T2K RESULTS ON NEUTRINO OSCILLATIONS AND INTERACTIONS

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T2K Results on Neutrino Oscillations and Interactions

- T2K: Physics goals and approach
- T2K: The facility and experiment
- Neutrino oscillation analyses
    - ν_e appearance
    - ν_μ disappearance
    - Joint fit
    - $\bar{\nu}_\mu$ disappearance
    - Future sensitivity
- Neutrino interactions

T2K: Physics goals and approach

- T2K's major physics goals:
  - Search for $\nu_\mu \rightarrow \nu_e$ appearance (found!) and measure precisely (underway)
  - Measure ν_μ disappearance precisely (done, improving)
  - Search for CP violation using antineutrino beam (underway)
  - Measure neutrino interaction cross-sections (some done, others underway)
  - Searches for exotic physics (underway)

Oscillation probabilities depend on several parameters...

Dominant oscillation terms at the atmospheric Δm² (ignoring matter effects):

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\Delta_{32}\left(\sin^2\theta_{23} - \frac{\sin(2\theta_{12})\sin(2\theta_{23})\sin\delta_{CP}}{2\sin\theta_{13}}\Delta_{21}\right)$$

$$P(\nu_\mu \to \not{\nu_\mu}) \approx \sin^2(2\theta_{23})\Delta_{32}$$

$$P(\nu_e \to \not{\nu_e}) \approx \sin^2(2\theta_{13})\Delta_{32}$$

$$\text{where } \Delta_{ij} \equiv \sin^2\frac{\Delta m^2_{ij}L}{4E}$$

Dependences on:

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Dependences on:

$\sin(2\theta_{23}) \sim 1$

$\sin^2(\theta_{23}) \sim 0.5$

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Dependences on: θ_{13} $\quad\sin(2\theta_{23})\sim1$ $\quad\sin^2(\theta_{23})\sim0.5$

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Dependences on: θ_{13} $\quad\sin(2\theta_{23})\sim 1$

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Disappearance modes (somewhat) simpler to interpret

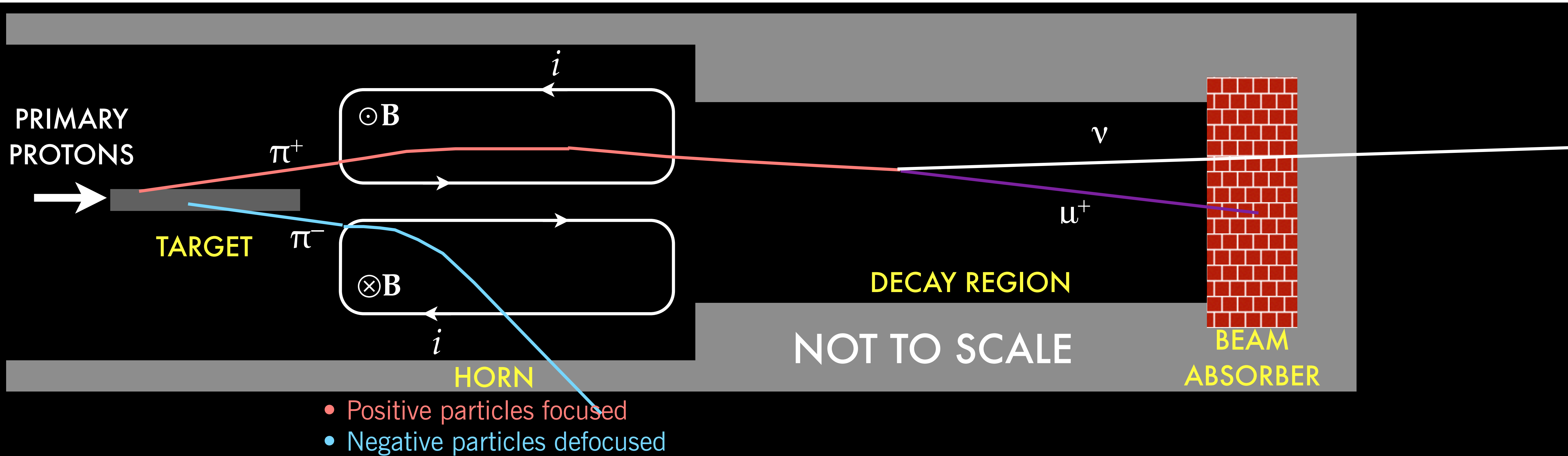
Two approaches to measuring θ_{13}:

- Search for $\nu_\mu \rightarrow \nu_e$ in long-baseline accelerator measurements:
  - Present: T2K, NOvA, MINOS
  - Future: Hyper-Kamiokande, DUNE
- Search for $\overline{\nu}_e$ disappearance at nuclear reactors
  - Daya Bay, RENO, Double Chooz

T2K design concepts

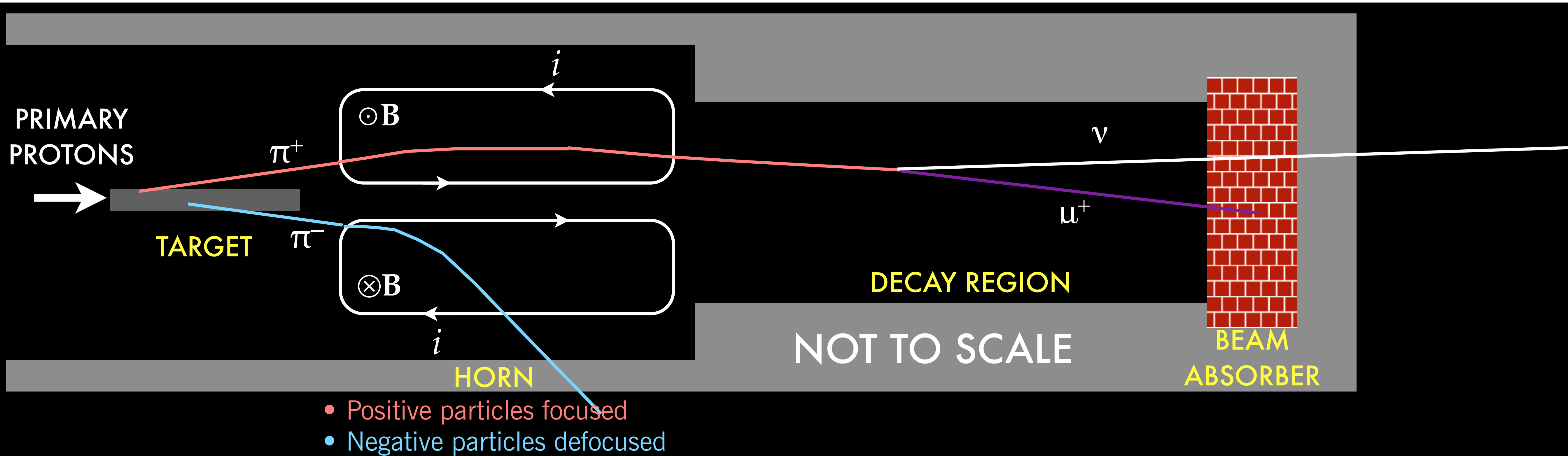
- Design:
  - First experiment to use off-axis technique to produce a narrow-band ν_μ beam
  - High-intensity 30 GeV proton beam from J-PARC synchrotron
  - Beam monitors to measure primary and secondary beam each pulse
  - On- and off-axis near neutrino detectors to characterize beam
  - Far detector Super-Kamiokande, 295 km baseline

Accelerator-based neutrino beams



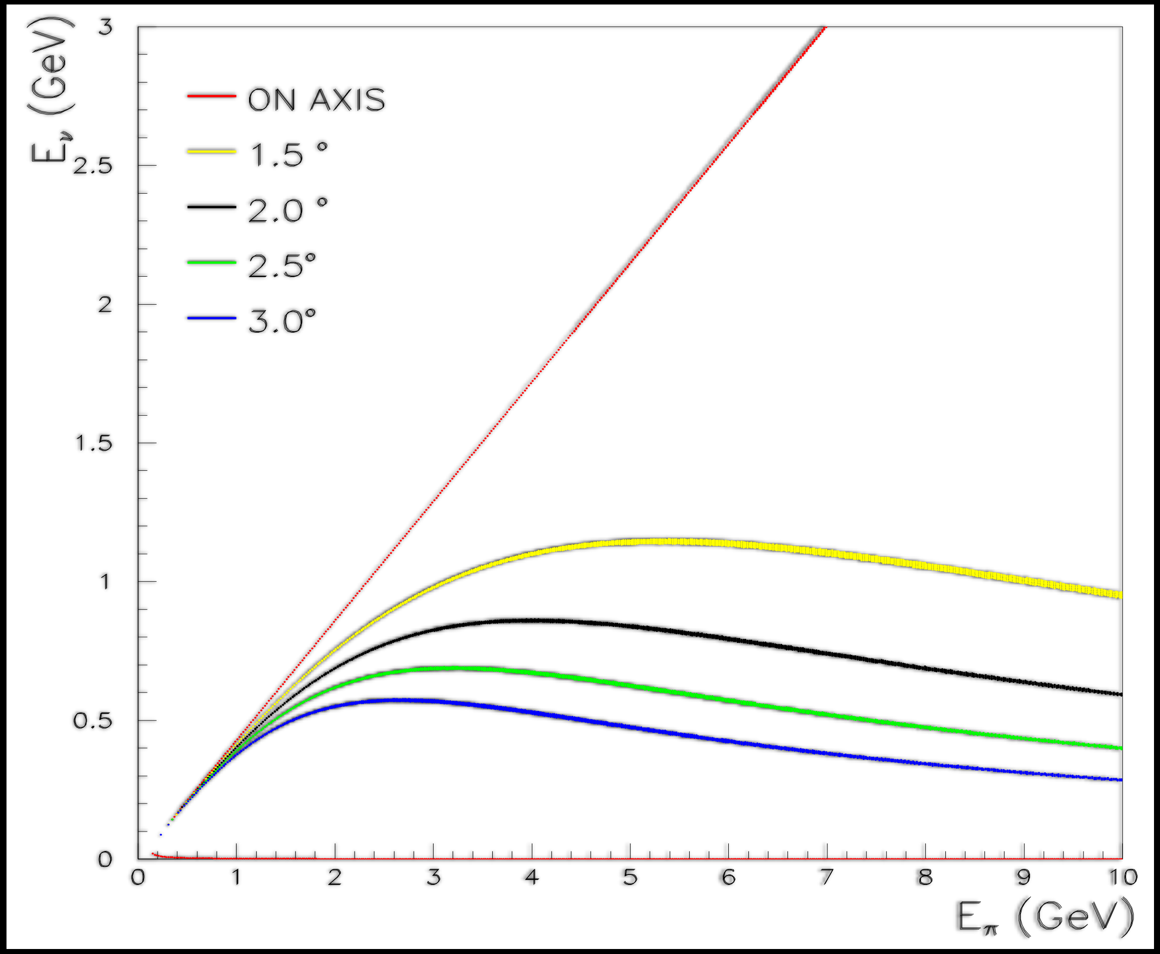
- Protons strike a target; the secondary mesons enter a decay region and decay in flight to neutrinos upstream of a beam stop.
- Leaving target, charged particles may be focused before entering decay volume
  - Several magnetic focusing schemes possible: most common is “horns” (coaxial conductors producing toroidal fields)
  - Horn current direction determines whether π^+ (for ν beam) or π^- (for $\bar{\nu}$ beam) focused

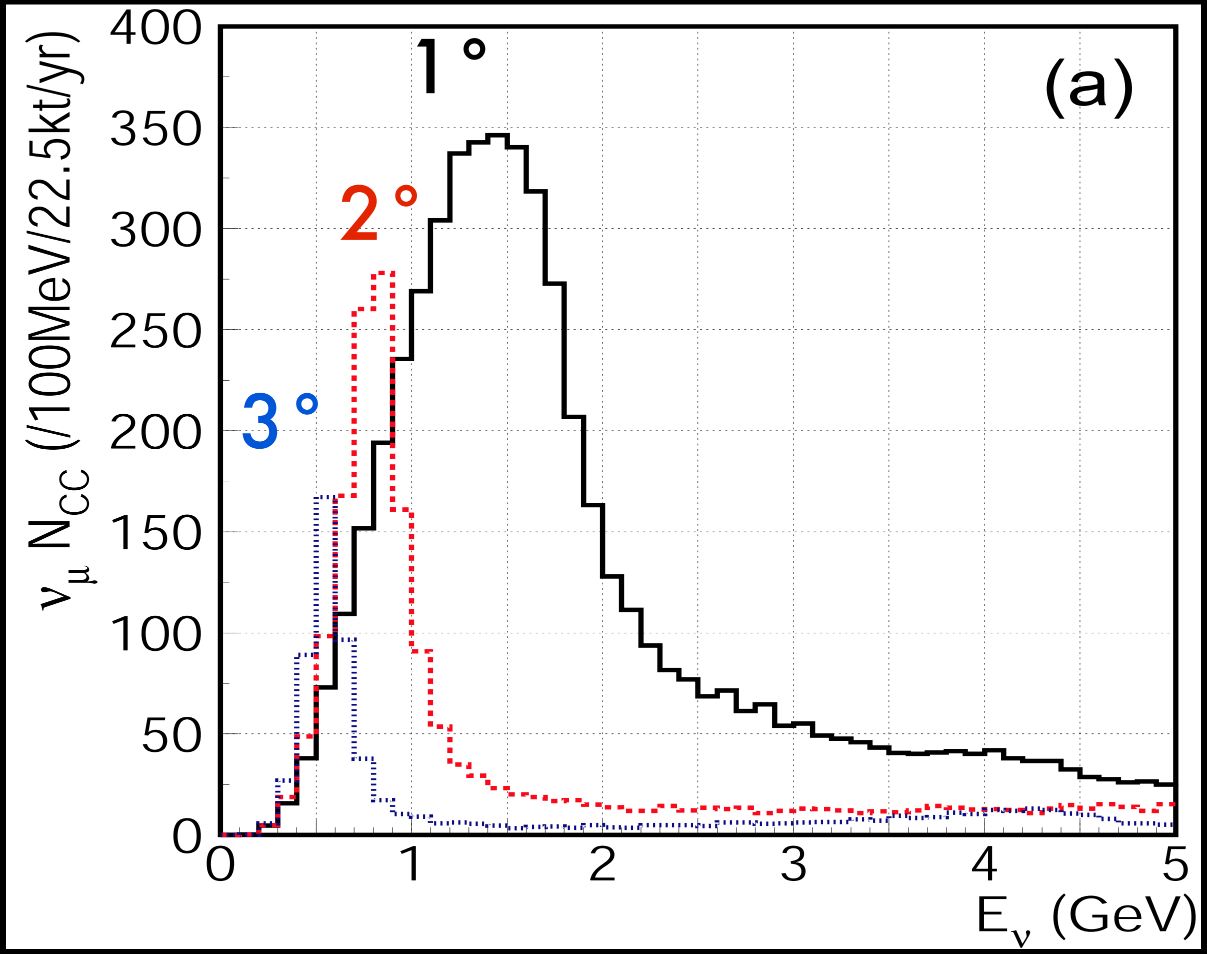
Accelerator-based neutrino beams



- There are numerous variants on the conventional beam: narrow-band and broad-band designs, off-axis beams, multiple horns, short (km) or long (100-1000 km) baseline...
- All have common properties:
  - Predominantly ν_μ, with ν_e contamination at the ~1% level from muon, kaon decays.
  - Neutrino energies can be from <0.5 GeV to >400 GeV
  - Even "narrow-band" beams tend to have tails to high energy
  - Fluxes have significant systematic errors

Off-axis beam technique





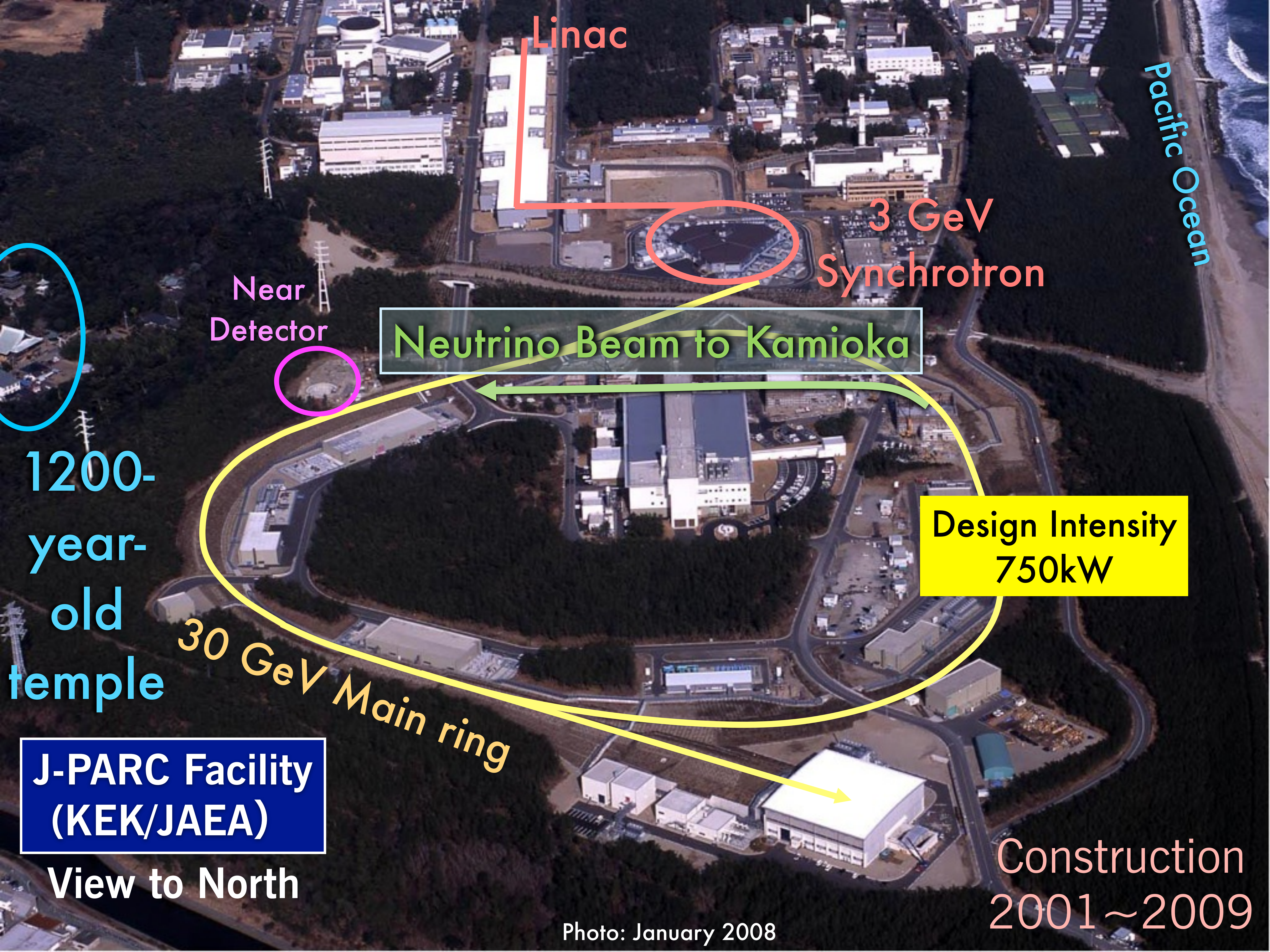
- For wide range of pion momenta, E_ν depends more on decay angle than E_π
- Exploit to make narrow-band ν_μ beams by going off-axis
- At 295 km baseline, first oscillation maximum is at 570 MeV for $\Delta m^2 = 2.4 \cdot 10^{-3}$ eV^2 $\Rightarrow$ T2K wants 2.5° off-axis angle

T2K: the facility and experiment

- J-PARC accelerator
- Neutrino beam facility
- Near detector complex
- Far detector: Super-Kamiokande
- Operations and data collection so far

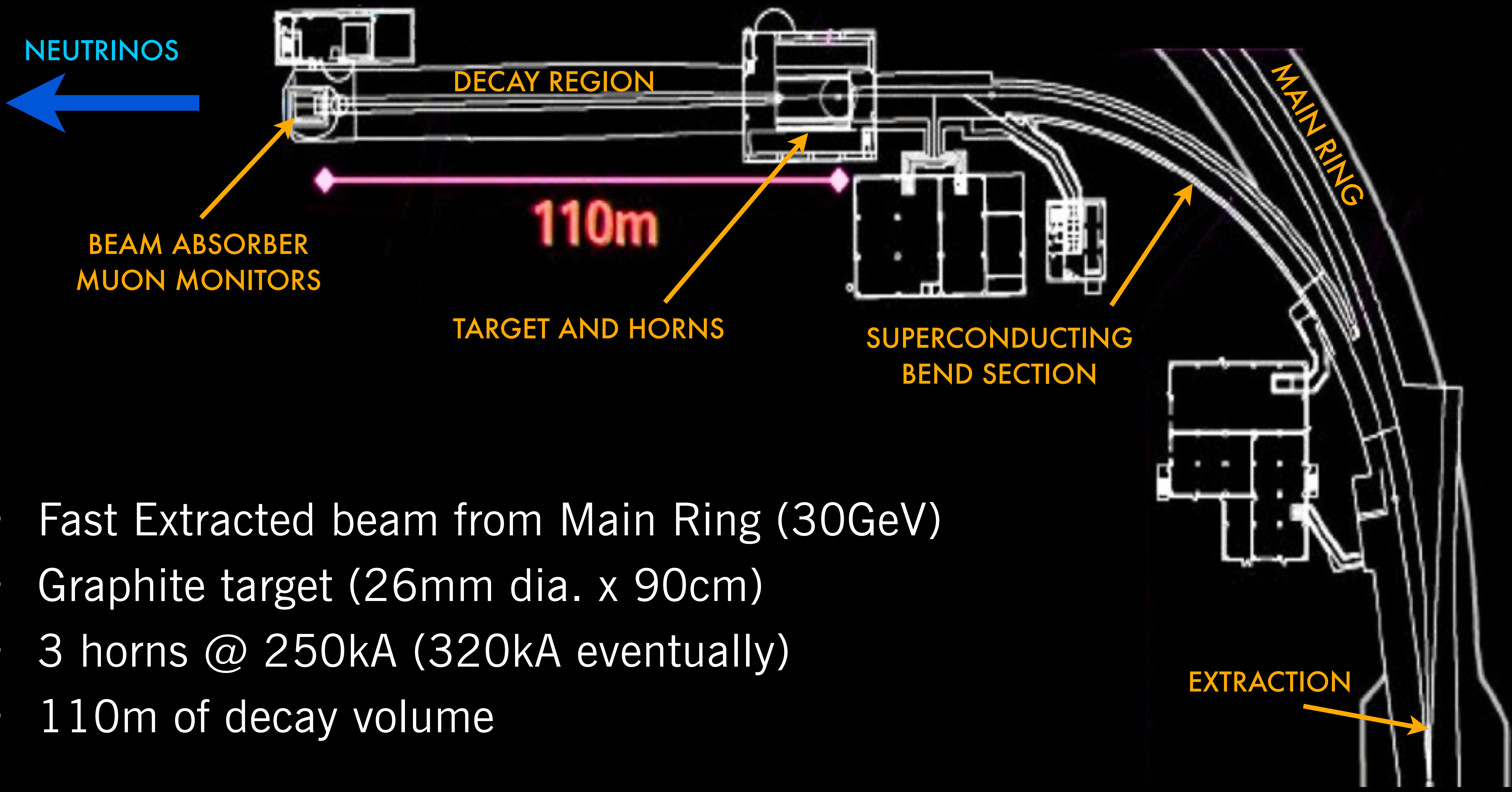
T2K


Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.
France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris
Germany
U. Aachen
Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma
Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metro U.
Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw T.U.
Wroclaw U.
Russia
INR
Spain
IFIC, Valencia
U. A. Barcelona
Switzerland
ETH Zurich
U. Bern
U. Geneva
UK
Imperial C. L.
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick
USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington
Near & Far sites:
KEK/JAEA
ICRR
~ 500 authors, 11 countries



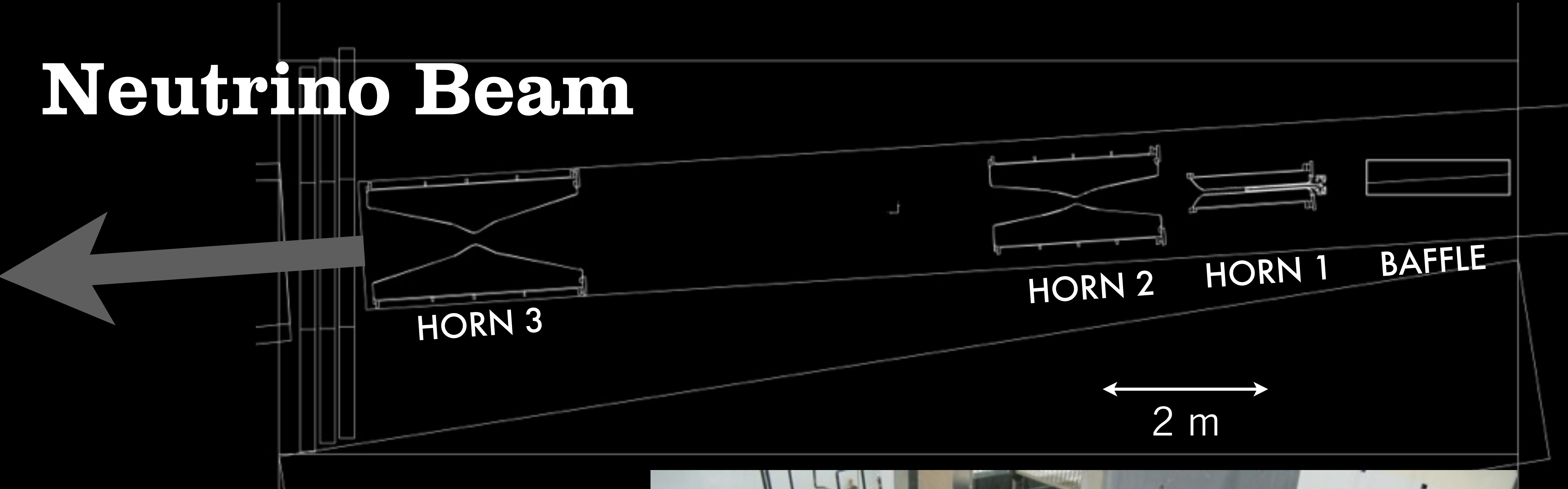
Linac
Pacific Ocean
3 GeV Synchrotron
Near Detector
Neutrino Beam to Kamioka
1200-year-old temple
Design Intensity 750kW
30 GeV Main ring
J-PARC Facility (KEK/JAEA)
View to North
Construction 2001~2009
Photo: January 2008

Neutrino Beam



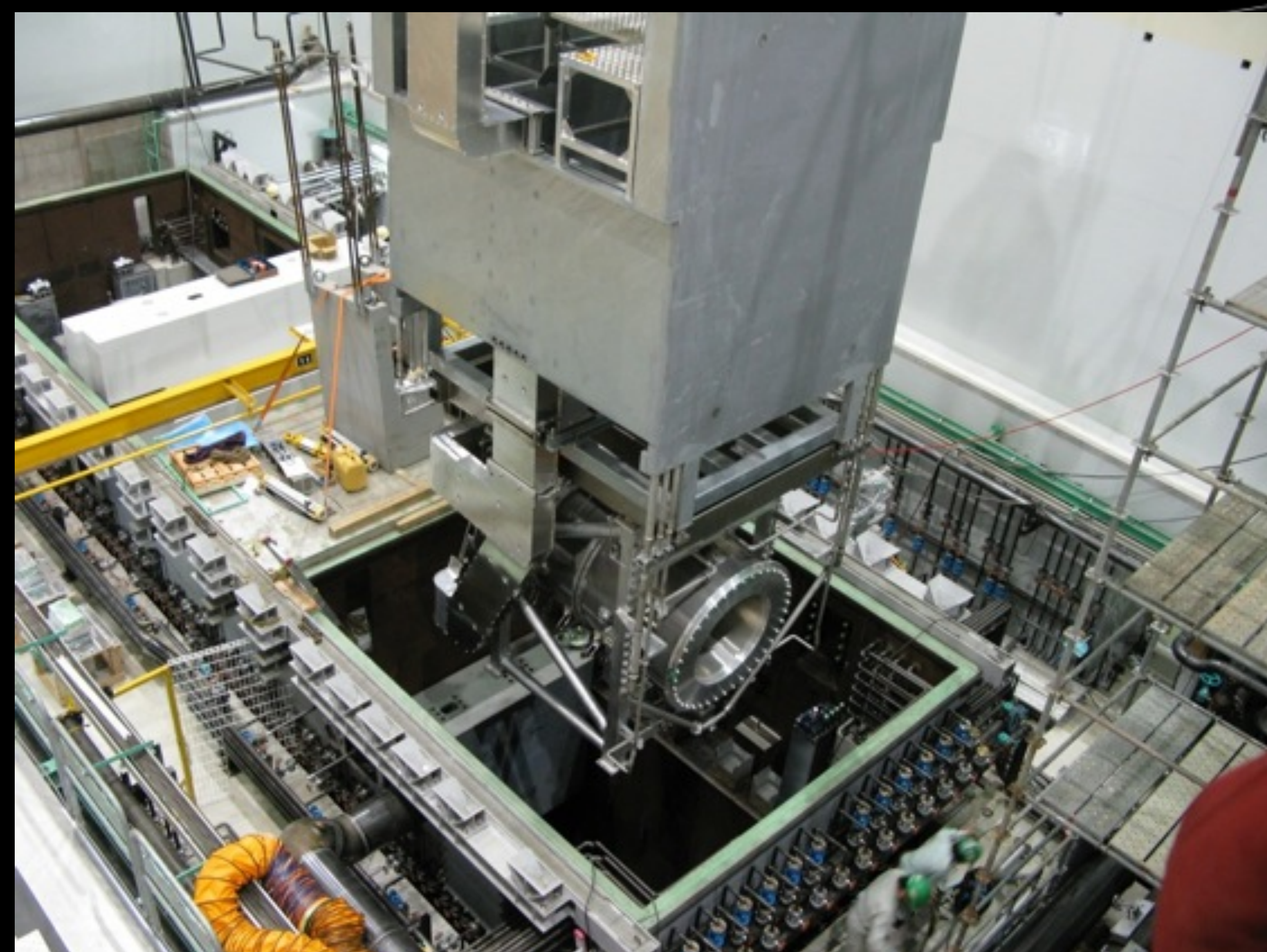
- Fast Extracted beam from Main Ring (30GeV)
- Graphite target (26mm dia. x 90cm)
- 3 horns @ 250kA (320kA eventually)
- 110m of decay volume

Neutrino Beam



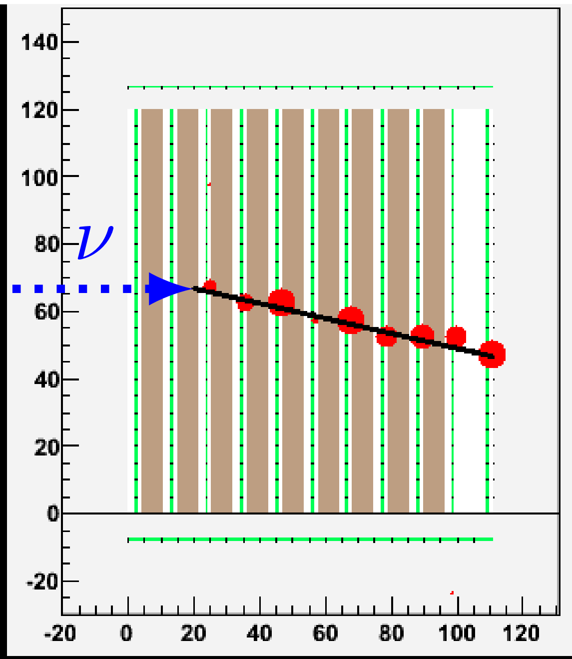
Target Station building: three horns in helium vessel

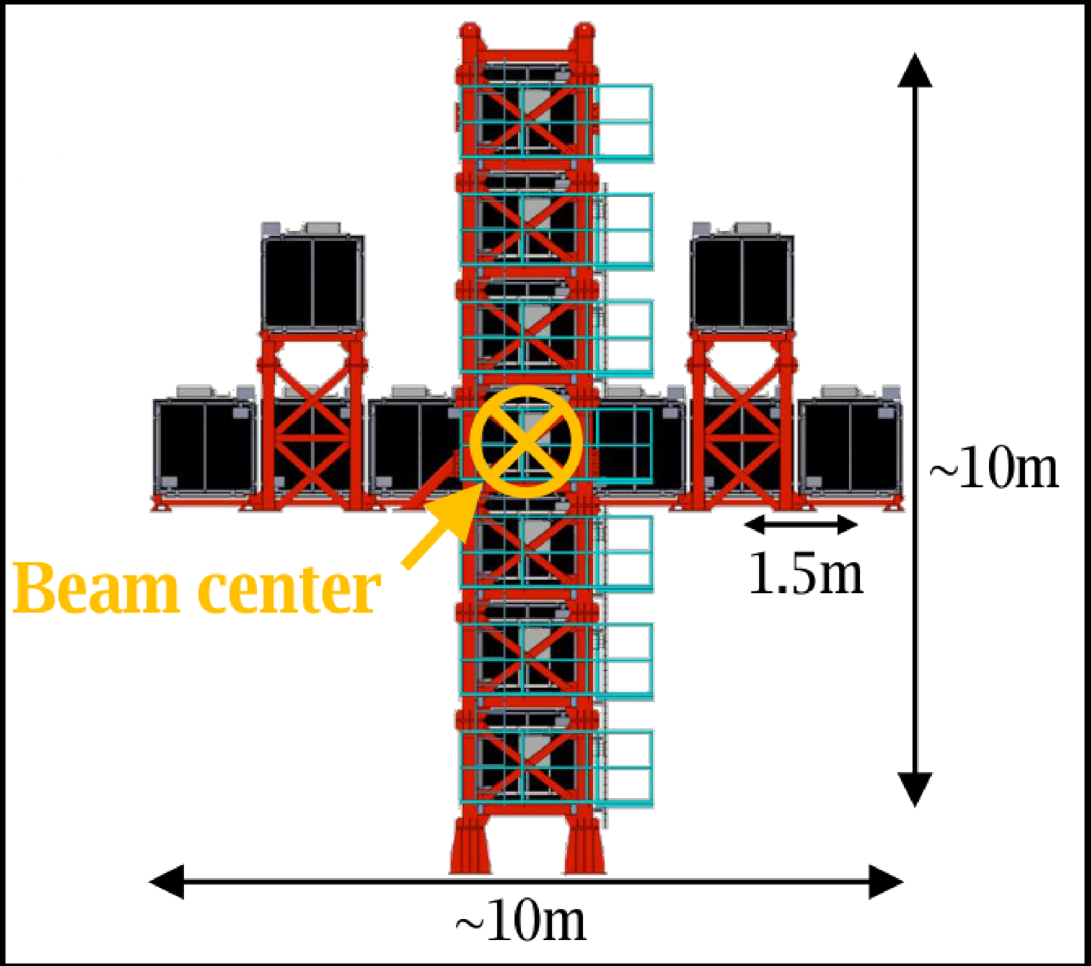
(Horn 3 shown during installation)



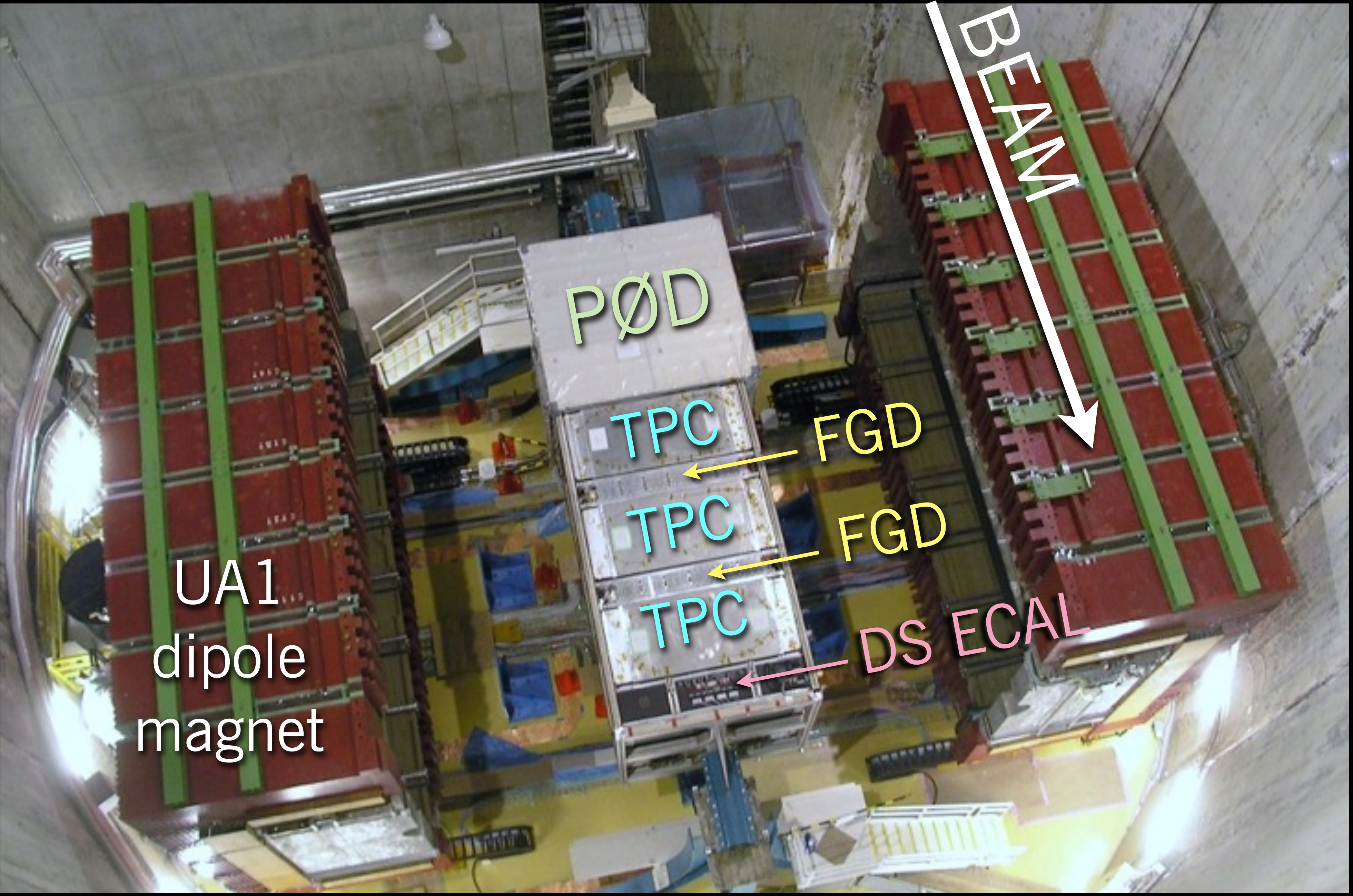
280m on-axis near detector: INGRID

- Array of 9-ton iron-scintillator neutrino detectors in cross shape centered on beam axis
- Designed to show neutrino beam profile, event rate, and precise measure of beam center/off-axis angle





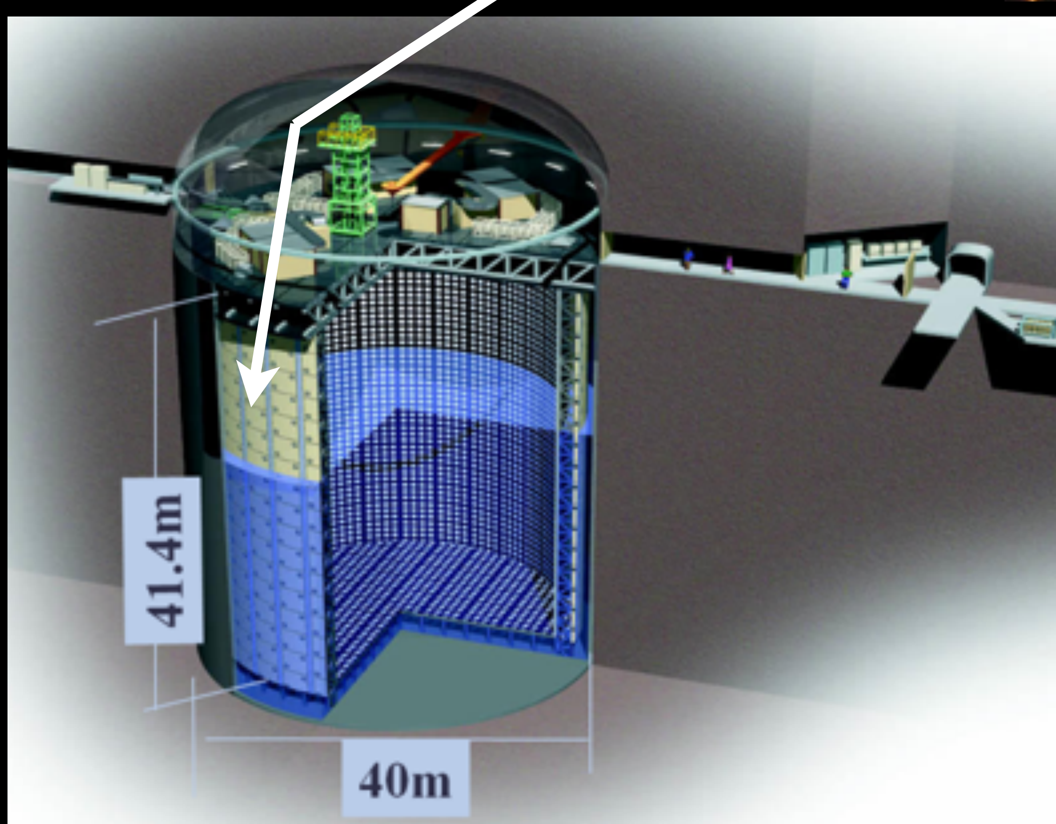
Off-axis Near Detector



- Pi Ø Detector (PØD): optimized for π^0 detection, includes H_2O target
- Tracker: 2 Fine-Grained Detectors (FGD), H_2O target, 3 TPCs: measure fluxes before oscillation
- ECAL: surrounding POD and Tracker, measure EM activity
- Side Muon Range Detector: in the magnet yokes, identify muons

Super-Kamiokande

- 50 kt water Cherenkov (22.5 kt fiducial)
- 11129 20-inch PMTs in inner detector; 1885 8-inch PMTs in outer veto detector

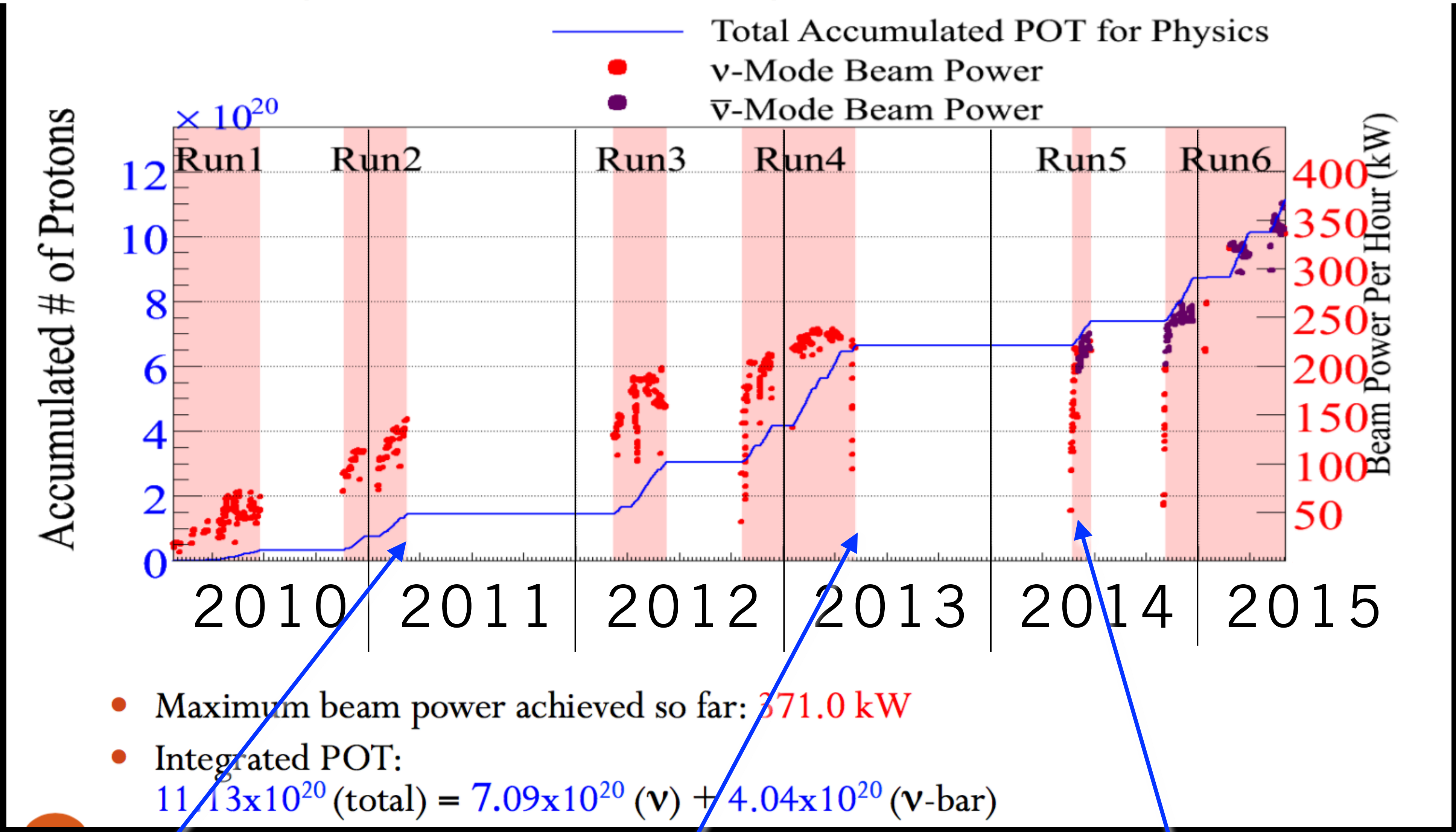


- Originally commissioned 1997
- Designed for proton decay and neutrino measurements
- Sensitive to solar and supernova neutrinos as well as atmospheric
- Now also used as far detector for T2K

First proton beam on target April 2009

Neutrino physics runs

- Beam delivered in six run periods so far, starting in early 2010
- 1.11×10^{21} protons on target so far
- Under 20% of approved total T2K beam
- Expecting to make improvements in the next few years through higher beam power, more months/year operation



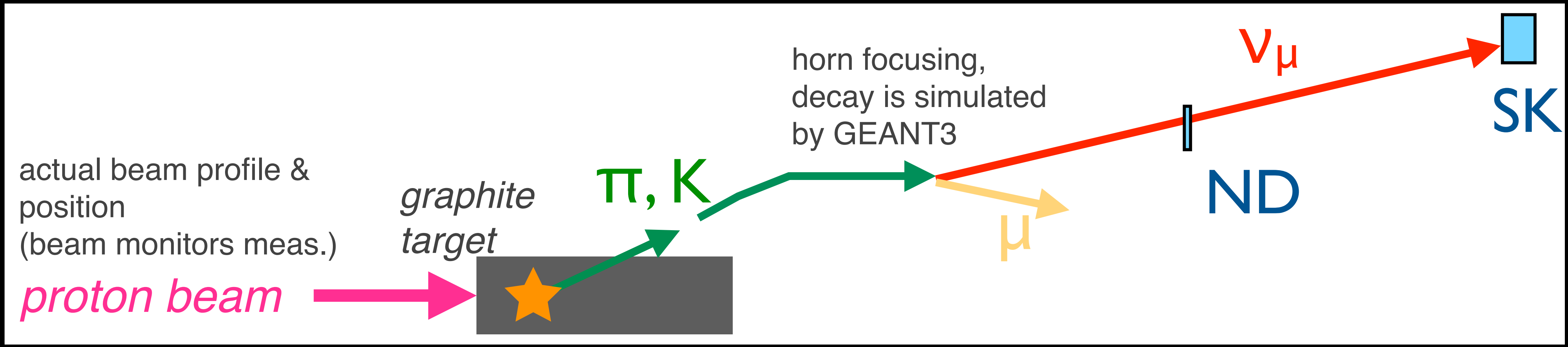
March 2011: Great East Japan Earthquake

May 2013: Hadron hall radiation incident

June 2014: Switch to antineutrino mode

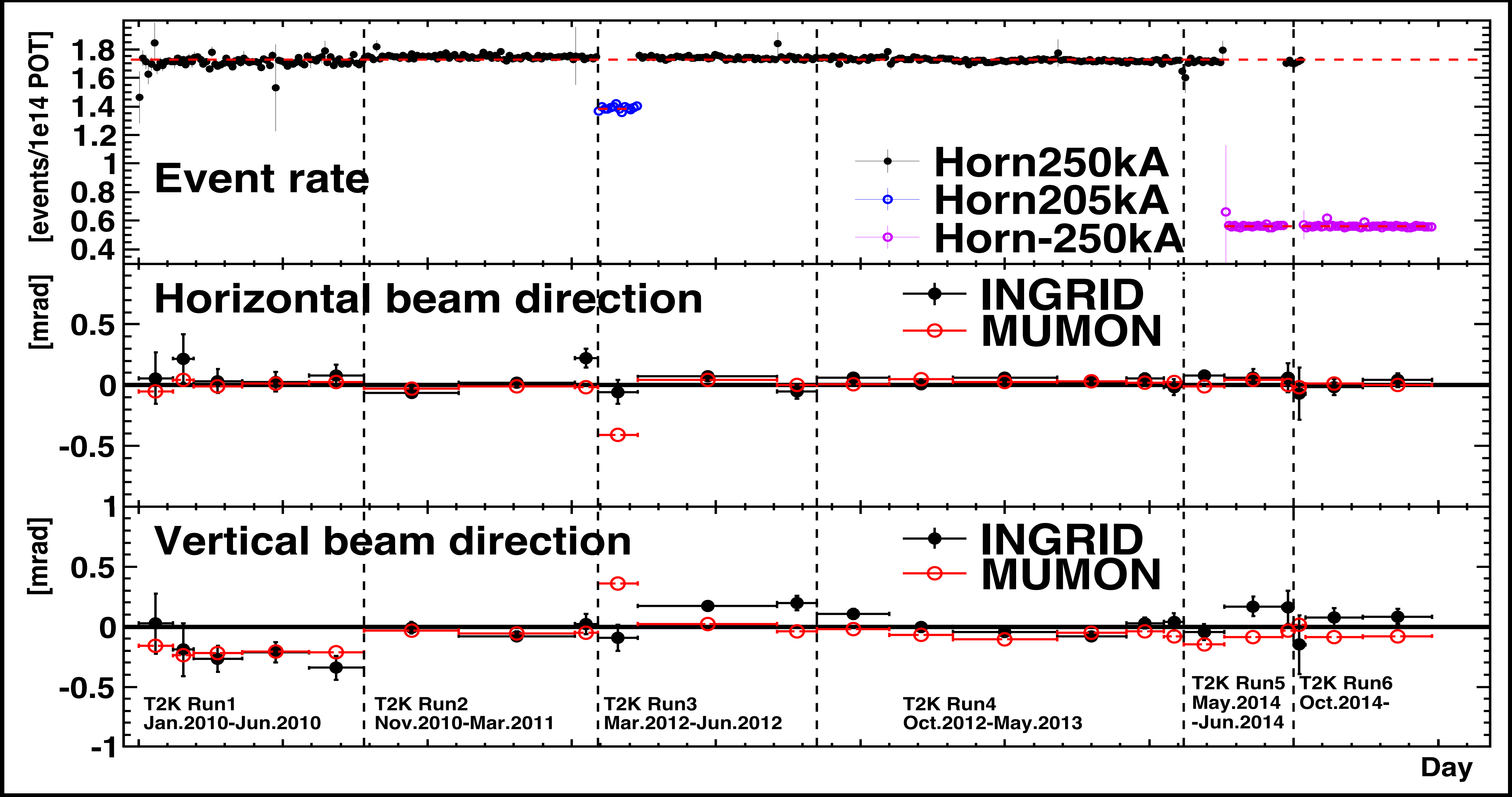
T2K data analysis

Neutrino flux prediction from beam MC



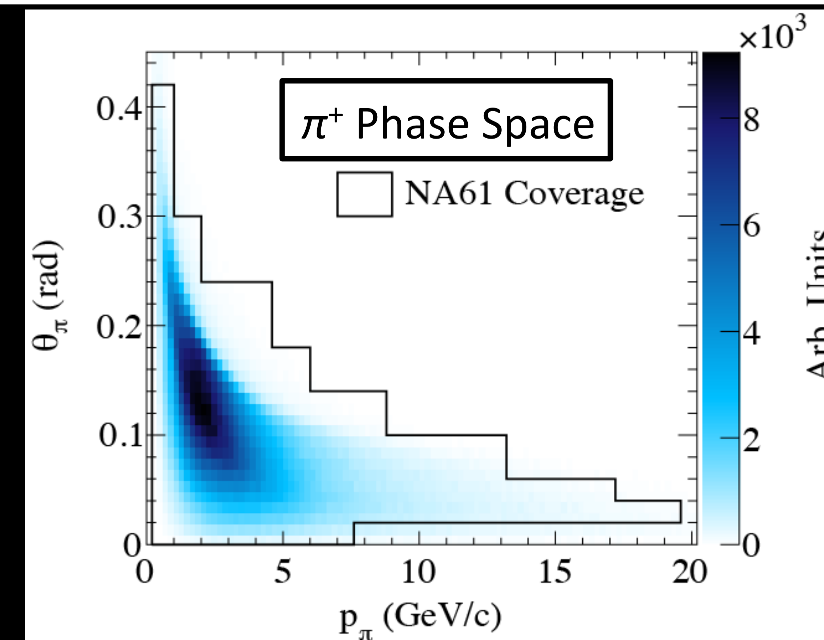
- Proton beam interaction in target: primary information comes from dedicated running of CERN NA61 experiment that measured particle production from 30 GeV protons on carbon (covers 95% of relevant production phase space for T2K). Crucial for T2K analysis!
- Kaon production, pions outside the NA61 acceptance, and secondary interactions all simulated with FLUKA
- Secondary interactions outside target tuned to external data
- Horn focusing, decay region, beam absorber simulated in GEANT3

Beam stability

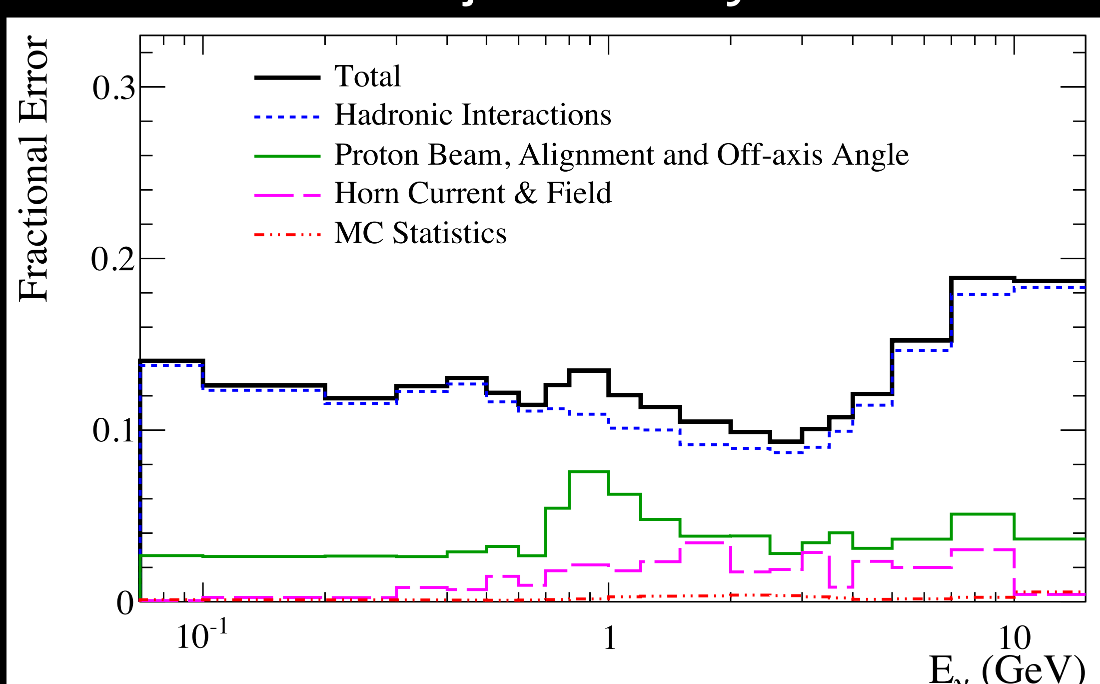


NA61 contribution to T2K flux measurements

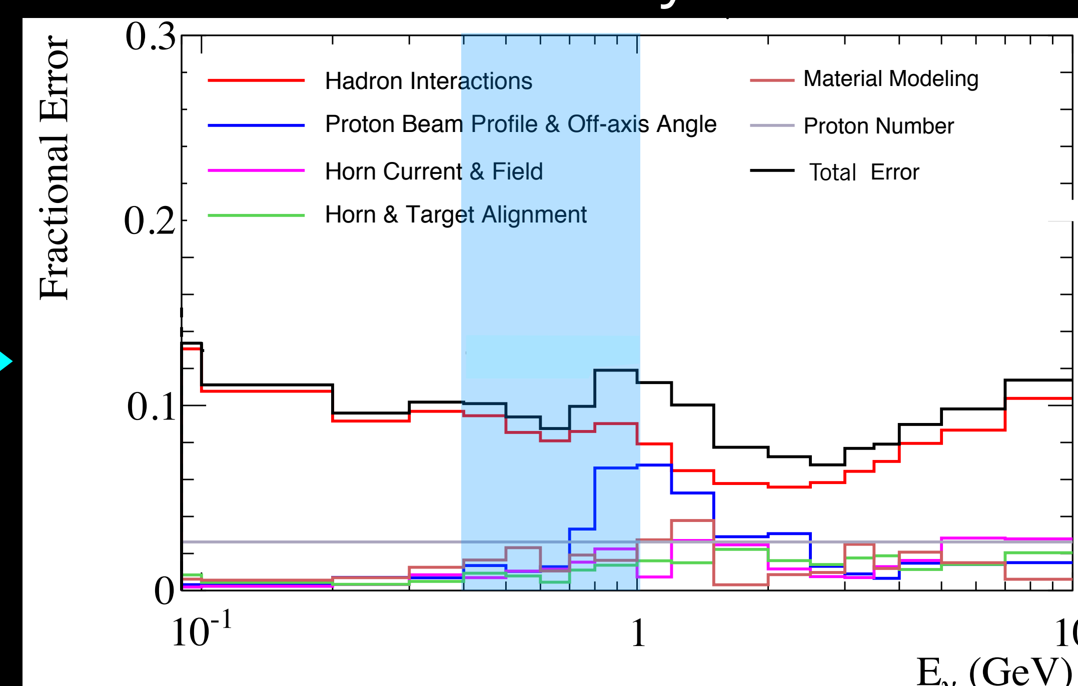
- NA61 at CERN measures distributions of pions and kaons produced from 30 GeV/*c* protons on carbon target
- T2K uses these results to tune the beam simulation and reduce systematic errors
- Improvement in the new T2K flux errors due to addition of 2009 NA61 data.
- Future improvements expected from analysis of T2K replica target data



2014 joint analysis

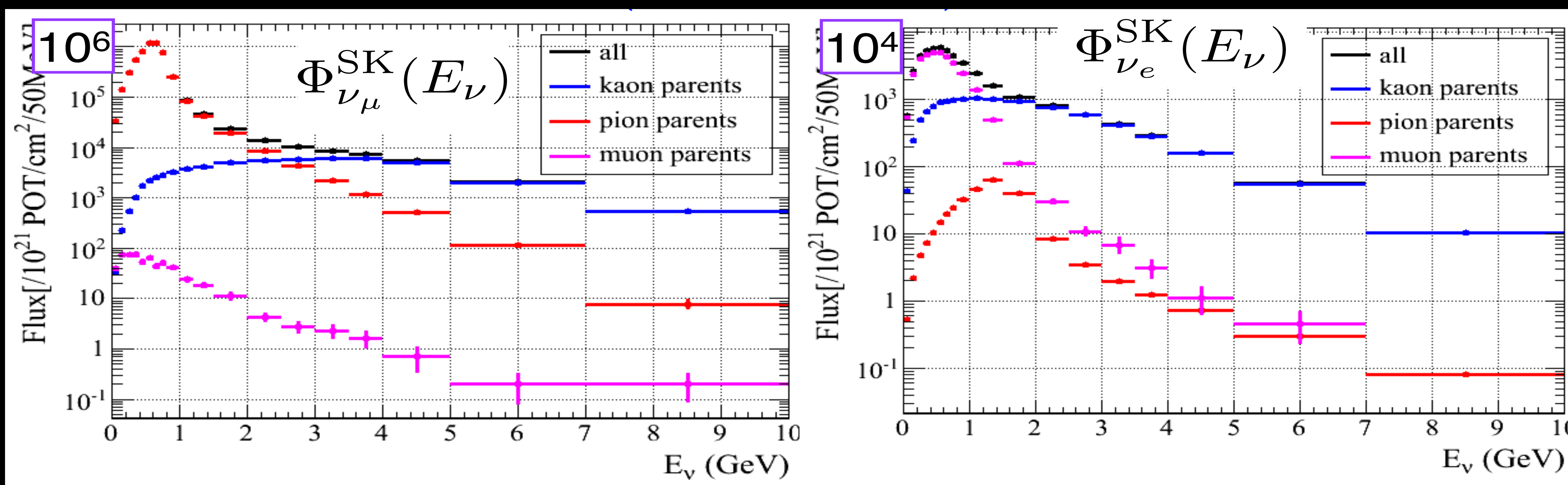


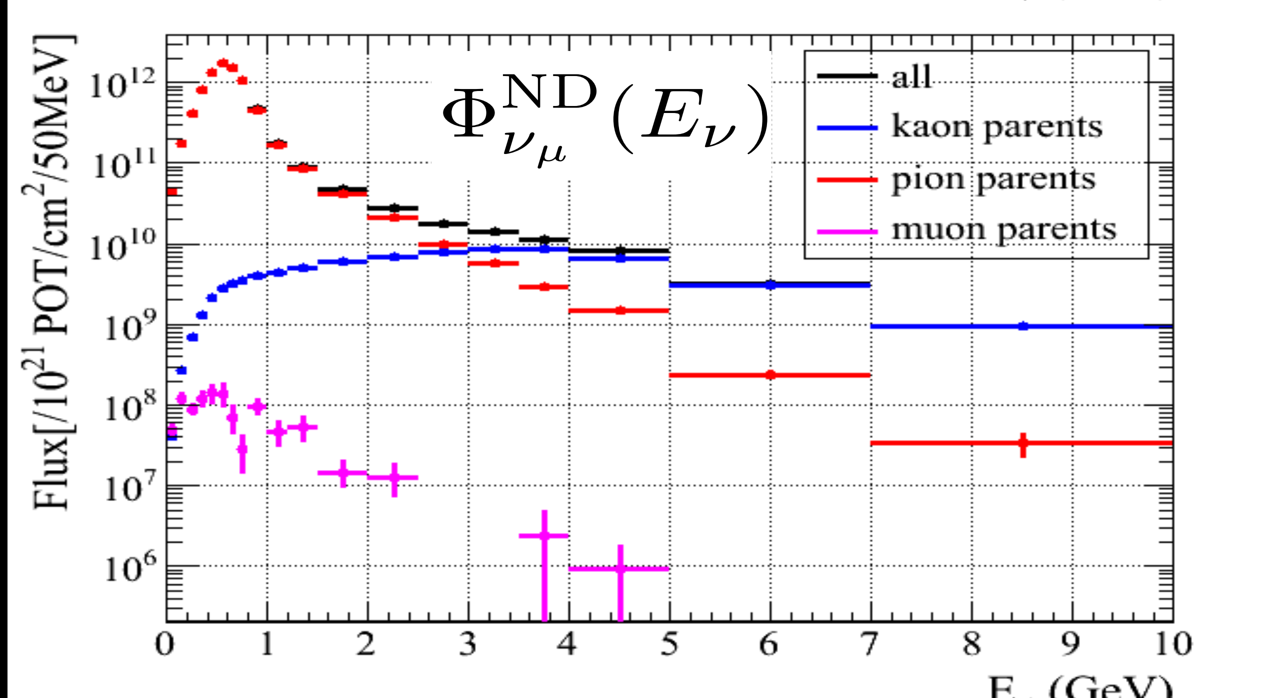
2015 analysis



ν_μ flux uncertainties in neutrino running mode

Predicted neutrino flux

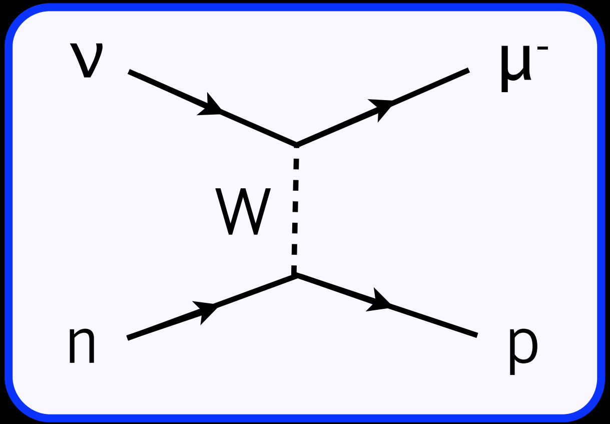




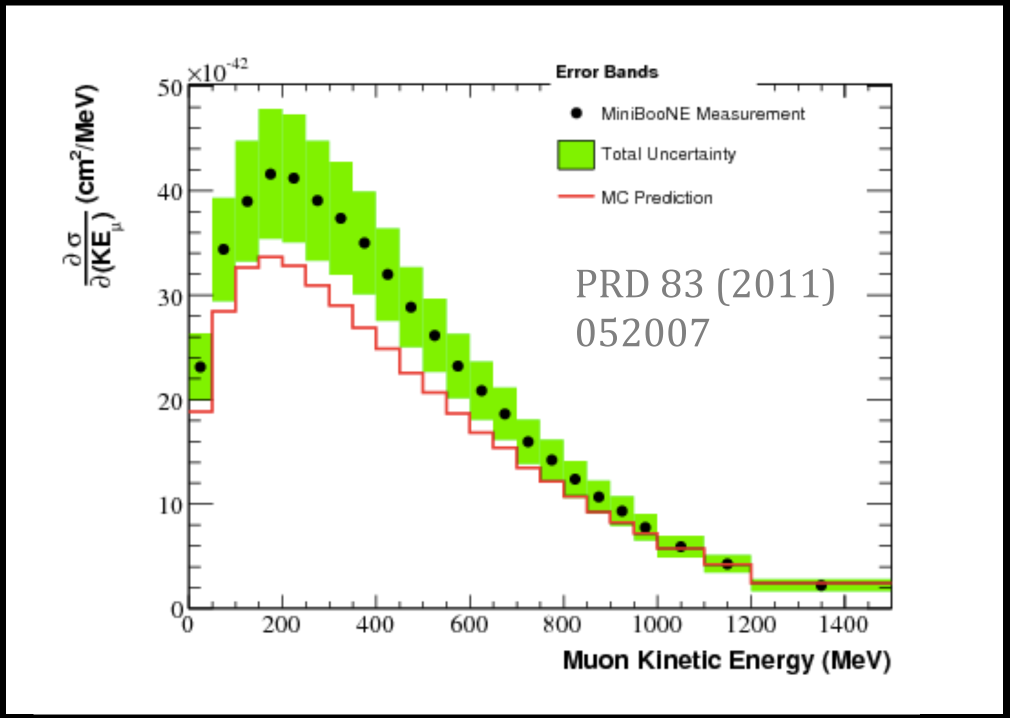
- Muon decay responsible for most low-energy ν_e flux: originates from pions already measured by NA61
- Kaon decay dominates high-energy flux

External cross-section info

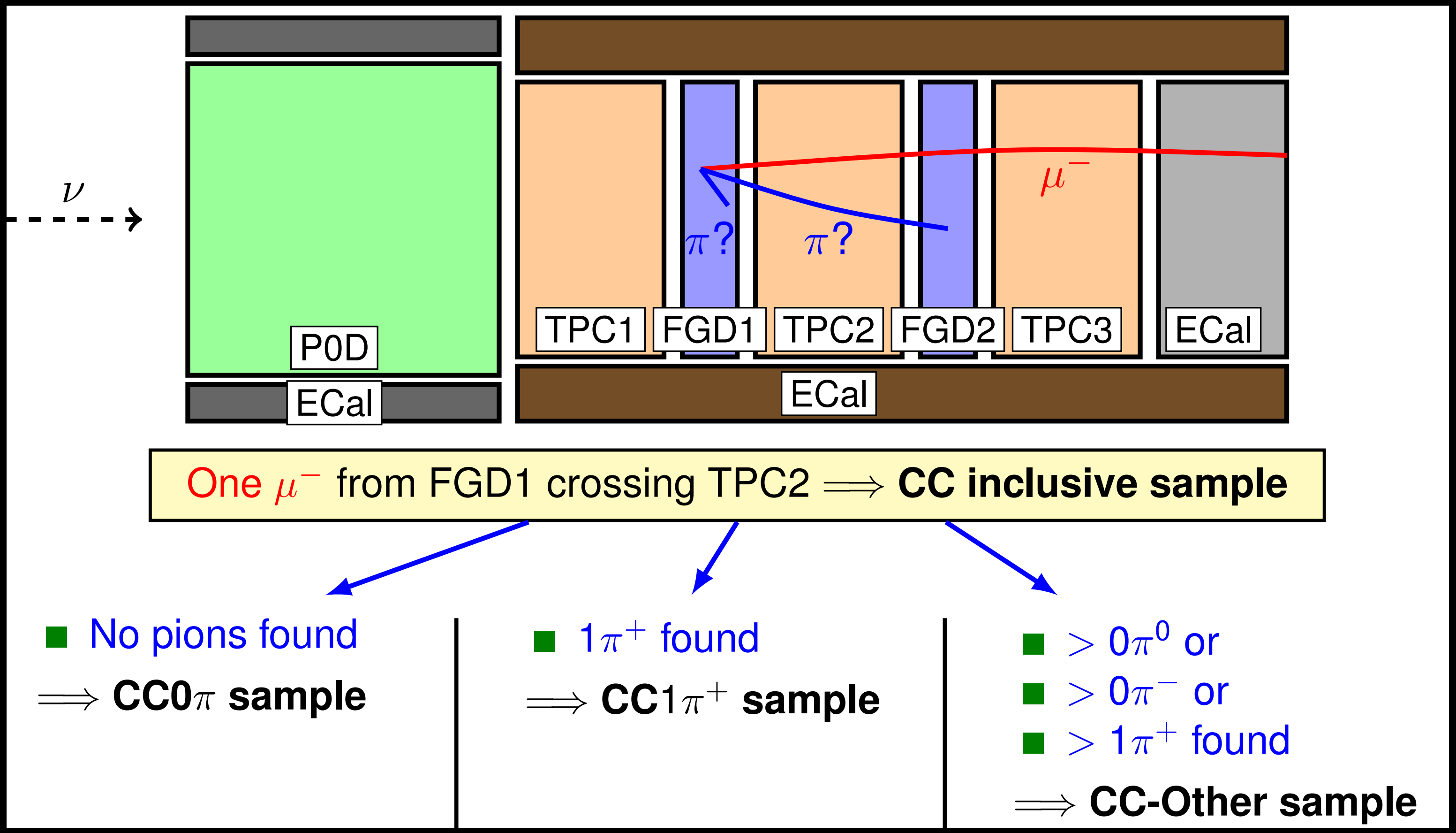
- Most common process at oscillation maximum (600 MeV) is *charged-current quasielastic scattering:*
  - $\nu_\ell + n \rightarrow \ell^- + p$



- Also have resonant pion production, NC elastic, and some coherent- and multi-pion events.
- Use NEUT simulation (2012) for initial interaction, final state nuclear effects (charge exchange, pion absorption, etc)
- Some model parameters are used (M_A, p_F, E_b); these are tuned to external neutrino data including MiniBooNE →

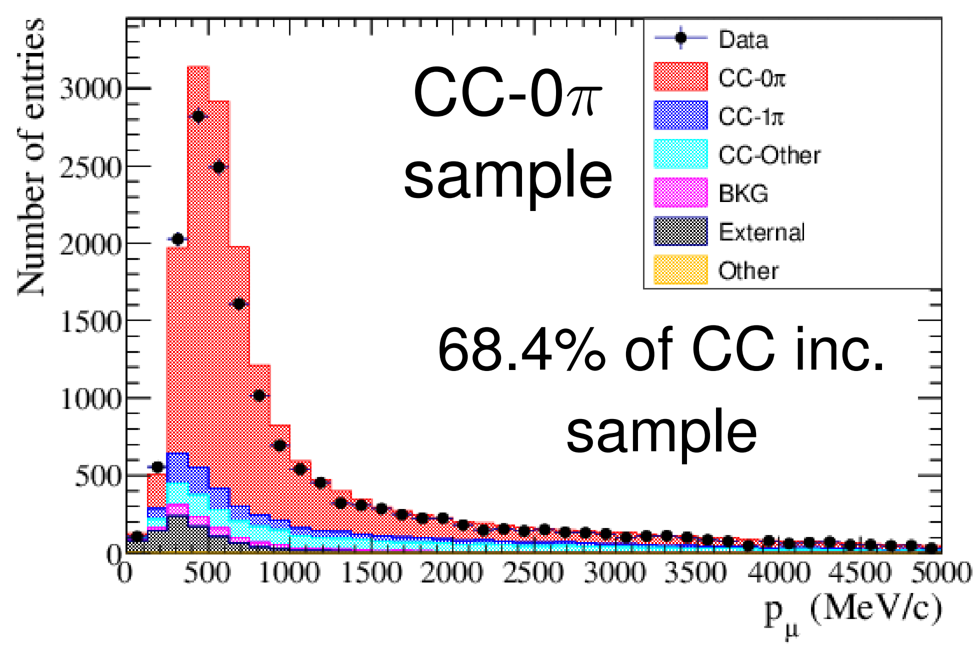


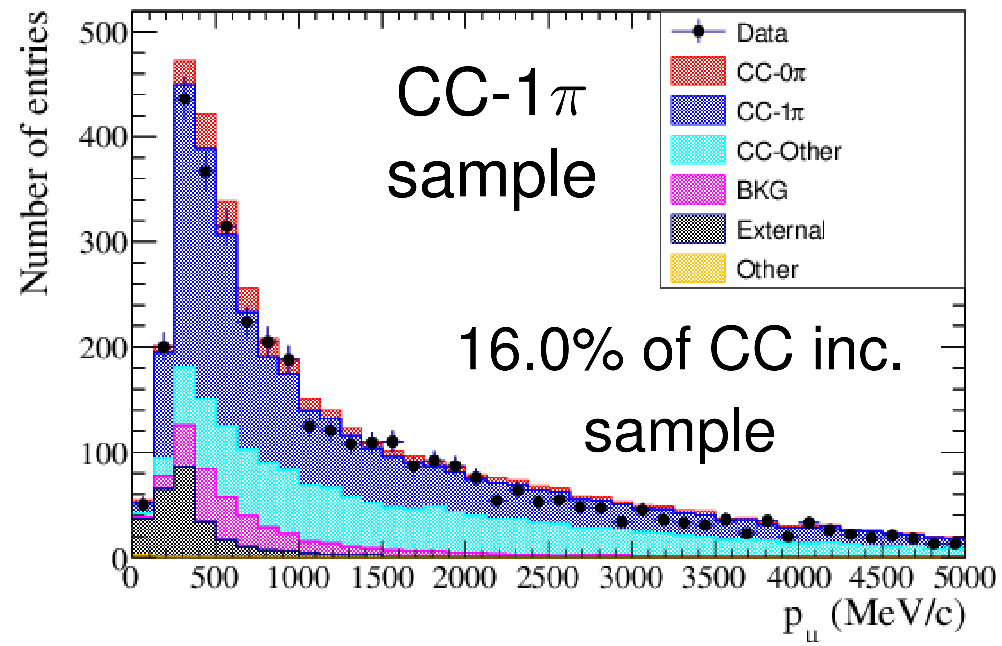
Near-detector analysis



- For further flux and cross-section constraint, identify ν_μ events originating in fine-grained tracker
- Classify in one of three samples based on extra-track topology

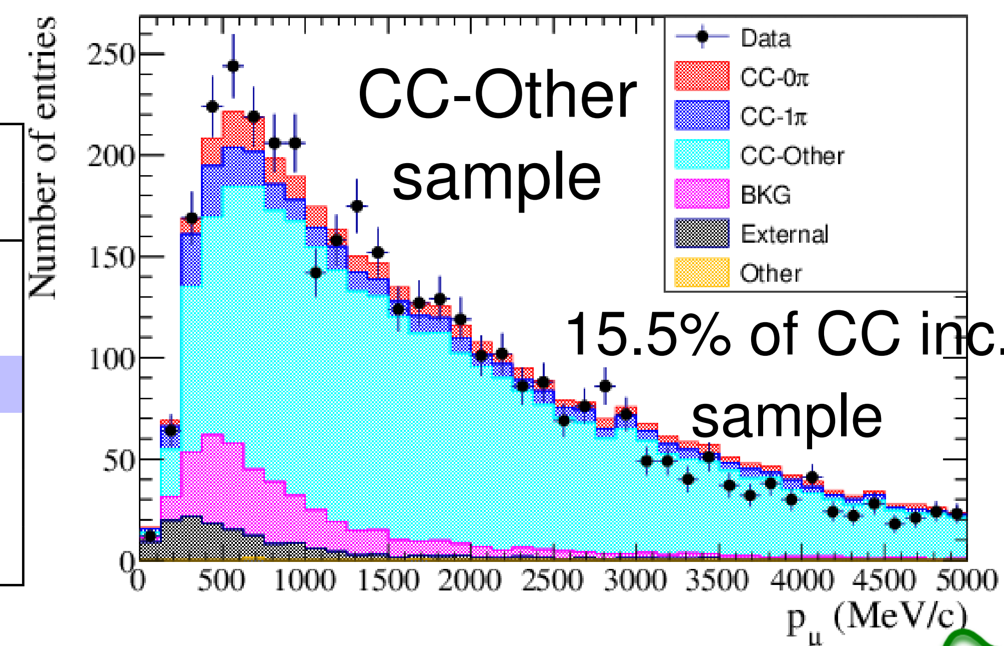
Near-detector muon samples for constraining flux/xsec





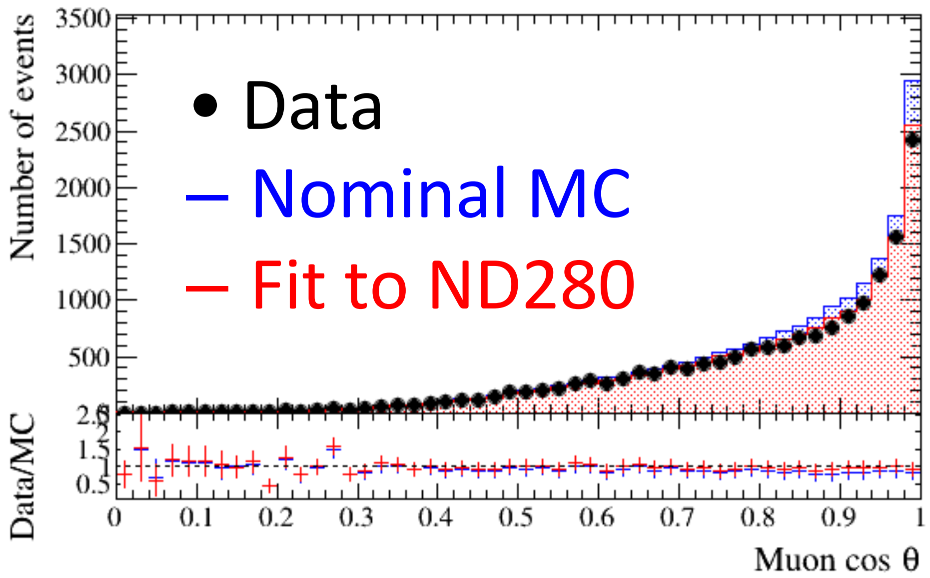
Data/MC distributions before any fit

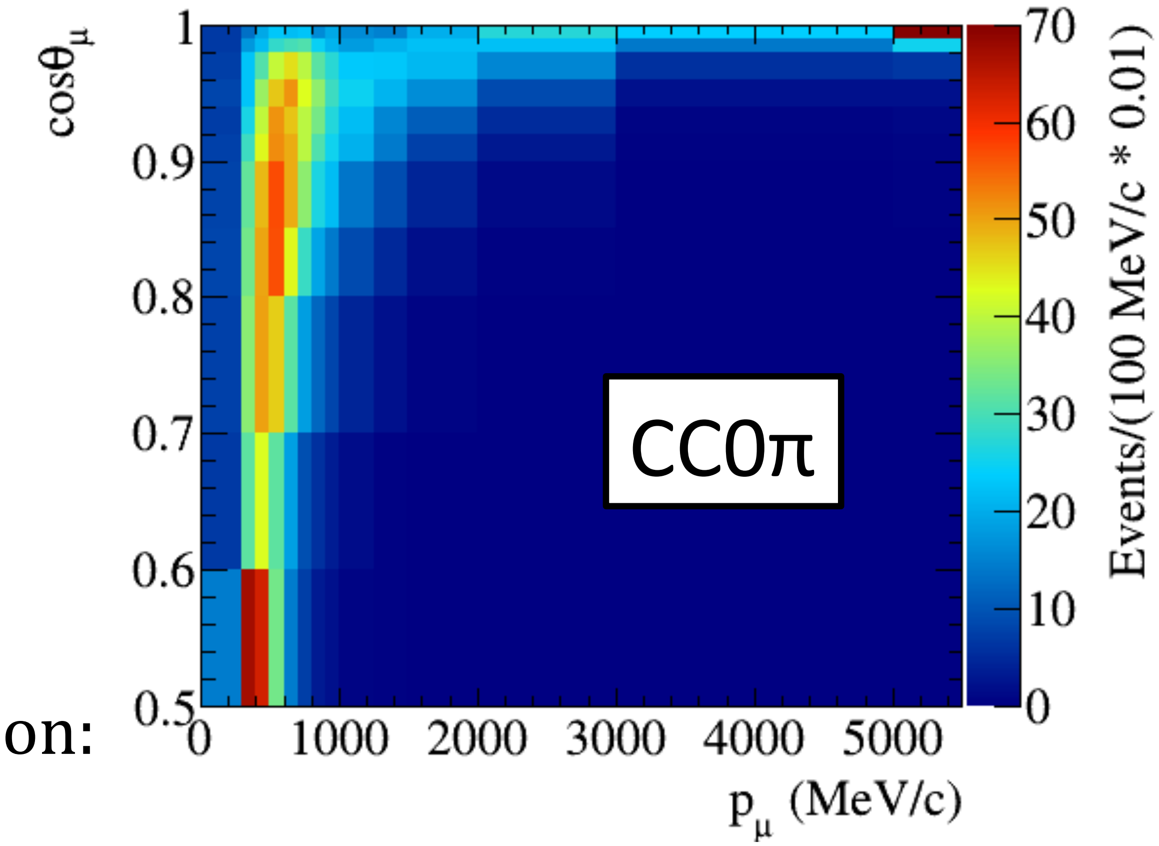
	Purity of each sample		
	CC-0π	CC-1π	CC-Other
CC-0π	72.6%	6.4%	5.8%
CC-1π	8.6%	49.4%	7.8%
CC-Other	11.4%	31.0%	73.8%
Bkg (NC+$\bar{\nu}_\mu$)	2.3%	6.8%	8.7%
Out of fiducial volume	5.1%	6.5%	3.9%



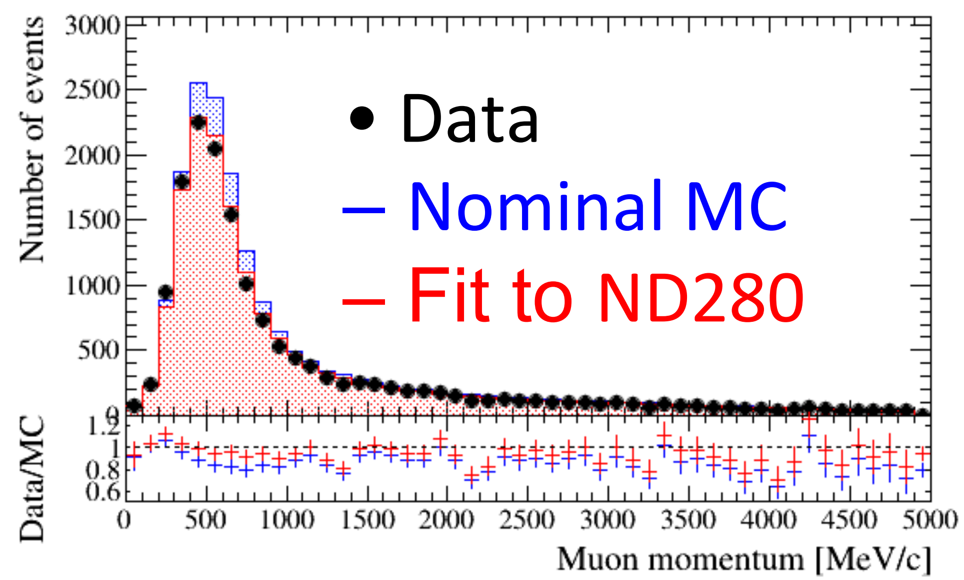
- Very high statistics!
- CC1π sample is particularly important in reducing systematic errors vs. pre-2013 results.

ND280 fit to constrain SK prediction

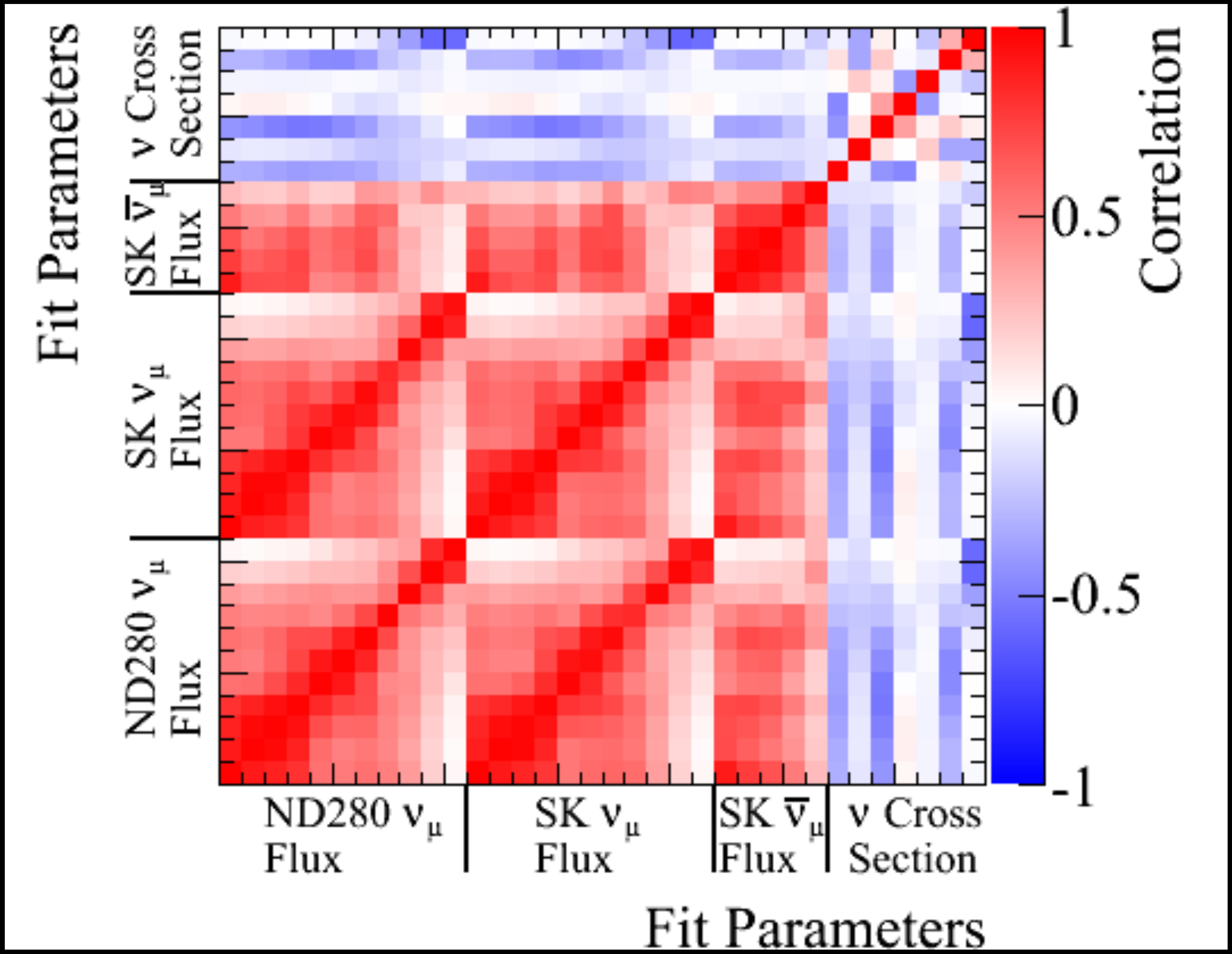




- Fit each sub-sample in 2 dimension:
  - μ^- momentum and angle
- All parameters in fit are systematic errors
  - Flux, cross sections, detector errors
  - No ND ν_μ oscillations

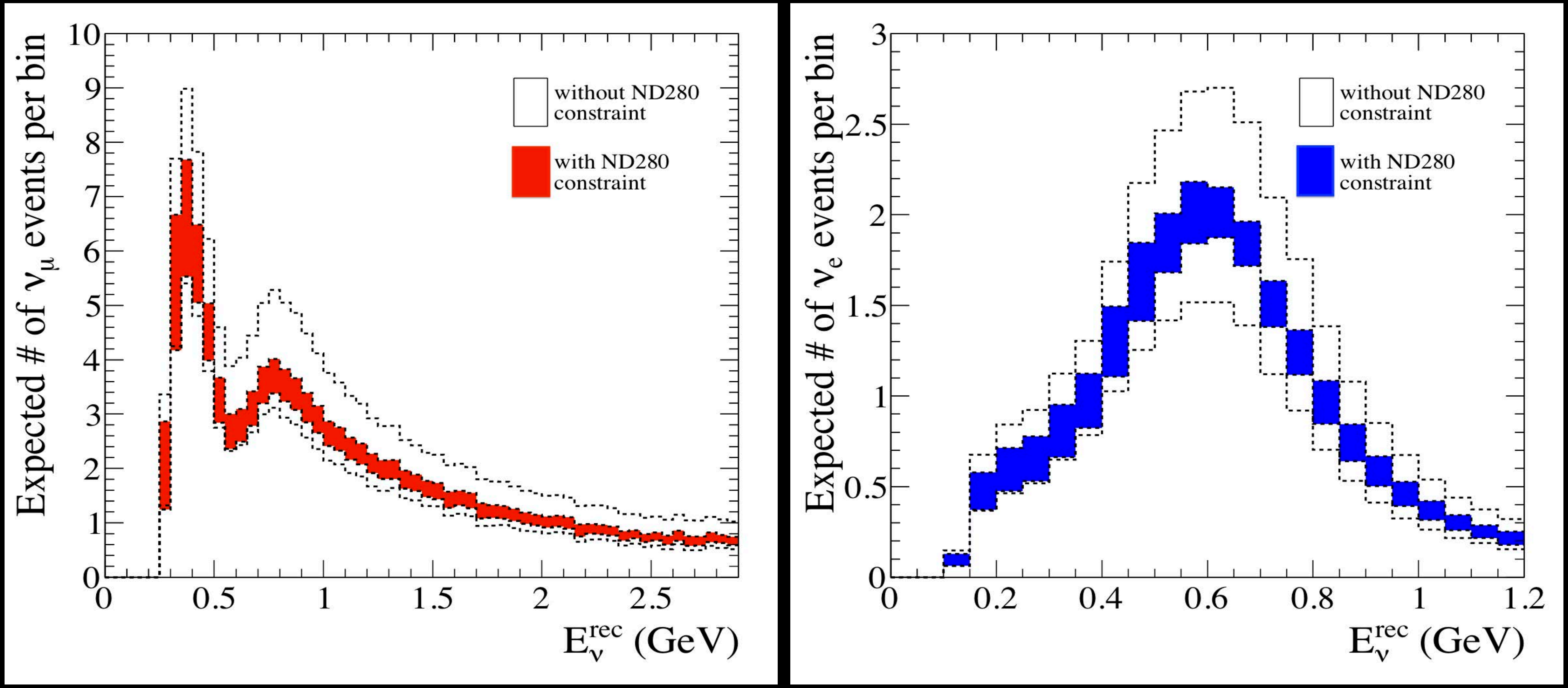


ND280 and flux fit for SK predictions



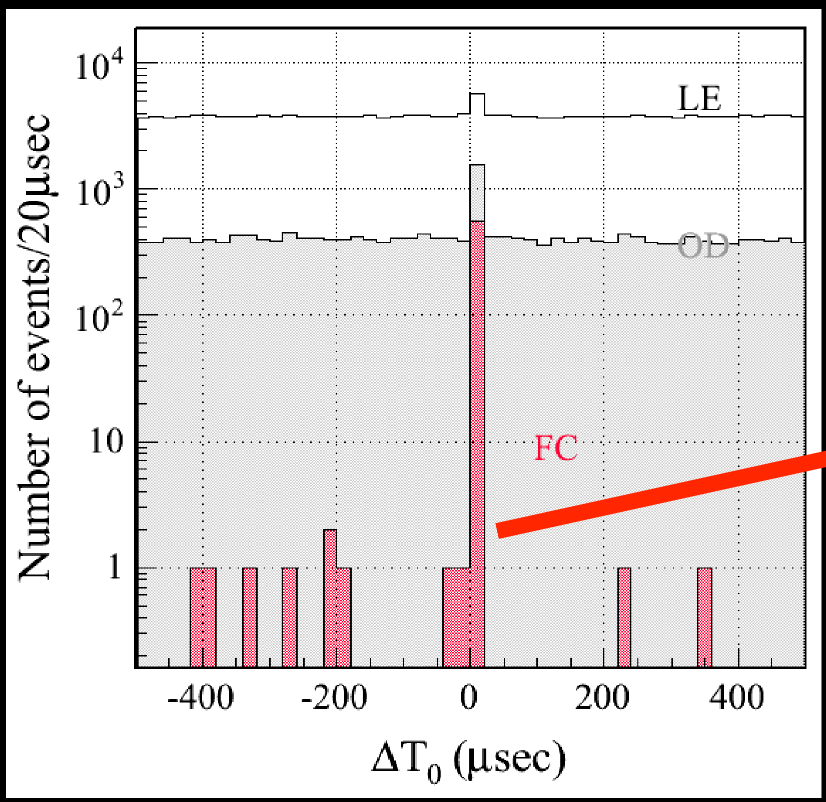
- Correlation matrix (improved since previous results)

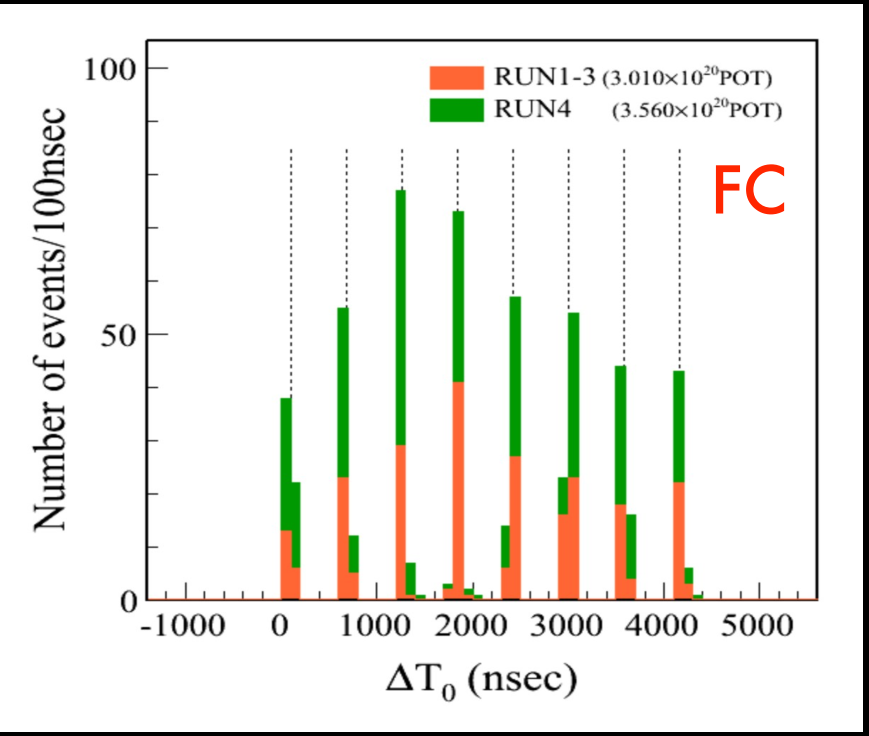
Near detector greatly reduces errors on predicted events at SK



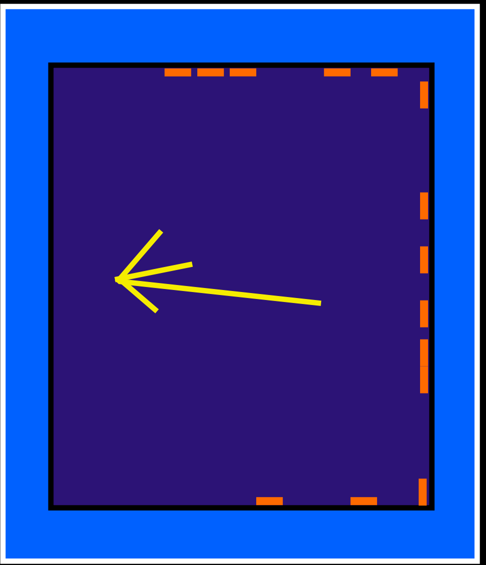
Neutrino physics runs: Super-Kamiokande

Event time relative to beam arrival + *L/c*

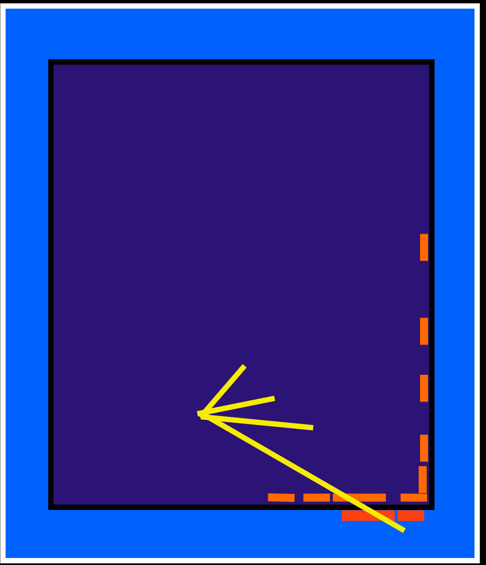




LE: Low energy triggered events
OD: Outer detector events
FC: Fully contained events



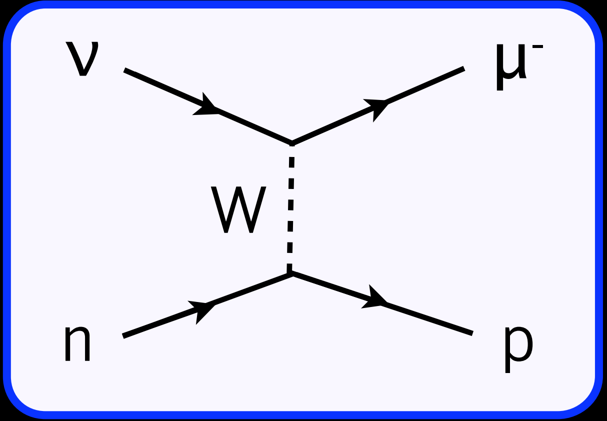
FC: Fully contained event



Uncontained event (in OD trigger)

- Event time distribution clearly shows eight-bunch (six in Run 1) beam structure
- Expected non-beam background: $\sim 10^{-2}$ events

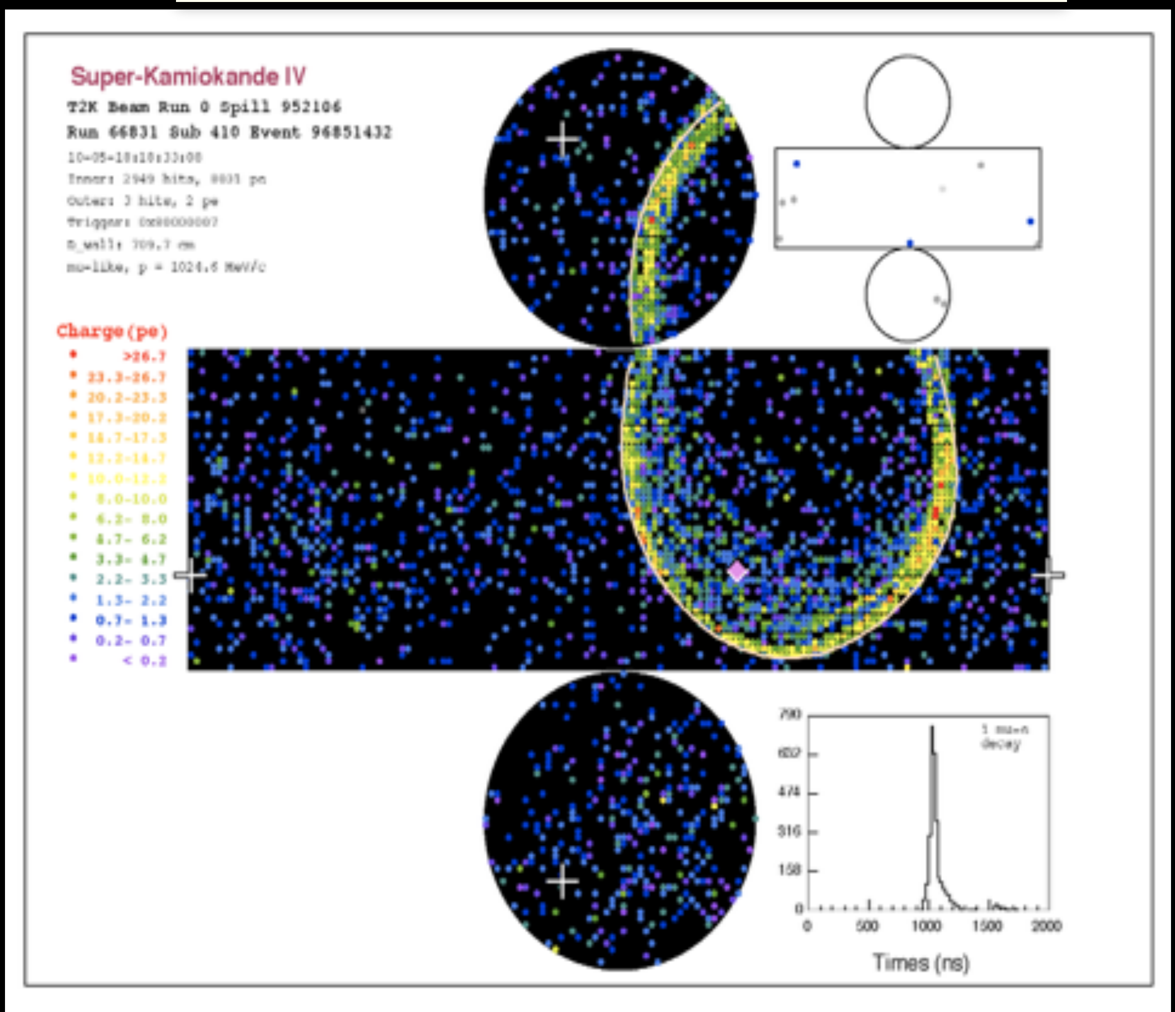
Signal and background for ν_e appearance analysis



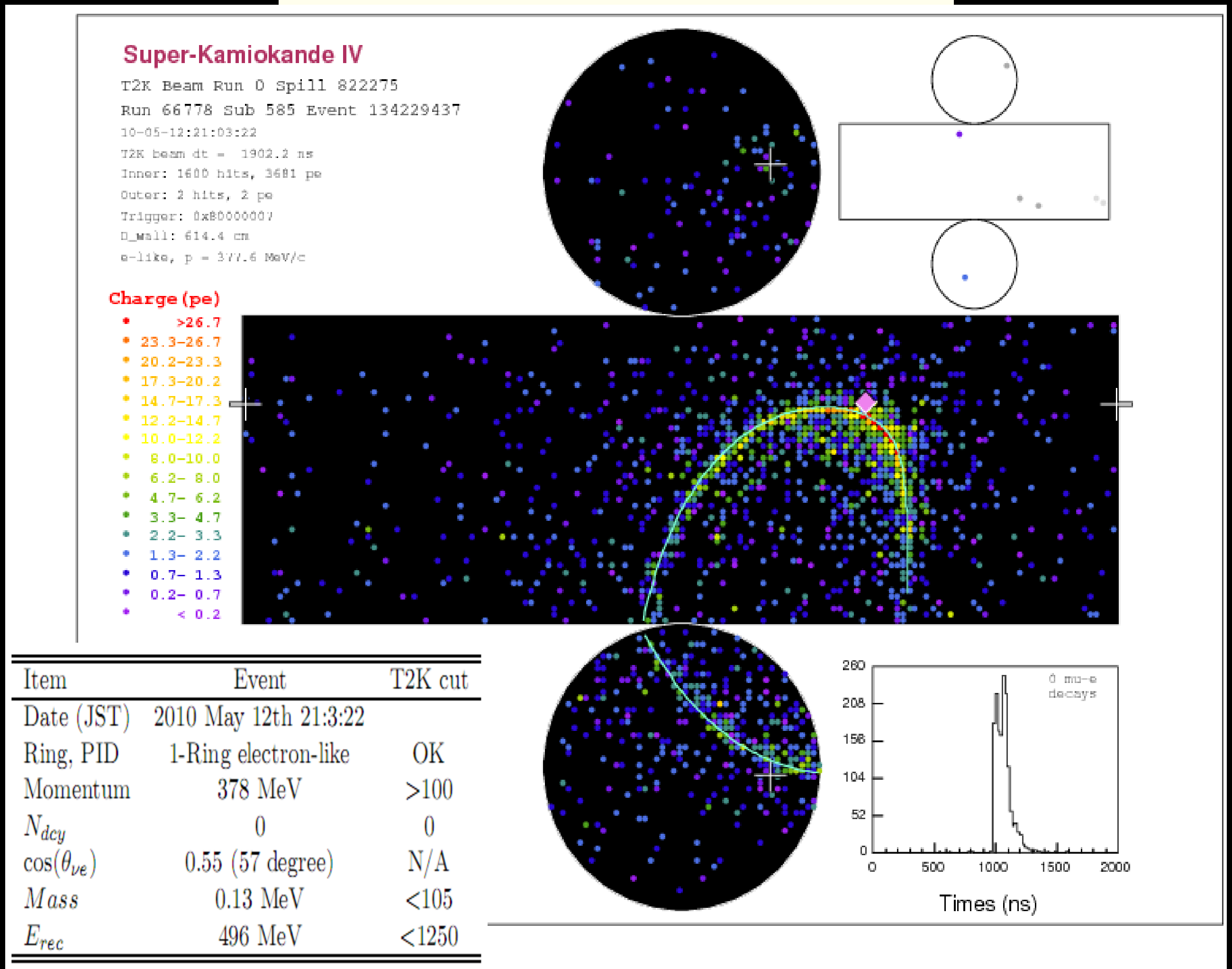
- Signal is CCQE scattering
  - e/μ separation is mostly via ring shape; decay electron identification helps too
- Signature in Super-Kamiokande is a single Cherenkov ring, as proton usually below threshold
- Largest background is intrinsic ν_e
- Most common non-ν_e background is neutral-current π^0 production, where one photon has very low energy

T2K neutrino events

Single-ring μ-like event



Single-ring e-like event

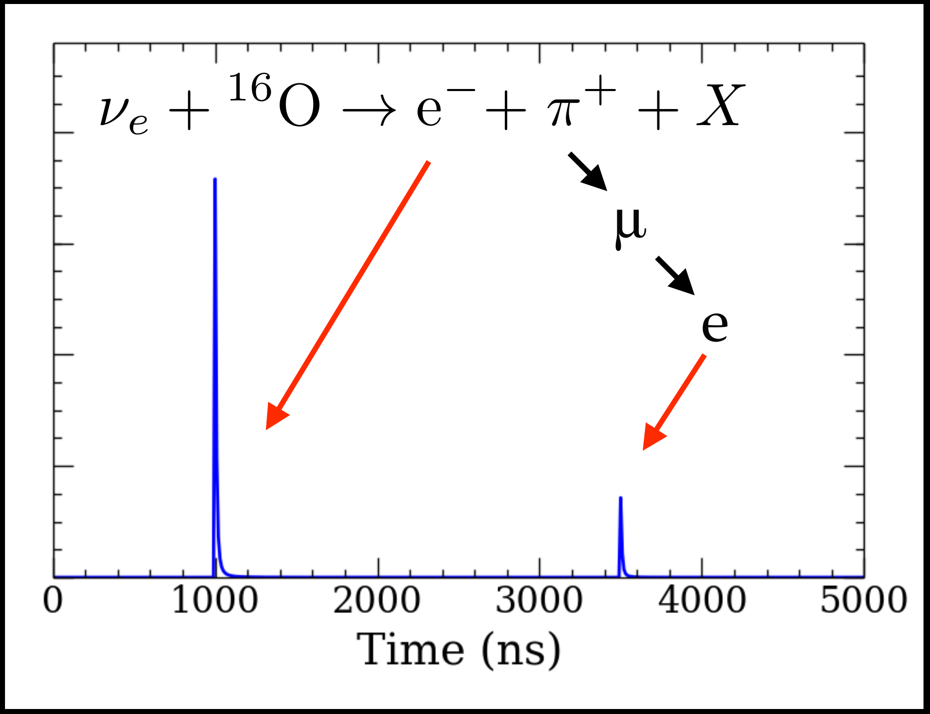


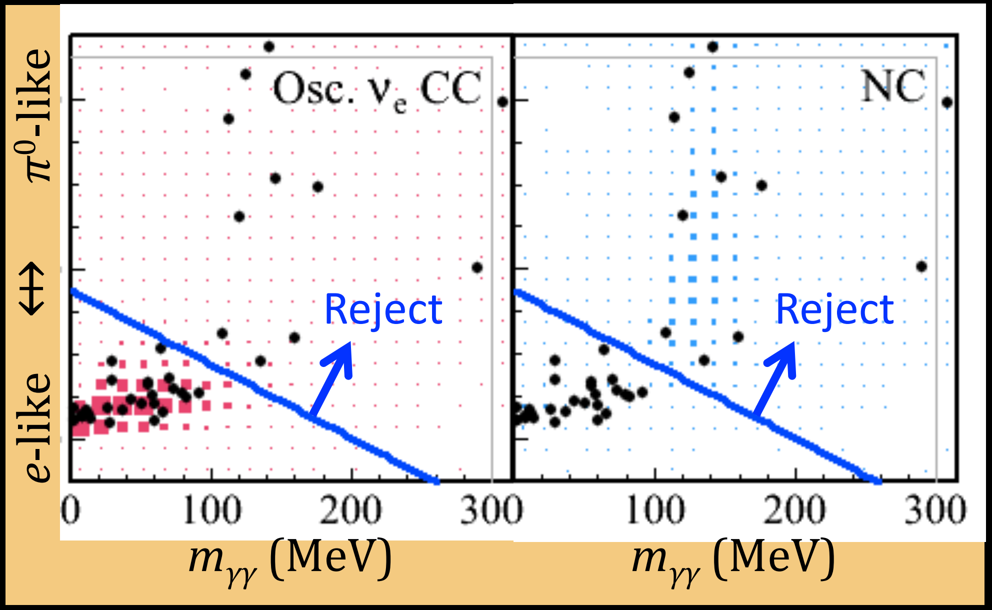
Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
$Mass$	0.13 MeV	<105
E_{rec}	496 MeV	<1250

- Pink diamonds are placed on the wall in the beam direction starting from the reconstructed vertex.

Reduction of non-CCQE background

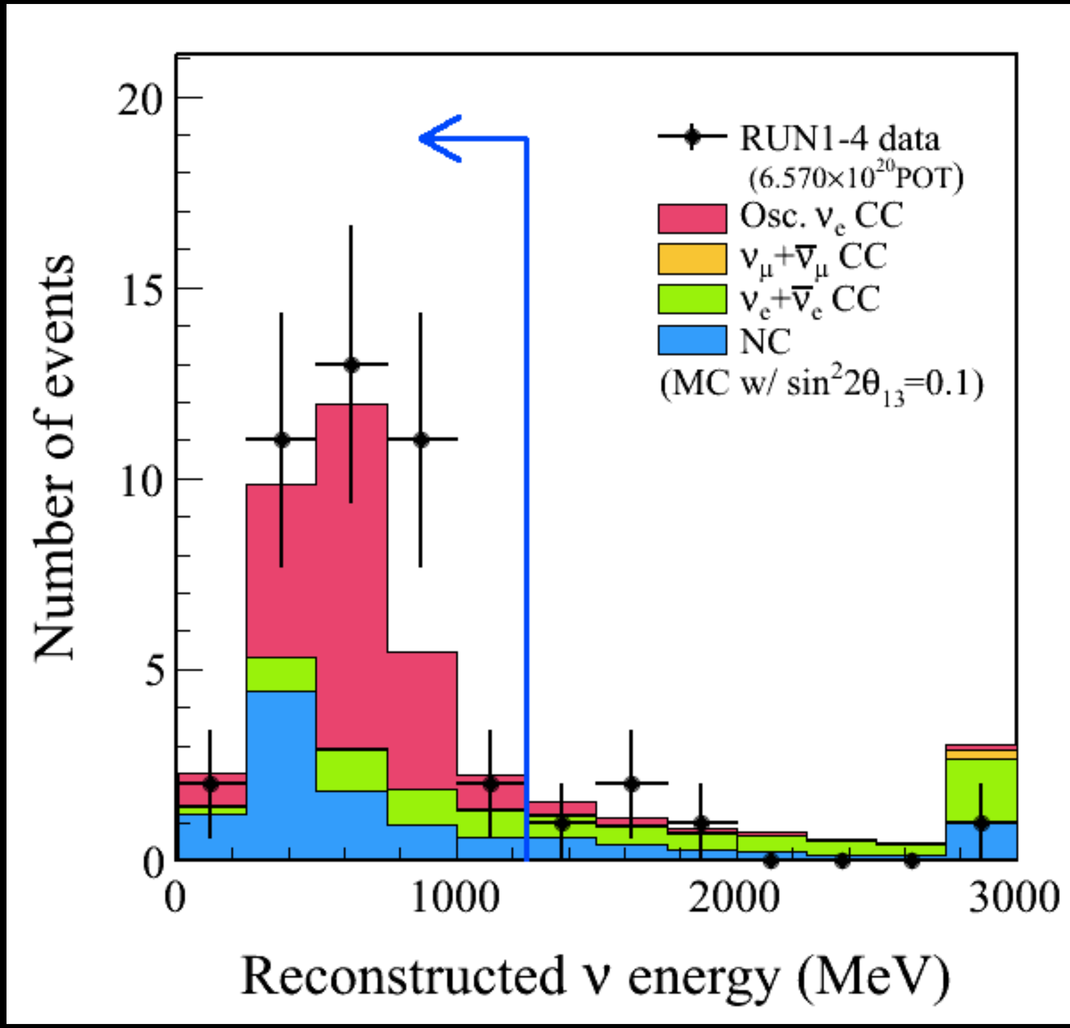
- Remove events with muon-decay electrons: these are likely to be from unseen pions in final state
  - $\pi^{\pm}$ Cherenk. threshold: 160 MeV
  - $e^{\pm}$ Cherenk. threshold: 0.8 MeV





- Likelihood-based reconstruction
  - Compare e-like and π^0-like hypotheses
  - Cut line optimized in likelihood-inv. mass space

Reduction of intrinsic ν_e



- Remove events with reconstructed energy >1250 MeV
  - Signal mostly at lower energy
  - Intrinsic beam ν_e dominate at higher energy

Far detector analysis: cuts

For ν_μ disappearance analysis	For ν_e appearance search
Timing coincidence w/ beam timing (+TOF)	
Fully contained (No OD activity)	
Vertex in fiducial volume (>2m from wall)	
Number of rings = 1	
E_{vis} > 30 MeV	E_{vis} > 100 MeV
μ-like ring	e-like ring
0 or 1 decay electron	No decay electron
p_μ > 200 MeV/c	Remove π^0-like events
	E_ν^{rec} < 1250MeV

After all cuts:

- Signal efficiency 66% for fiducial volume
- Intrinsic beam ν_e background efficiency is 23%
- NC efficiency <1%

Systematic Uncertainties

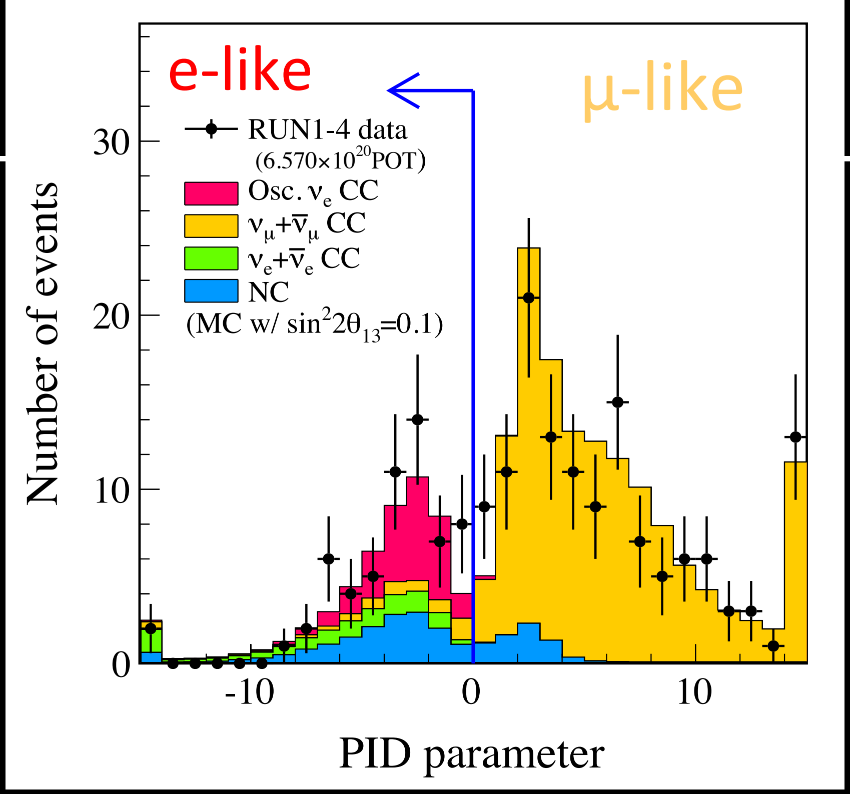
ν_e Events	
ND280-constrained flux and cross section	3.1%
Unconstrained cross section	4.7%
SK detector efficiency	2.4%
Final or secondary hadronic interactions	2.7%
Total	**6.8%**

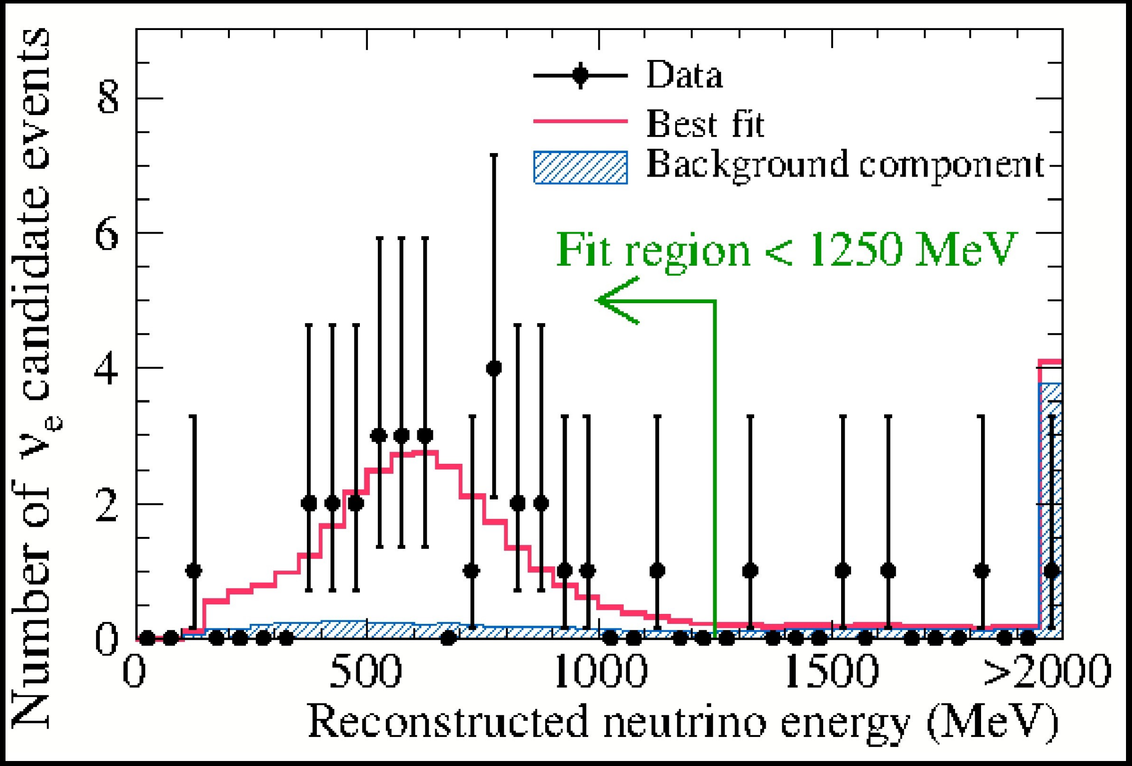
ν_μ Events	
ND280-constrained flux and cross section	2.7%
Unconstrained cross section	5.0%
SK detector efficiency	3.0%
Final or secondary hadronic interactions	4.0%
Total	**7.7%**

Flux and cross section would be > 20% without ND280 constraint

Final candidates at SK

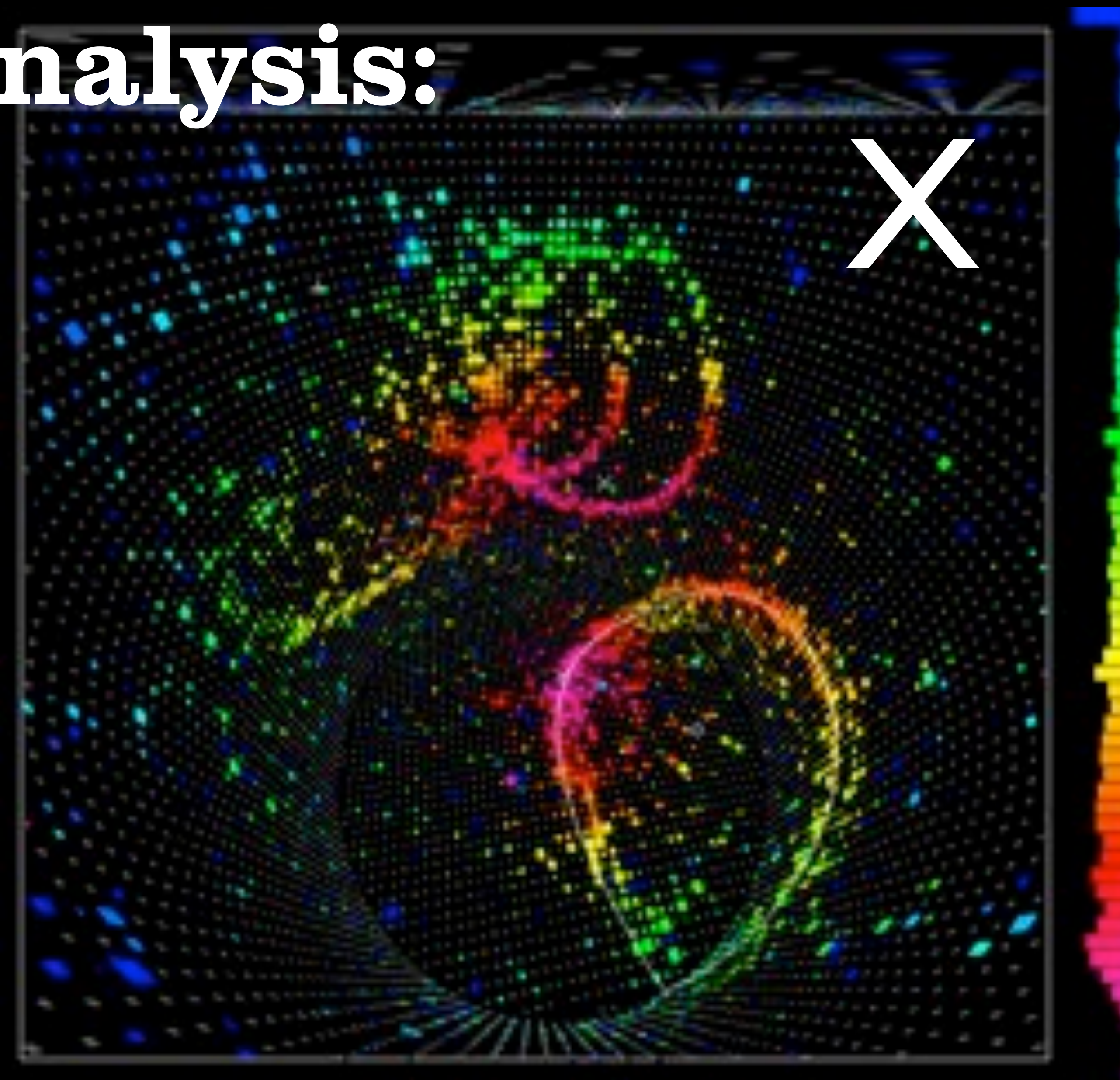
- Predicted background events: 4.9±1.6
- Observe 28 events
- 7.3σ significance for ν_e appearance
- 21.6 events expected if $\sin^2 2\theta_{13}$= 0.1, δ_{CP}= 0, $\sin^2\theta_{23}$= 0.5
- Assuming above δ_{CP}, θ_{23}, $\sin^2 2\theta_{13}$=
  - 0.140 +0.038 −0.032 (Assuming normal hierarchy)
  - 0.170 +0.045 −0.037 (Assuming inverted hierarchy)
- PRL 112, 061802 (2014)

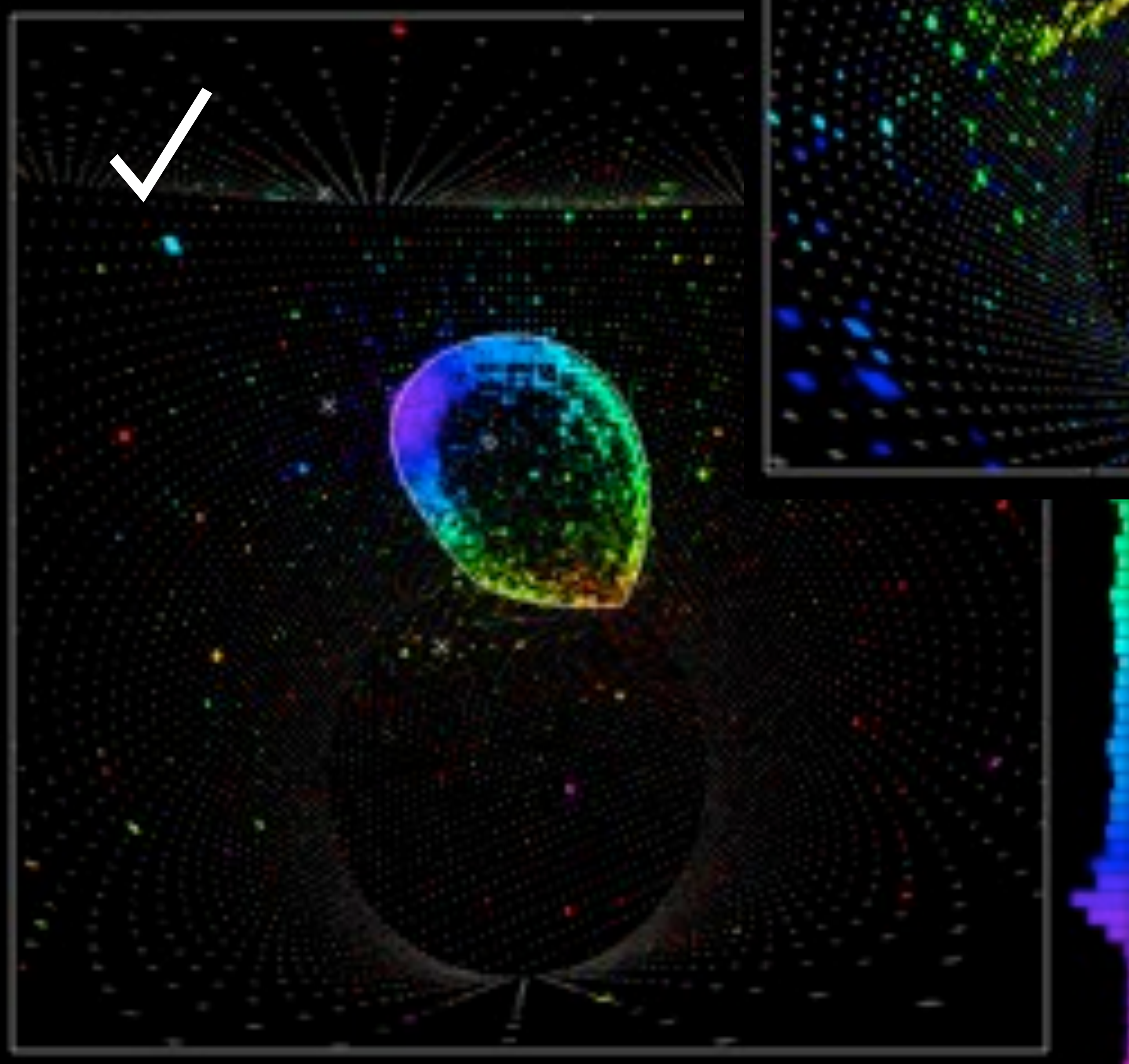




ν_μ disappearance analysis: CCQE selection

- One mu-like ring





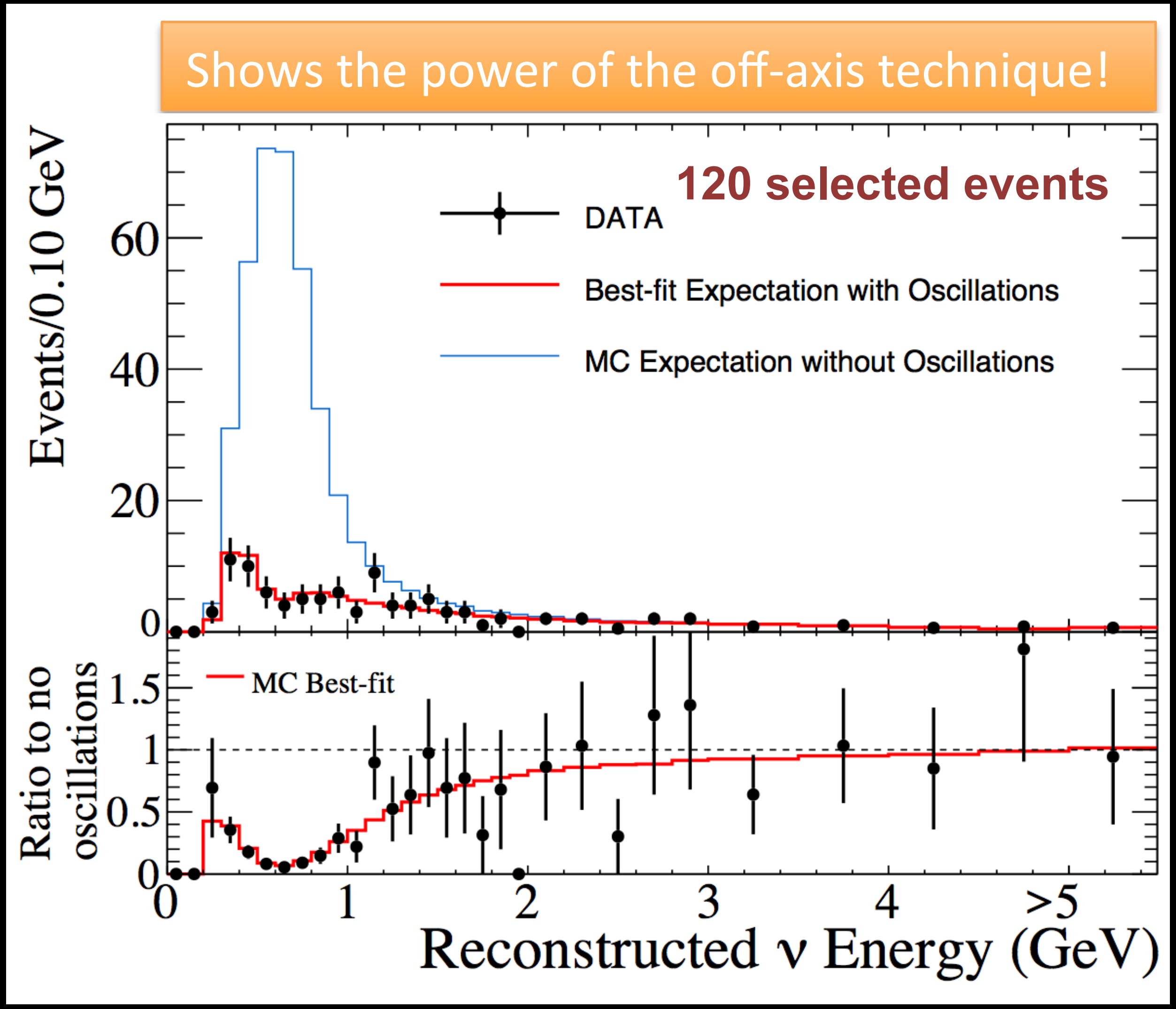
ν_μ disappearance analysis

- Data selection cuts very similar to appearance, but with particle ID cuts reversed

For ν_μ disappearance analysis	For ν_e appearance search
Timing coincidence w/ beam timing (+TOF)	
Fully contained (No OD activity)	
Vertex in fiducial volume (>2m from wall)	
Number of rings = 1	
E_{vis} > 30 MeV	E_{vis} > 100 MeV
μ-like ring	e-like ring
0 or 1 decay electron	No decay electron
p_μ > 200 MeV/c	Remove π^0-like events
	E_ν^{rec} < 1250MeV

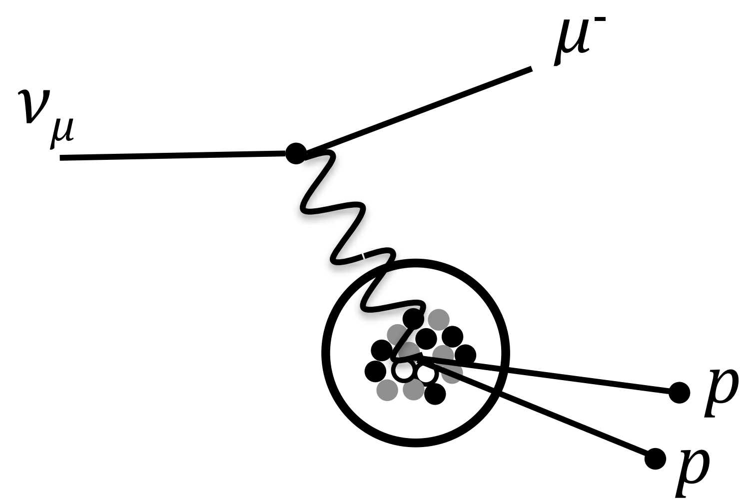
ν_μ disappearance analysis

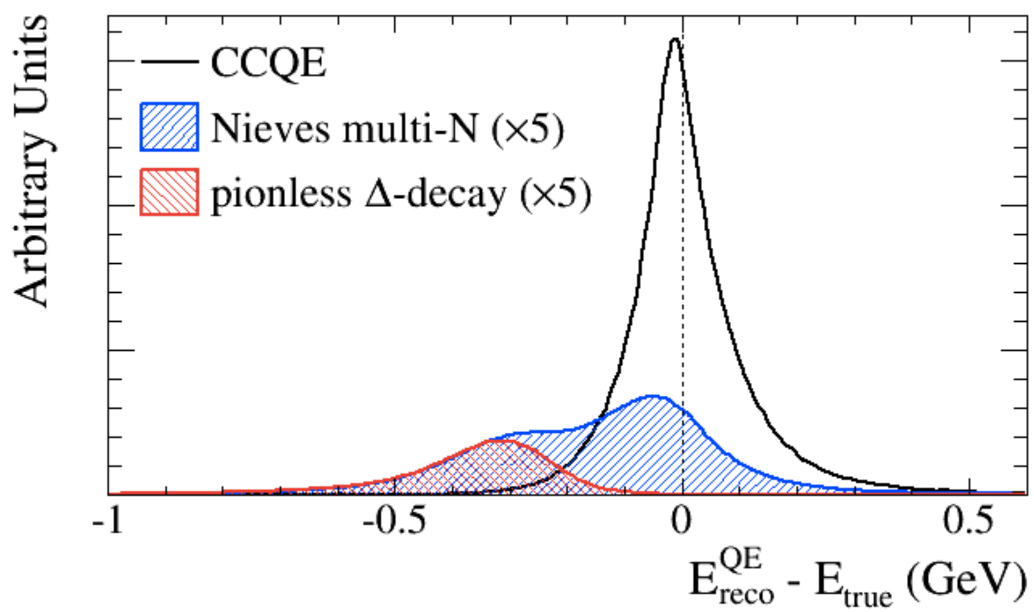
- Off-axis beam (by design) puts maximum disappearance at the energy peak!
- Fit favors maximal disappearance
- Not quite the same as maximal $\sin^2 2\theta_{23}$ because of higher-order terms depending on θ_{13}:



$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1 - \cos^2(\theta_{13}) \times \sin^2(\theta_{23})]\sin^2(1.267\Delta m^2 L/E_\nu),$$

An aside: multi-nucleon 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)

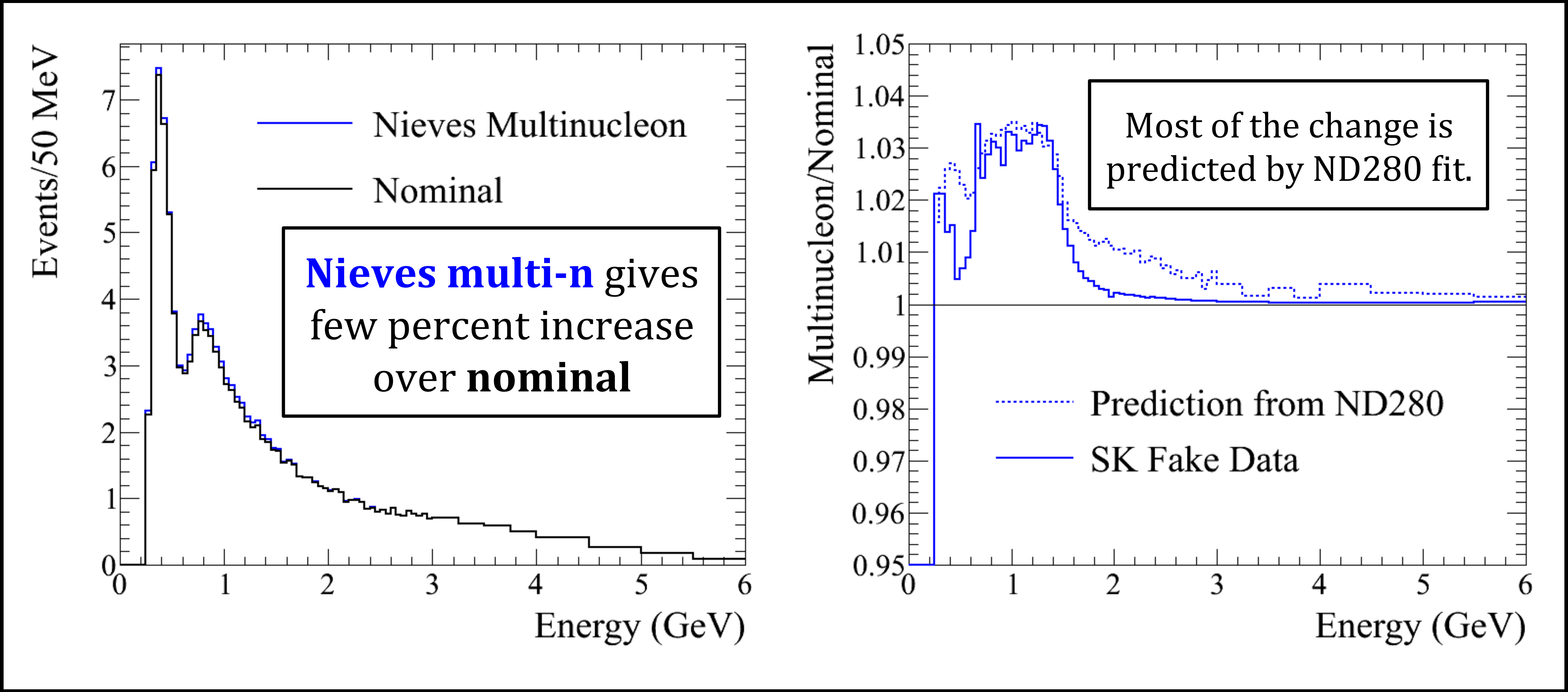
Suggested potential for bias in oscillations:

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

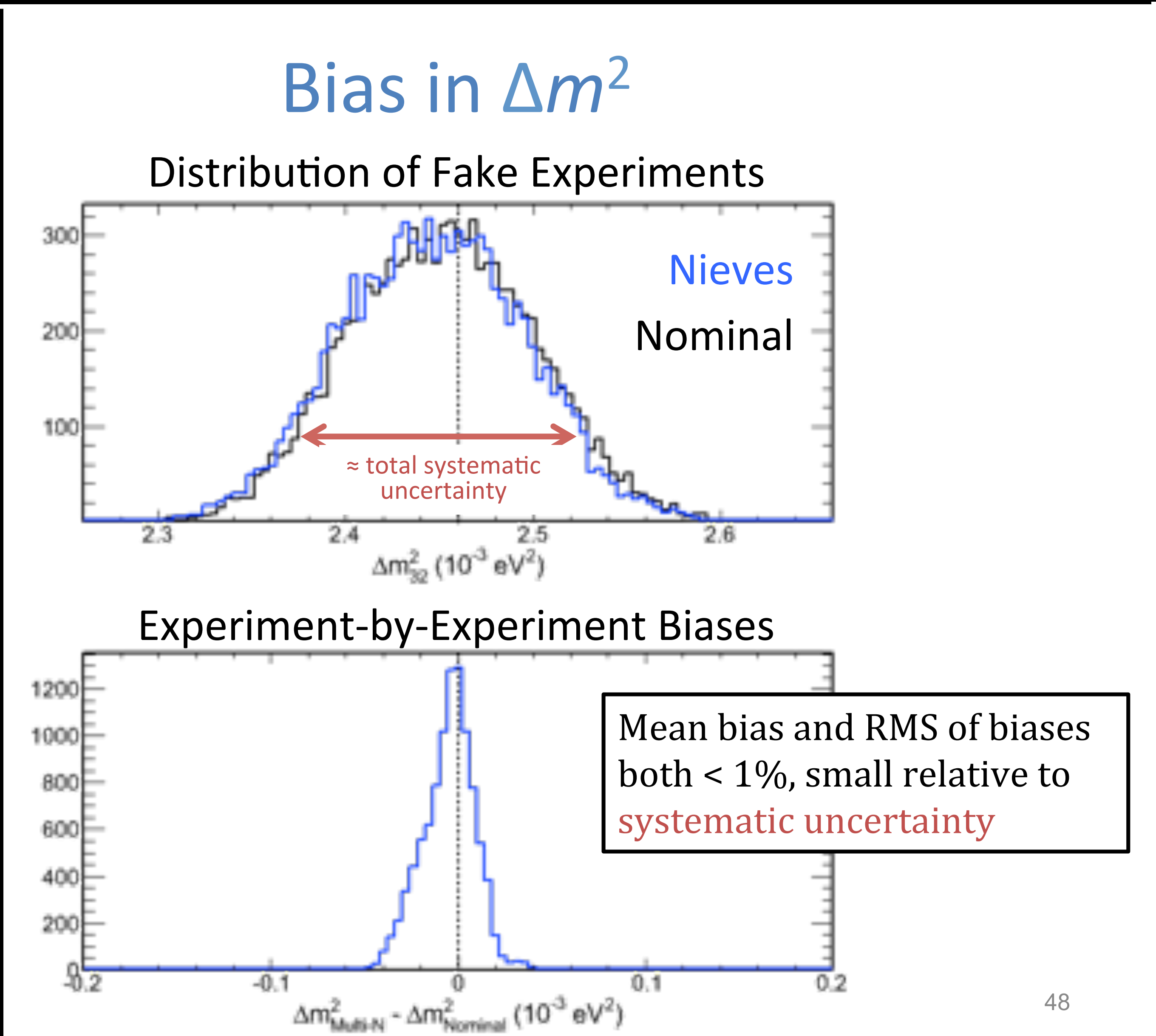
D. Meloni and M. Martini, PLB716, 186 (2012).

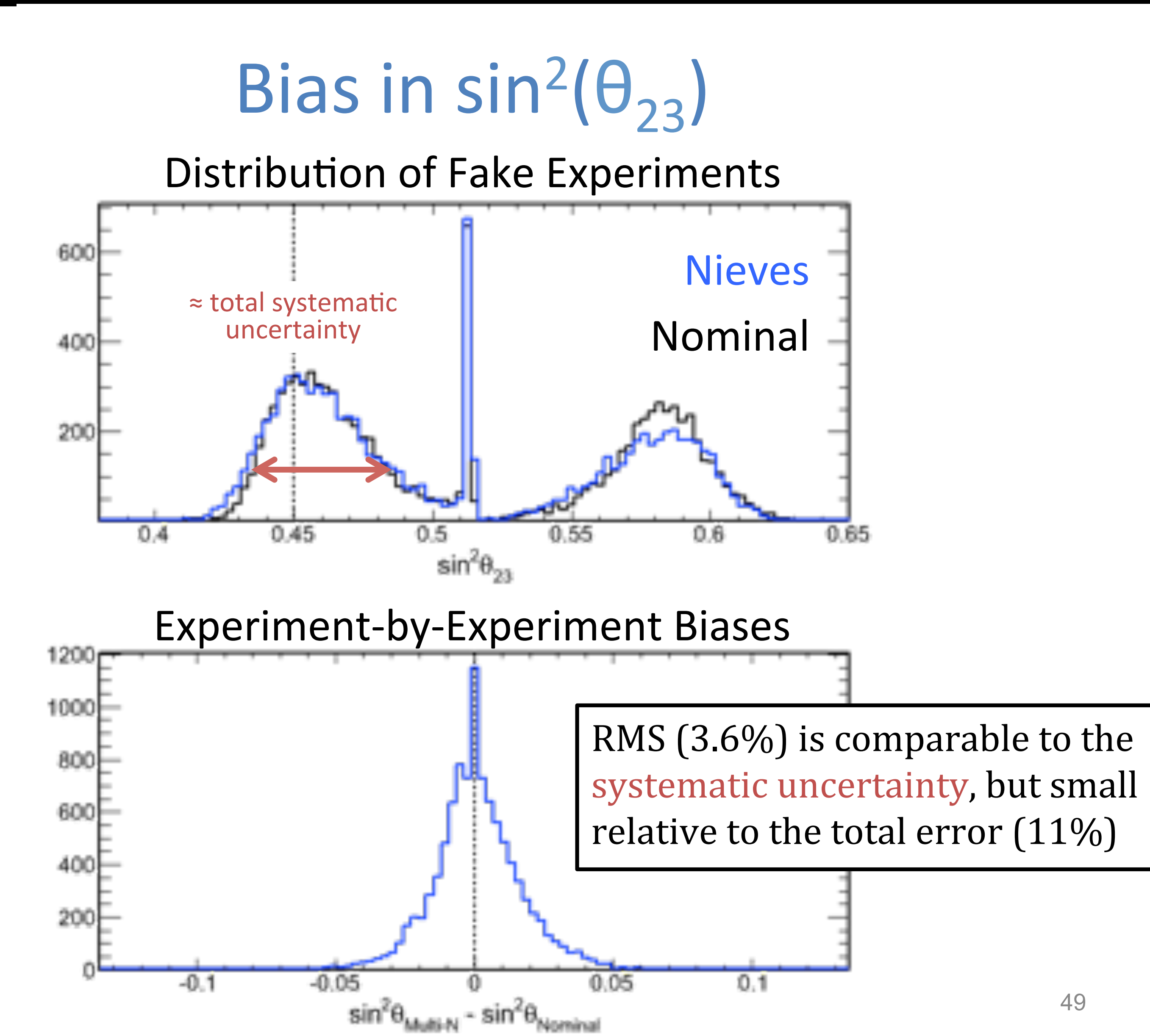
P. Coloma, et al, arXiv:1311.4506 (2013).

Effect on SK spectrum



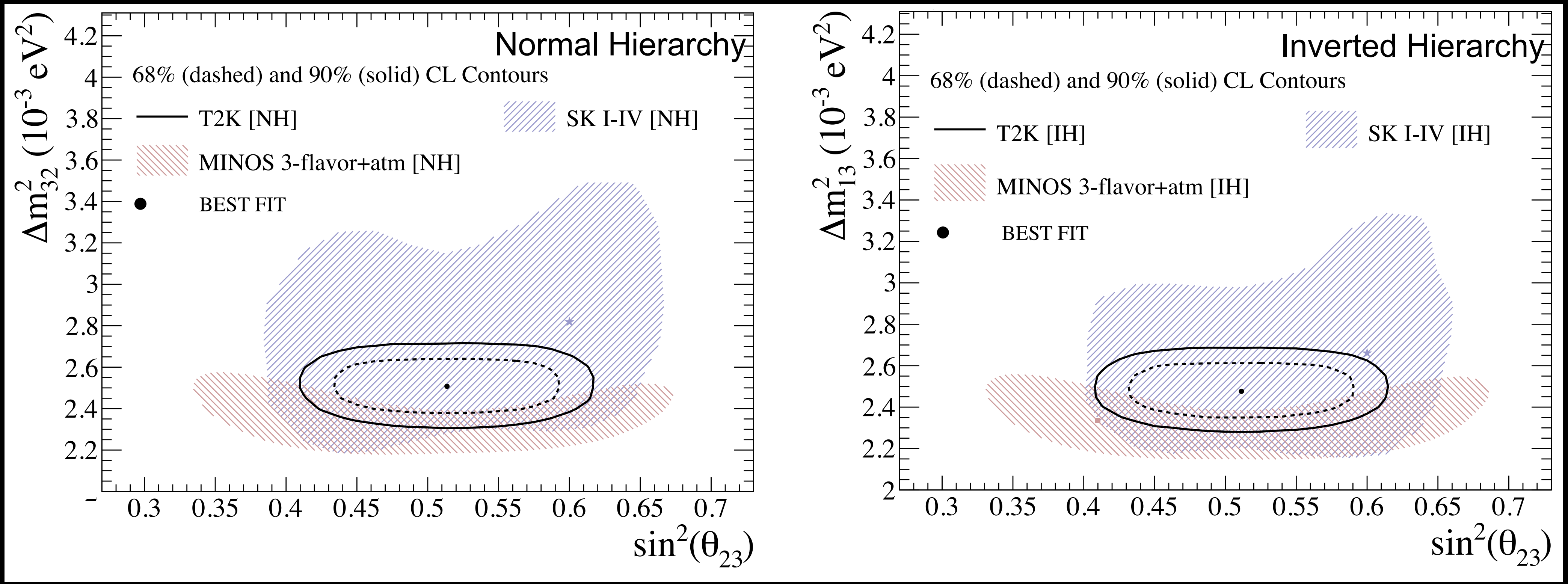
Reconstruction bias from multi-nucleon interactions





- Will be included in later analyses as systematic error

ν_μ disappearance analysis

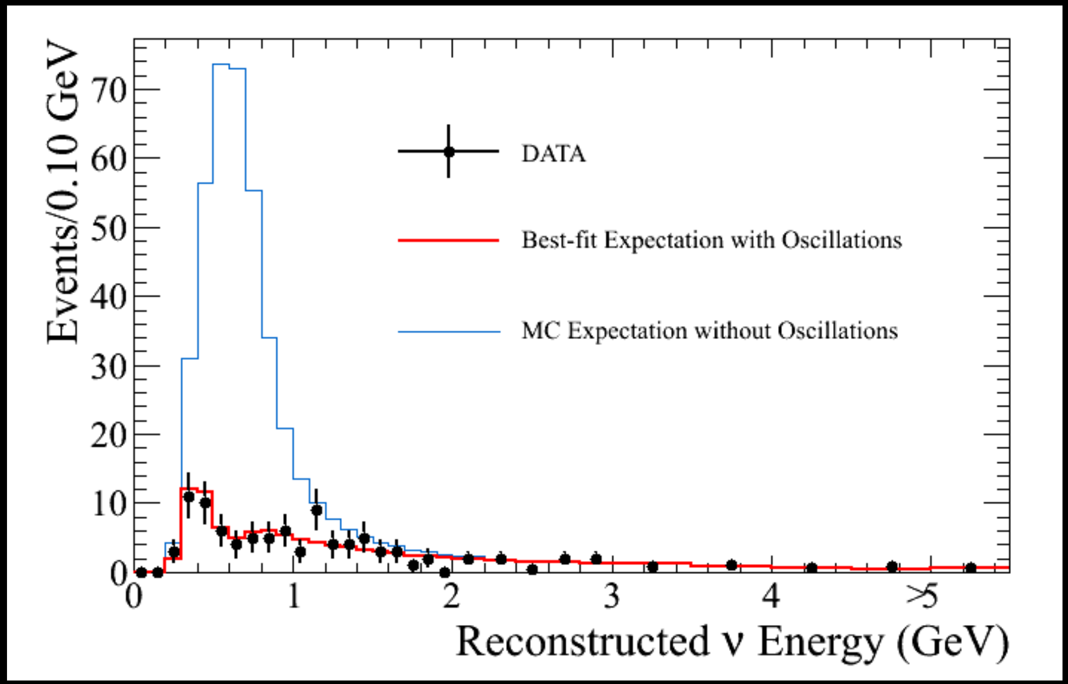


- T2K now has most precise result on θ_{23}
- Result depends slightly on hierarchy assumption
- Before this result, atmospheric neutrinos dominated this parameter
- Phys. Rev. Lett. 112, 181801 (2014)

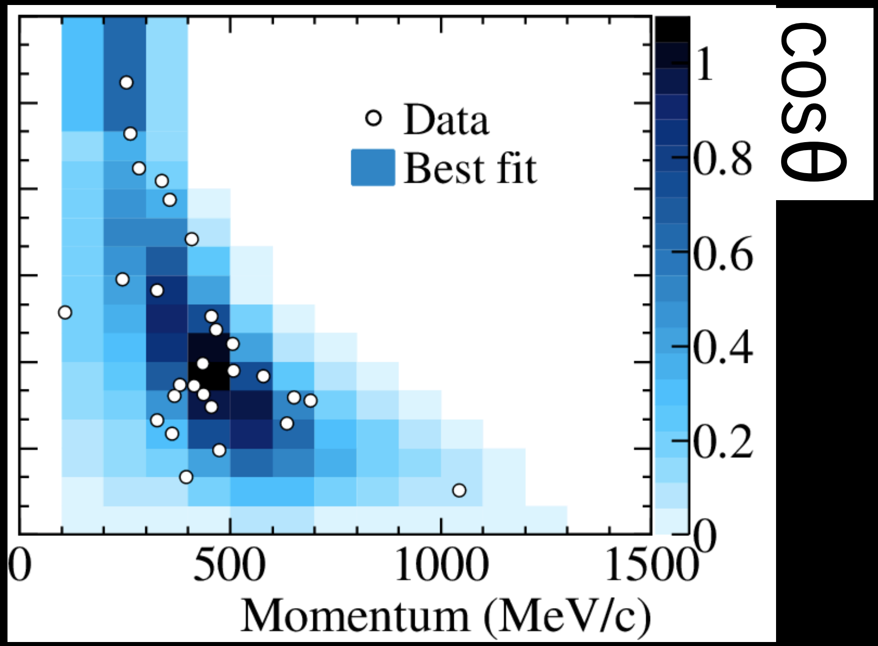
Joint fit to appearance and disappearance

- Likelihood ratio fit of ν_μ and ν_e samples
- Both frequentist and Bayesian analyses performed
- Simultaneous fit for δ_{CP}, θ_{13}, θ_{23}, Δm^2_{32}

ν_μ



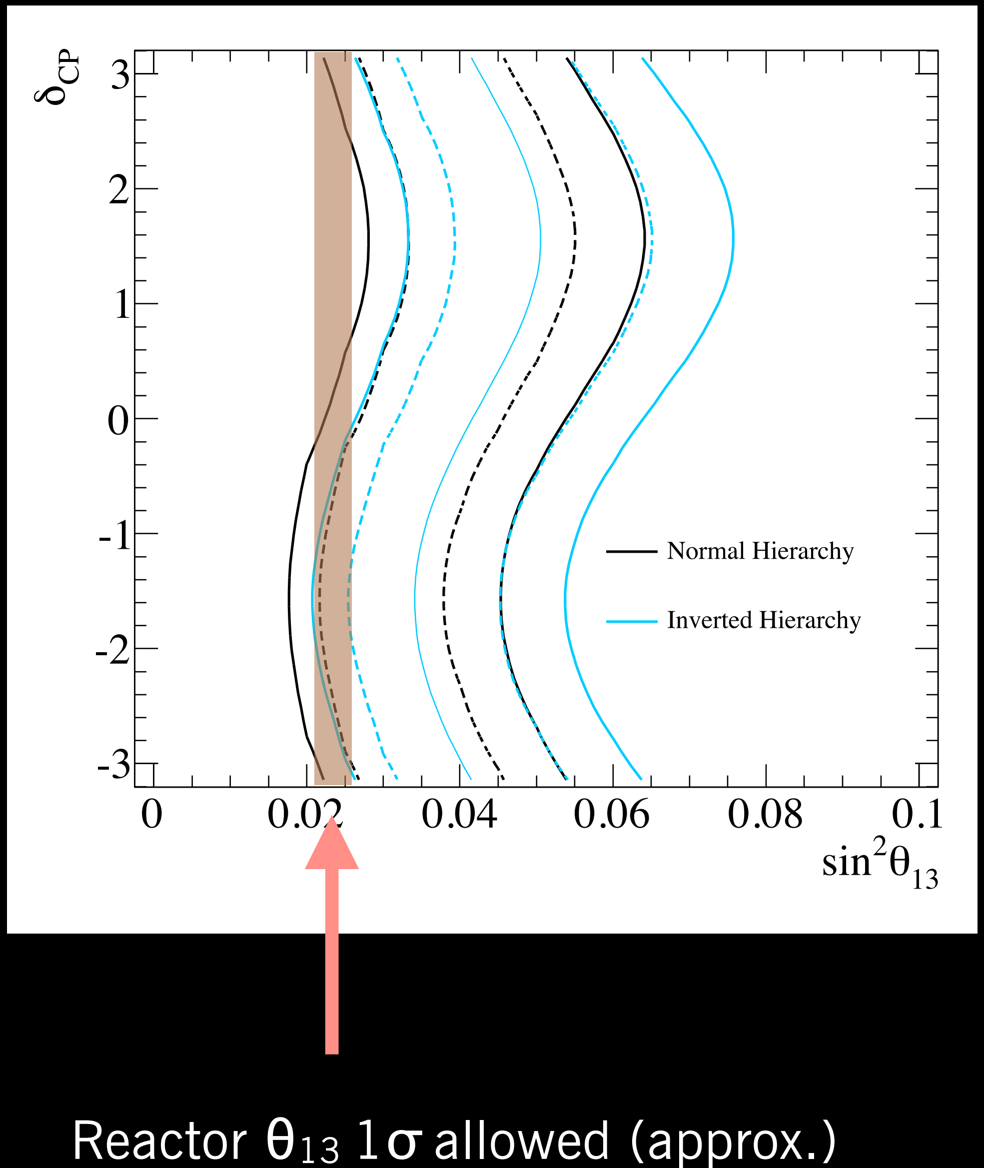
ν_e



Dependence on other parameters

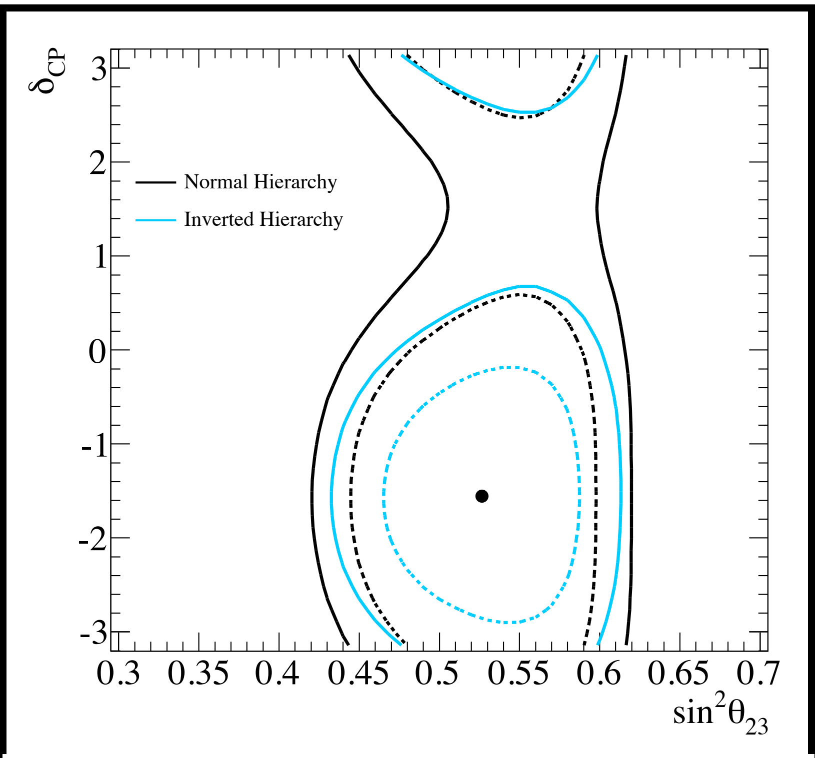
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\Delta_{32}\left(\sin^2\theta_{23} - \frac{\sin(2\theta_{12})\sin(2\theta_{23})\sin\delta_{CP}}{2\sin\theta_{13}}\Delta_{21}\right)$$

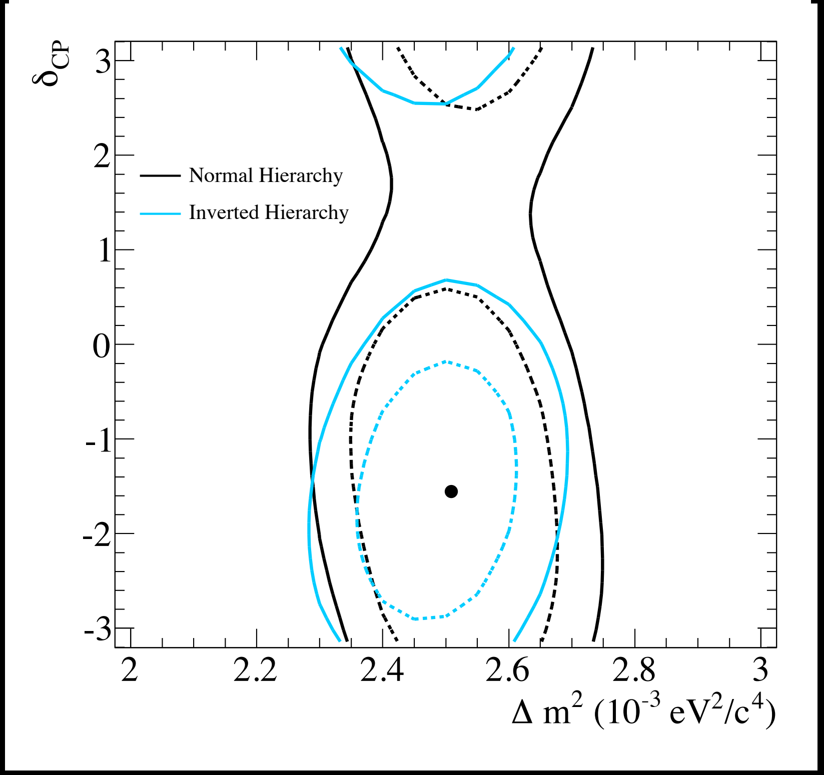
- Appearance probability also depends strongly on θ_{23} and δ_{CP}
- Can marginalize over these parameters and extract θ_{13}, but result is uncompetitive with reactor measurements (PDG 2012: $\sin^2 2\theta_{13}=0.098\pm0.013$; PDG 2014: 0.093 ± 0.008)
- One approach: scan value of δ_{CP}, marginalize over θ_{23}, look for regions consistent with reactor θ_{13}. (Frequentist intervals shown)
- Combined T2K+reactor favor larger θ_{23}, $\delta_{CP}<0$

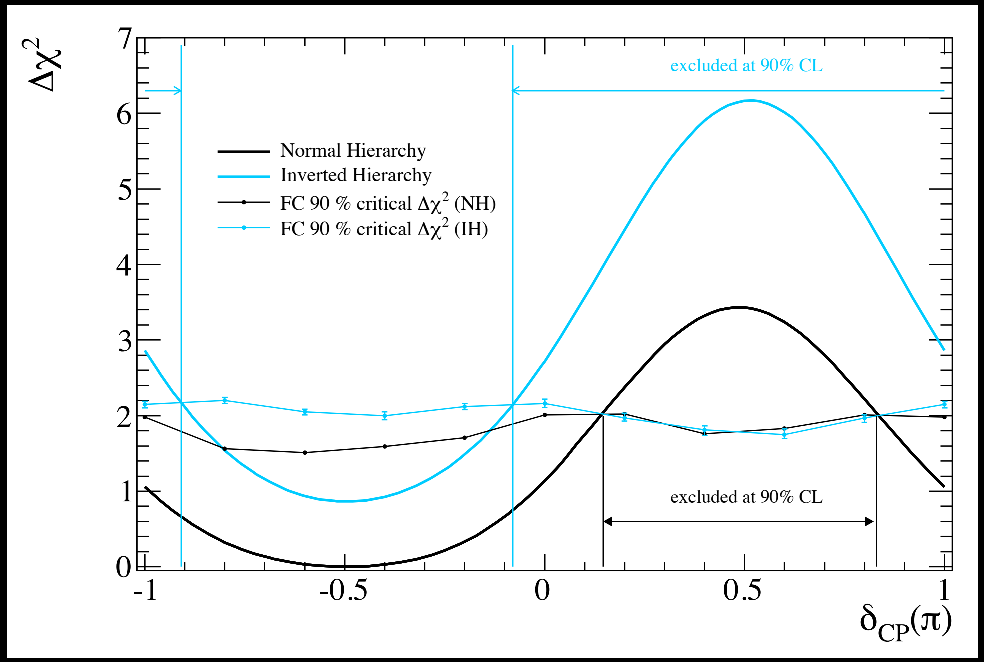


Dependence on other parameters

- Can also use reactor data (2012 PDG) as a constraint on θ_{13} and show T2K data as an allowed region in θ_{23} and δ_{CP}.
- Large T2K ν_e rate is favoring δ_{CP} values in the $-\pi/2$ range, especially in inverted hierarchy

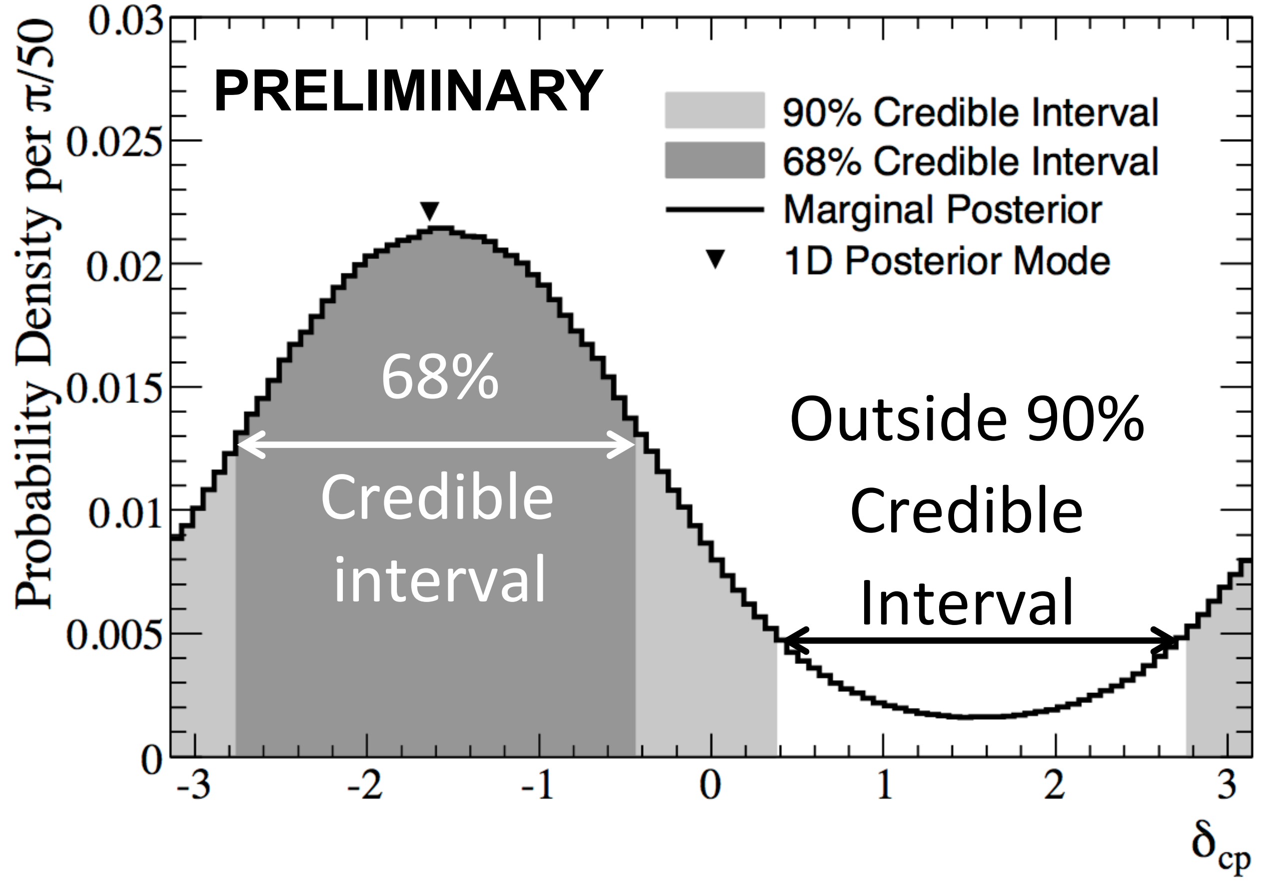






Bayesian δ_{CP}, MH, Octant Constraints

- 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%	

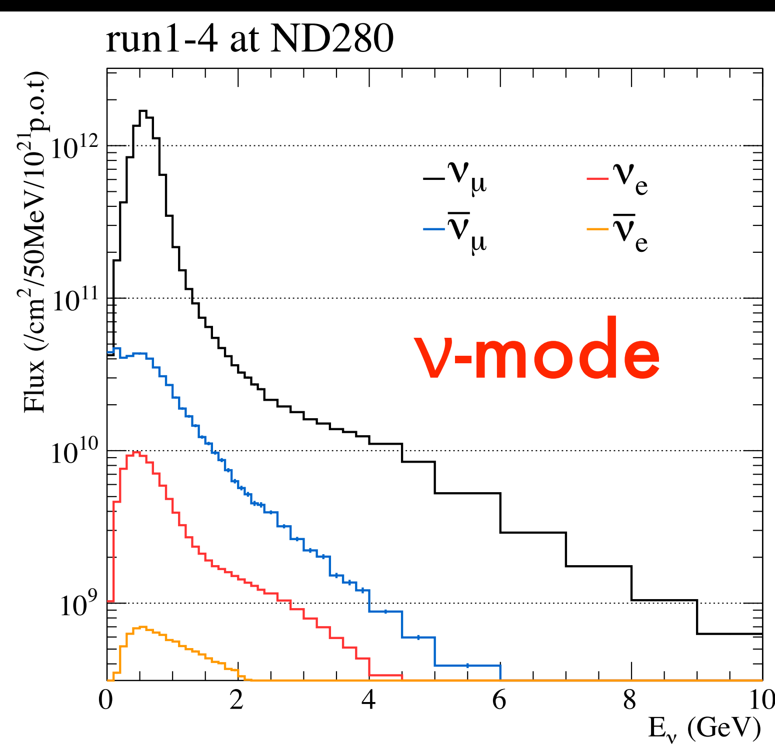
New this season: antineutrino oscillation searches

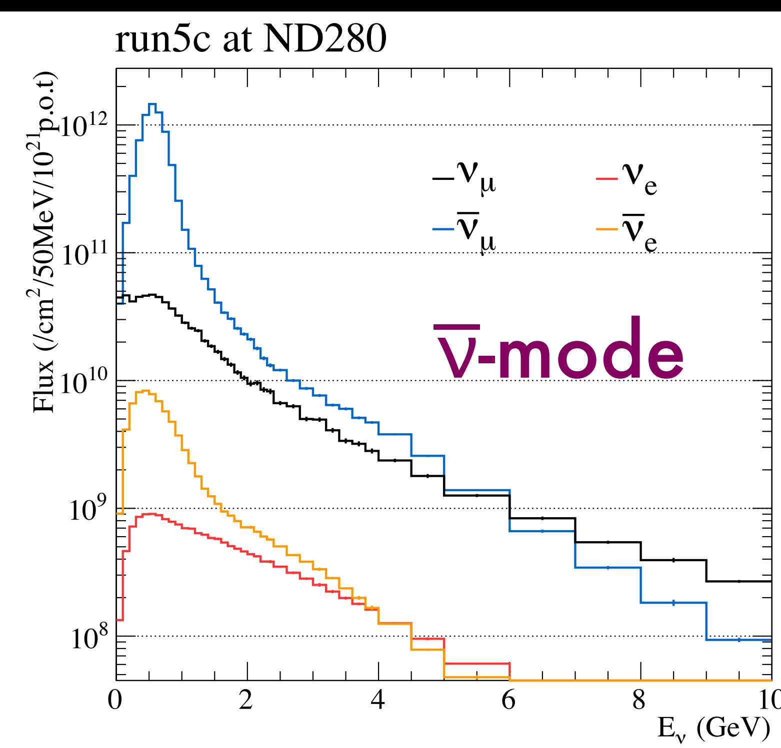
- Next step toward getting ultimate sensitivity for T2K physics (CP and θ_{23} octant)
- Sensitivity is roughly optimized by 50/50 POT between two modes
- Started data collection in antineutrino mode last year; now have over 1/3 of POT in this mode
- Initial look at data: $\bar{\nu}_\mu$ disappearance
- Coming soon: search for $\bar{\nu}_e$ appearance

Muon antineutrino disappearance

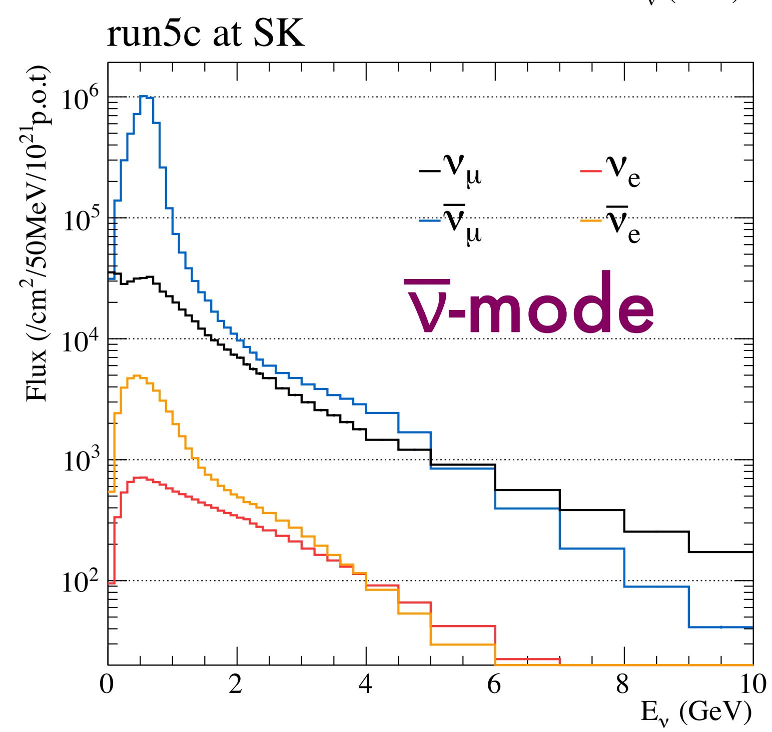
- Using data through March for far detector (2.3E20 POT) (only half of what's been collected by now)
- Using small ND280 samples for now (0.43E20 POT)

Flux predictions





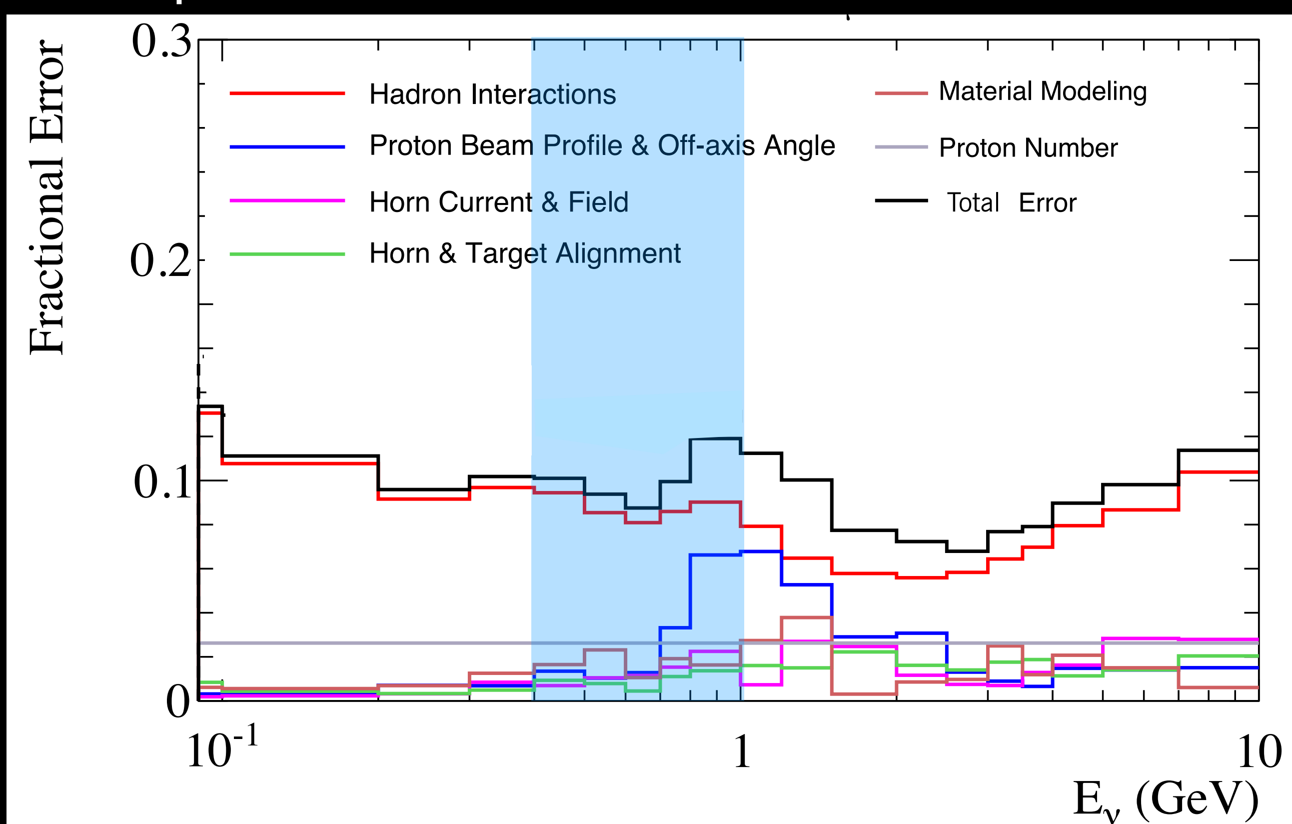
- Note that "wrong sign" backgrounds are much higher in $\bar{\nu}$ mode
- SK flux is highly correlated with ND280 flux



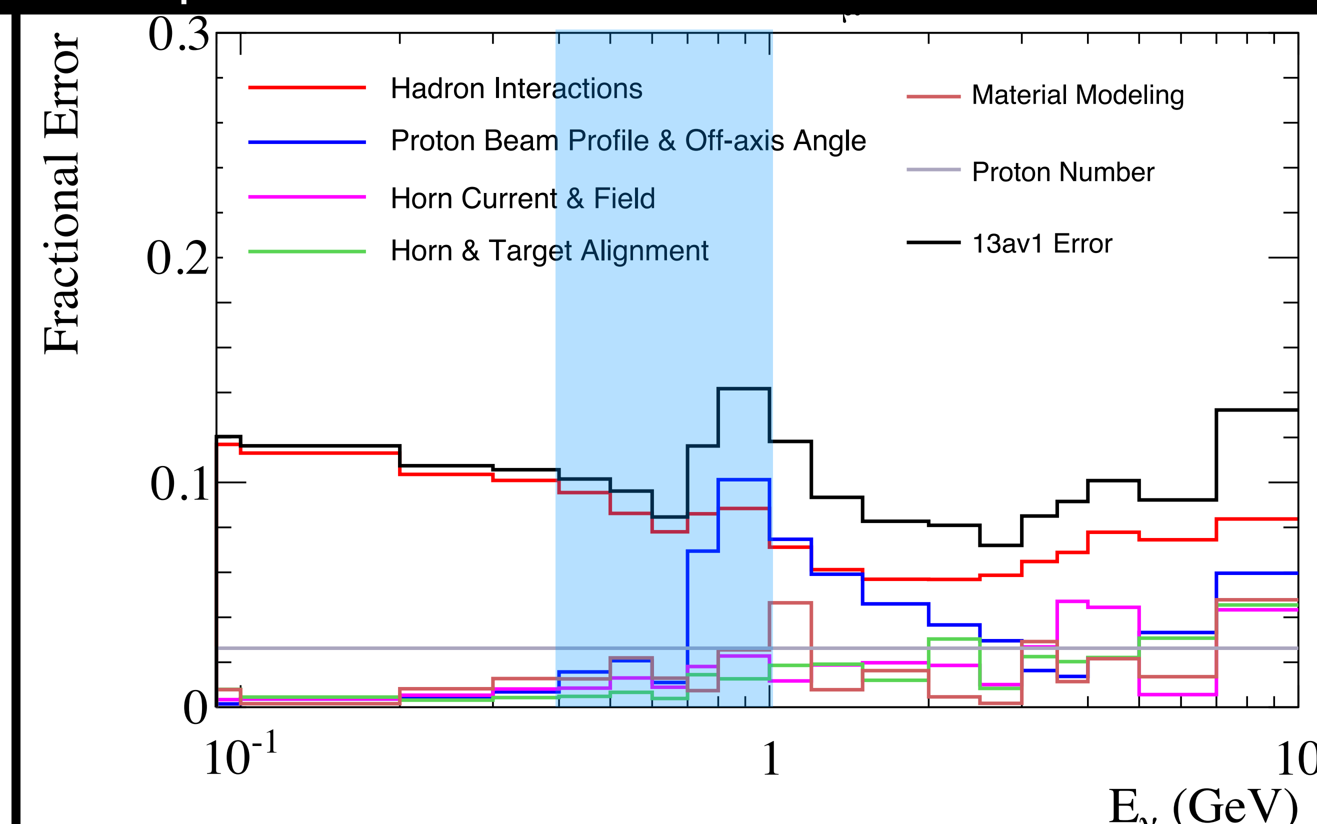
Flux uncertainties

- Flux errors very small compared to expected statistics

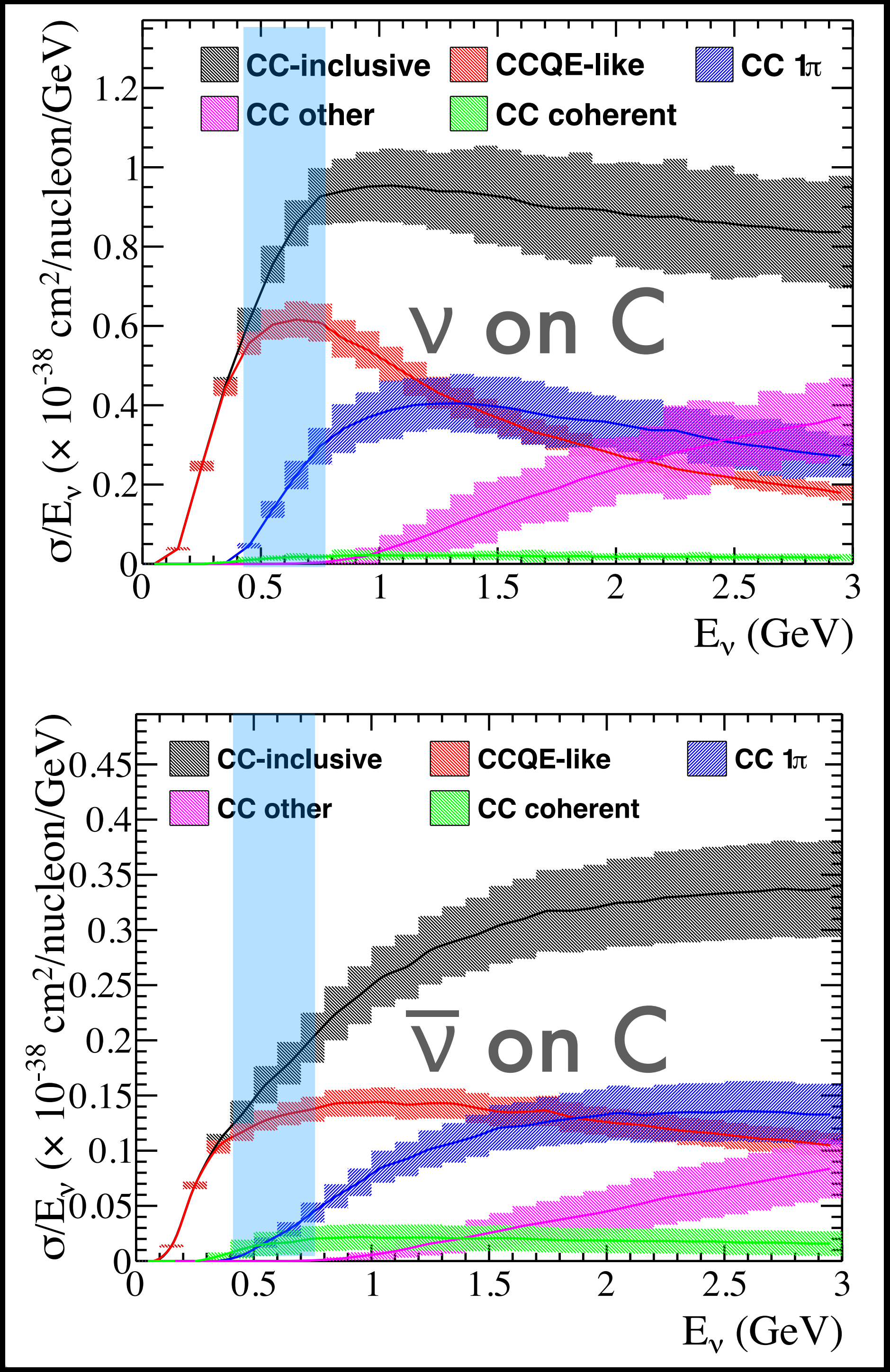
SK ν_μ in neutrino mode



SK $\bar{\nu}_\mu$ in antineutrino mode

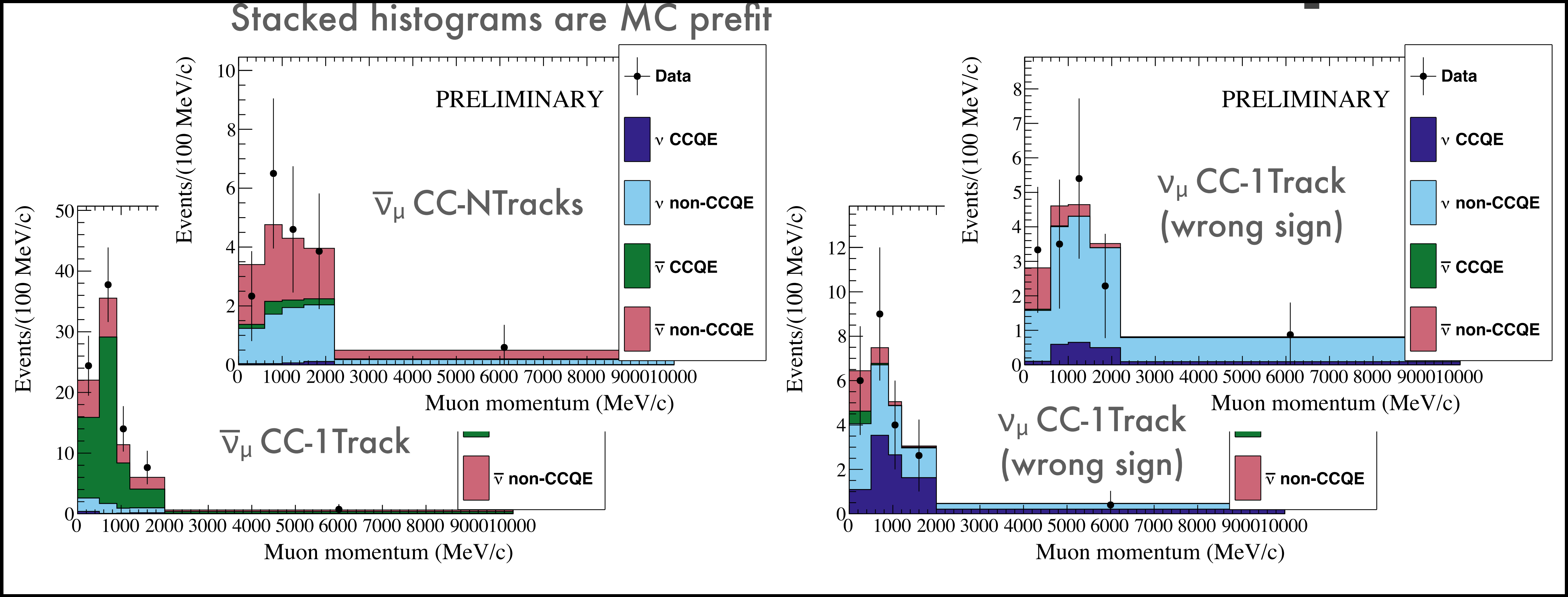


Cross-sections



- Errors come from underlying model parameters and normalizations (similar to neutrino mode)
- Are already comparable to neutrino mode

Near detector data

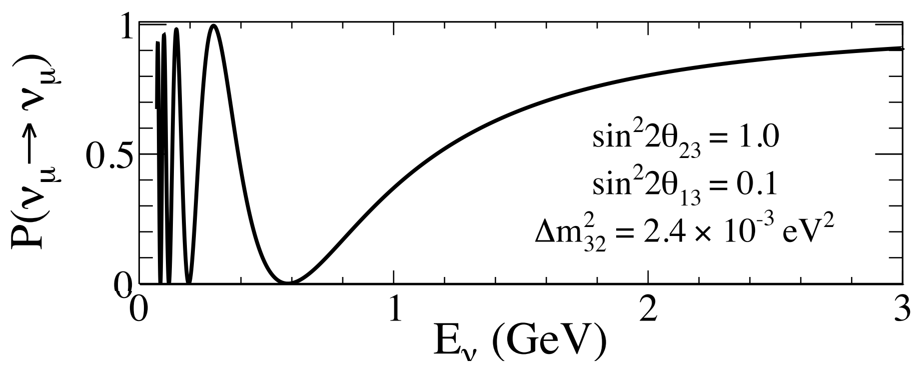


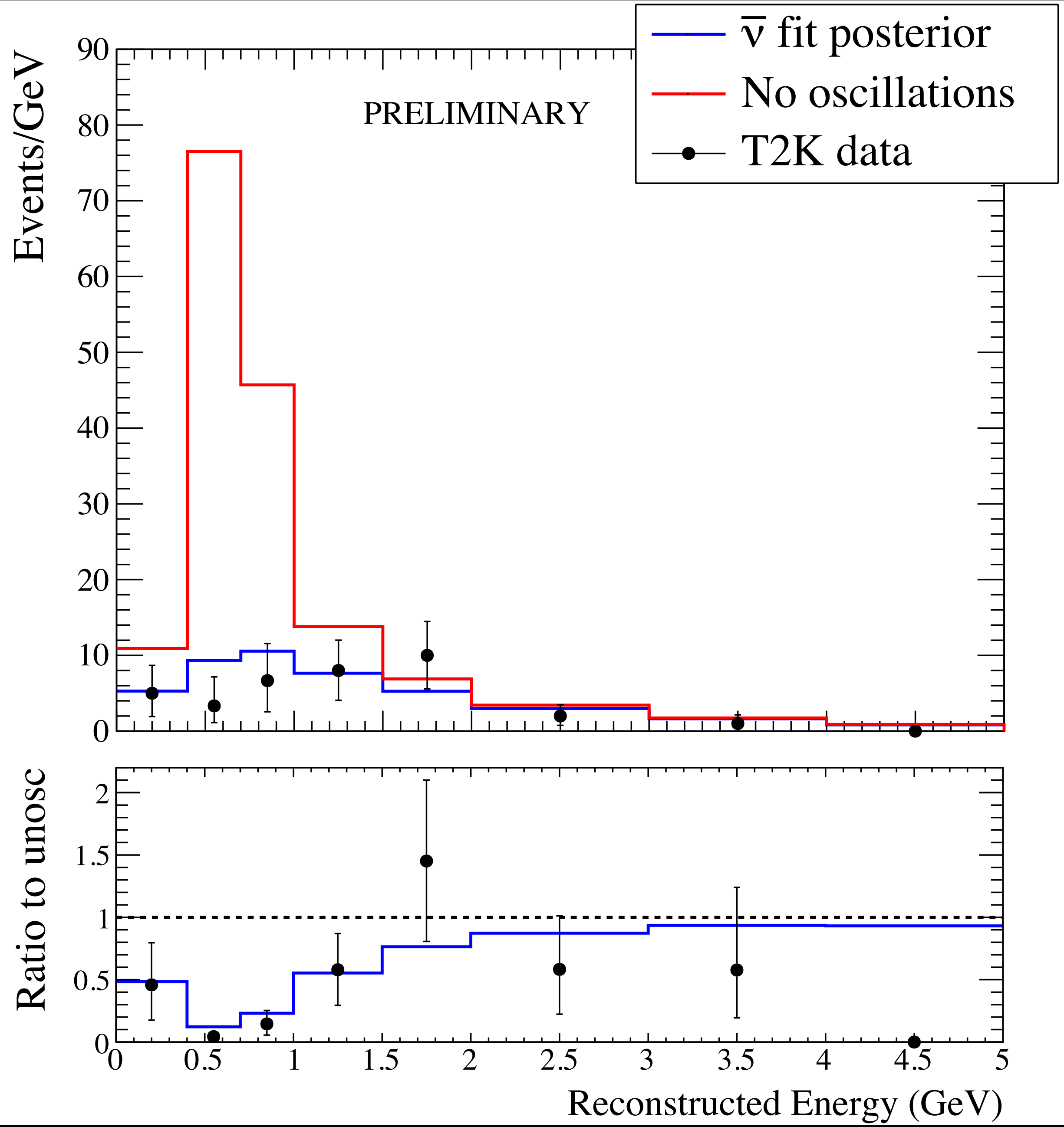
- Samples are very small (even compared to full current data set)
- Important look at what ND280 will see in antineutrino data

SK data

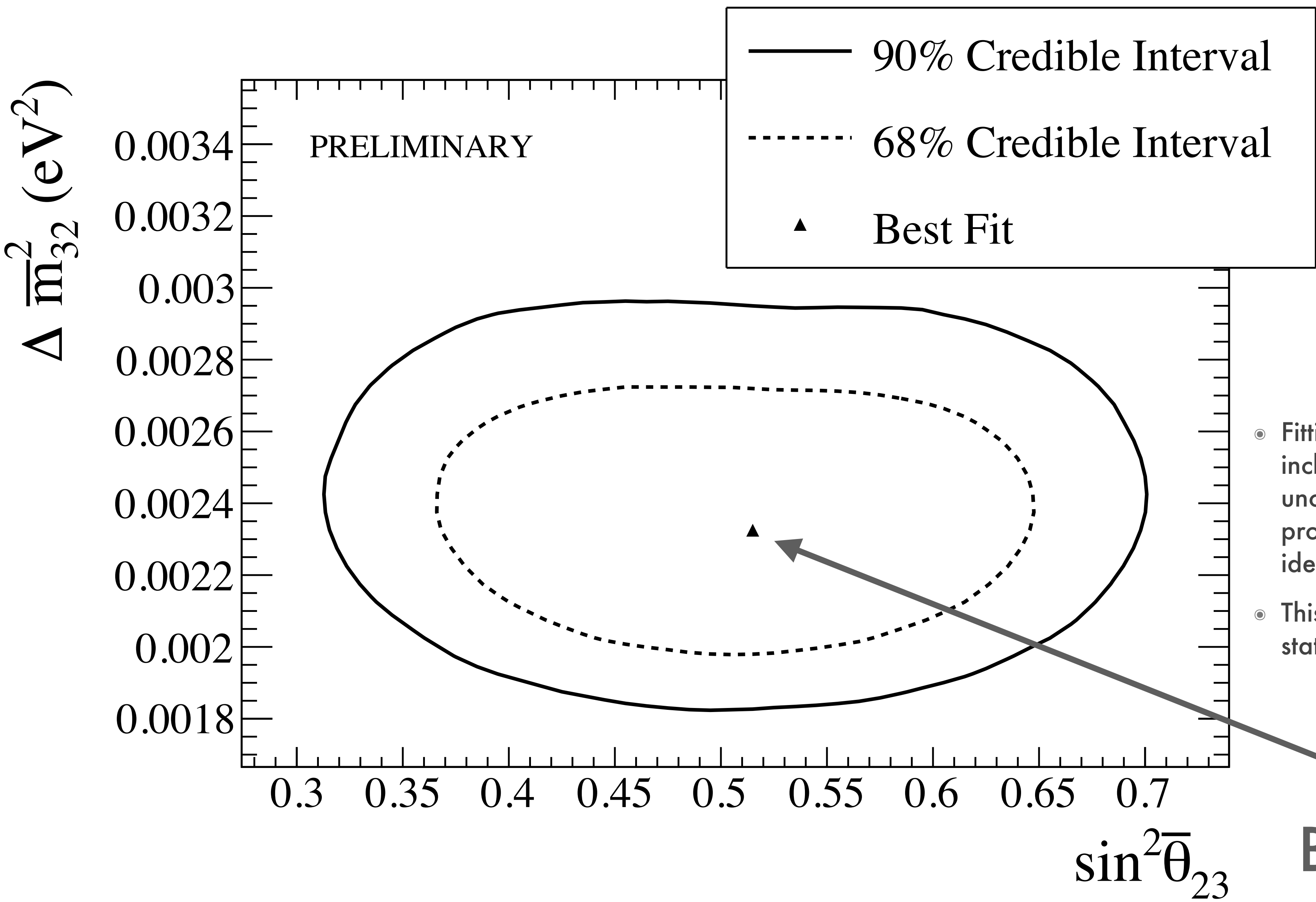
17 events observed

- Data show clear evidence of oscillation
- Clear, visible oscillation “dip” in the data



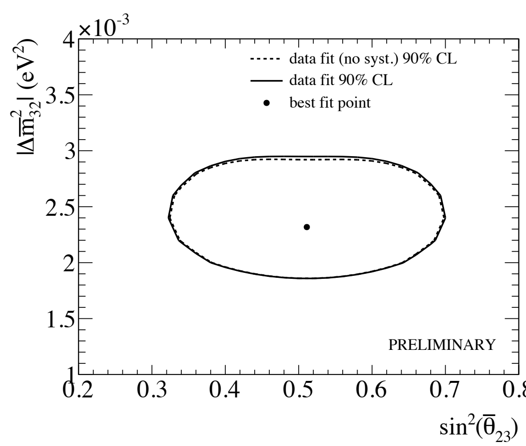


Oscillation fit



$\lvert\Delta\bar{m}^2_{32}\rvert$	$\sin^2(\bar{\theta}_{23})$
$2.33^{+0.27}_{-0.23}\times10^{-3}$ eV^2	$0.515^{+0.085}_{-0.095}$

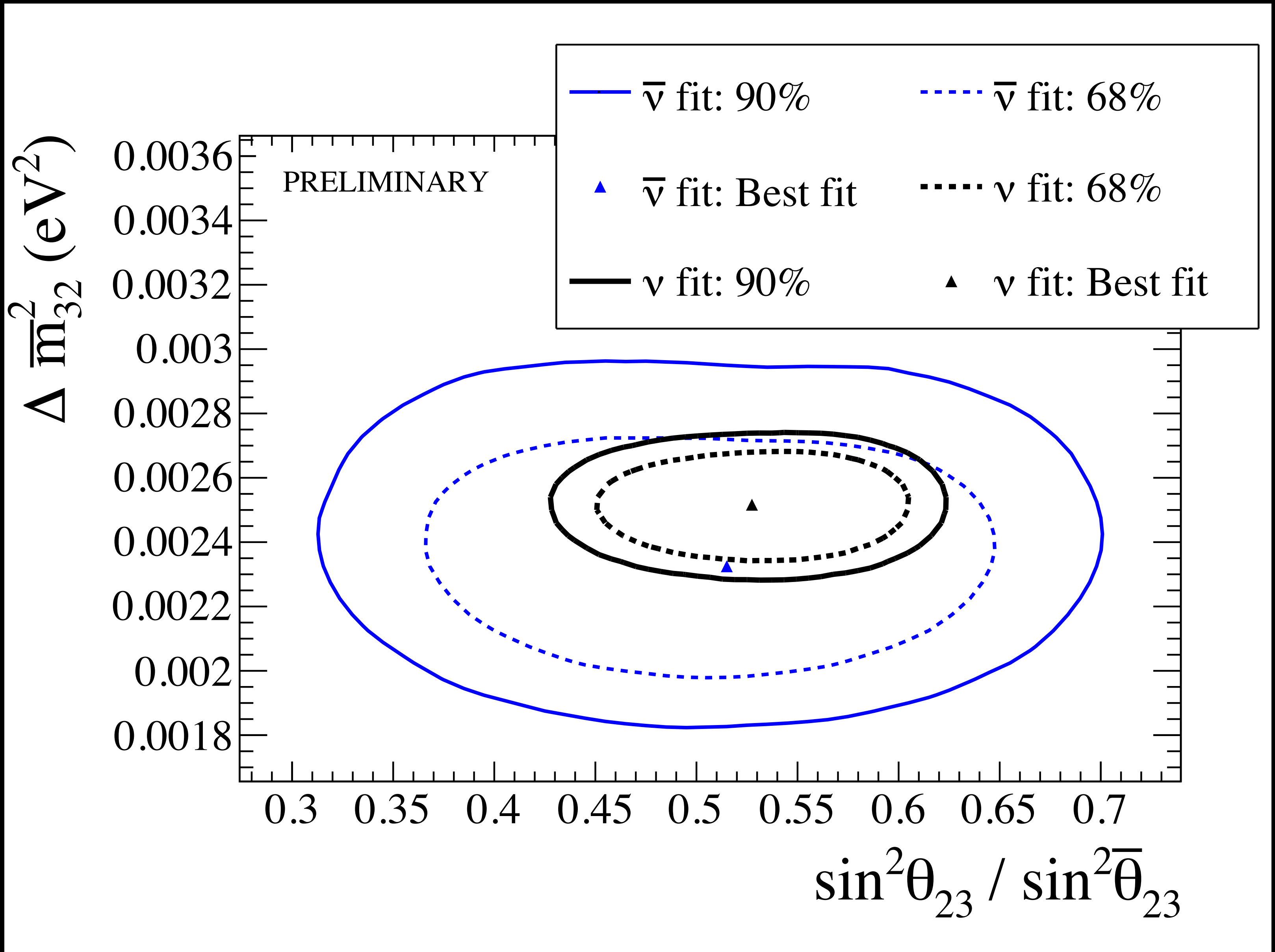
- Fitting without including systematic uncertainties produces nearly identical contours
- This analysis is statistics dominated



Best fit is near maximal disappearance

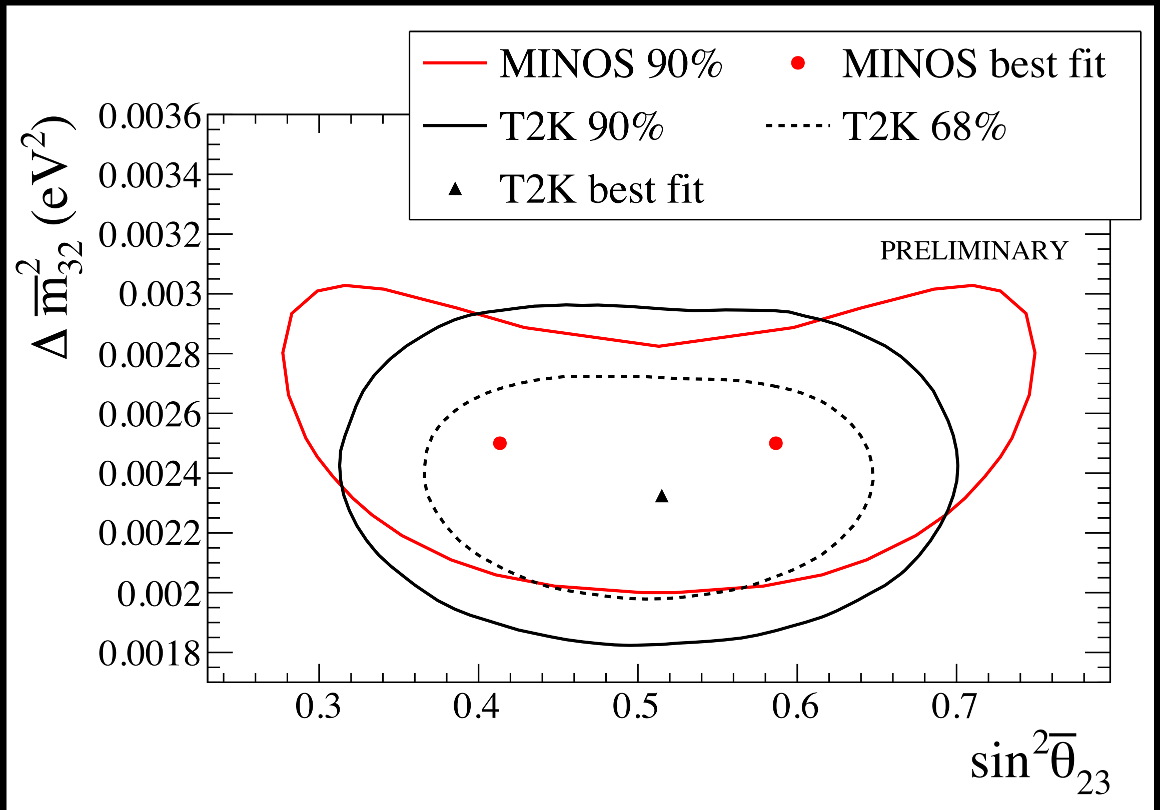
Comparing to neutrino result

- Errors are of course larger than for neutrino mode
- CPT is under no threat at present



Comparing to MINOS

- MINOS has best previous measurement (SK also measured in 2011)
- We agree quite well: our errors now smaller in mixing angle, still slightly larger in Δm^2



MINOS data is beam and cosmic combined

P. Adamson et al., Phys. Rev. Lett. 110 (2013) 25, 251801

Neutrino interactions

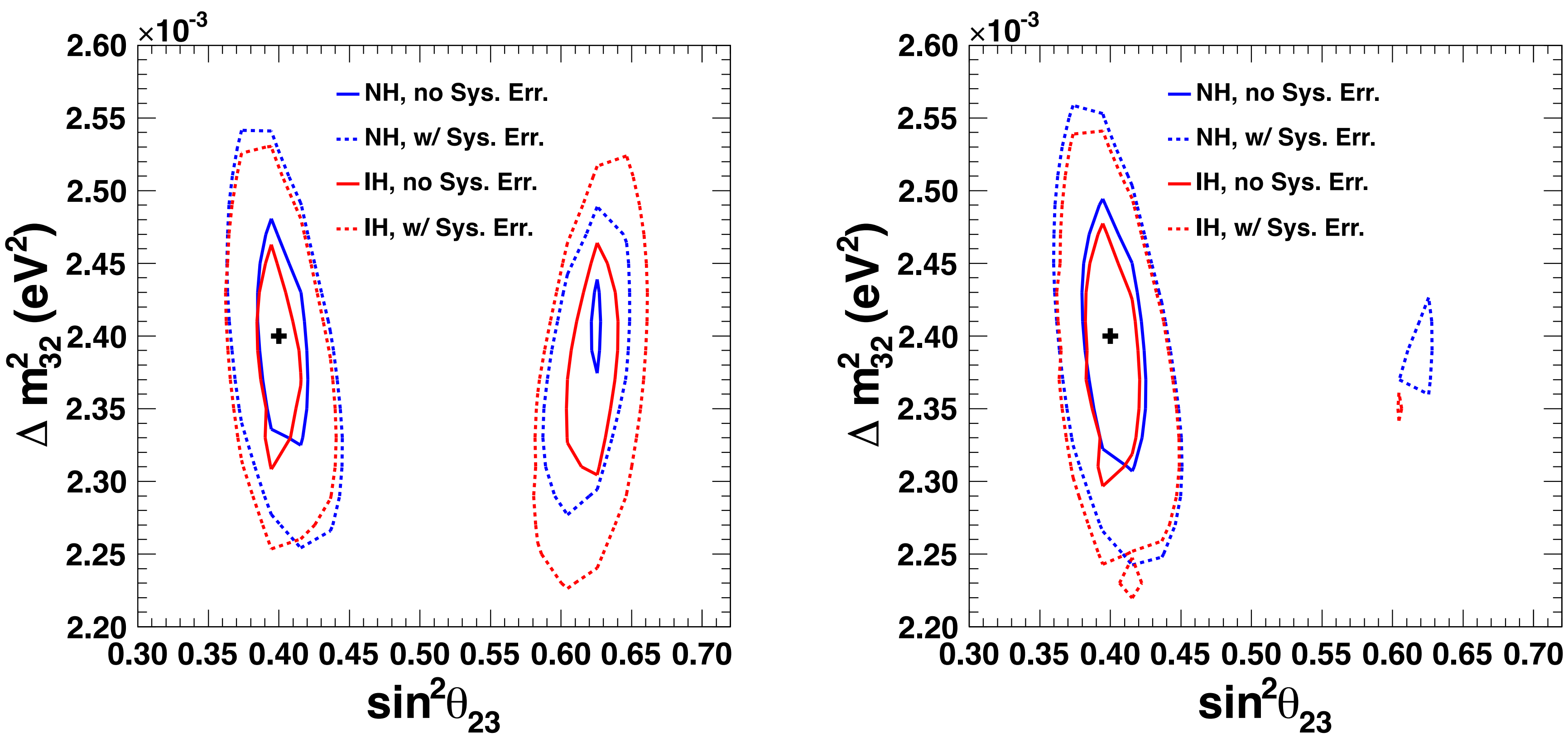
- Lots of results from:
  - INGRID (on axis)
  - Off-axis ND
  - …and even SK

Oscillations: future sensitivity

- Recently published a long paper on future sensitivity: PTEP 2015 (2015) 4, 043C01
- Sensitivities were calculated with full approved T2K running (7.8E21 POT) and various assumptions of neutrino/ antineutrino split, plus combinations with other experiments
- Most physics sensitivities optimized with 50% neutrino/50% antineutrino operation

θ_{23} octant sensitivity

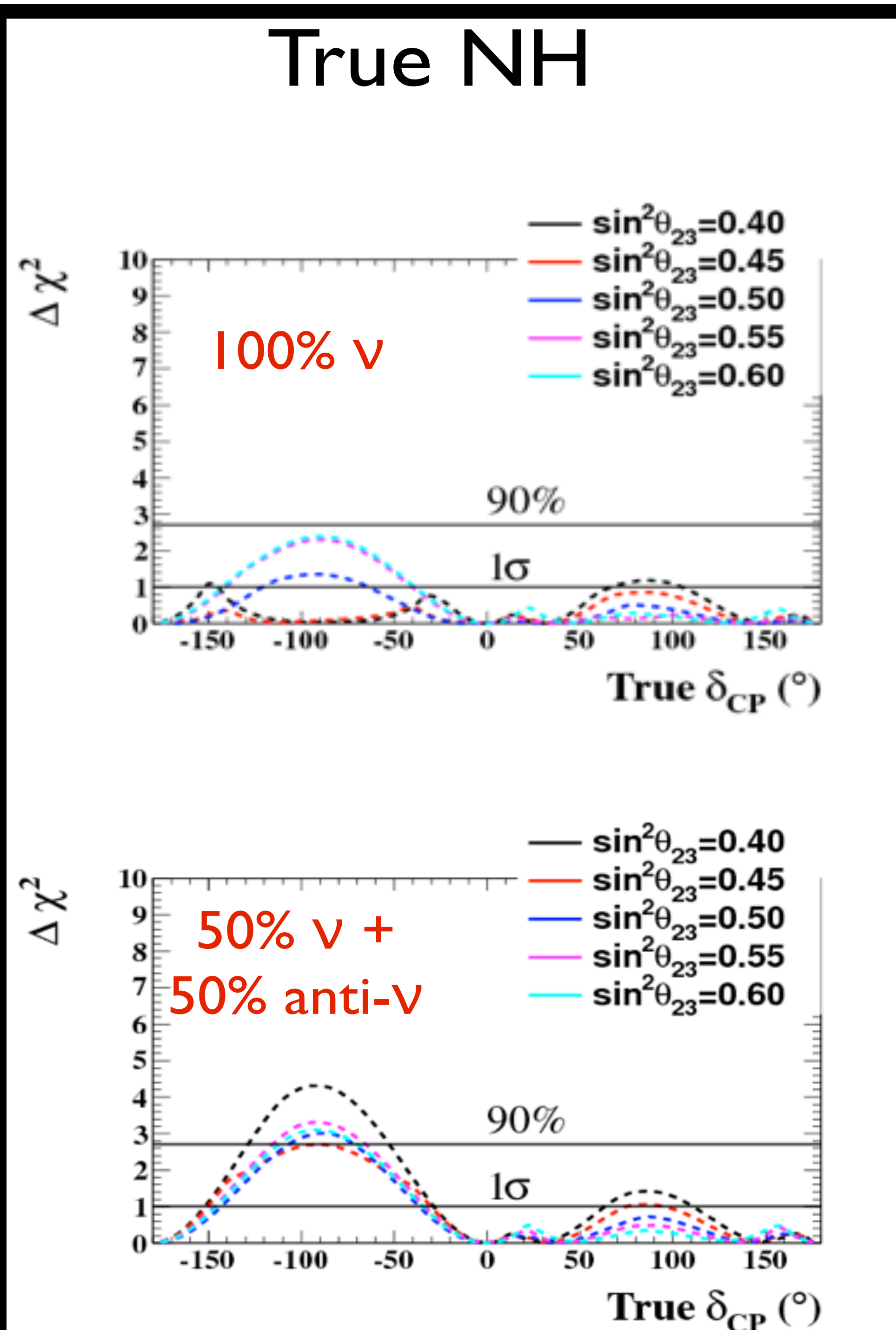
- Sensitivity assuming "ultimate" reactor error on θ_{13}

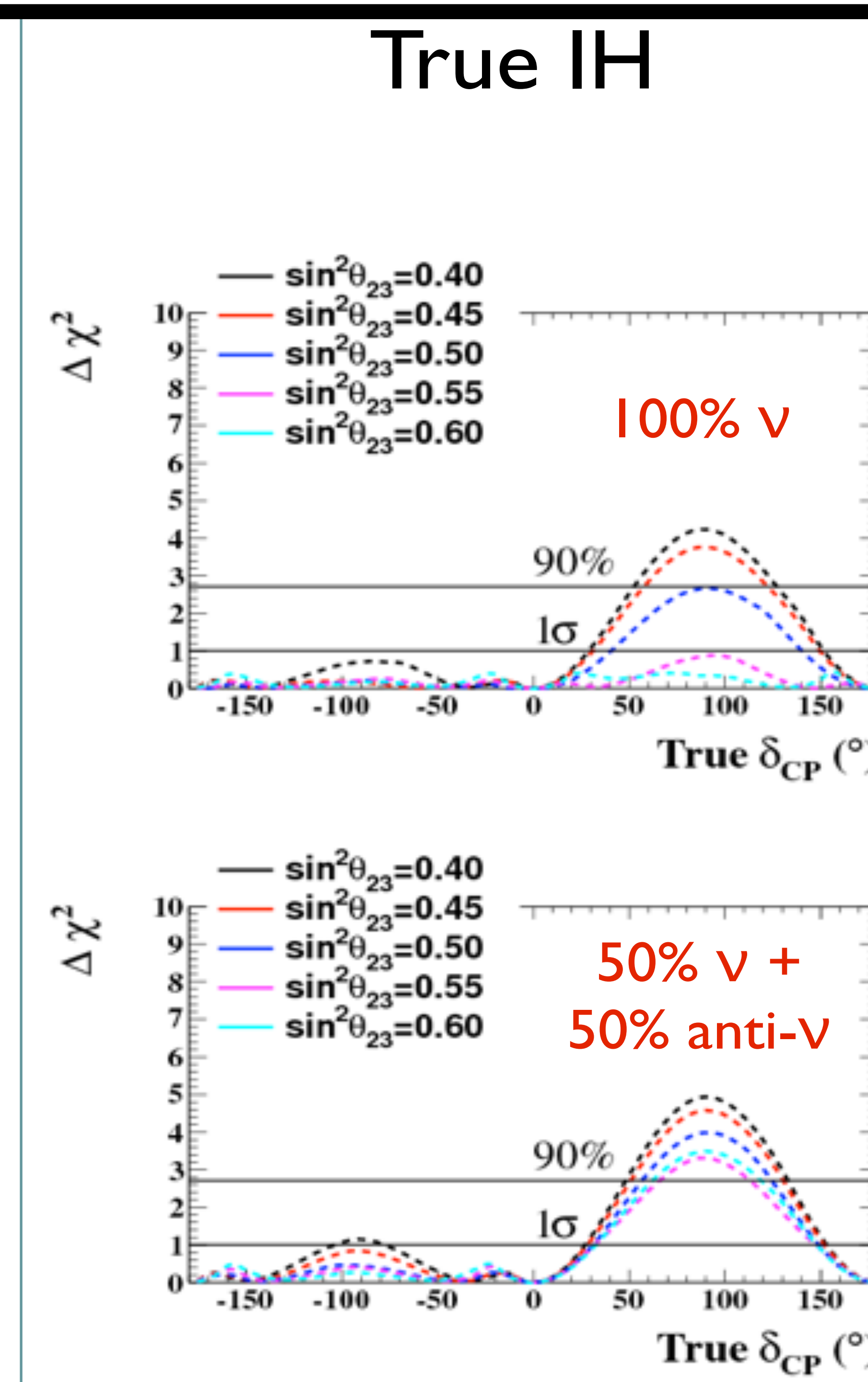


(c) 100% ν-mode, with ultimate reactor error.

(d) 50% ν-, 50% $\bar{\nu}$-mode, with ultimate reactor error.

CPV sensitivity: T2K alone

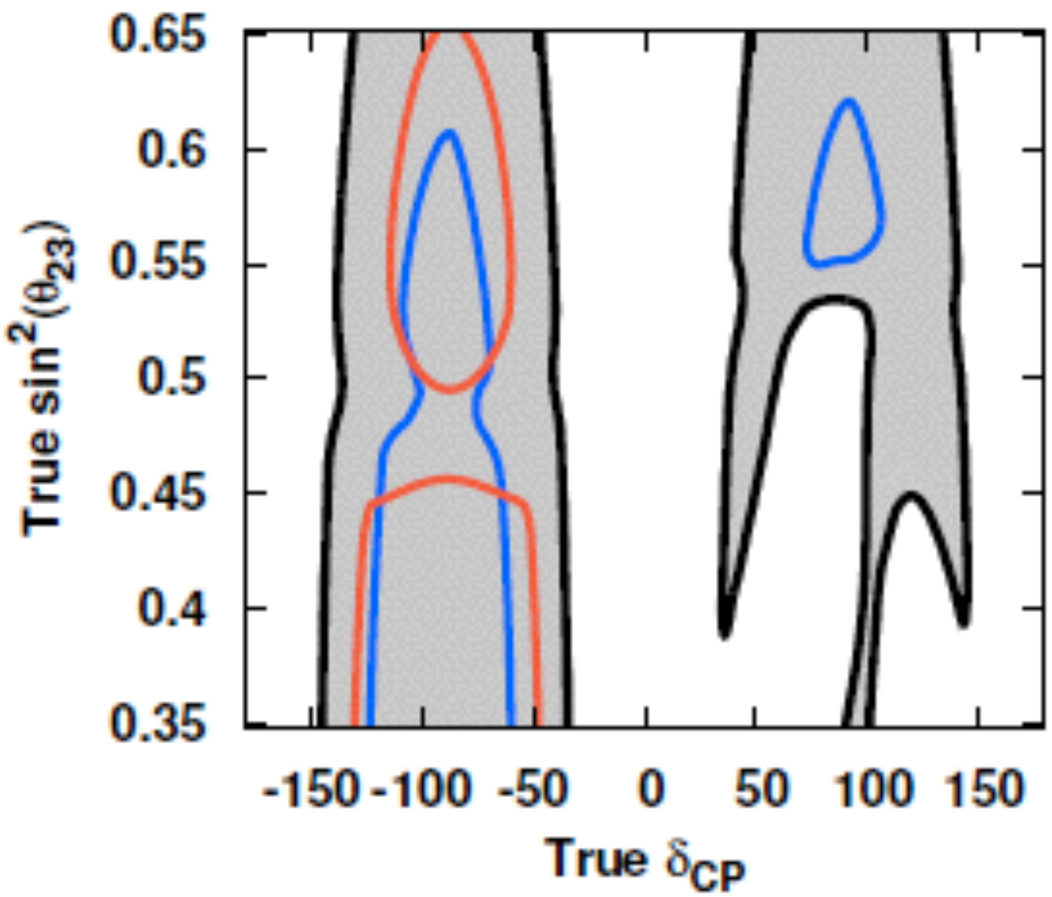




7.8×10^{21} POT $\sin^2 2\vartheta_{13}$ =0.1, δCP =0°, $\sin^2 2\vartheta_{23}$ =0.5, Δm^2= 2.4×10^{-3} eV^2 + 2012 systematics

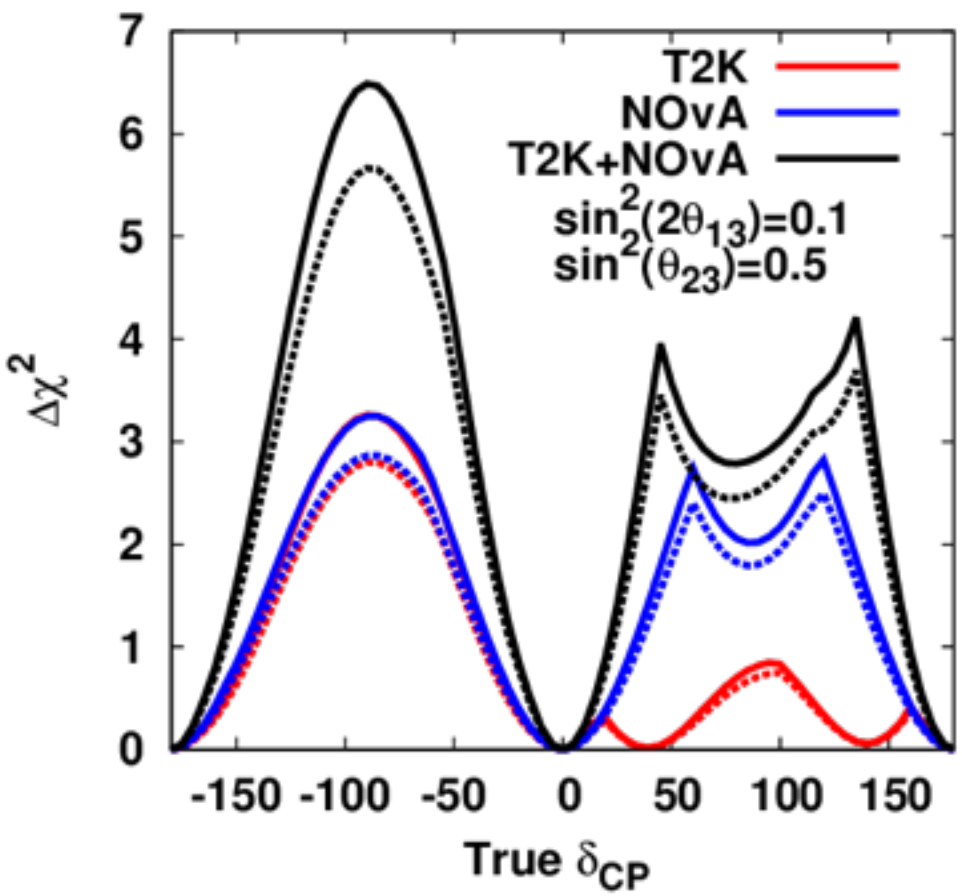
CPV sensitivity: T2K+NOvA

Region where δ_{CP} can be discovered at 90% CL



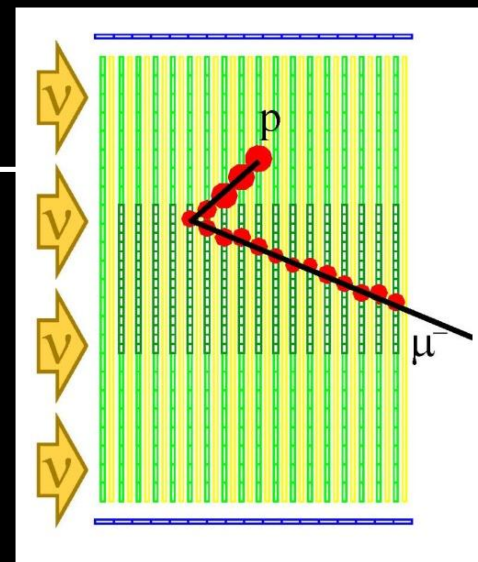
T2K alone | Nova alone | T2K+ Nova

Sensitivity to sinδ /= 0



solid (dash) : w/o (w/) systematics

Inclusive ν_μ CC cross-section on Fe and CH (on-axis)



- Motivation: very few ν cross sections on heavy nuclei.
- Event selection:
  - Identify the μ- track in an interaction starting within a central module
  - μ- candidate: should be in-time with the beam and the longest track.

- Results
  - Flux average CC inclusive cross section

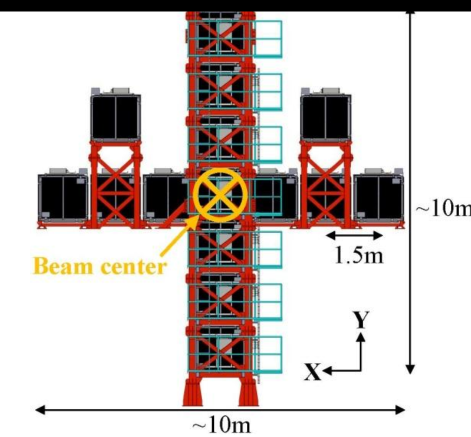
$$\sigma_{CC}^{Fe} = \left(1.444 \pm 0.002(\text{stat}) \;^{+0.189}_{-0.157}(\text{syst})\right) \times 10^{-38}\ \text{cm}^2/\text{nucleon}$$

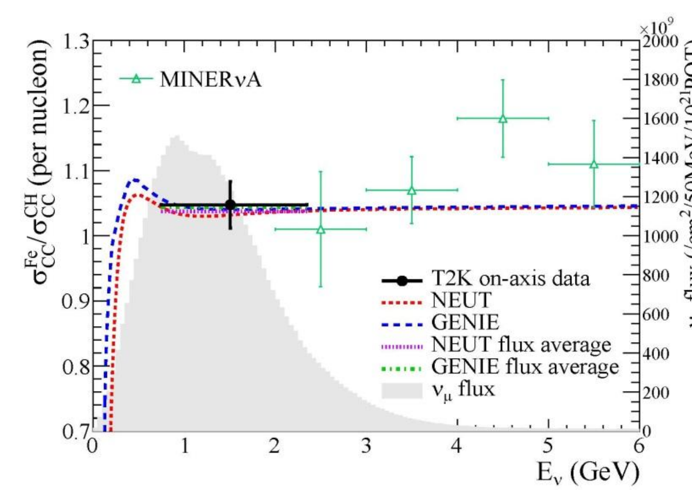
$$\sigma_{CC}^{CH} = \left(1.379 \pm 0.009(\text{stat}) \;^{+0.178}_{-0.147}(\text{syst})\right) \times 10^{-38}\ \text{cm}^2/\text{nucleon}$$

  - Dominated by flux systematic (~11.5%)
  - Cross section ratio

$$\frac{\sigma_{CC}^{Fe}}{\sigma_{CC}^{CH}} = 1.047 \pm 0.007(\text{stat}) \pm 0.035(\text{syst})$$

    - Flux systematic mostly cancels out



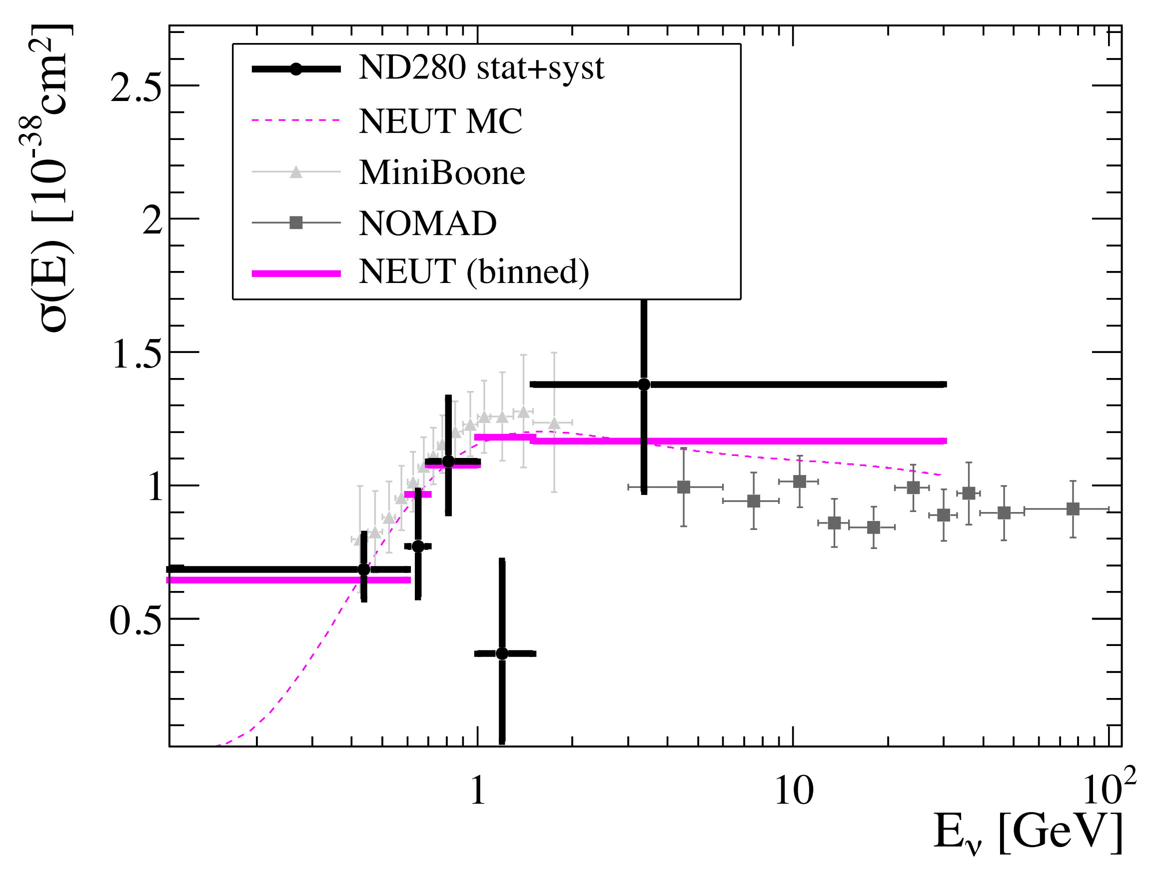


Note: NEUT and GENIE = ν MC generators

PRD 90 (2014) 052010

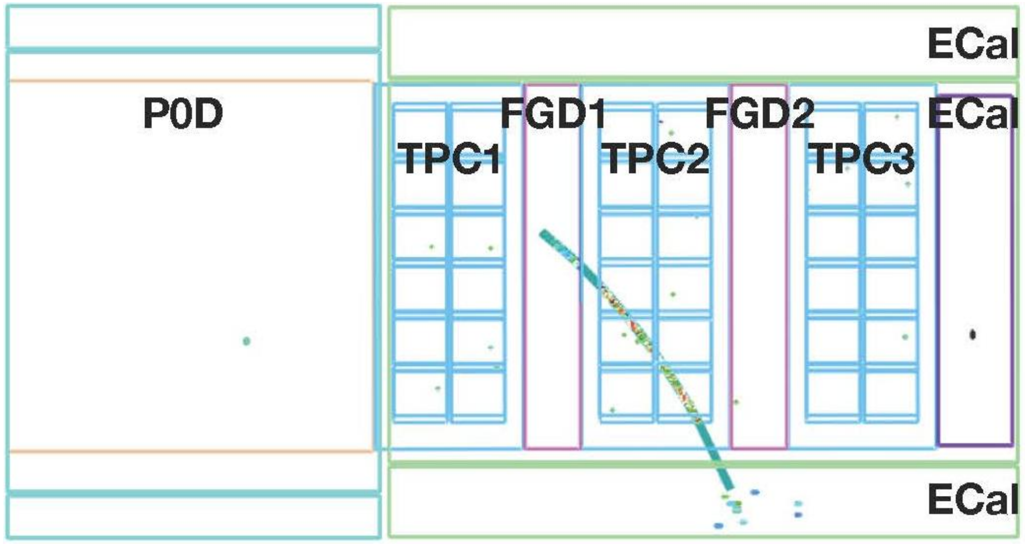
ν_μ CCQE cross-section on carbon (off-axis)

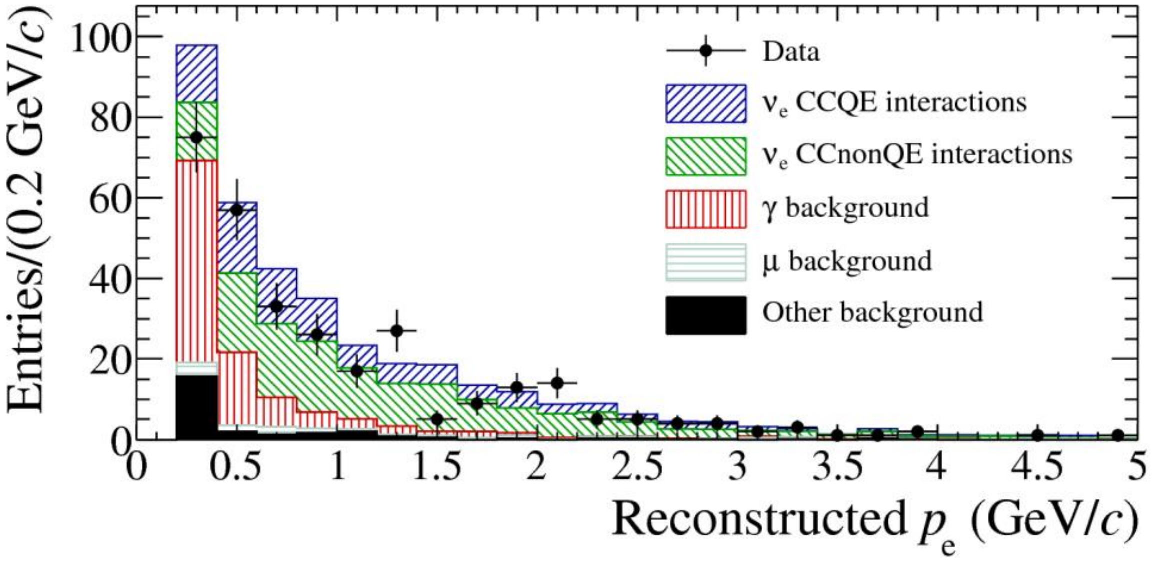
- Interactions are required to have one muon track starting in fine-grained tracker, and no pions reconstructed. Analysis is based on muon momentum and angle vs. neutrino beam.
- Using Smith-Moniz/RFG, fit M_A to be $1.26{+}0.21{-}0.18$ GeV/c^2 using normalization; $1.43{+}0.28{-}0.22$ GeV/c^2 from shape only
- arXiv:1411.6264 (in press at PRD)



ν_e CC Inclusive Cross-section on hydrocarbon

- Motivation
  - ν_e contamination is the largest background in $\nu_\mu \rightarrow \nu_e$ Appearance
- Events selection
  - Identify the e^- track in an interaction starting within FGD1
  - e^- candidate: Highest momentum, negative charged track that pass electron TPC dE/dx and ECal PID cuts.
  - Main background $\gamma \rightarrow e^+e^-$ treat
    - Veto activity upstream of FGD1
    - e^+e^- invariant mass cut
  - <u>Selected:</u> 315 ν_e CC events



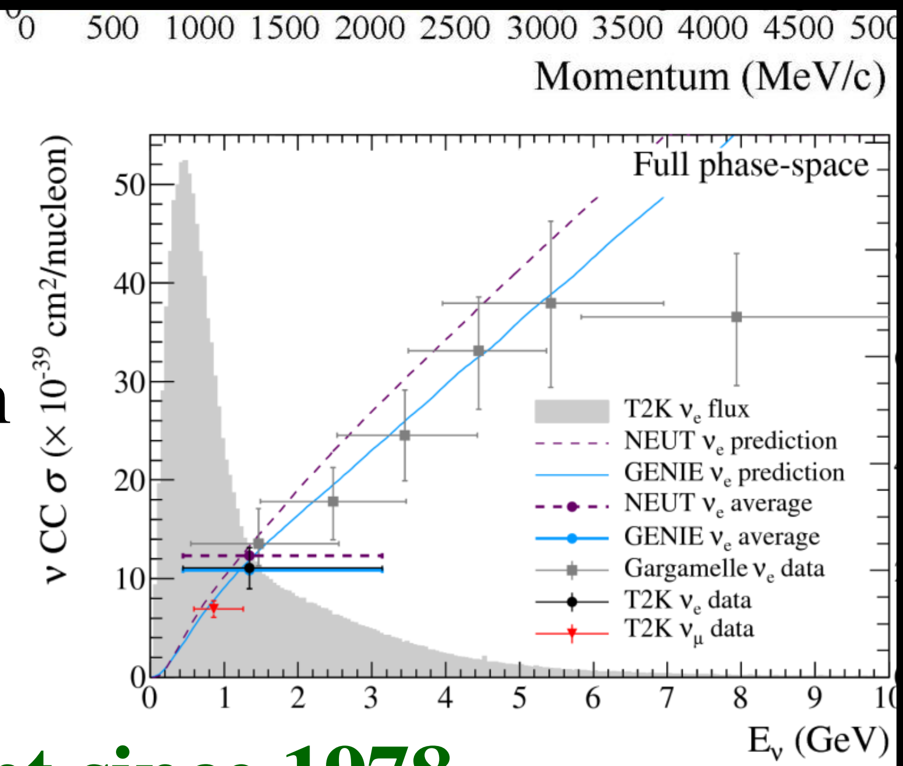


ν_e CC Inclusive Cross-section

- Results
  - Differential distributions: p_e, $\cos\theta_e$ and Q^2
  - Total ν_e CC inclusive cross section

$$\langle\sigma\rangle_\varphi = 1.11 \pm 0.10(\text{stat}) \pm 0.18(\text{syst}) \times 10^{-38}\text{cm}^2/\text{nucleon}$$

  - Dominant systematics:
    Flux (12.9%), Statistics (8.7%),
    Detector (8.6%)



- **First total ν_e cross section measurement since 1978**

(Gargamelle, Nucl. Phys. B 133, 205)

PRL 113 (2014) 241803

Neutral-current elastic on oxygen (SK data)

- Measurement method
  - Cross section extracted from

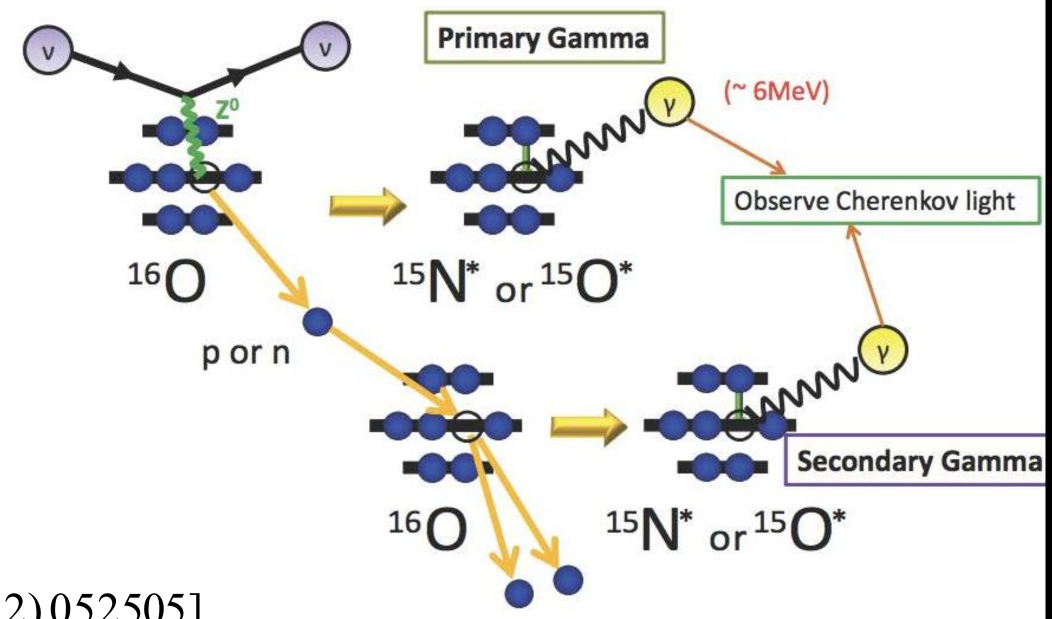
$$\langle \sigma_{NCQE}^{obs} \rangle = \frac{N^{obs} - N_{BG}^{exp}}{N^{exp} - N_{BG}^{exp}} \langle \sigma_{NCQE}^{theory} \rangle$$

obs = observed in data

exp = expected by MC

BG = background

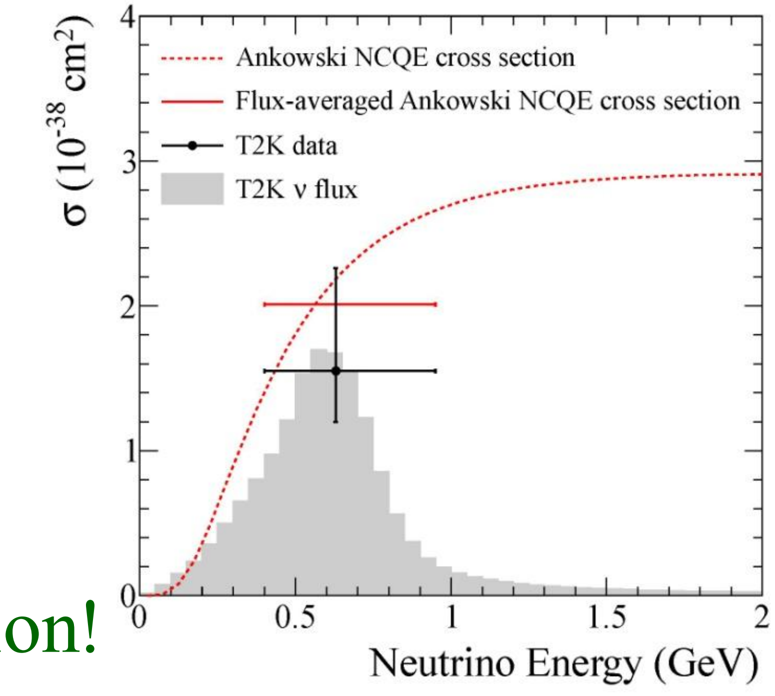
$\langle \sigma_{NCQE}^{theory} \rangle = 2.01 \times 10^{-38} \mathrm{cm}^2$ [PRL 108 (2012) 052505]



- Results
  - Flux-average ν-Oxygen NCE

$$\langle \sigma_{NCQE}^{obs} \rangle = 1.55_{-0.35}^{+0.71} \times 10^{-38} \mathrm{cm}^2/\mathrm{nucleus}$$

  - Dominant systematics
    - Primary (15%) and secondary (13%) γ productions
    - Flux uncertainty (10%)
- First measured ν-Oxygen NCE cross section!



PRD 90 (2014) 072012

More exotic physics

- Neutrino time-of-flight: relative TOF analysis in preprint (arXiv:1502.06605), no evidence of non-zero mass

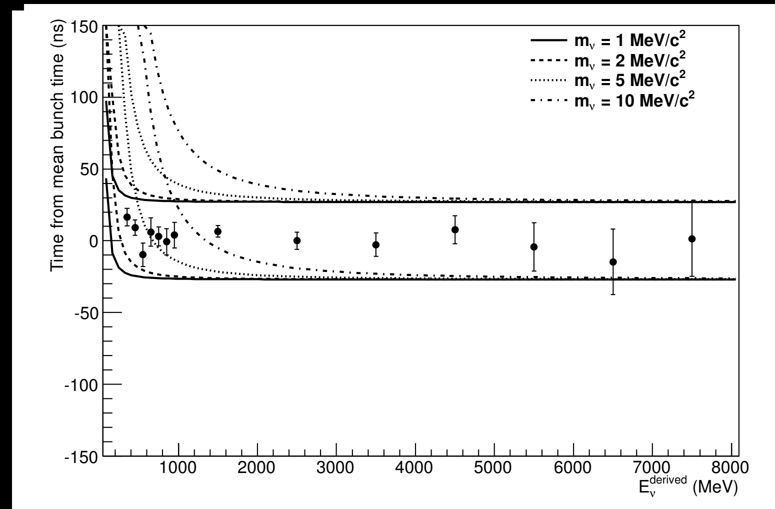
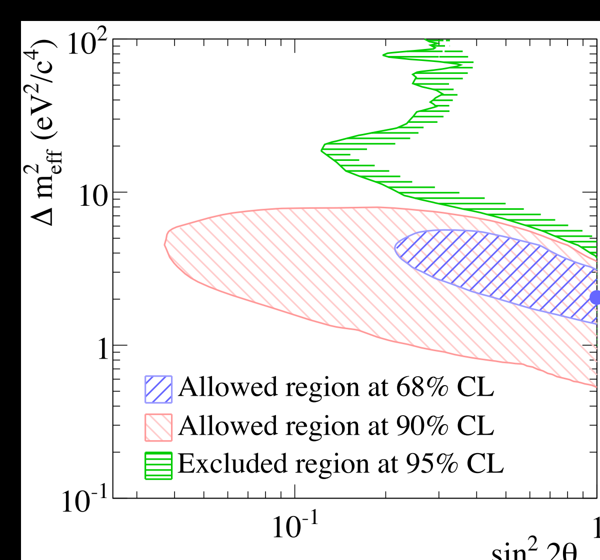
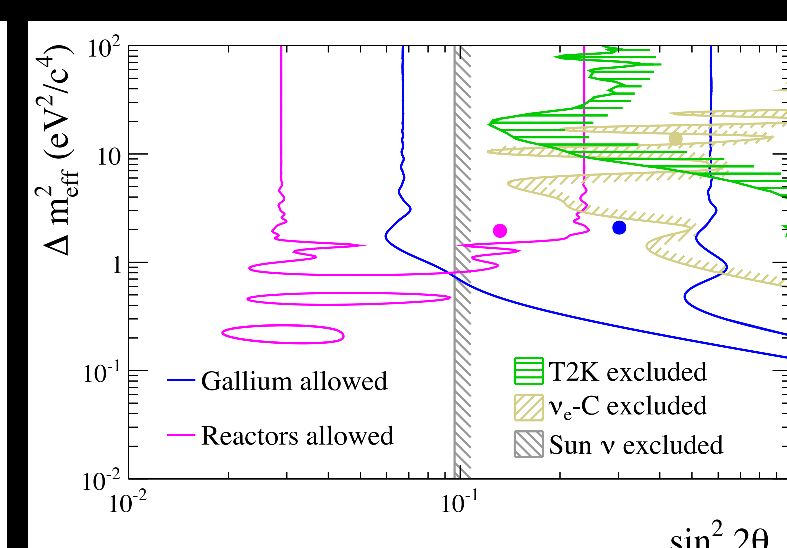


FIG. 14. Timing residuals of T2K CCQE neutrino candidate events as a function of derived neutrino energy. Events have been grouped into energy bins of 100 MeV below 1 GeV and bin sizes of 1GeV above 1 GeV.

- Short-baseline ν_e disappearance search: Phys.Rev. D91 (2015) 5, 051102
  - Allowed regions shown are consistent with reactor/gallium anomalies but null-result p-value is 0.085





Summary

- T2K has:
  - Discovered and measured $\nu_\mu \rightarrow \nu_e$ appearance at the atmospheric Δm^2
  - Made the most precise measurement of θ_{23}, still favoring maximal disappearance
  - Seen $\bar{\nu}_\mu$ disappearance consistent with CPT conservation
  - Made many precise measurements of neutrino interaction channels
- T2K will:
  - Continue progress and improve precision on all the above
  - Measure $\bar{\nu}_e$ appearance (first results very soon)
  - Eventually have significant sensitivity to θ_{23} octant and δ

BACKUPS

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 constrained:
  - 52% W-shape
  - 3% $\sigma(\nu_e)/\sigma(\nu_\mu)$
  - 40% $\sigma(\bar{\nu})/\sigma(\nu)$
  - 30% out of fiducial volume
  - 4% Final state interactions