Long Baseline Neutrino Oscillations Now and in the Future: T2K and DUNE

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Outline

- Neutrino oscillations
  - What we know and what we don't
- The T2K Experiment
  - Long-baseline oscillation analyses
- The DUNE Experiment
  - Current status
  - Future sensitivity

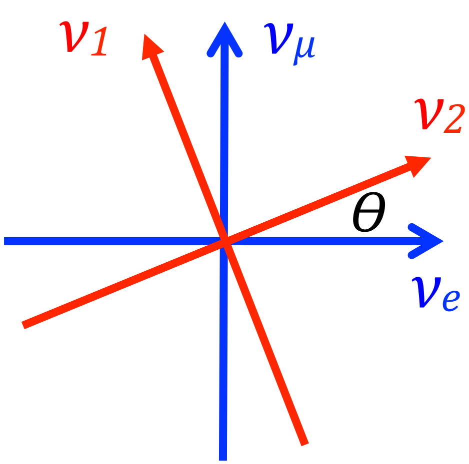
Neutrino Oscillations

- Create in one flavor (ν_μ), but detect in another (ν_e)

- Each flavor (e, μ) is a superposition of different masses (1, 2)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

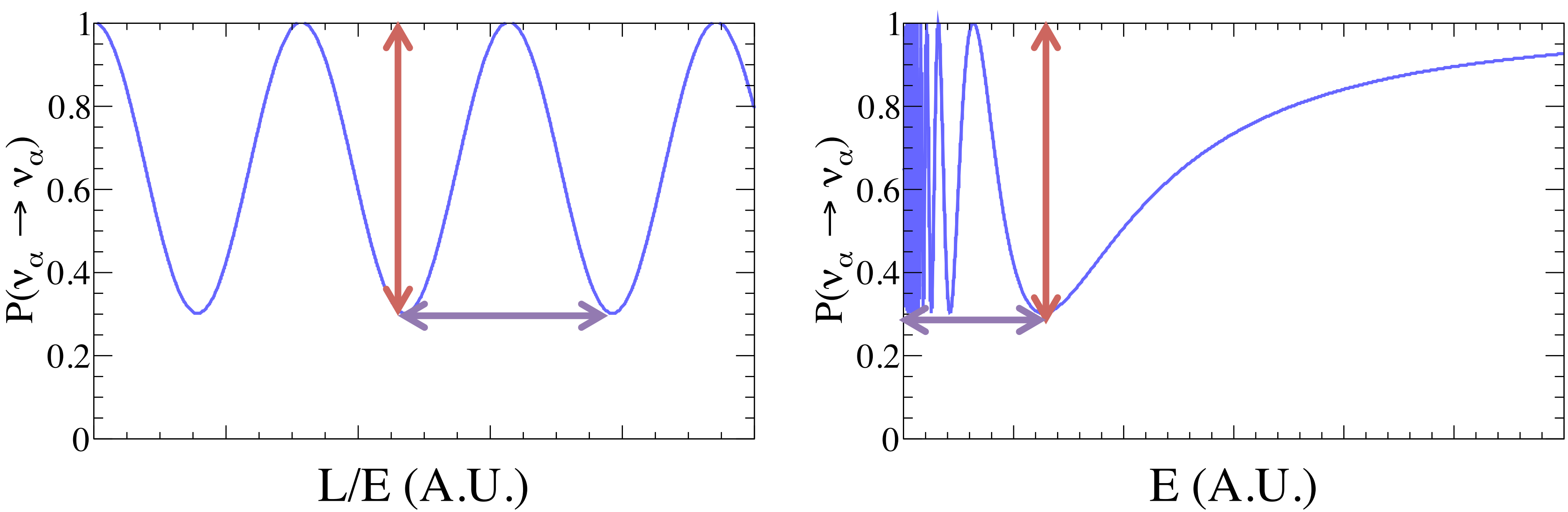
"Mixing Matrix"



Neutrino Oscillations

- With only 2 neutrinos, the oscillation formula is simple:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \boxed{\sin^2(2\theta)} \sin^2\left(\boxed{\Delta m^2} \frac{L}{4E}\right)$$

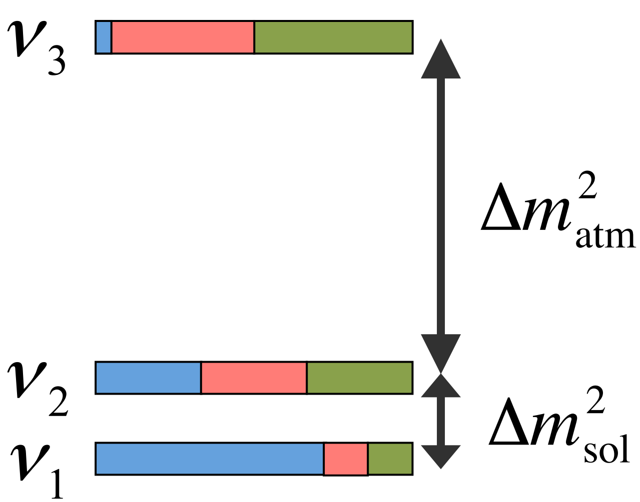


The PMNS Mixing Matrix

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass



Pontecorvo

Sov.Phys.JETP 6:429, 1957

Sov.Phys.JETP 26:984-988, 1968

Maki, Nakagawa, Sakata

Prog.Theor.Phys. 28, 870 (1962)

What We Know

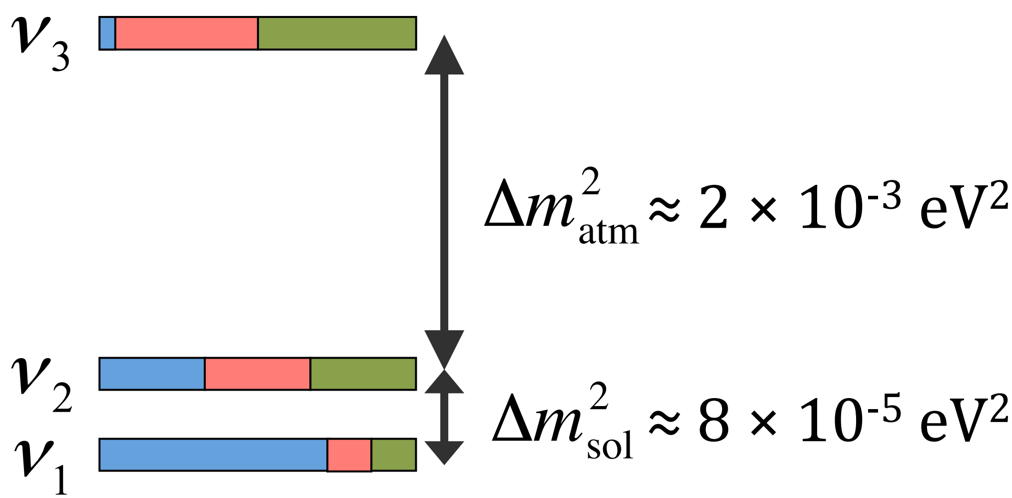
atmospheric / accelerator ν_μ | short baseline reactor / accelerator ν_e | solar / long baseline reactor

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass

$\theta_{23} \approx 45°$ $\theta_{13} \approx 9°$ $\theta_{12} \approx 34°$



What We Don't Know

atmospheric — accelerator ν_μ

short baseline reactor — accelerator ν_e

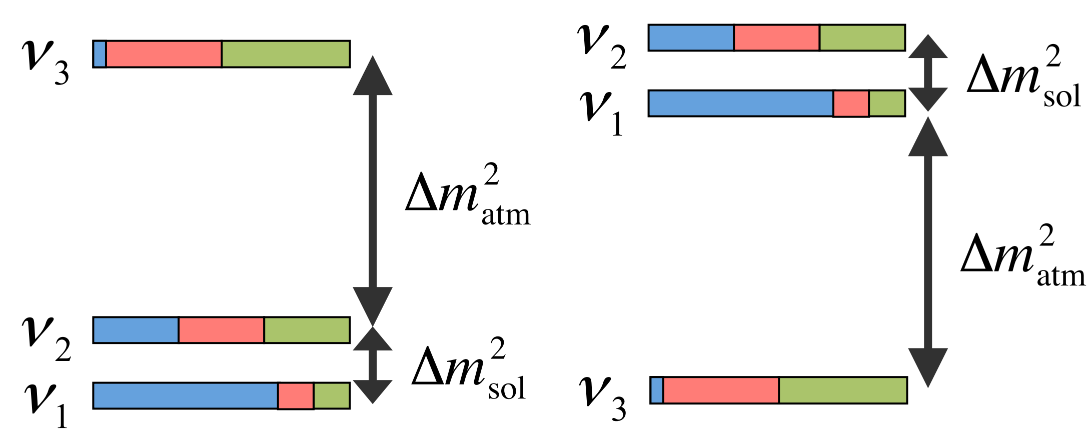
solar — long baseline reactor

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass

Phase δ_{CP}, and potentially CP violation



The "mass hierarchy," the sign of the atmospheric Δm^2

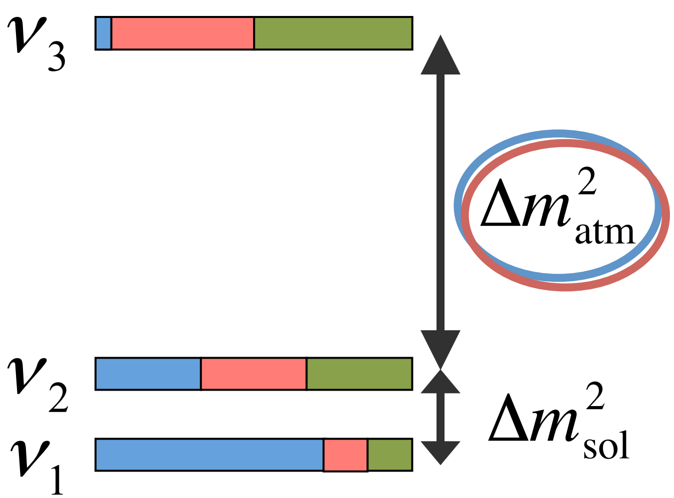
Oscillation Physics at T2K

atmospheric accelerator ν_μ	short baseline reactor accelerator ν_e	solar long baseline reactor

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass

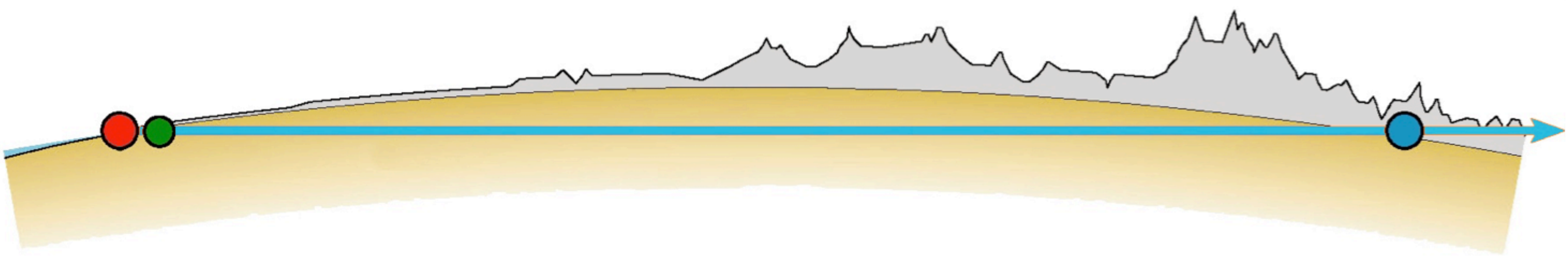


Long Baseline

ν_μ Disappearance: θ_{23}, $|\Delta m^2{}_{\text{atm}}|$

$\nu_\mu \rightarrow \nu_e$ Appearance: θ_{13}, δ_{CP}

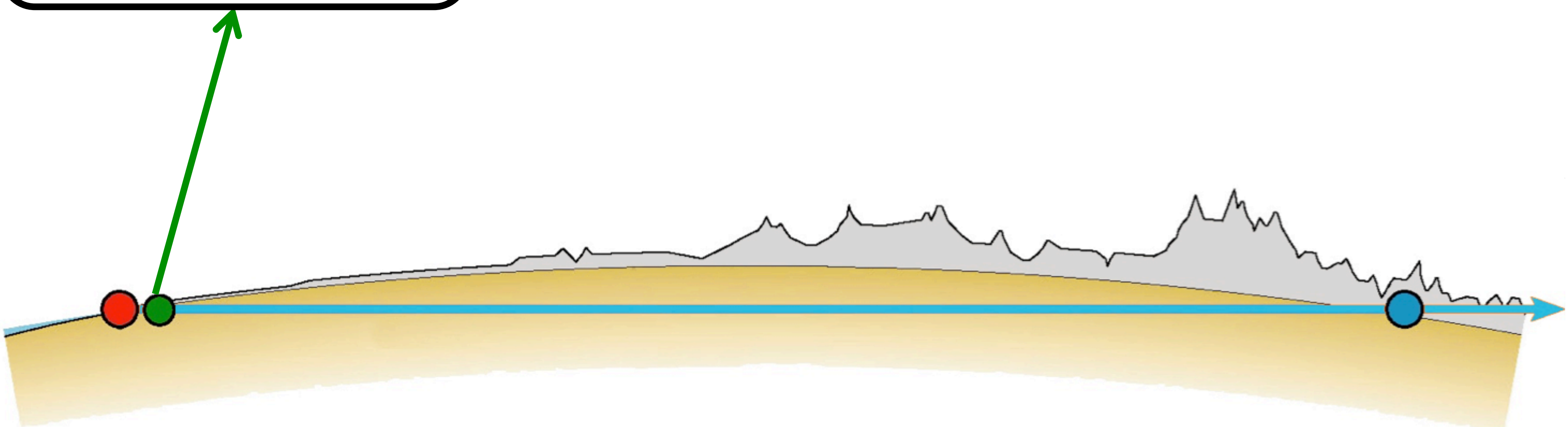
Long-baseline Analyses



ν_μ

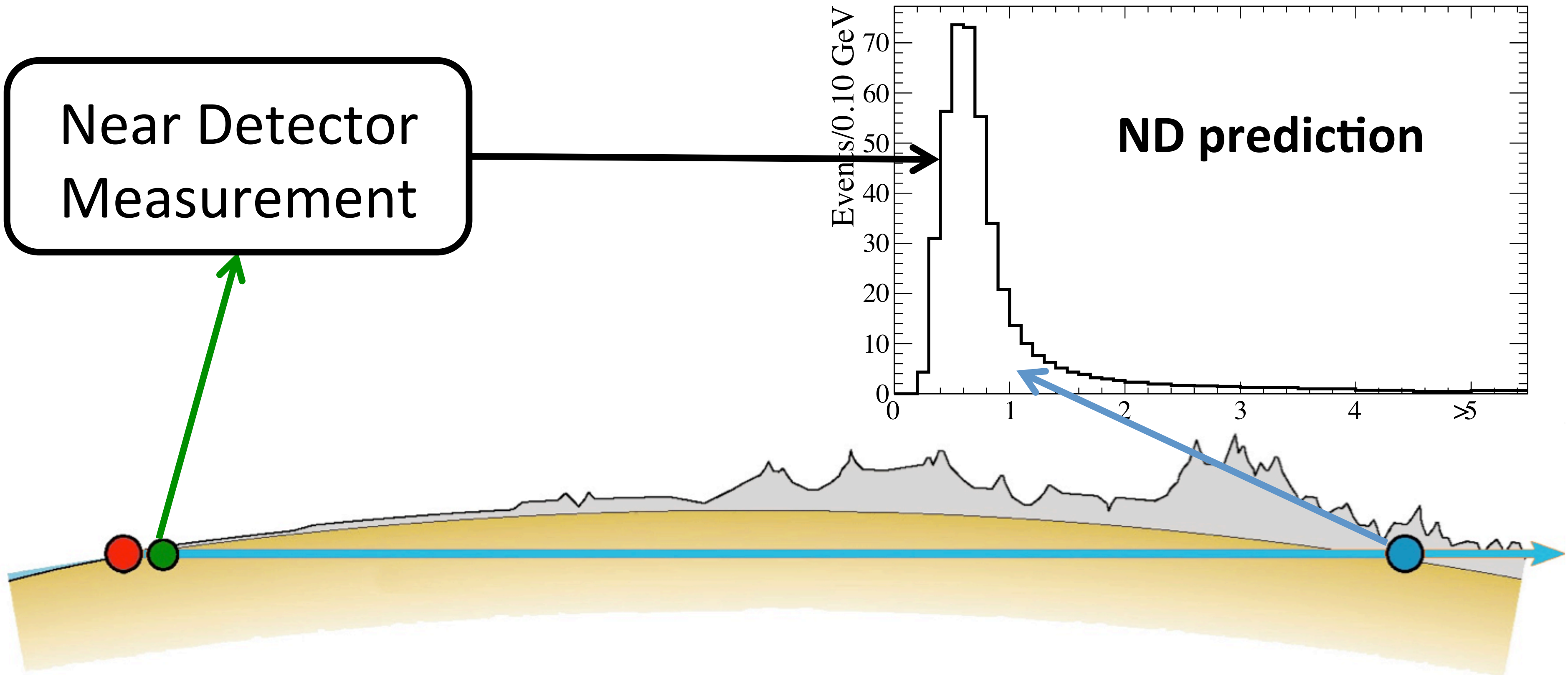
Long-baseline Analyses

Near Detector Measurement



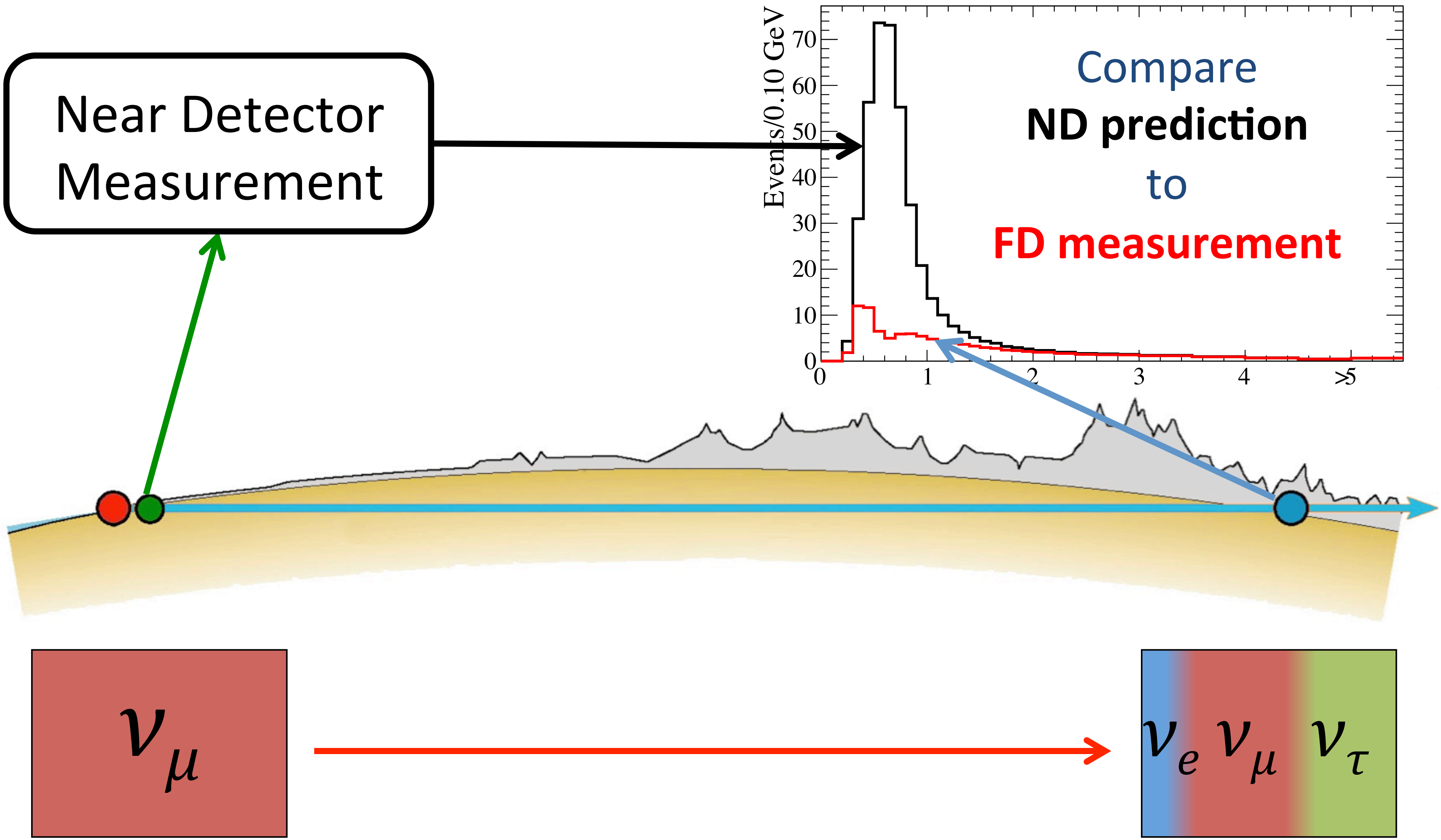
ν_μ →

Long-baseline Analyses

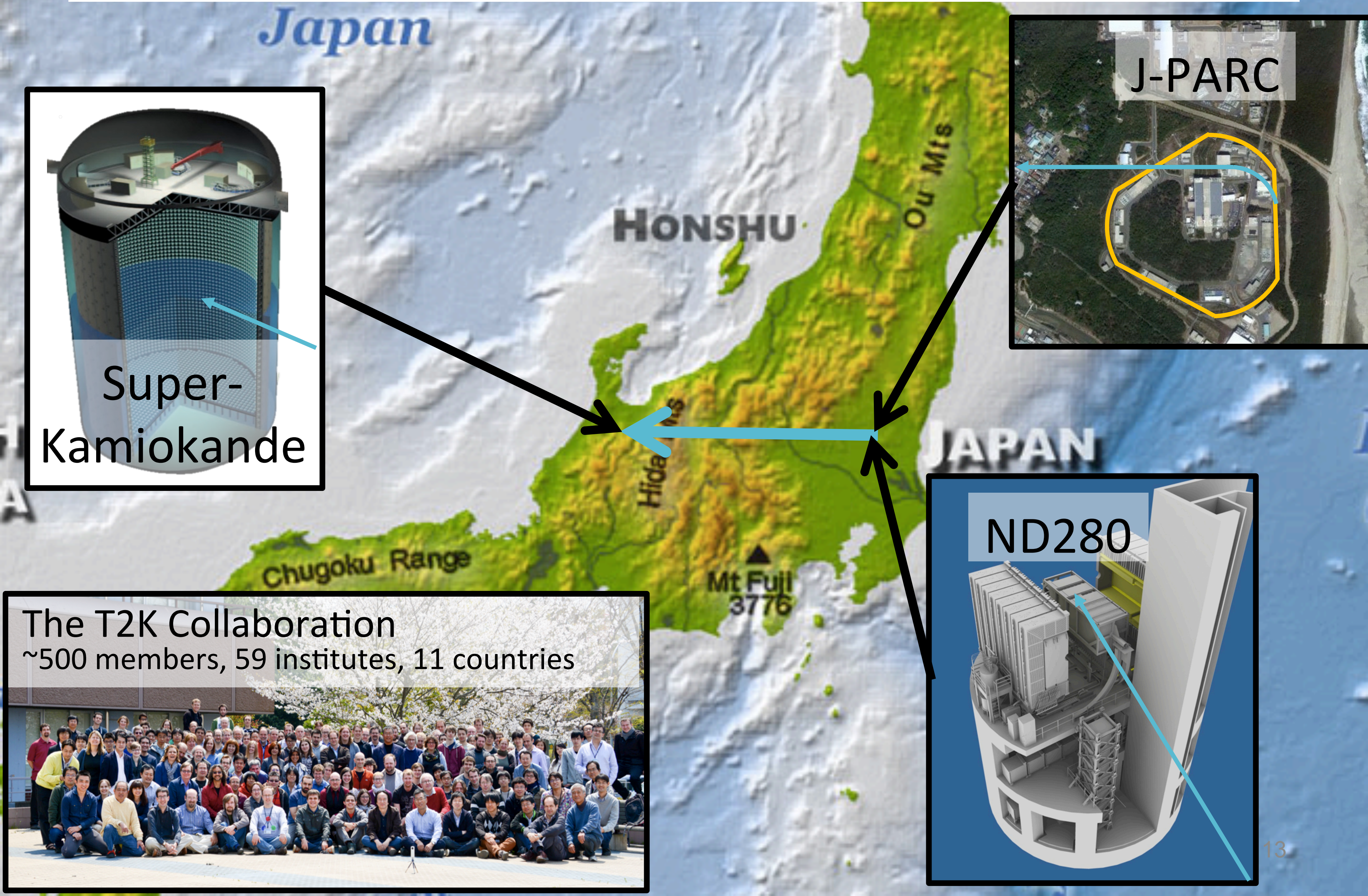


ν_μ

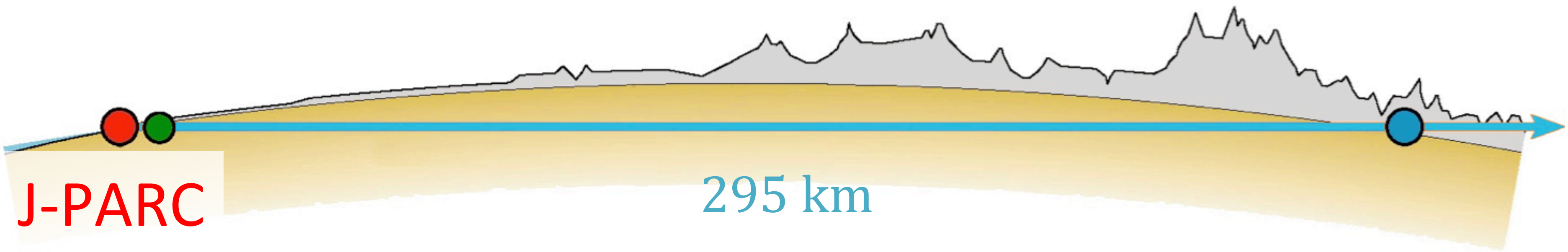
Long-baseline Analyses



The T2K Experiment

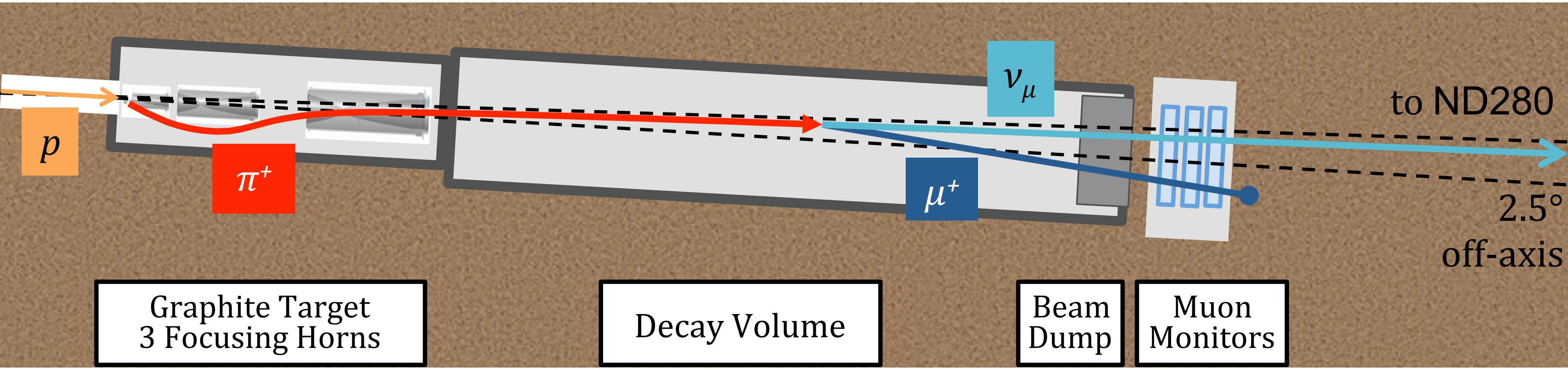


Long-baseline Analyses

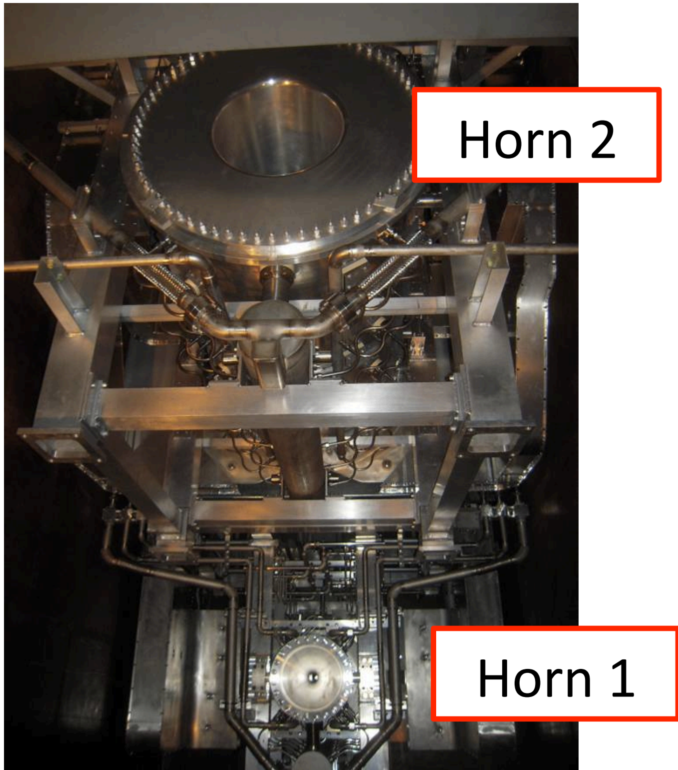


ν_μ →

J-PARC Neutrino Beam



- 30 GeV p beam on graphite target to produce $\pi^\pm$, $K^\pm$
- Focus charged mesons
  - 3 Large electromagnetic "horns" act like lenses
  - 250,000 amps every ~2 seconds
- Mesons decay to produce a beam of neutrinos



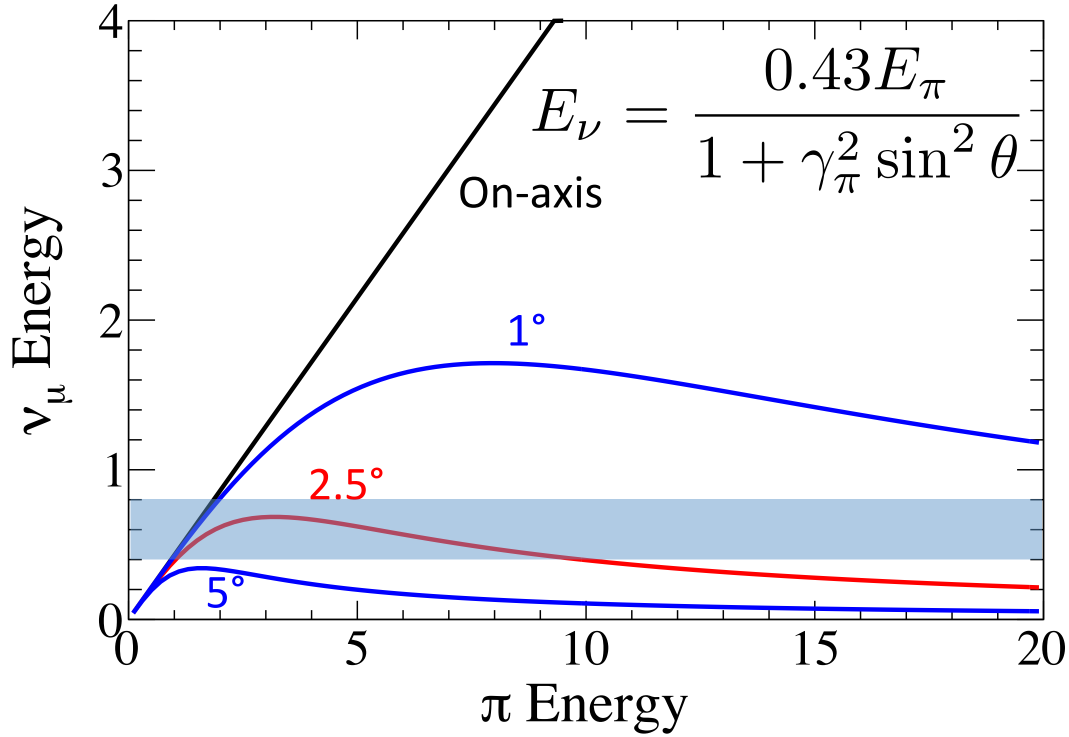
Off-axis Beam

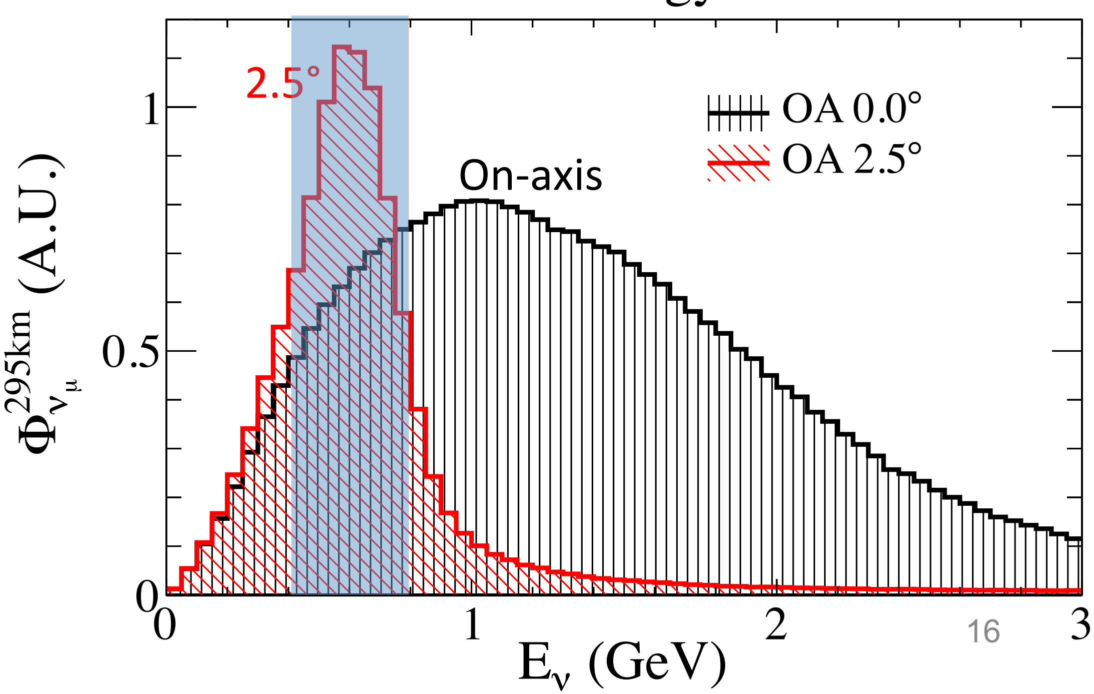
2.5° off-axis angle

- 2-body π decay gives narrow range of ν energies

Tune peak energy for oscillations

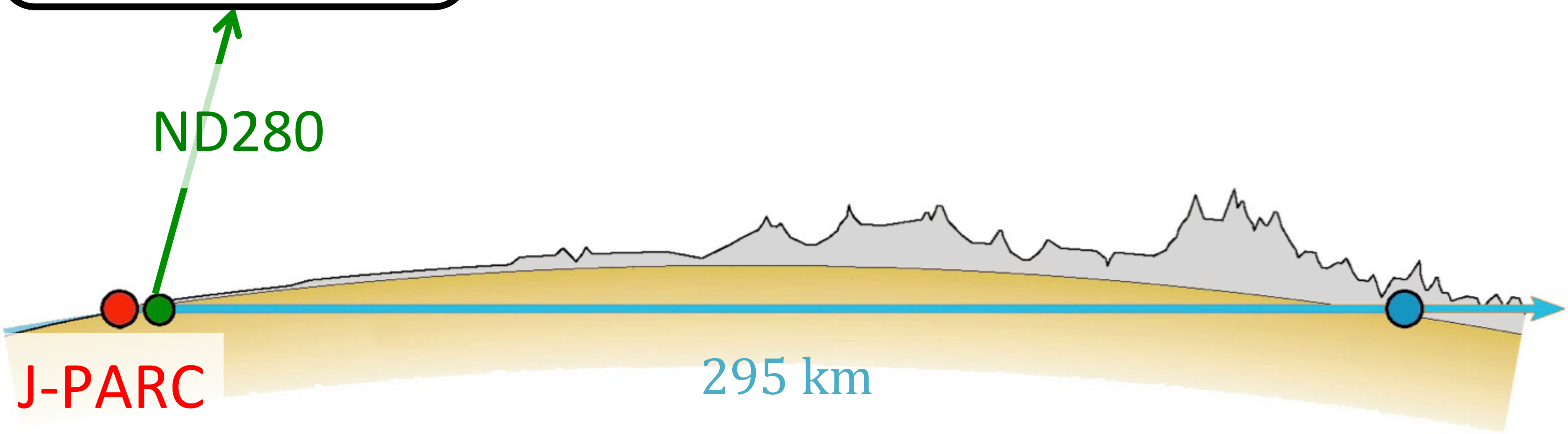
- More events at max oscillations
- Fewer backgrounds from high energy





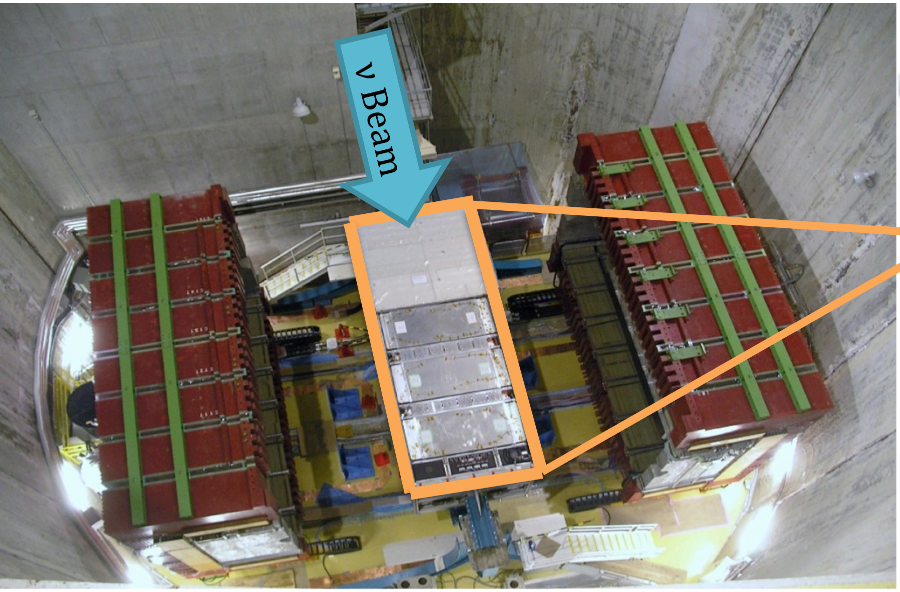
Long-baseline Analyses

Near Detector Measurement

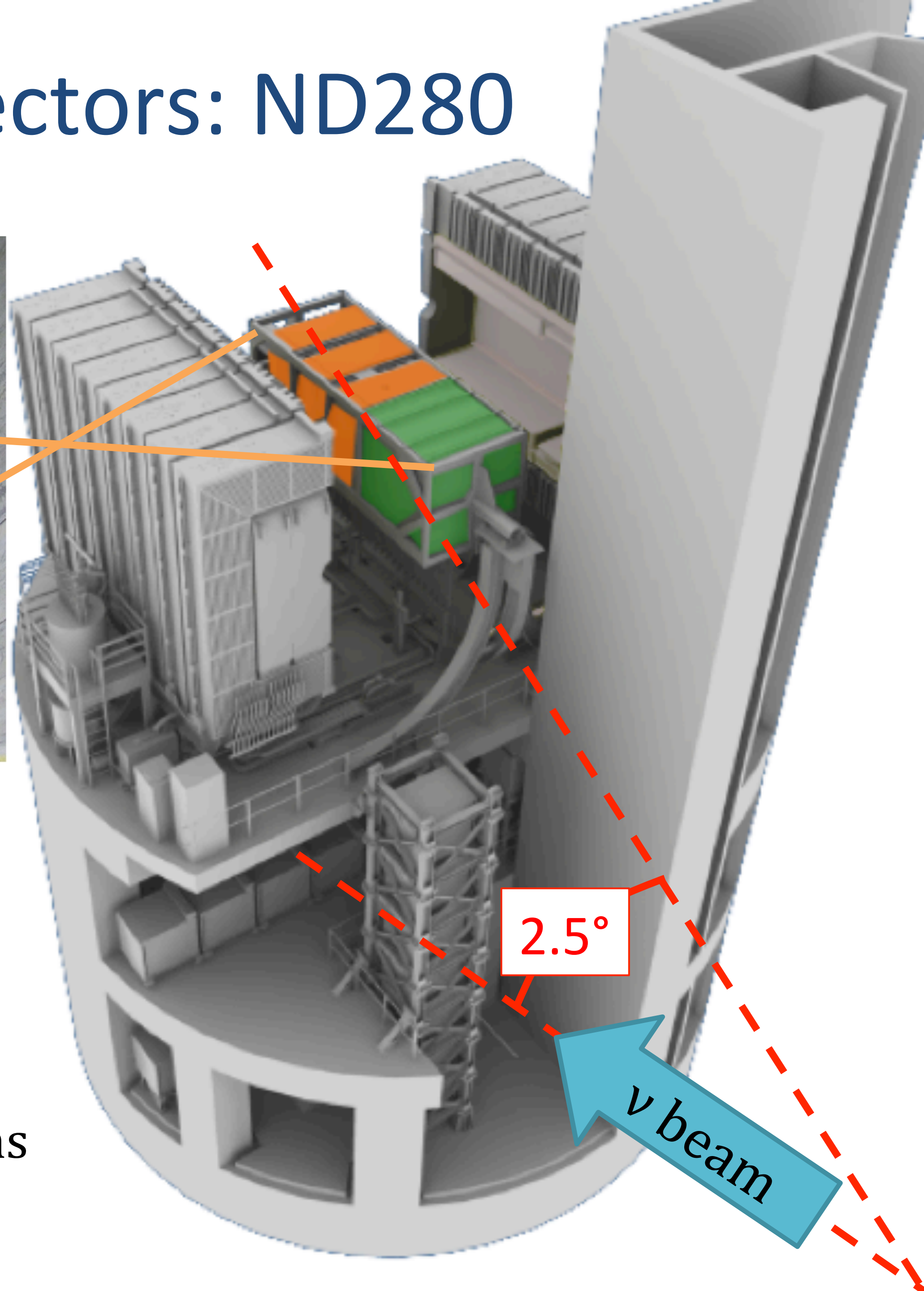


ν_μ →

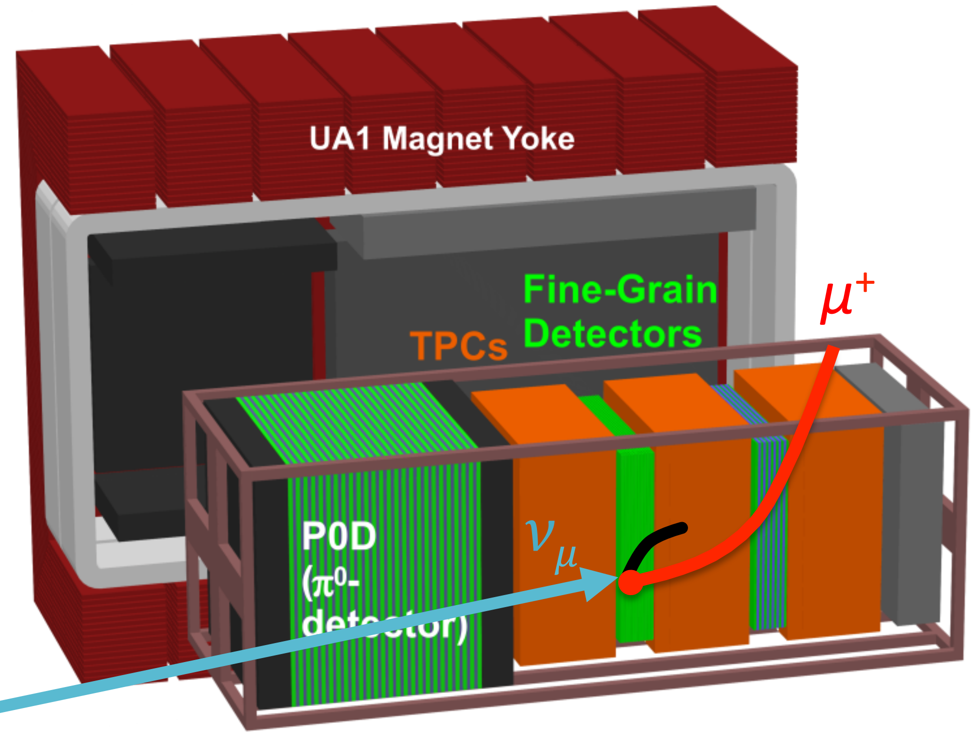
Near Detectors: ND280



- Multi-component magnetized detector.
- 2.5° off-axis
- Measure spectrum and composition before oscillations

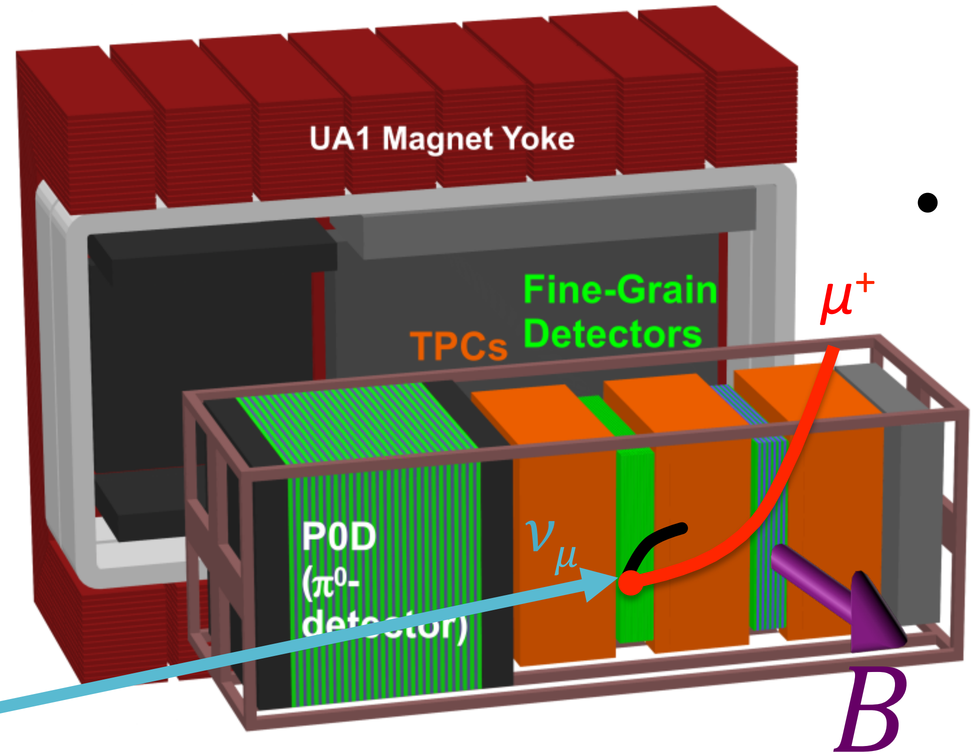


ND280



- Multiple components
  - 2 scintillator trackers
  - 3 time-projection chambers
  - P0D π^0 detector
  - EM Calorimeter
  - Muon range detector interleaved in magnet
- Select CC ν_μ events
  - Long muon tracks

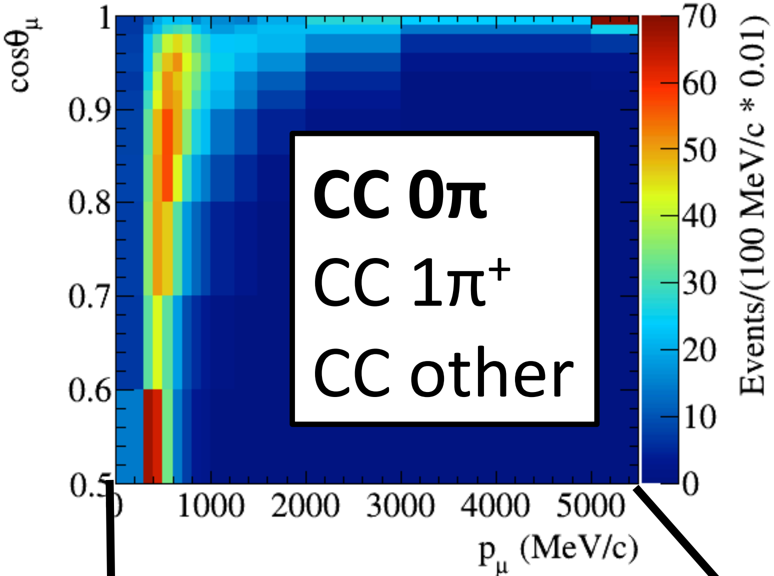
ND280



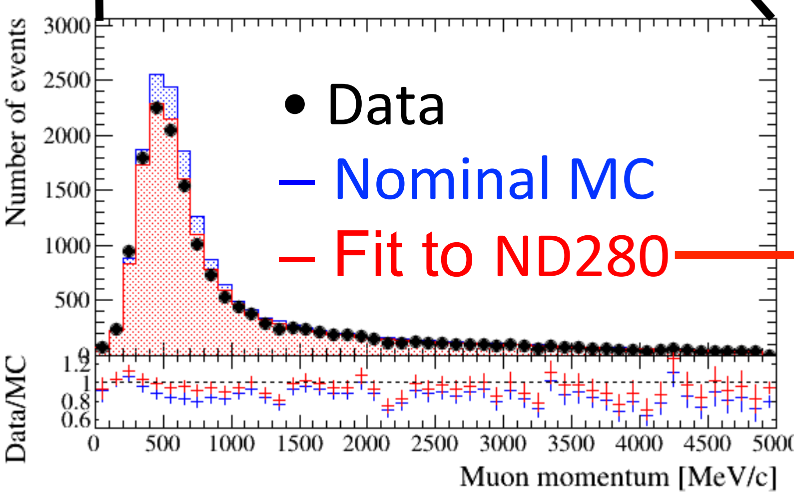
- ND280 magnetized to 0.2T
  - Magnet from CERN UA1
- Curvature gives momentum and charge:

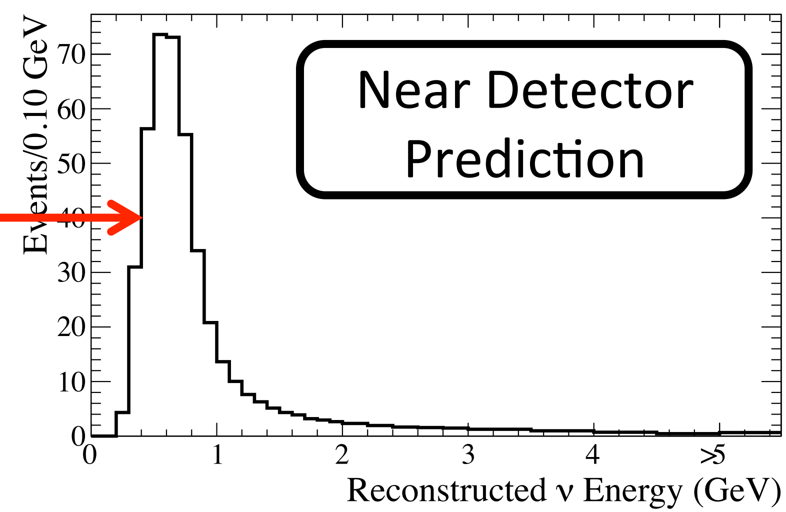
$$\boxed{\frac{p}{q} = B\, r_{\mathrm{curv}}}$$

ND280 Fit to Constrain Systematics

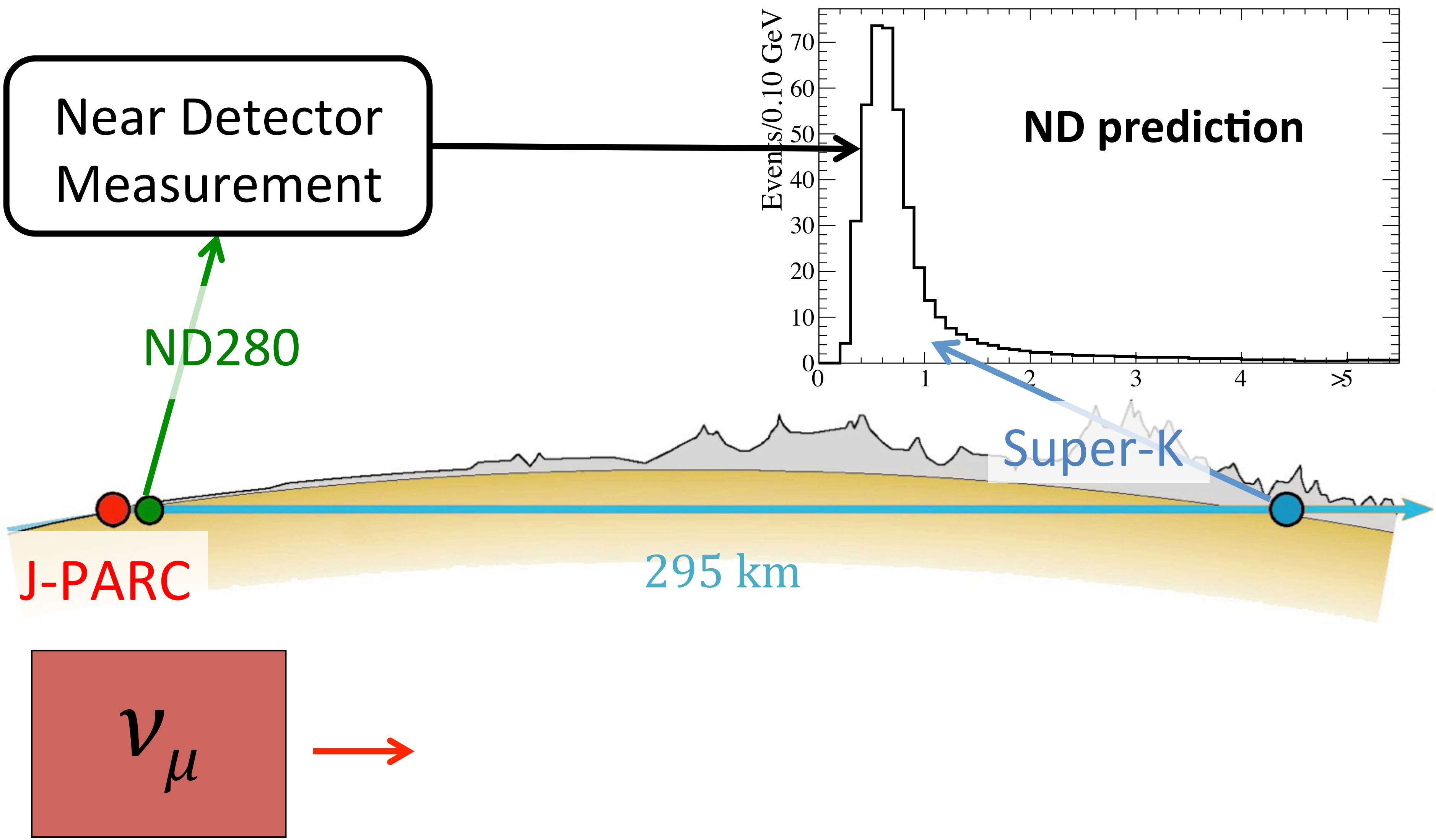


- 3 samples, 2D fit:
  - μ^- momentum and angle
- Dramatically reduces uncertainty on **Neutrino rate = Flux × Cross section**
- Systematic uncertainty at far detector reduced from **>20% to 7-8%**

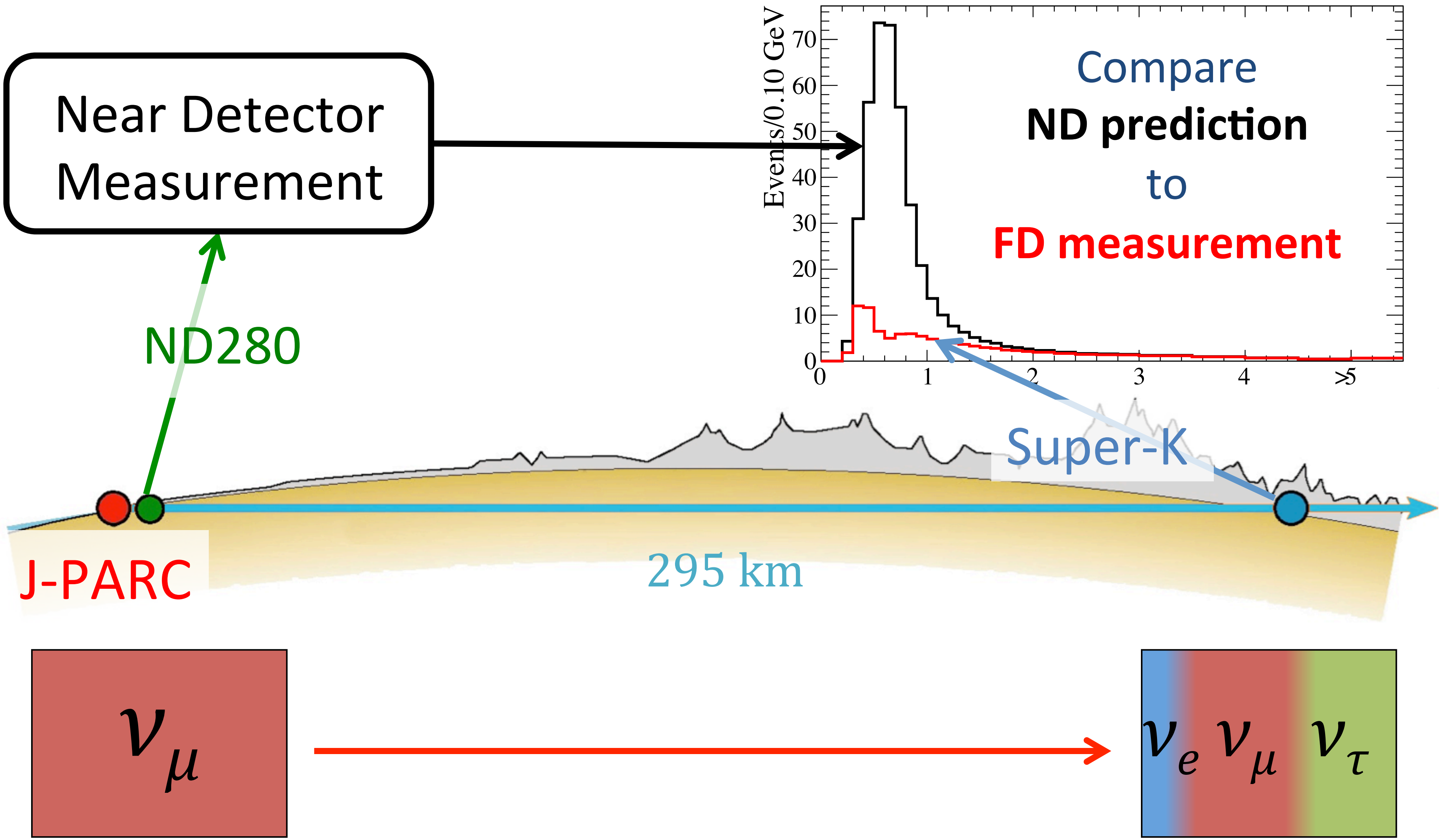




Long-baseline Analyses



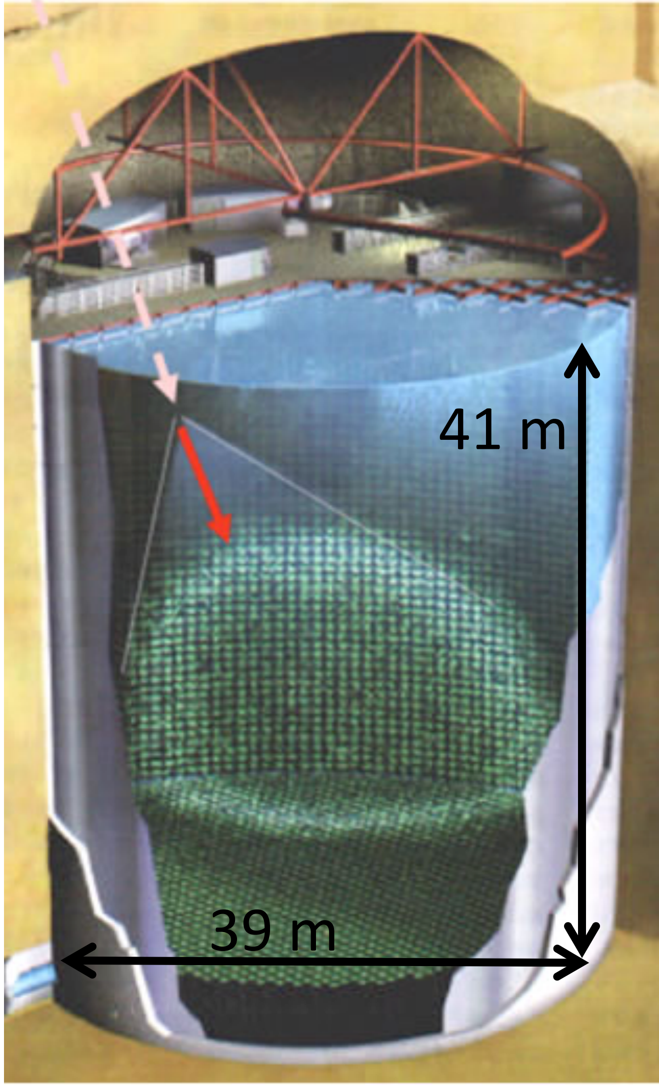
Long-baseline Analyses



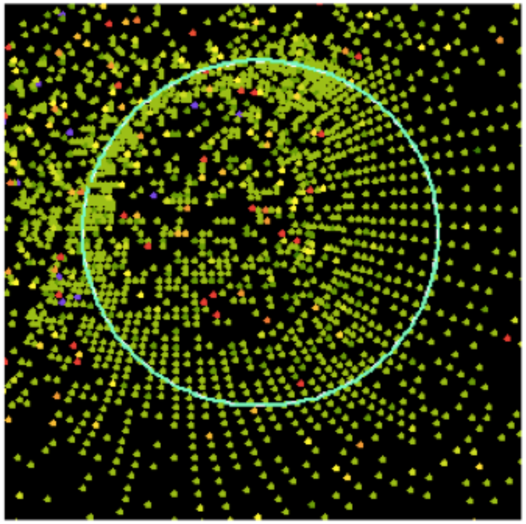
Detecting Neutrinos at the FD

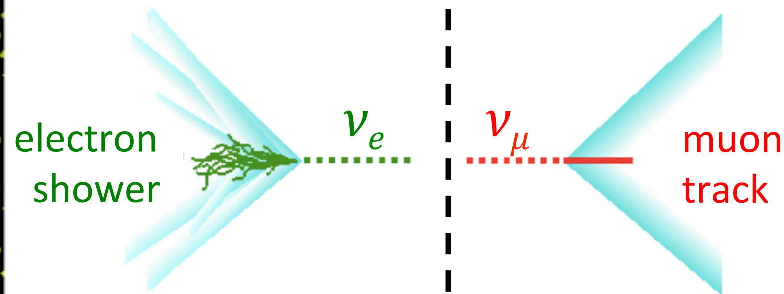
- Large water Chernekov detector
  - 22.5 ktons of ultra pure water
  - 11,129 20" PMTs, 40% coverage
- Cherenkov cones appear as a rings.
  - More energetic particles leave brighter rings.
- Cherenkov threshold
  - Constant *velocity* threshold gives energy thresholds proportional to *mass*

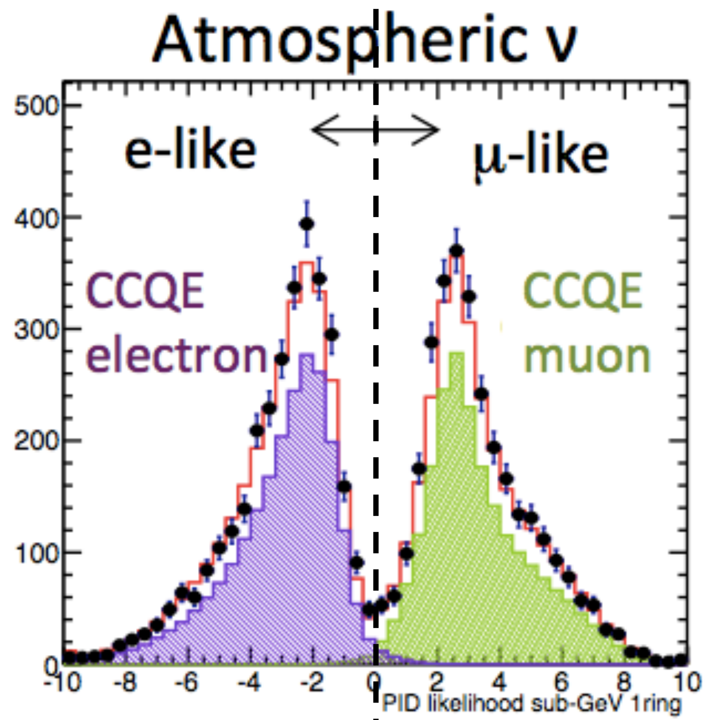
e: 780 keV	μ: 160 MeV
π: 212 MeV	p: 1.4 GeV

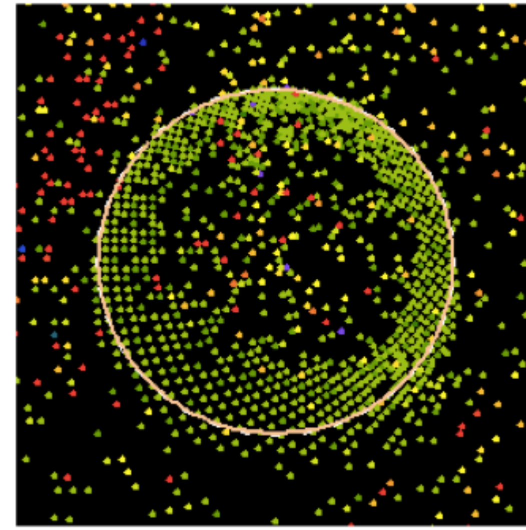


Particle Identification









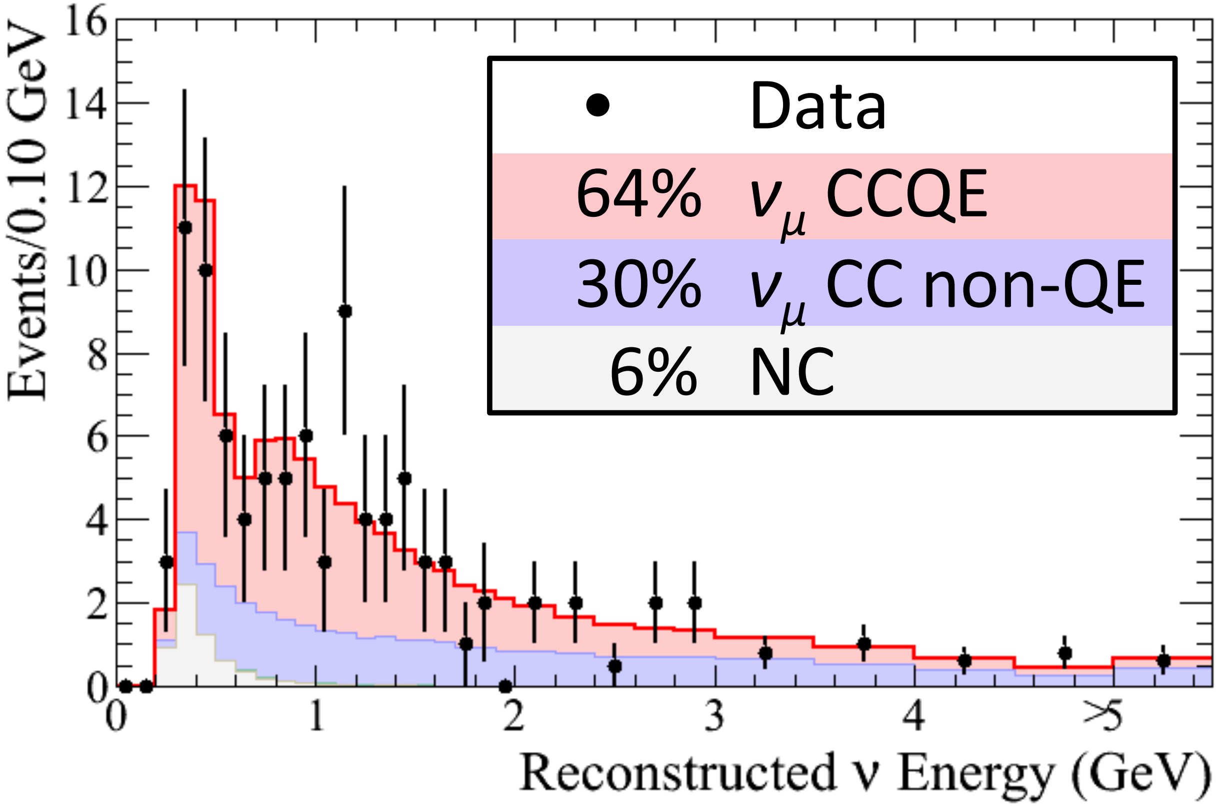
Shower-like

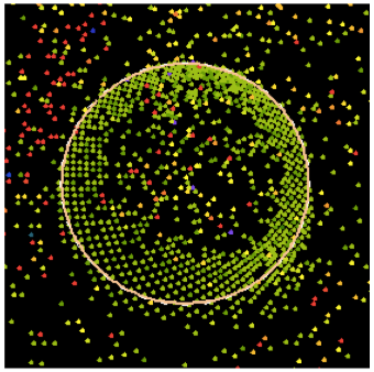
- $e^{\pm}, \gamma$

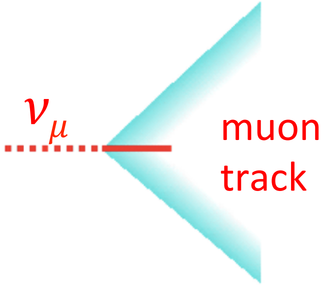
Track-like

- $\mu^{\pm}, \pi^{\pm}, p$

CC ν_μ Events







120 Events

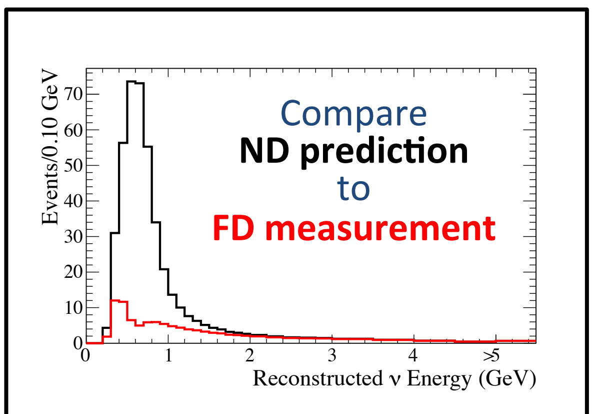
91% efficiency

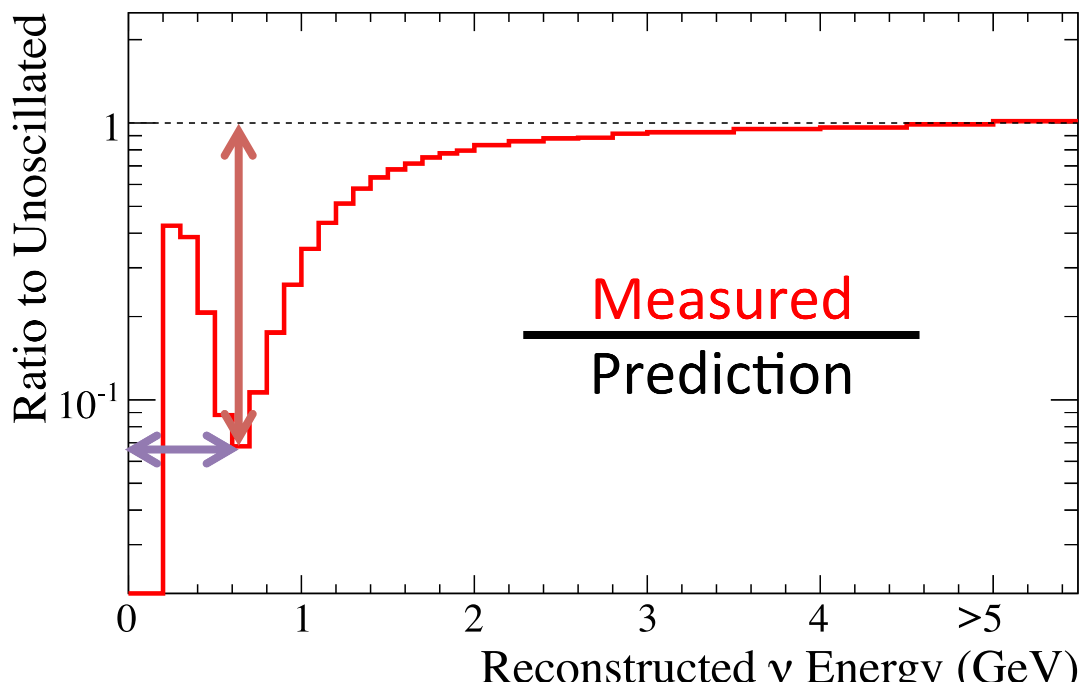
How We Measure Oscillations:
Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 -$$

$$\left(\cos^4 \theta_{13} \boxed{\sin^2 2\theta_{23}} + \boxed{\sin^2 \theta_{23}} \sin^2 2\theta_{13} \right) \sin^2 \left(\frac{\boxed{\Delta m^2} L}{4E_\nu} \right)$$

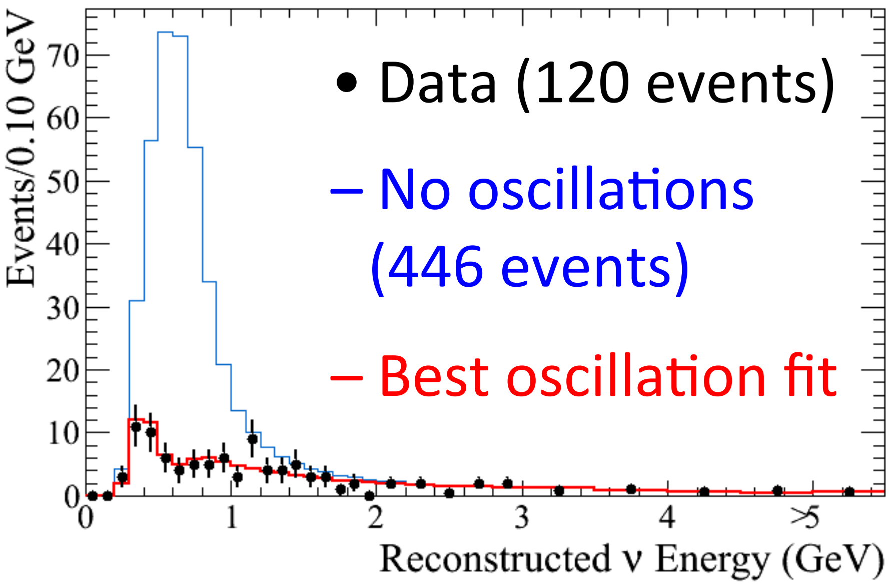
PDG 2013

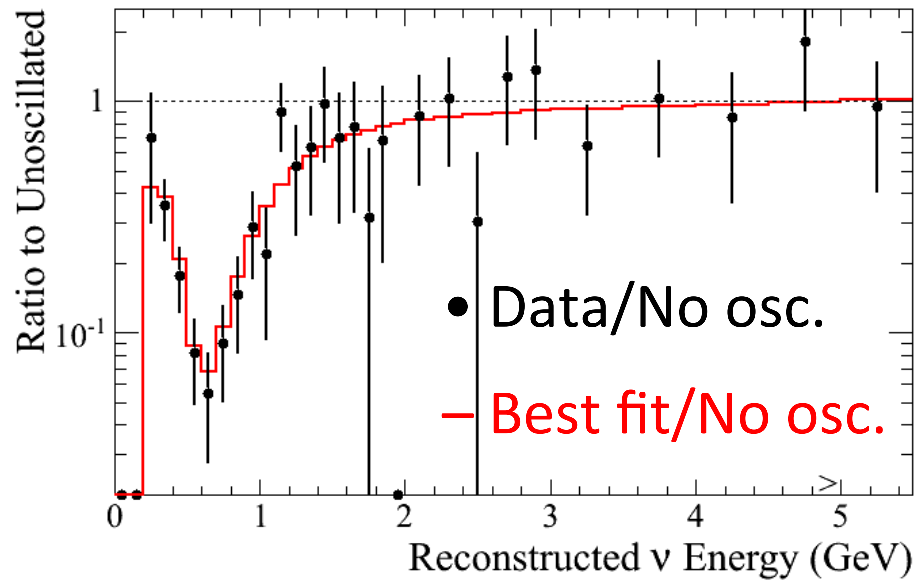




Alex Himmel

Fit for ν_μ Disappearance





Normal Hierarchy

$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$

$$\Delta m^2_{32} = (2.51 \pm 0.10) \times 10^{-3}\,\mathrm{eV}^2$$

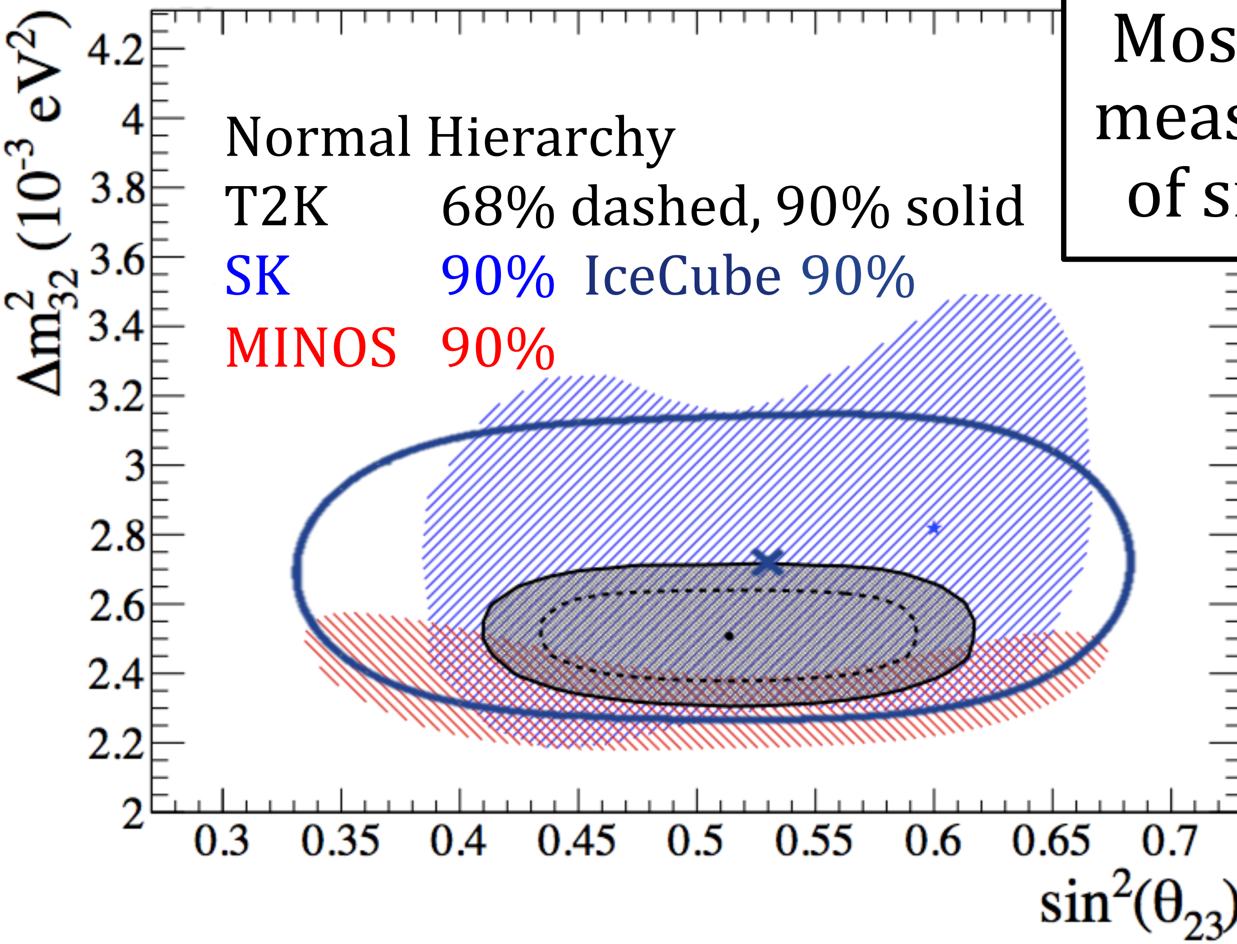
Inverted Hierarchy

$$\sin^2\theta_{23} = 0.511 \pm 0.055$$

$$\Delta m^2_{13} = (2.48 \pm 0.10) \times 10^{-3}\,\mathrm{eV}^2$$

PRL 112 (2014) 181801

Fit for ν_μ Disappearance



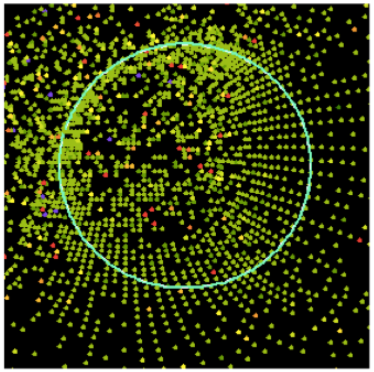
Most precise measurement of $\sin^2(\theta_{23})$!

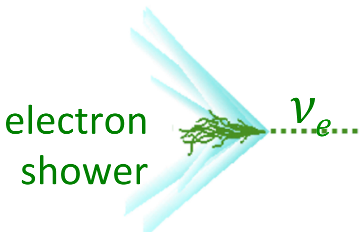
Best fit at maximal disappearance

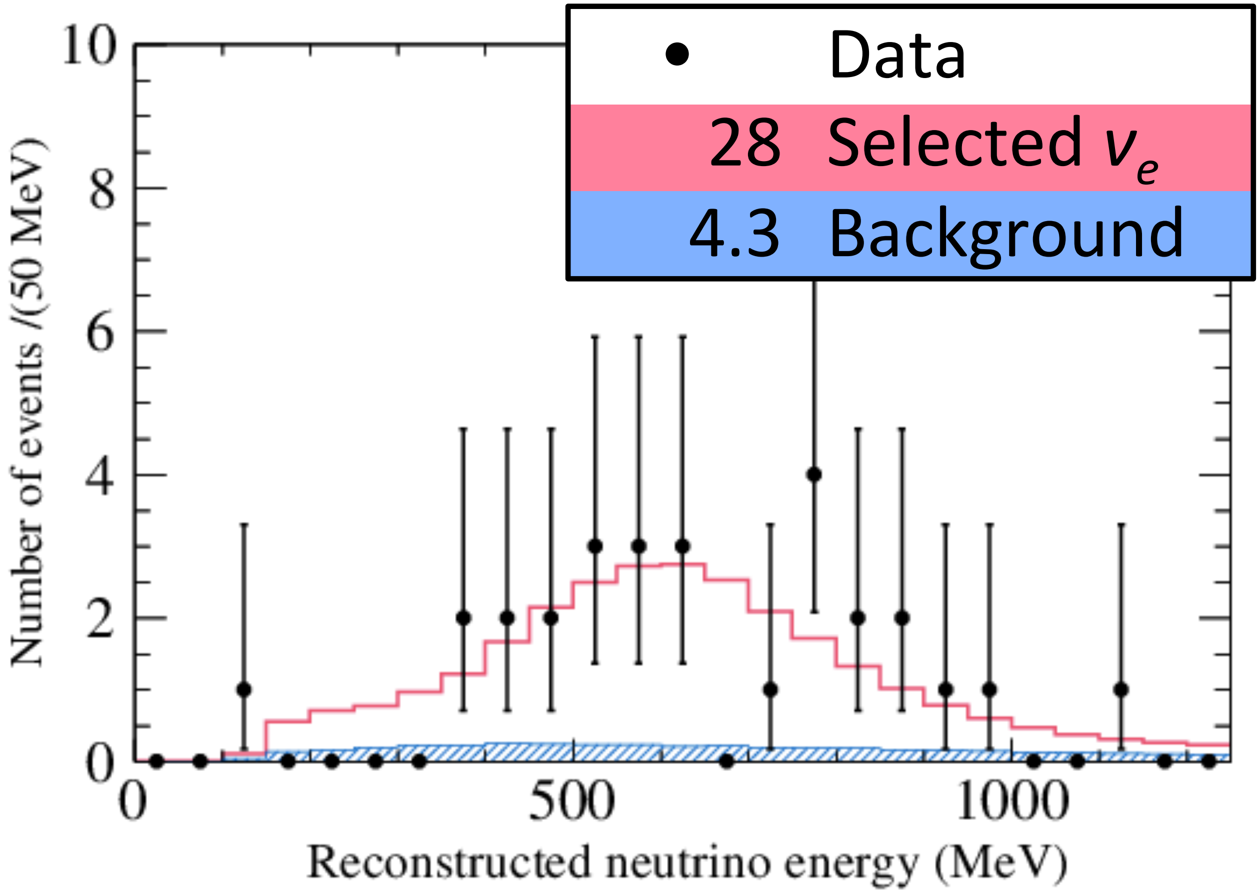
– Result narrower than sensitivity by 0.04 in $\sin^2(\theta_{23})$

PRL 112 (2014) 181801

CC ν_e Events





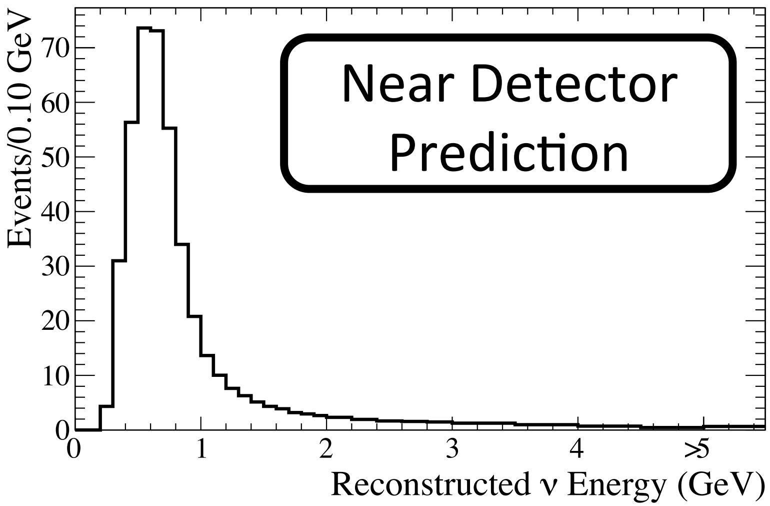


28 Events

66% efficiency

Background-only excluded at > 7σ

Fit for ν_e Appearance



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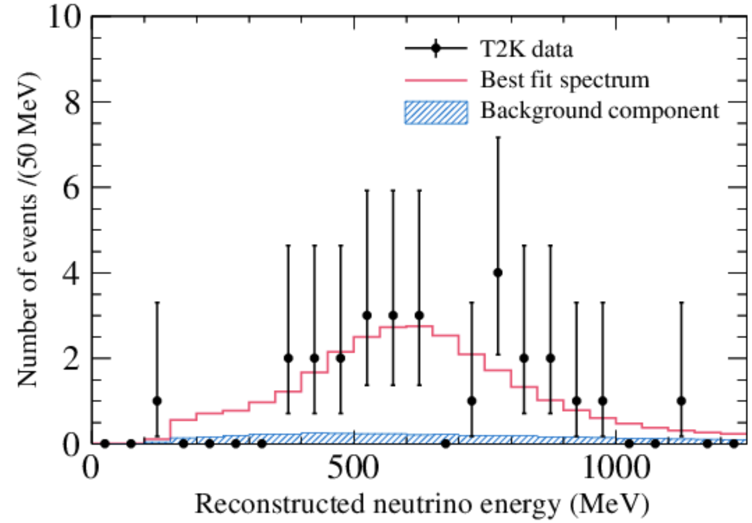
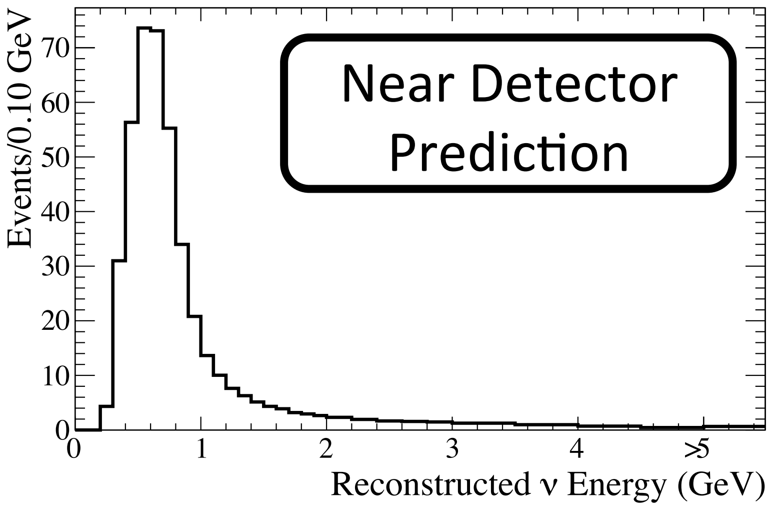


Combine ***ν_e* appearance sample** with near detector **unoscillated prediction** to extract oscillation parameters.

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\boxed{\sin^2 2\theta_{13}}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{4\sqrt{2}G_F n_e E}{\Delta m^2_{31}}\left(1-2\boxed{\sin^2\theta_{13}}\right)\right)$$
$$-\sin 2\theta_{12}\sin 2\theta_{23}\boxed{\sin 2\theta_{13}\cos\theta_{13}}\boxed{\sin\delta}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

CP violation

Fit for ν_e Appearance



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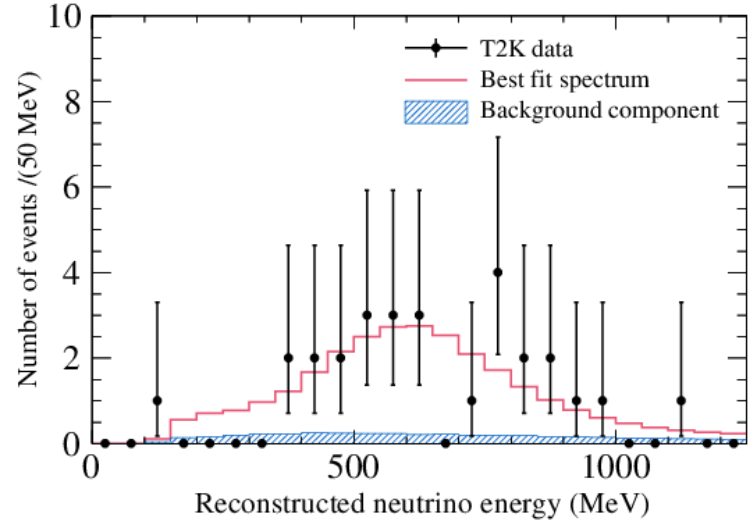


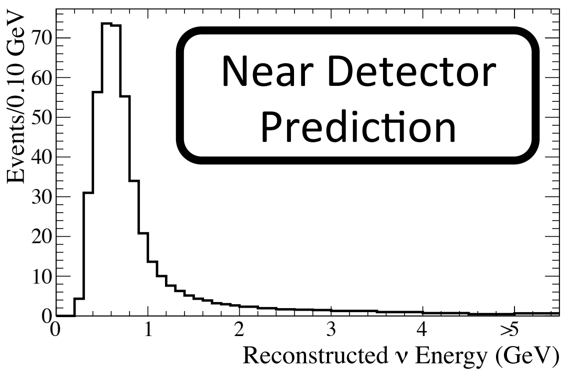
Combine **ν_e appearance sample** with near detector **unoscillated prediction** to extract oscillation parameters.

$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2\theta_{23}}\,\boxed{\sin^2 2\theta_{13}}\sin^2\left(\frac{\boxed{\Delta m^2_{32}}L}{4E_\nu}\right)\left(1+\frac{4\sqrt{2}G_F n_e E}{\boxed{\Delta m^2_{31}}}\left(1-2\boxed{\sin^2\theta_{13}}\right)\right)$$

$$-\sin 2\theta_{12}\,\boxed{\sin 2\theta_{23}}\,\boxed{\sin 2\theta_{13}\cos\theta_{13}}\,\boxed{\sin\delta}\,\sin^2\left(\frac{\boxed{\Delta m^2_{32}}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

CP violation

Joint Fits to $\nu_\mu + \nu_e$



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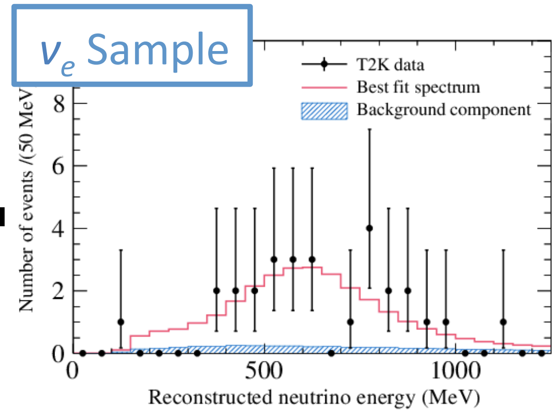

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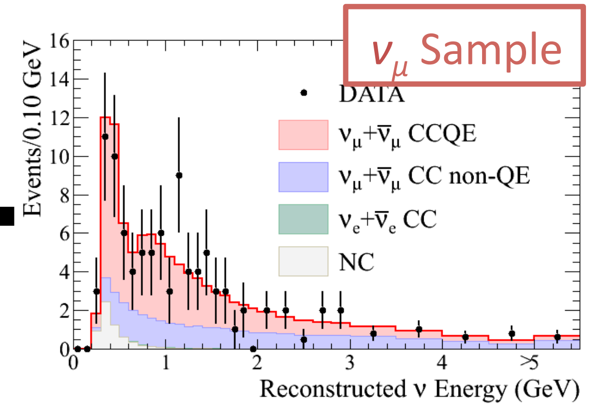
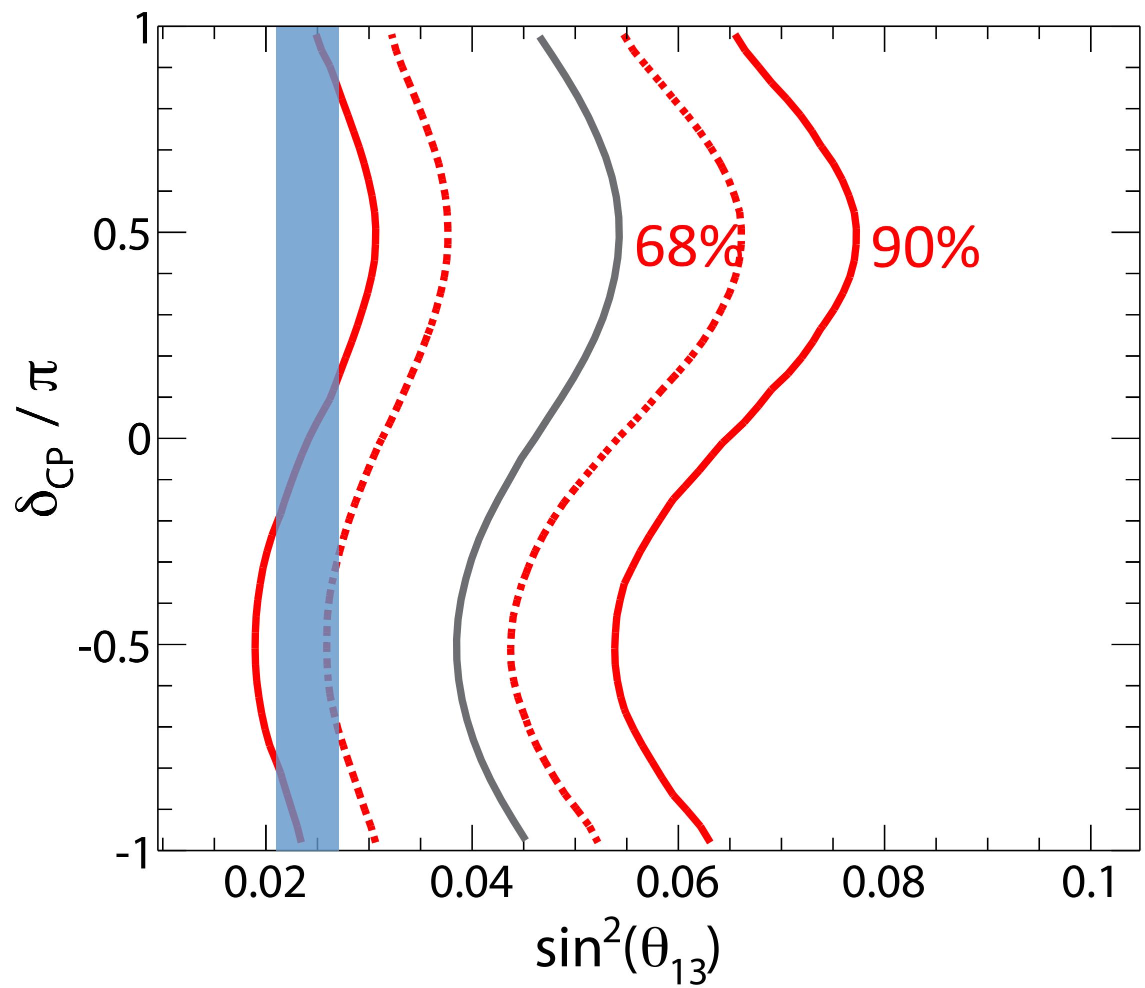


- Likelihood ratio fit of ν_μ and ν_e samples
- Both Frequentist and Bayesian analyses performed
- Simultaneous fit for: $\boxed{\delta_{cp},\ \theta_{13},\ \theta_{23},\ \Delta m^2_{32}}$

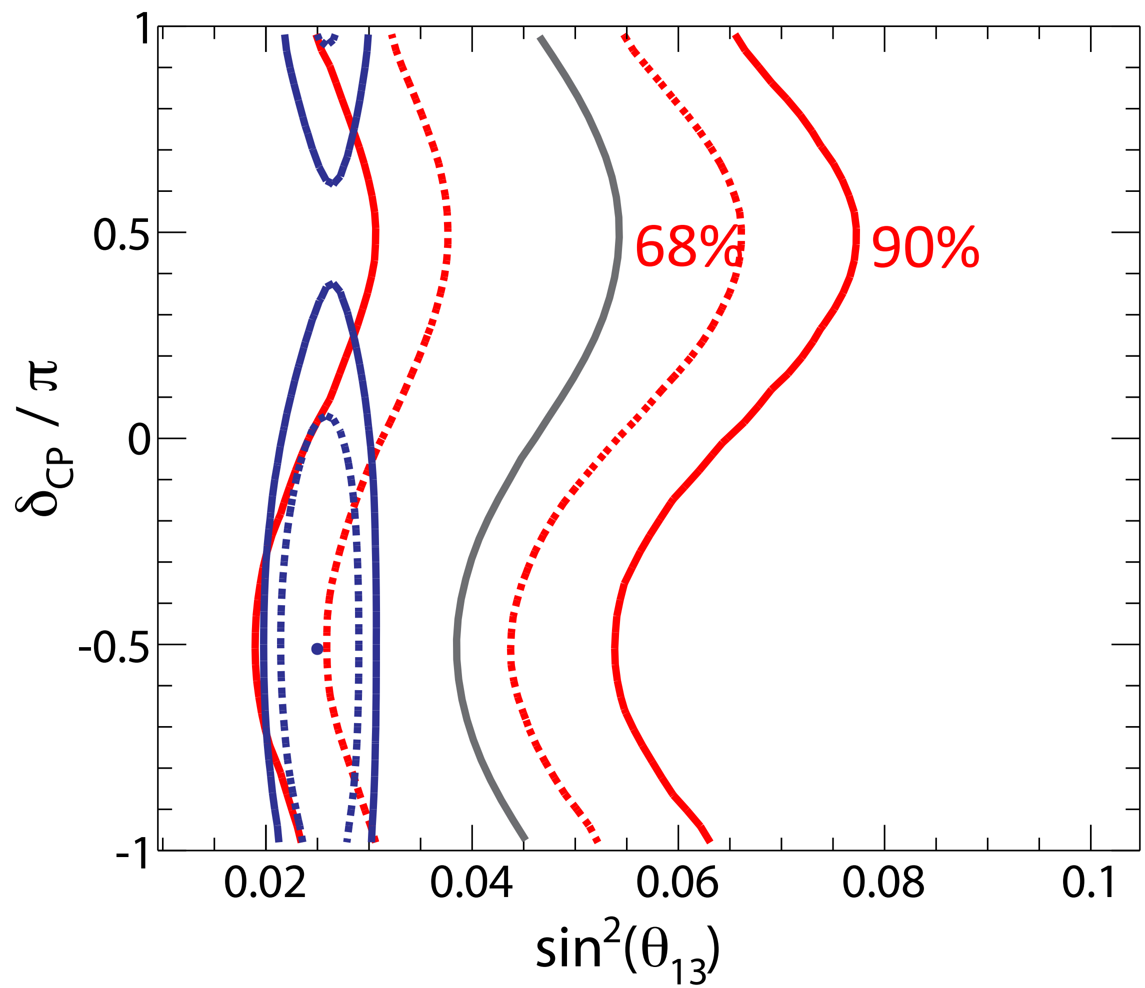
Contours using T2K Data Only

- $\sin^2(\theta_{23})$ shifts up to 0.52 in response to large appearance signal
- Our appearance signal is large relative to reactor measurements
  - 2013 Weighted average
    - Daya Bay
    - RENO
    - Double Chooz
  - $\sin^2(2\theta_{13}) = 0.095 \pm 0.010$



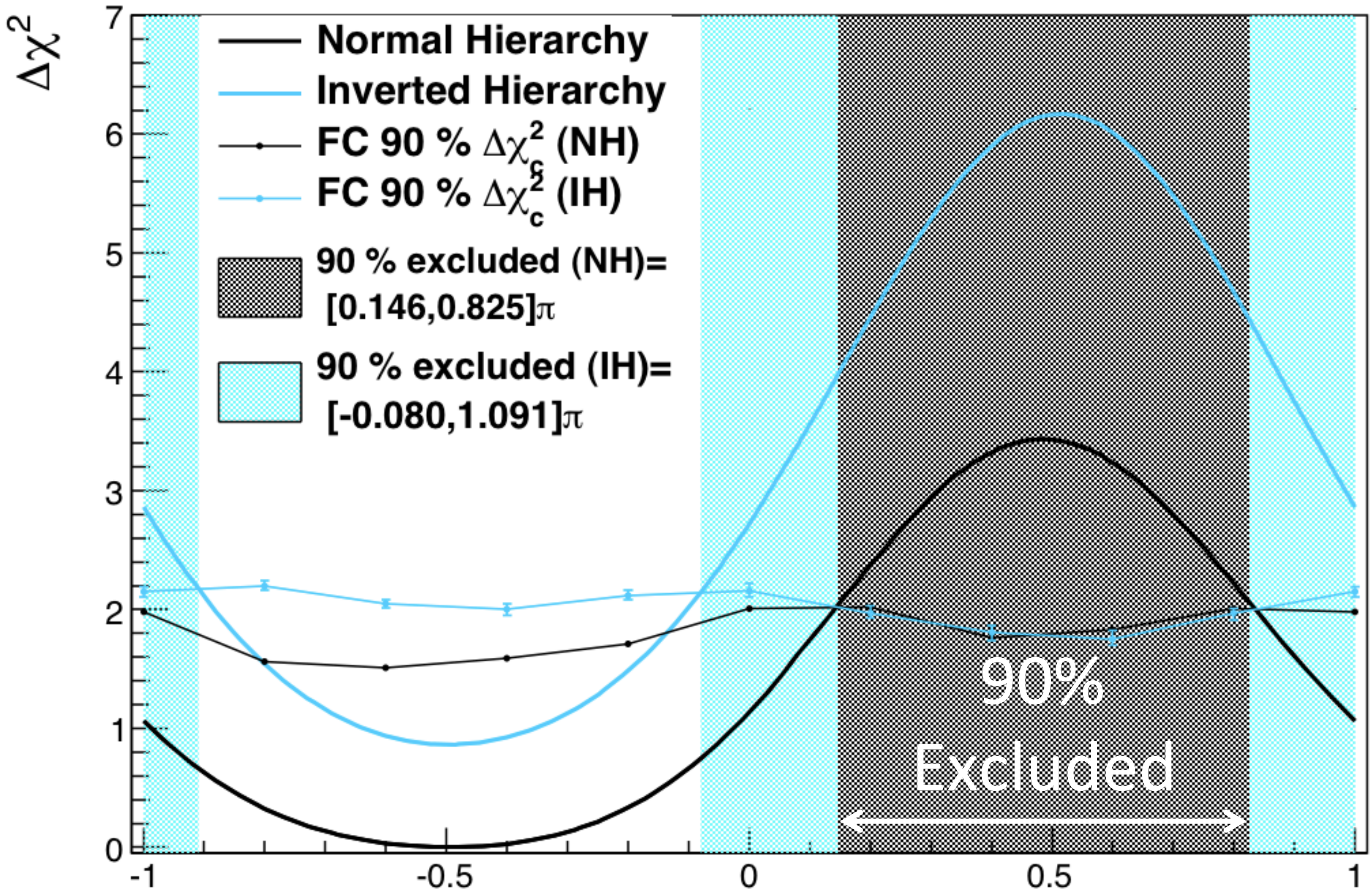
Contours with Reactor Constraint

- $\sin^2(\theta_{23})$ shifts up to 0.52 in response to large appearance signal
- Our appearance signal is large relative to reactor measurements
  - 2013 Weighted average
    - Daya Bay
    - RENO
    - Double Chooz
  - $\sin^2(2\theta_{13}) = 0.095 \pm 0.010$



PRD 91 (2015) 072010

Constraint on δ_{CP}

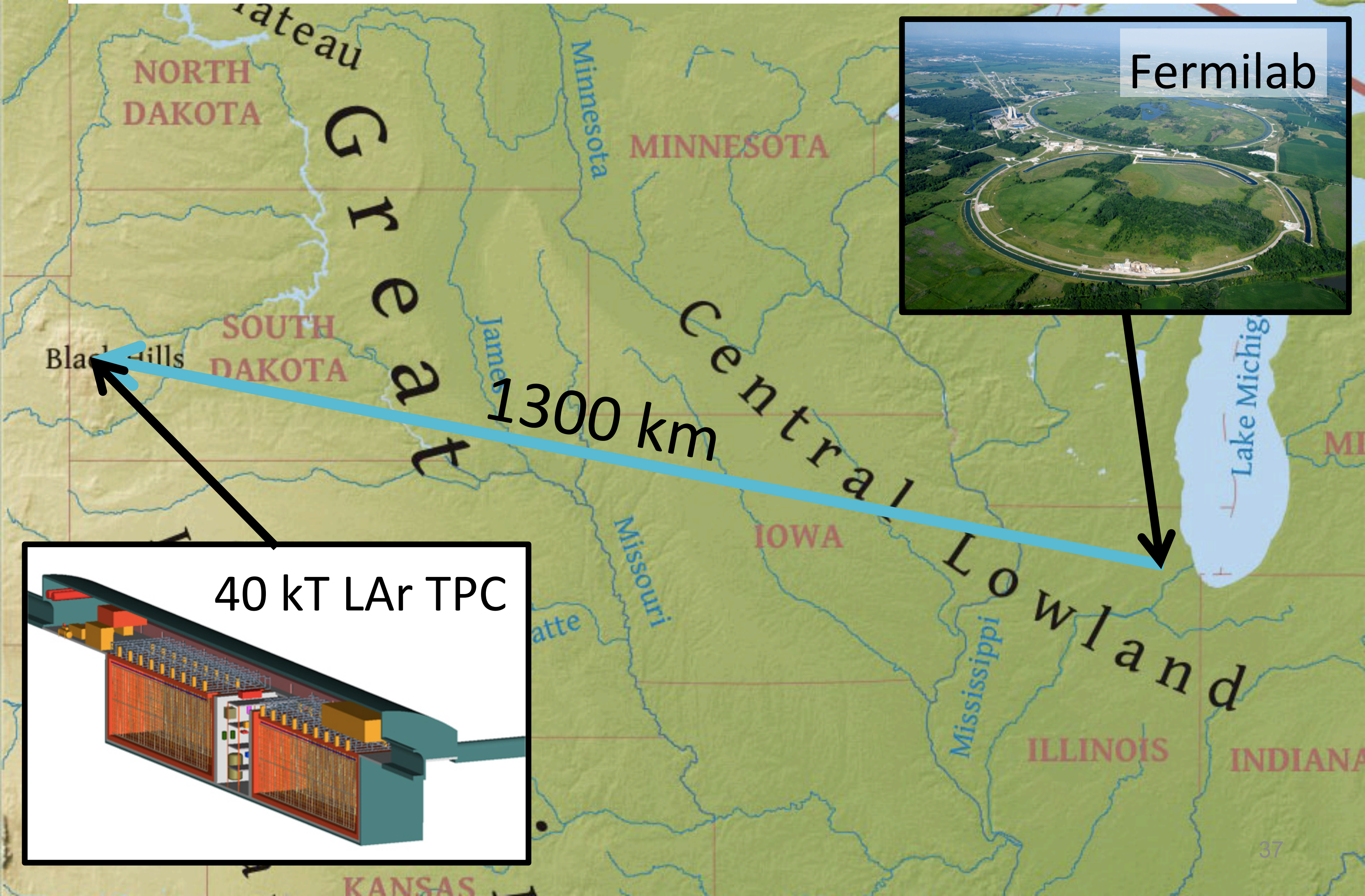


27°–149°

First exclusion of a region of δ_{CP}!

PRD 91 (2015) 072010

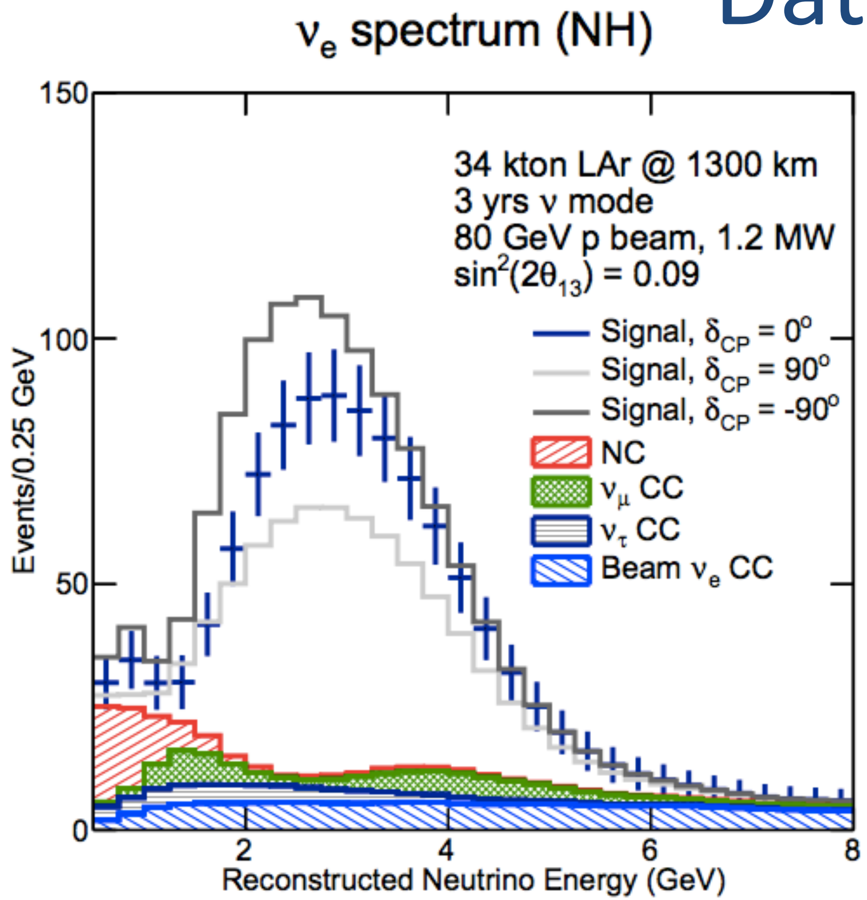
The DUNE Experiment

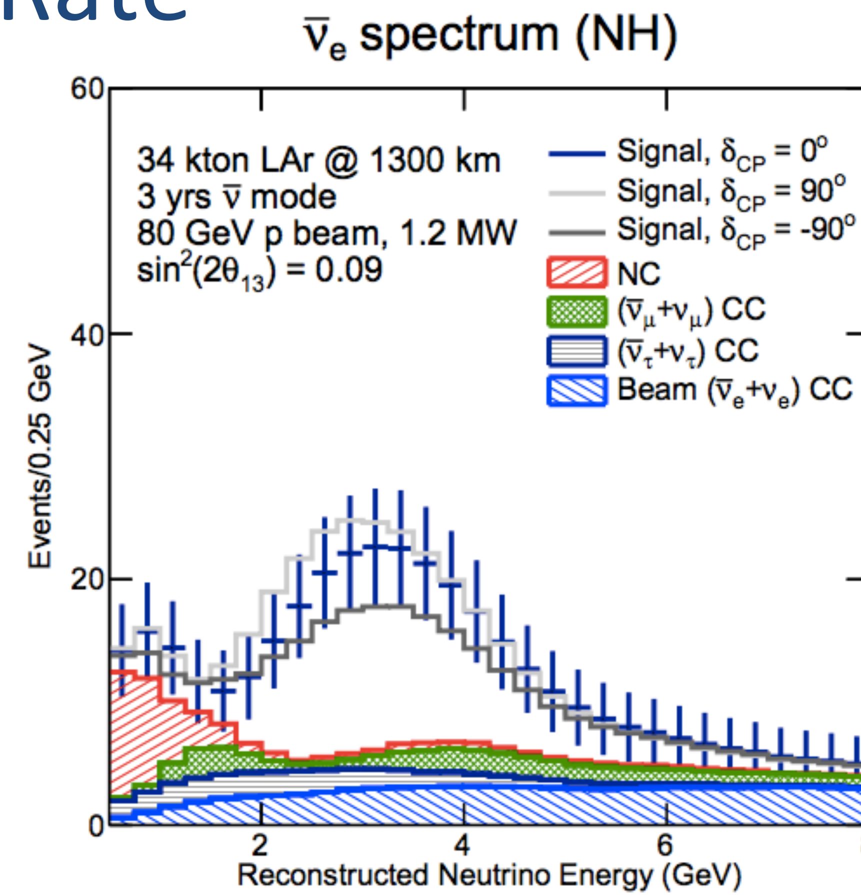


DUNE Status

- Recently reformed as a new international collaboration
  - 769 collaborators from 147 institutions

Data Rate

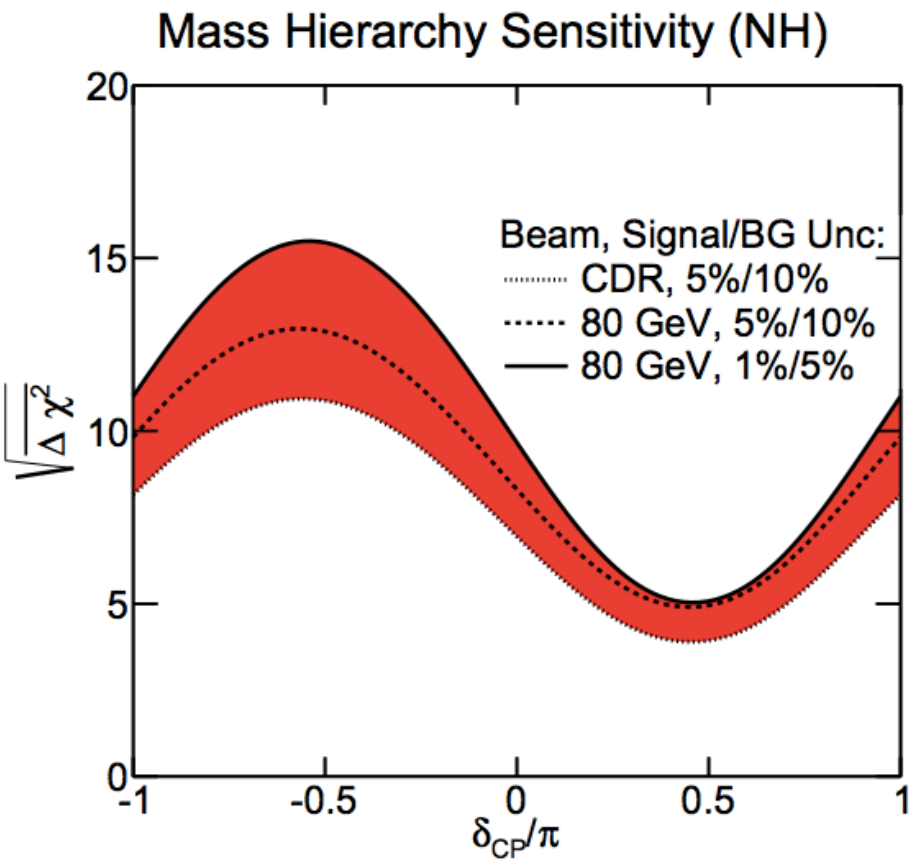


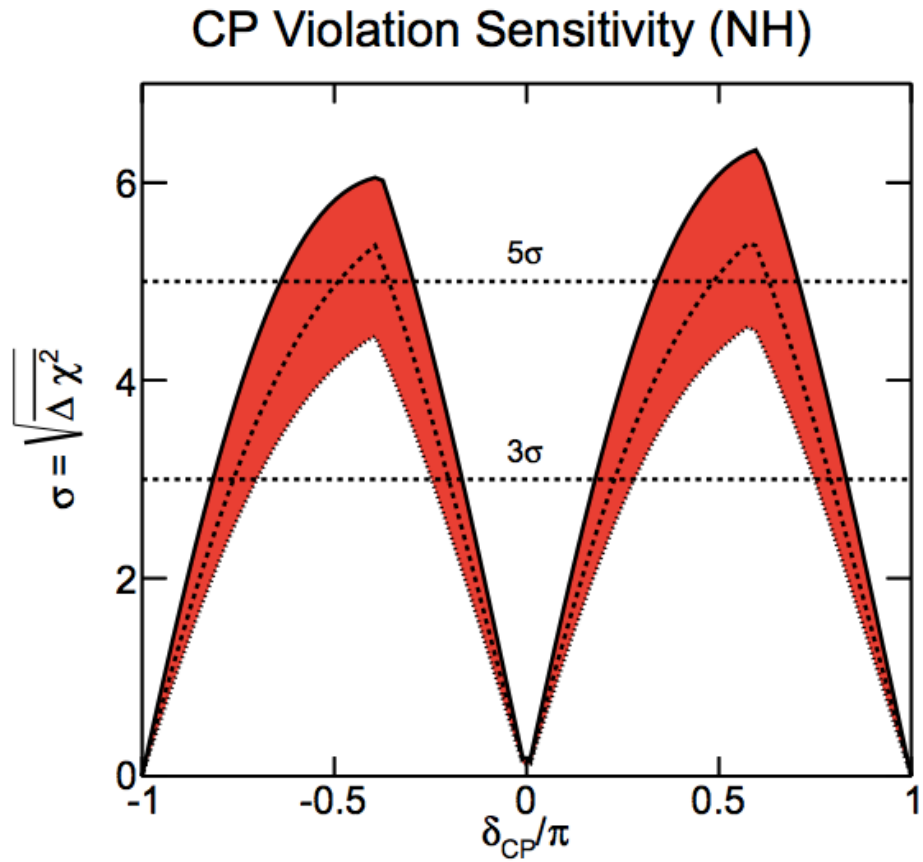


Long baseline, wide band beam allows mass hierarchy, and potentially second maximum measurements.

LBNE	ν_e	anti-ν_e
Signal	779	139
Background	374	238

MH and CP Violation Sensitivity

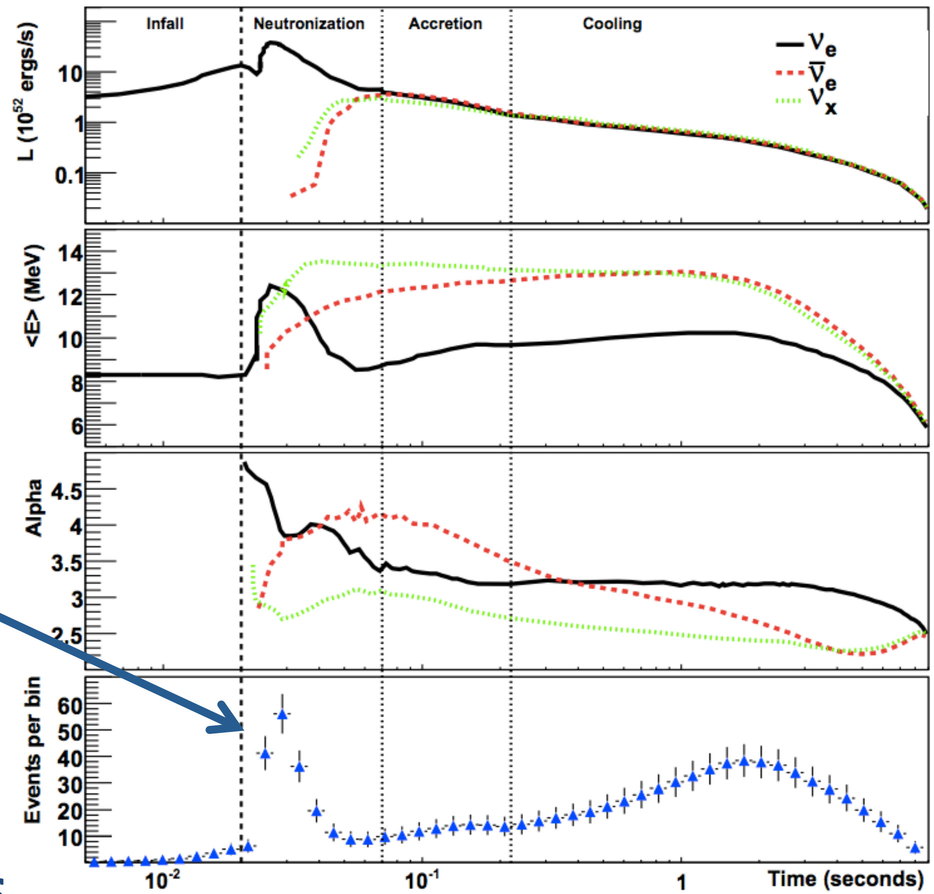




LBNE sensitivities (34 kTon × 3+3 years × 1.2 MW), but not so far off from DUNE sensitivity

More Physics with DUNE

- Other oscillation physics
  – Precision measurements of all mixing angles
- Supernova neutrinos
  – ν_e in DUNE, can see neutronization
- Near detector physics
  – Cross sections, exotics
- Non-neutrino physics
  – Low or no background searches for proton decay to Kaons



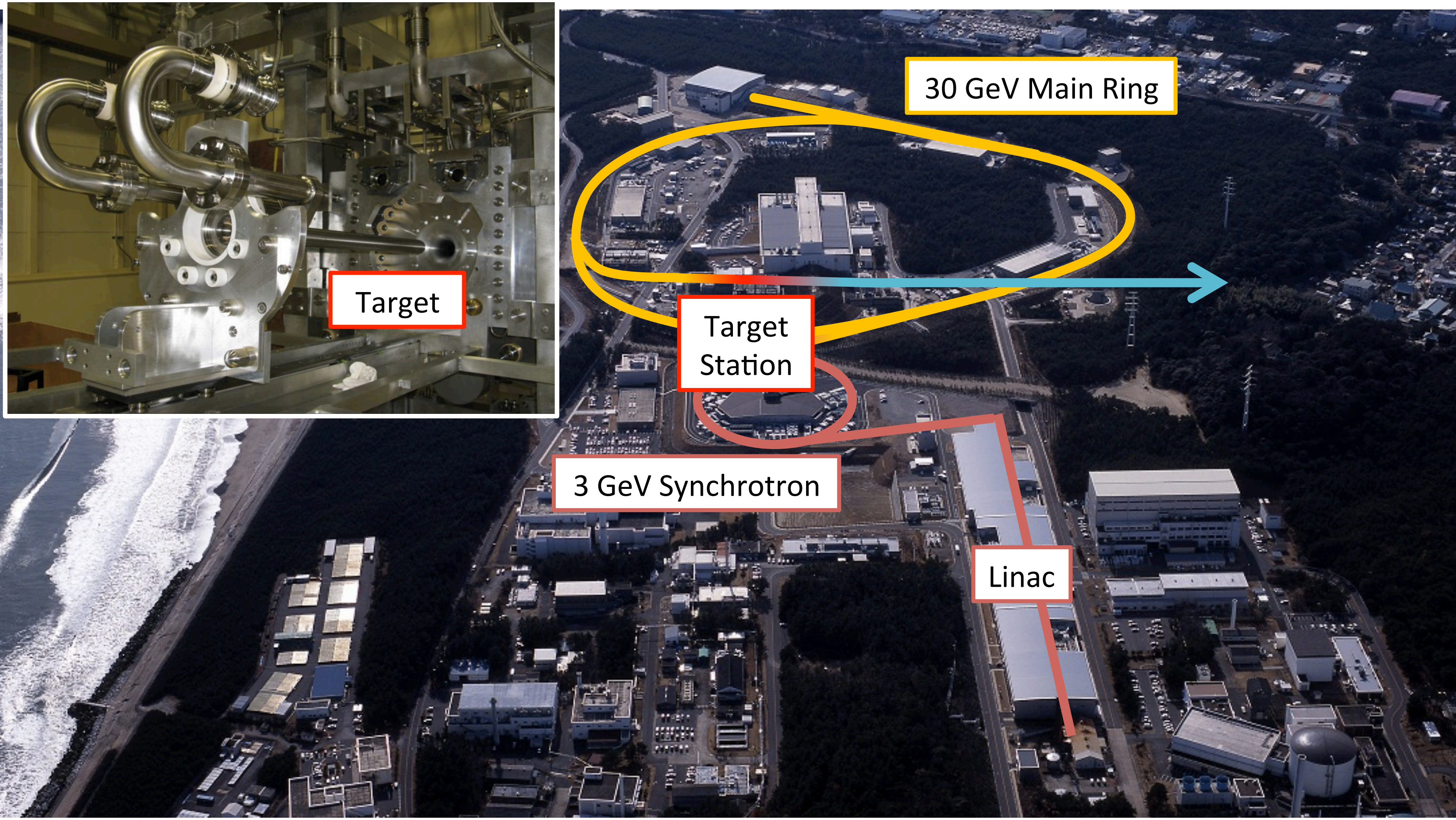
[1] Phys. Rev. Lett., 103:071101, 2009

Conclusions

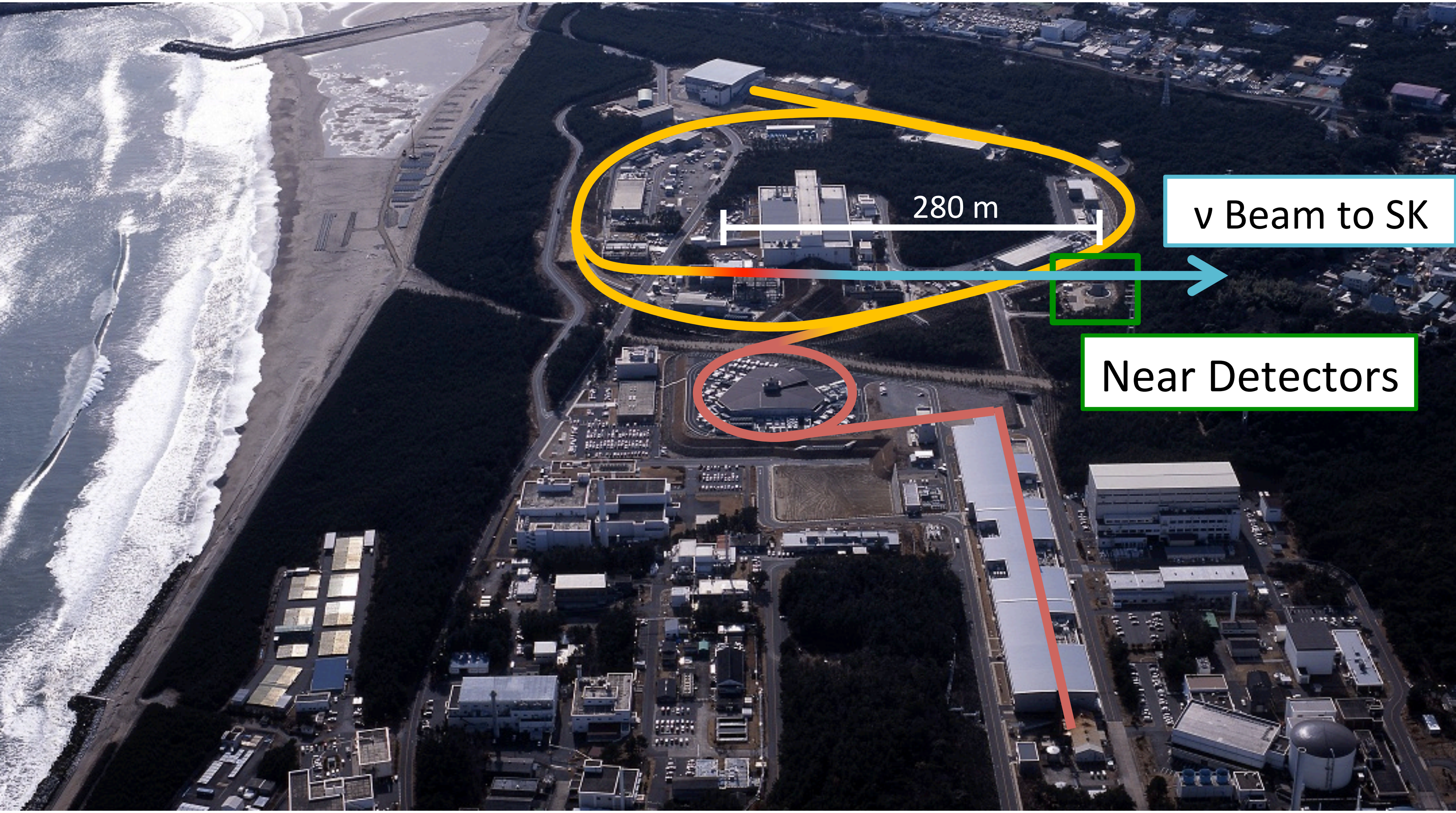
- T2K uses a narrow-band off-axis beam to measure three-flavor neutrino mixing
  - Most precise measurement of θ_{23}
    - Favoring maximal disappearance
  - >7σ evidence of ν_e appearance
  - First exclusion of a range of δ_{CP}
- With full exposure, T2K may see a hint of CP violation
- DUNE is the next generation neutrino oscillation experiment
  - Good sensitivity to CP violation and mass hierarchy
  - Precision test of the 3-neutrino model
  - Lots of other oscillation and non-oscillation physics

Backup Slides

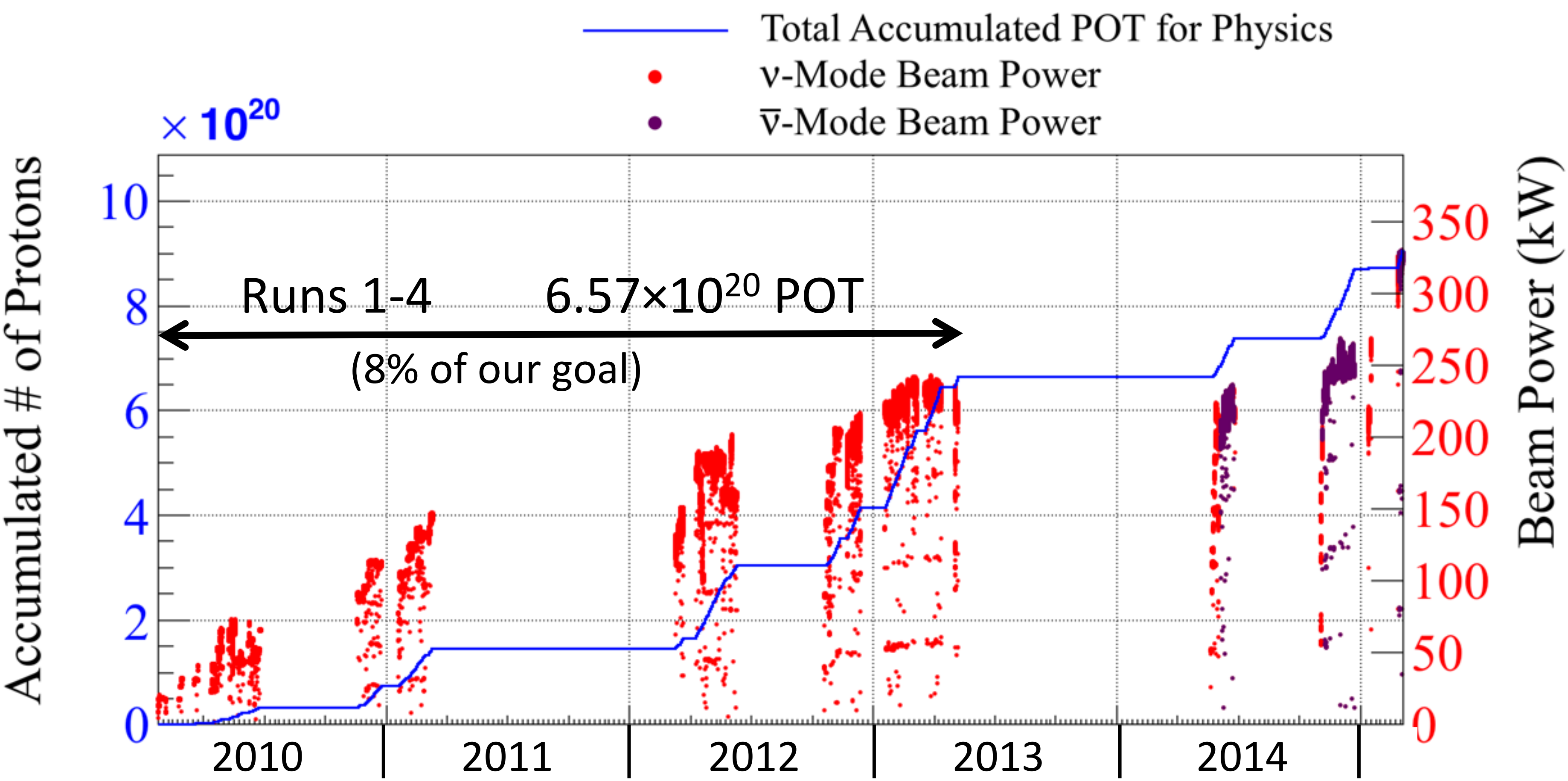
J-PARC Neutrino Beam



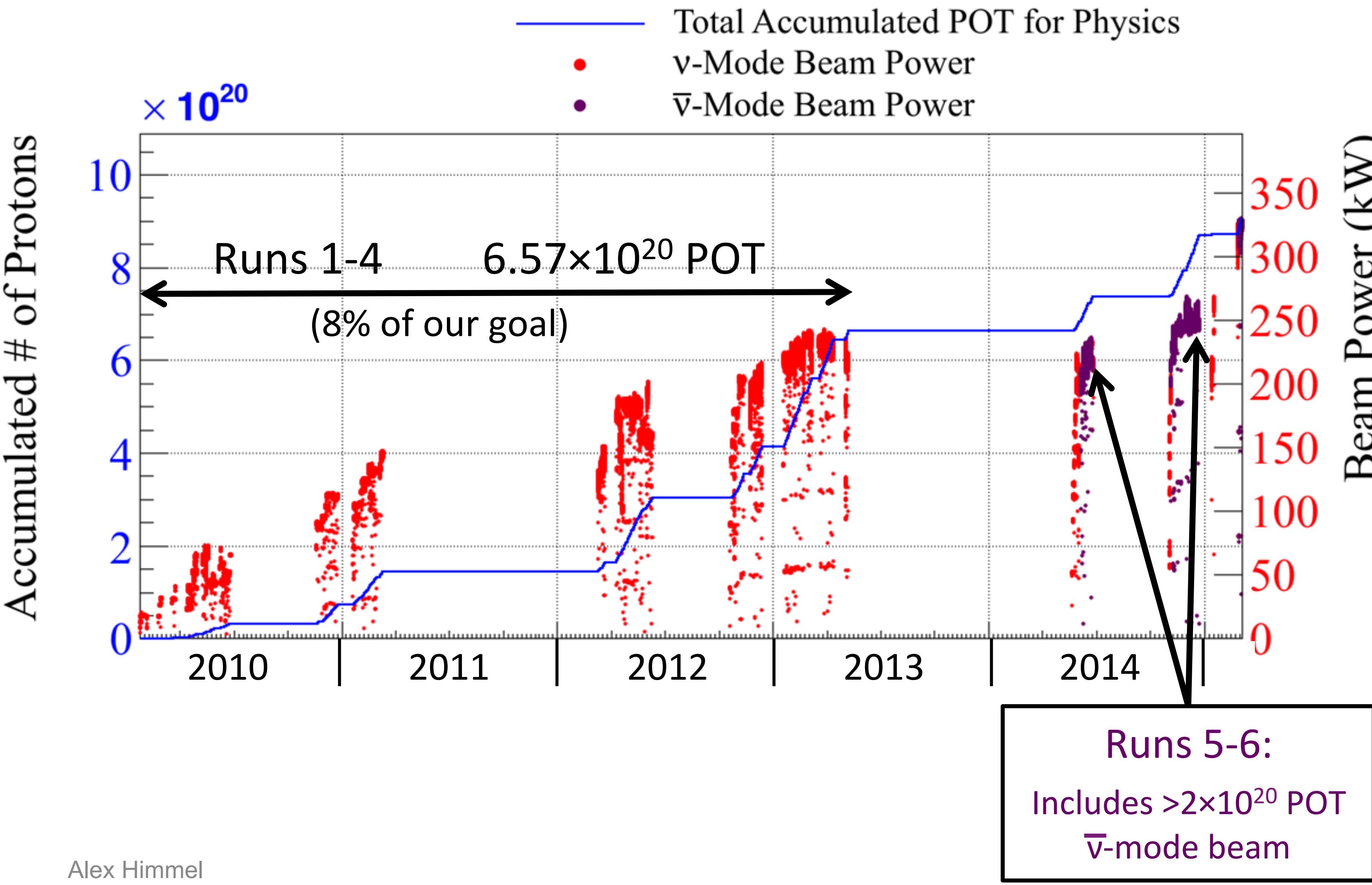
Near Detector



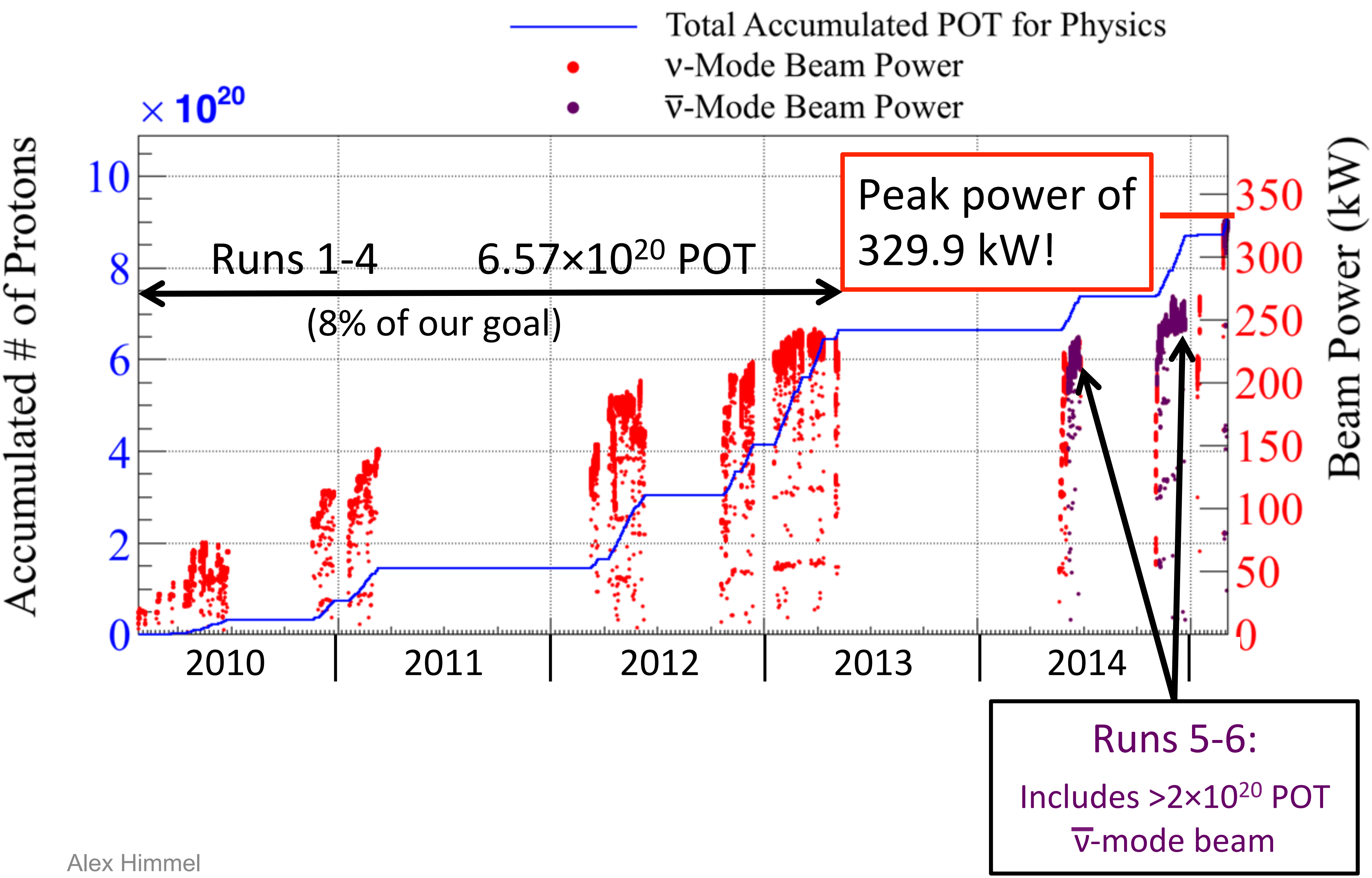
Accumulated Protons-on-Target



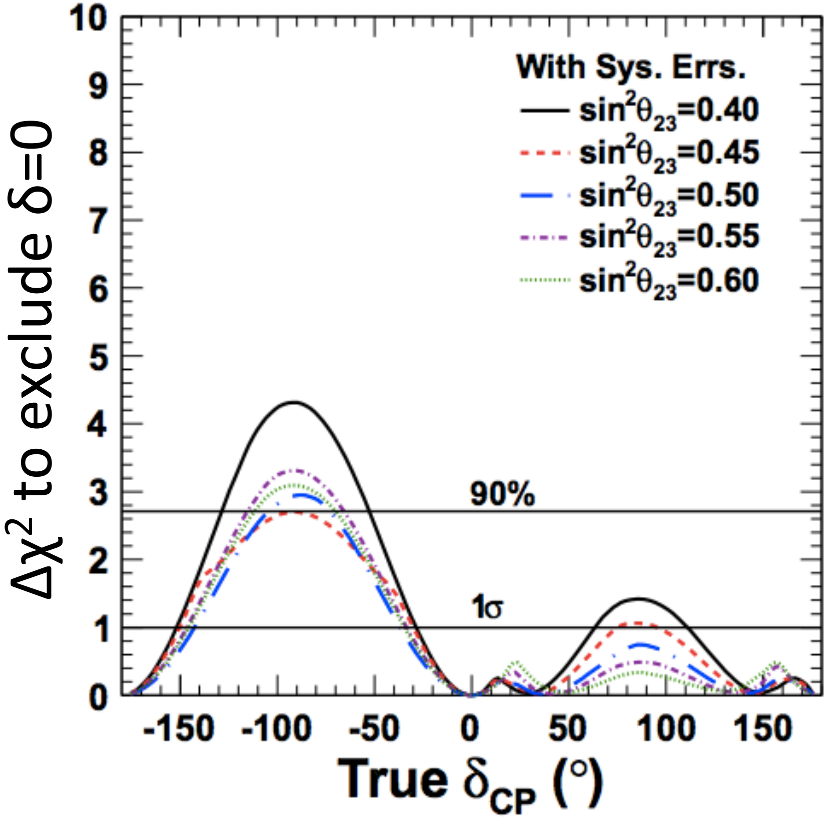
Accumulated Protons-on-Target



Accumulated Protons-on-Target



Future Sensitivity



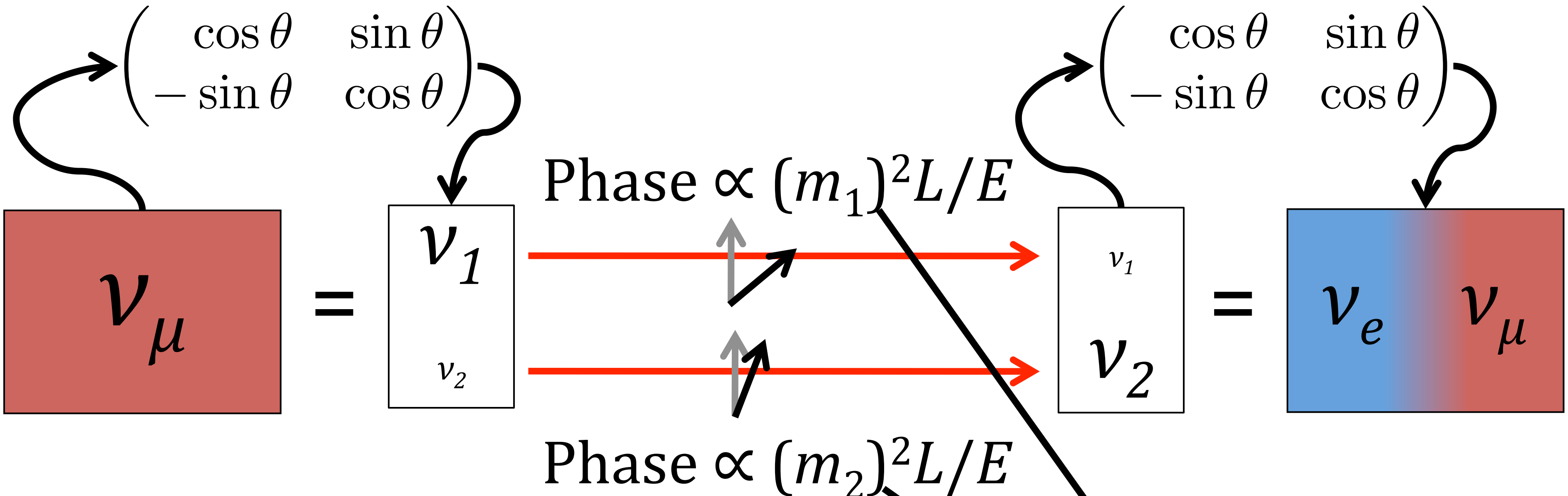
Assumptions

- 7.8×10^{21} POT
- $\sin^2(2\theta_{13}) = 0.1$ with ultimate reactor precision
- $\Delta m^2 = 2.4 \times 10^{-3}$ eV^2
- $\sin^2(\theta_{23})$ as shown
- Normal Hierarchy
- Conservative (2012) systematic errors, correlated between nu and antinu

- Evaluated potential future sensitivity under different running conditions
  - 50% neutrino/50% antineutrino best sensitivity for the widest range of true parameters values

Accepted by PTEP, arXiv:1409.7469 [hep-ex]

Neutrino Oscillations



Muon Neutrino Survival Probability

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

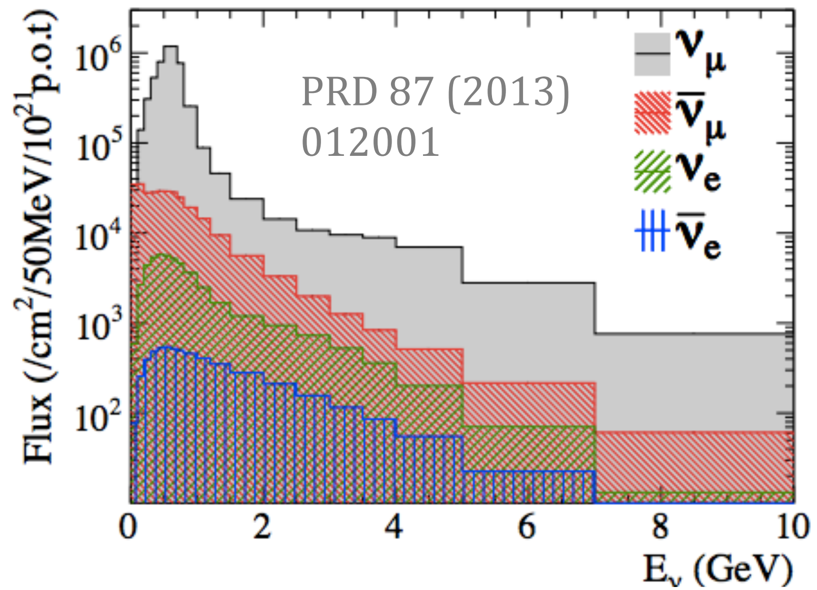
Beam Modeling and Constraint

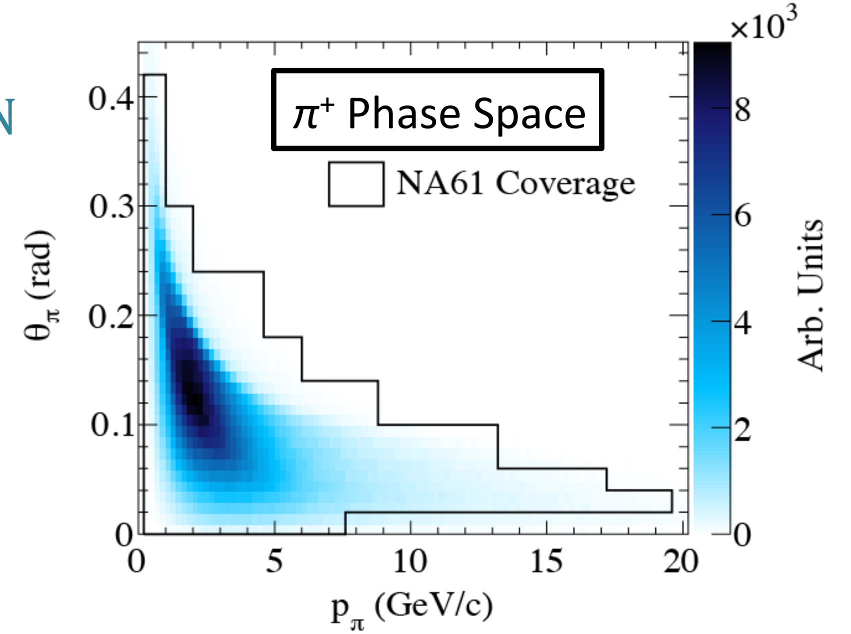
- Simulate the beam with:
  - Fluka in target, Geant3 in beamline
- Components:

  $93\%\ \nu_\mu$ $6\%\ \bar{\nu}_\mu$

  $1\%\ \nu_e$ $0.1\%\ \bar{\nu}_e$

- Reweight hadronic interactions and π/K production with external data
  - Reweight in target (C) and horns (Al)
  - Primary source is NA61/SHINE at CERN
    - Same beam energy and carbon target
  - Other sources for aluminum interactions

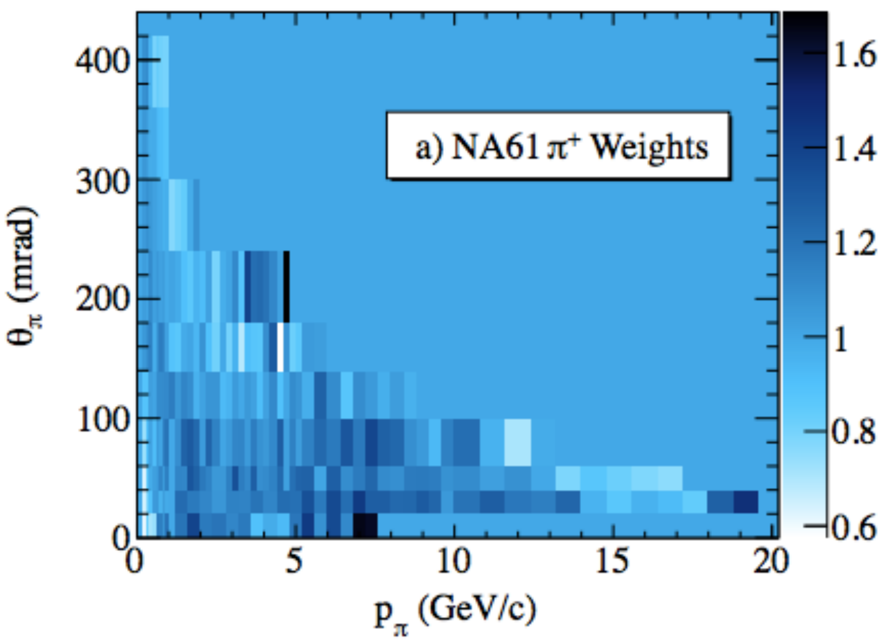


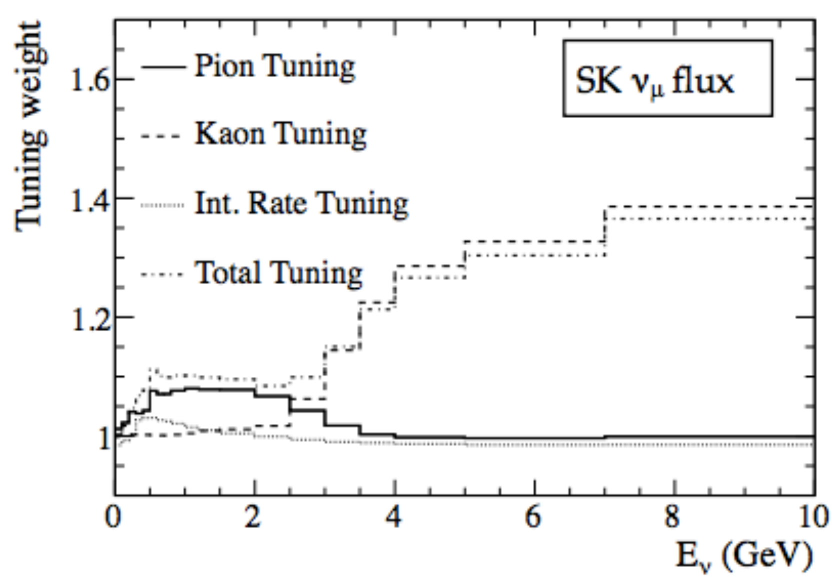


[1] N. Abgrall *et al.* (NA61/SHINE Collaboration), Phys. Rev. C 84, 034604 (2011)
[2] N. Abgrall *et al.* (NA61/SHINE Collaboration), Phys. Rev. C 85, 035210 (2012)
[3] T. Eichten *et al.*, Nucl. Phys. B 44 (1972)
[4] J. V. Allaby *et al.*, Tech. Rep. 70-12 (CERN,1970)

Flux Constraints with External Data

- Reweight the beam MC based on external hadron production data
  - NA61/SHINE (CERN) [1][2] which has 30 GeV *p*-C collisions
  - Eitchen et al. [3] , and Allaby et al. [4]
- We reweight hadron production in both the target (carbon) and horns (aluminum)
- Tune hadron interaction rate and π/K production

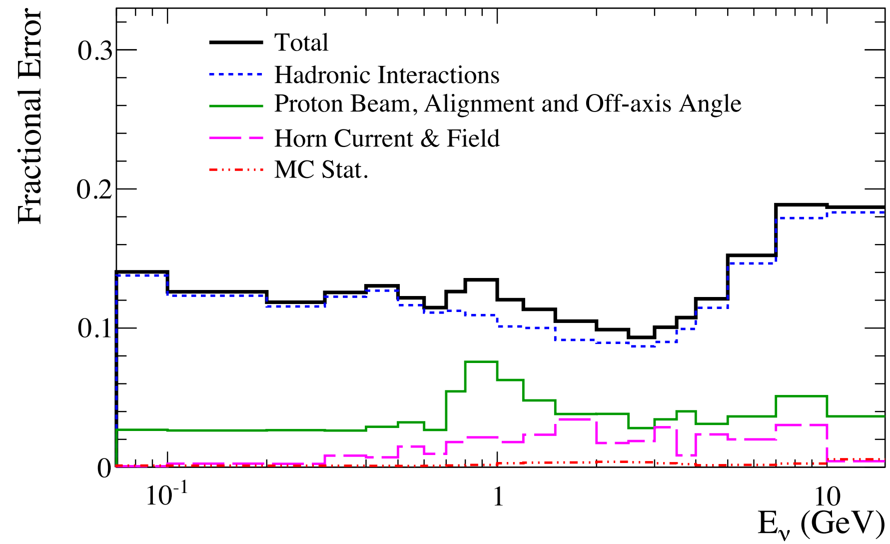


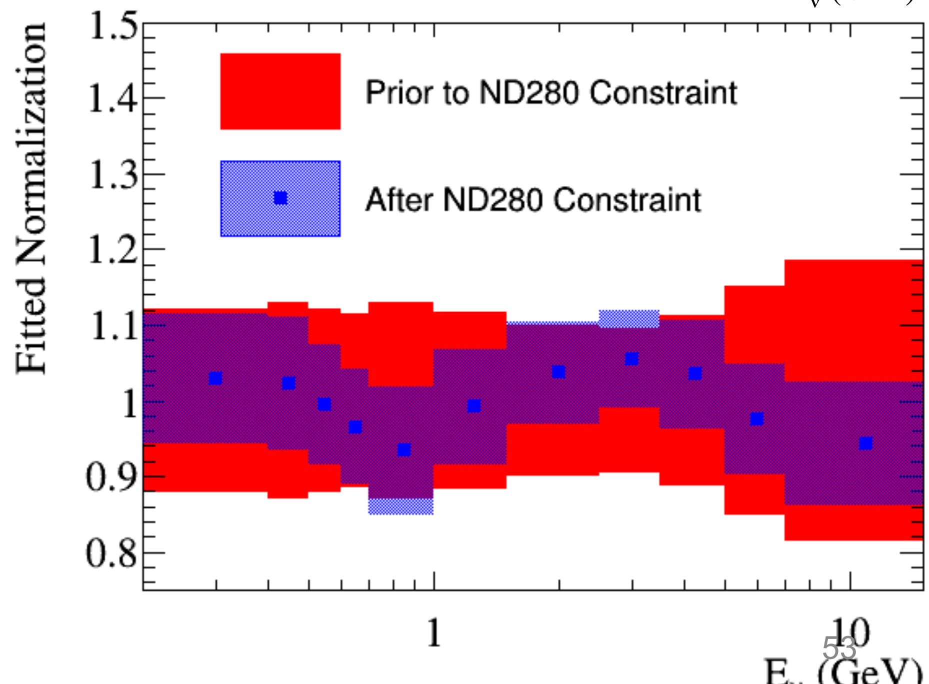


[1] N. Abgrall *et al.* (NA61/SHINE Collaboration), Phys. Rev. C 84, 034604 (2011)
[2] N. Abgrall *et al.* (NA61/SHINE Collaboration), Phys. Rev. C 85, 035210 (2012)
[3] T. Eichten *et al.*, Nucl. Phys. B 44 (1972)
[4] J. V. Allaby *et al.*, Tech. Rep. 70-12 (CERN,1970)

Flux Systematic Uncertainties

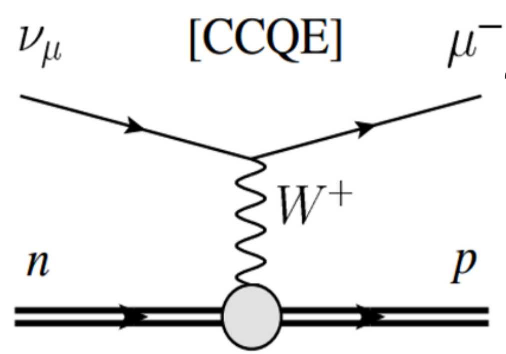
- 10-15% error on flux w/ external data
  - Hadron production
  - Beam alignment
- After fit to ν_μ CC data
  - Flux error alone goes from 12% → 8% at osc. peak
  - Central values shifted to better fit the data

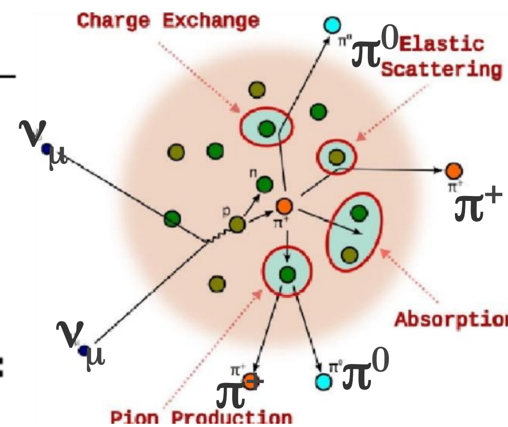




Cross Section Simulation and Constraints

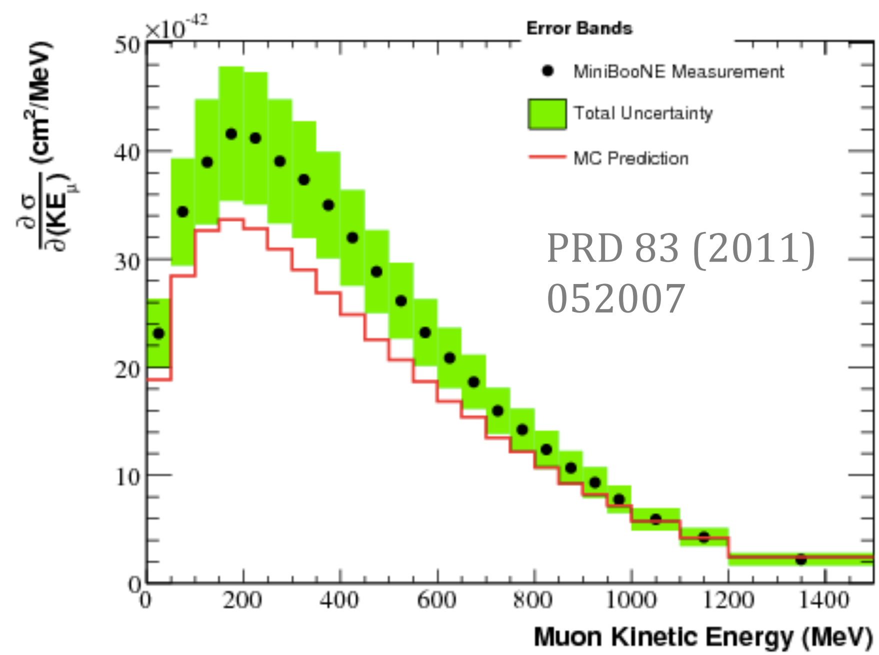
- NEUT simulation (2012)
  - Initial interaction
    - CCQE, resonant-π, etc.
  - Final State nuclear effects
    - charge exchange, π absorption, etc.





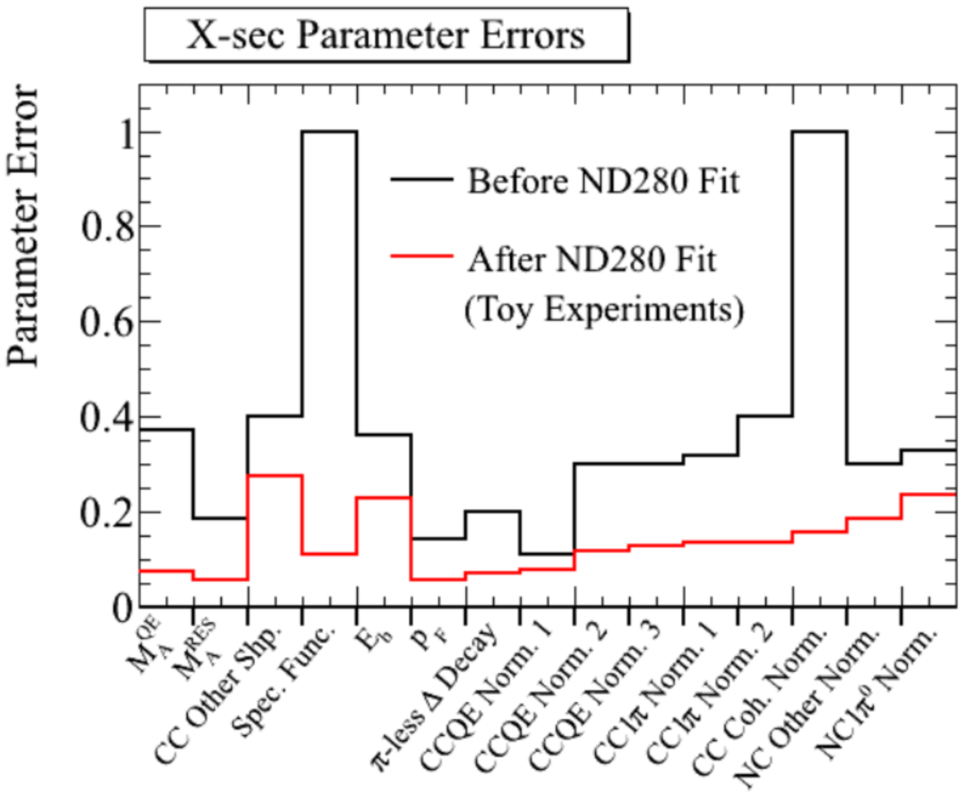
- Parameterize models
  - Some model parameters like M_A, p_F, E_b
  - Some energy-dependent normalizations

- Tune model parameters to external neutrino data
  - Primarily MiniBooNE



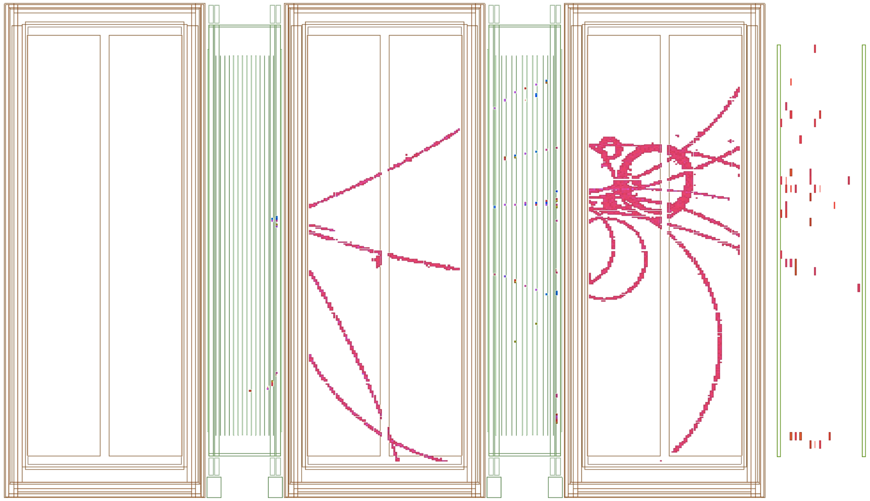
Cross Section Systematic Uncertainties

- Fit to ND280 ν_μ data reduces errors correlated between ND280 and SK
  - Reduced by a factor of 2 or more
- Not all uncertainties constrained:
  - Final state nuclear effects
  - Carbon-Oxygen differences
  - $\sigma(\nu_e)/\sigma(\nu_\mu)$
  - σ(anti-ν)/$\sigma(\nu)$

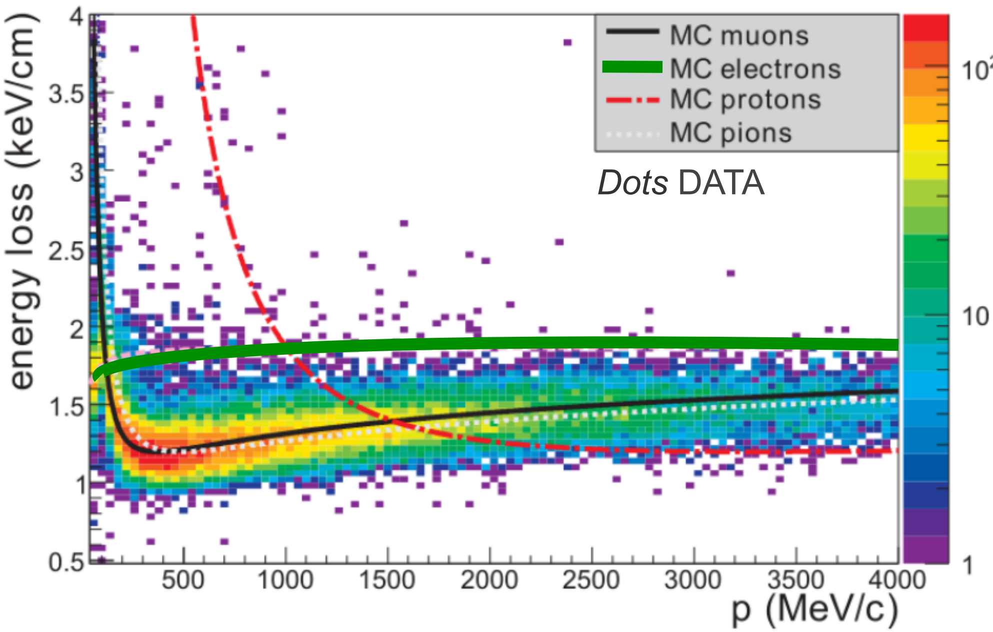


Particle Identification at the ND

- Identify particle types using topology:
  - Track-like or shower-like

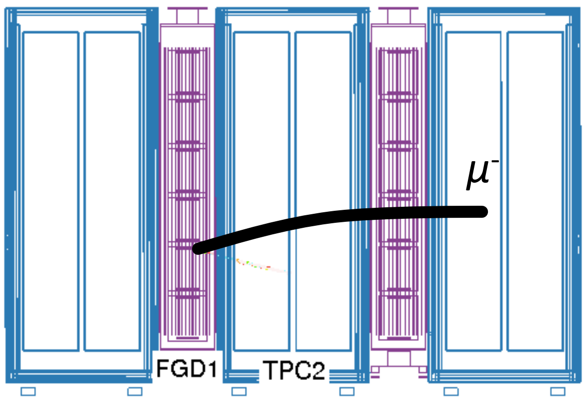


- Identify individual tracks using energy deposition
  - *dE*/*dx* vs. *p* in the TPC's



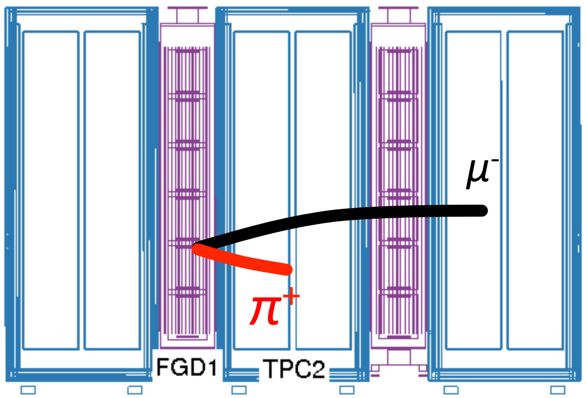
Selecting CCν_μ in ND280

- Divide into 3 sub-samples:



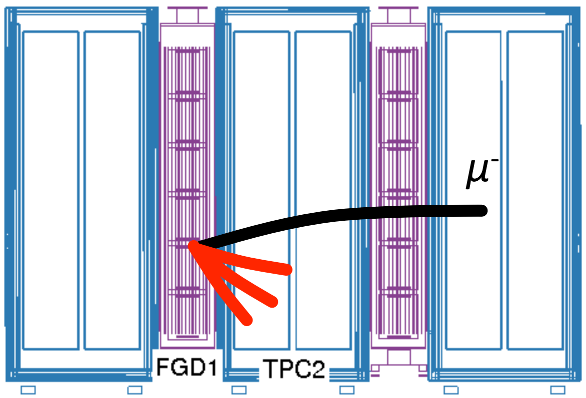
CC 0π

- Quasielastic enhanced sample
- 73% purity



CC 1π$^+$

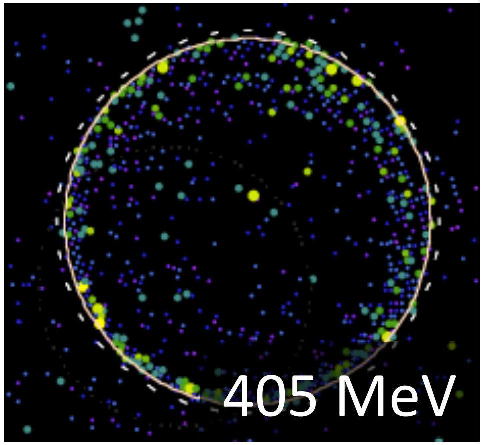
- Δ resonance enhanced sample
- 49% purity

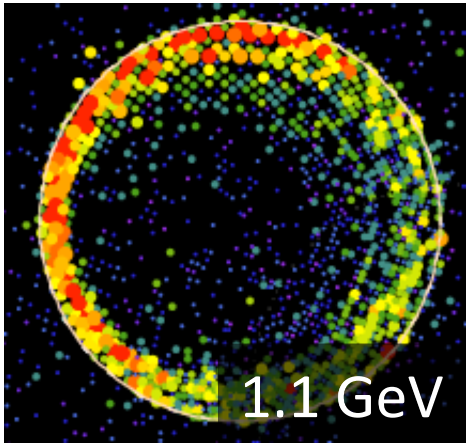


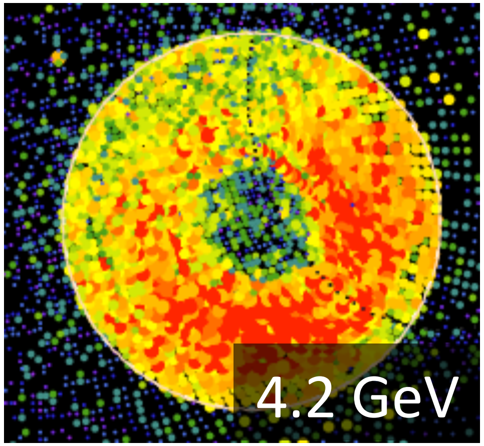
CC other

- Primarily deep inelastic scattering
- 74% purity

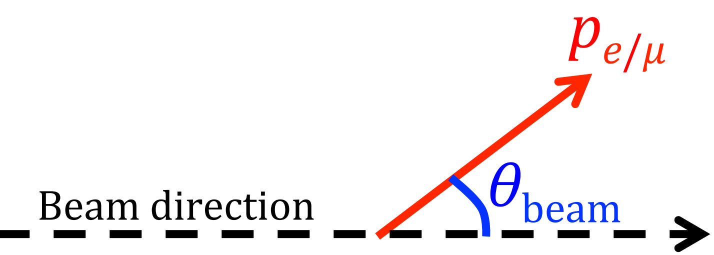
Measuring Neutrino Energy







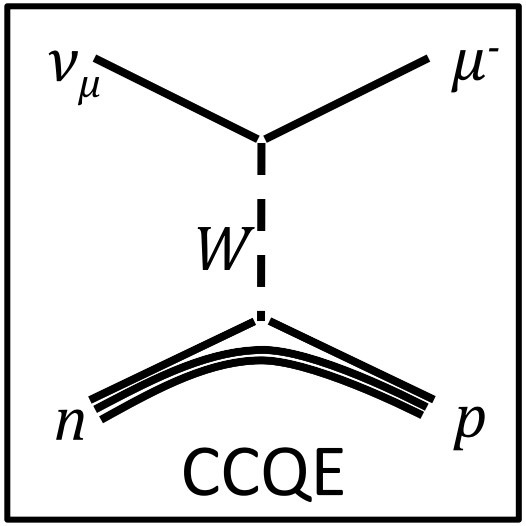
- The more energetic the particle, the more Cherenkov light
- In quasi-elastic events, momentum + beam angle give original neutrino energy
  - Need no information from the invisible proton



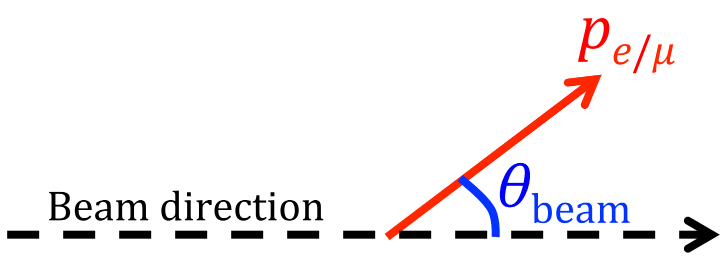
$$E_\nu = \frac{m_p^2 - m_{n'}^2 - m_\ell^2 + 2m_{n'}^2 E_\ell}{2(m_{n'} - E_\ell + p_\ell \cos \theta_{\text{beam}})}$$

SK Event Selection

- Beam Timing
- Fiducial Volume
- Contained in ID
- **1 Ring**
- *e*-like PID
- $p_e > 100$ MeV/c
- No decay-*e*
- $E_{rec} < 1250$ MeV
- π^0-rejection



- Beam Timing
- Fiducial Volume
- Contained in ID
- **1 Ring**
- μ-like PID
- $p_\mu > 200$ MeV/c
- Decay-*e* ≤ 1



$$E_\nu = \frac{m_p^2 - m_{n'}^2 - m_\ell^2 + 2m_{n'}E_\ell}{2(m_{n'} - E_\ell + p_\ell \cos\theta_{\mathrm{beam}})}$$

SK Event Selection

Beam Timing

Fiducial Volume

Contained in ID

1 Ring

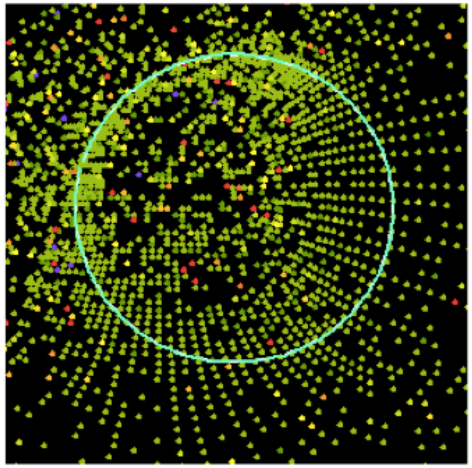
***e*-like PID**

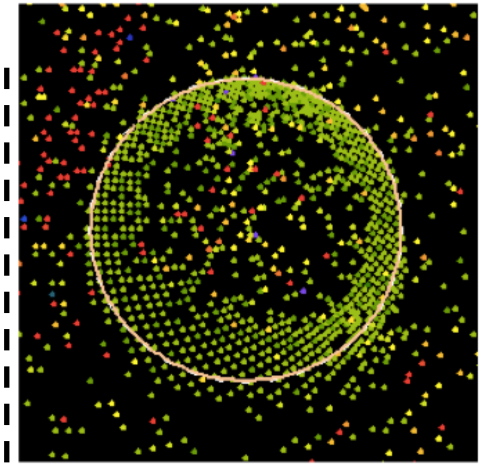
$p_e > 100$ MeV/c

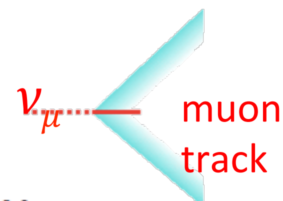
No decay-e

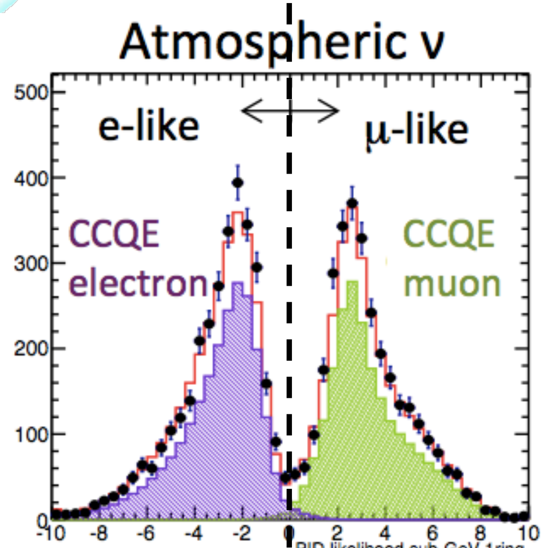
$E_{rec} < 1250$ MeV

π^0-rejection









Beam Timing

Fiducial Volume

Contained in ID

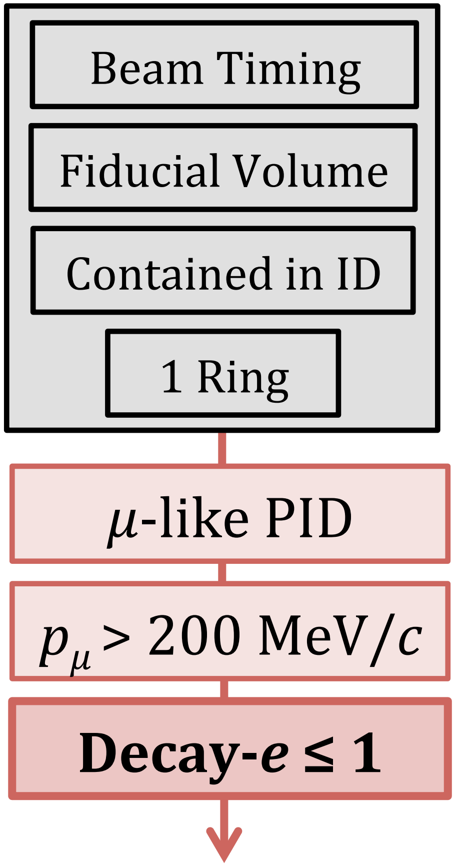
1 Ring

μ-like PID

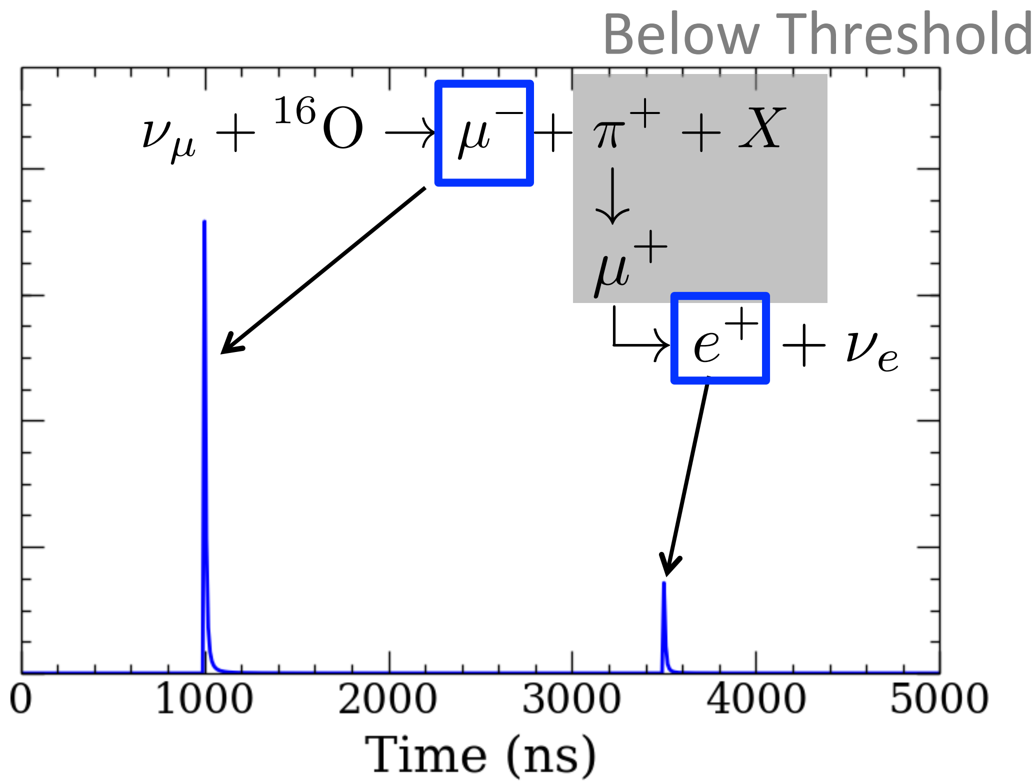
$p_\mu > 200$ MeV/c

Decay-$e \leq 1$

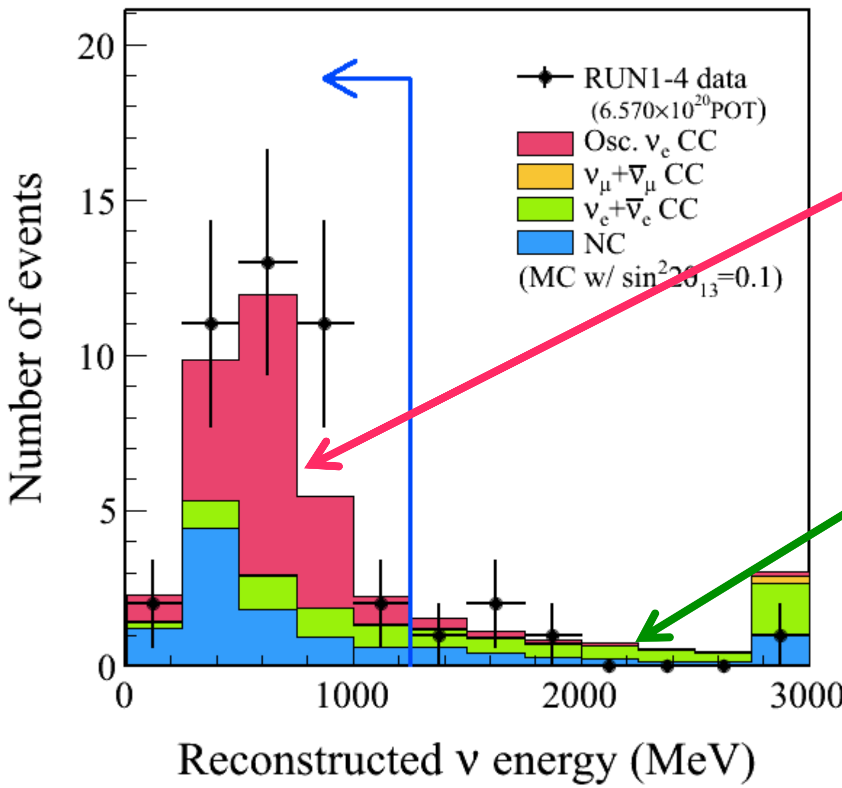
SK ν_μ Event Selection



- Limit decay electrons to exclude events with invisible $\pi^{\pm}$'s
  - $\pi^{\pm}$ threshold: 212 MeV
  - $e^{\pm}$ threshold: 0.8 MeV



SK ν_e Event Selection



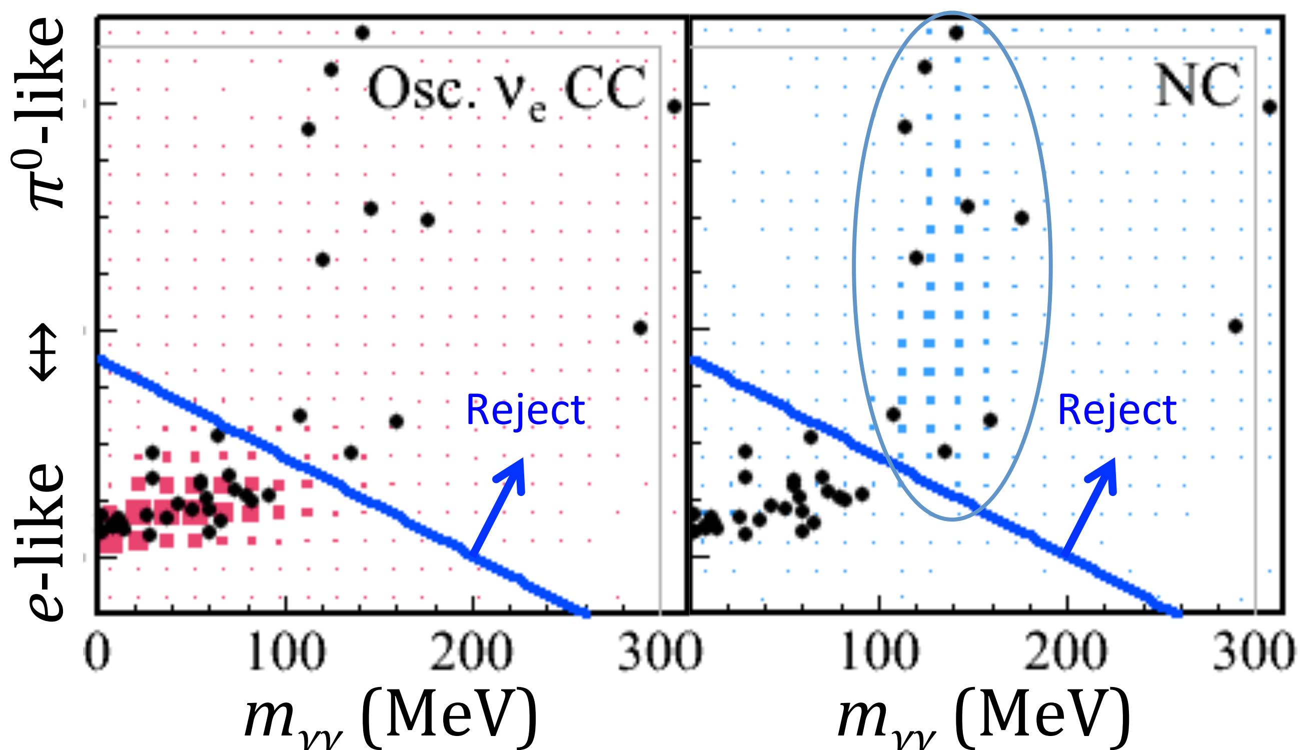
Signal ν_e primarily at low energy

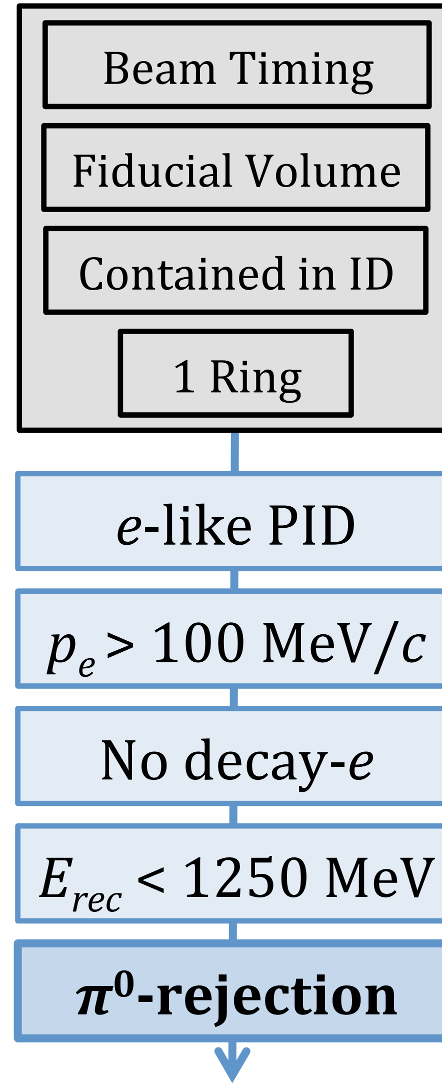
Intrinsic ν_e bkgd. primarily at high energy

- Beam Timing
- Fiducial Volume
- Contained in ID
- 1 Ring
- e-like PID
- $p_e > 100$ MeV/c
- No decay-e
- **$E_{rec} < 1250$ MeV**
- π^0-rejection

SK ν_e Event Selection

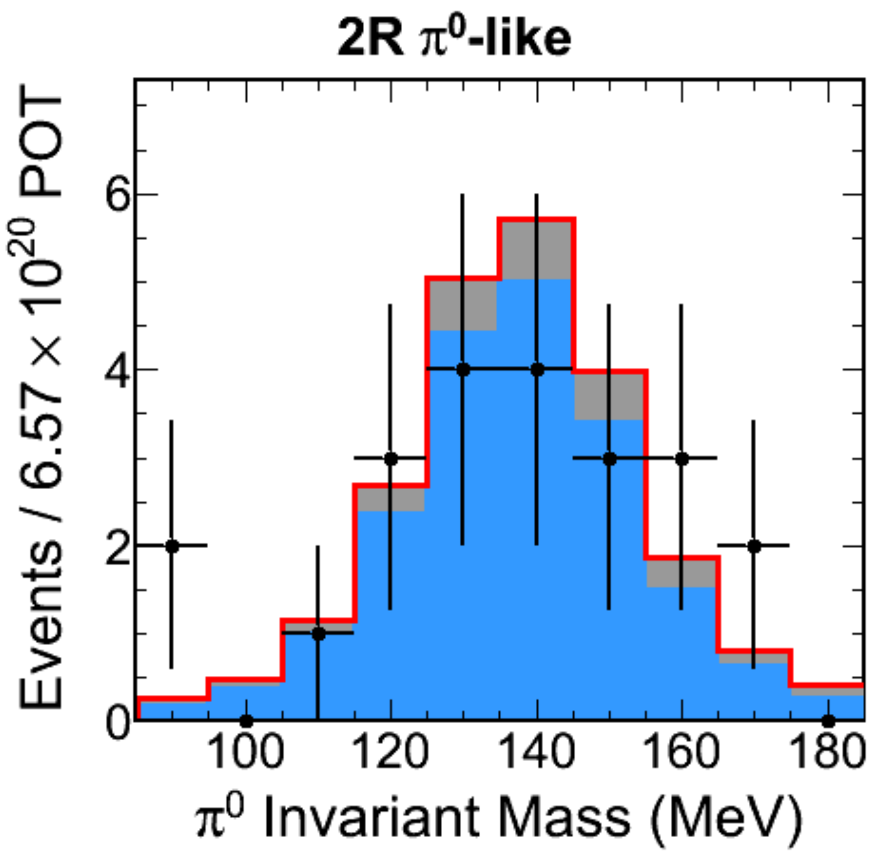
- Likelihood-based reco.
  - Compare e-like and π^0-like hypotheses
  - Exclude events with $m_{\text{inv}} \sim 135$ MeV

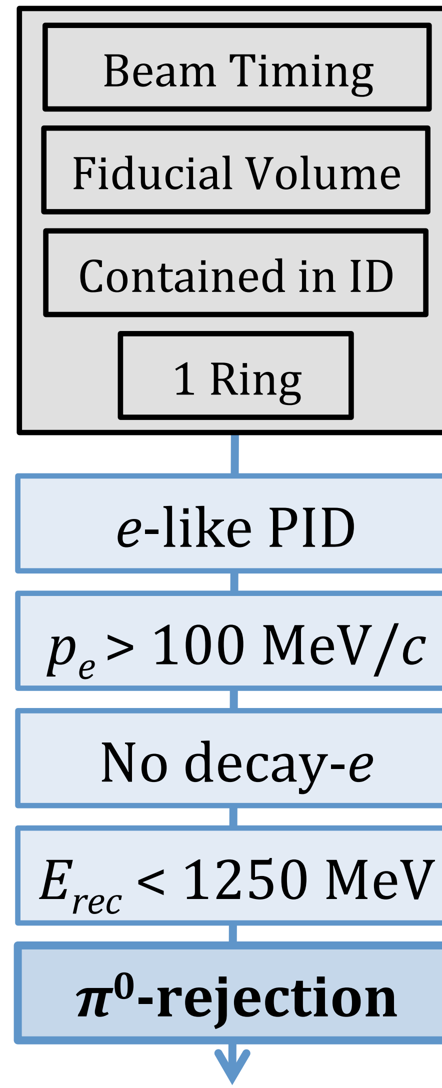




SK ν_e Event Selection

- Cross-check π^0 background using an enriched sample of π^0 events
  - 2 e-like rings with $m_{\gamma\gamma}$ = 135±50 MeV



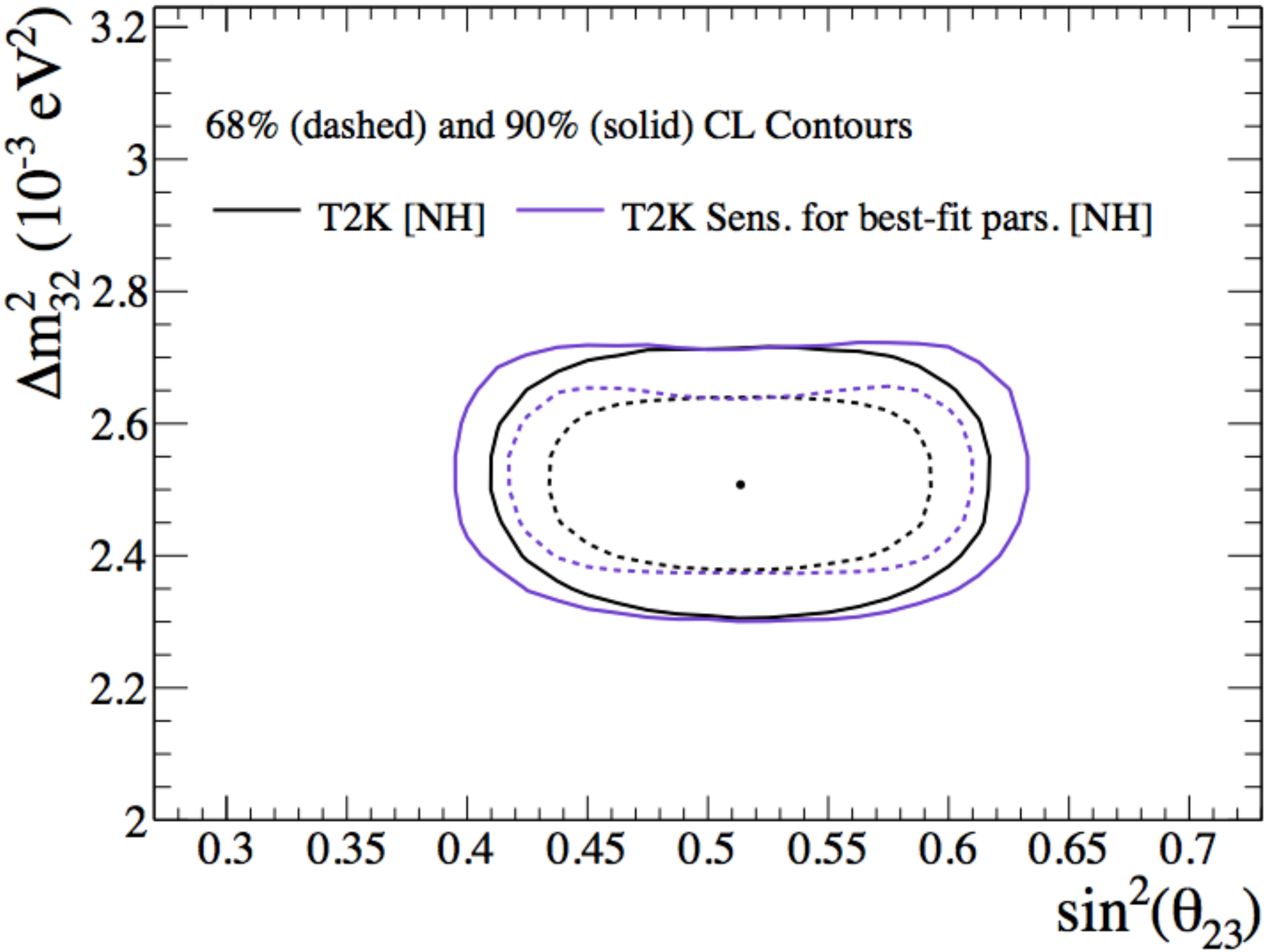


Systematic Uncertainties at Super-K

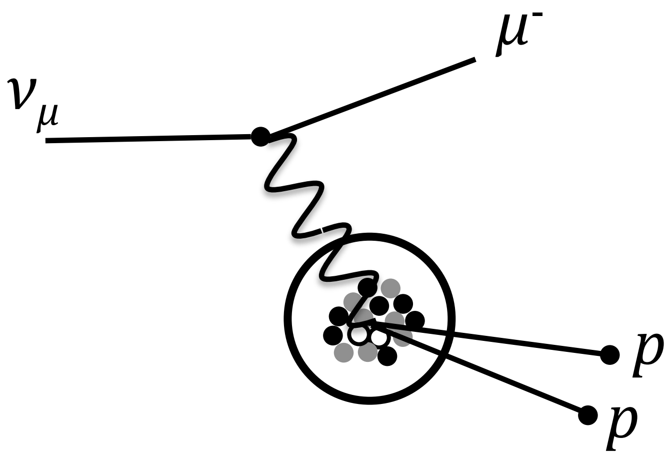
ν_e Events	ν_e	ν_μ
ND280-constrained flux and cross section	3.1%	2.7%
Unconstrained cross section	4.7%	5.0%
SK detector efficiency	2.4%	3.0%
Final or secondary hadronic interactions	2.7%	4.0%
Total	**6.8%**	**7.7%**

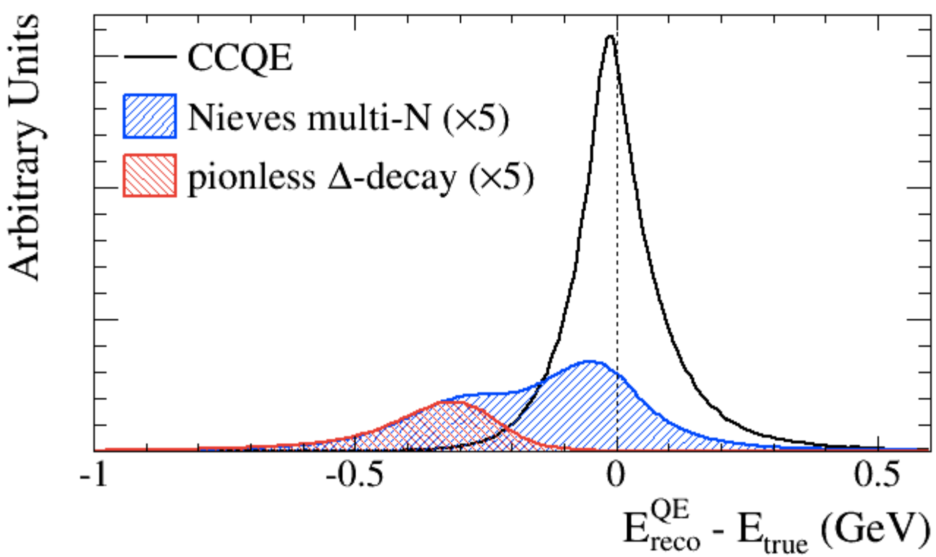
>20% without ND280

Sensitivity vs. Data Fit



Multinucleon Interactions





- Neutrinos may interact with multiple nucleons
  - Looks CCQE, but has different kinematics
  - Potential explanation for $M_A \approx 1.2$ GeV instead of 1.0 GeV
- Studied potential for bias in our result from neglecting multinucleon interactions
  - Use many fake experiments with random systematic errors

Our model:

J. Nieves et. al., PRC83, 045501 (2011)

J. Sobczyk, PRC86, 015504 (2012)

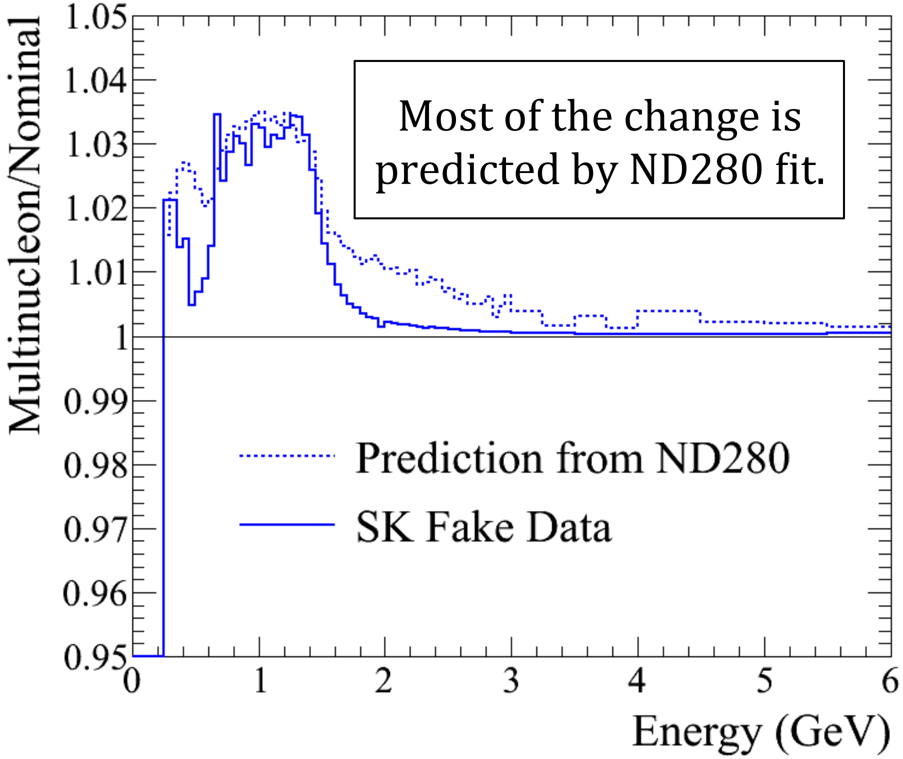
Suggested potential for bias in oscillations:

O. Lalakulich and U. Mosel, PRC86, 054606 (2012).

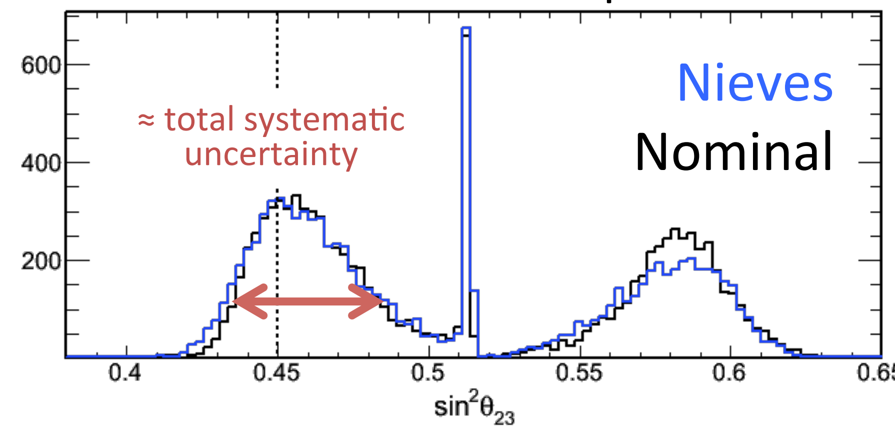
D. Meloni and M. Martini, PLB716, 186 (2012).

P. Coloma, et al, arXiv:1311.4506 (2013).

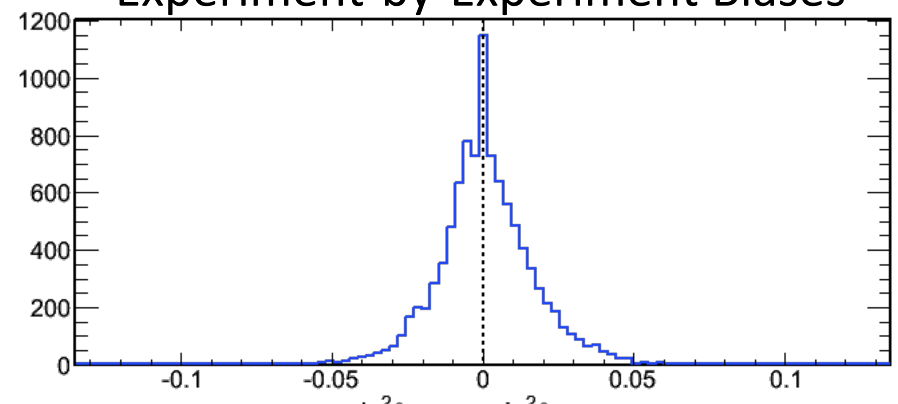
Effect of Multinucleon Interactions



Distribution of Fake Experiments



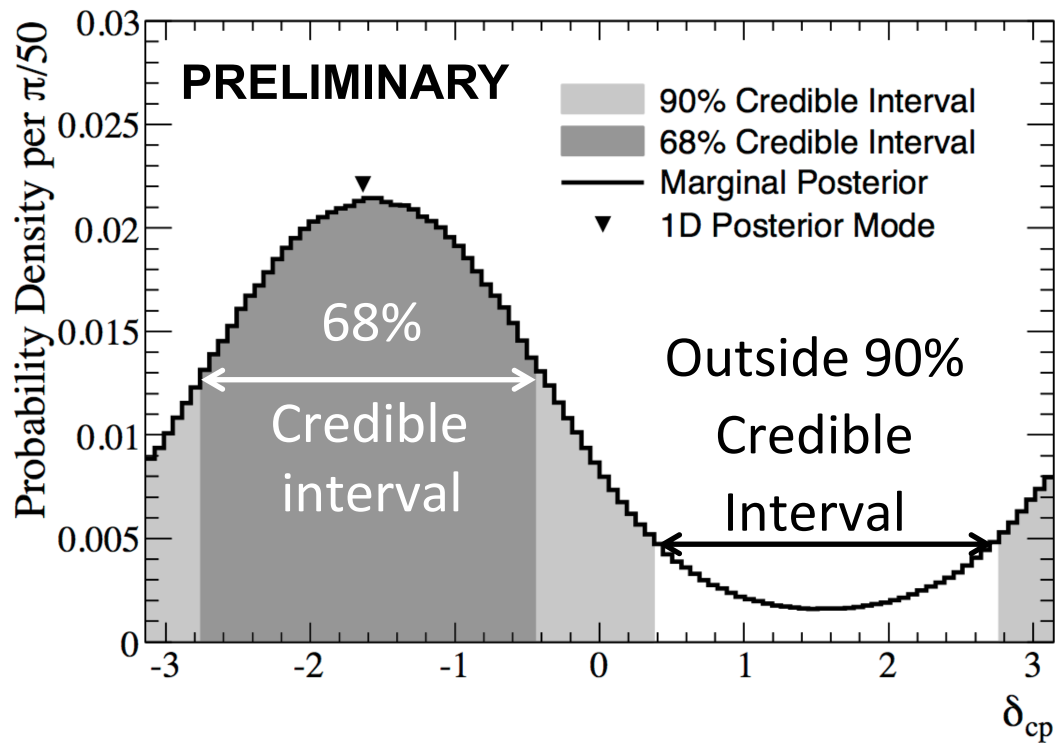
Experiment-by-Experiment Biases



RMS (3.6%) is comparable to the systematic uncertainty, but small relative to the total error (11%)

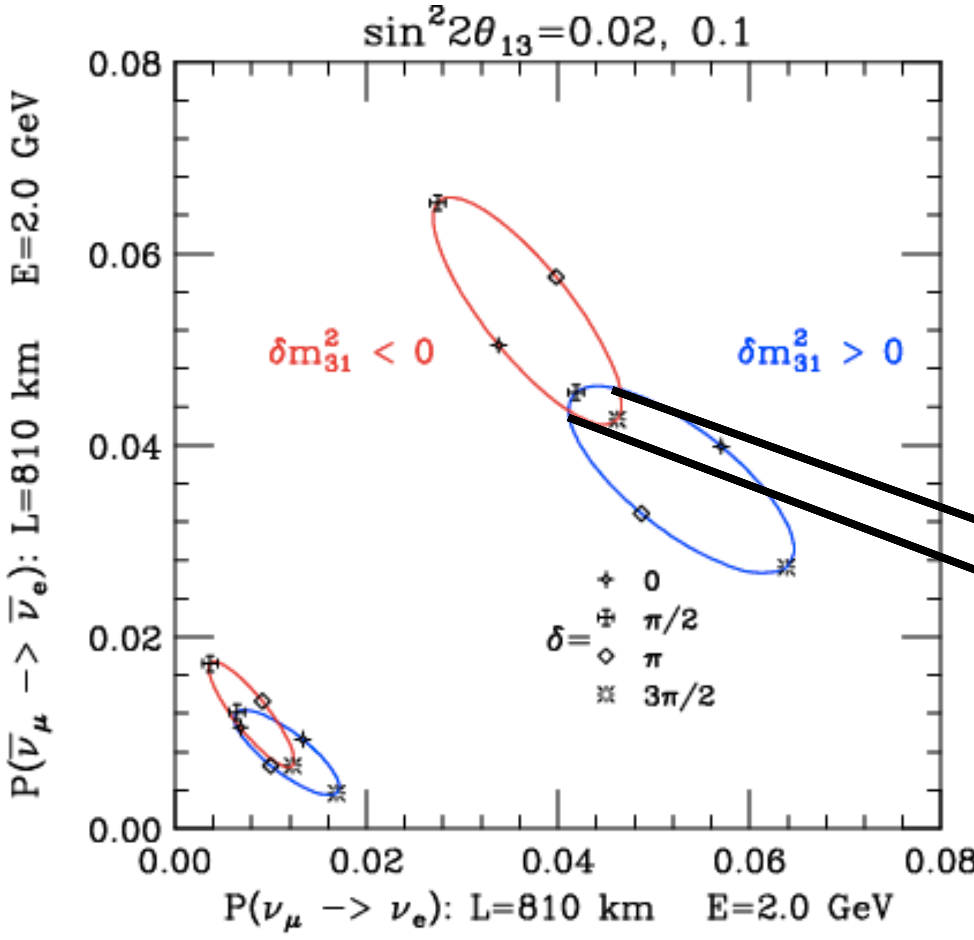
Bayesian δ_{CP}, MH, Octant Constraints

- Bayesian analysis can marginalize over the mass hierarchy
- Compare probabilities of different hierarchies and θ_{23} octants

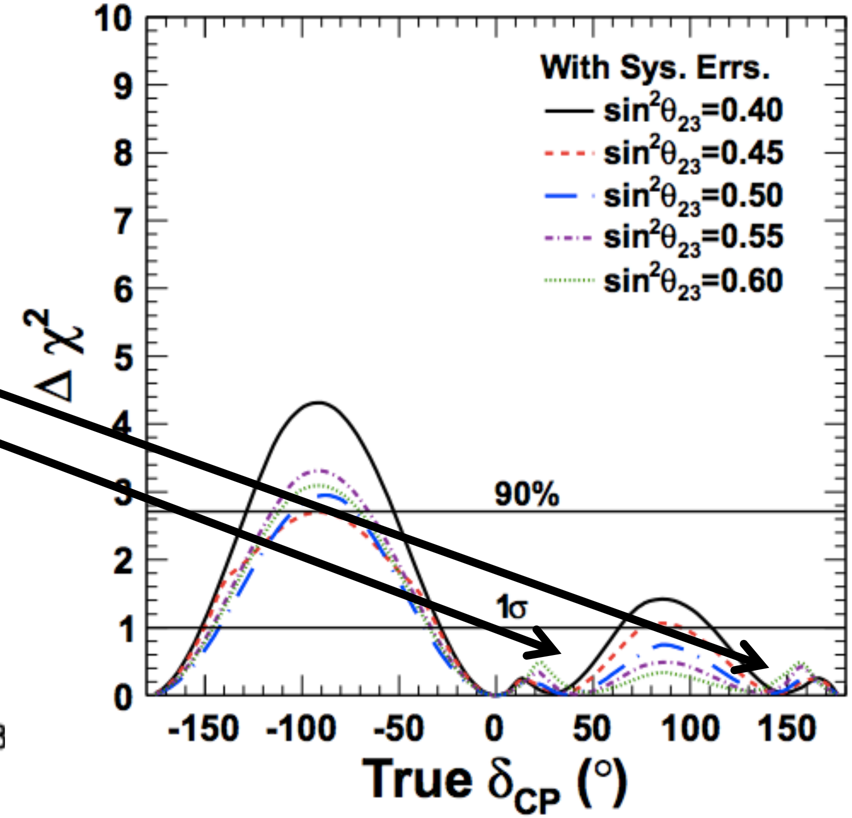


	NH	IH	Sum
$\sin^2(\theta_{23}) \leq 0.5$	18%	8%	26%
$\sin^2(\theta_{23}) > 0.5$	50%	24%	74%
Sum	68%	32%	

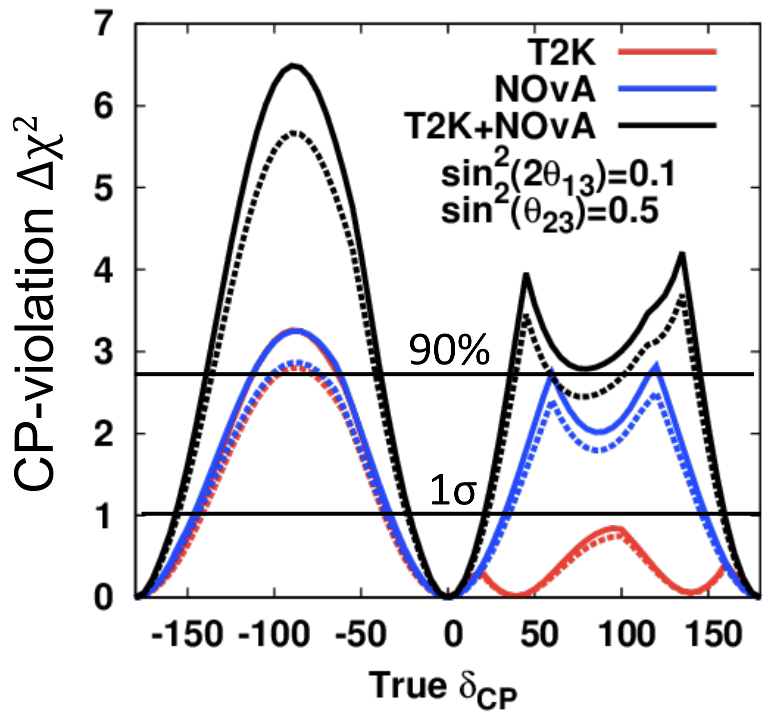
Bi-probability

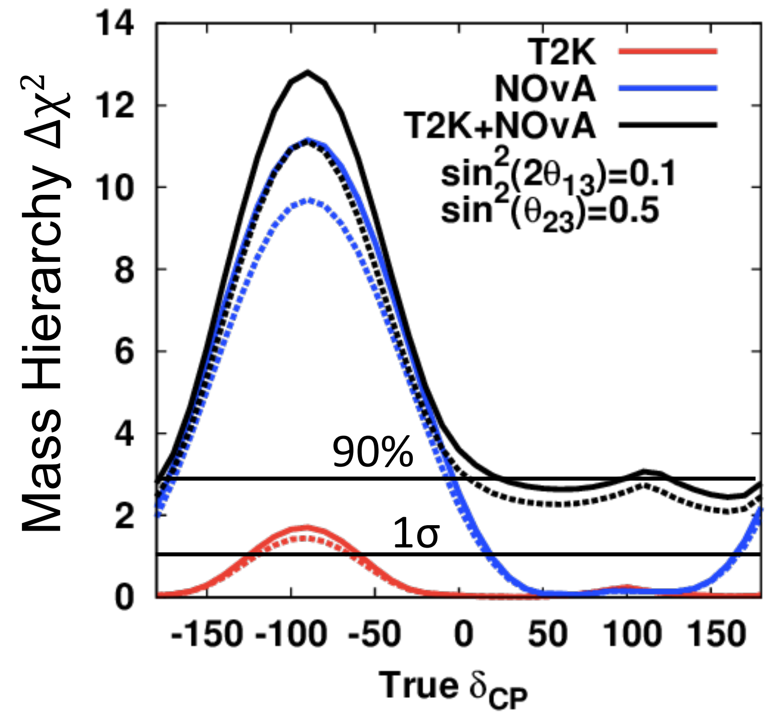


O. Mena PoS NUFACT08 (2008) 005



Future Sensitivity with NOvA





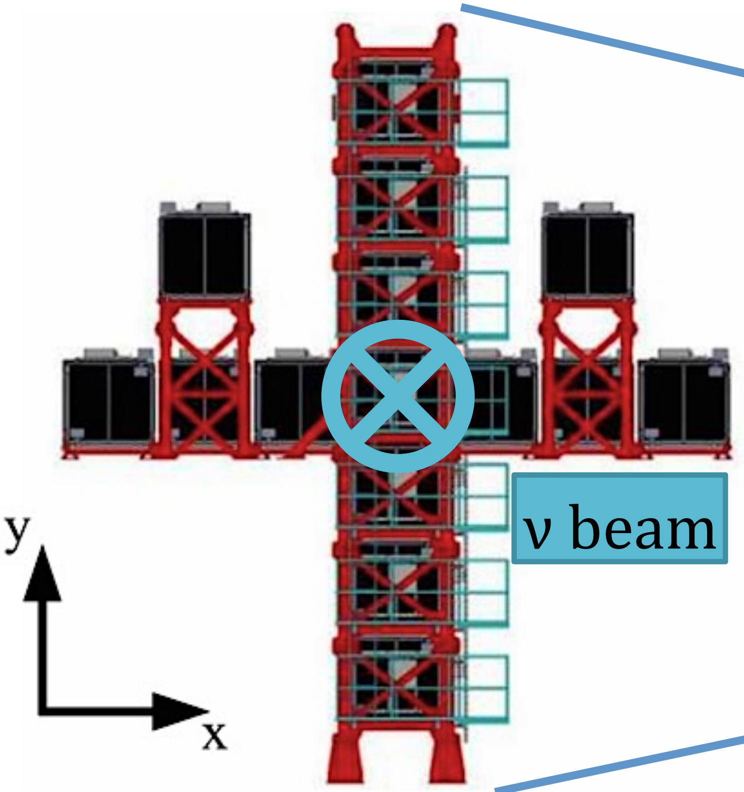
- A joint analysis with NOνA:
  - Increases significance of the "luckiest" point
  - Adds sensitivity in δ_{CP} regions where there would be none.

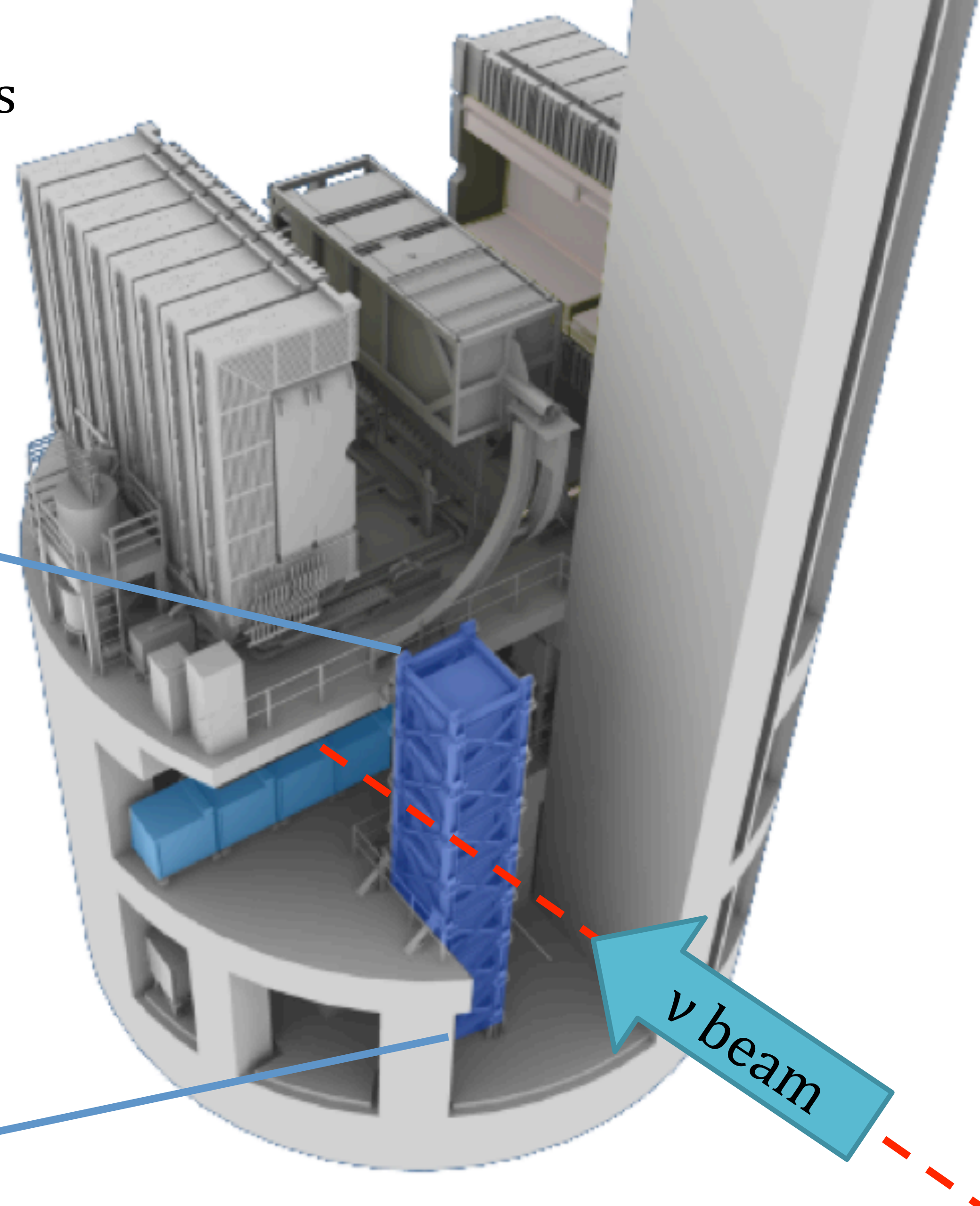
- Same assumptions, plus
  - Choose $\sin^2(\theta_{23}) = 0.5$
  - 3.6×10^{21} NOνA POT, even split
  - Shown both without (solid) and with (dashed) systematic errors

Accepted by PTEP, arXiv:1409.7469 [hep-ex]

Near Detectors: INGRID

- Modules with alternating planes of iron and plastic scintillator
- On-axis
- Measures beam intensity and direction over time.





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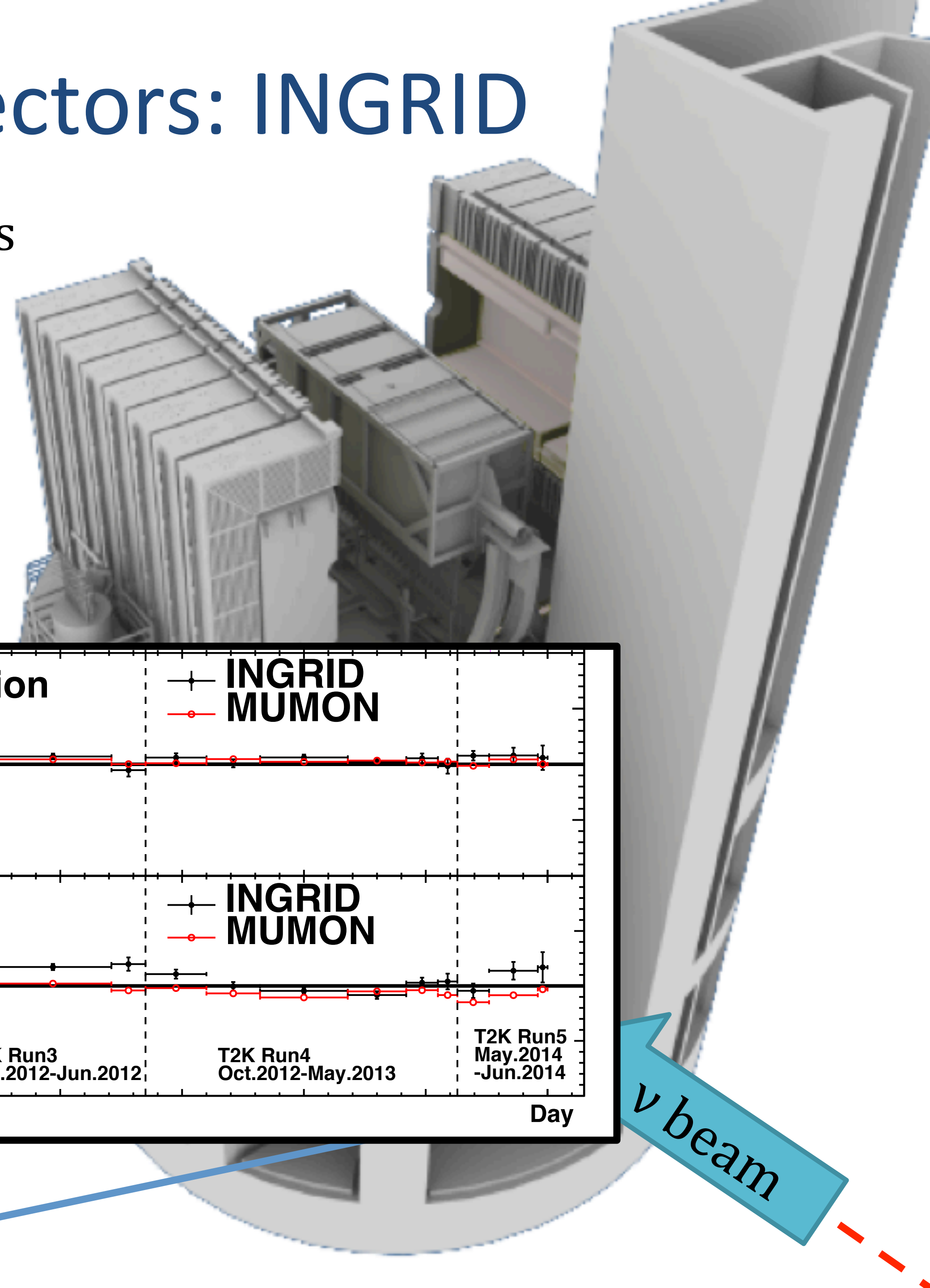
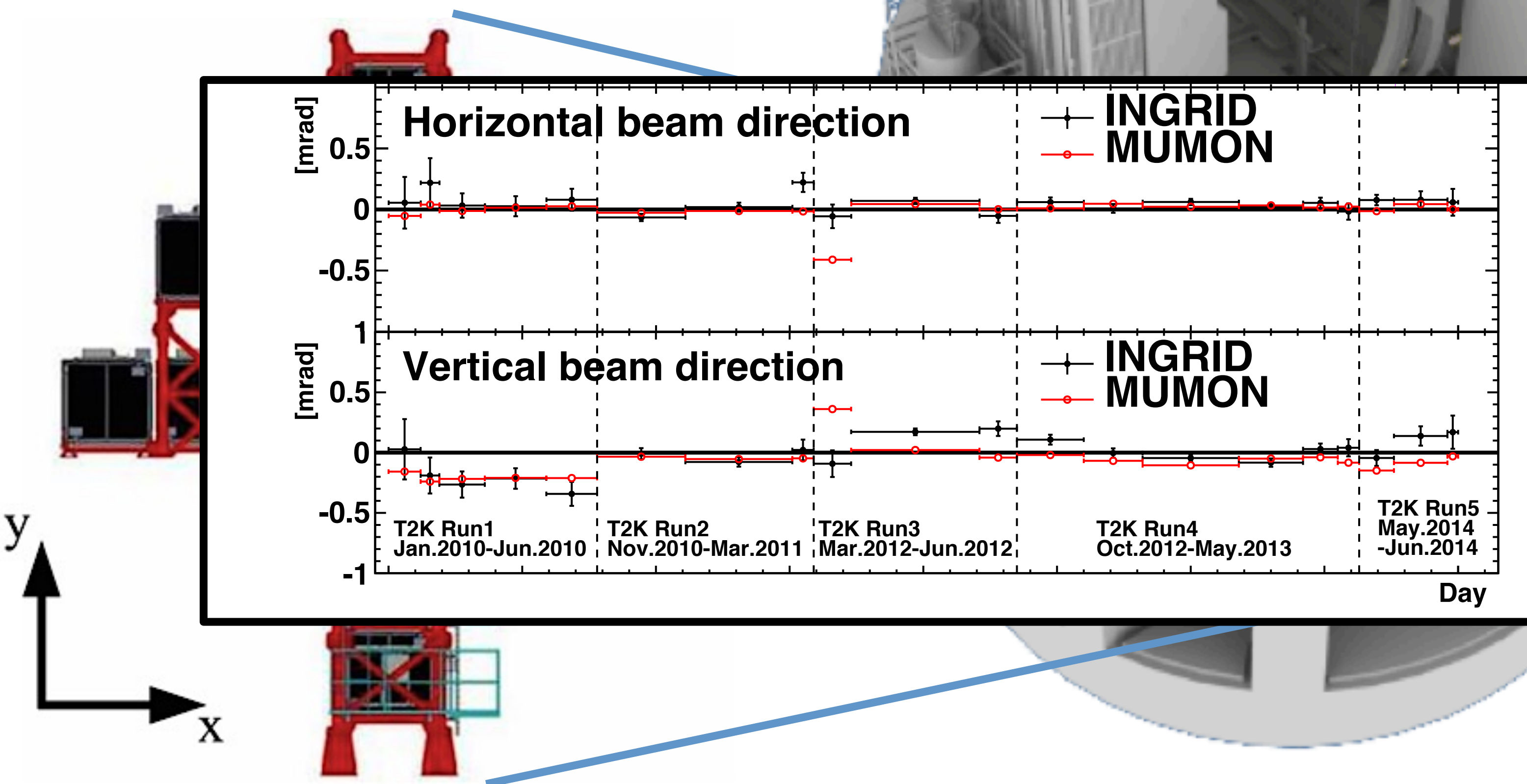
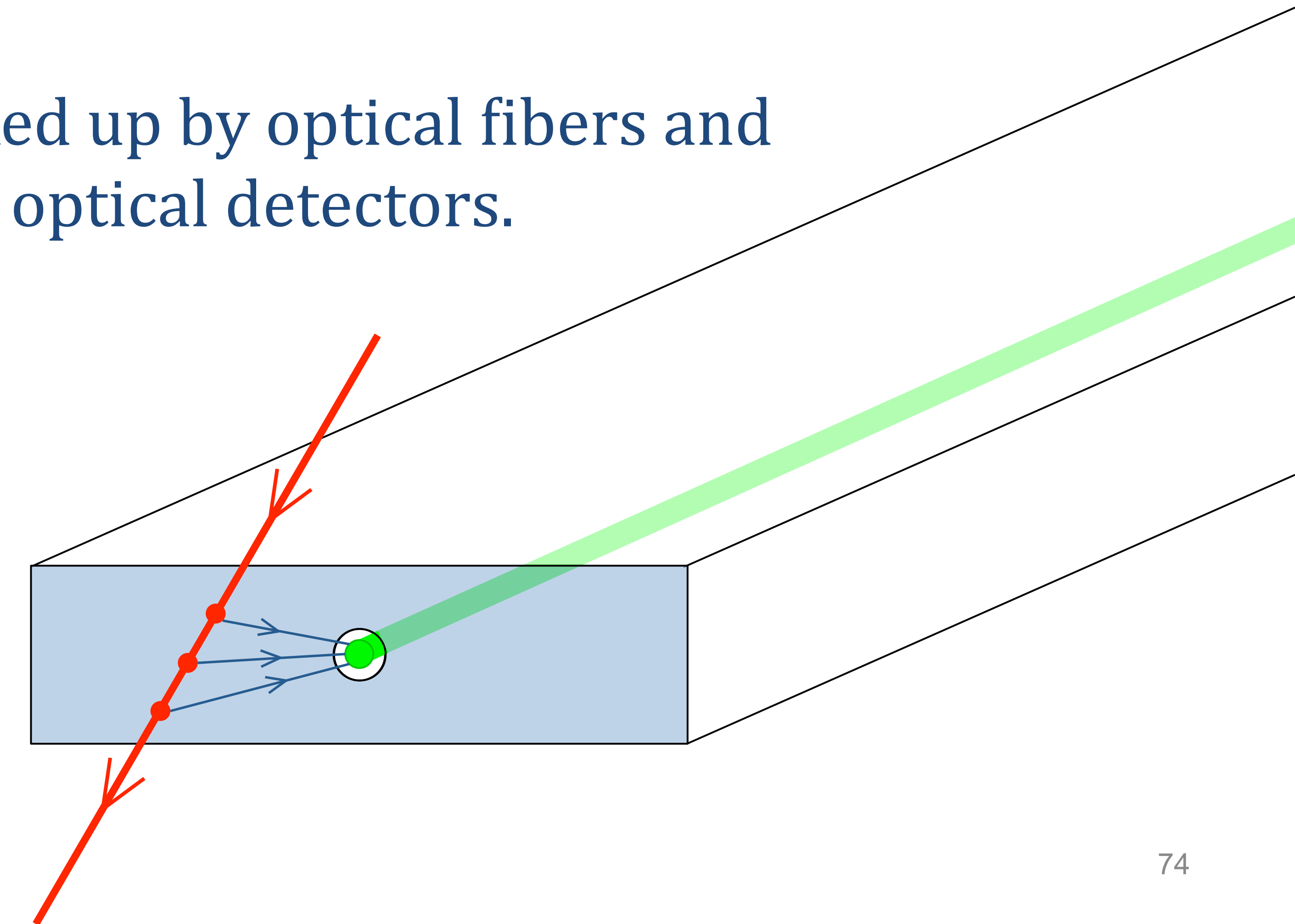


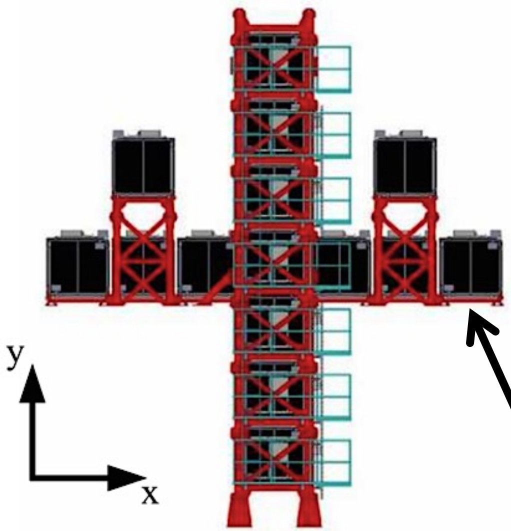


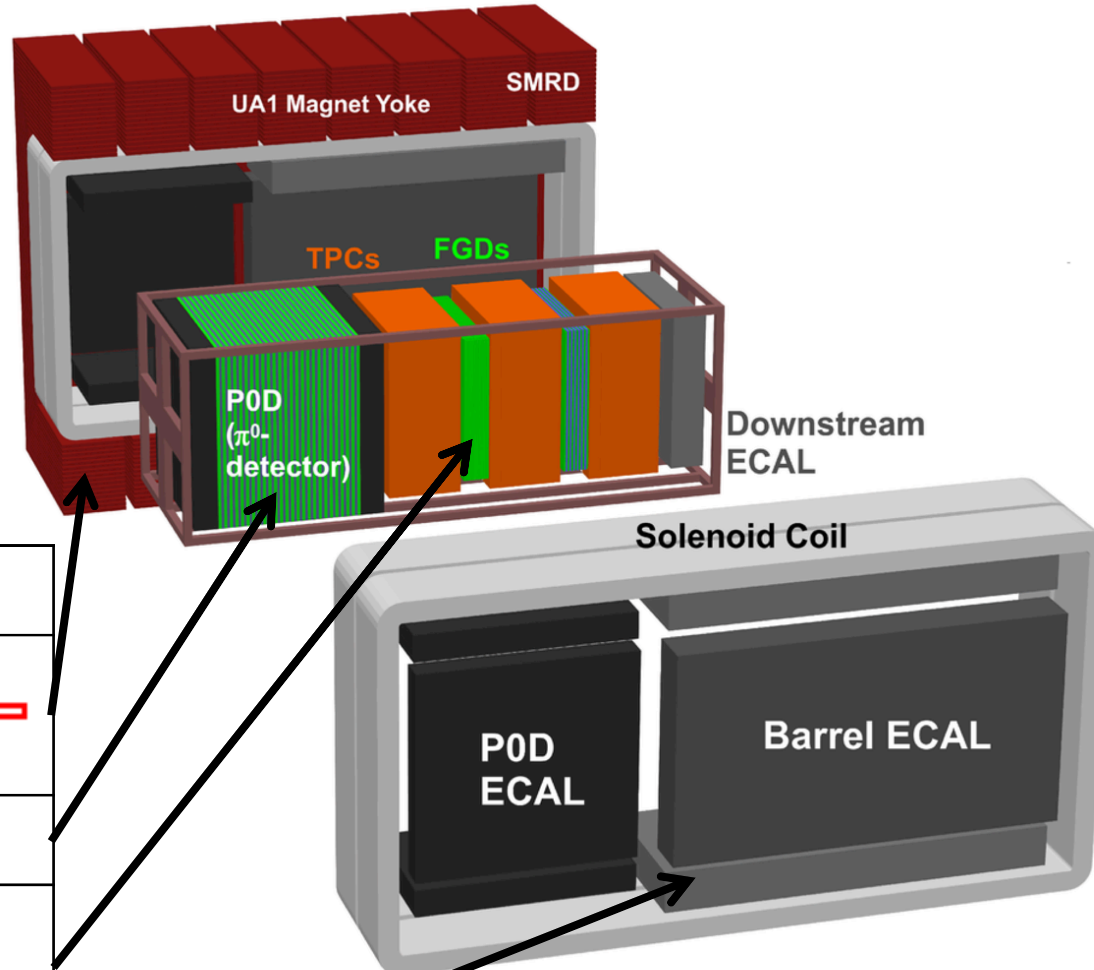
Detecting Charged Particles at the ND

- Plastic scintillator
  - Light emitted as charged particles pass through
  - Light picked up by optical fibers and carried to optical detectors.



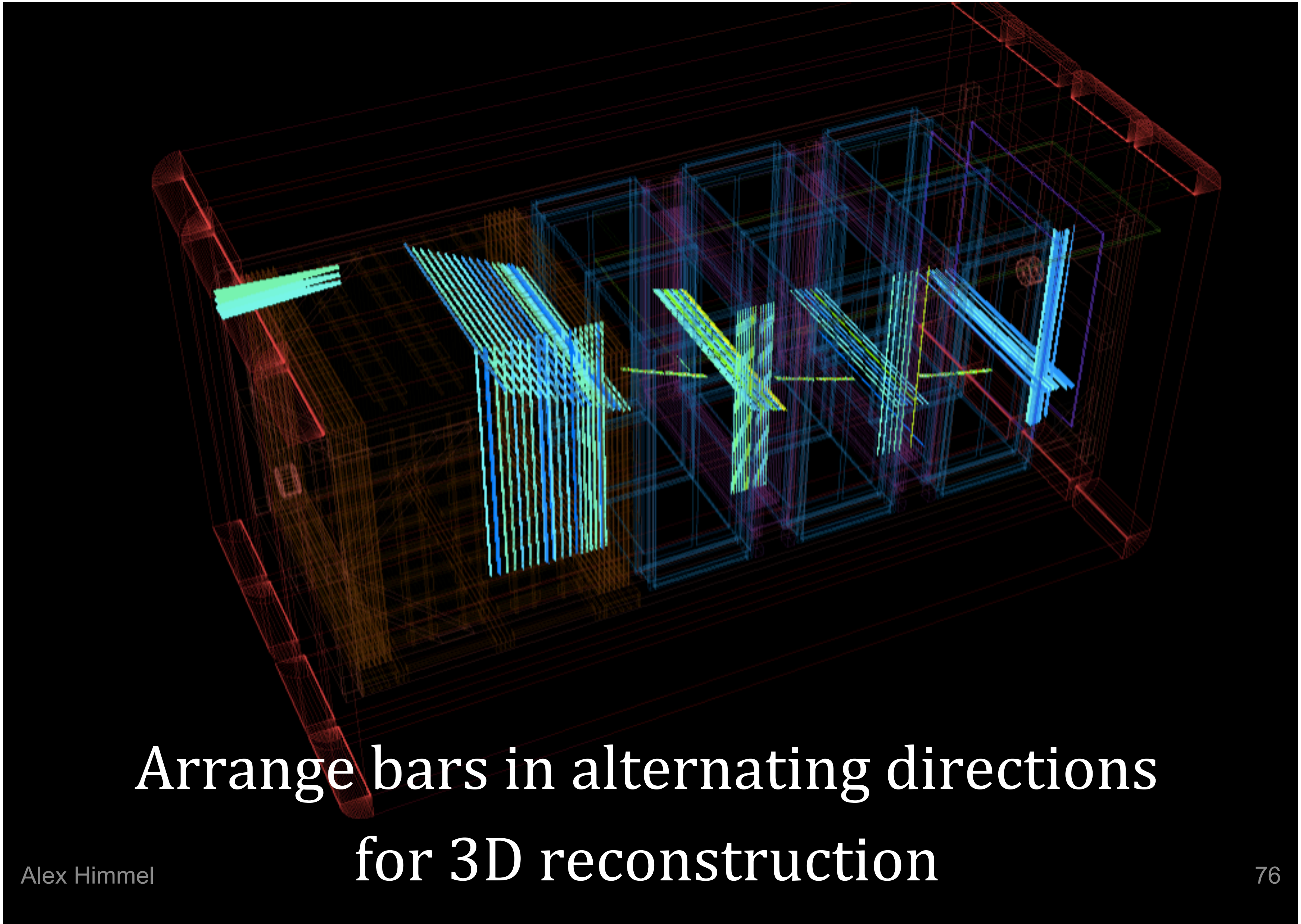
Detecting Charged Particles at the ND





INGRID	
Side Muon Range Detector	
PØD (π^0 detector)	
Fine Grained Detector	
Electromagnetic Calorimeter	

Detecting Charged Particles at the ND



Arrange bars in alternating directions
for 3D reconstruction

Detecting Charged Particles at the ND

- Argon Gas Time Projection Chamber
  - Charged particles ionize argon gas
  - Electric field drifts the electrons towards the readout plane
- Position and arrival time give full 3D reconstruction