The T2K and KamLAND-Zen Physics Programs

Outline:

- Introduction
- T2K
  - -> Overview
  - -> Oscillation Results
  - -> Neutrino Cross Sections
  - -> Future Sensitivity
- KamLAND-Zen
  - -> Overview
  - -> Results
  - -> Outlook
- Summary

A 40th Anniversary

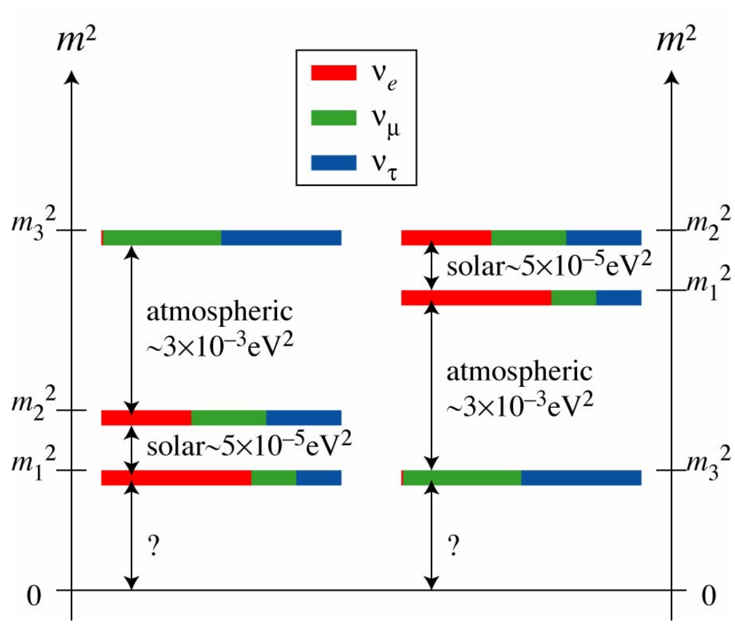
Erice, 1973

Three-Flavor Picture

- The MNSP picture:

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- Oscillation/mixing measurements have told us:
  - "Solar" θ_{12}, Δm^2_{21}
    - -> Includes sign of Δm^2_{21}
    - -> Solar experiments, KamLAND
  - "Atmospheric" θ_{23}, Δm_{23}
    - -> Atmospheric, accelerator expts
    - -> No sign information for Δm^2_{23}
    - -> θ_{23} octant unknown, near maximal
  - θ_{13} measurements
    - -> Reactor, accelerator expts
- We don't know:
  - δ_{CP} – CP violation in neutrinos
  - absolute mass scale or hierarchy
  - nature of neutrino



Common theme?

What do T2K and KamLAND-Zen have in common?

- One collaborator - BEB
- Japan
  -> KamLAND-Zen and Super-K (T2K far detector) are the Kamioka mine
- Motivated by a larger question:
  Why does the universe contain matter but little antimatter?

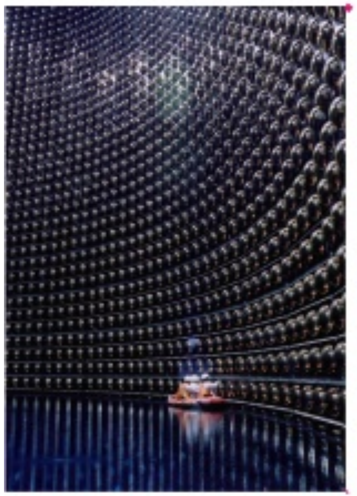
  Leptogenesis
  (Conventional) leptogenesis requires:

  - CP violation in the neutrino sector:
    -> Measuring CP violation is a major goal
    of the neutrino oscillation program
  - Majorana neutrinos
  - Seesaw mechanism

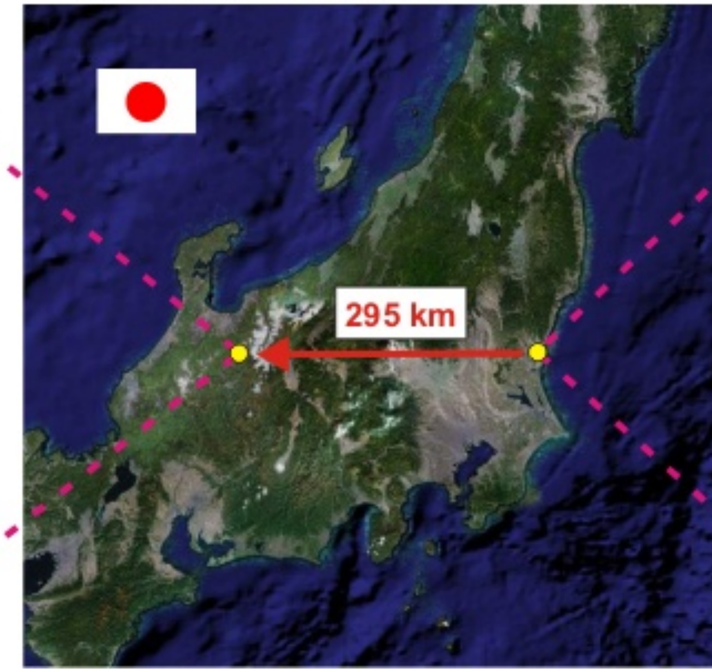
  -> Decays of right-handed neutrinos produce L violation,
  which the B-L conserving sphaleron process in the SM
  converts to a baryon number asymmetry

The T2K Experiment

Super Kamiokande
50,000 tons of water
10,000 phototubes

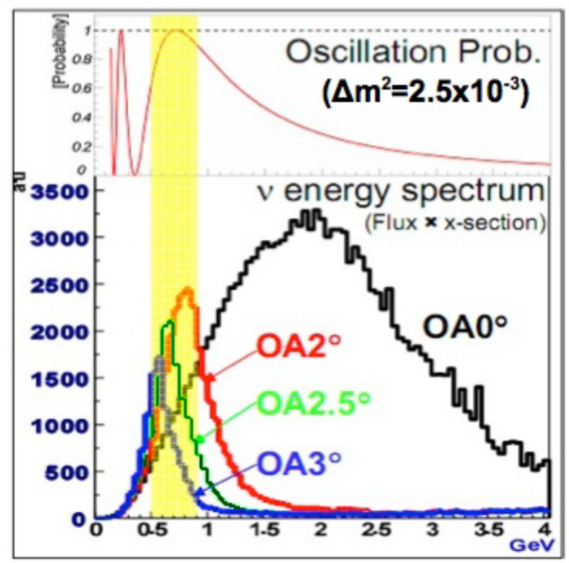


Neutrino beam directed across Japan



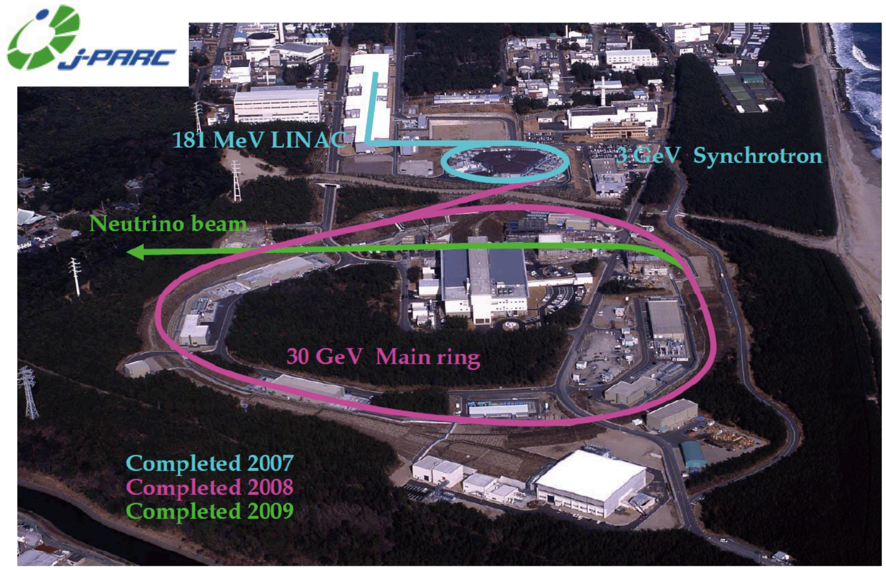
Tokai accelerator complex and
location of near detector (ND280)

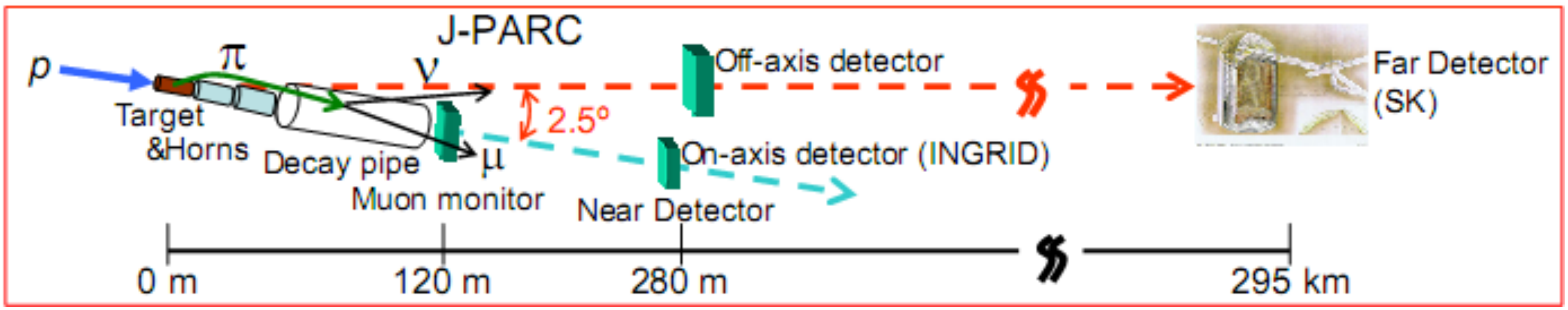
- 295 km baseline
- 'Quasimonochromatic' beam
  -> first use of the off-axis technique
- Beam peak energy tuned to ~600 MeV, to give L/E at
  -> first maximum in ν_μ oscillation probability
  -> first maximum in ν_e appearance probability



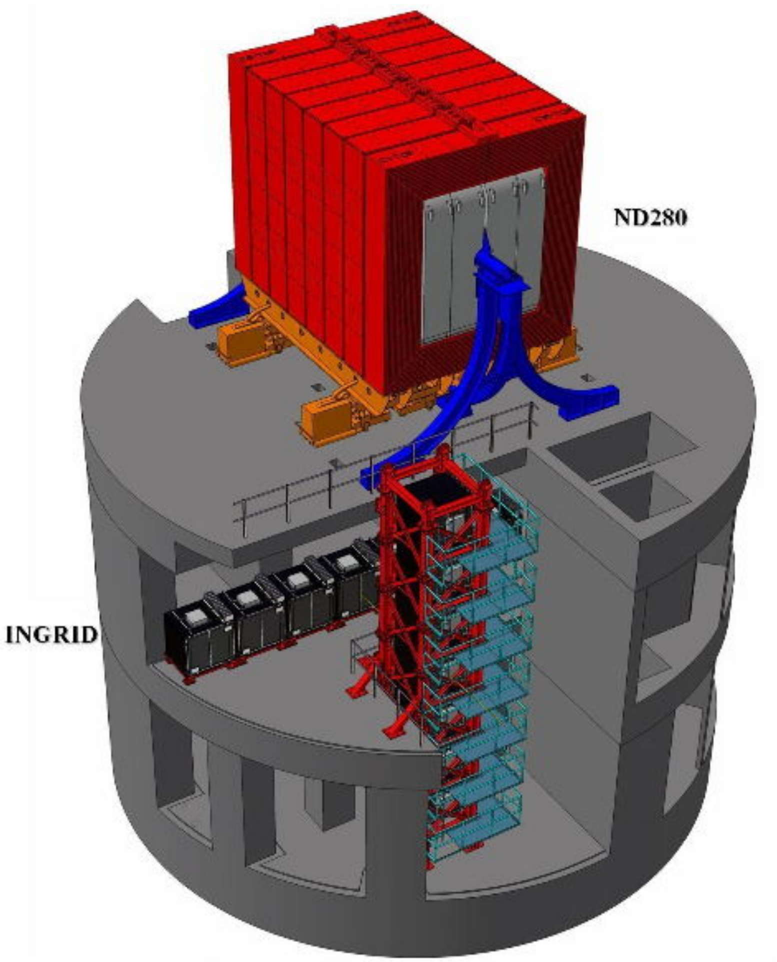
The T2K Experiment

- Beam produced at J-PARC
- Conventional beam,
  31 GeV protons on graphite target
- Muon neutrino beam is produced
  by decays of pions in flight:
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- 96 m decay pipe; length chosen to
  suppress muon decays
- Decay kinematics give a correlation
  between neutrino energy, direction
- Off-axis angle: peaked beam, suppression of feed-down backgrounds





T2K Near Detectors



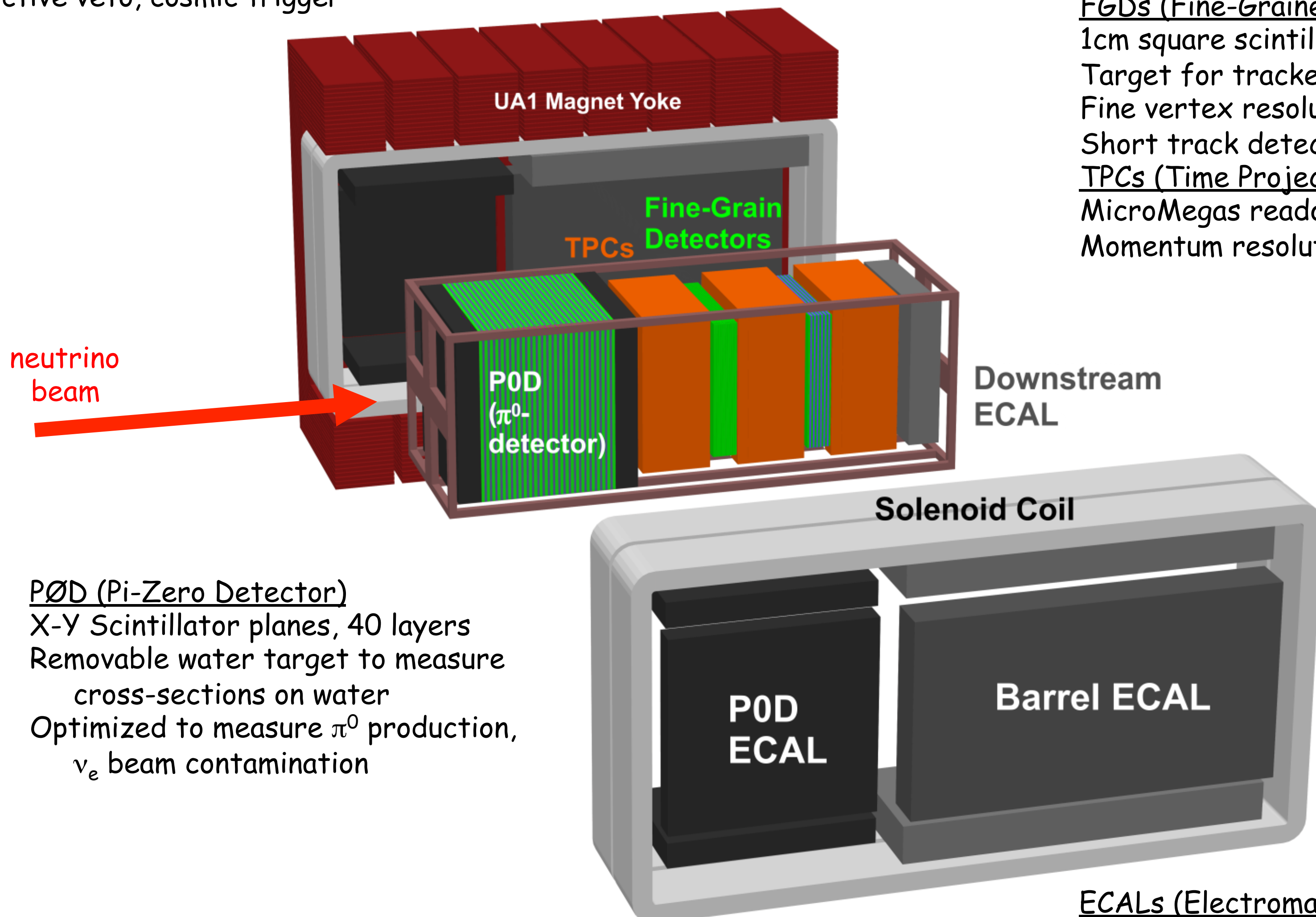
- On-axis and off-axis detectors in a cylindrical 'pit' 280 m from the target
- INGRID - on axis
  -> measures beam profile, position, and stability
- ND280 off-axis detector inside former UA1/NOMAD magnet

ND280 Off-Axis Detectors

<u>SMRD (Side Muon Range Detector)</u>
Scintillator interleaved in magnet yoke
Active veto, cosmic trigger

<u>Magnet</u>
UA1 magnet, B=0.2T nominal

<u>Tracker</u>
<u>FGDs (Fine-Grained Detectors)</u>
1cm square scintillator bars
Target for tracker
Fine vertex resolution
Short track detection: recoil protons
<u>TPCs (Time Projection Chambers)</u>
MicroMegas readout (7mmx10mm pads)
Momentum resolution <10% @ 1GeV



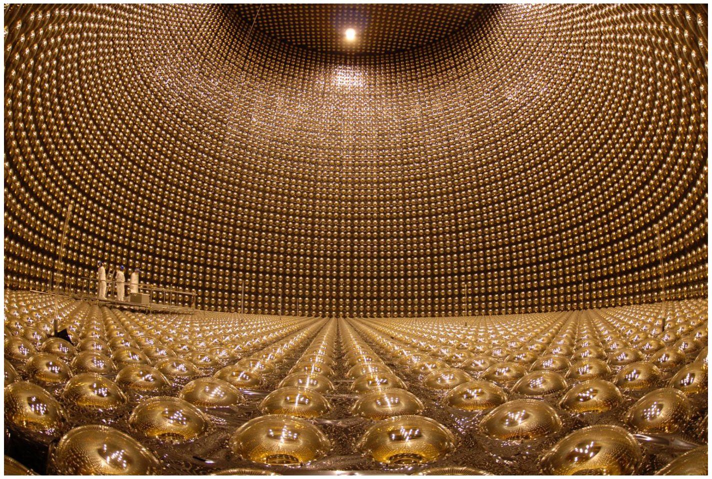
<u>PØD (Pi-Zero Detector)</u>
X-Y Scintillator planes, 40 layers
Removable water target to measure
cross-sections on water
Optimized to measure π^0 production,
ν_e beam contamination

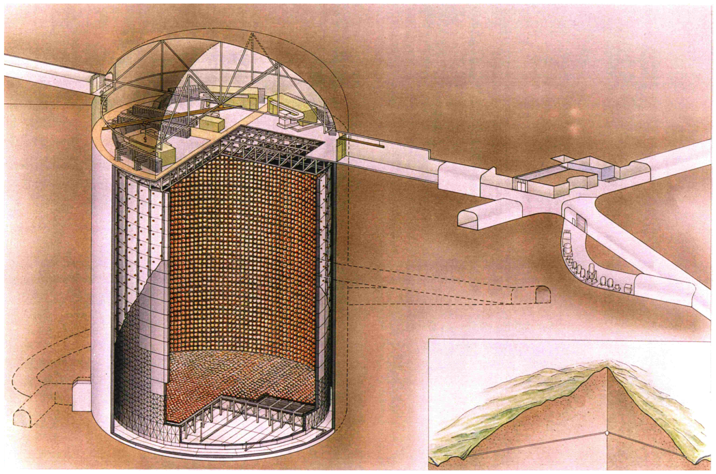
<u>ECALs (Electromagnetic Calorimeter)</u>
Scintillator + lead
Measure photons, electrons from
tracker, PØD

Far Detector: Super-K

50 kiloton water Cherenkov detector

- Fiducial volume 22.5 kt
- Overburden 2700 m water equivalent
- Inner detector
  - -> 11,129 20" PMTs
  - -> 40% photocathode coverage
- 1885 8" OD PMTs
- Dead-time free DAQ system (2008)
  - -> Time and charge of all PMT hits recorded and processed offline
- Good performance for sub-GeV ν detection
  - -> Energy reconstruction: $\Delta E/E$ ~10% (for CCQE 2-body kinematics)
  - -> Good e / μ separation



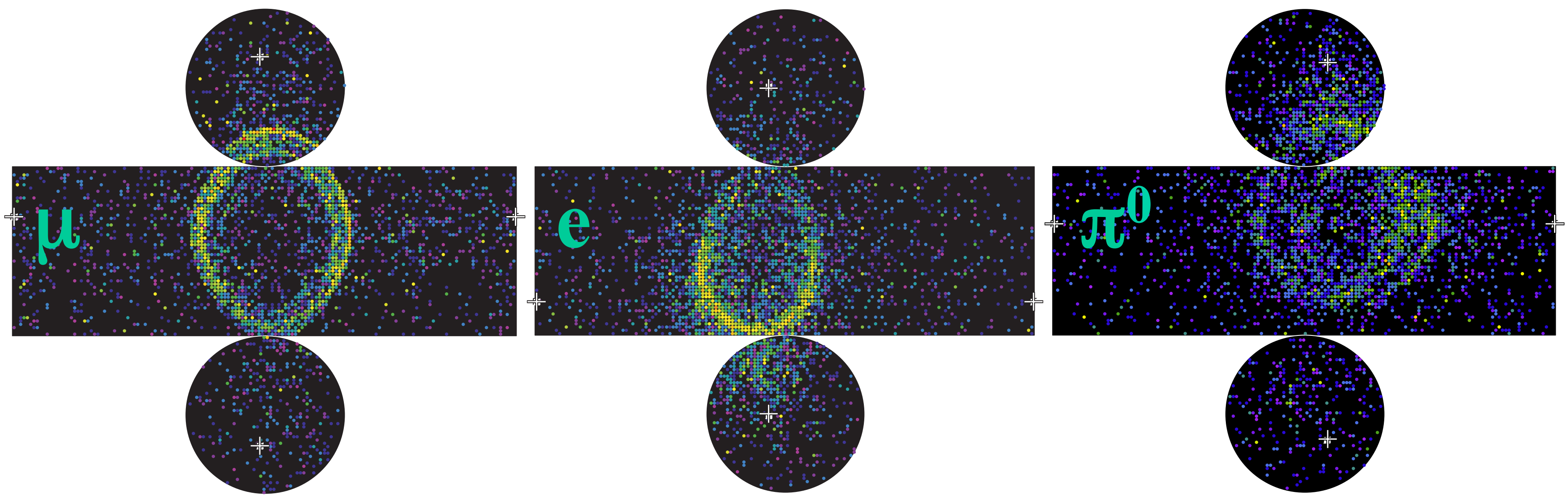


Events in Super-K

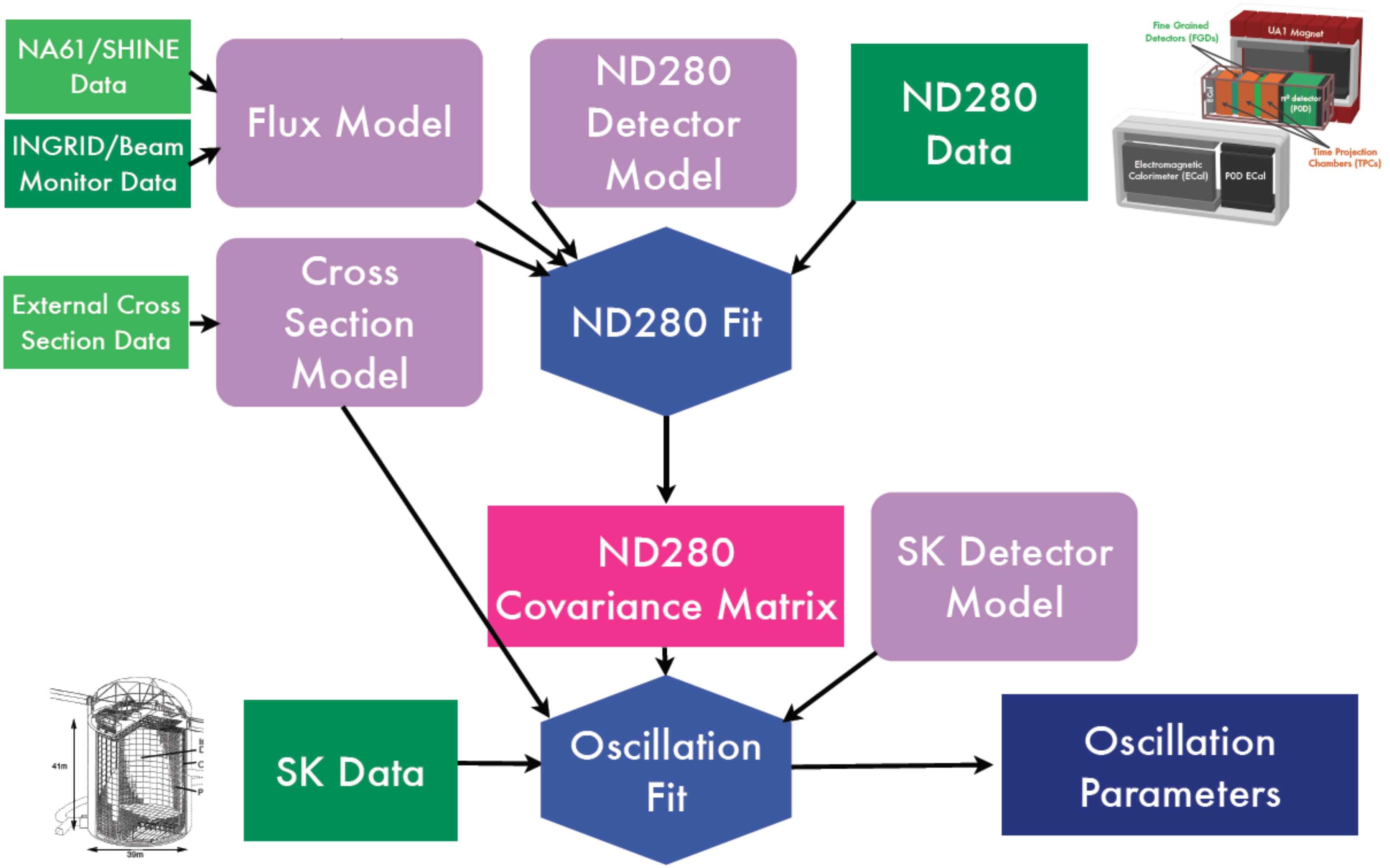
Examples of fully-contained events in Super-K (MC)

Muon vs. electron discrimination based on ring shape:
electron rings are 'fuzzier' due to electron scattering

π^0 event: two rings, can mimic electron if rings overlap or if one ring is not reconstructed

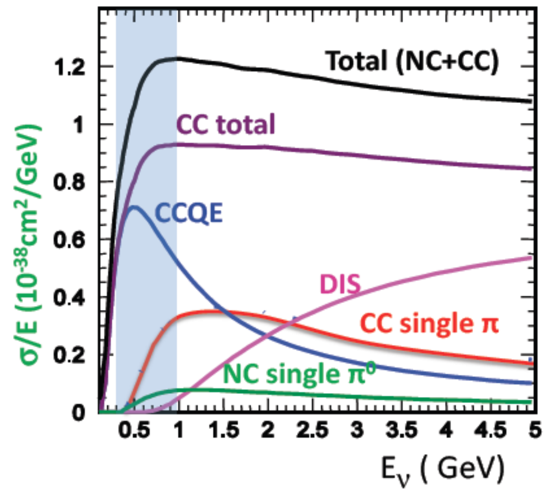


Oscillation Analysis Structure



Cross-Section Model

Analyses done with the NEUT and GENIE generators



Charged-Current Quasielastic (CCQE)

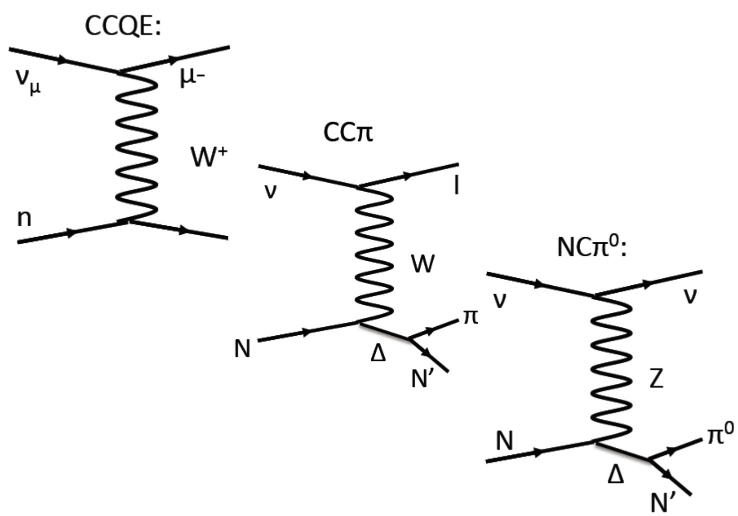
- Llewellyn-Smith base model
- Smith-Moniz fermi gas model for nucleus
- Spectral function implemented for comparison to RFG

Single Pion Production (CC/NC1π)

- Rein-Seghal resonance model

Deep Inelastic Scattering (DIS) and Charged Current multi-pion

- GRV98 PDF
- Bodek-Yang correction



Final State Interactions (FSI)

- Cascade model – track secondary particles until they leave the nucleus
- Separate models used for low (<500 MeV) and high momentum

Note: in analyses, MC "true" event classification done after FSI

Systematic Variations

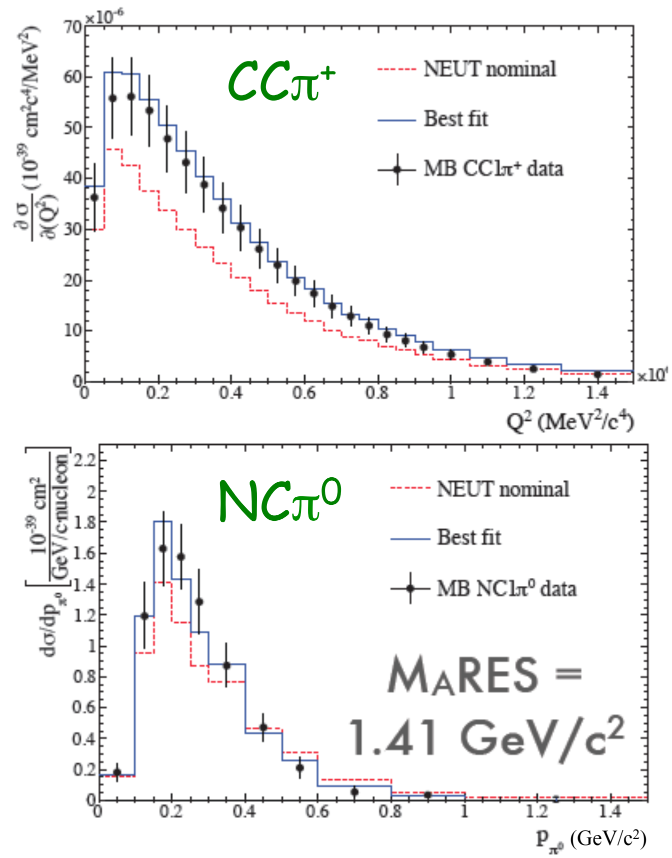
Generator parameters are varied within conservative prior uncertainties constrained by fits to external data

Example: we use MiniBooNE 1π data (CC and NC) and fit to NEUT predictions to generate input value

-> Add *ad hoc* parameters to improve the fit – but break internal theoretical purity

Parameter	Type	Interaction Type
M_AQE	axial mass	CCQE
$M_a$res	axial mass	CC/NC 1p
CCQE (3 E_n bins)	normalization	CCQE
CC1p (2 E_n bins)	normalization	CC1p
NCp^0	normalization	NC1p
p_F	Fermi momentum	CCQE-RFG
E_b	binding energy	CCQE-RFG
spectral function	model comparison	CCQE-SF

MiniBooNE data



ND280 Data Inputs

Charged-current (CC) sample:

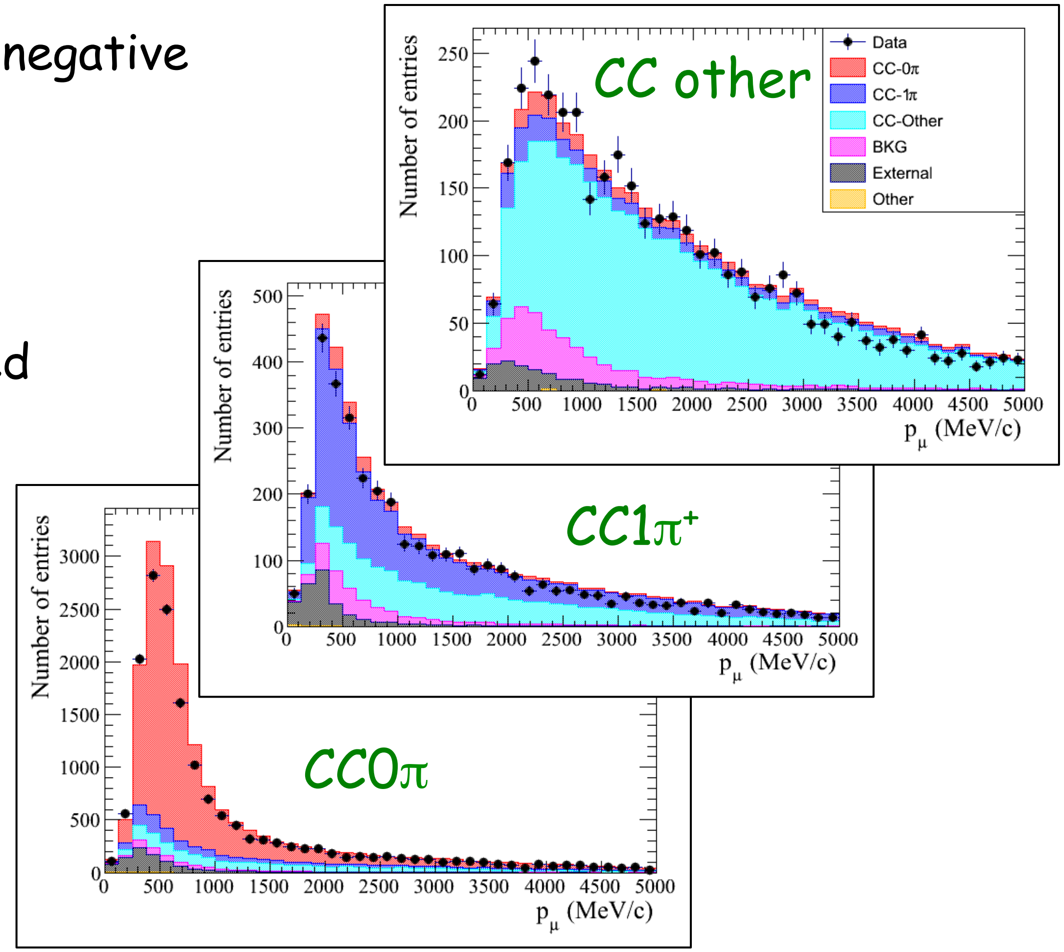
- Select the highest-momentum negative track starting in FGD1
- TPC particle ID consistent with a muon

Charged-current sample separated into three subsamples by event topology:

CC0π
no pions in the final state

CC1π^+
exactly 1π^+ in the final state

CC other
any other number of pions, or any tagged photons



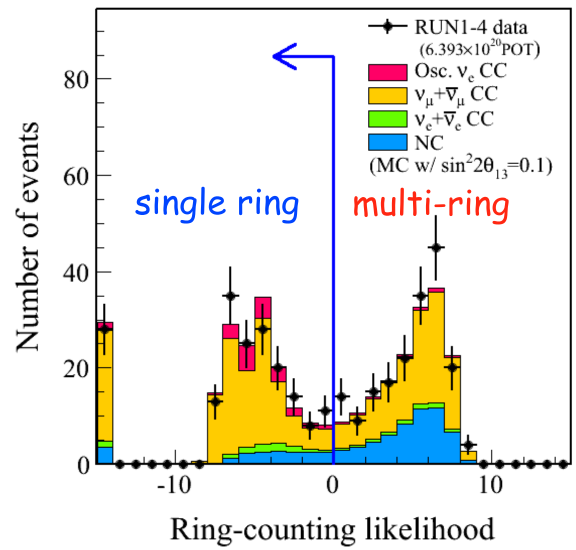
-> Samples constrain CCQE and CCπ+ cross-section model parameters

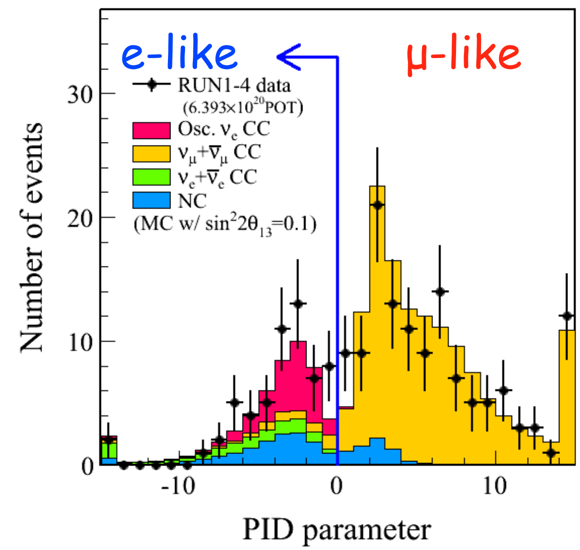
Far Detector ν_e Event Selection

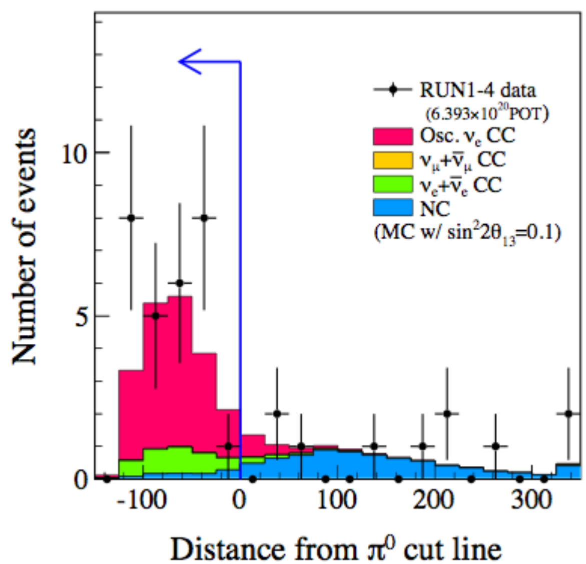
T2K

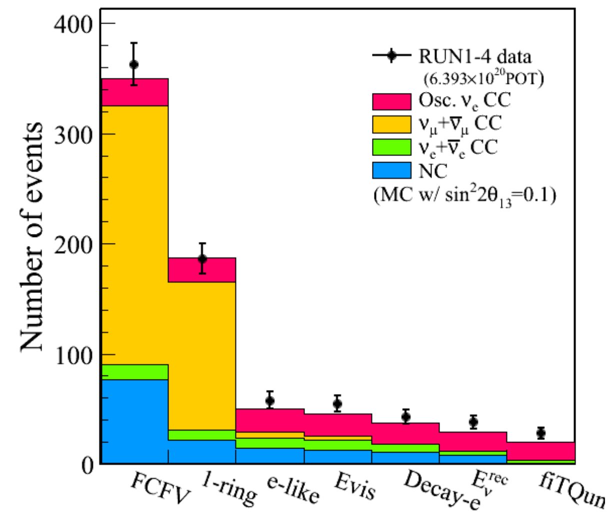
ν_e Selection Cuts

- # veto hits < 16
- Fid. Vol. = 200 cm
- # of rings = 1
- Ring is e-like
- $E_{visible}$ > 100 MeV
- no Michel electrons
- fiTQun π^0 cut
- 0 < E_ν < 1250 MeV



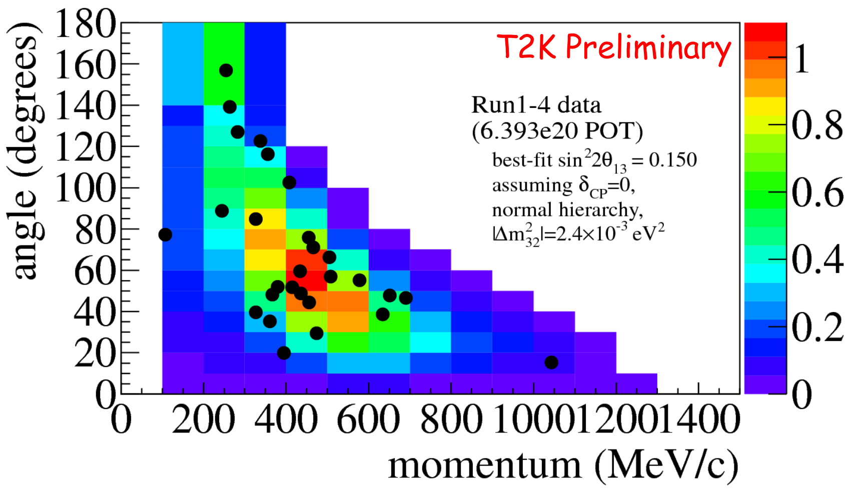




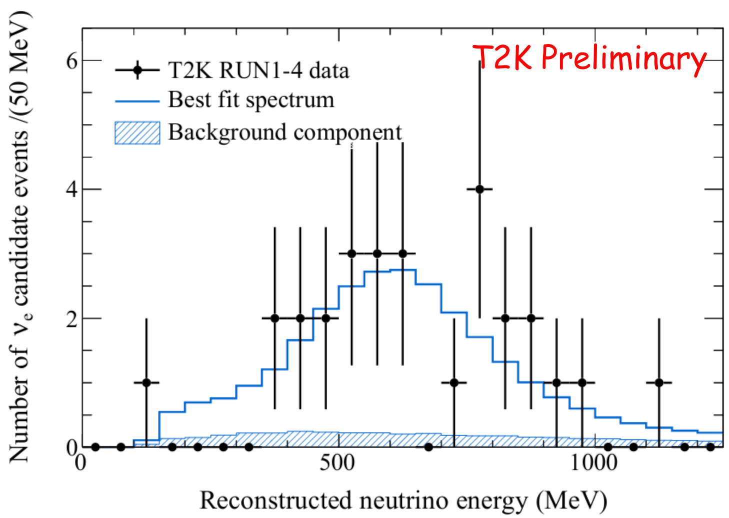


ν_e Appearance Analysis

- Dataset: 6.39×10^{20} protons on target (p.o.t) through April 12, 2013
- Expected background: 4.64 ± 0.53 events
- Signal level: 20.4 ± 1.8 events
  - $\sin^2 2\theta_{13} = 0.1$
  - $\sin^2 2\theta_{23} = 1.0$
  - $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2
  - $\delta_{CP} = 0$



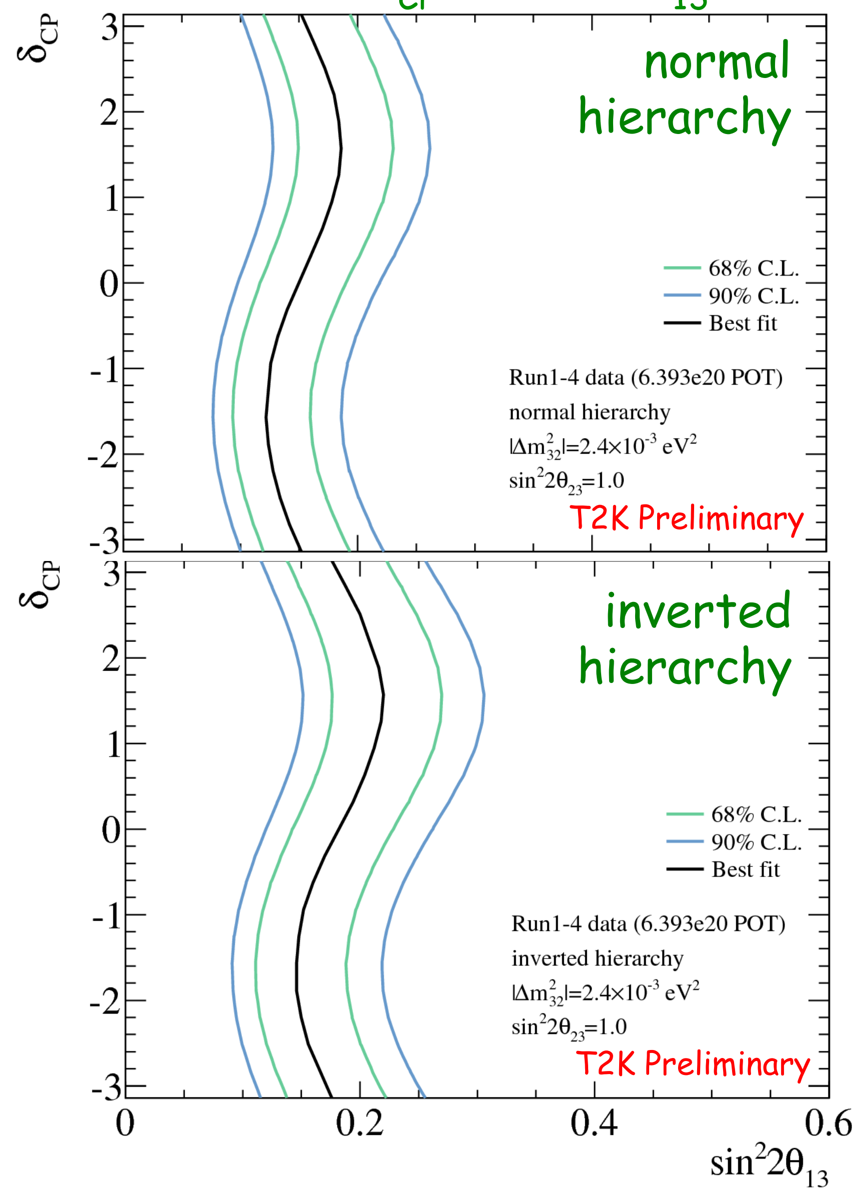
- 5.5σ sensitivity to exclude $\theta_{13} = 0$
- Oscillation parameters extracted with two different methods
  - -> electron p-θ distribution
  - -> reconstructed E_ν distribution



ν_e Appearance Results

- Observed 28 events
  (vs. 4.64 ± 0.53 background)
- Comparing best fit vs. null hypothesis:
  7.5σ significance for non-zero θ_{13}
  (normal hierarchy, $\sin^2 2\theta_{23}$ = 1.0, δ_{CP} = 0)
- First observation (>5σ) of a
  neutrino appearance channel

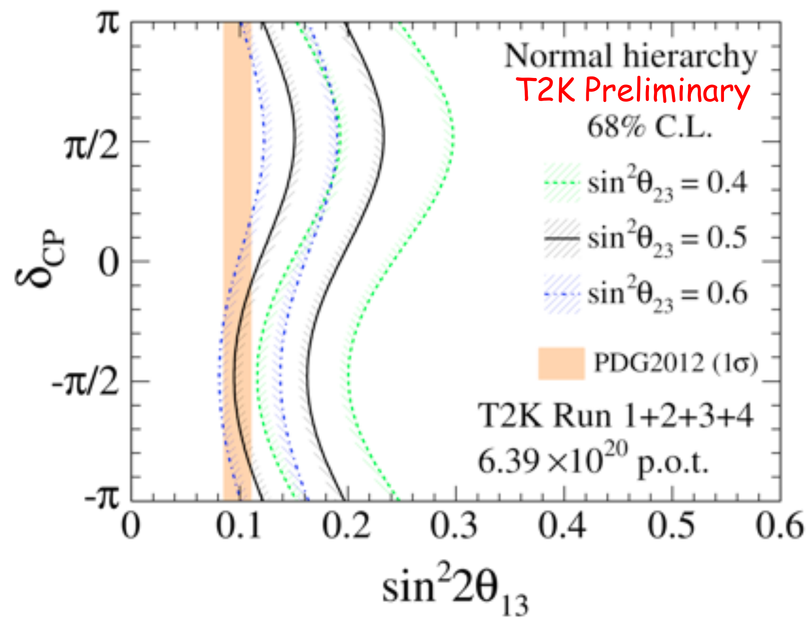
T2K δ_{CP} vs $\sin^2 2\theta_{13}$

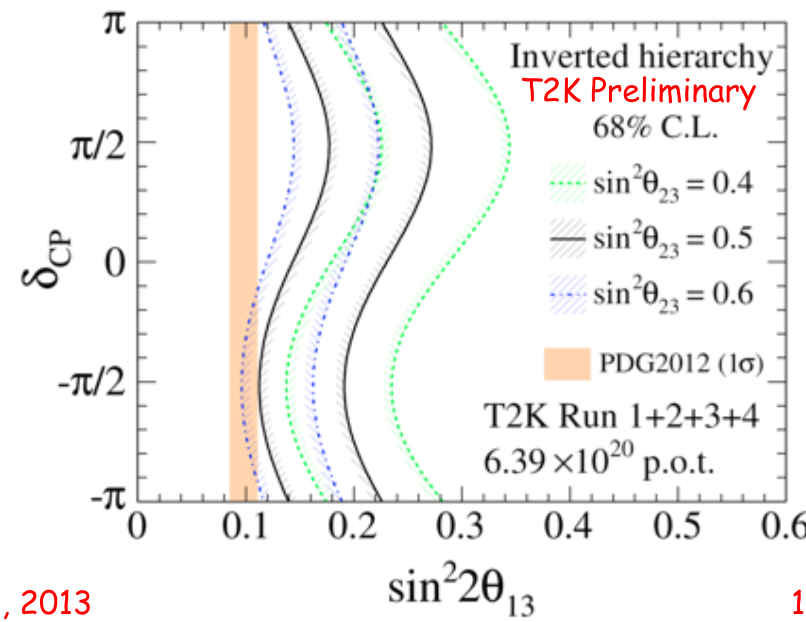


Note: contours are 1D contours at
fixed values of δ_{CP}, not 2D contours

Effects of θ_{23} Uncertainty

- ν_e appearance probability also depends on the value of θ_{23}
- Fixing θ_{23} to values at the edges of the current allowed region shifts the contours -> currently less than 1σ effect
- Future improved θ_{23} measurements will be important for parameter extraction in long-baseline experiments
- T2K is working on a combined analysis of appearance and disappearance modes

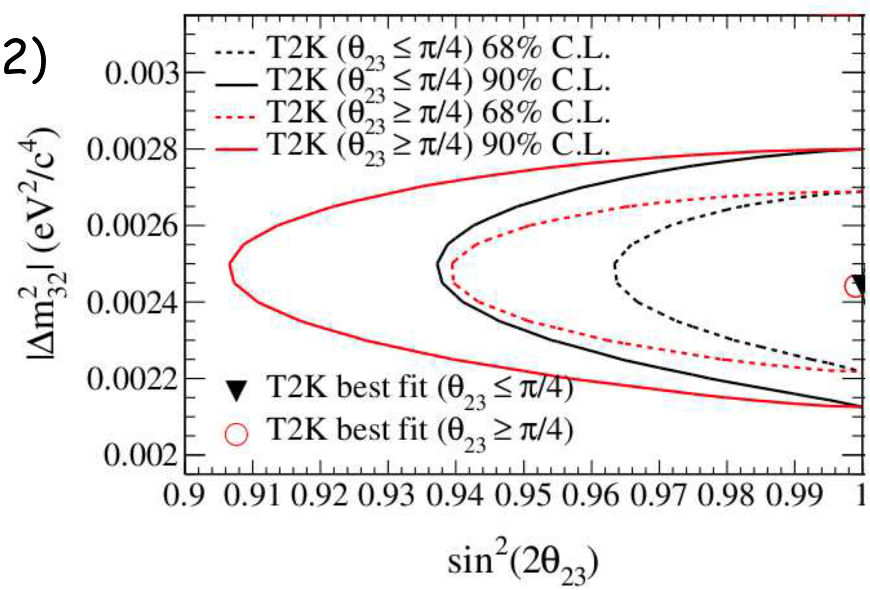


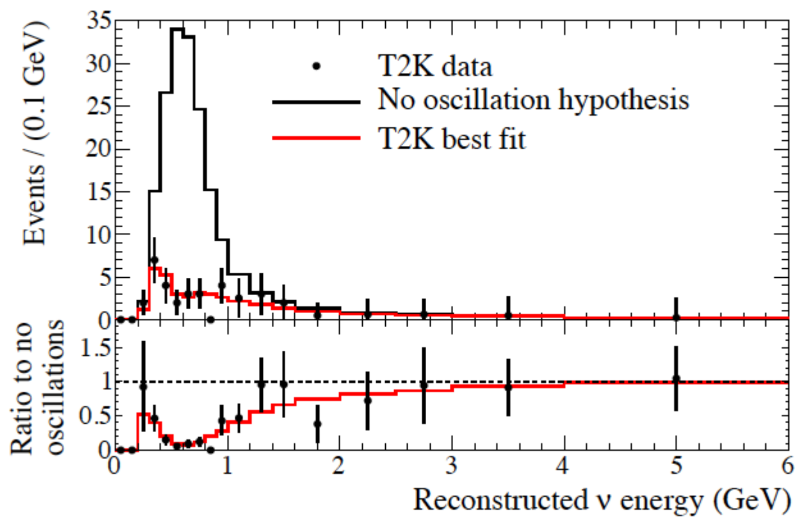


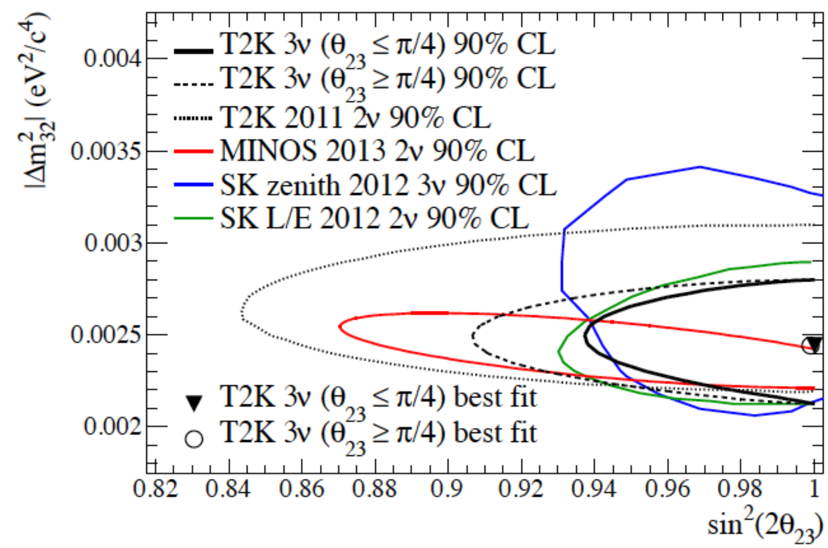
Note: contours are 1D contours at fixed values of δ_{CP}, not 2D contours

ν_μ Disappearance Results

- Dataset: 3.01 x 10^{20} p.o.t (-> summer 2012)
- Updated result now shows contours for both octants of θ_{23}
  -> difference due to effects of θ_{13}
  (fixed to $\sin^2 2\theta_{13}$ = 0.098)
- Best-fit point: $\sin^2 2\theta_{23}$ = 1.00
  (same for both) Δm^2_{32} = 2.44 x 10^{-3} eV^2
- Future results likely to be reported vs. $\sin^2\theta_{23}$ instead of $\sin^2 2\theta_{23}$







arXiv:1308.0465 [hep-ex]

Cross Section Measurements

T2K has an ambitious program to measure a range of neutrino interaction cross sections
- -> multiple targets (C, H_2O, lead, iron)
- -> reconstruction of pions, π^0s, nucleons

First measurements:

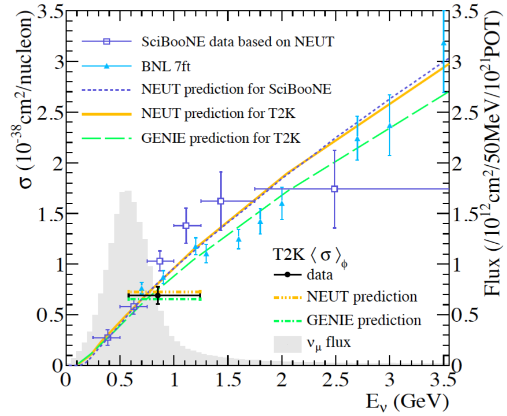
-> CC inclusive on carbon
Phys. Rev. D 87, 092003 (2013), arXiv:1302.4908

-> CCQE vs. E_ν on carbon
Preliminary result: David Hadley at NuFact 2013

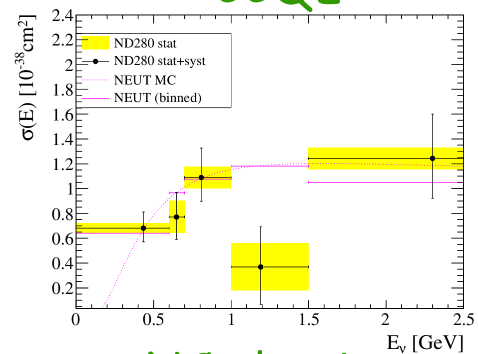
-> NC elastic
Preliminary result: Dan Ruterbories at NuFact 2013

Upcoming measurements:
- -> Differential cross-sections with more data
- -> $CC1\pi^+$
- -> Event selections sensitive to multinucleon effects
- -> Coherent pion production
- -> CC measurements on iron with INGRID
- -> Antineutrinos cross sections, etc…

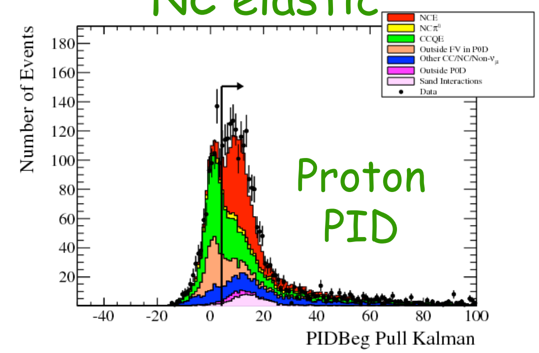
CC inclusive



CCQE



NC elastic



T2K Future

Initial T2K goals

-> Observe ν_e appearance – DONE

-> Constrain oscillation parameters θ_{13}, δ_{CP}

-> Measure θ_{23} oscillation precisely

Updated goals

-> Precisely measure:

- θ_{23}
- Δm^2_{32}

-> Constrain as well as possible:

- δ_{CP}
- θ_{23} octant
- Mass hierarchy?

What future running configuration will optimize T2K's sensitivity?

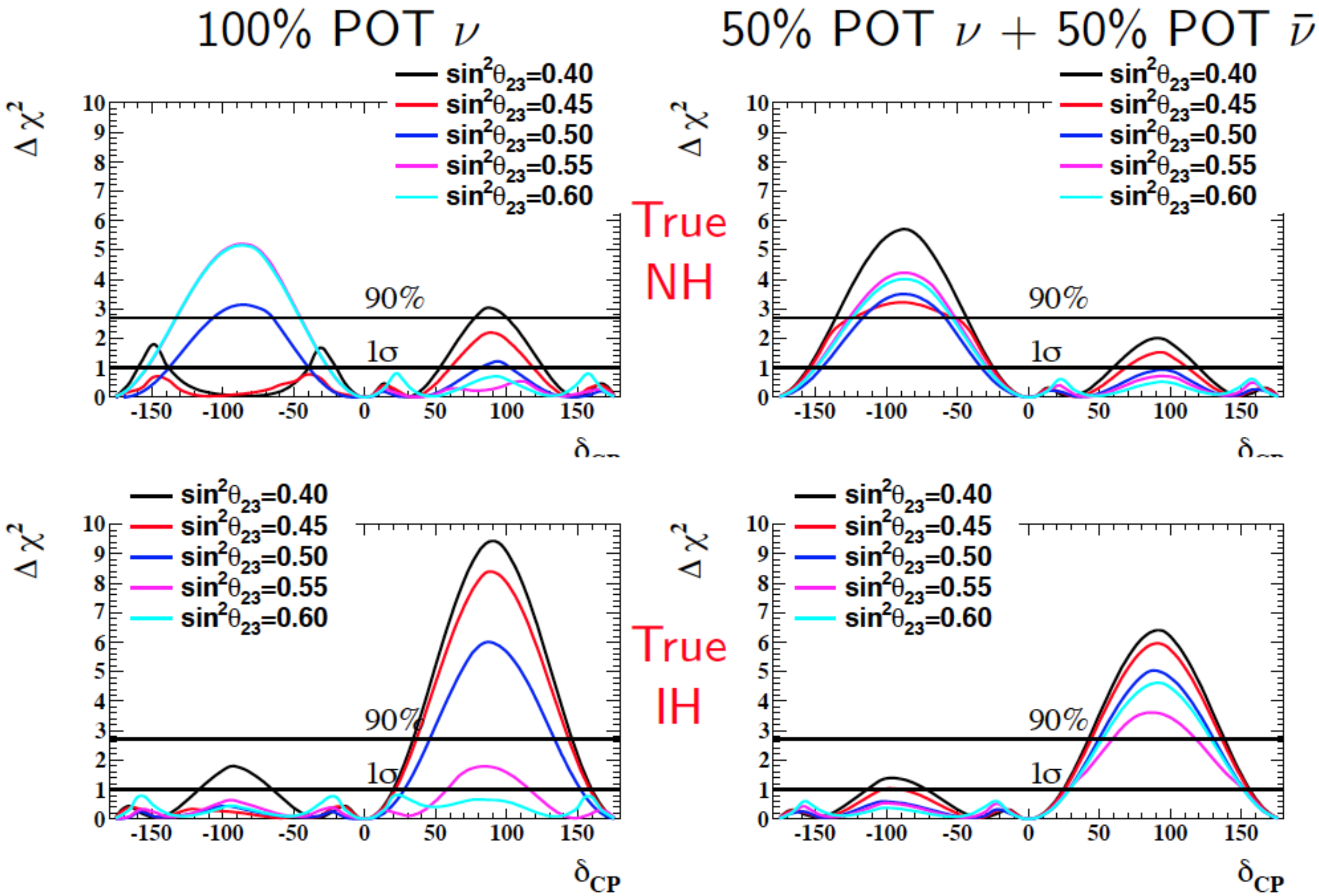
-> Charge to the Future Sensitivity Task Force

-> Detailed studies over the last year

Decision will be made based on these studies,
plus input on accelerator status and prospects

T2K Sensitivity for $\delta_{CP} \neq 0$

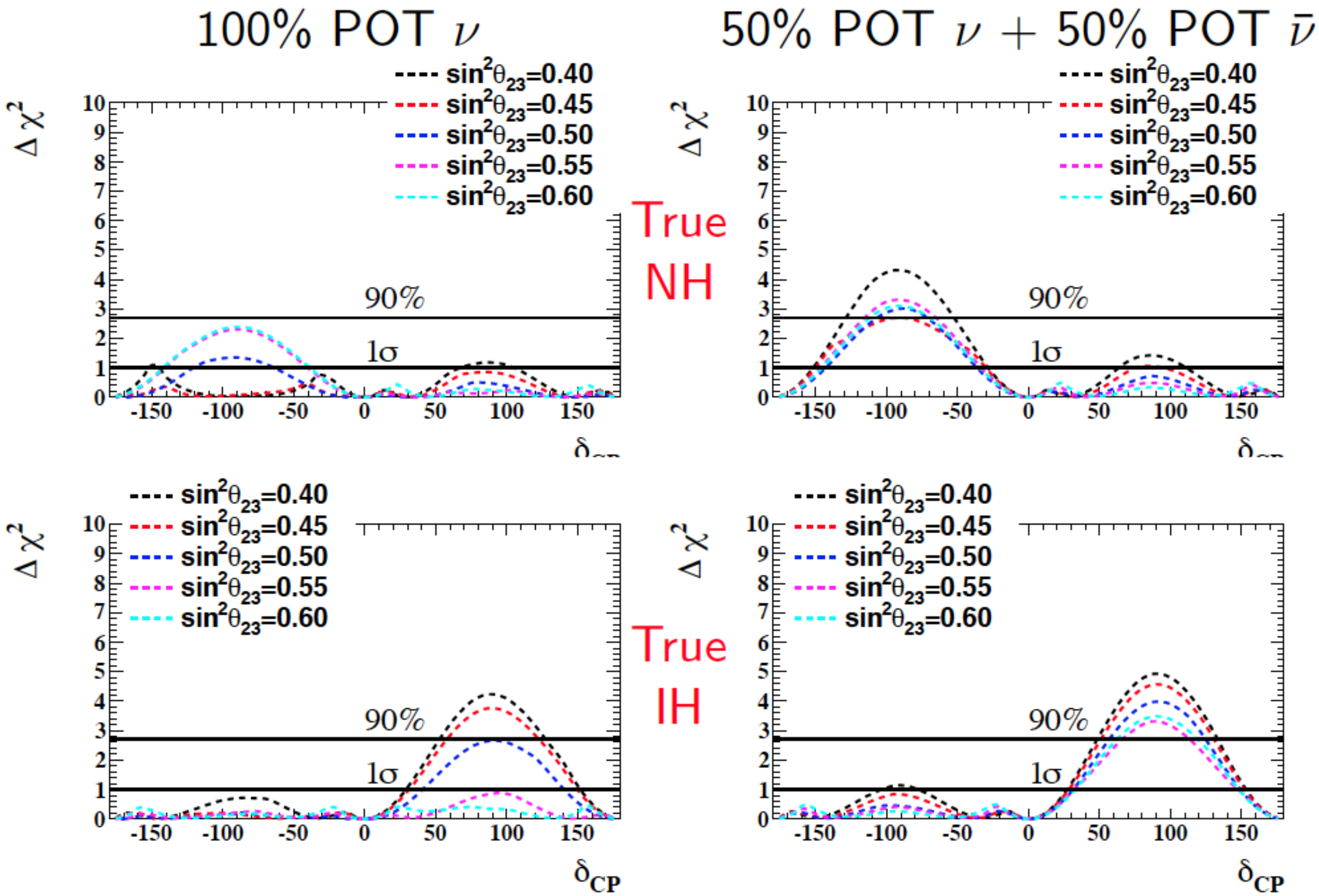
- 7.8×10^{21} protons on target, no systematic errors



-> Assumes true $\sin^2 2\theta_{13}$ = 0.1, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2,
θ_{13} constrained by projected reactor sensitivity: $\delta(\sin^2 2\theta_{13}) = 0.005$

T2K Sensitivity for $\delta_{CP} \neq 0$

- 7.8×10^{21} protons on target, current systematic errors



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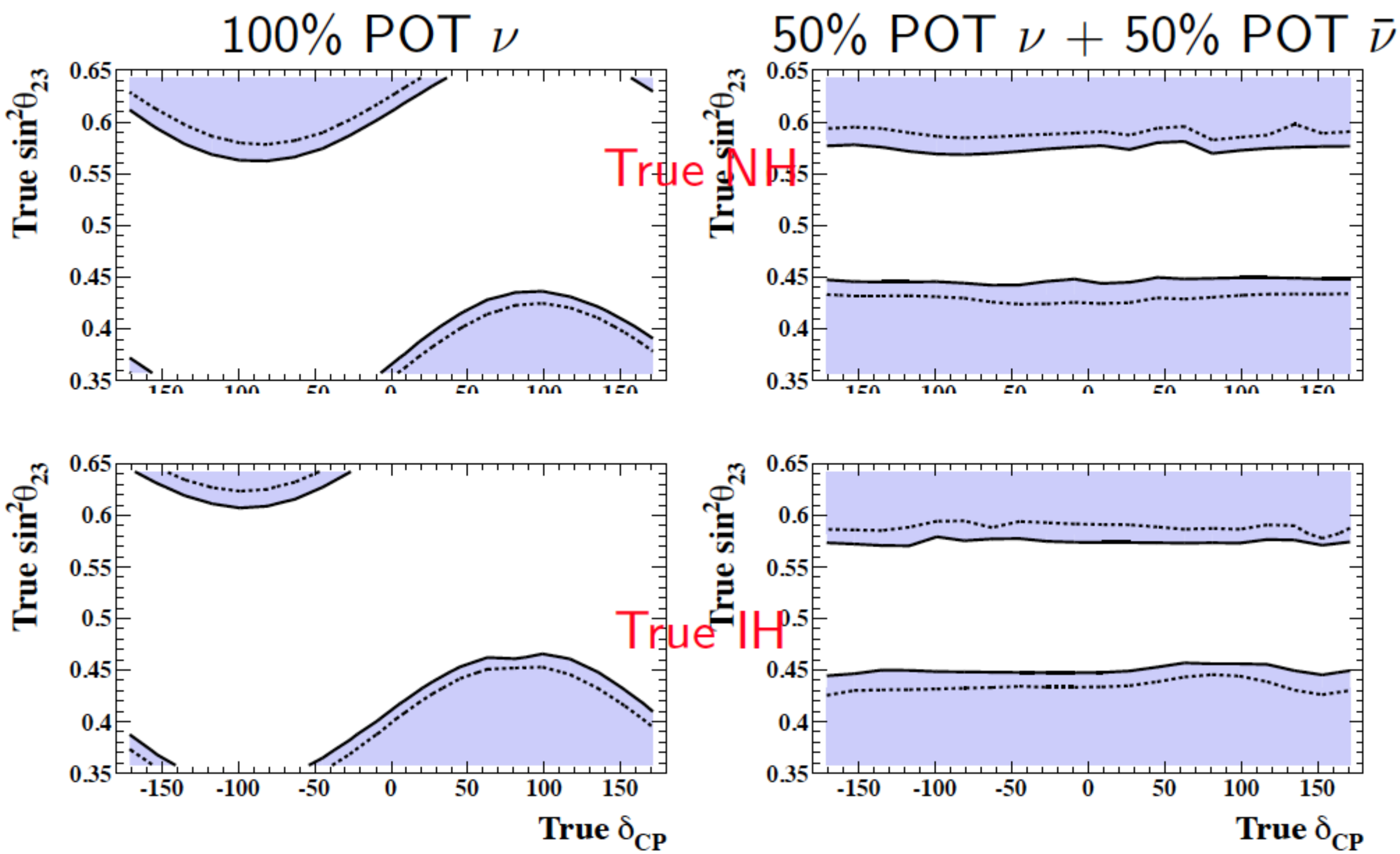
θ_{13} constrained by projected reactor sensitivity: $\delta(\sin^2 2\theta_{13}) = 0.005$

T2K Sensitivity for θ_{23} Octant

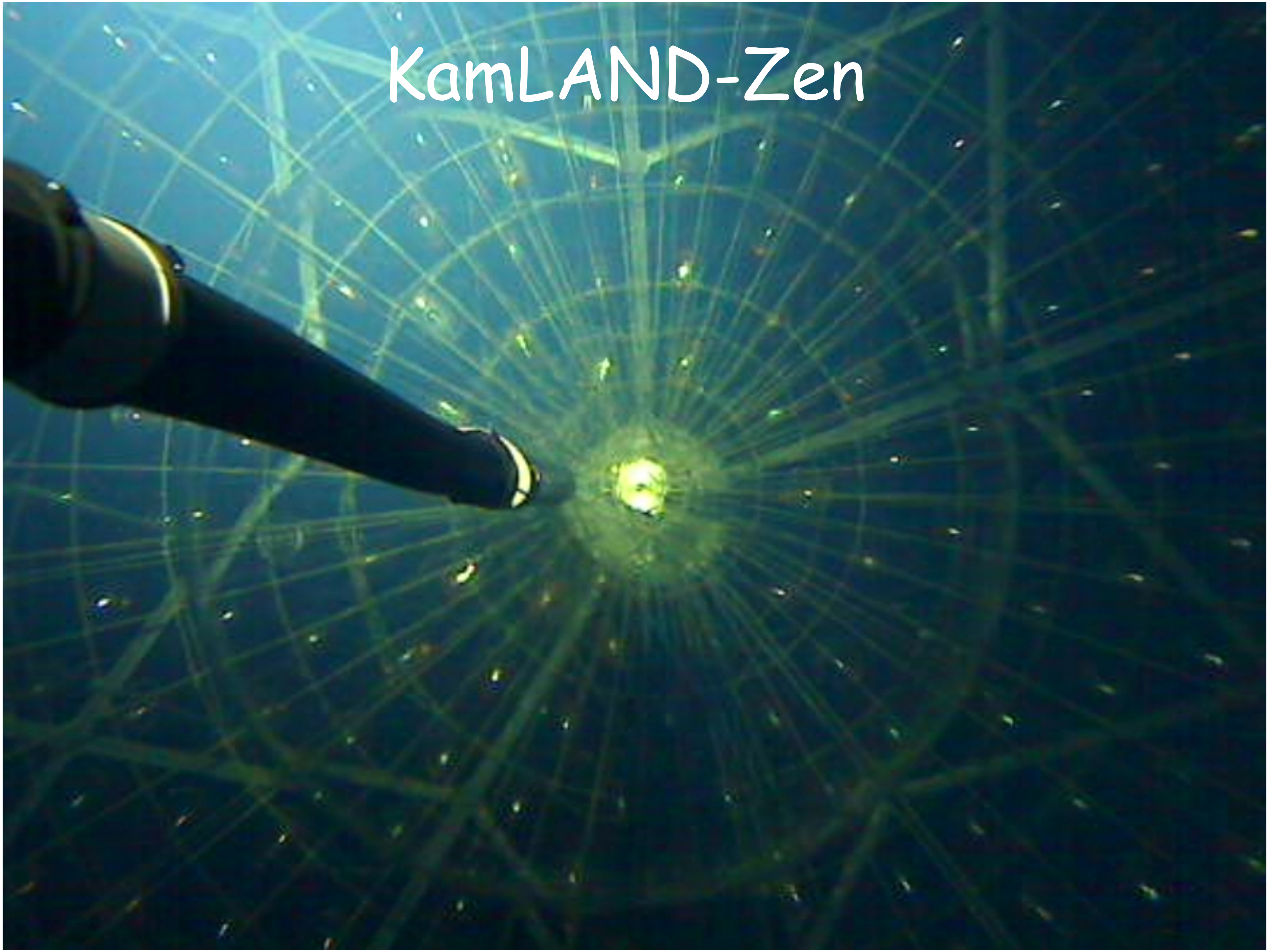
- Solid: no systematics, Dashed: current systematics



-> Assumes true $\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}\ eV^2$,
θ_{13} constrained by projected reactor sensitivity: $\delta(\sin^2 2\theta_{13}) = 0.005$

Conclusions – T2K

- 7.5σ discovery of ν_e appearance in a ν_μ beam
- Improved ν_μ disappearance results
- Continued improvement in oscillation analyses to come!
  -> More statistics, combined analysis
  -> Analysis improvements, e.g. neutrino interaction modeling
- Broad program of neutrino cross-section measurement
- Collaboration is assessing future run plans to optimize sensitivity
  -> At full statistics, T2K may have sensitivity to constrain δ_{CP} and the θ_{23} octant


KamLAND-Zen

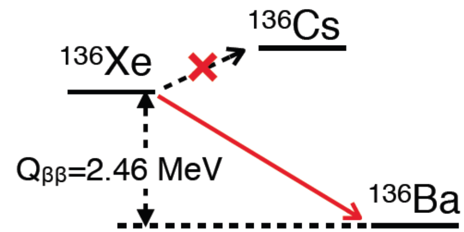
Neutrinoless Double Beta Decay

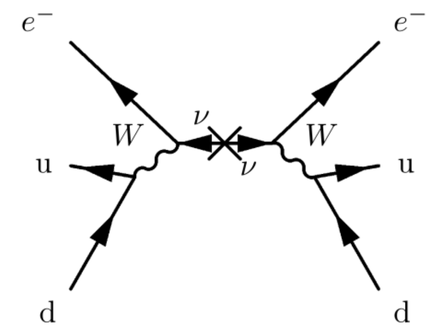
- Double beta decay in even-even nuclei when ordinary β-decay is energetically forbidden
- If neutrinos are Majorana, neutrinoless double-beta decay can proceed by a loop diagram with no neutrinos in the final state
- This process is sensitive to a $m_{\beta\beta}$, a weighted sum over all three masses, all mixing angles, δ_{CP}, plus Majorana phases (weighted by U_{e1}, U_{e2}, U_{e3}: m_1, m_2 dominate)
  -> Allowed regions depend on hierarchy

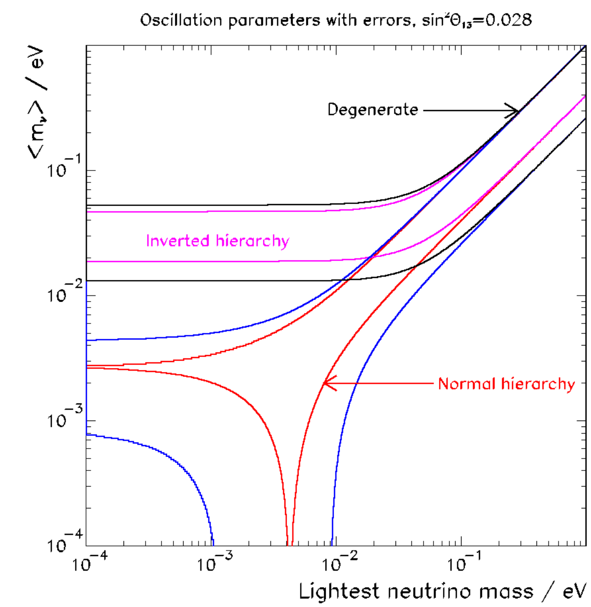
$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} |U_{ei}|^2 \, m_i \epsilon_i$$

- Rate also depends on phase space and nuclear matrix elements

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} \left| M^{0\nu} \right| |\langle m_{\beta\beta} \rangle|^2$$





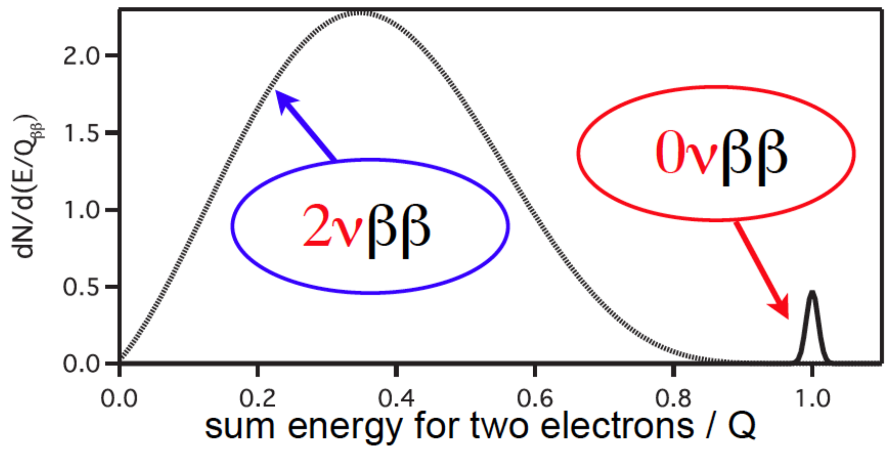


Detecting 0νββ

- KamLAND-Zen is sensitive to the total energy of the two β's

2νββ $(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e$

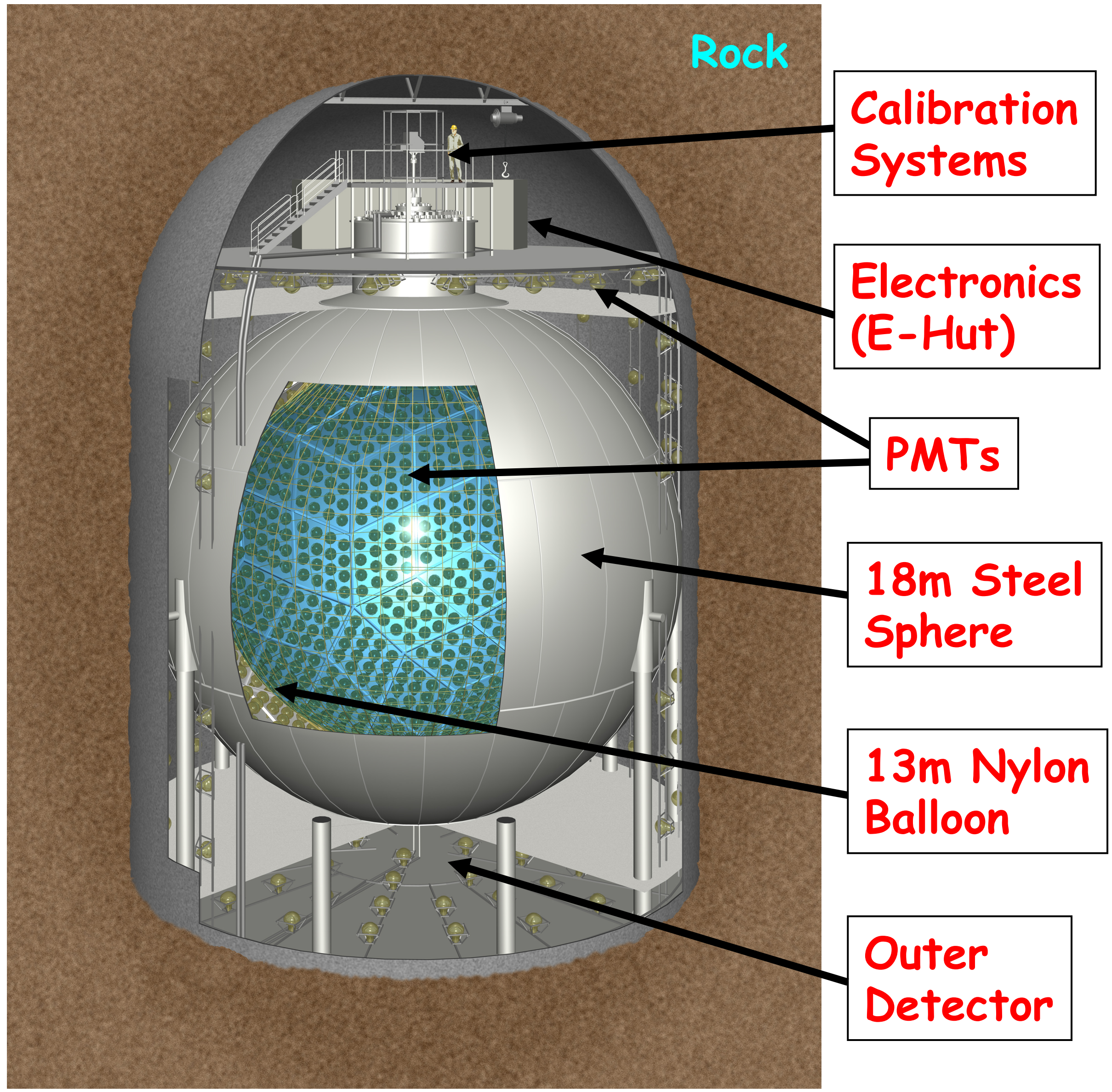
0νββ $(Z, A) \rightarrow (Z+2, A) + 2e^-$



- 0νββ experimental goals:
  -> Low background under 0νββ peak
  -> Good energy resolution
  -> 2νββ can be a background!

KamLAND Detector

- 1 kton liquid scintillator
- Mineral oil buffer
  outside 120-μm
  nylon balloon
- 1879 PMTs
  1325 17" - fast
  554 20" - efficient
- Water Čerenkov
  Outer Detector
- Event position from
  light arrival times
  ~12 cm resolution
- Event energy from
  total light yield
  ~6.2%/$\sqrt{E}$(MeV)
  resolution



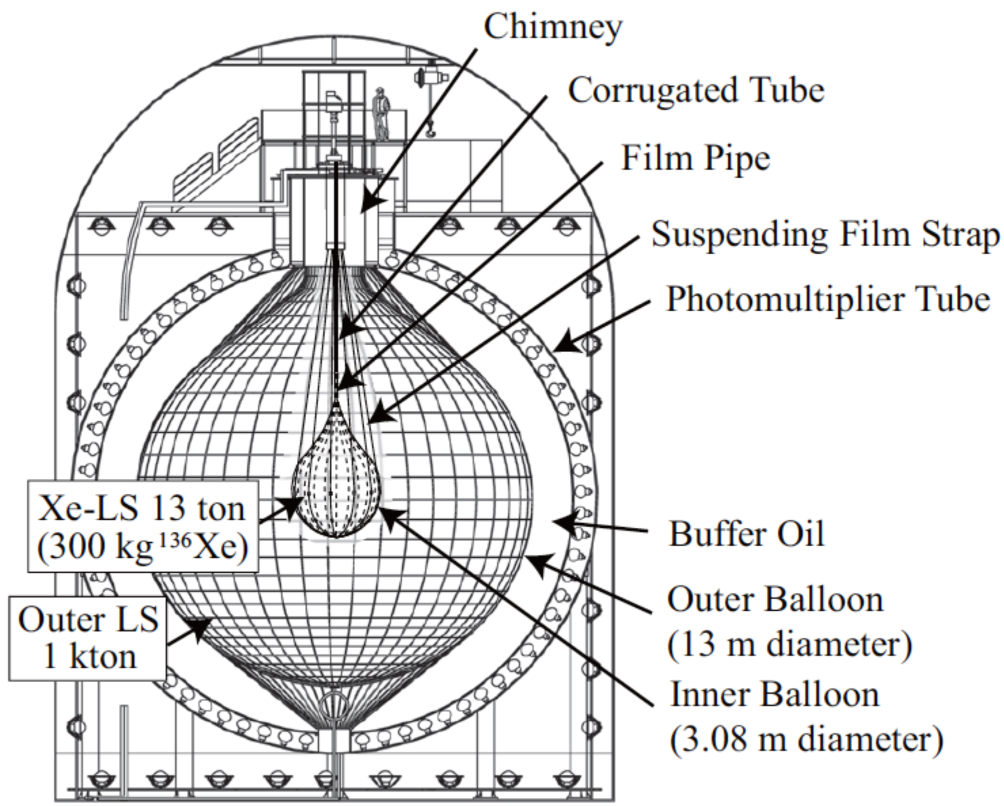
KamLAND-Zen

Basic idea: Deploy a mini-balloon full of Xe-loaded scintillator into the middle of KamLAND

Running detector
-> relatively low cost, quick start
-> detector well understood
-> experience with balloons, LS purification
-> ongoing antineutrino program outside Xe mini-balloon

Large and clean
-> negligible external backgrounds
-> no escaping/invisible β/γ energy

Highly scalable
-> 100s of kg of ^{136}Xe in first phase
-> up to several tons with larger mini-balloon



Disadvantage: energy resolution (4.0% at 2.458 MeV)

Xe-Loaded LS

Technical challenges: Xe-loaded liquid scintillator (LS)

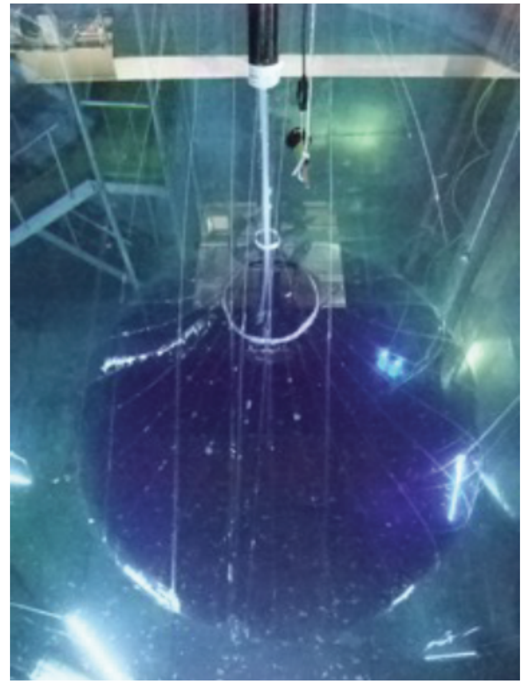
- Match light yield to existing KamLAND LS
  -> Achieved: matched to within 3%
- Similar overall density to existing KamLAND LS, for mini-balloon integrity
  -> Tuned to 0.10% higher density
- Xe loading: (2.52 ± 0.07) % by weight
- Composition:
  82% decane
  18% pseudocumene
  2.7 g/L PPO
  (2.52 ± 0.07) % Xe
- Xe is (90.93 ± 0.05)% ^{136}Xe, (8.89 ± 0.01)% ^{134}Xe
- 129 kg ^{136}Xe in the fiducial volume

Mini-Balloon

Technical challenges: Mini-Balloon

- Very thin: 25 μm nylon
- Welded seams (!)
- Must be Xe barrier
- High transparency
- Low contaminations of U, Th, K

Tests in water to establish procedures for deployment, inflation, LS replacement



80 μm polyethylene test balloon

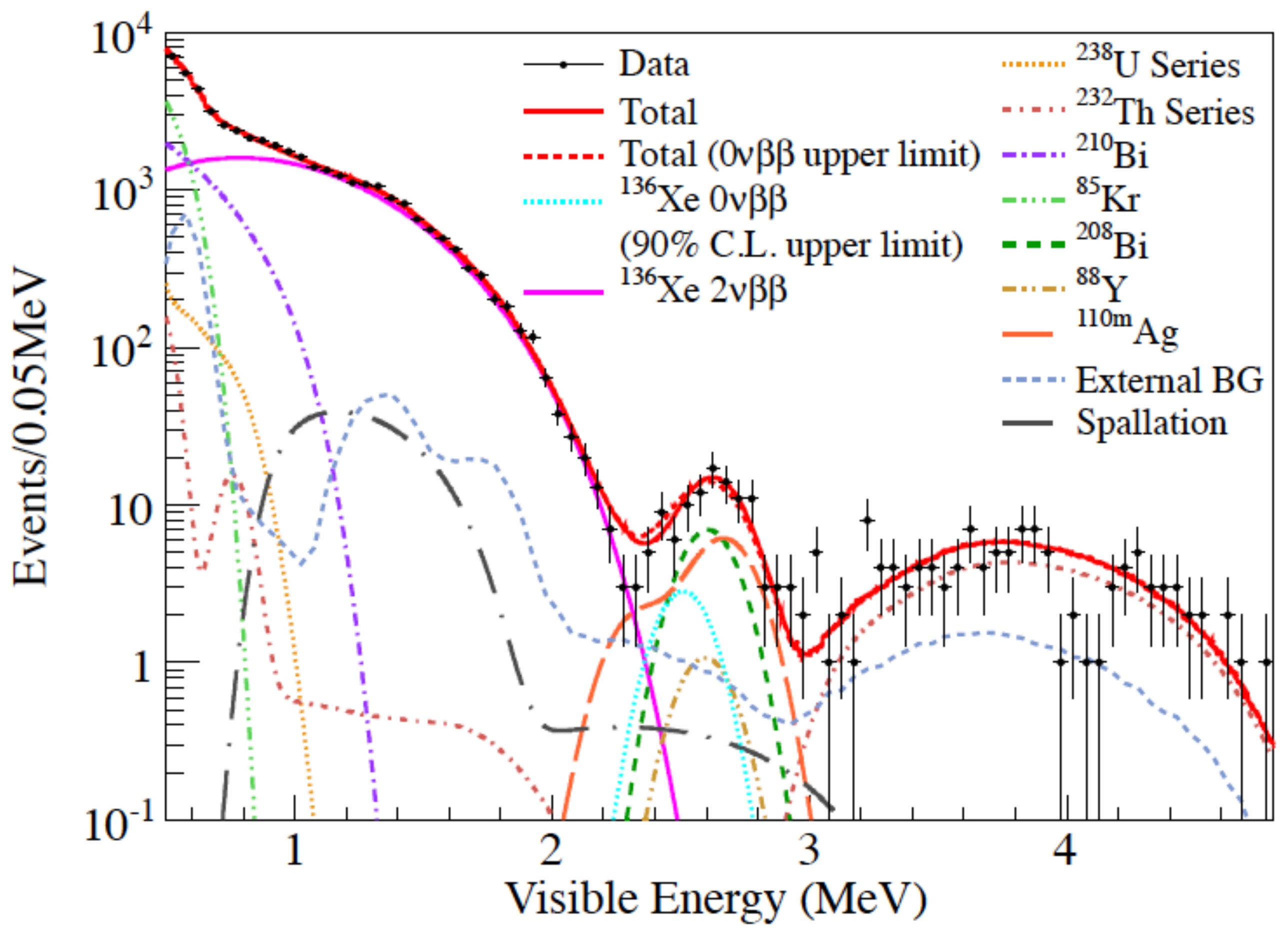
25 μm Nylon 6 balloon

First Results

77.6 days of data, 129 kg ^{136}Xe in fiducial volume (1.2 m radius)

-> Clear $2\nu\beta\beta$ signal

-> Very interesting peak just above 2.458 MeV…



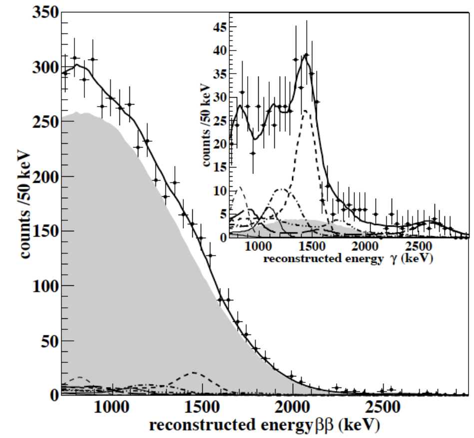
^{136}Xe 2νββ Half Life

First measured by EXO-200 (2011)

$T^{2\nu}_{1/2}$ = 2.11 ± 0.04 (stat) ± 0.21 (syst) x 20^{21} yr

PRL 107, 212501 (2011)

-> 5x larger than 2002 DAMA limit

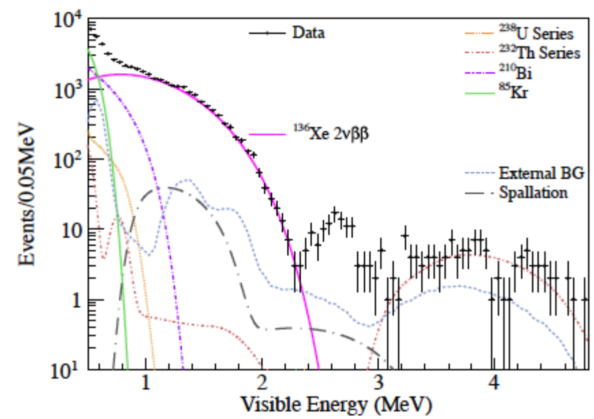


KamLAND-Zen (2012)

$T^{2\nu}_{1/2}$ = 2.38 ± 0.02 (stat) ± 0.14 (syst) x 20^{21} yr

Phys.Rev.C 85, 045504 (2012)

-> Consistent with EXO-200 result



Current results:

KamLAND: $T^{2\nu}_{1/2}$ = 2.30 ± 0.02 (stat) ± 0.12 (syst) x 20^{21} yr

Phys.Rev.C 86, 021601 (2012)

EXO-200: $T^{2\nu}_{1/2}$ = 2.172 ± 0.017 (stat) ± 0.060 (syst) x 20^{21} yr

arXiv:1306.6106 (June 25, 2013)

Background Identification

Peak at 2.6 MeV is too high to be $0\nu\beta\beta$

-> Inconsistent at $>8\sigma$

2.6 MeV background properties

- uniformly distributed in the Xe-LS
  -> not seen in LS outside the mini-balloon
- no correlation with muon events
- long-lived background: stable on ~30 day timescale

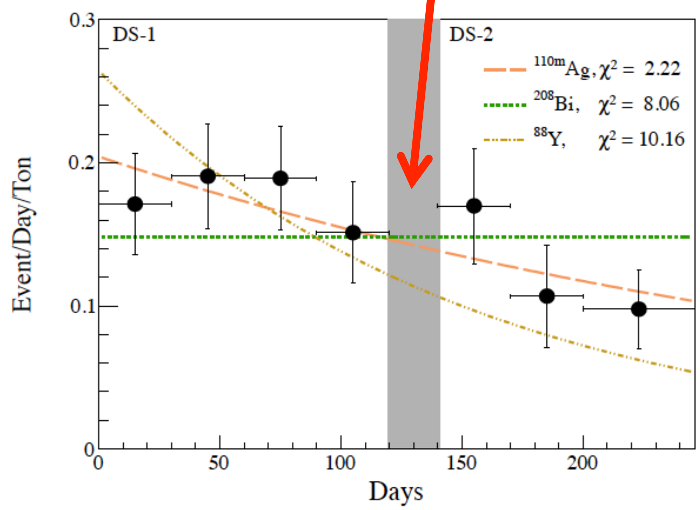
Search of all decays in the ENSDF database identified 4 candidates with peak in the $0\nu\beta\beta$ region, $T_{1/2} > 30$ days

- ^{110m}Ag $T_{1/2}$ = 250 days
- ^{208}Bi $T_{1/2}$ = 3.68 x 10^5 years
- ^{88}Y $T_{1/2}$ = 107 days
- ^{60}Co $T_{1/2}$ = 5.27 years

-> Fits to peak shape prefer ^{110m}Ag

-> ^{110m}Ag also most consistent with decay rate

Filtration campaign:
remove background if particulate



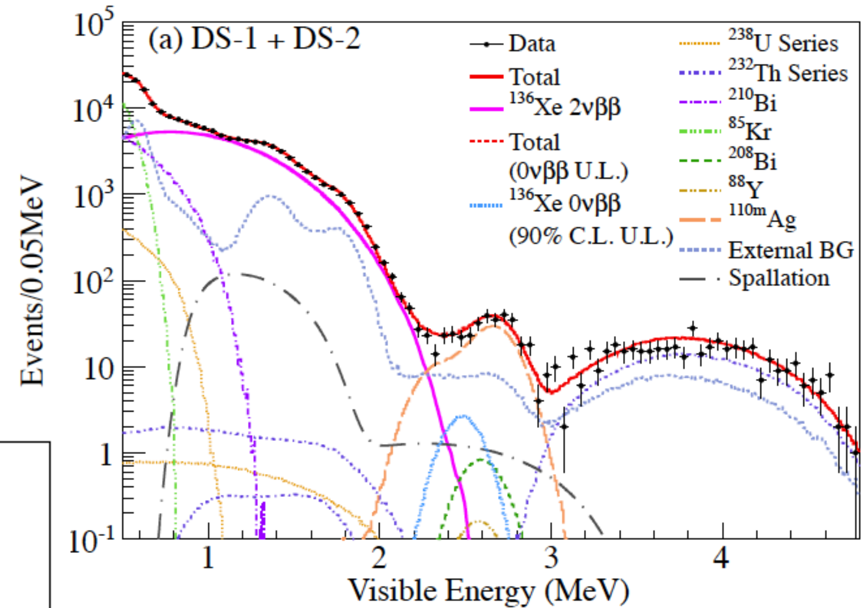
^{136}Xe 0νββ Results

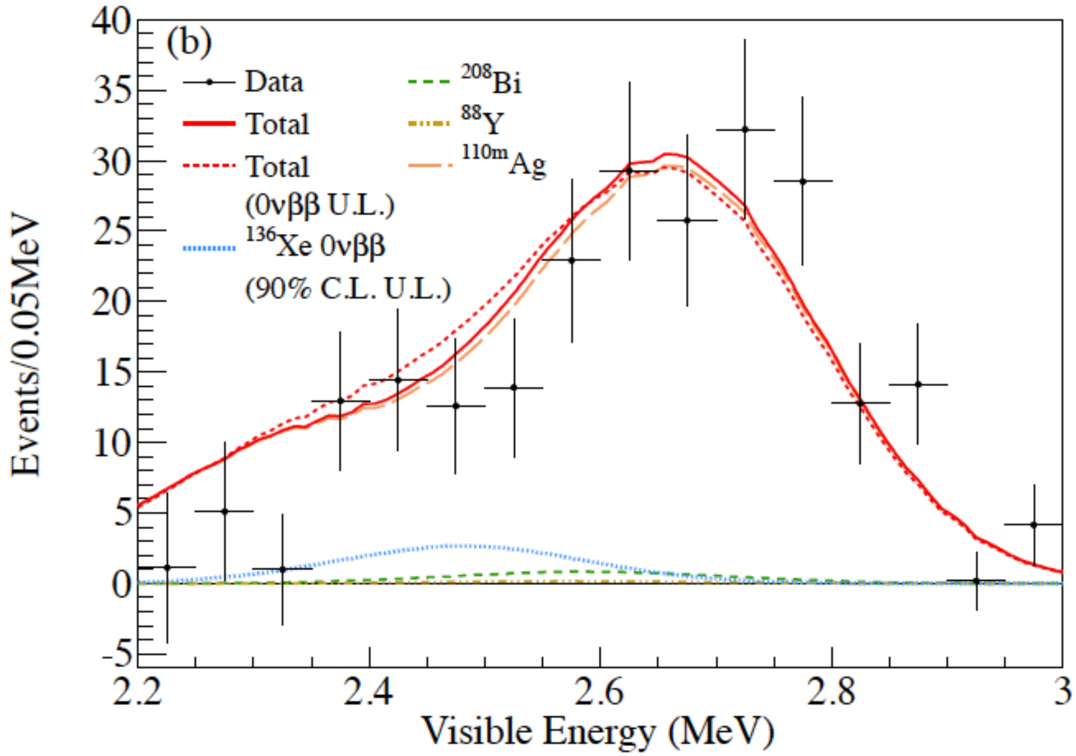
Full Phase I data: 213.4 days

90% CL: $T_{1/2}$ (^{136}Xe 0νββ) > 1.9 x 10^{25} yr

PRL 110, 062502 (2013)

Note: Sensitivity: 1.0 x 10^{25} yr





Comparison with ^{76}Ge claim

Comparisons between isotopes are complicated by nuclear matrix element (NME) uncertainties

Plot $T_{1/2}$ (^{76}Ge) vs. $T_{1/2}$ (^{136}Xe):

NME models are diagonal lines, marked by $\langle m_{\beta\beta} \rangle$ in eV

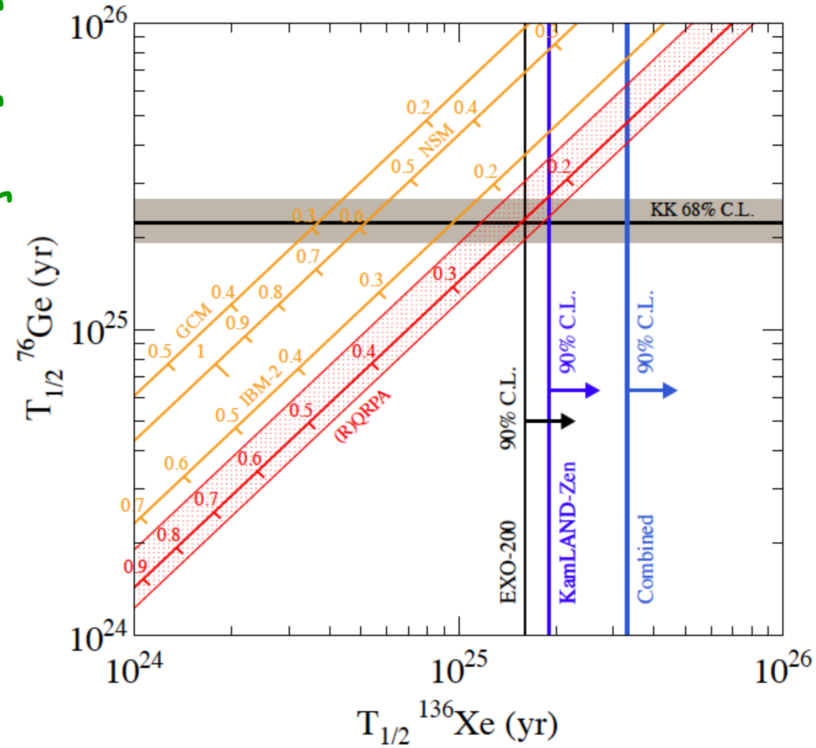
KamLAND-Zen: $T_{1/2}$ (^{136}Xe) > 1.9×10^{25} yr

EXO-200: $T_{1/2}$ (^{136}Xe) > 1.6×10^{25} yr

Combined: $T_{1/2}$ (^{136}Xe) > 3.4×10^{25} yr

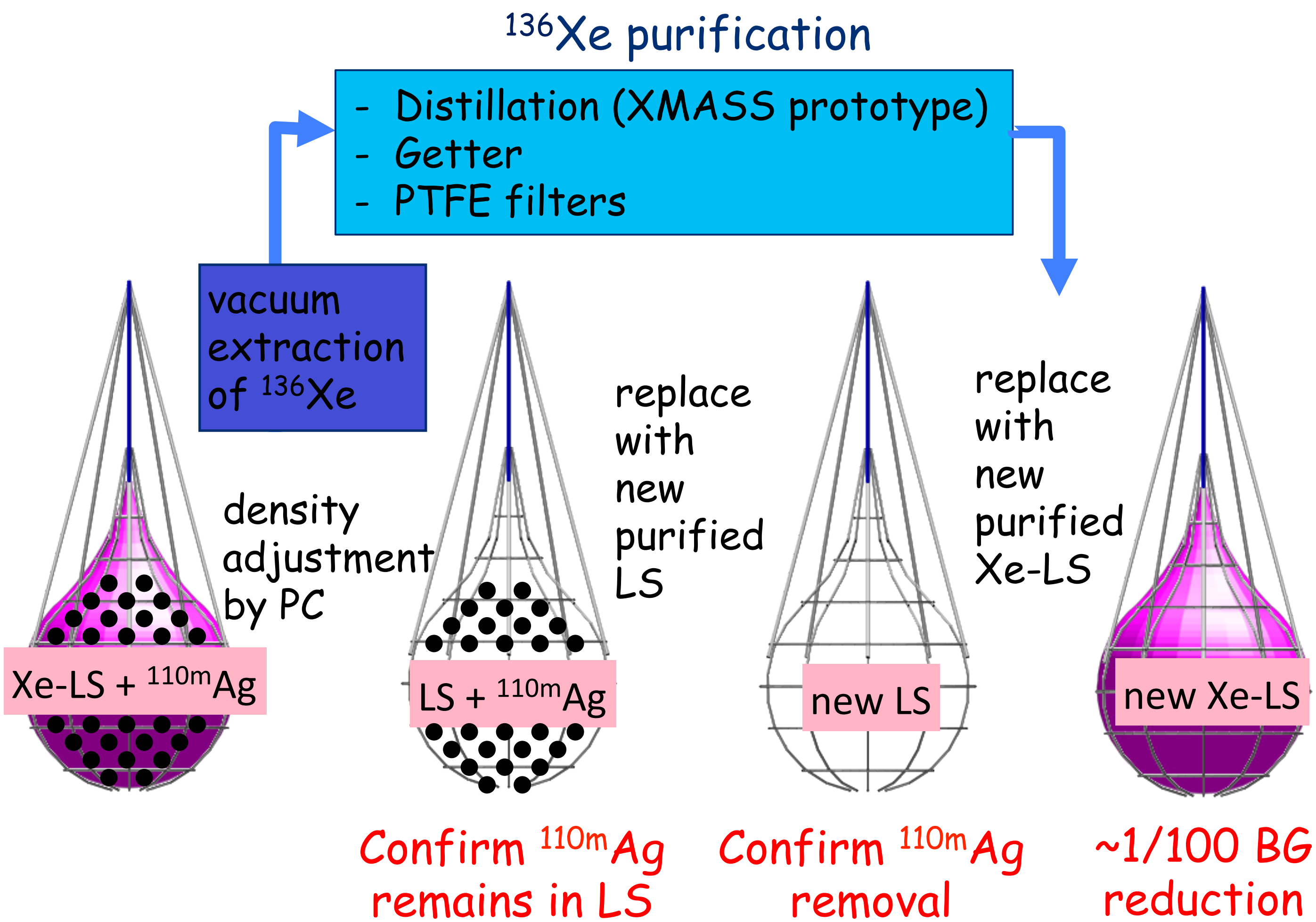
(Sensitivity: 1.6×10^{25} yr)

-> Incompatible with KK 2006 claim at 97.5% CL

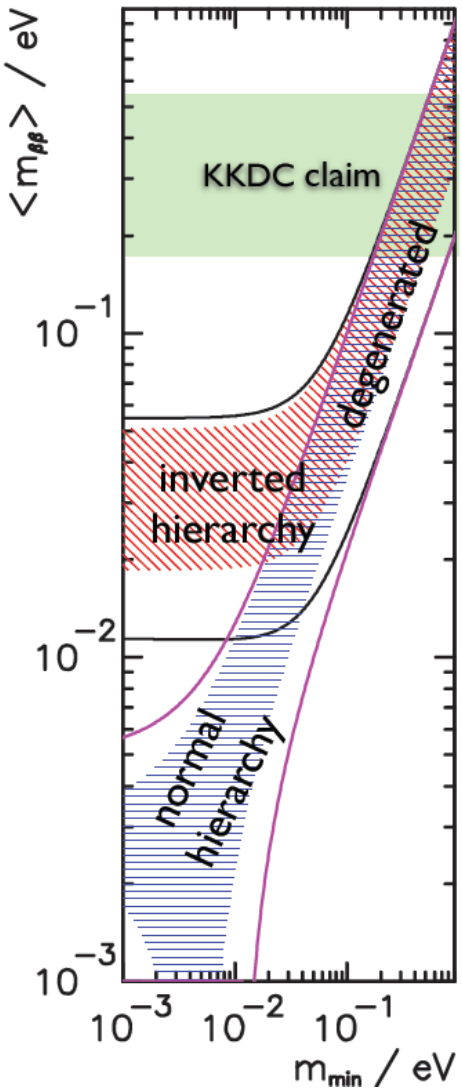


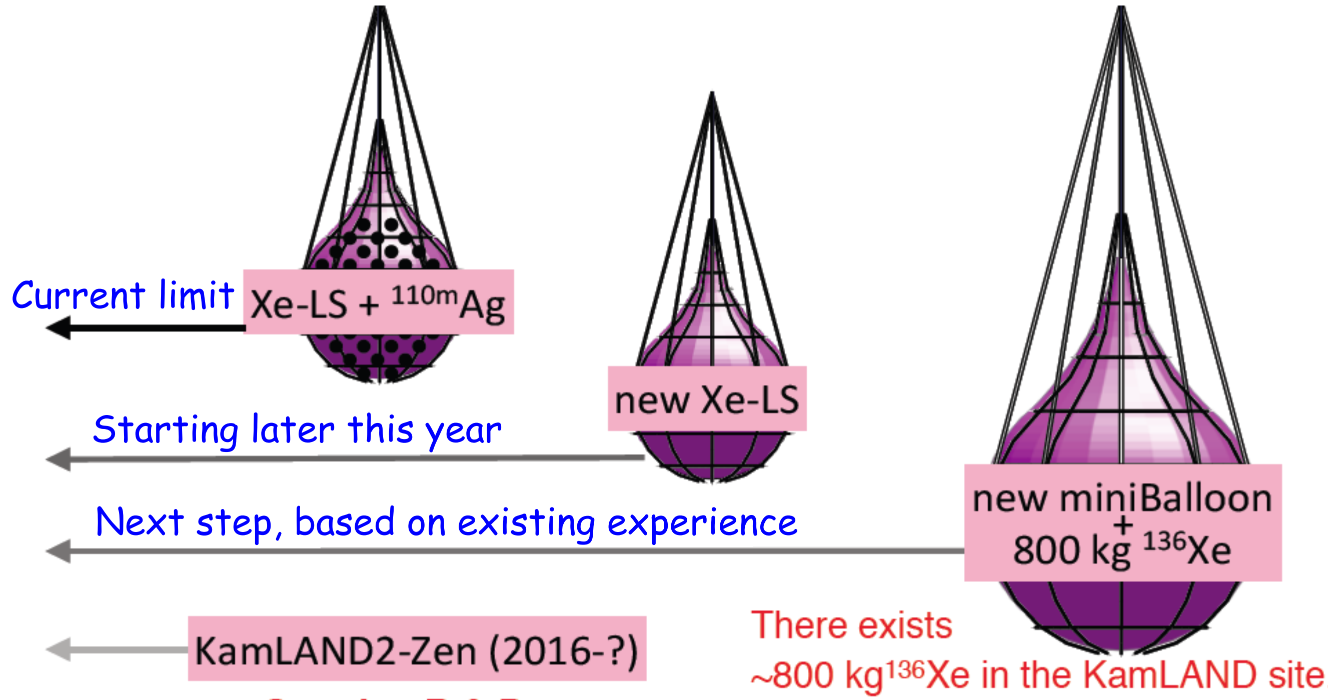
Near Future: Background Reduction

Next step for KamLAND-Zen: removing the ^{110m}Ag



Future KamLAND-Zen Upgrades





Ongoing R & D

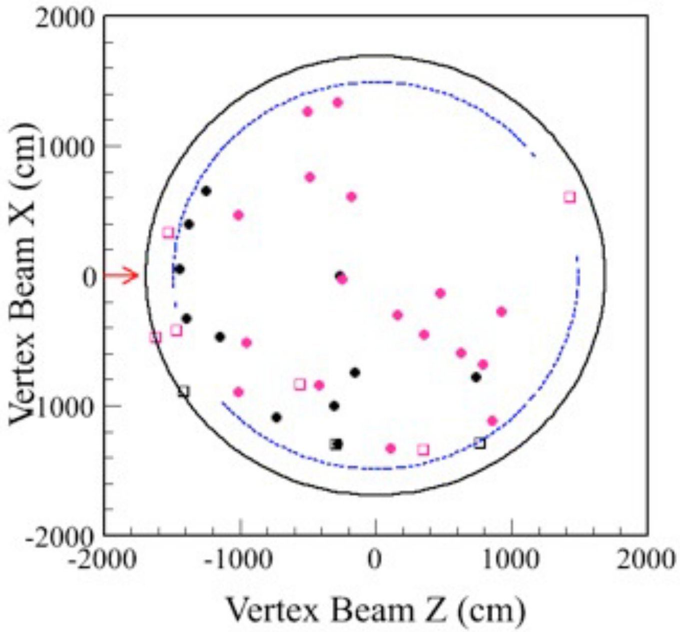
- Light collector
- LS replacement
- γ/β discrimination
- **Open KamLAND**
- New photo senser
-
-

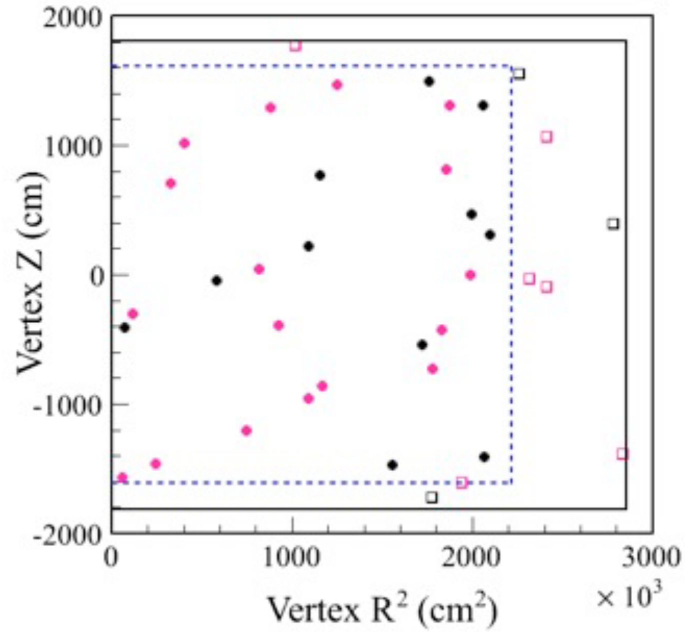
Conclusions – KamLAND-Zen

- Discovery of the Majorana nature of the neutrino via neutrinoless double beta decay helps address several critical questions:
  -> absolute neutrino mass
  -> neutrino mass mechanism
  -> matter dominance of the Universe
- KamLAND-Zen measurements to date
  -> $T_{1/2}$ (^{136}Xe $0\nu2\beta$) > 1.9×10^{25} yr
  -> $m_{\beta\beta}$ < (0.16-0.33) eV
- Combined analysis of KamLAND-Zen and EXO-200 excludes the Klapdor-Kleingrothaus 2006 claim at 97.5% CL
- We expect a sensitivity of ~80 meV with one year of running after the current purification
- Future phases of KamLAND-Zen and KamLAND2-Zen will allow us to push the limit well into the inverted hierarchy region

Backup Slides

ν_e Vertex Distributions at SK





-> With increased statistics,
the p-values for the test distributions have increased

	RUN1+2+3	RUN4	RUN1+2+3+4
Dwall	34.4%	54.7%	20.9%
Fromwall $\text{beam}_{\parallel}$	6.04%	85.6%	8.93%
$R^2 + Z$	32.4%	98.1%	64.5%

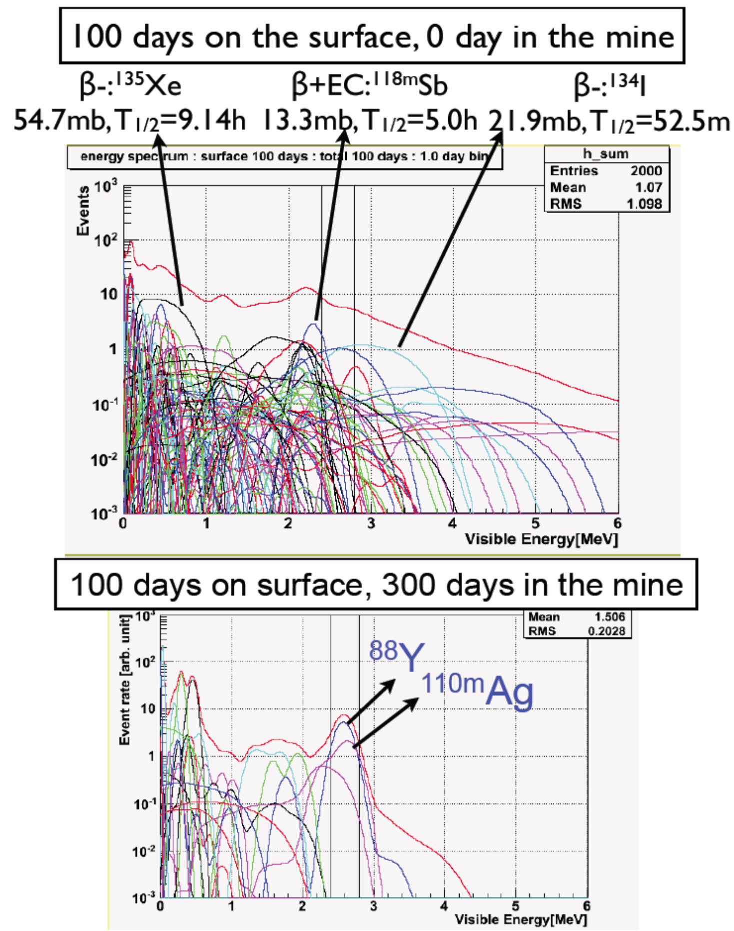
^{110m}Ag background source?

Fallout:

-> Already observed Cesium likely from Fukushima-I

-> ^{110m}Ag is a component of reactor fallout

-> ^{110m}Ag found in assayed of soil at Tohoku, where the mini-balloon was produced



Spallation:

-> Estimated spallation production of many isotopes on ^{136}Xe

-> Large uncertainties due to limited data

-> Spallation production underground should be negligible based on GEANT4 simulation

-> Spallation production above ground before the ^{136}Xe was brought into the mine is a possible source of ^{110m}Ag, ^{88}Y