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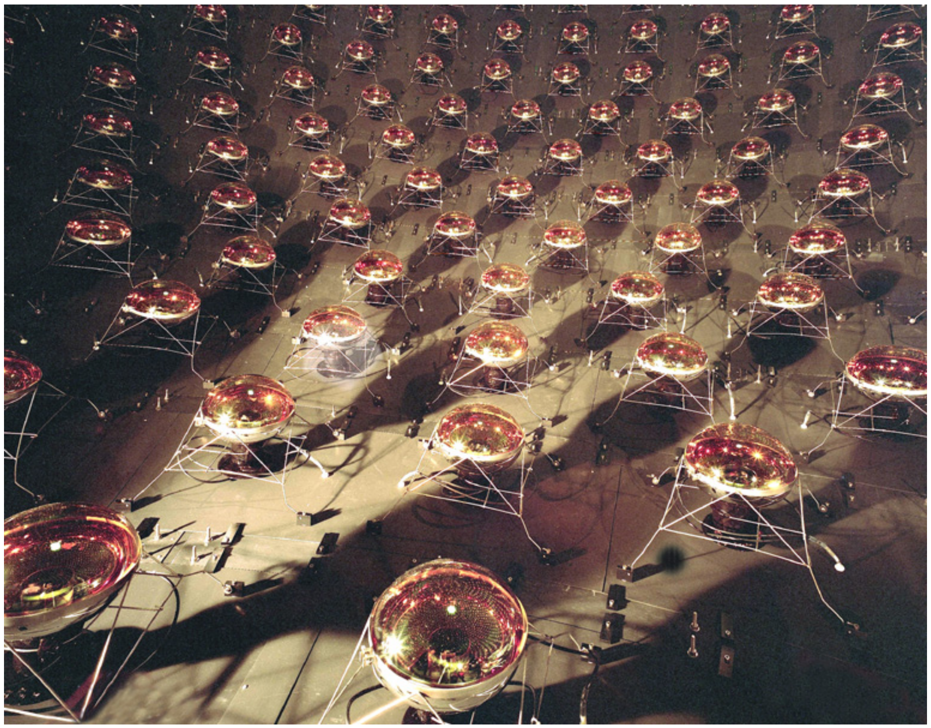
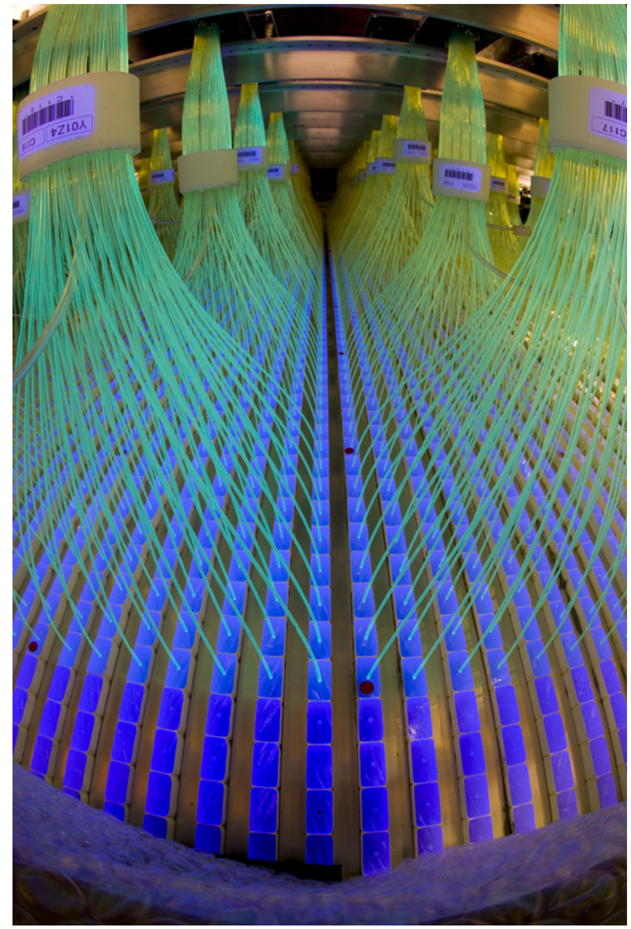
Cherenkov vs. Fine Grained measurement techniques





Kendall Mahn, Michigan State University

Outline

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- What is a Cherenkov detector?
- Combinations of fine grained detectors and Cherenkov detectors in oscillation analyses: MiniBooNE+SciBooNE, T2K
  - How do fine grained detectors compare to Cherenkov in performance?
  - How do uncertainties in the cross section model affect oscillation analyses?
  - How are the different detectors sensitive to the cross section model?
- Future improvements of Cherenkov detectors

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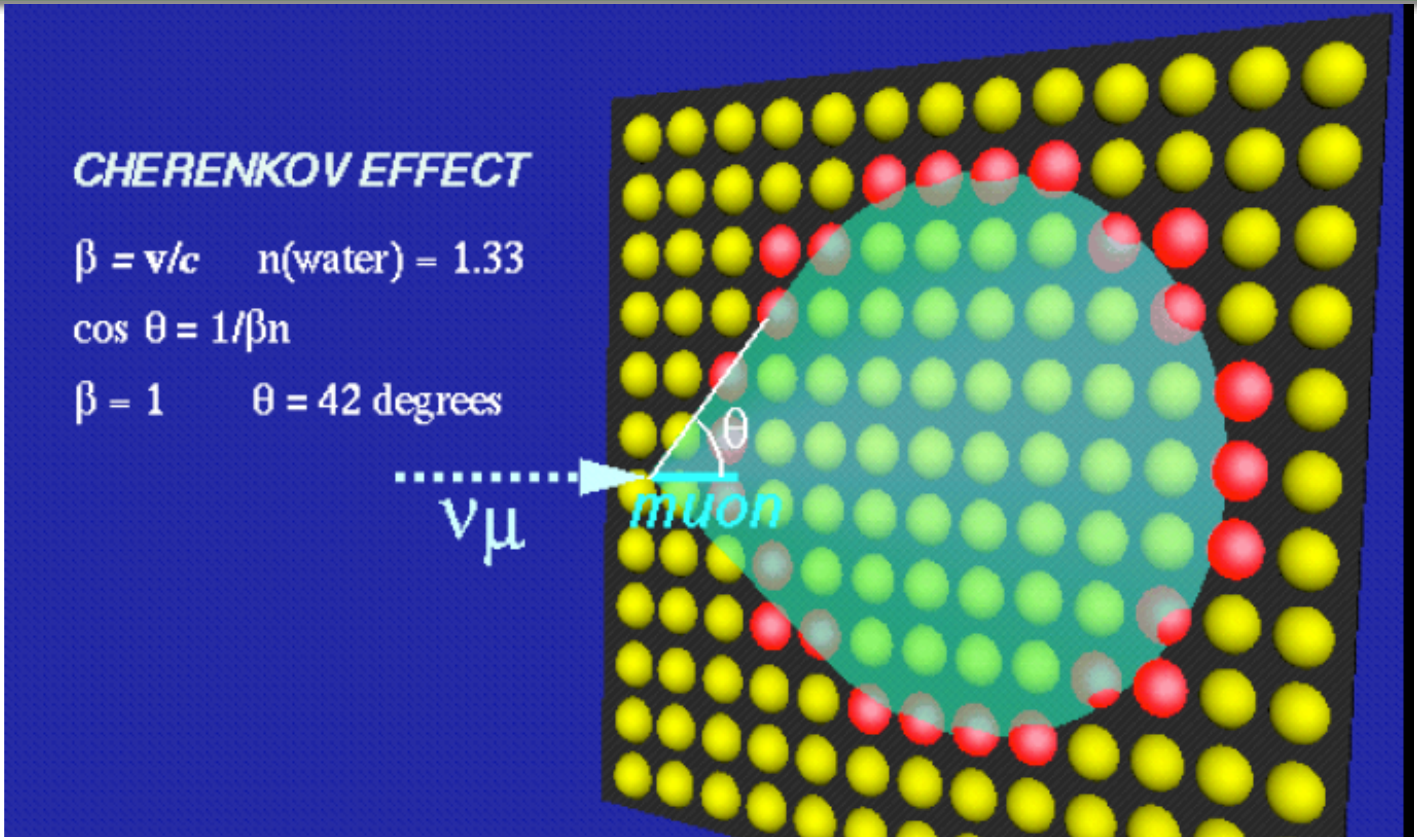
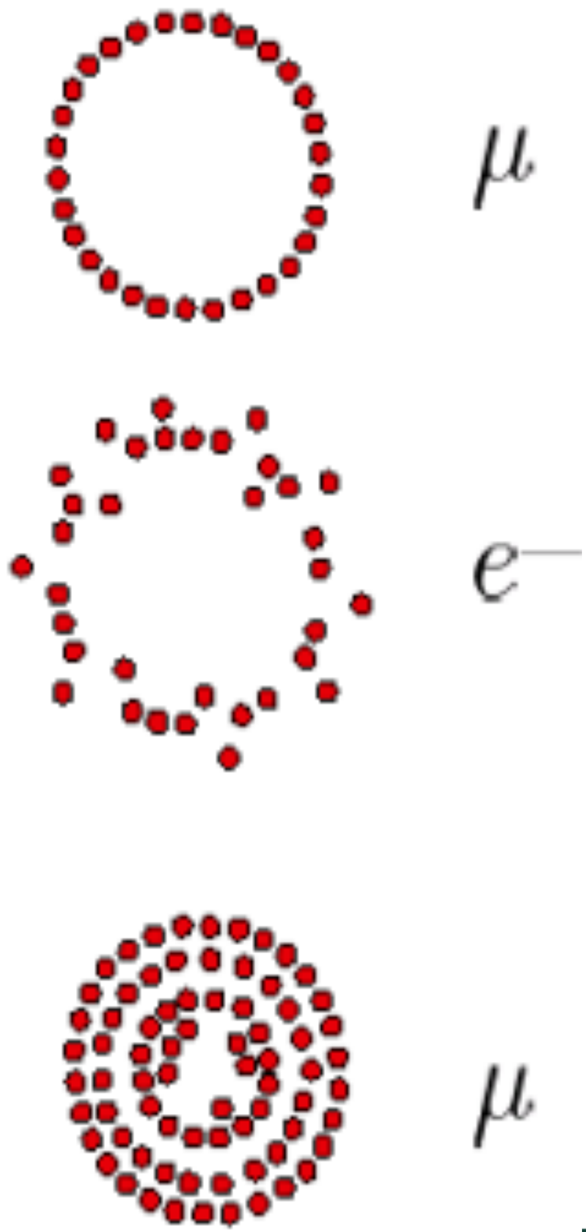
A Cherenkov detector



Particle moving faster than the speed of light in a medium radiates Cherenkov (Čerenkov light, discovery was1958 Nobel Prize)

- Threshold based on medium and momentum of particle
- Imaged as a cone (or a circle) on a flat plane of light detectors (photomultiplier tubes)

Lepton identification in Č detectors



Charged lepton out of CC interactions are typically above Cherenkov threshold

- Tau is massive, lifetime is short, and is identified indirectly through decay products above Cherenkov threshold
- Muons produce well defined rings
- Electrons pair produce and scatter, producing "fuzzy" rings.
- Exiting particles will produced filled-in rings

Reconstruction software finds the ring, and determines particle type from charge deposited, topology and timing

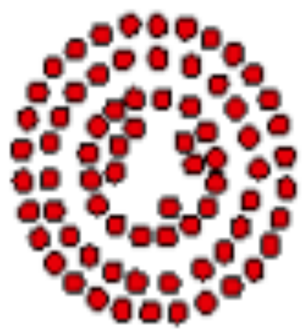
- Ring determines origin (vertex) and end point of track
- Momentum, angle depend on particle type and track

Example events in MiniBooNE

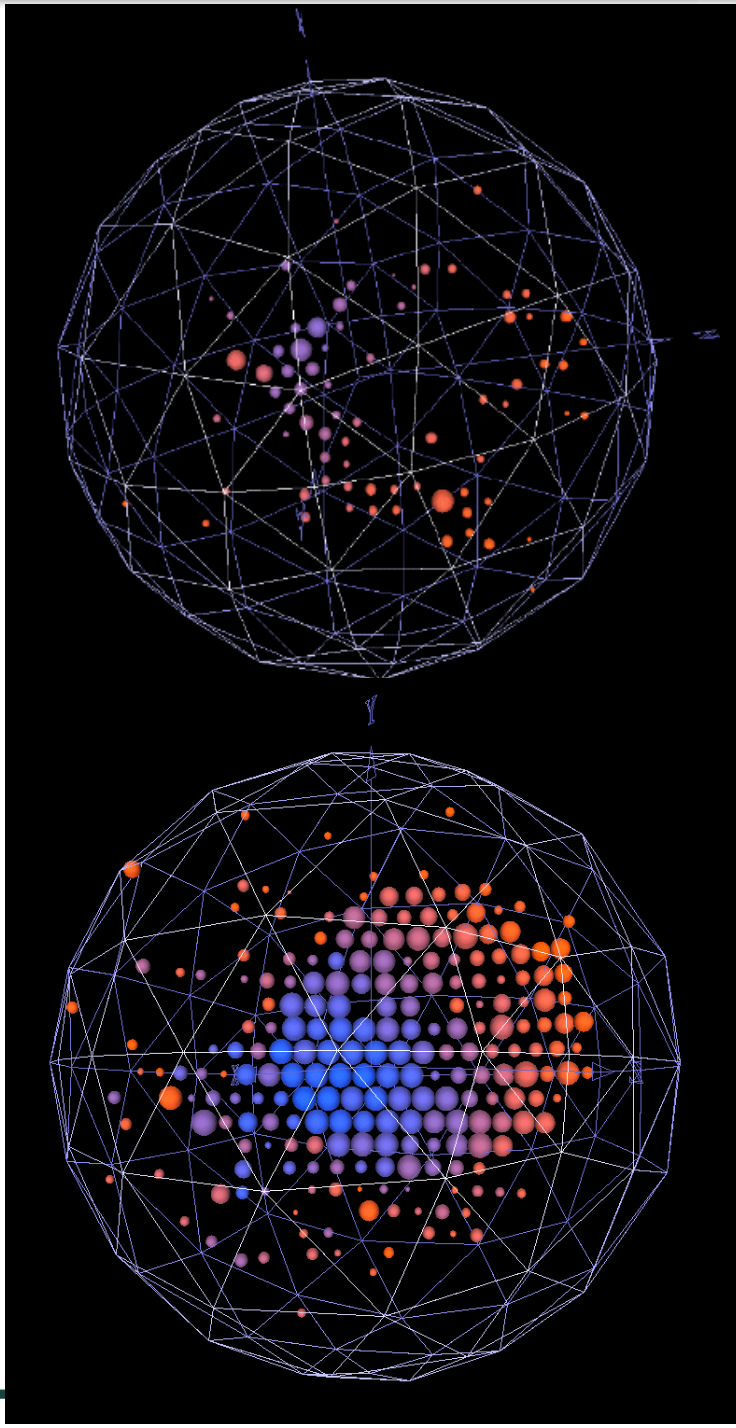
Spherical mineral oil Cherenkov detector

- Resolution of ring depends on photocathode/PMT coverage (10% here) and particle momentum
- Color indicates timing, dot size indicates charge

e^-



μ



Example events in Super-Kamiokande

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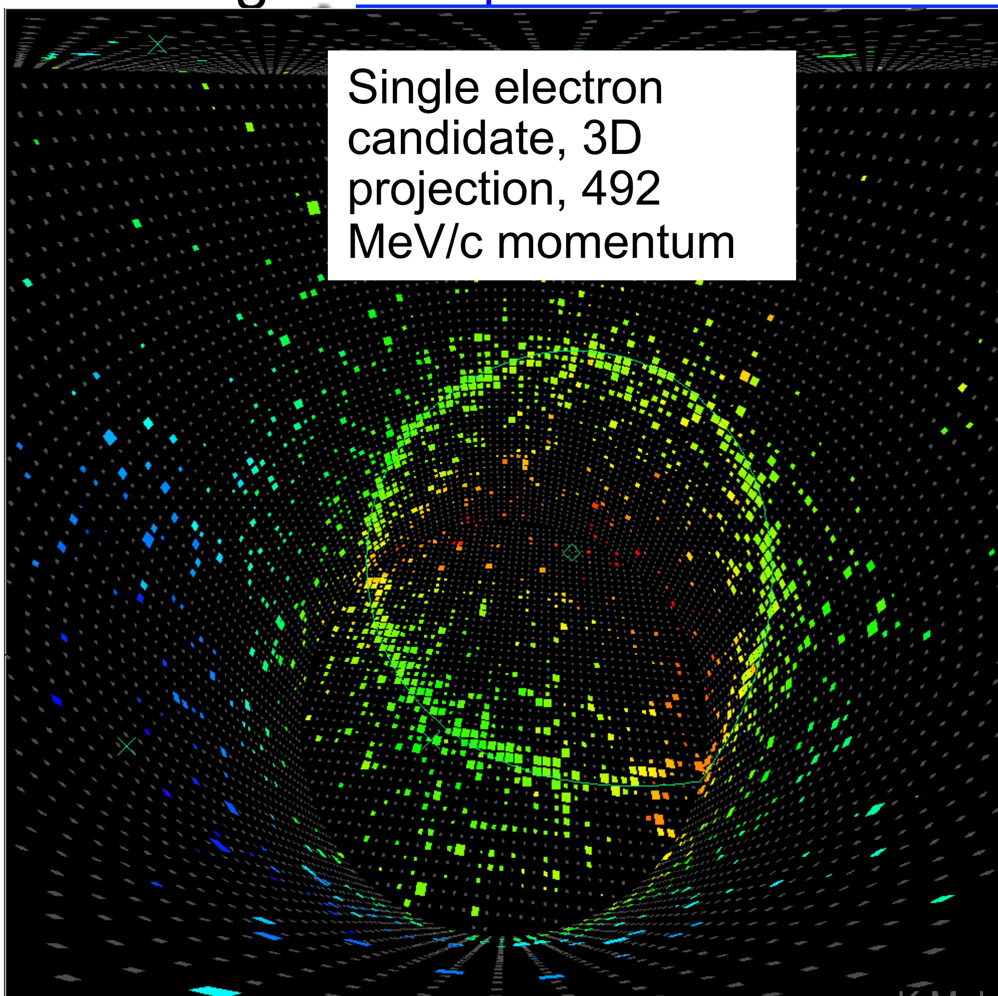
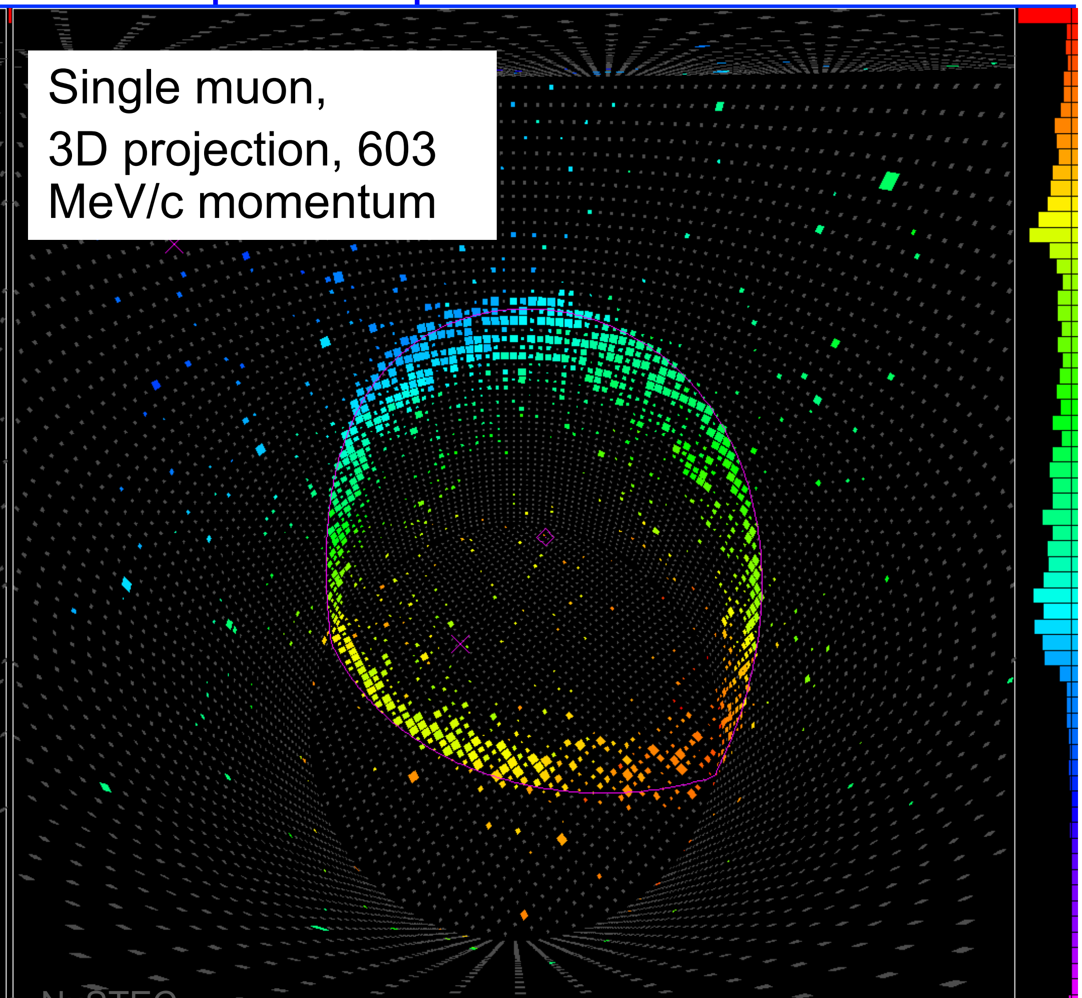
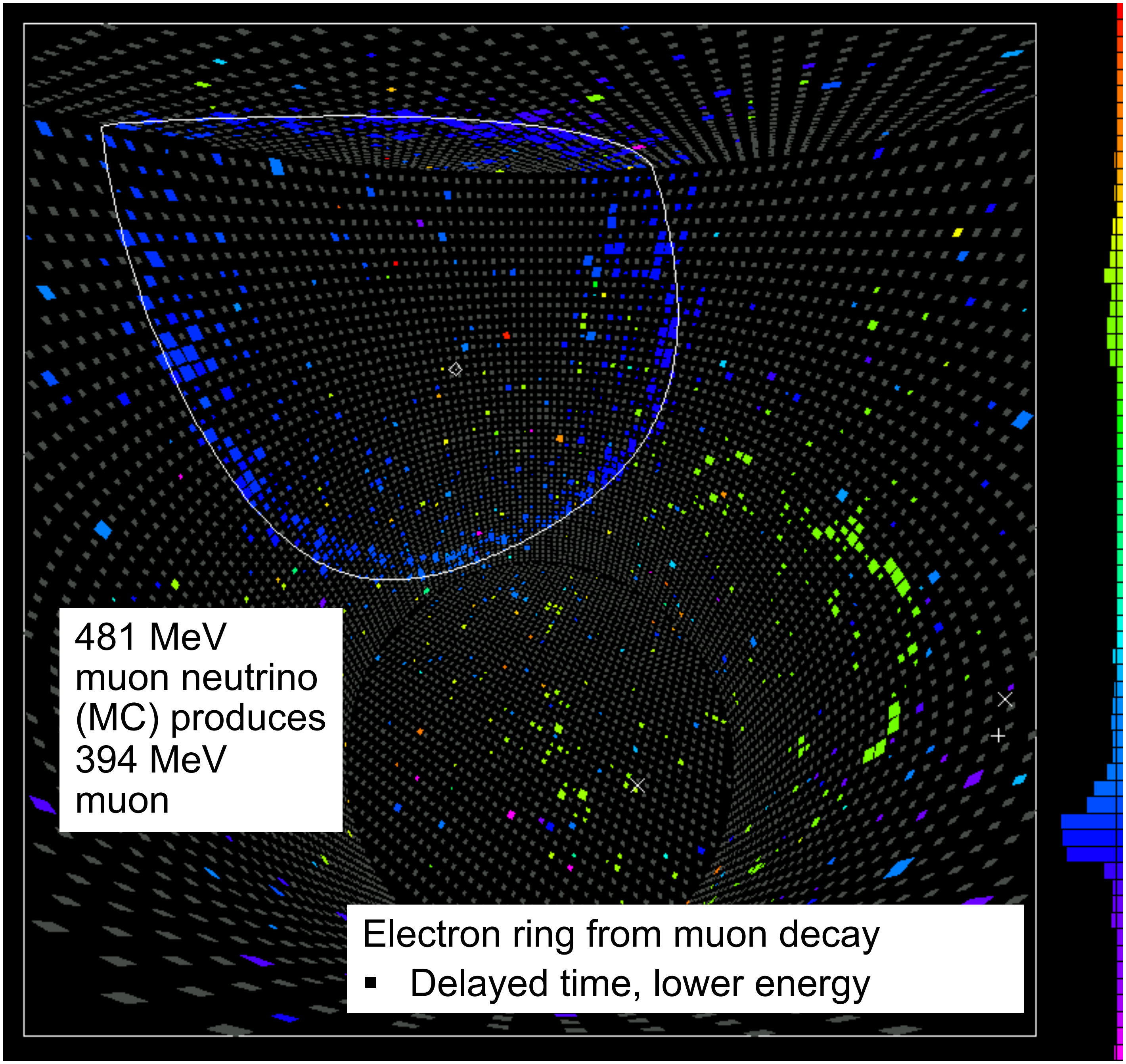
Cylindrical water Cherenkov detector

- Resolution of ring depends on photocathode/PMT coverage (40% here) and particle momentum
- Color indicates timing, dot size indicates charge
- Images www.ps.uci.edu/~tomba/sk/tscan/http://www.ps.uci.edu/~tomba/sk/tscan/

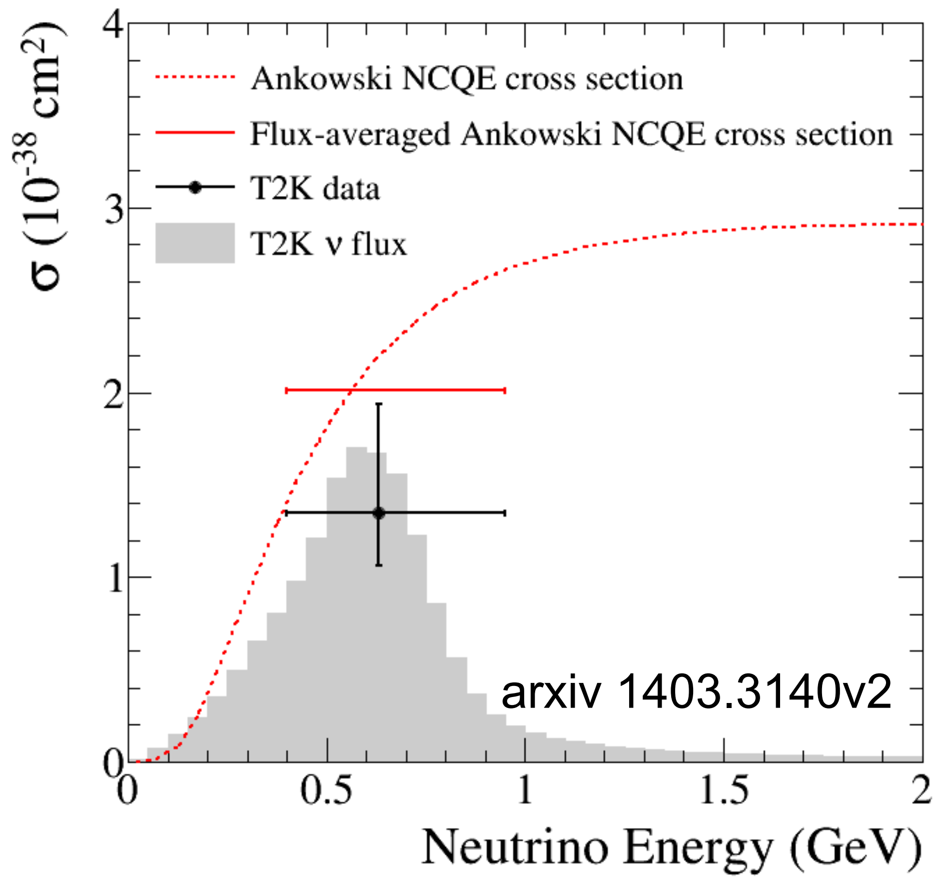




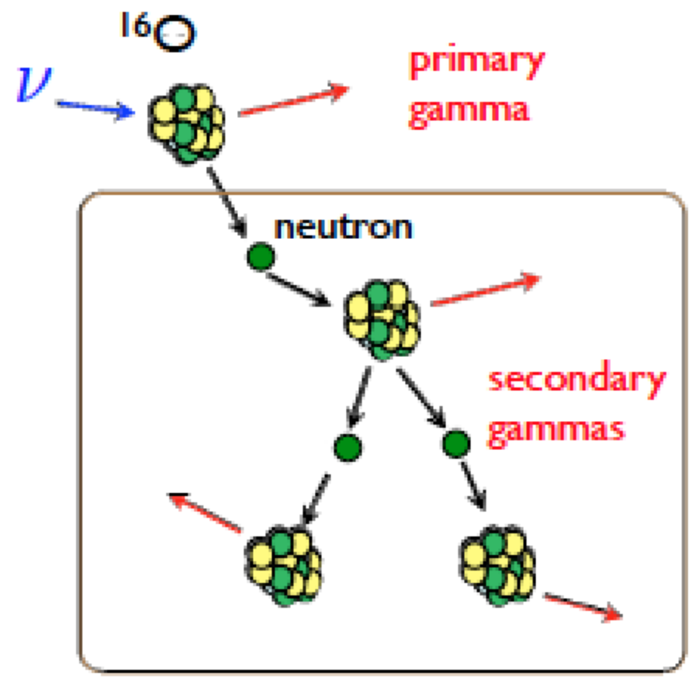
Example events in Super-Kamiokande



Low energy cross section physics



arxiv 1403.3140v2

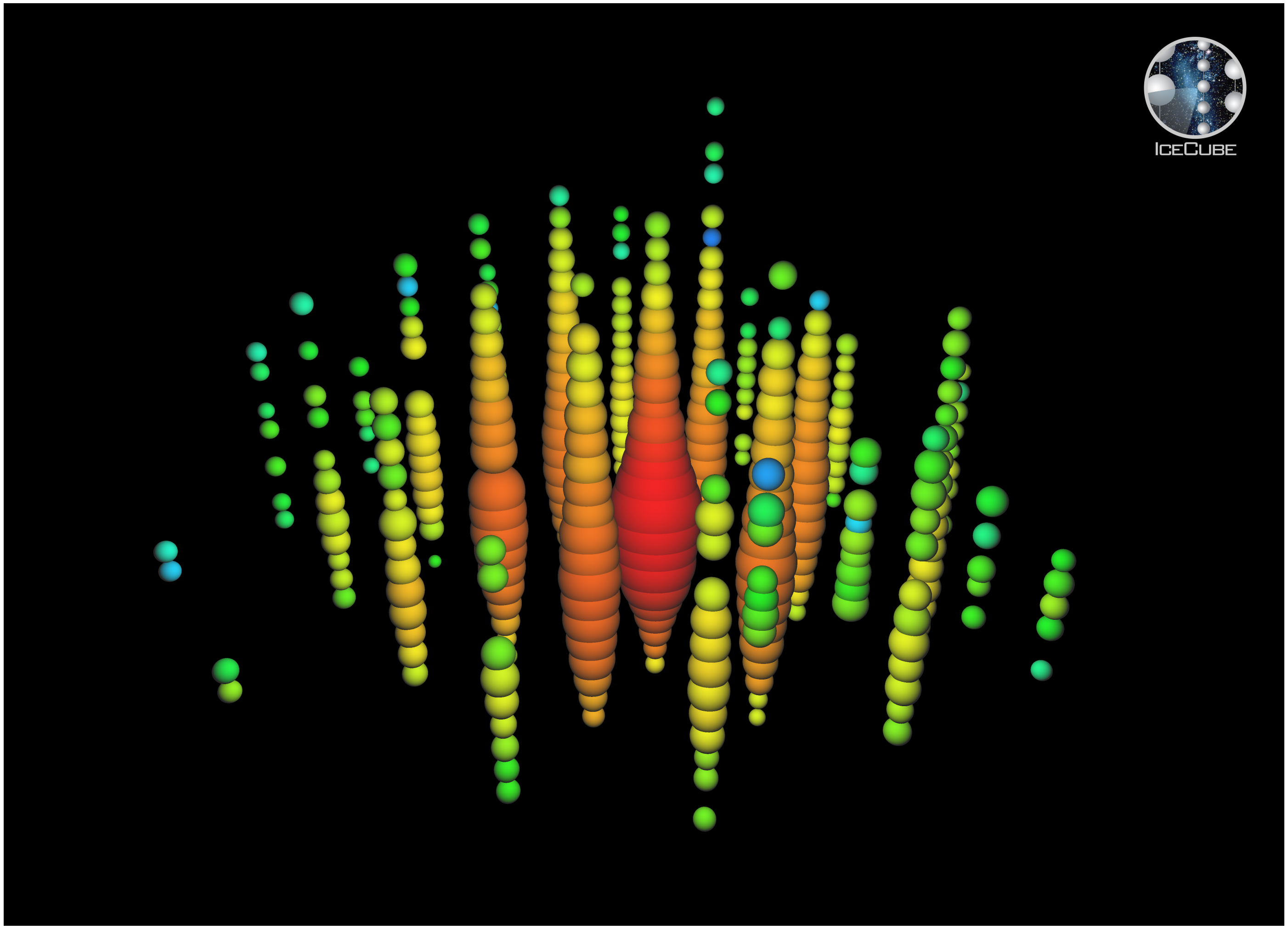


C. Nantais, CAP2014

De-excitation (~6 MeV) photons from NCQE interactions are visible in Super-Kamiokande

- Separable from background using timing (T2K beam pulse)

Example events in IceCube



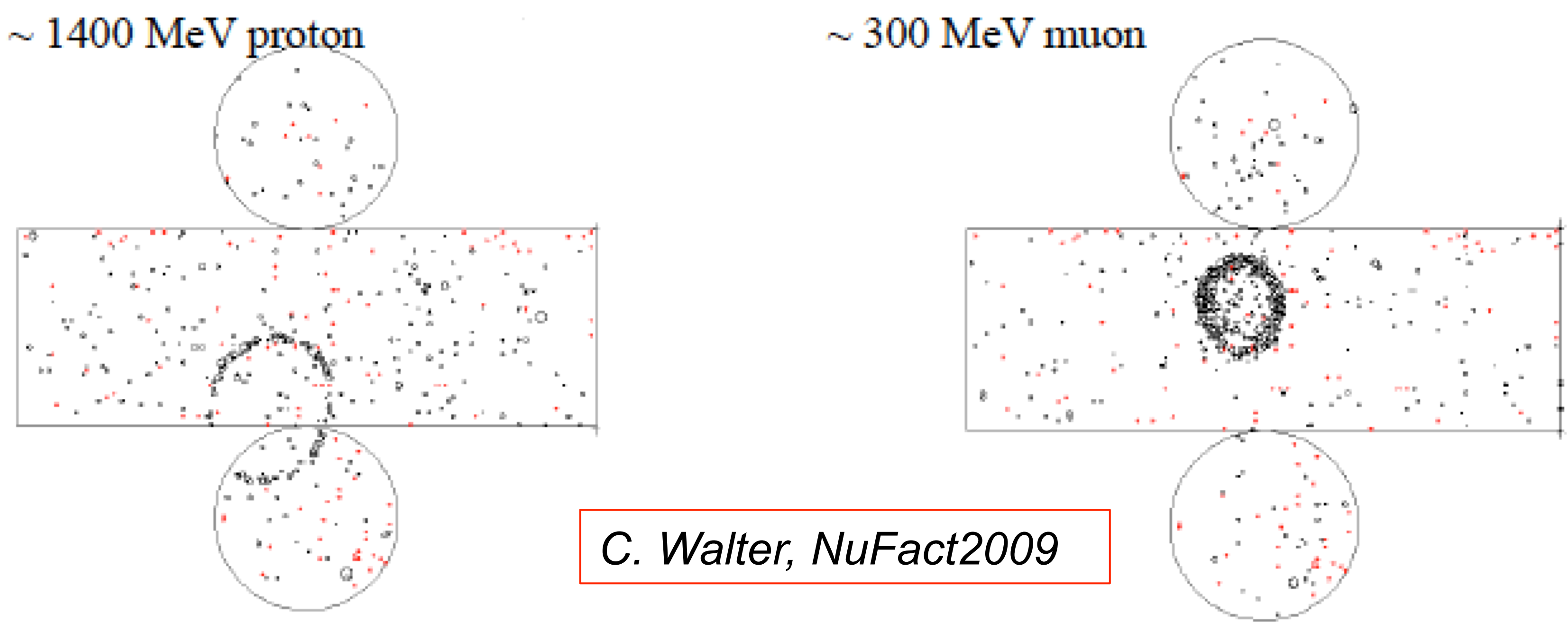
PMTs suspended in ice detect light profile (instead of ring)

- Much higher energy interaction (1.14 PeV)

Cherenkov detectors are stable, scalable

- Not possible to instrument 1 km^3 easily any other way

Protons in Cherenkov detectors



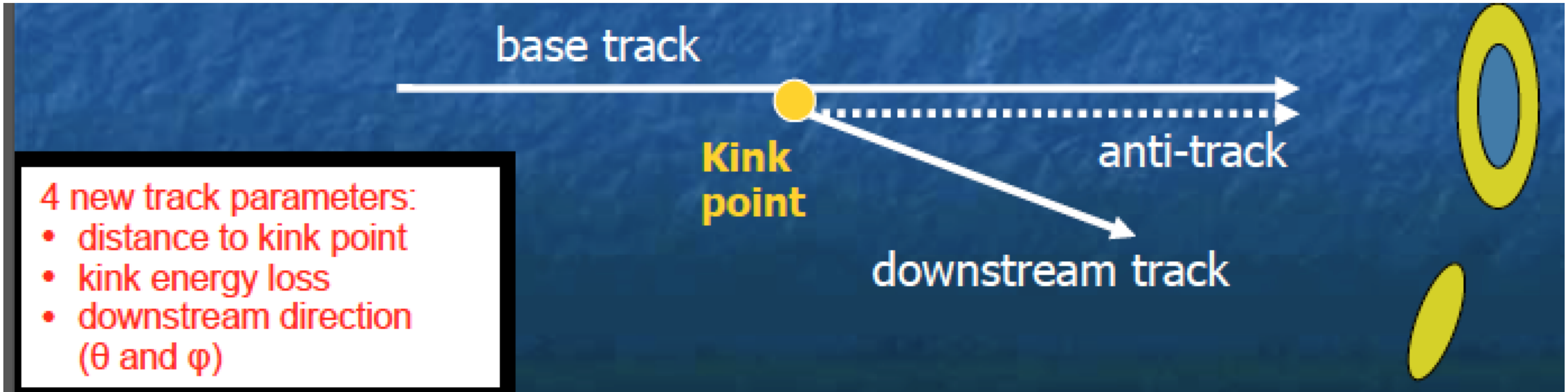
C. Walter, NuFact2009

Proton Cherenkov threshold is ~1 GeV

- Super-Kamiokande atmospheric analysis was able to select and reconstruct protons (Phys. Rev. D 79 (2009) 112010)
- Protons interact hadronically, sharp inner ring edge, short tracks

MiniBooNE also used scintillation light from mineral oil to select protons: Phys. Rev. D82, 092005 (2010)

Charged pions in Cherenkov detectors



M. Wilking, NuInt2009

Dedicated pion fitter developed for MiniBooNE

- Pions interact hadronically, scatter, creating "donut and hole"
  - 88% correct mu-pi identification, >90% purity for CC1π^+ interactions
- Can be challenging for fine grained detectors to separate kinks from vertex, or to reconstruct pion tracks
  - Dedicated tracking used for recent CC1π^+ MINERvA result (arxiv:1406.6415)
  - MINERvA also relies on calorimetry for pions

Neutral pions in Cherenkov detectors

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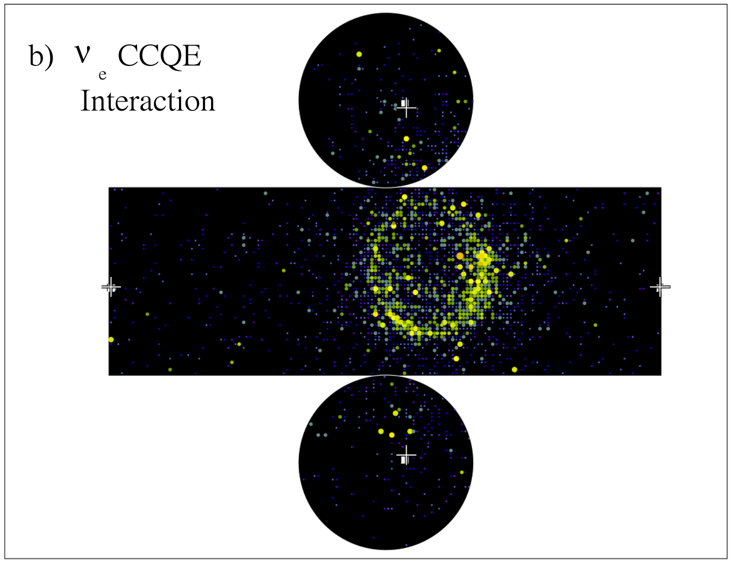
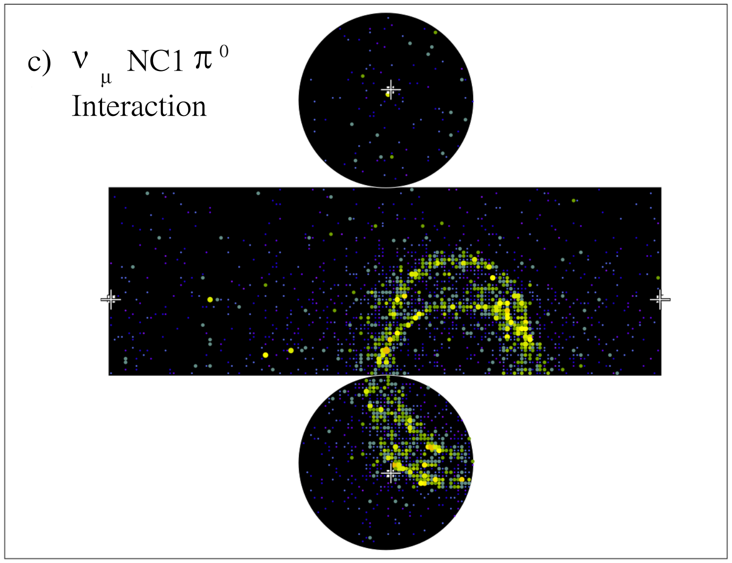
Neutral pions decay to two photons, which produce two electron-like rings

- NC background to ν_e appearance searches if 1 photon is not reconstructed
  - NC1gamma production ~irreducible (small difference in vertex position of e+/e- pair)
- New fitter for T2K analysis reduces NCπ^0 background significantly
  - Phys. Rev. Lett. 112, 061802 (2014)
- MiniBooNE analysis produced differential pion kinematics of NCπ^0 interactions
  - Phys. Rev. D81, 013005 (2010)
  - With both neutrinos and antineutrino





Events in Super-Kamiokande: Phys. Rev. D 88, 032002 (2013)

Multiple rings in Cherenkov detectors

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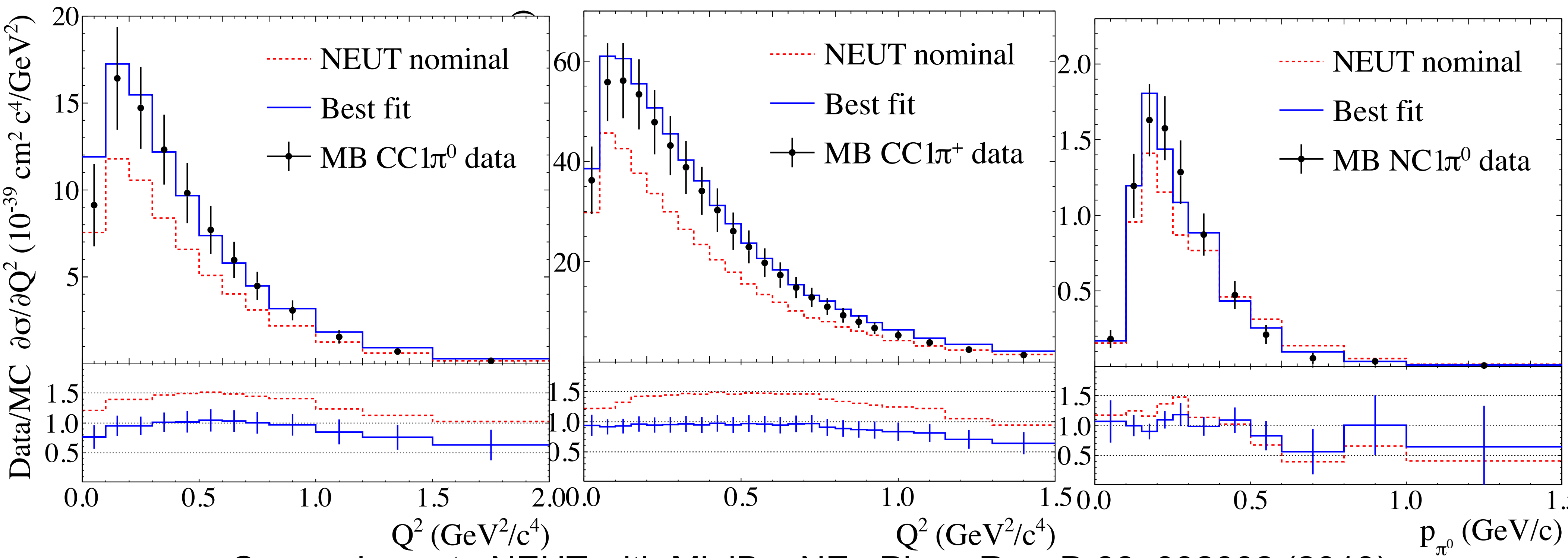
MiniBooNE analysis fit for three rings: muon + two electron rings (π^0)

- "Three ring circus", CC1π^0 57% purity:
  - Phys. Rev. D83, 052009 (2011)
- Efforts on Super-Kamiokande to fit multiple rings as well

Impressive differential information on both lepton, pion kinematics from MiniBooNE



Comparisons to NEUT with MiniBooNE, Phys. Rev. D 88, 032002 (2013)

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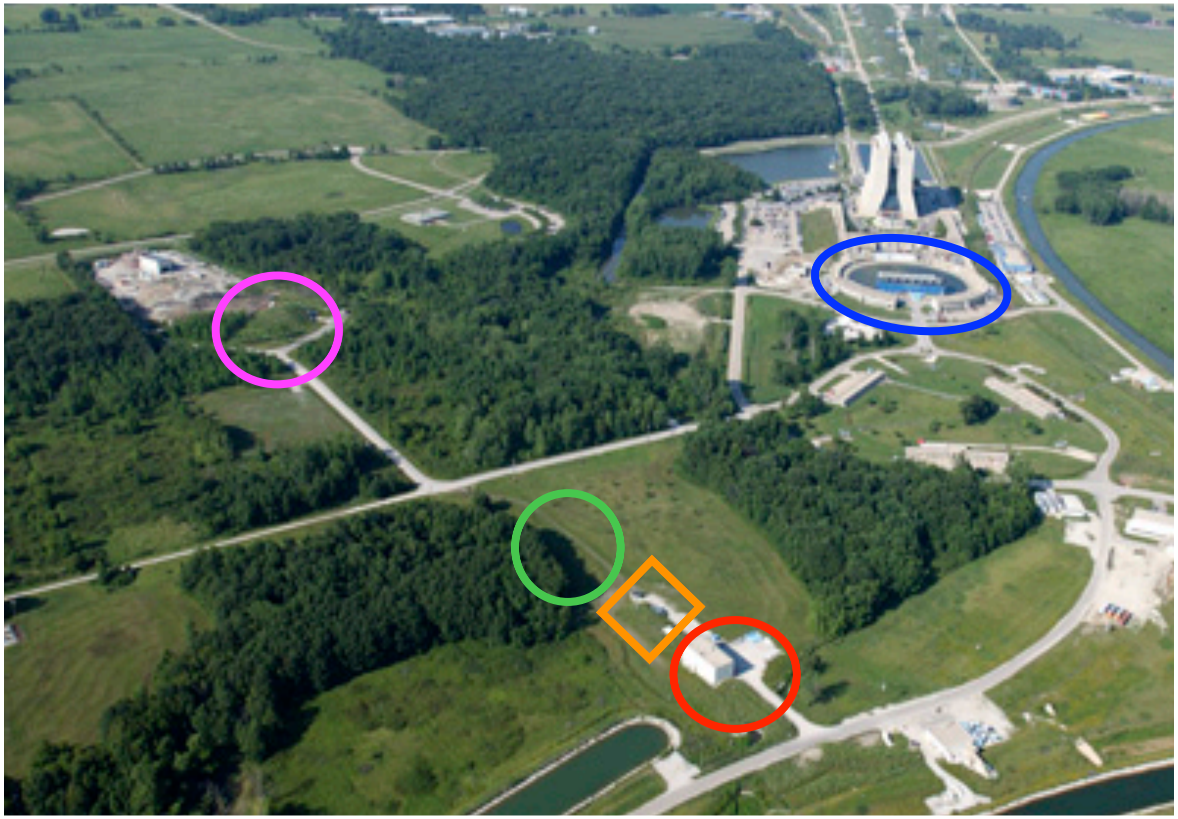
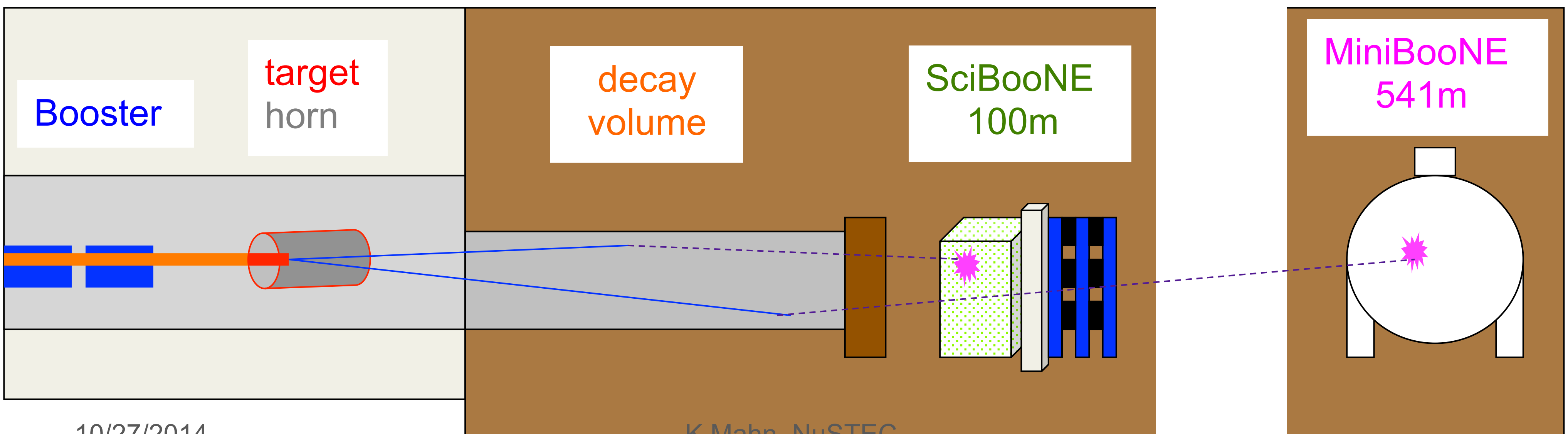
The Booster Neutrino Experiments (BooNEs)

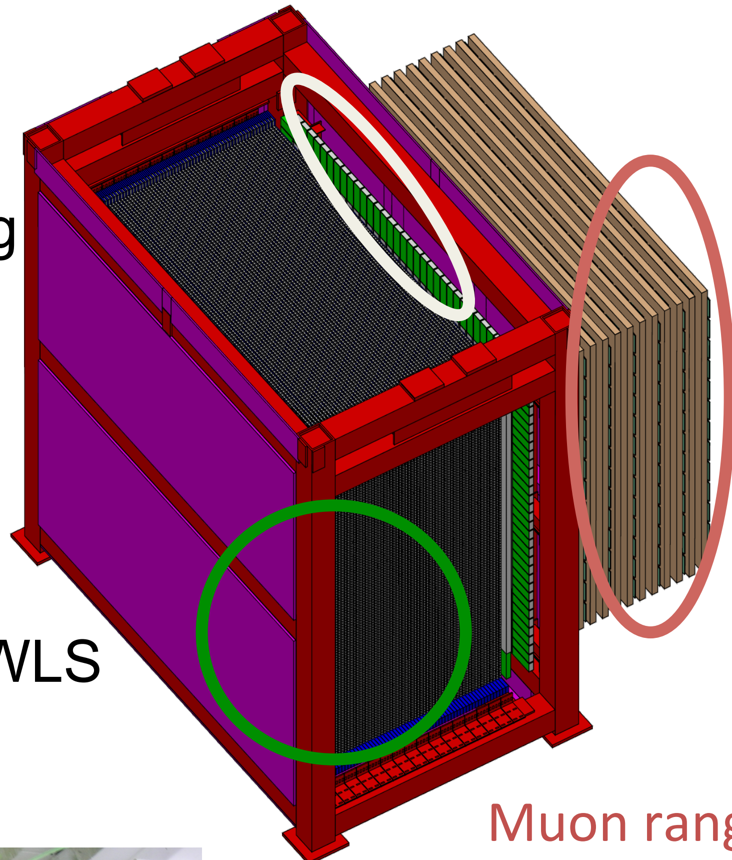


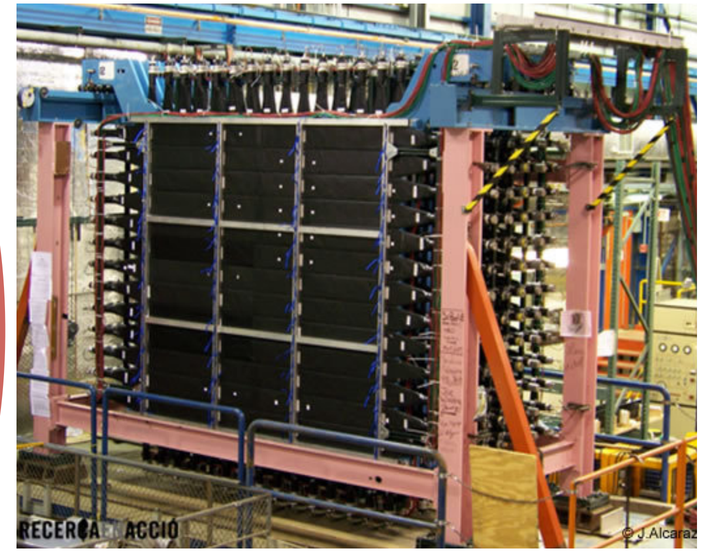
- 8.9 GeV/c protons from Booster accelerator
- protons hit a target within a magnetic focusing horn and produce mesons
- The mesons decay into neutrinos the ~50 m decay region
- Neutrinos are observed in MiniBooNE and SciBooNE



Electron Calorimeter (EC)

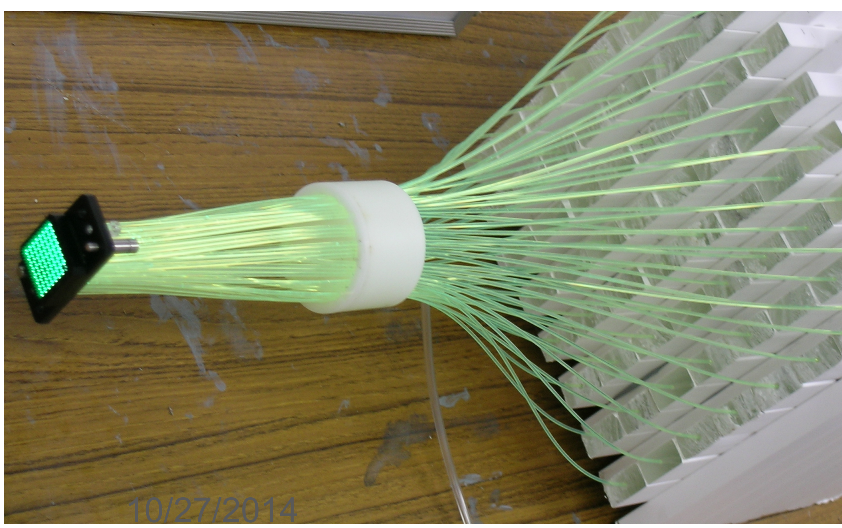
2 plane "spaghetti" calorimeter (scintillating fiber & lead foil)





SciBar vertex detector

32 x-y planes of 14,336 extruded scintillator bars instrumented with WLS fiber and 64ch. MAPMT (CH target)

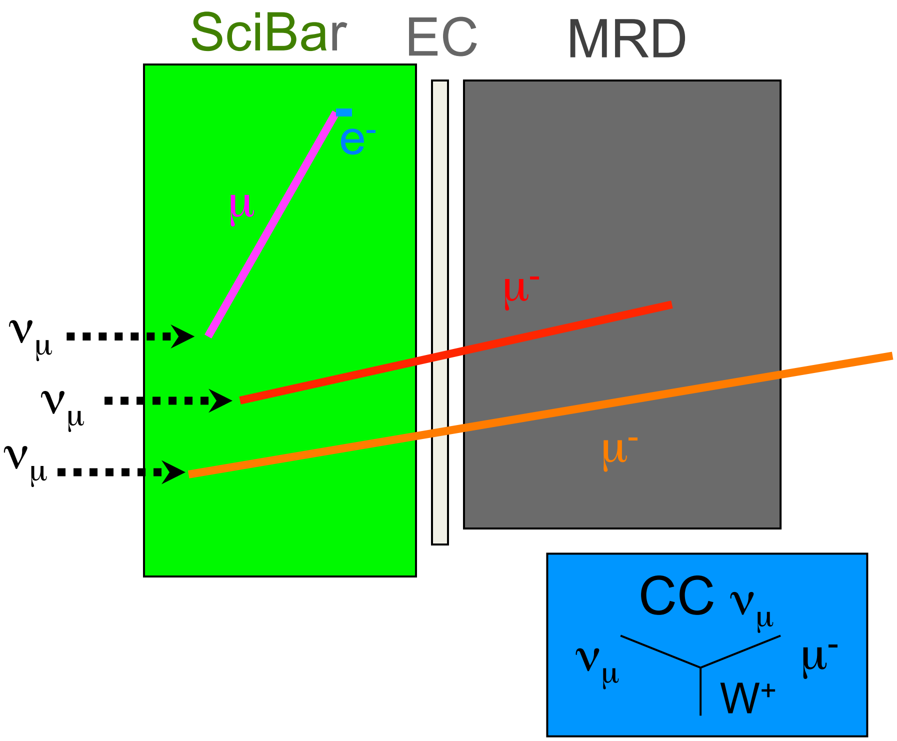


Muon range detector (MRD)

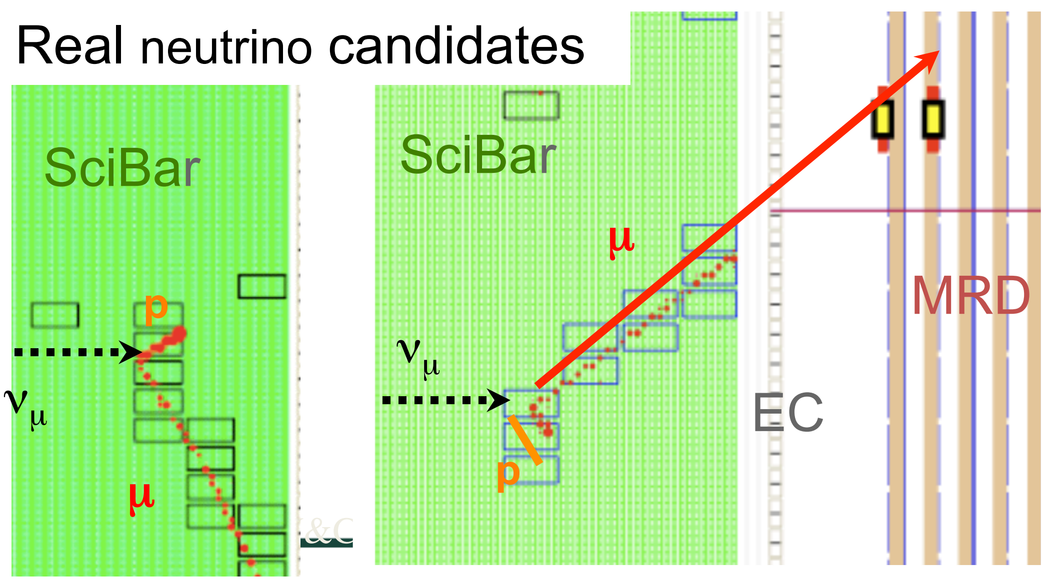
362 scintillator counters strapped vertically and horizontally to 12 iron plates

All detectors are recycled from previous experiments

Selecting CC ν_μ interactions in SciBooNE



Real neutrino candidates



- Select events with the highest momentum track with a vertex in SciBar fiducial volume which pass data quality, beam timing cuts
- p_μ>250 MeV/c reduces NC events
- Use energy loss in scintillator to select muon-like tracks

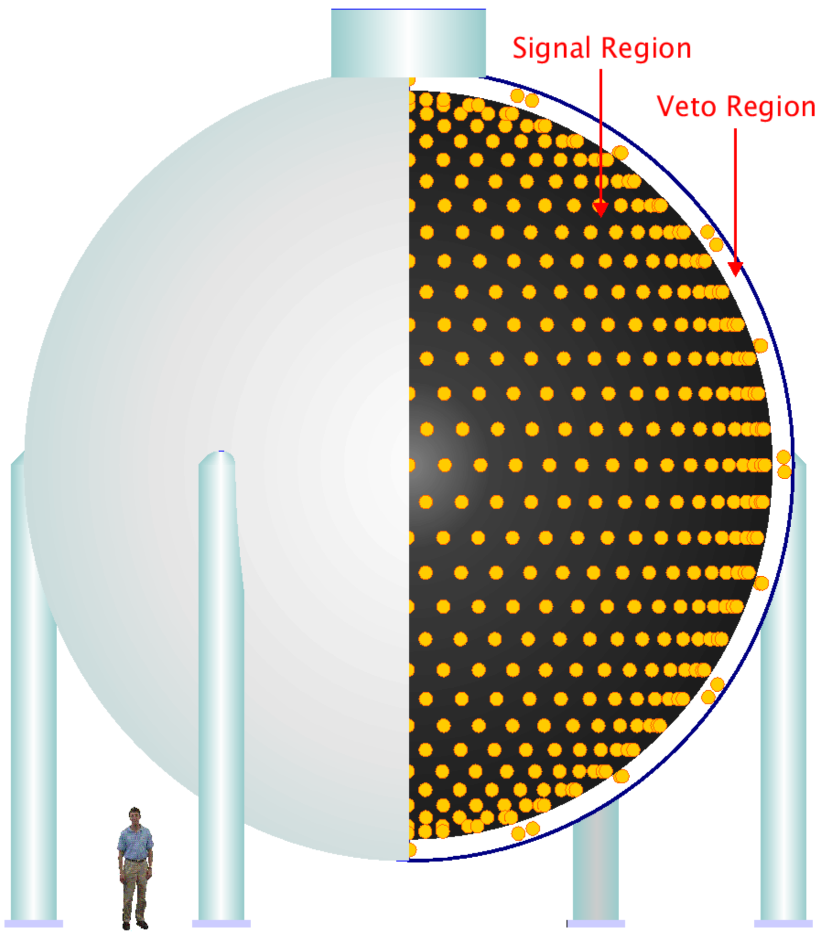
- "SciBar contained": stopped in SciBar

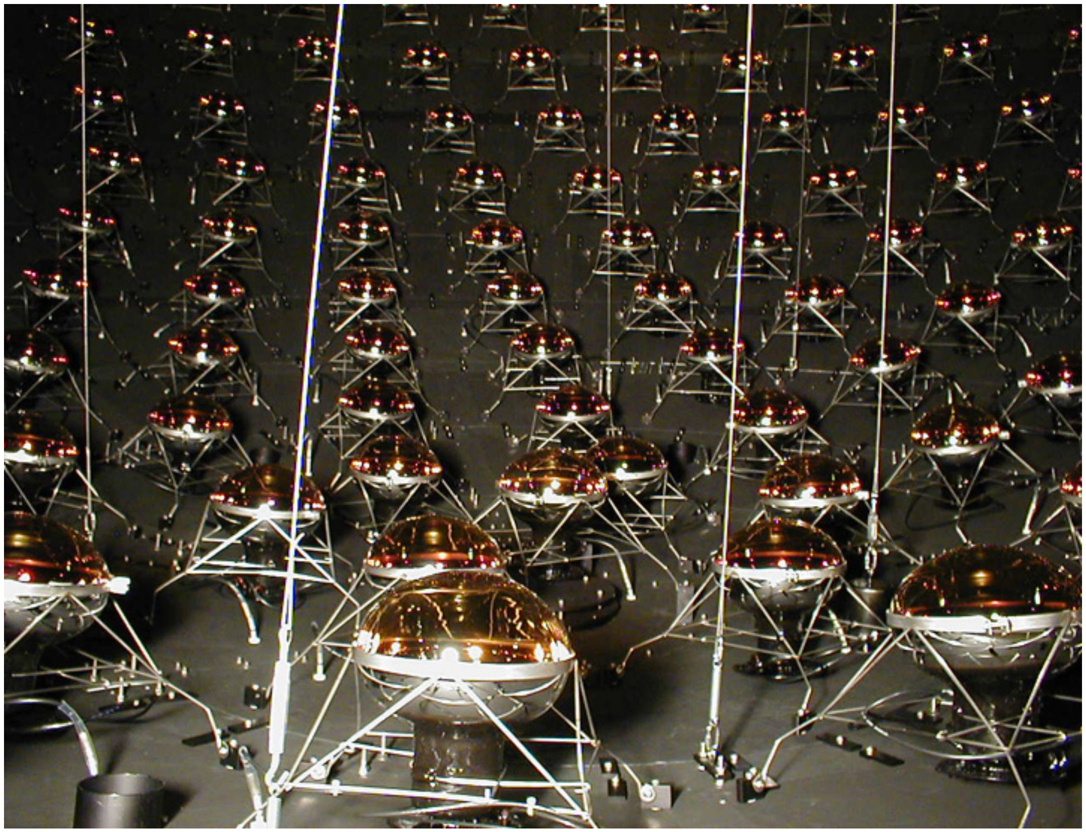
  Decay electron tag to determine track direction
- "MRD Stopped": stopped in MRD
- "MRD Penetrated": exits end of MRD

  Angular information only

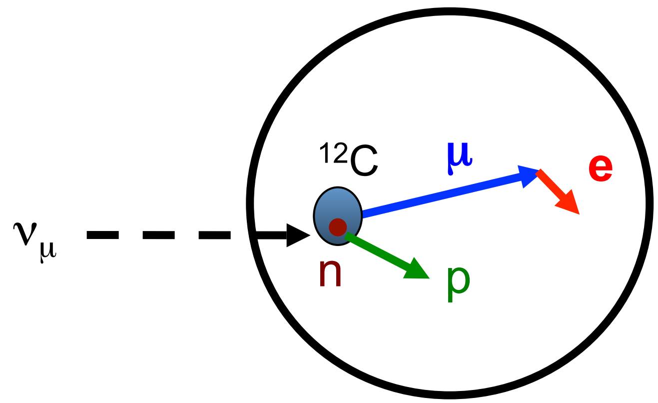
The MiniBooNE detector is a ~1kton mineral oil (CH_2) Cherenkov detector

12 m diameter, 1280 inner PMTs, 240 outer 'veto' PMTs





Selecting CCQE ν_μ interactions in MiniBooNE



Tag single muon events and their decay electron

- Events produce Cherenkov light recorded by PMTs as hits (charge, time)
- Two sets of hits separated in time (μ, e)
- Require 1st set of hits above decay electron energy endpoint, 2nd set of hits below
- Endpoint of 1st track consistent with vertex of 2nd track
- Also require events within fiducial volume, beam timing and data quality selections, minimal veto activity

Comparisons of Sci, MiniBooNE

Momentum resolution, angular resolution were similar

- ~10% dE/E on SciBooNE, MiniBooNE muon neutrino candidates

MiniBooNE's size provided impressive statistics for cost (~1-2M$)

- SciBar detector cost ~1.2M$
- Located closer (~25x flux) but ~50x smaller
- Beam time matters, SciBooNE ran for 1/5th the time

SciBooNE (MiniBooNE) could select muon candidates with momentum 100 (250) MeV/c

- Significant NC backgrounds due to entering events
- MiniBooNE's threshold due to removal of decay electron events

Comparisons of Sci, MiniBooNE

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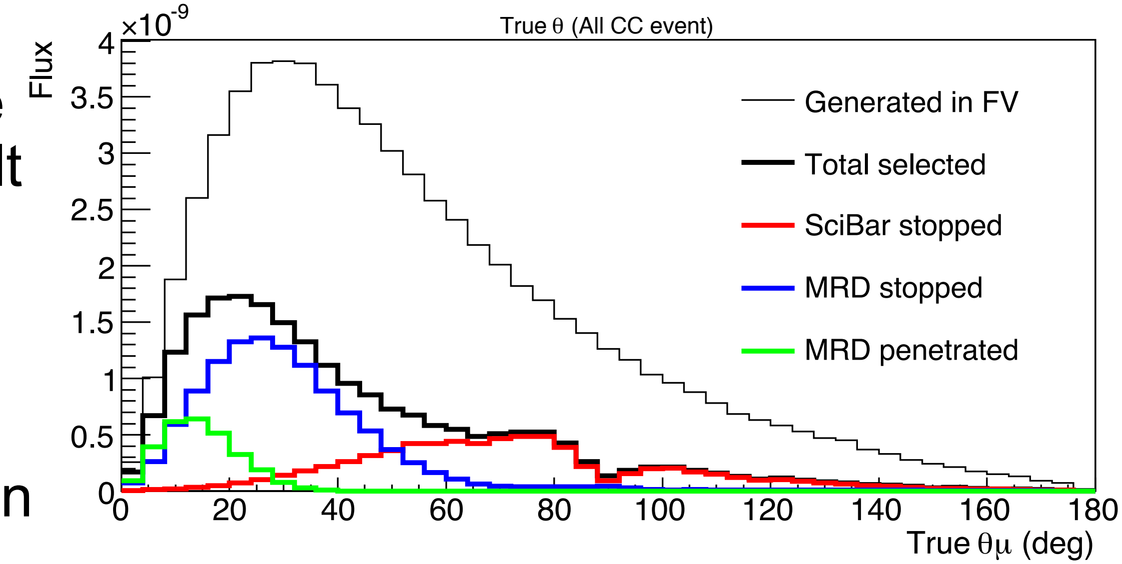
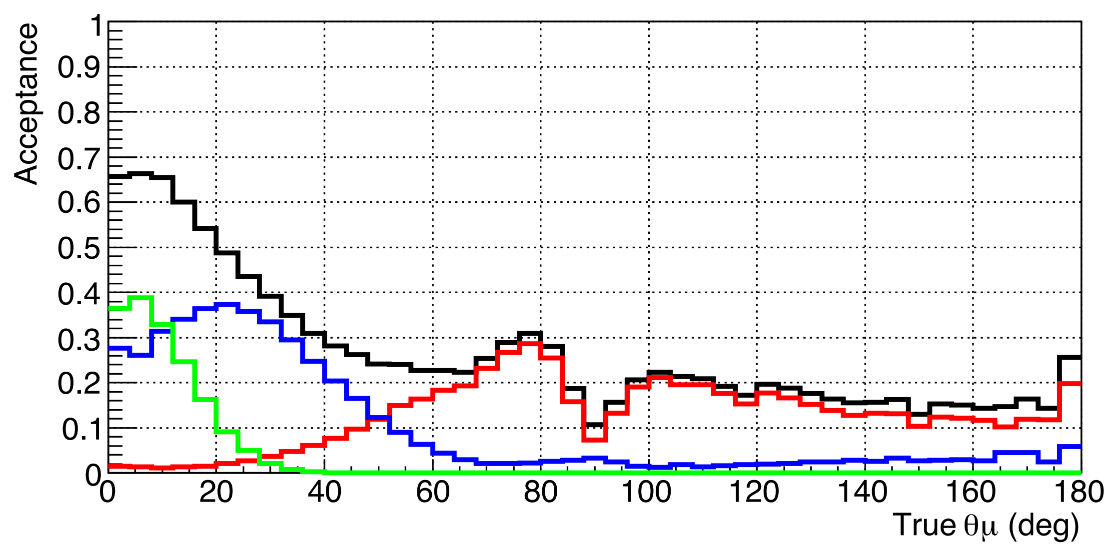
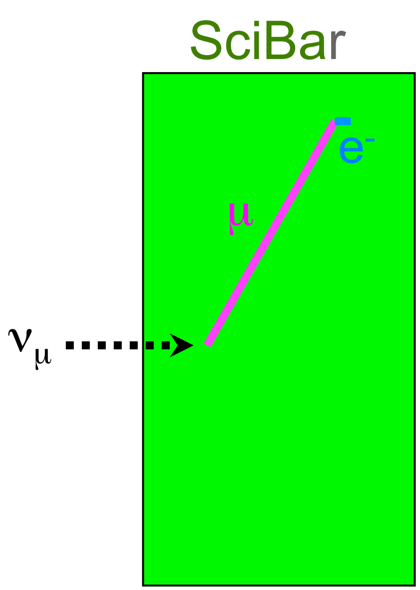
4π acceptance

- Tracking detectors may have geometries where it is difficult to reconstruct (high angles ~parallel to orientation of bars/readout)
- "SciBar stopped" sample includes muons entirely within scintillator



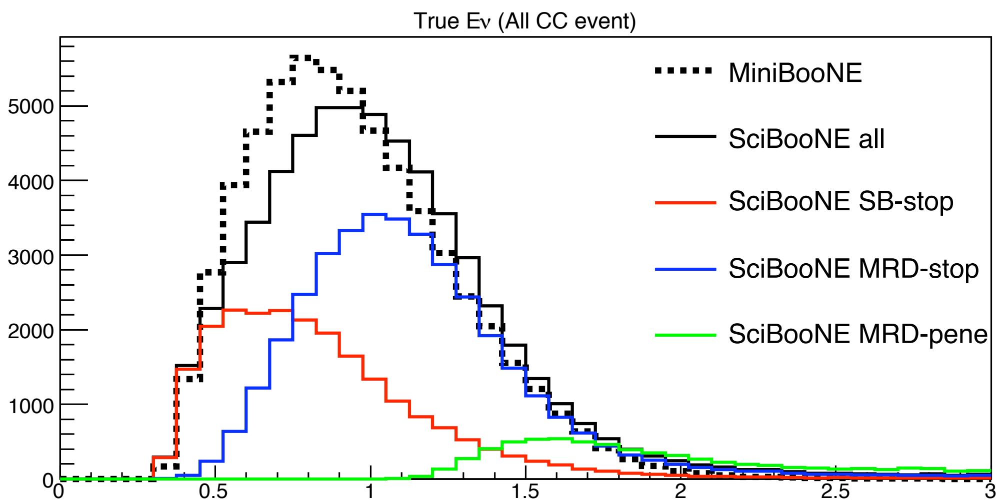


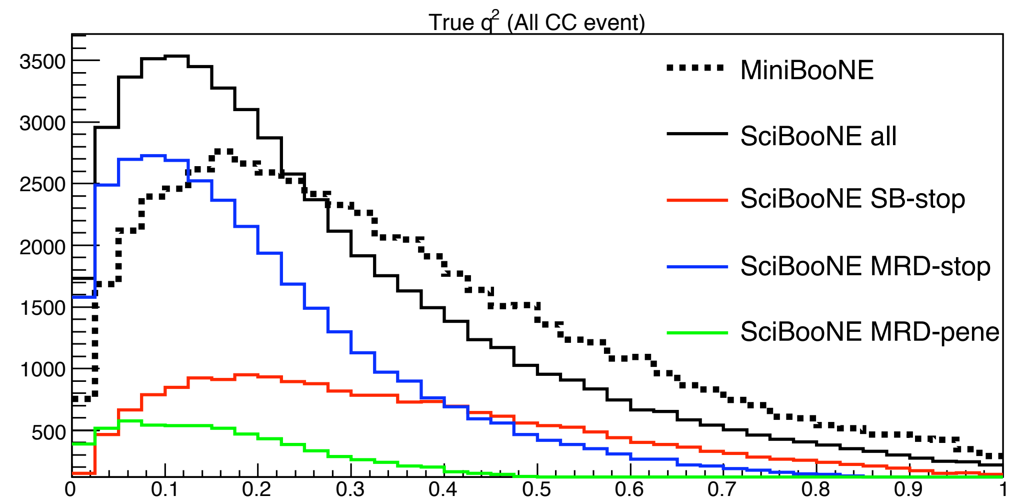


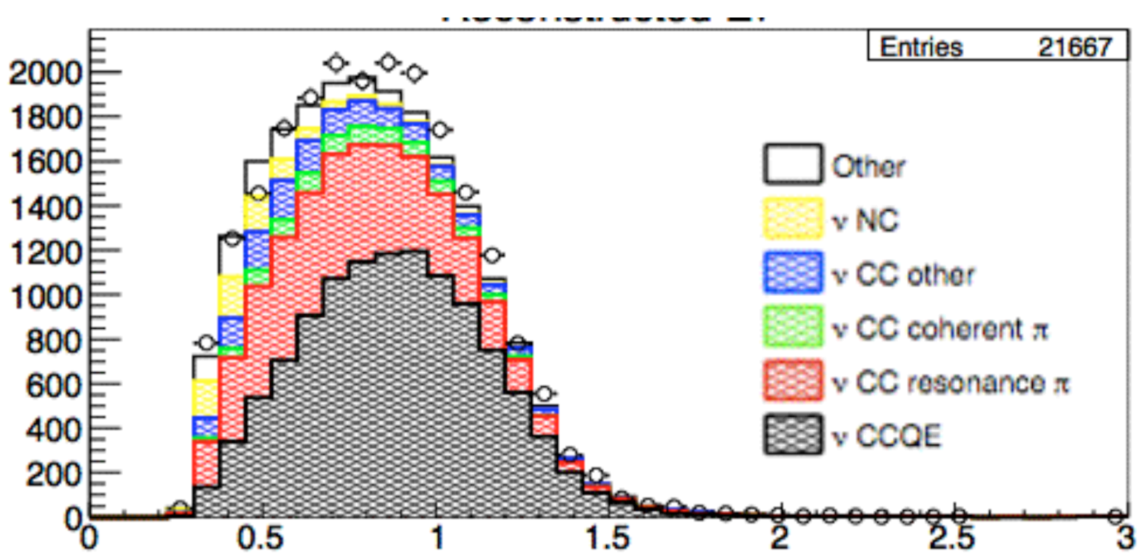
Acceptance, selection comparison

SciBooNE samples cover relevant flux (E_ν) and cross section (Q^2) for MiniBooNE

- SciBar stopped: 49% CCQE, 30% CC1π; MRD stopped: 54% CCQE, 34% CC1π
- MiniBooNE: 74% CCQE, 25% CC1π







MRD stopped sample vs. Ereco

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

Joint disappearance analysis

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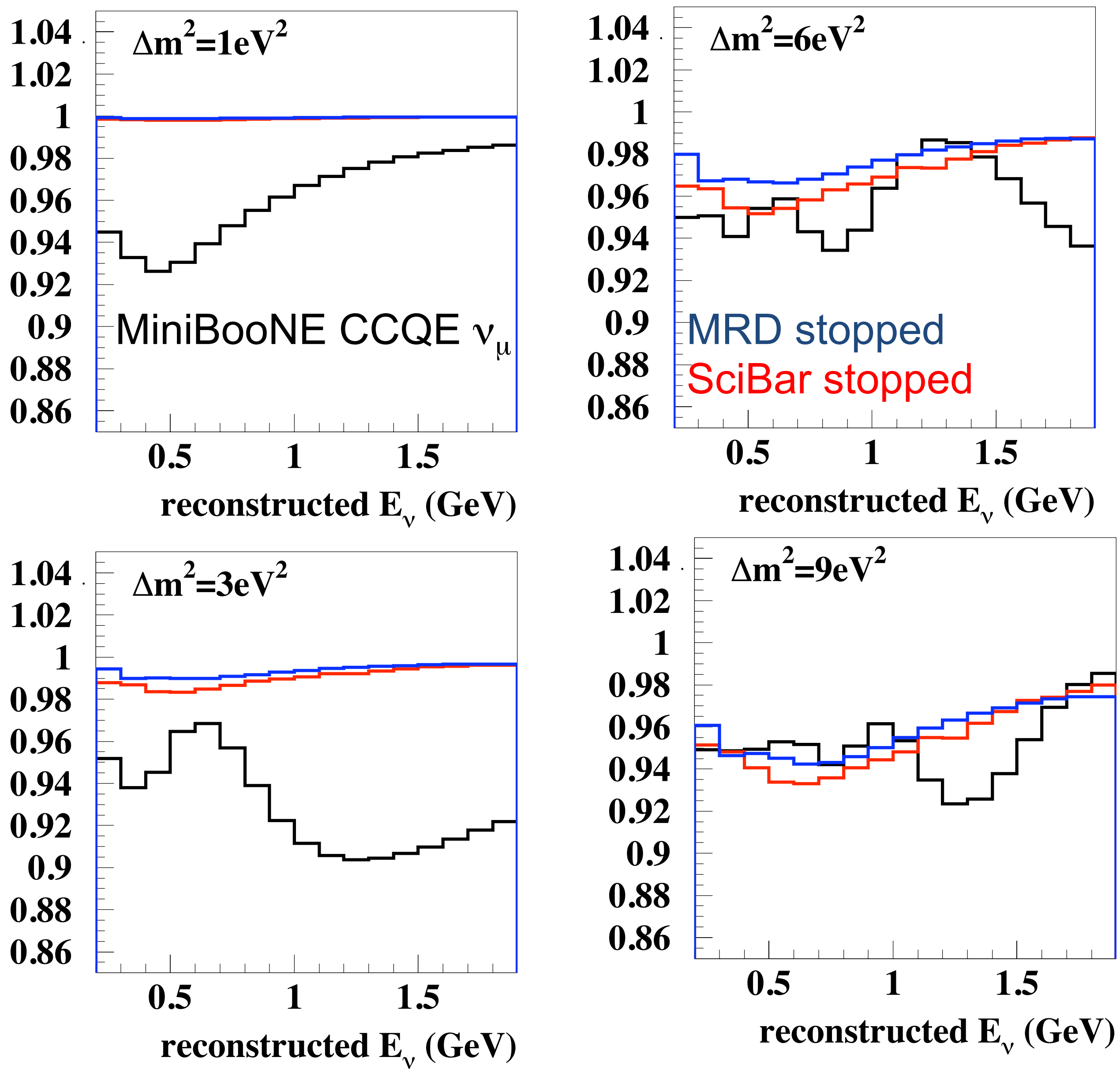
Disappearance due to sterile state (3+1) observable as a deficit and distortion to neutrino energy spectrum

Includes:
- Oscillation of all CC ν_μ interactions at SciBooNE and MiniBooNE
- Distribution of distance travelled by neutrinos (L)

	Mean L
SciBooNE	~76m
MiniBooNE	~520m

~50m spread in L due to finite decay volume

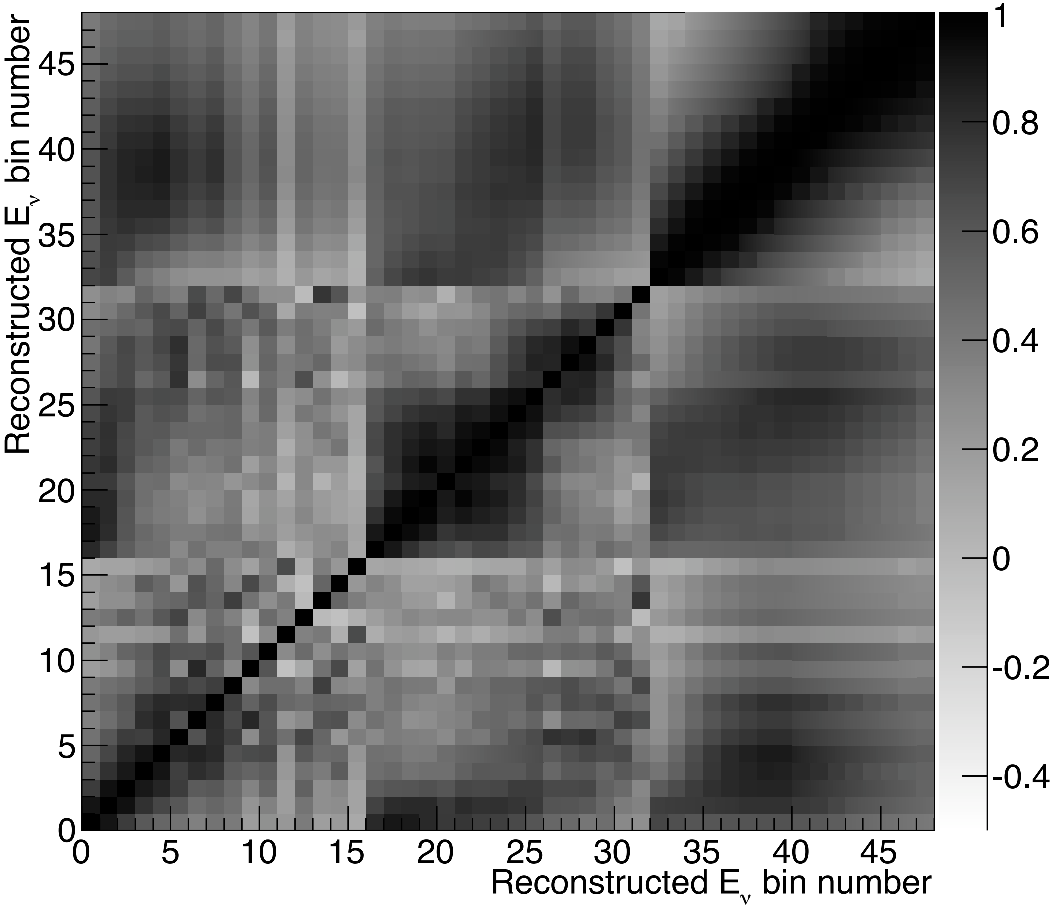
Ratio of oscillated spectrum to unoscillated ($\sin^2 2\theta = 0.10$)



Effect of SciBooNE data constraint

Significant correlations between SciBooNE and MiniBooNE energy bins

- (i=0-15 SciBar stopped, 16-31 MRD stopped, 32-47 MiniBooNE



Strong correlations from:

- Similar flux at MiniBooNE and SciBooNE
- Similar event composition between SciBooNE, MiniBooNE

A modification to the CCQE cross section (MAQE effective on C) affects both detectors simultaneously, oscillation affects the two differently

Any systematics (e.g. NC backgrounds) which affect one sample but not the other reduce the power of the constraint and correlations

Effect of SciBooNE data constraint

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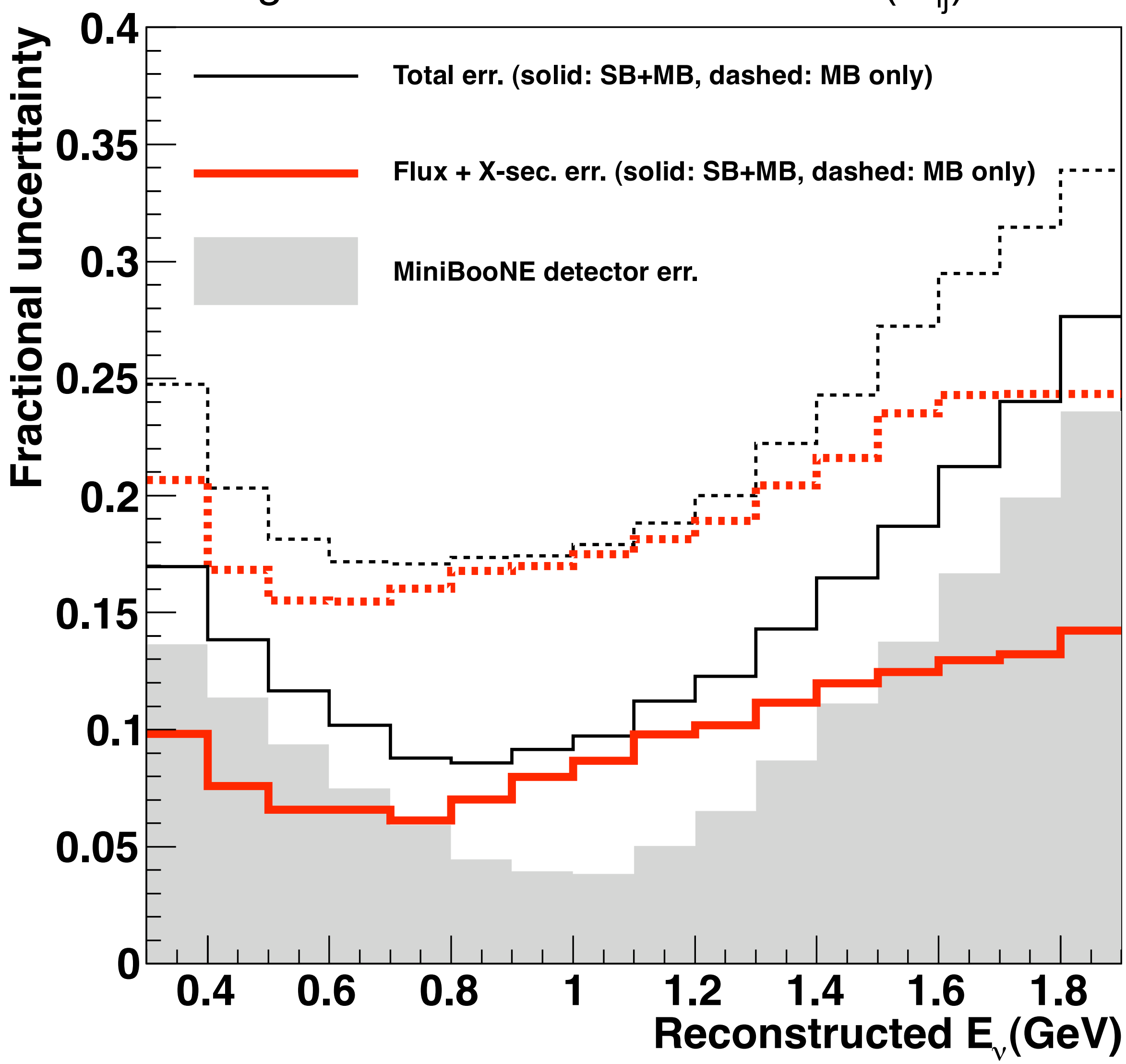
Diagonal elements of error matrix (M_{ij})



Rate constraint reduces flux and cross section uncertainties by approximately a factor of 2

Results of ν_μ disappearance fit

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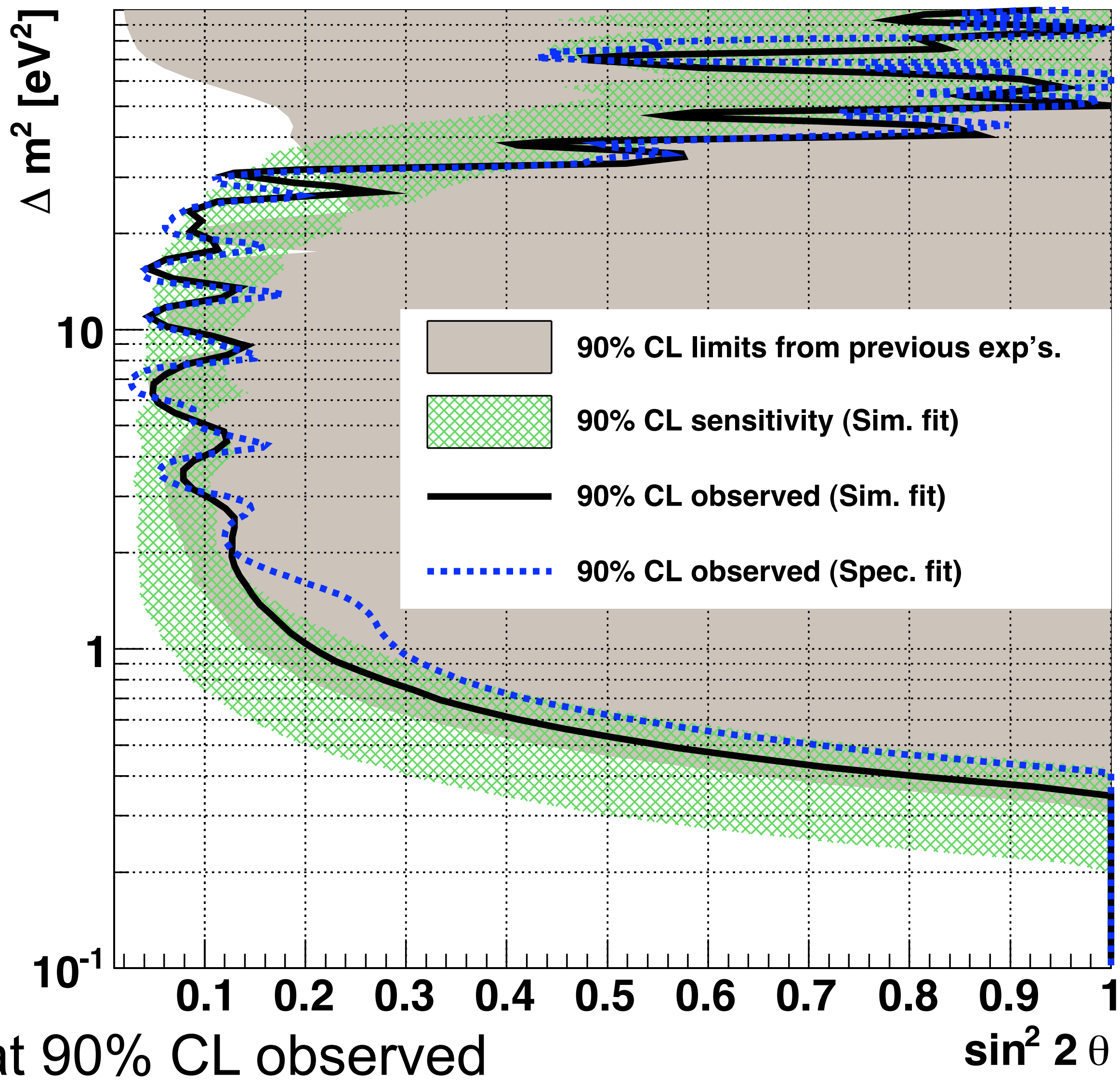
Limits for simultaneous fit (black consistent with alternate spectrum fit(blue)

Green hatched region indicates 68% of 90%CL limits to fake data with no underlying oscillation

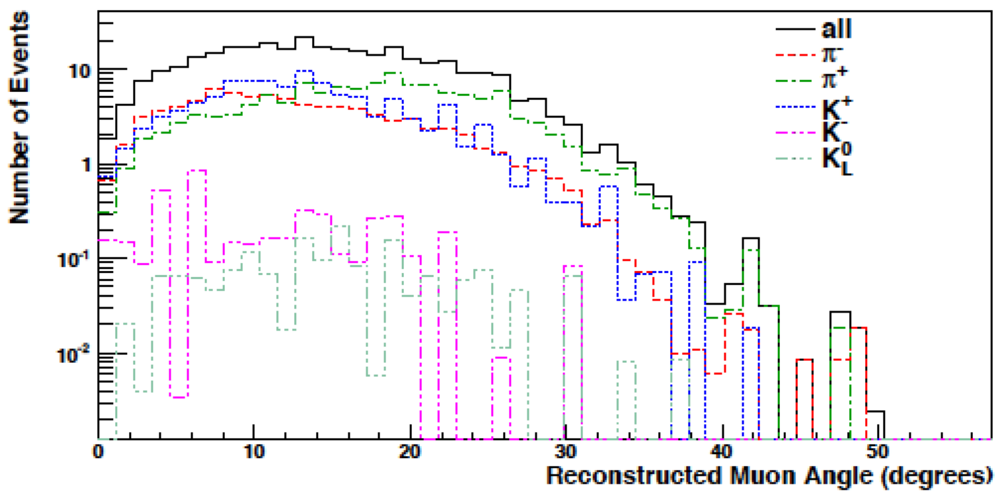
Average of these limits is sensitivity, comparable for both analysis methods



No disappearance at 90% CL observed
(Phys. Rev. D85, 032007 (2012)
Similar analysis performed with antineutrinos
(Phys. Rev. D86, 052009 (2012))

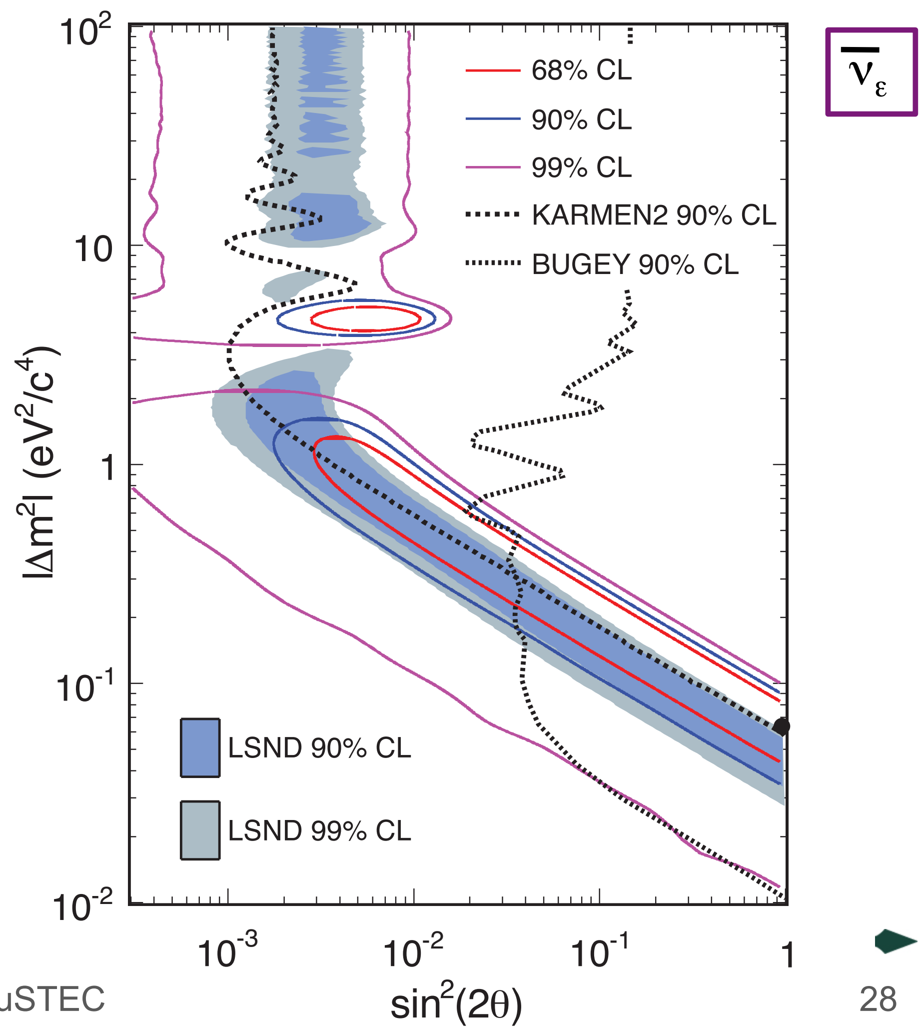
Joint neutrino/antineutrino appearance MiniBooNE result benefitted from SciBooNE information, constraint

- Measurement of K+ reduced intrinsic ν_e component using selected SciBooNE 1, 2, 3 track samples



Phys. Rev. D 84, 012009 (2011)

Phys.Rev.Lett.105:181801,2010



T2K oscillation analyses

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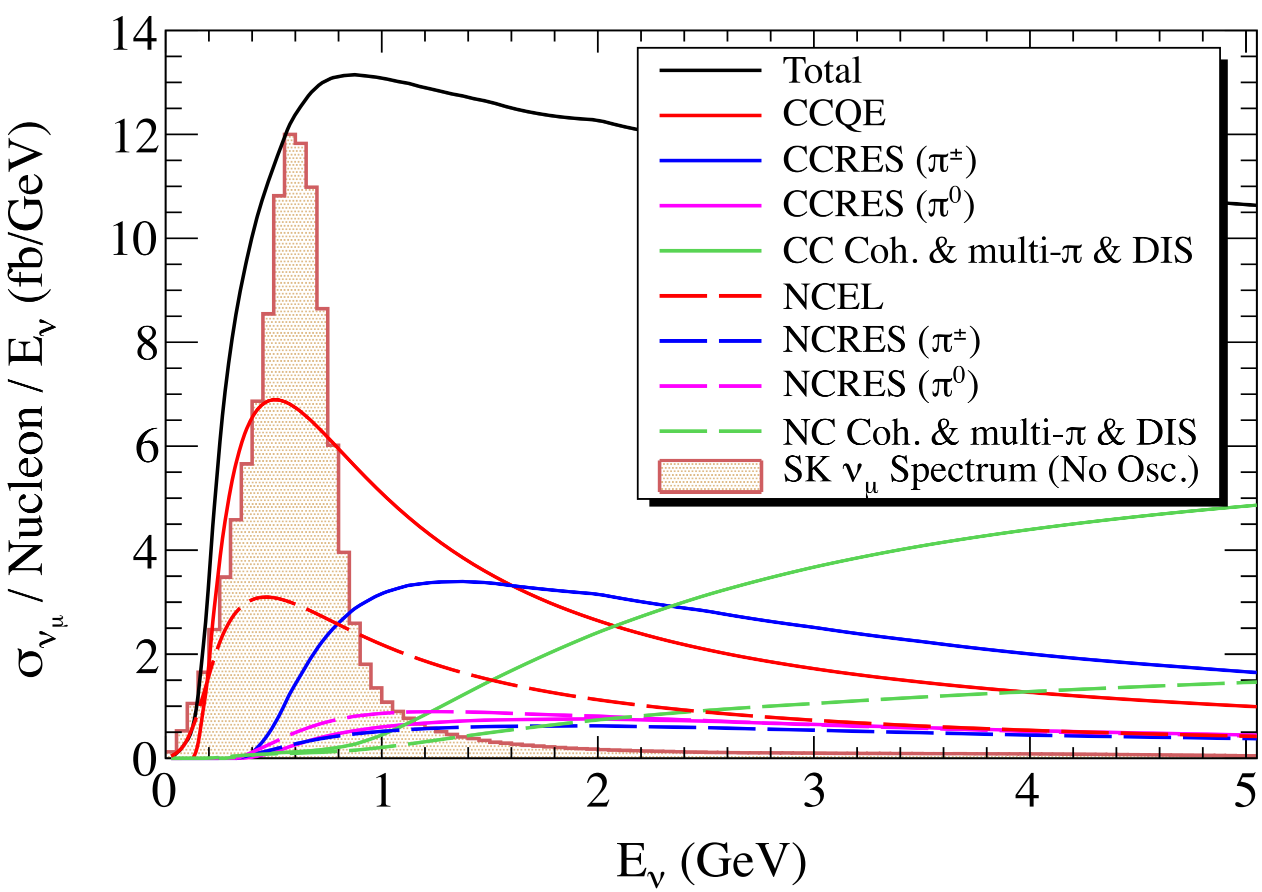
``Long baseline" (L~ 295km) neutrino experiment designed to measure ν_e appearance (θ_{13} and more) and ν_μ disappearance (Δm^2_{32}, θ_{23})

Infer neutrino energy from CCQE (dominant process for T2K's flux) to determine oscillation parameters



T2K event selection

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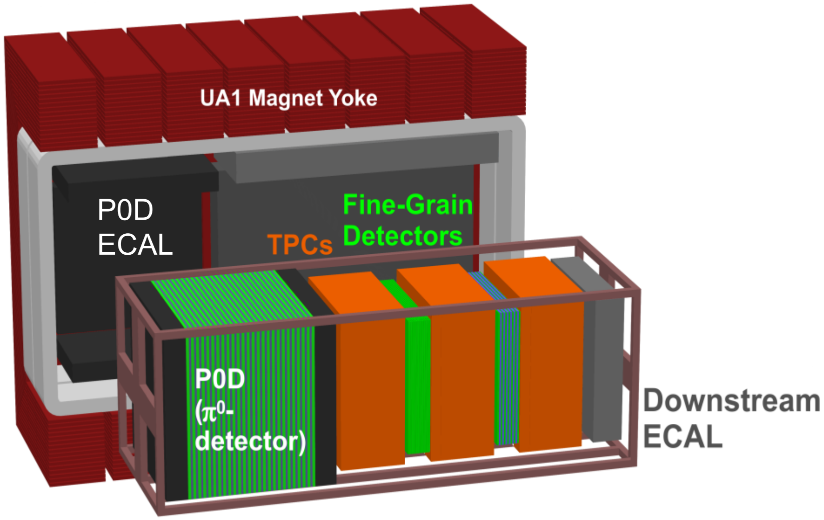
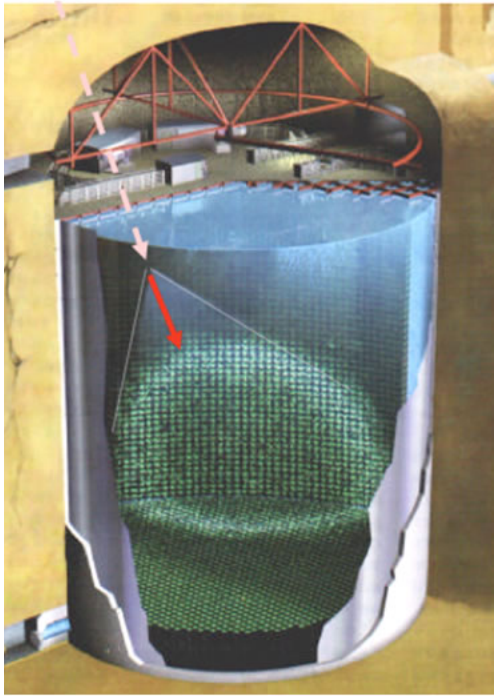


Select CC ν_μ candidates prior to oscillations in an off-axis tracking detector (ND280)

- Neutrino interacts on scintillator tracking detector, muon tracked through scintillator and TPCs
- Muon momentum from curvature in magnetic field
- Events separated based on presence of charged pion in final state

Select CC ν_e and ν_μ candidates after oscillations, in a 50kton water Cherenkov detector (Super-Kamiokande)

- Select single ring; determine lepton flavor from ring shape and topology
- Reject CC nonQE interactions using ring multiplicity and decay electron tagging
- For the ν_e selection, NC events with π^0 removed based on invariant mass



T2K event selection at ND280

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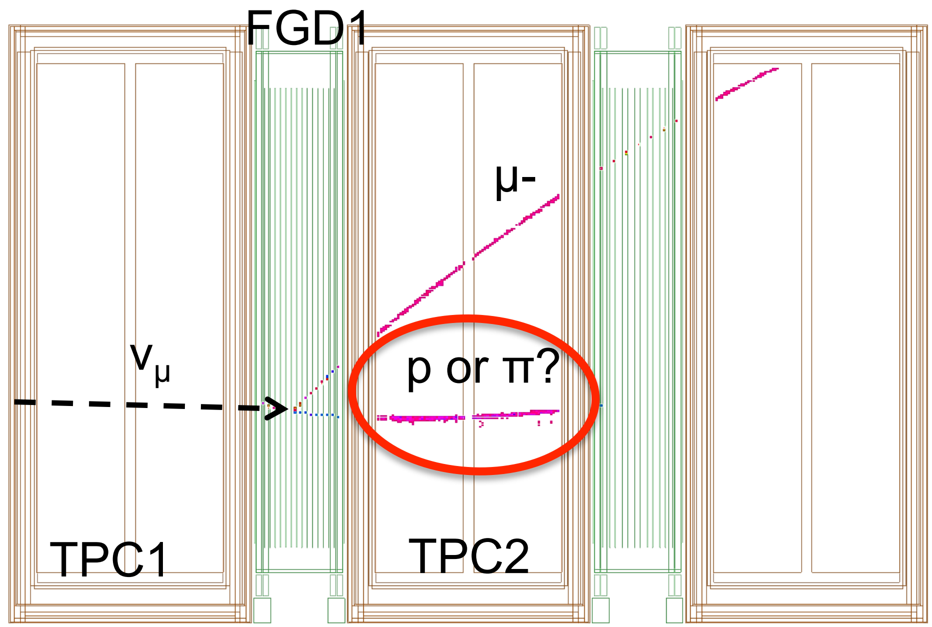
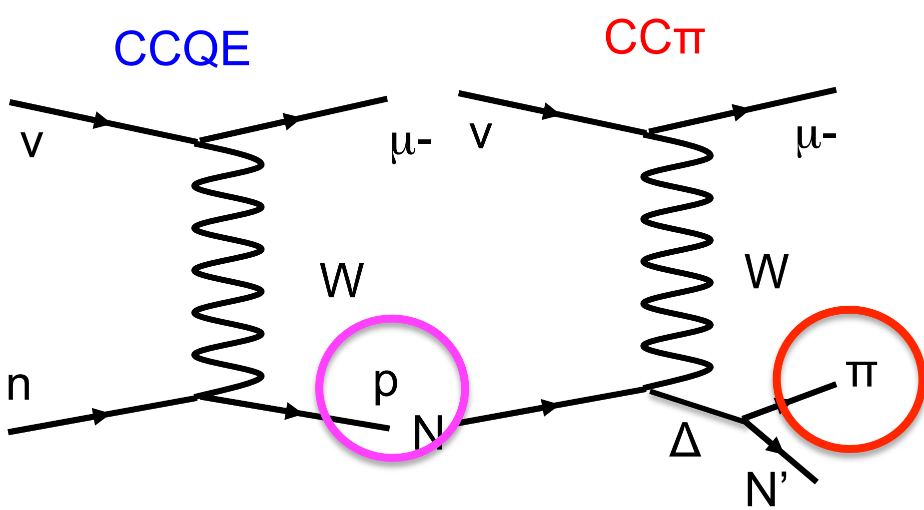
Measure unoscillated ν_μ(CC) rate

1. Neutrino interaction in FGD1
- Veto events with TPC1 tracks
- Events within FGD1 fiducial volume

2. Select highest momentum, negative curvature track as μ^- candidate
- Energy loss of the track in TPC also consistent with muon hypothesis





Further separate sample into three categori
based on final state: CC0π / CC1π / CC other
to increase sensitivity to cross section:
- FGD track: decay electron / π-p dE/dx
- TPC-FGD matched track: π-p dE/dx
- Electrons identify π^0 (often from DIS events)

Near vs. Far selection (2012 analysis)

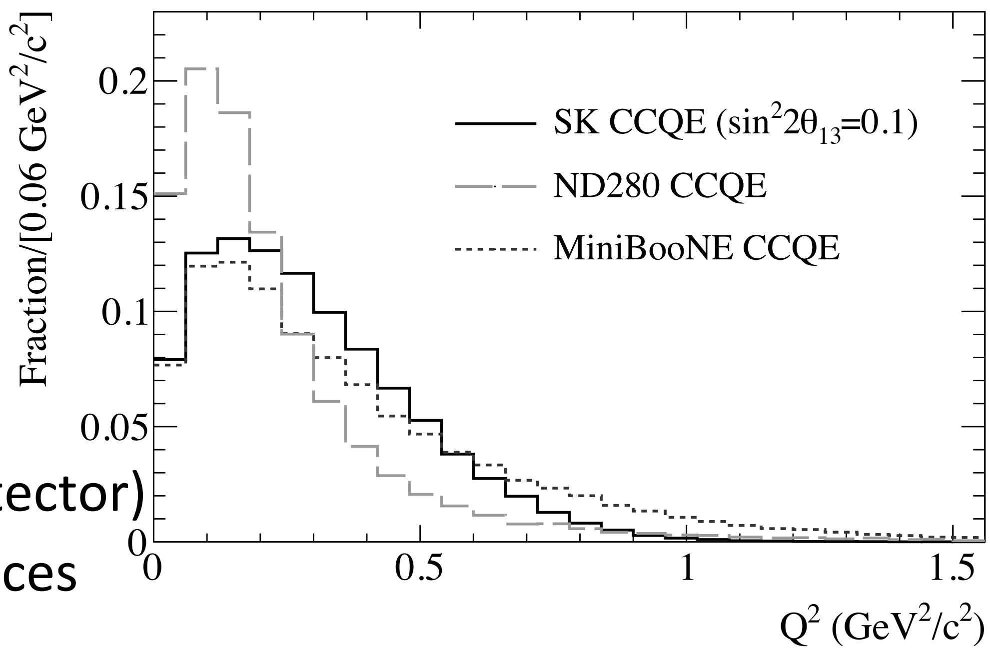
Interaction Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e Bgnd.
CCQE	76.6%	14.6%	85.8%	45.0%
CC1π	15.6%	29.3%	13.7%	13.9%
CC coh.	1.9%	4.2%	0.3%	0.7%
CC other	4.1%	37.0%	0.2%	0.7%
NC	1.5%	5.3%	-	39.7%

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

Caveats: 2012 selection, does not include recent NC fitter improvements

Acceptance: ND sample is currently forward going (small angle, low Q^2)

- Motivates use of external data with larger Q^2 (MiniBooNE, 4π Cherenkov detector)
- Alternate nuclear models (C, O differences



Use of near detectors on T2K

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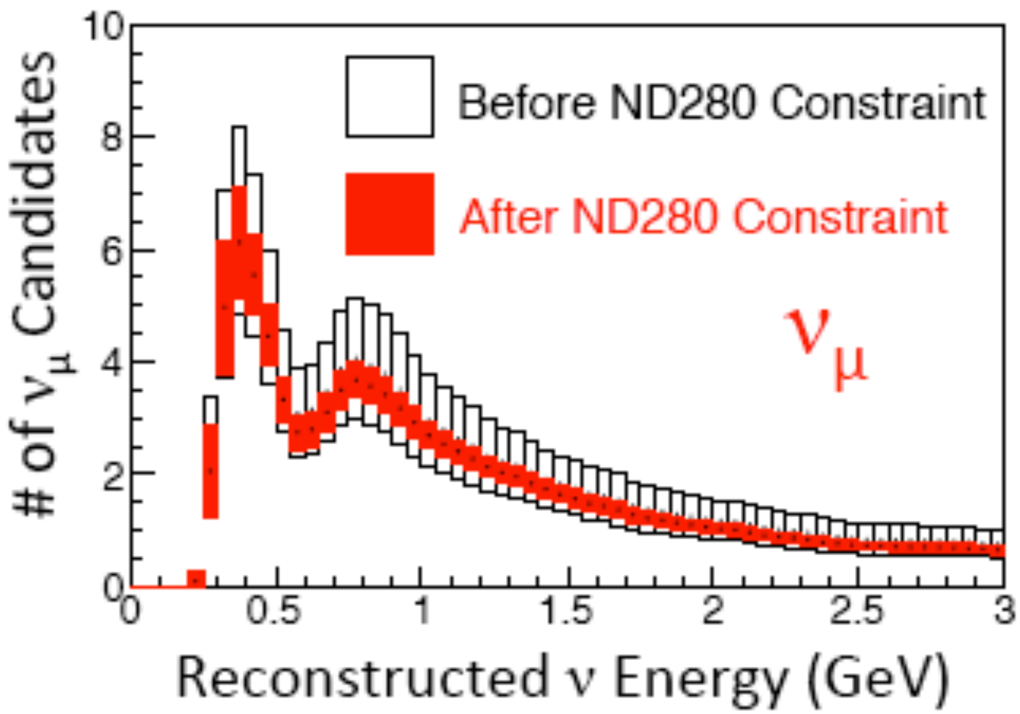
Expected number of events at the far detector is tuned based on near detector information. Near detector also provides a substantial constraint on the uncertainties of ν_e and ν_μ events:

$$FD(\nu_e) = \boxed{\Phi \times \sigma} \times \epsilon \times P(\nu_\mu \rightarrow \nu_e)$$
$$ND(\nu_\mu) = \boxed{\Phi \times \sigma} \times \epsilon_{ND}$$

uncertainties for ν_e appearance	ν_e sig+bkrd	ν_e bkrd
ν flux+xsec (before) after ND constraint	(25.9%) ±2.9%	(21.7%) ±4.8%
ν unconstrained xsec	±7.5%	±6.8%
Far detector	±3.5%	±7.3%
Total	(27.2%) ±8.8%	(23.9%) ±11.1%



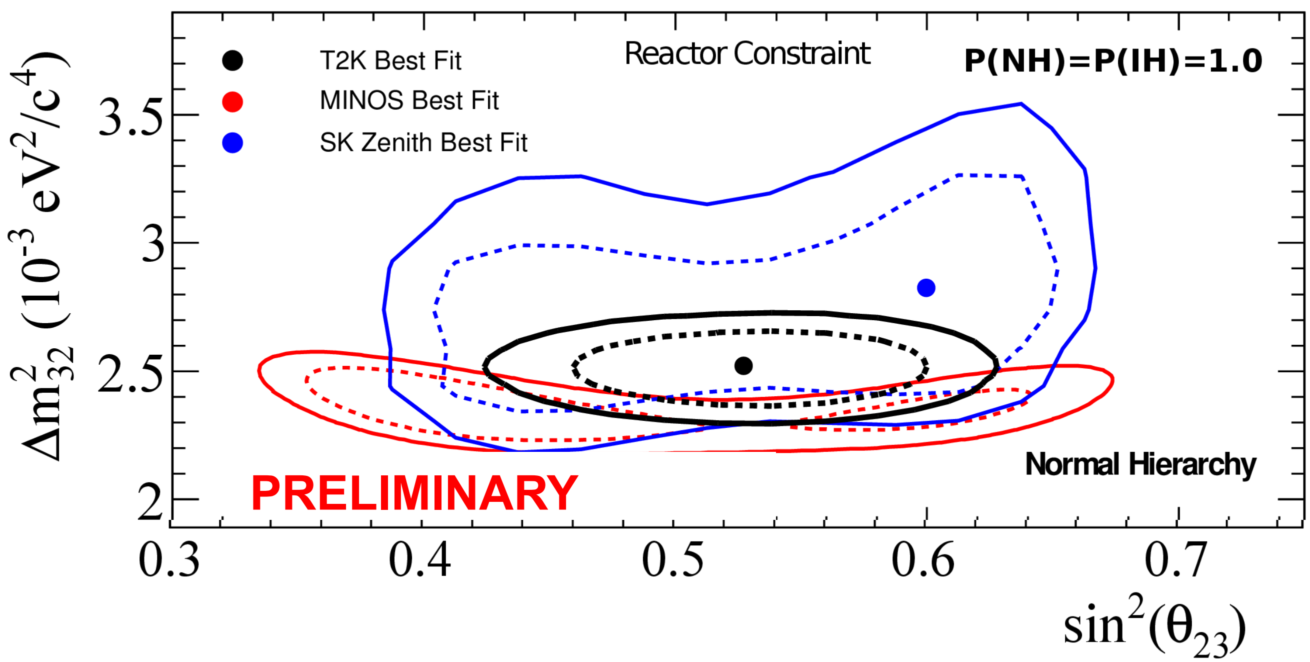
After ND: expect 21.6 ν_e candidates (background only: 4.92)

After ND: expect 124.8 ν_μ events

T2K joint ν_μ-ν_e fit results: Δm^2_{32}, $\sin^2\theta_{23}$

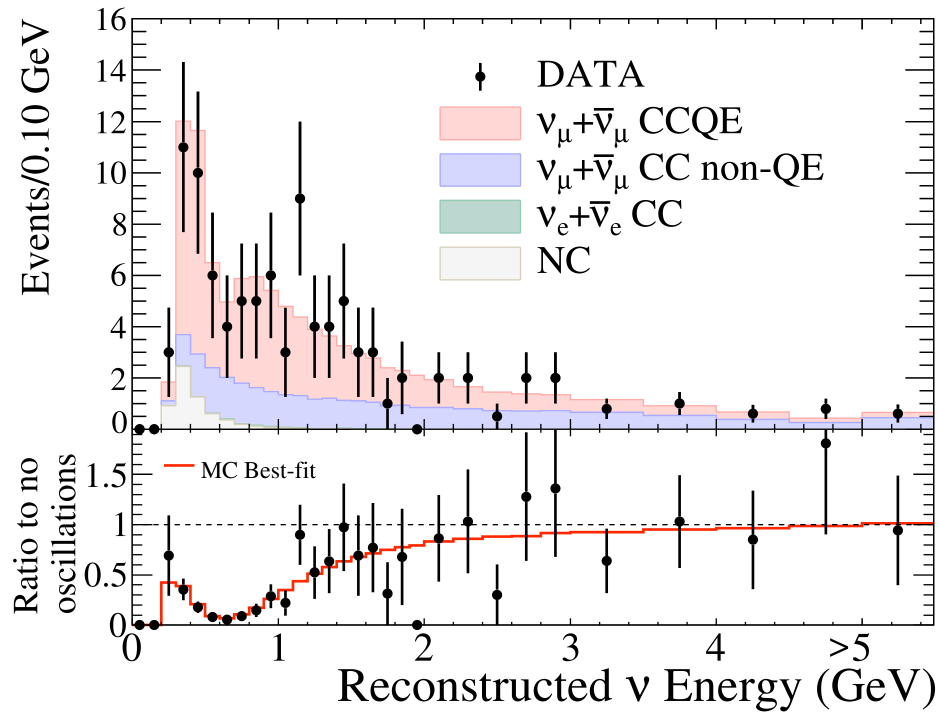
Markov Chain Monte Carlo-based analysis

- Simultaneous fit to near detector ν_μ, far detector ν_μ, ν_e samples
- Includes correlations between ν_μ, ν_e samples,



T2K data favors maximal disappearance

- Provides best constraint on θ_{23} to date, consistent with maximal (45°) mixing
- Includes NC, CC backgrounds which feed into oscillation dip (and determination of θ_{23})



T2K systematic uncertainties

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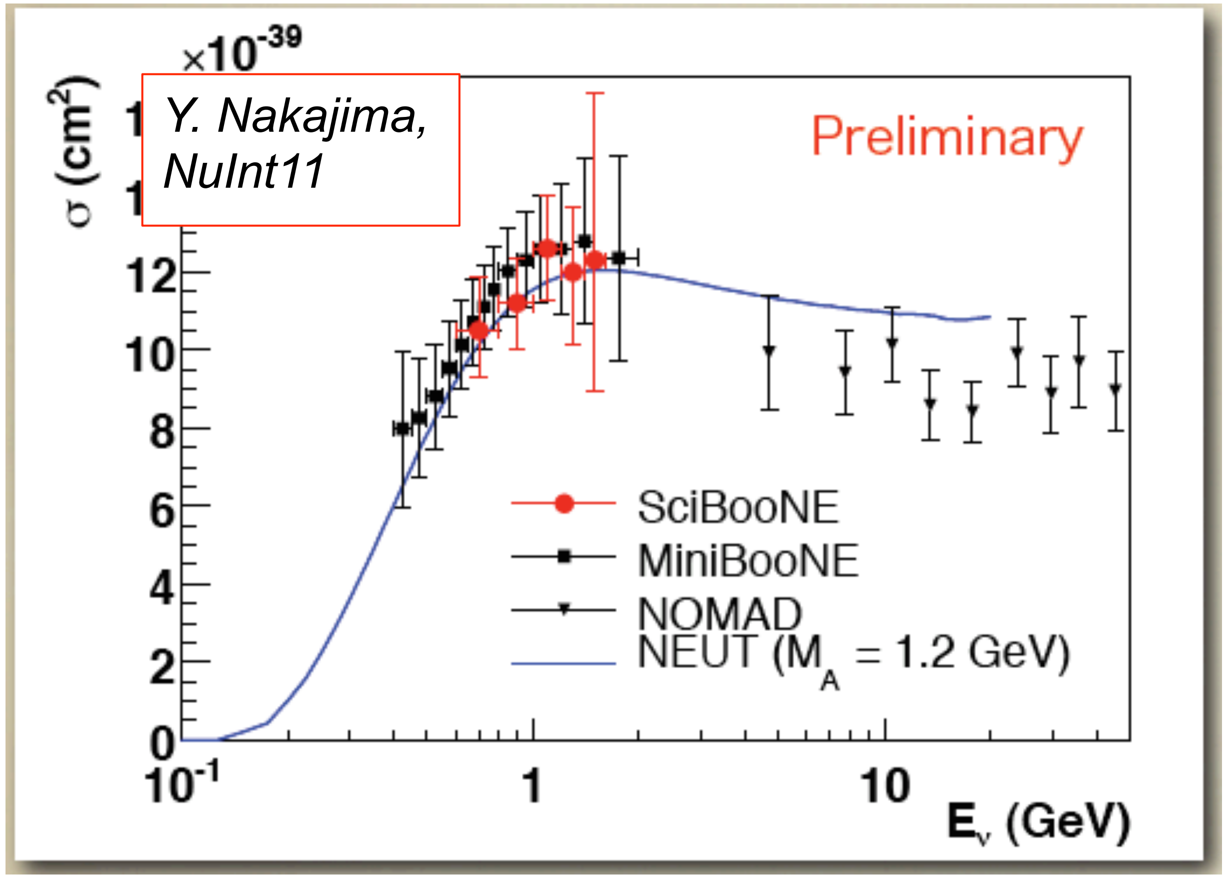
Uncertainties	ν_e sig+bkrd
ν flux+xsec (constrained by ND280)	±2.9%
ν xsec (unconstrained by ND280)	±7.5%
Far detector	±3.5%
Total	±8.8%



The largest systematic uncertainties currently on the T2K oscillation analyses are from uncertainties on the CCQE, CC1π neutrino interaction models

- Disagreements between models and existing neutrino experiment data (e.g. MiniBooNE, SciBooNE, NOMAD)
- Differences between new theoretical models and those currently used by T2K

Are we really measuring "CCQE"?

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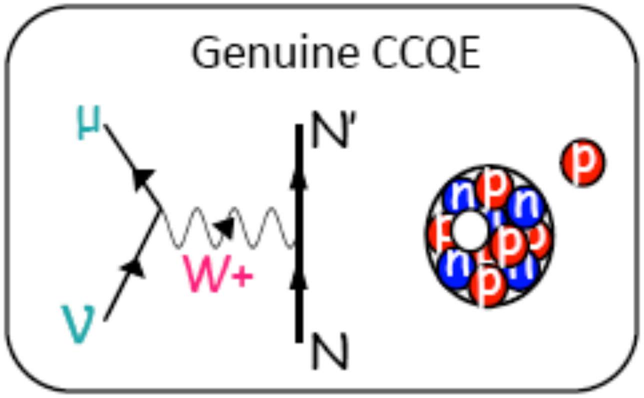

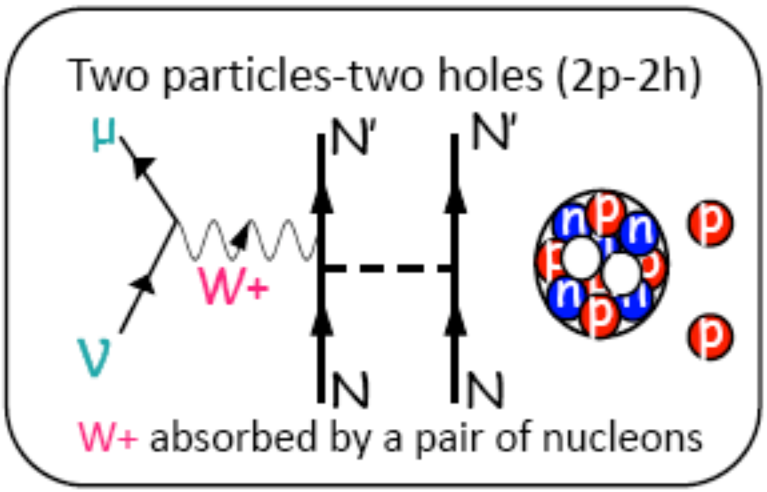

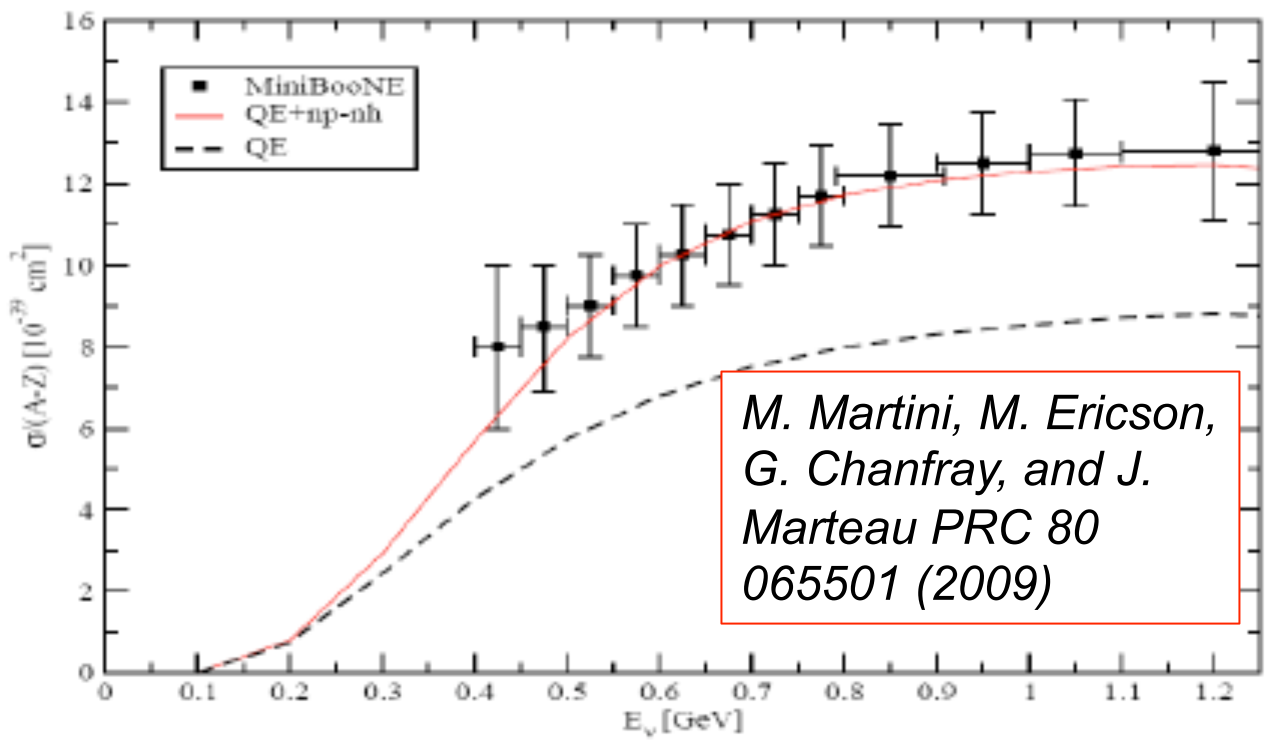

"Multinucleon" processes may explain the enhanced CCQE cross section observed by MiniBooNE, SciBooNE experiments

- Neutrino can also interact on a correlated pair of nucleons
- CCQE interaction simulated as interaction on a single nucleon

Near detector selection chosen to minimize dependance on relative efficiency of CCQE, multinucleon events

Complications of multinucleon models

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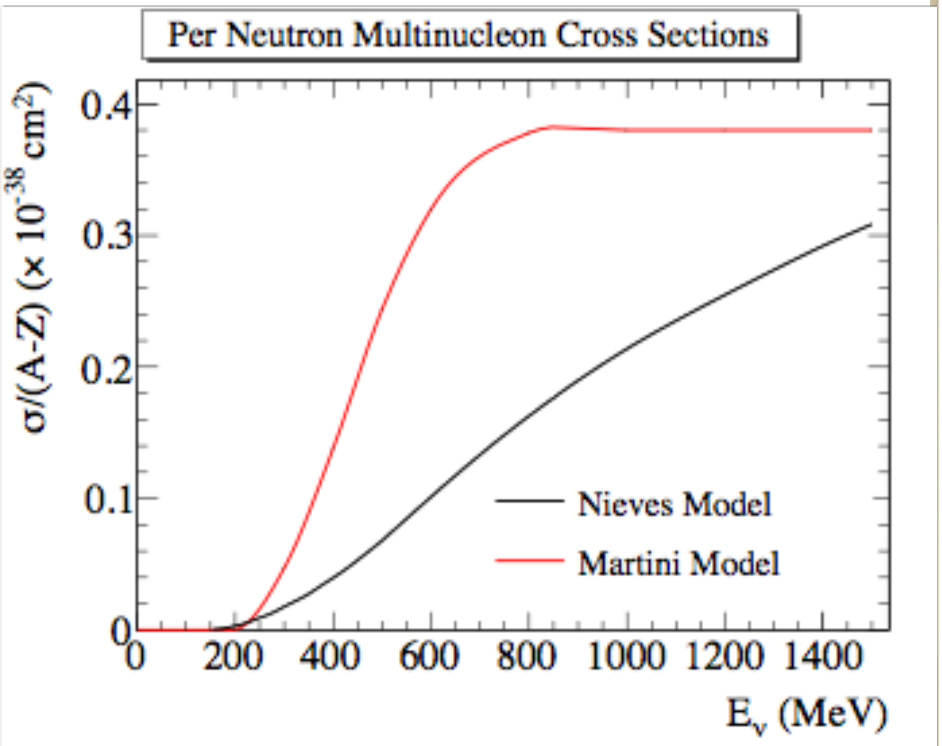

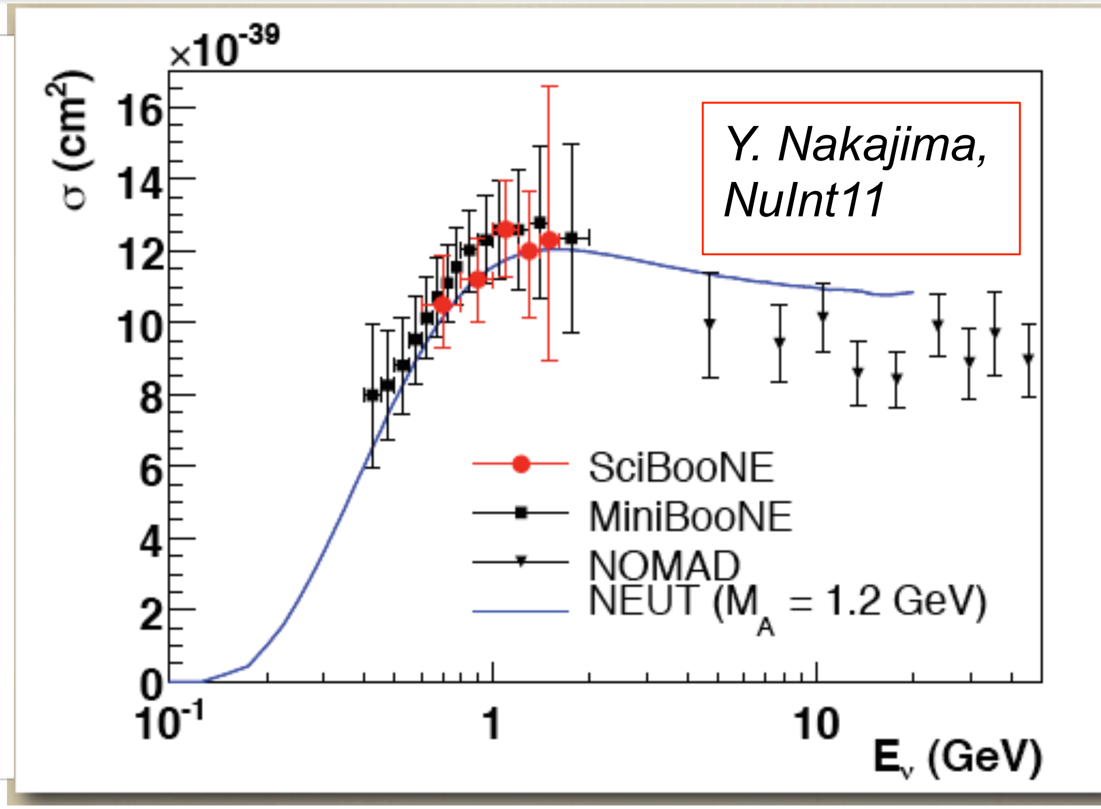

Significant differences between models?

- J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83 045501 (2011)
- M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80 065501 (2009)

Significant differences between experiments

- Enhanced cross section not seen by NOMAD, why?

What about hadronic information?

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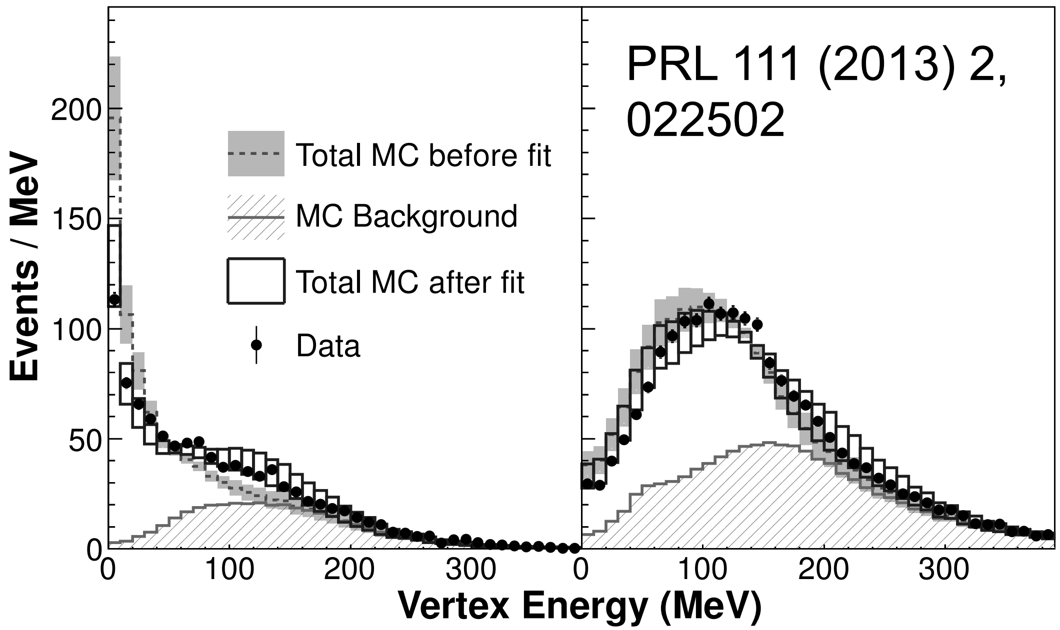

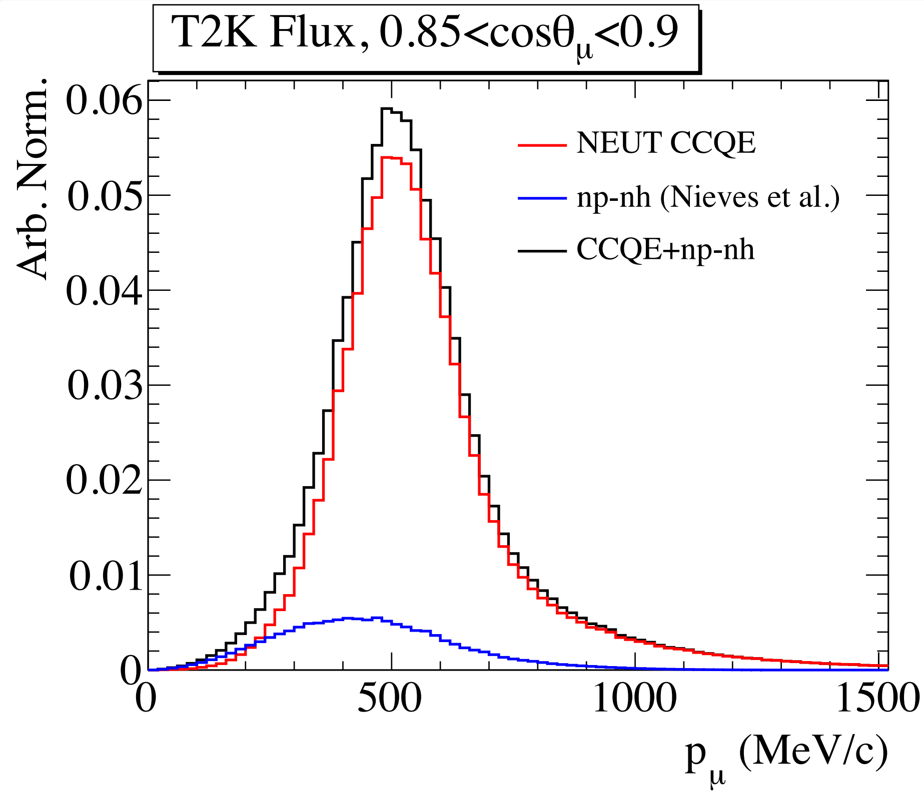

MINERvA observation of extra charge near vertex implies extra proton(s)

- Current experiments will measure this (T2K ND, MINERvA, NOvA ND) and proton kinematics

Challenge is multinucleon interactions are under flux peak, difficult to isolate a sample of events with (unknown) proton final state information

- Need to examine detector, FSI and cross section model carefully for signal and backgrounds to infer something about multinucleon models

What about hadronic information?

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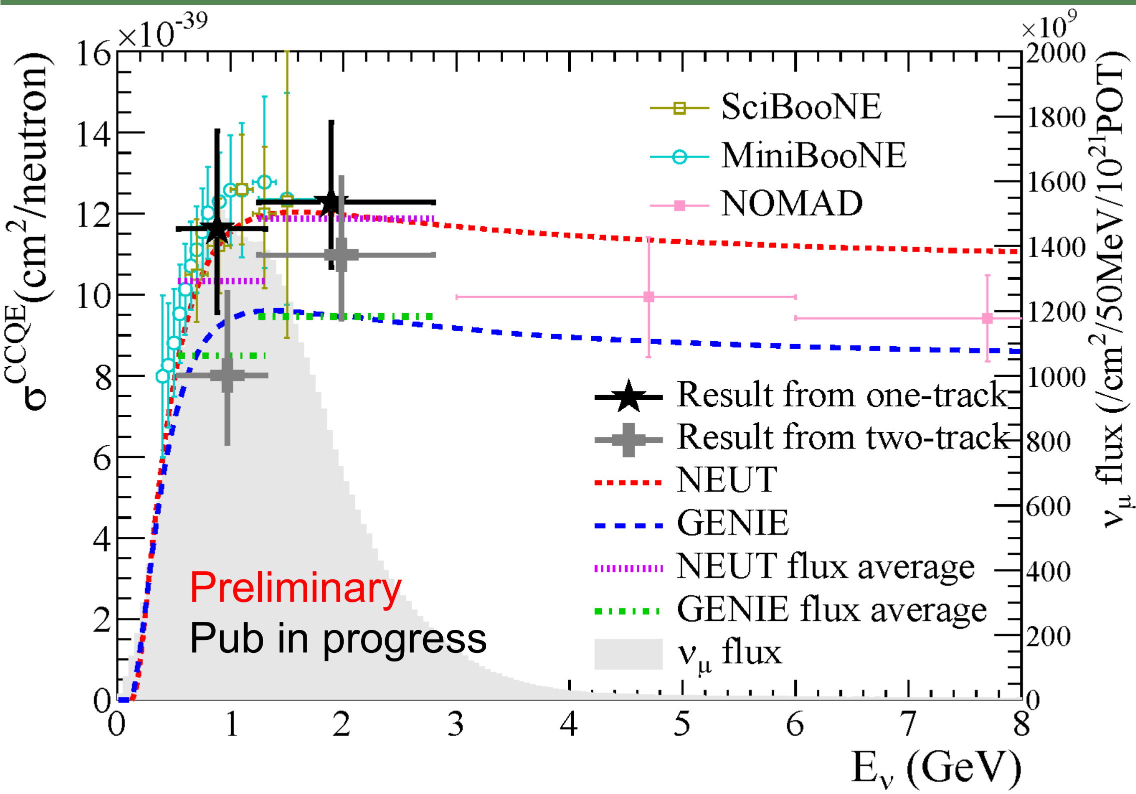

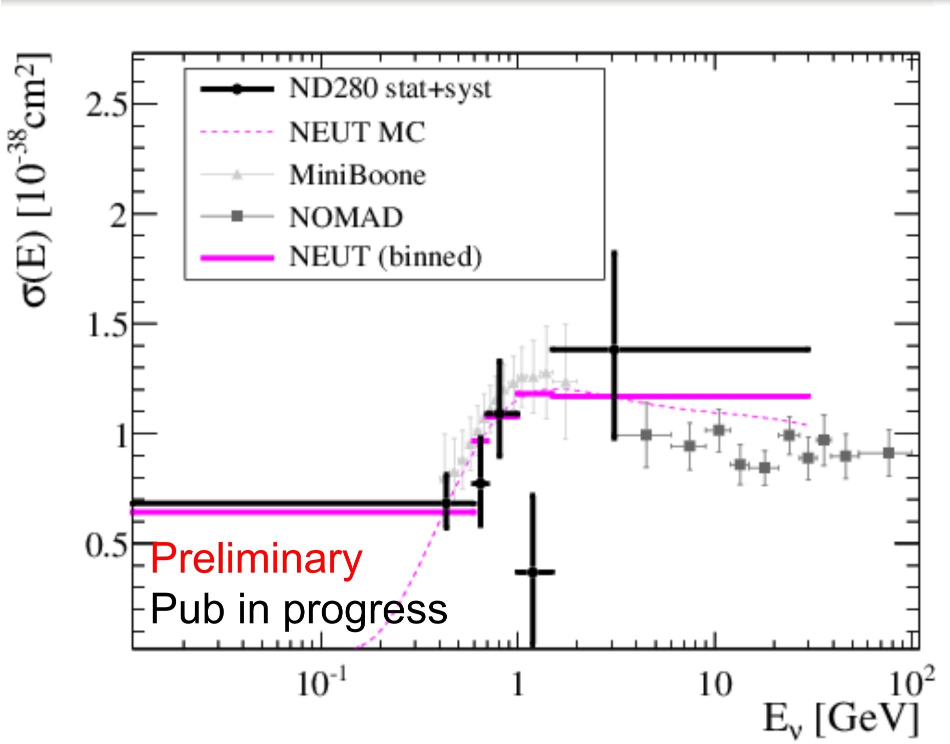

Difference in reported QE cross section does not depend on detection method

- Recent T2K results on-axis INGRID detector (left) and off-axis (right) also indicate increased cross section (~consistent with NEUT, MiniBooNE)
  - Not necessarily consistent with MINERvA, NOMAD at higher energies
- SciBooNE, INGRID detectors use both 1 track (muon) and 2 track (muon +proton track) selections
  - Threshold typically ~3 bars to perform tracking
  - May reject pions with dE/dx and/or decay electron tag

Multinucleon effect on T2K analysis

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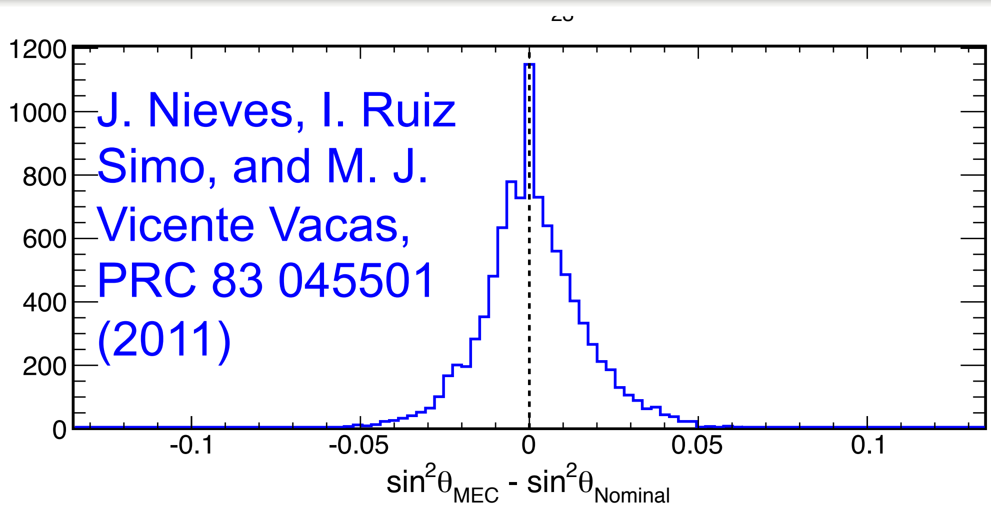
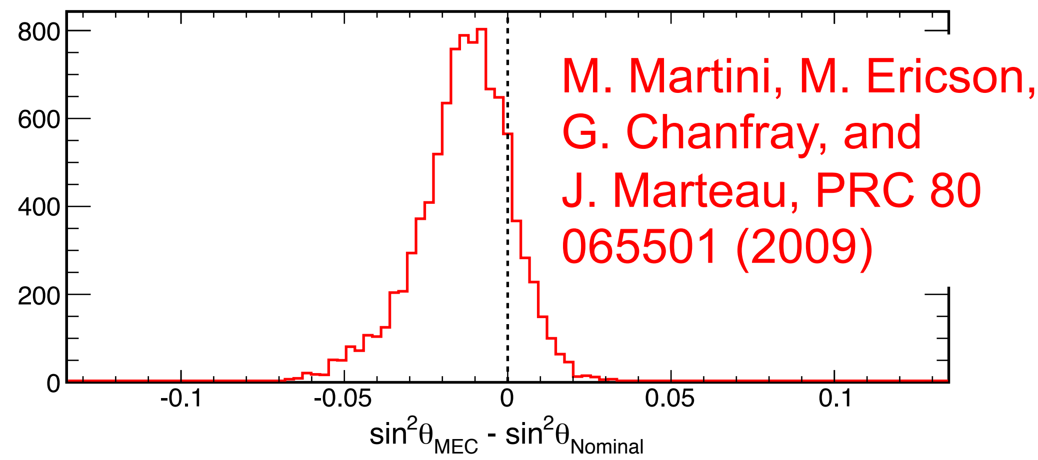




Tested possible bias on T2K disappearance measurement

- Generate fake data under flux, detector, cross section variations, and perform full oscillation analysis including ND constraint
- For each fake data set, compare fitted θ_{23} with and without a 2p2h model present

Nieves et al model: 0.3% mean, 3.2% RMS

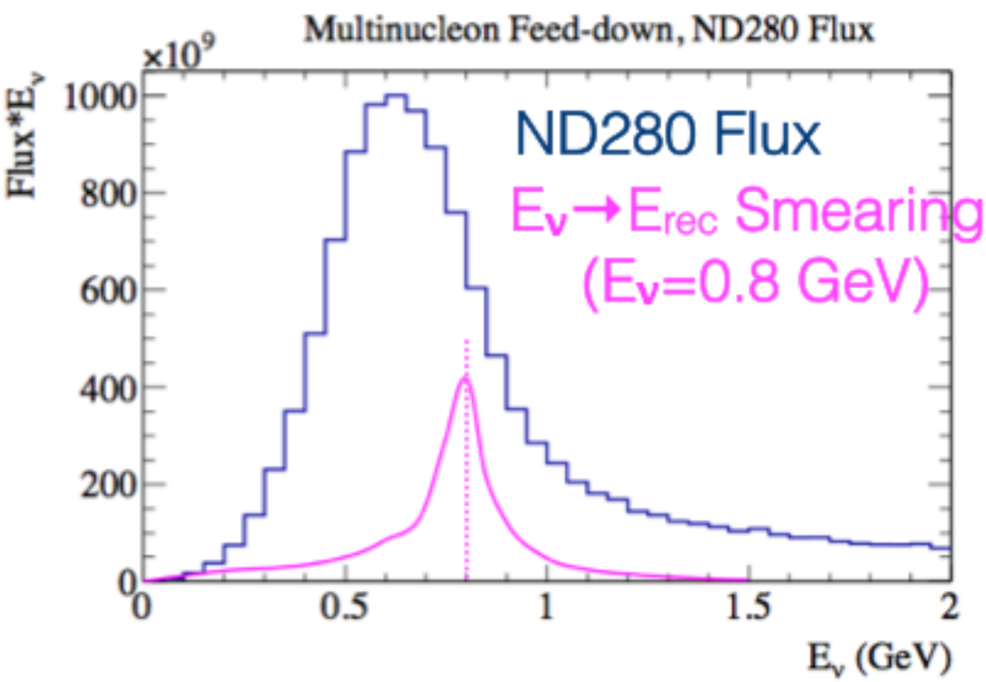
“increased Nieves” = Martini model: -2.9% mean, 3.2% RMS

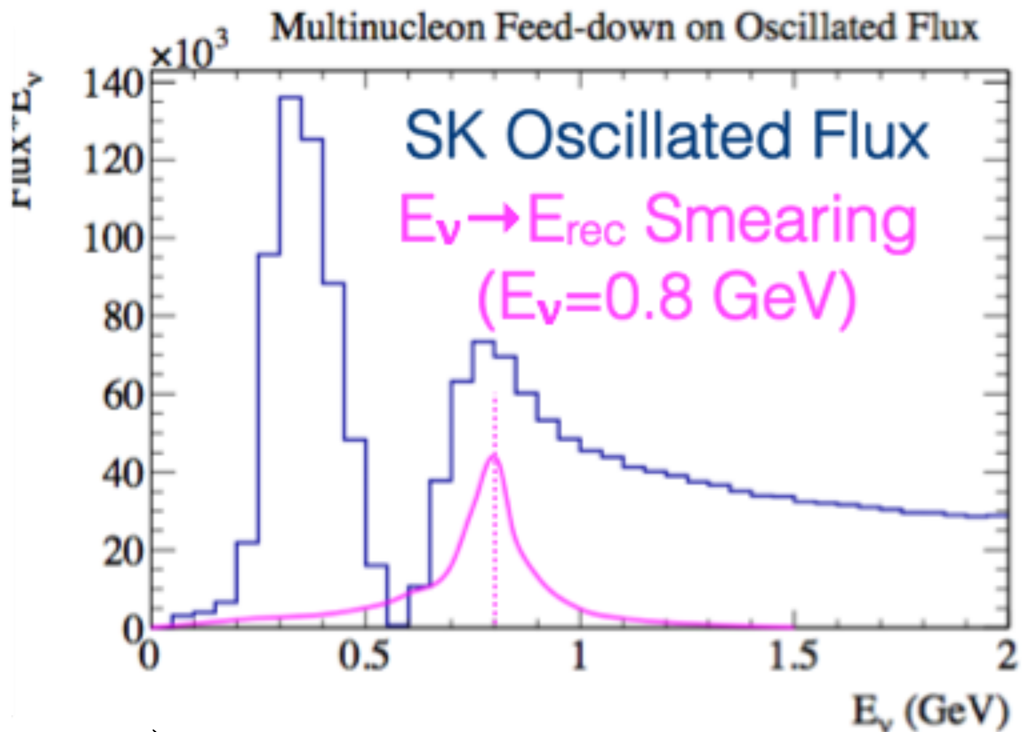
Significant relative to current systematic uncertainty on disappearance analysis (vs. 4.9% non-cancelling cross section uncertainty, 8.1% total)

Important for future long baseline program (1-5% uncertainties)

Limitations of current ND constraints

Cross section model couples through the different fluxes measured by ND and FD





$$FD(\nu_e) = \Phi \times \sigma \times \epsilon \times P(\nu_\mu \rightarrow \nu_e)$$

$$ND(\nu_\mu) = \Phi \times \sigma \times \epsilon_{ND}$$

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

Overall increase to cross section cancels in extrapolation, but any shifts between true to reconstructed E feed down into oscillation dip and are ~degenerate with θ_{23} measurement

- Similar issue for CC1π+ backgrounds where pion is not tagged (absorbed in nucleus or detector)

Outline

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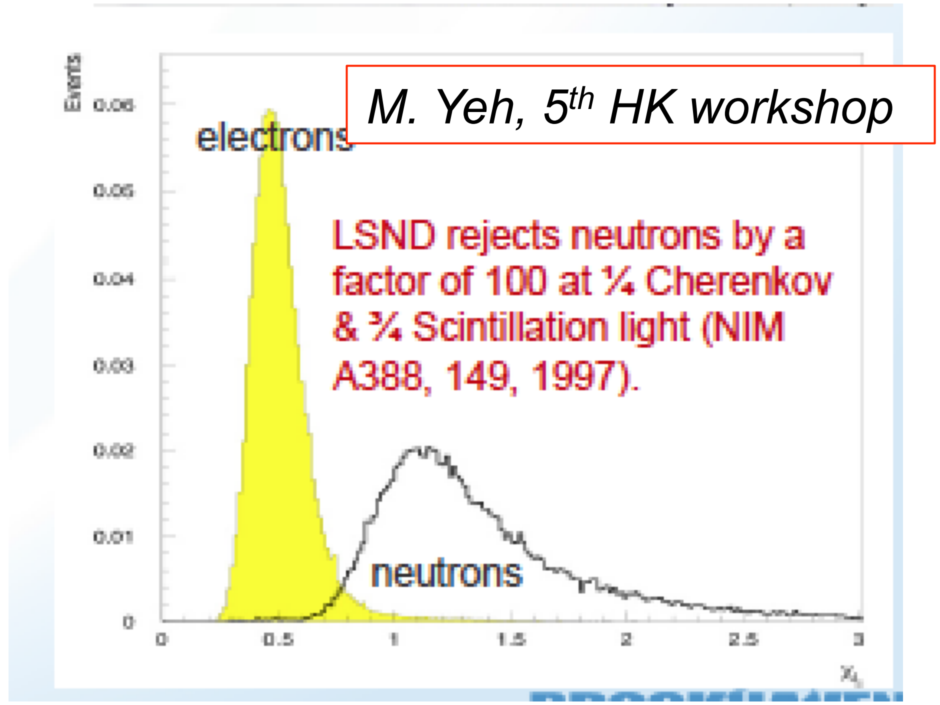
- What is a Cherenkov detector?
- Combinations of fine grained detectors and Cherenkov detectors in oscillation analyses: MiniBooNE+SciBooNE, T2K
  - How do fine grained detectors compare to Cherenkov in performance?
  - How do uncertainties in the cross section model affect oscillation analyses?
  - How are the different detectors sensitive to the cross section model?
- Future improvements of Cherenkov detectors

WBLS and Gd

Advantages to water-based liquid scintillator (WBLS)

- Cherenkov light is prompt and directed, scintillation light is "slow" and isotropic
- Cheaper than pure LS detector (~1% loading)
- Provides information on nucleons in final state (neutron rejection)
- Studies of stability, light yield ongoing

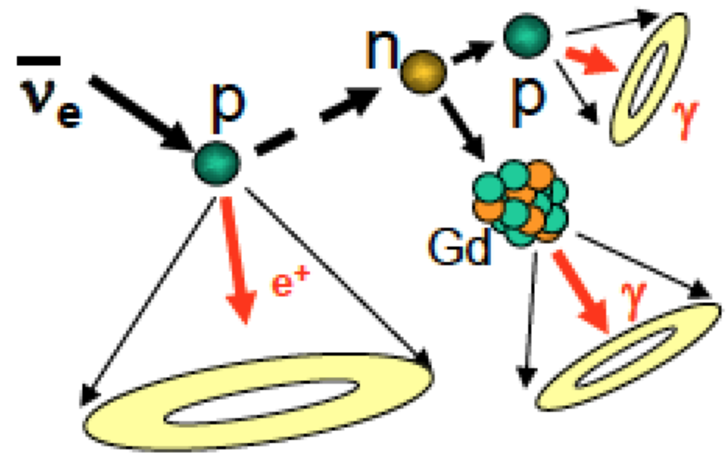


Advantages to Gadolinium doping:

- Provides a tag for neutrons with photon from capture on Gd
- Studies to prove purity and deployment

Challenges:

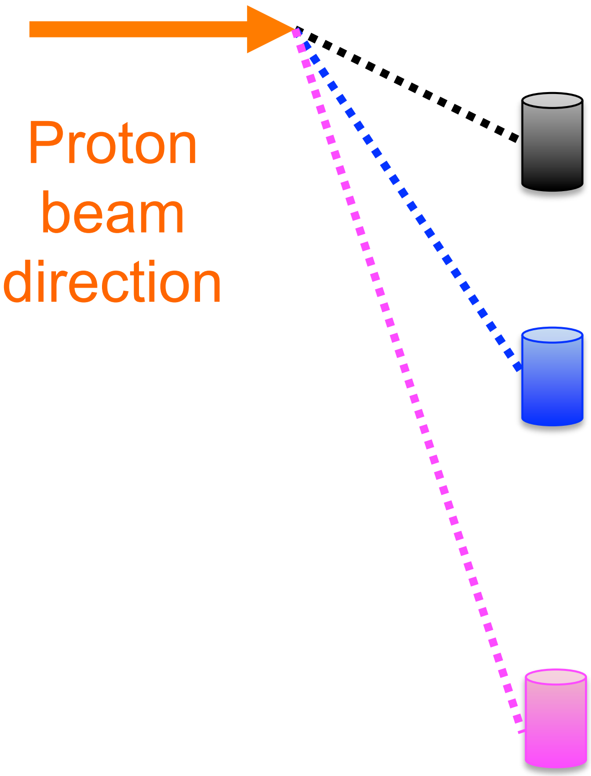
- Neutrons travel through detector (and can be captured far from vertex, or be due to backgrounds from outside the detector)

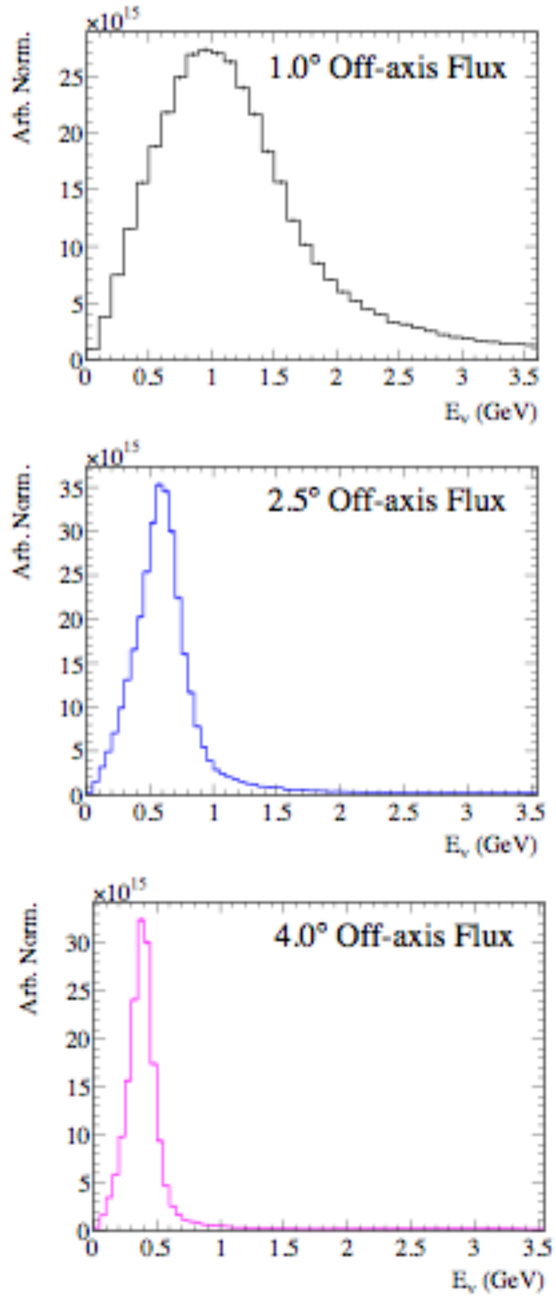


Phys. Rev. Lett., 93:171101, 2004

Revisiting off-axis beams

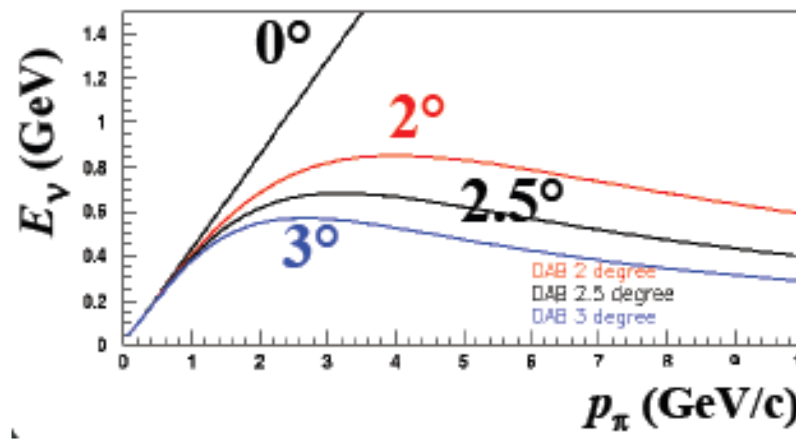
Proton beam direction





Example using T2K beamline

As off-axis angle increases, flux spectrum narrows and peak shifts down, due to the kinematics of pion decay



Combining different off-axis angles

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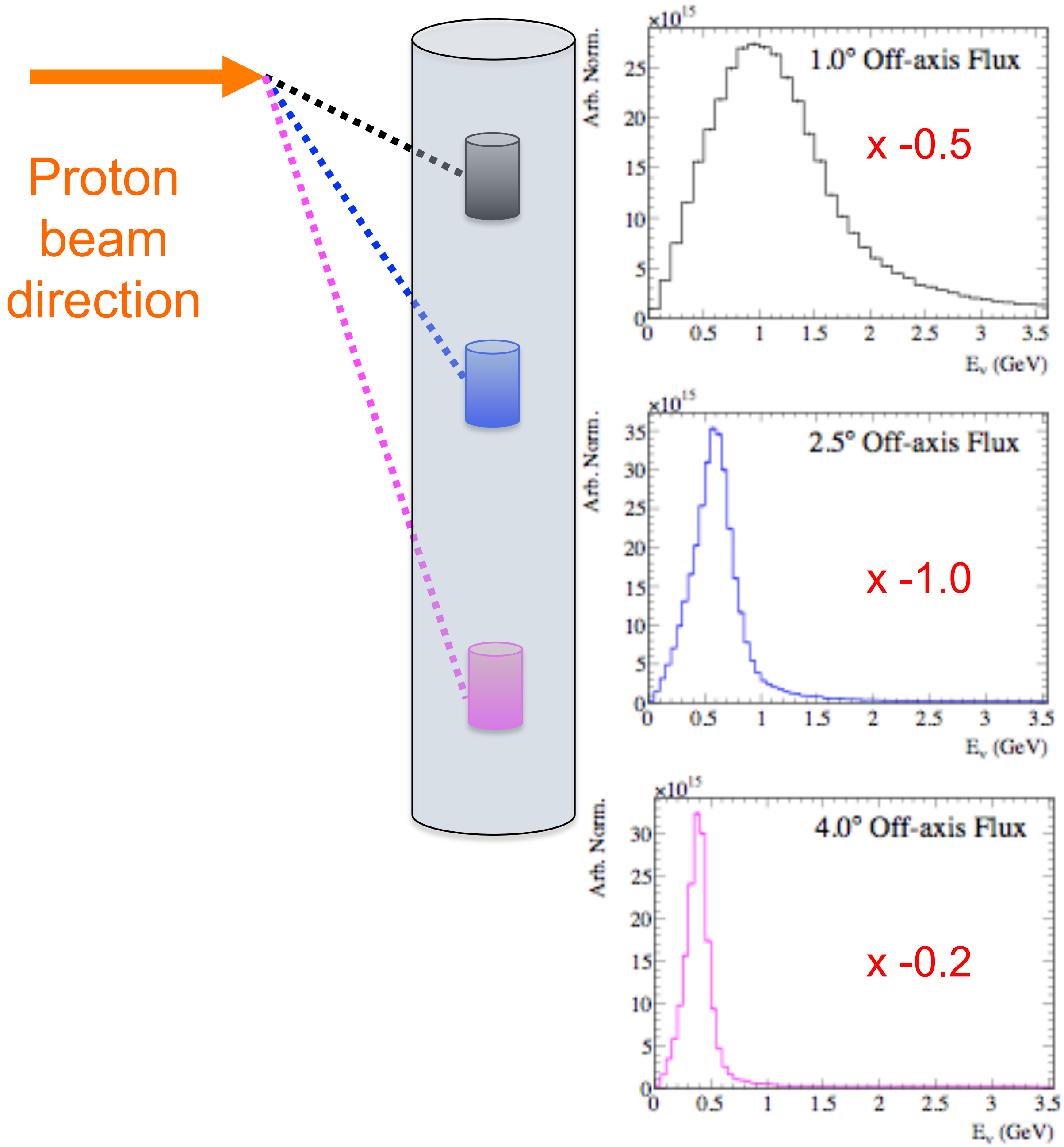
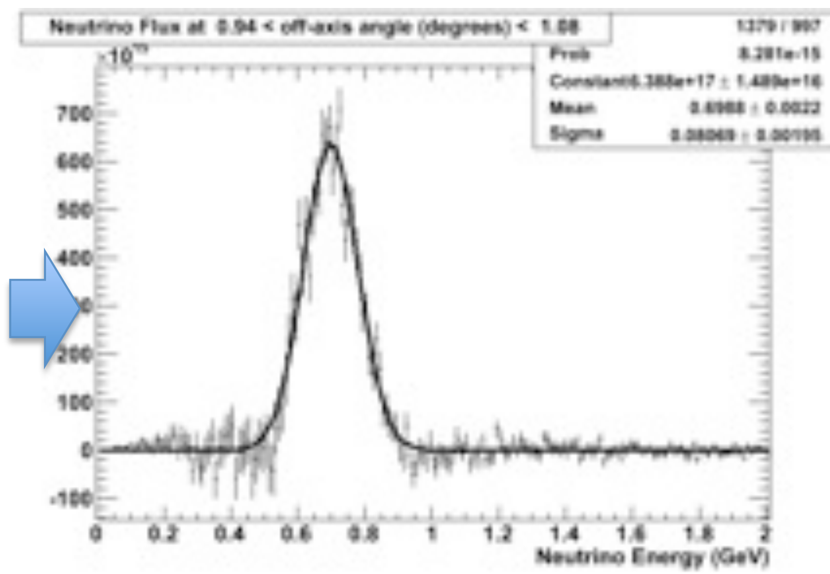


$$\Phi(E_\nu) = \sum_{i=0^\circ}^{\theta_{max}} C_i \; \phi_i(E_\nu)$$



For a Gaussian beam peaked at 700 MeV, use linear combination of 30 offaxis angles:

- 0°– 6° corresponds to 1.2 GeV -0.25 GeV
- Cancels HE tail

Relating observables to true E_ν

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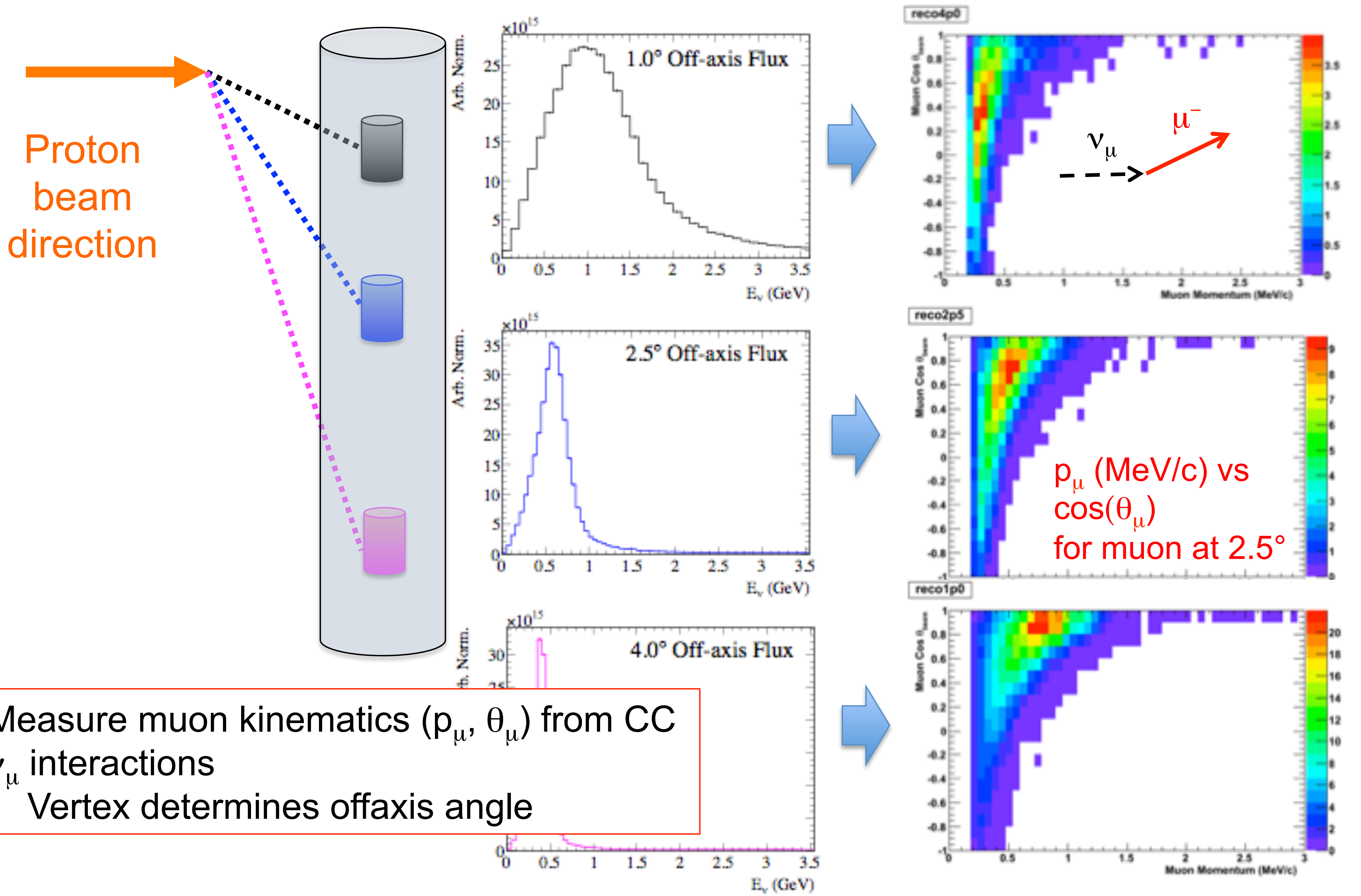

Measure muon kinematics (p_μ, θ_μ) from CC ν_μ interactions

- Vertex determines offaxis angle

Relating observables to true E_ν

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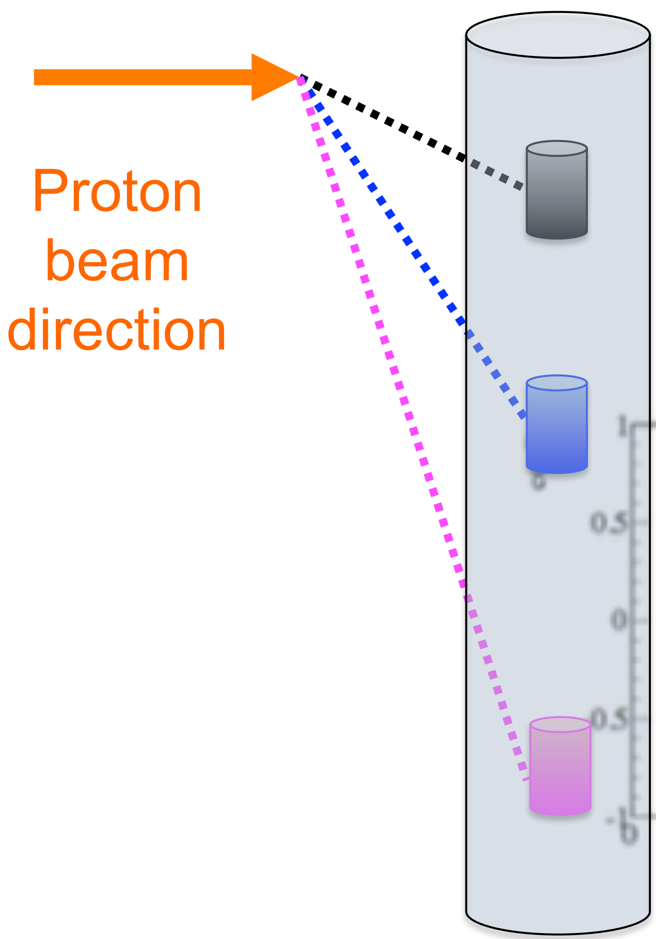

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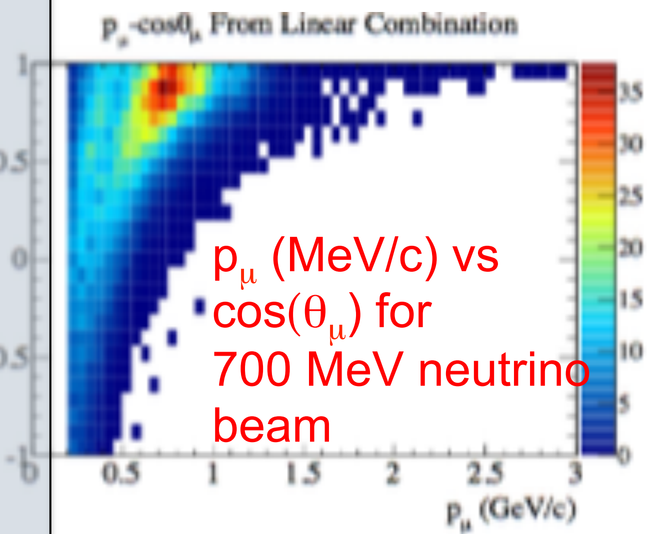
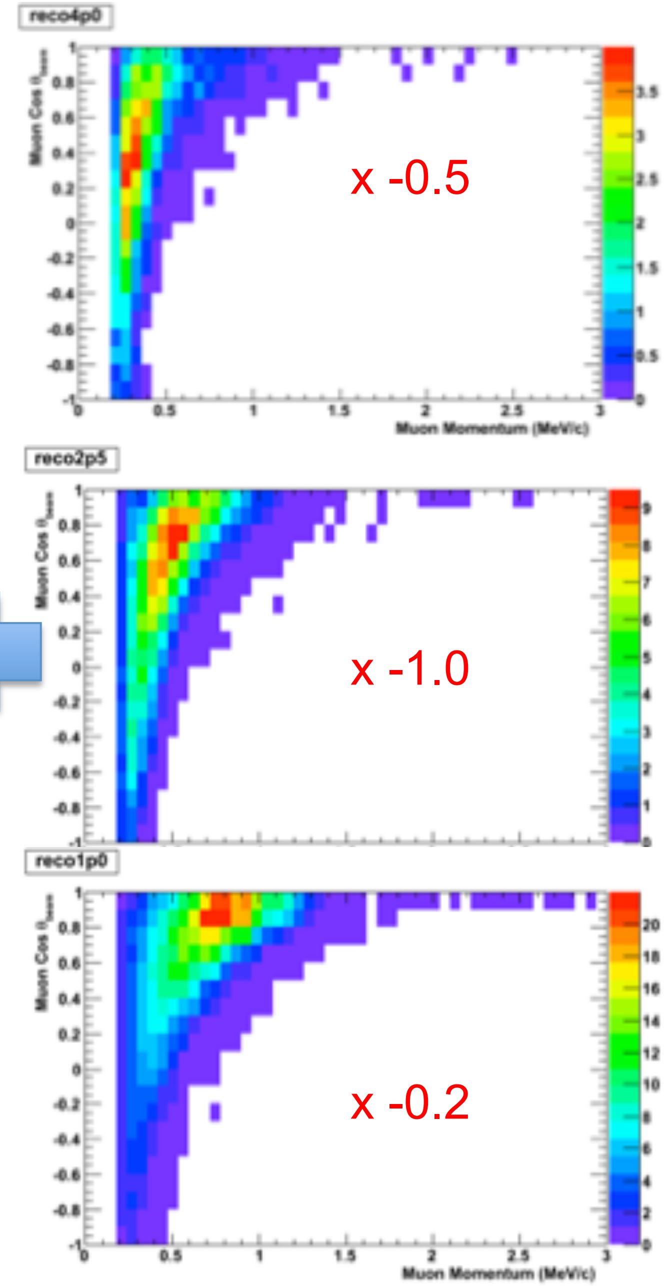
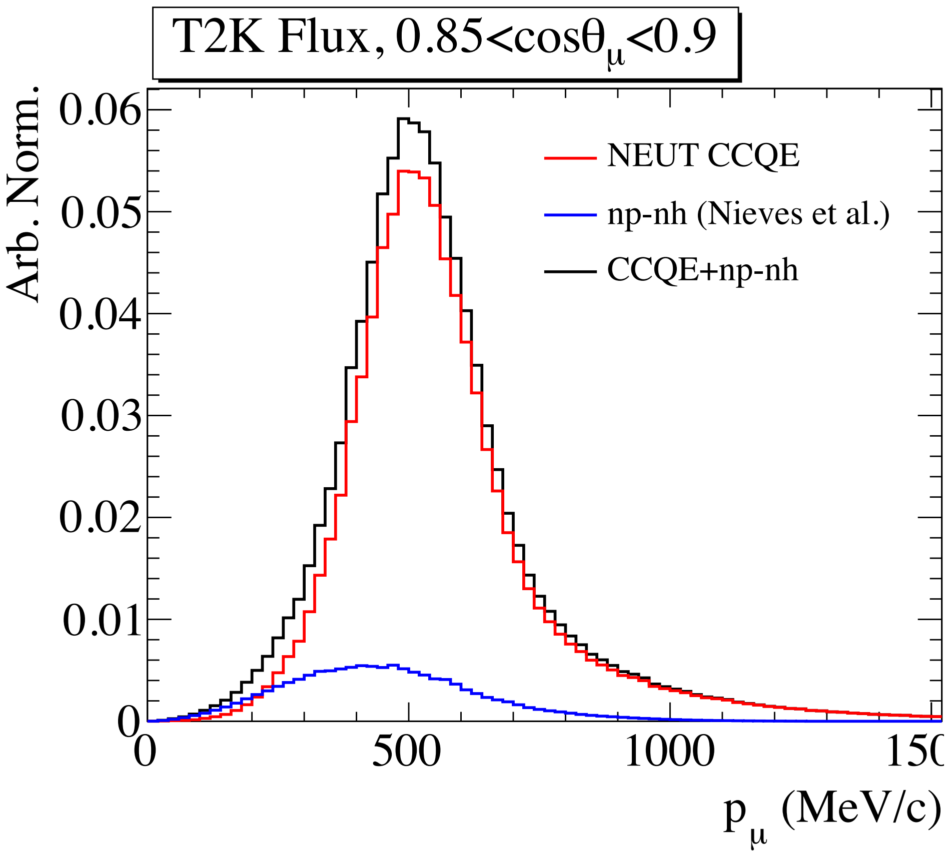


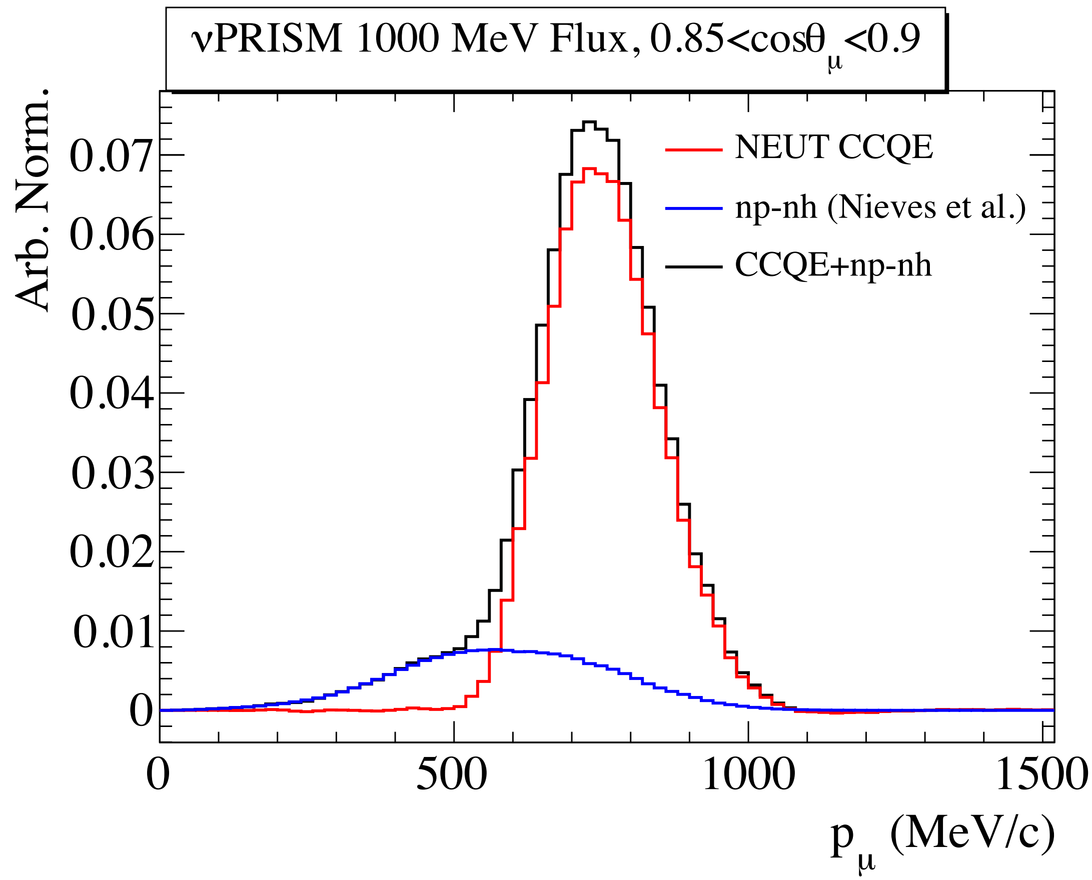


Measure muon kinematics (p_μ, θ_μ) from CC ν_μ interactions

- Vertex determines offaxis angle
- Linear combinations of (p_μ, θ_μ) provide observable for monoenergetic E_ν beam

Resolving nuclear effects with only lepton info

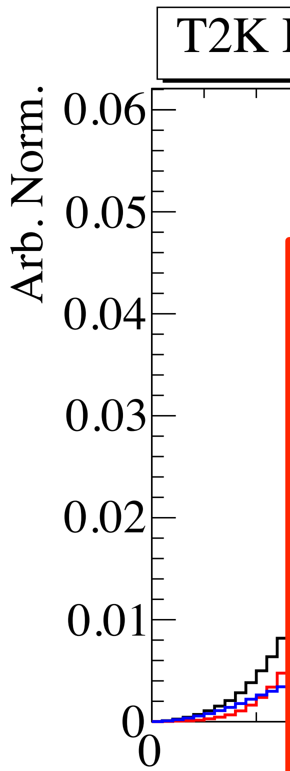


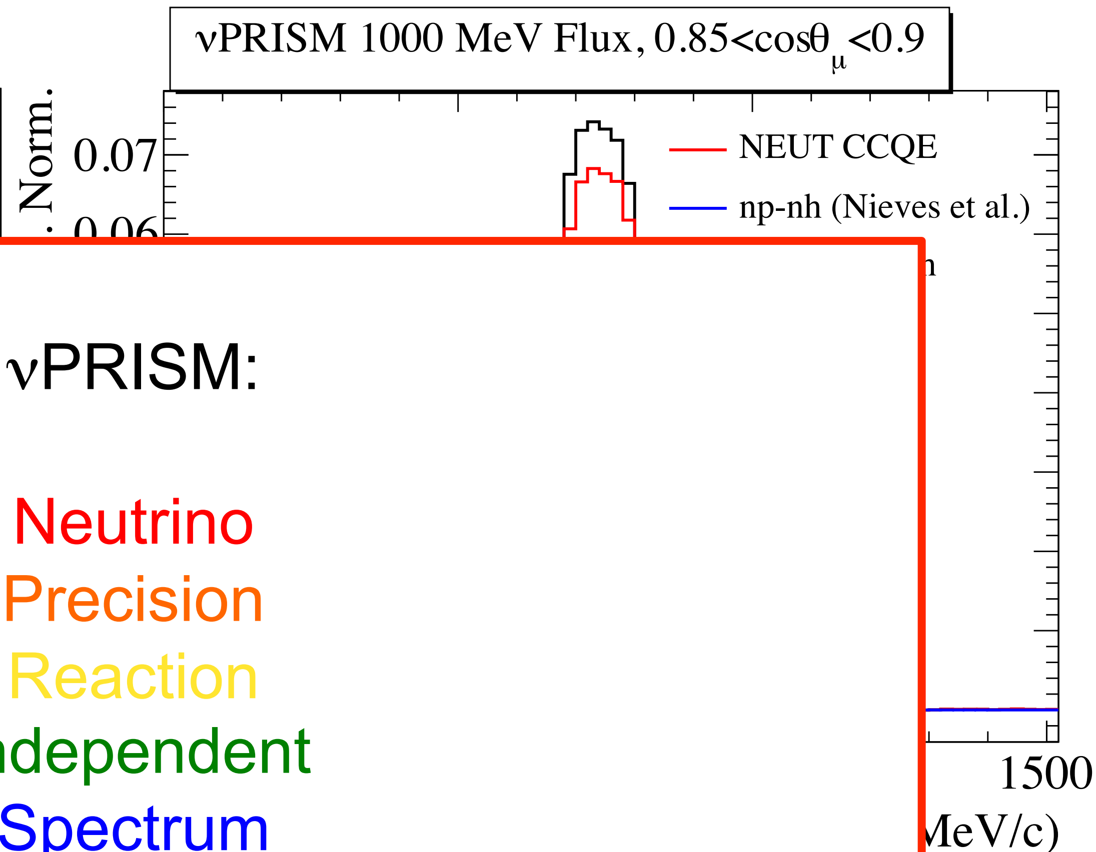


With the T2K flux, multinucleon (npnh) interactions from higher E_{ν} feed down into same momentum region as CCQE.

With a νPRISM generated 1 GeV "monoenergetic" flux, processes can be separated in observable muon kinematic variables

- Combinations of nearby monoenergetic fluxes provide energy dependence of cross section





νPRISM:

Neutrino
Precision
Reaction
Independent
Spectrum
Measurement

With the … into
same mo…

With a νPRISM generated 1 GeV "monoenergetic" flux, processes can be separated in observable muon kinematic variables

- Combinations of nearby monoenergetic fluxes provide energy dependence of cross section

Summary

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Cherenkov detectors are an effective way to measure neutrino oscillations and neutrino scattering

- Stable, scalable to enormous sizes
- Detailed information about leptonic, pion and sometimes proton final state
  - MiniBooNE differential results
- Inherent limitation of Cherenkov threshold reduces information about final state
  - Future improvements with WBLS, Gd doping for nucleons

Chernekov and fine grained detectors can be combined effectively in oscillation analyses

- MiniBooNE, SciBooNE: coverage in relevant phase space of Cherenkov detector with fine grained detector, substantial reduction of flux x cross section uncertainties achieved
- T2K: substantial reduction of flux x cross section uncertainties achieved

Final thoughts

Regardless of detector type, we always need to know our (detector) capabilities and limitations

- Everyone's got thresholds (Cherenkov or scintillator or Liquid or Gaseous Ar…)

Even with an identical near and far detector, oscillation analyses must represent the cross section model right

- Inherently different CC flux at near and far detector spectrum, due to oscillation

Dream big!

- Revolutionary functionality of Cherenkov detectors achieved due to hard work of students, postdocs

Backup

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Near vs. Far selection (2012 analysis)

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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%

Fit to MiniBooNE CC, NC1π samples to tune 1π model

- Emperical parameters to cover disagreements between NC, CC parameters
- Retuning with fundamental parameters