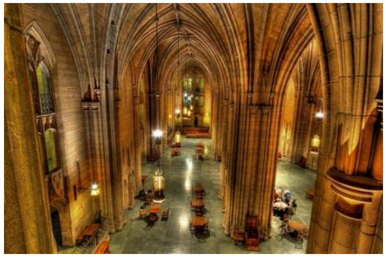
	Setups	ν app	$\bar{\nu}$ app	ν dis	$\bar{\nu}$ dis
Benchmark	NF10	44880/35	8701/61	159532/19	209577/21
	BB350	2447/378	2262/330	93775/–	106750/–
	T2HK	4754/2106	2006/2290	33788/544	168685/5502
	WBB	1830/248	147/148	5526/763	1884/515
Alternative	NF5	11022/4	2916/11	18337/2	32891/2
	BB100	1203/96	1048/81	65926/–	44776/–
	SPL	10455/1546	4453/1695	214524/9	93039/4
	LBNE$_{\text{mini}}$	389/162	63/102	3330/533	941/1419
	NOνA$^+$	752/590	155/386	7335/1255	3179/2397

See P. Coloma’s talk tomorrow!

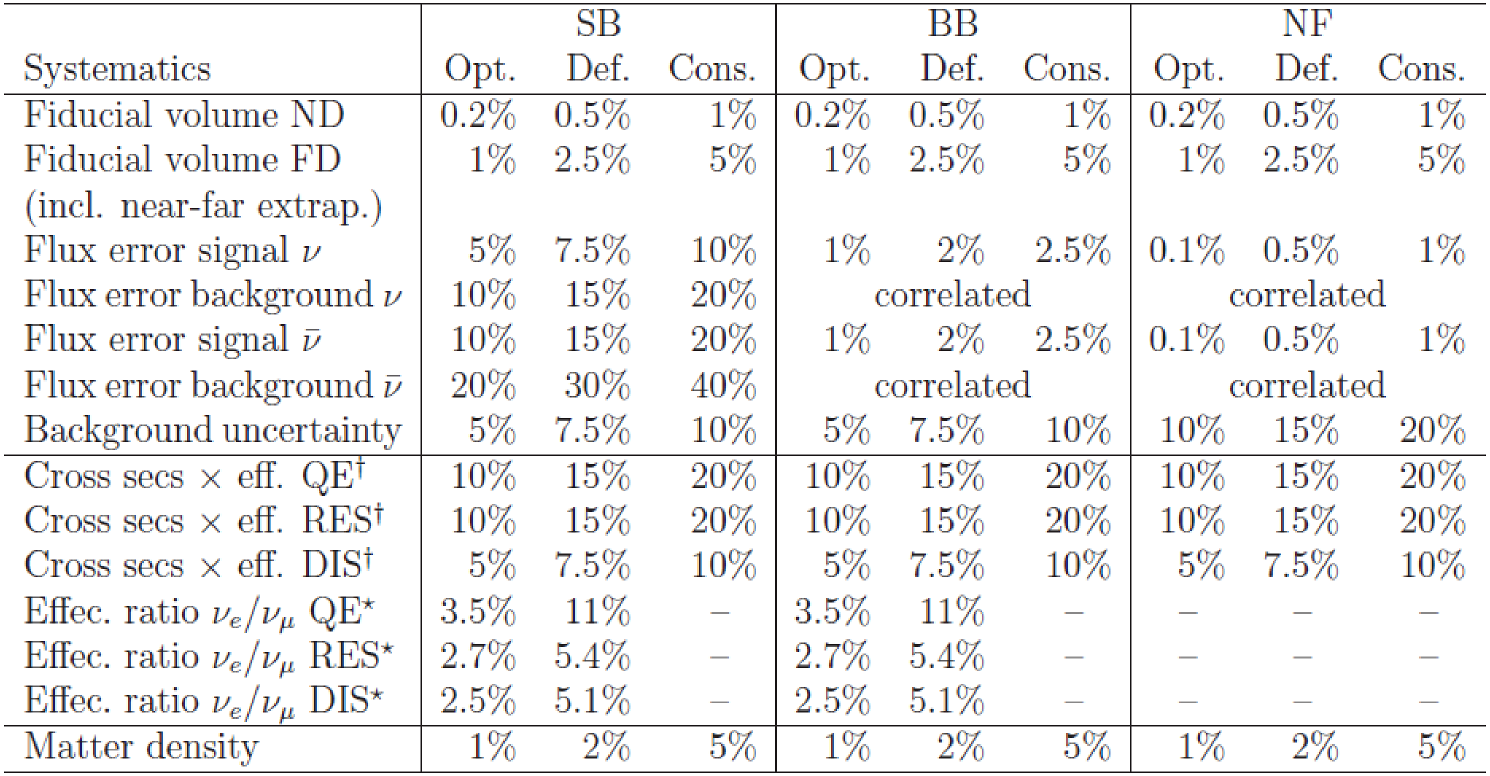
$$\theta_{12} = 32^\circ,\ \theta_{23} = 45^\circ,\ \theta_{13} = 9^\circ,\ \delta = 0,$$

$$\Delta m^2_{21} = 7 \times 10^{-5}\ \text{eV}^2 \text{ and } \Delta m^2_{31} = 3 \times 10^{-3}\ \text{(normal hierarchy)}$$

Cross Section Uncertainties: trust but verify…

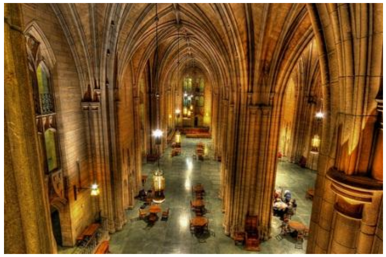


- Note: cross section x efficiency at 10% implies flux known much better for cross section experiments
- No shape uncertainties on Flux or Cross Sections…

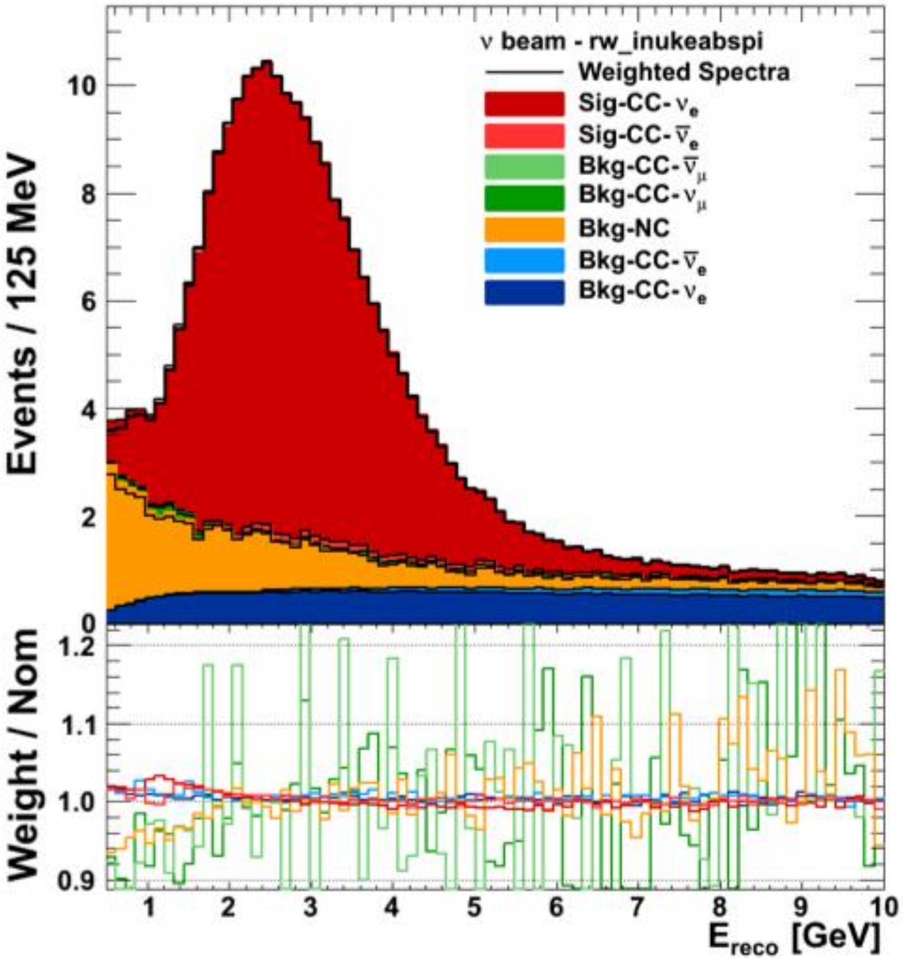


	SB			BB			NF		
Systematics	Opt.	Def.	Cons.	Opt.	Def.	Cons.	Opt.	Def.	Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
(incl. near-far extrap.)									
Flux error signal ν	5%	7.5%	10%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background ν	10%	15%	20%	correlated			correlated		
Flux error signal $\bar{\nu}$	10%	15%	20%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background $\bar{\nu}$	20%	30%	40%	correlated			correlated		
Background uncertainty	5%	7.5%	10%	5%	7.5%	10%	10%	15%	20%
Cross secs × eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. DIS†	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE⋆	3.5%	11%	–	3.5%	11%	–	–	–	–
Effec. ratio ν_e/ν_μ RES⋆	2.7%	5.4%	–	2.7%	5.4%	–	–	–	–
Effec. ratio ν_e/ν_μ DIS⋆	2.5%	5.1%	–	2.5%	5.1%	–	–	–	–
Matter density	1%	2%	5%	1%	2%	5%	1%	2%	5%

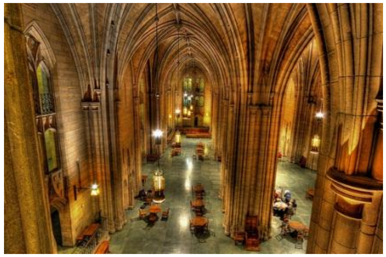
Future



- Wouldn’t it be great to do this study for new detector capabilities?
- Next steps: get the right energy dependence on uncertainties in flux and cross sections…figure out which energy dependences matter the most
- Get the right detector acceptance in
- LBNE working on this now…
- Plot at right shows what happens if you vary varying pion absorption in the FSI model (made by D. Cherdak and R. Gran, thanks to G. Zeller)



Summary and Conclusions



- Any time you are saying that cross section matters for oscillation experiments, you are ultimately saying that flux matters:
  - Not just for the oscillation experiments
  - But for the cross sections to get to oscillation measurements…
- No such thing as an “Identical Near Detector”
- Precious few standard candles
- Need to take advantage of what we have: both for cross section and oscillation experiments
- Need new/complementary ways to get at the fluxes