Electron Neutrino Appearance Experiments and the Third Neutrino Mixing Angle

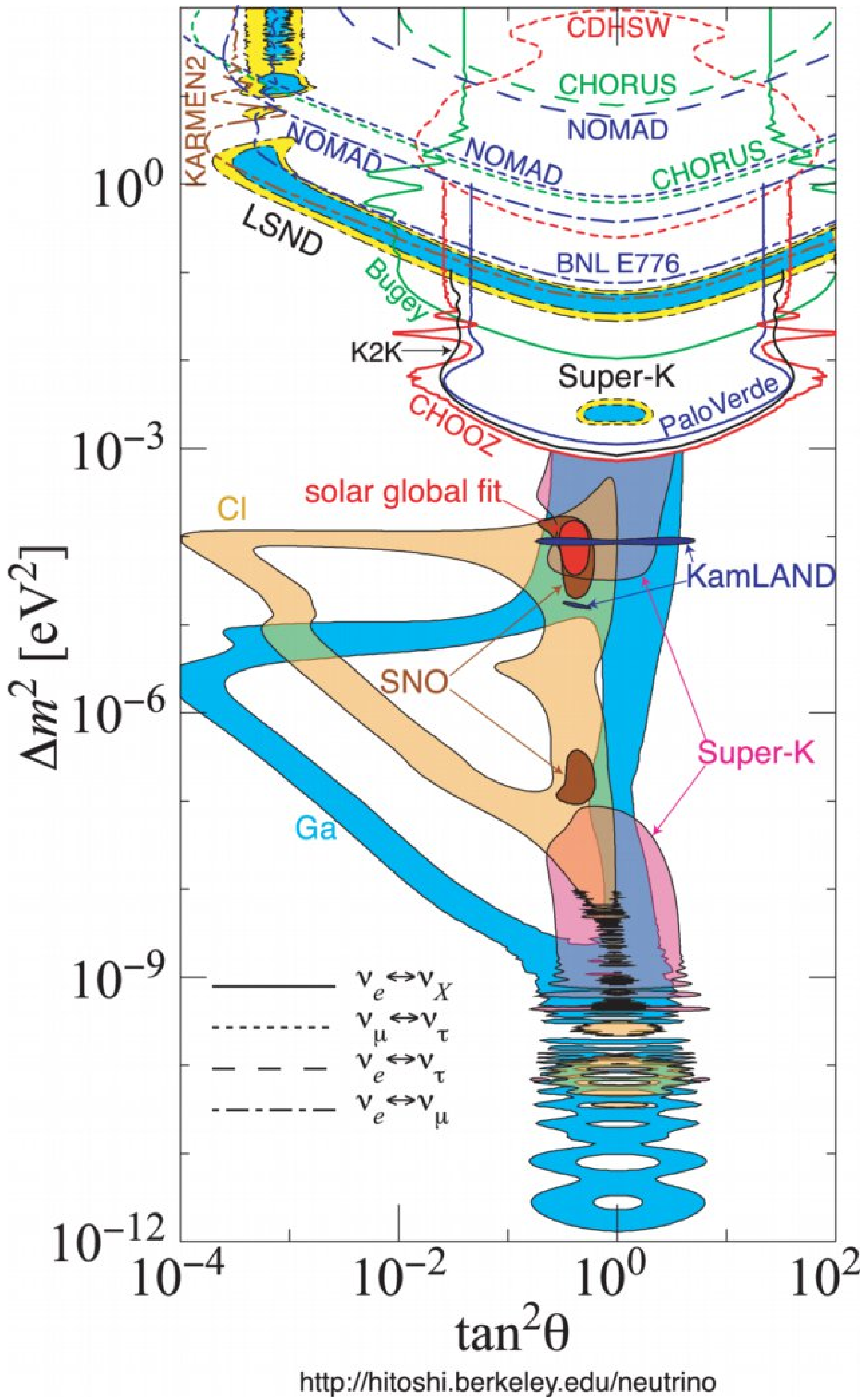
—a year of discovery—

Yoshi Uchida
13 September 2012

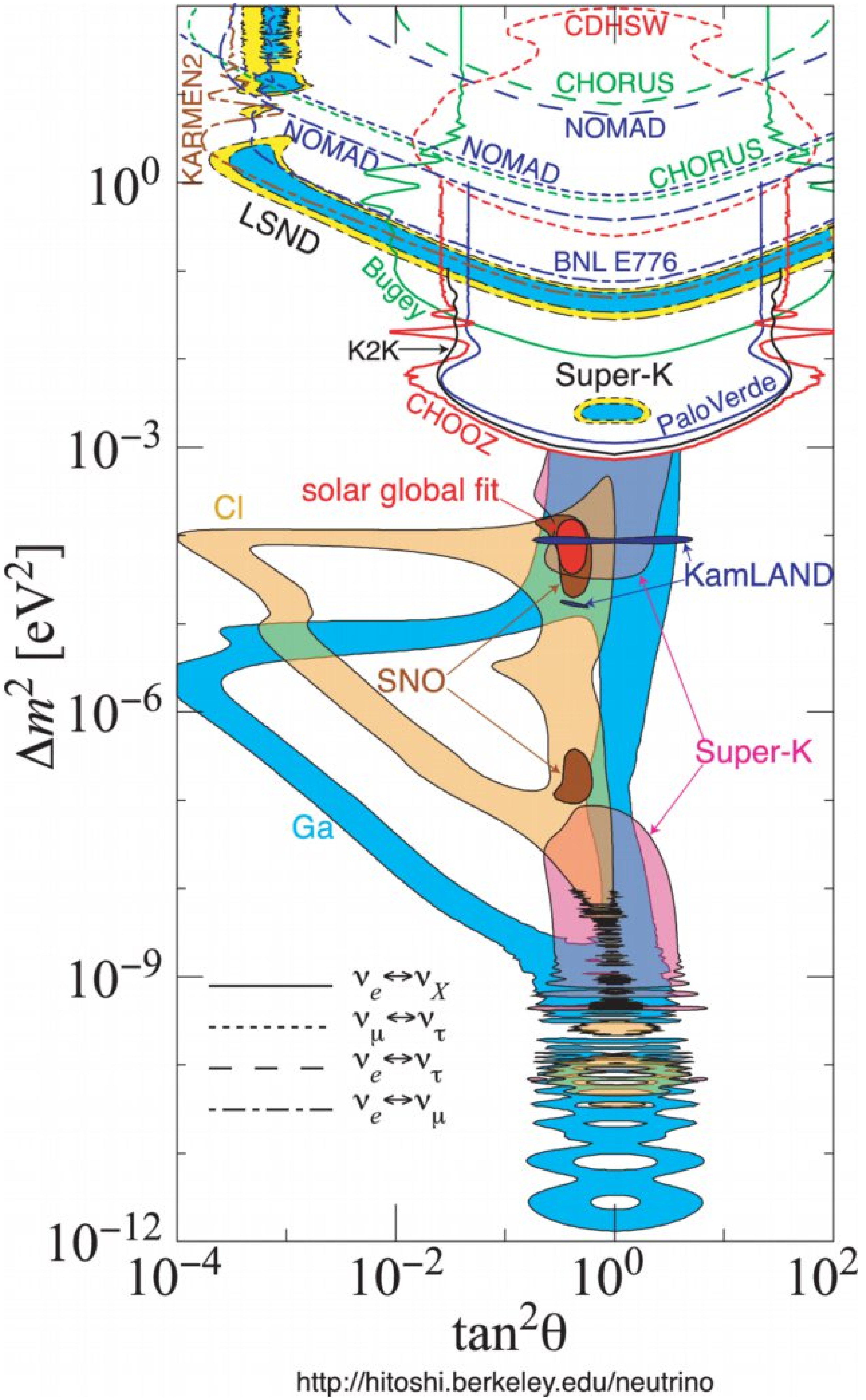
Physics in Collision 2012, Štrbské Pleso, Slovakia

ν_e Appearance Experiments and θ_{13}

- Before the new "large θ_{13}" paradigm
- ν_e appearance at T2K
- Current and near future experiments
- The future



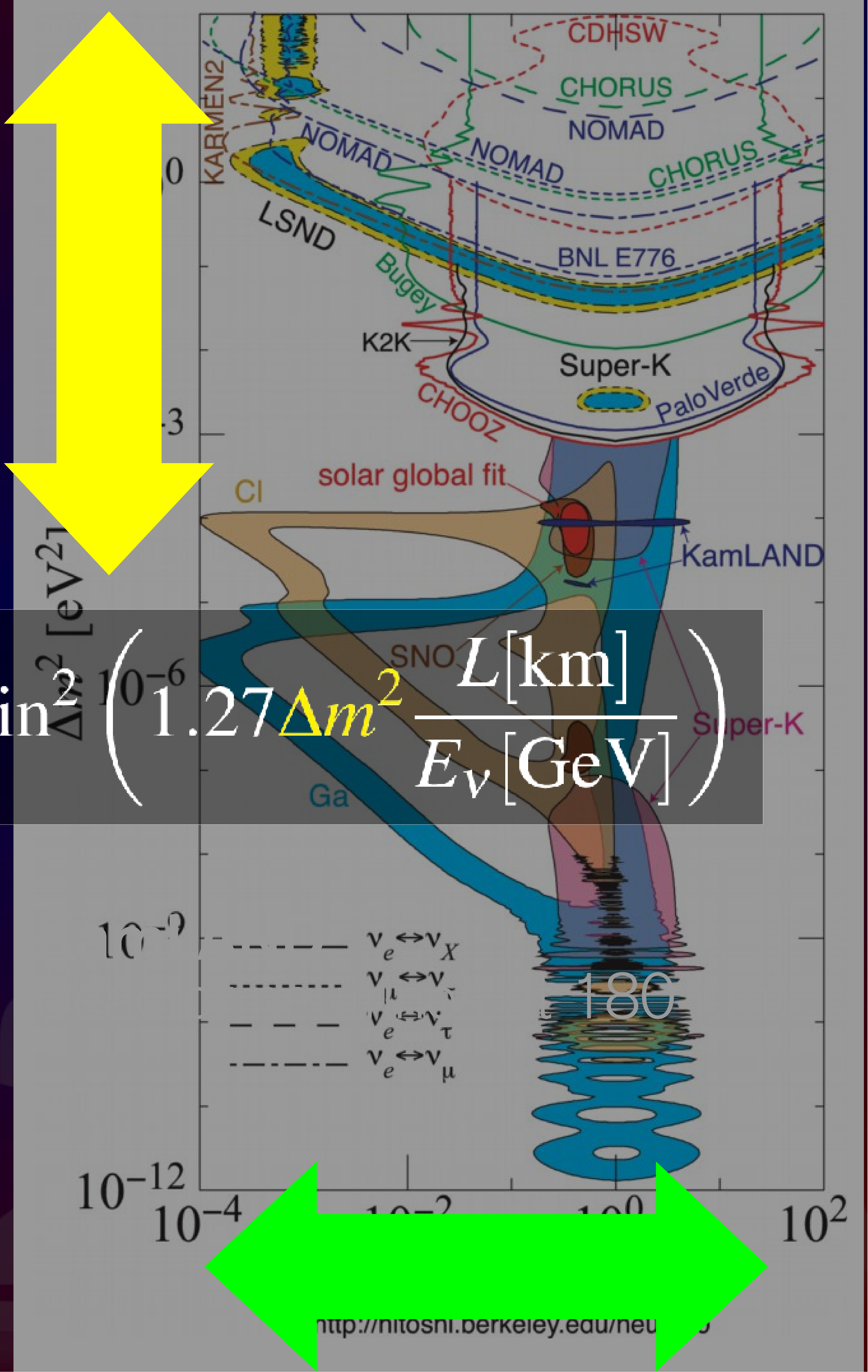
Neutrino Oscillations (2004)



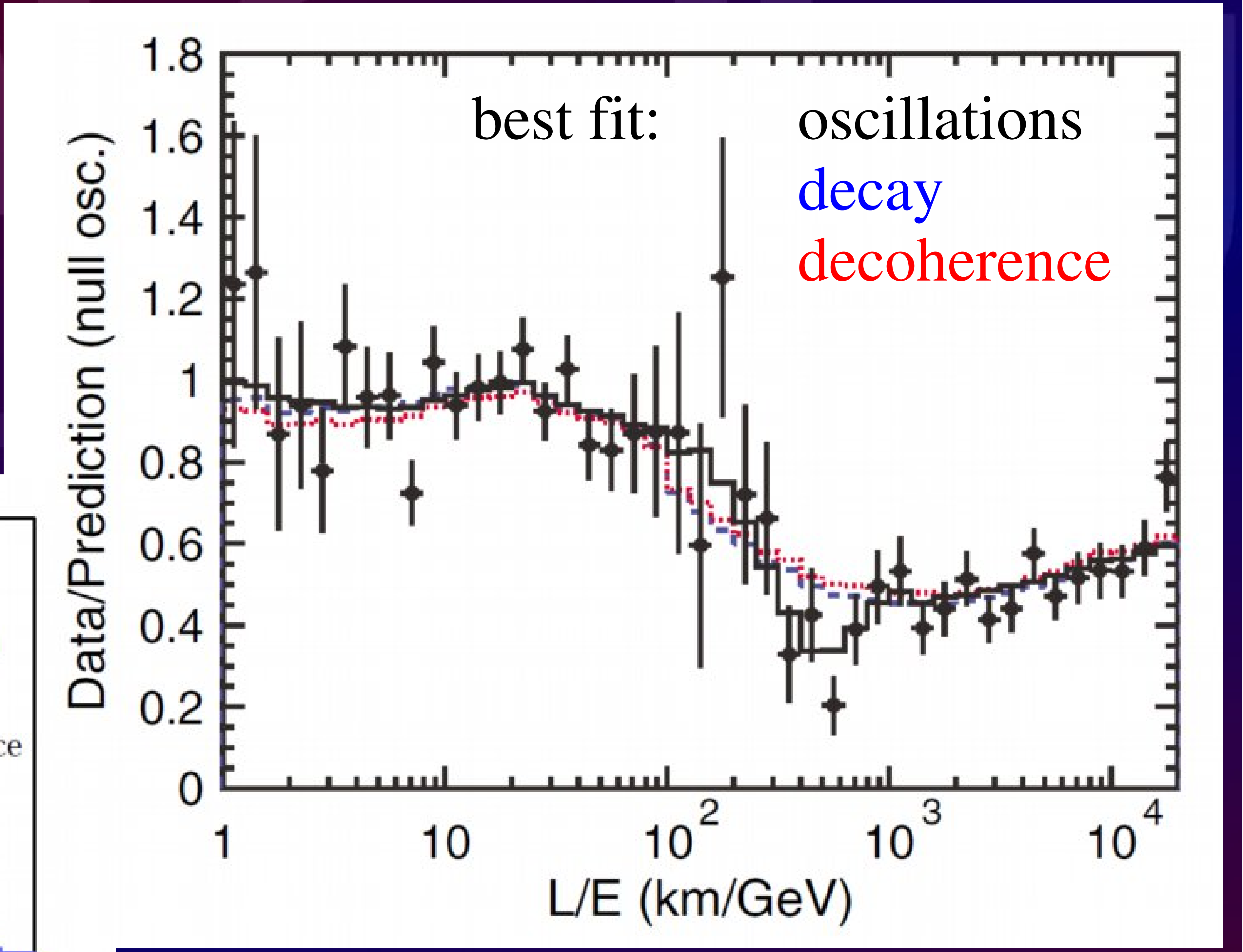
Neutrino Oscillations (2004)

Two-neutrino oscillations in vacuum:

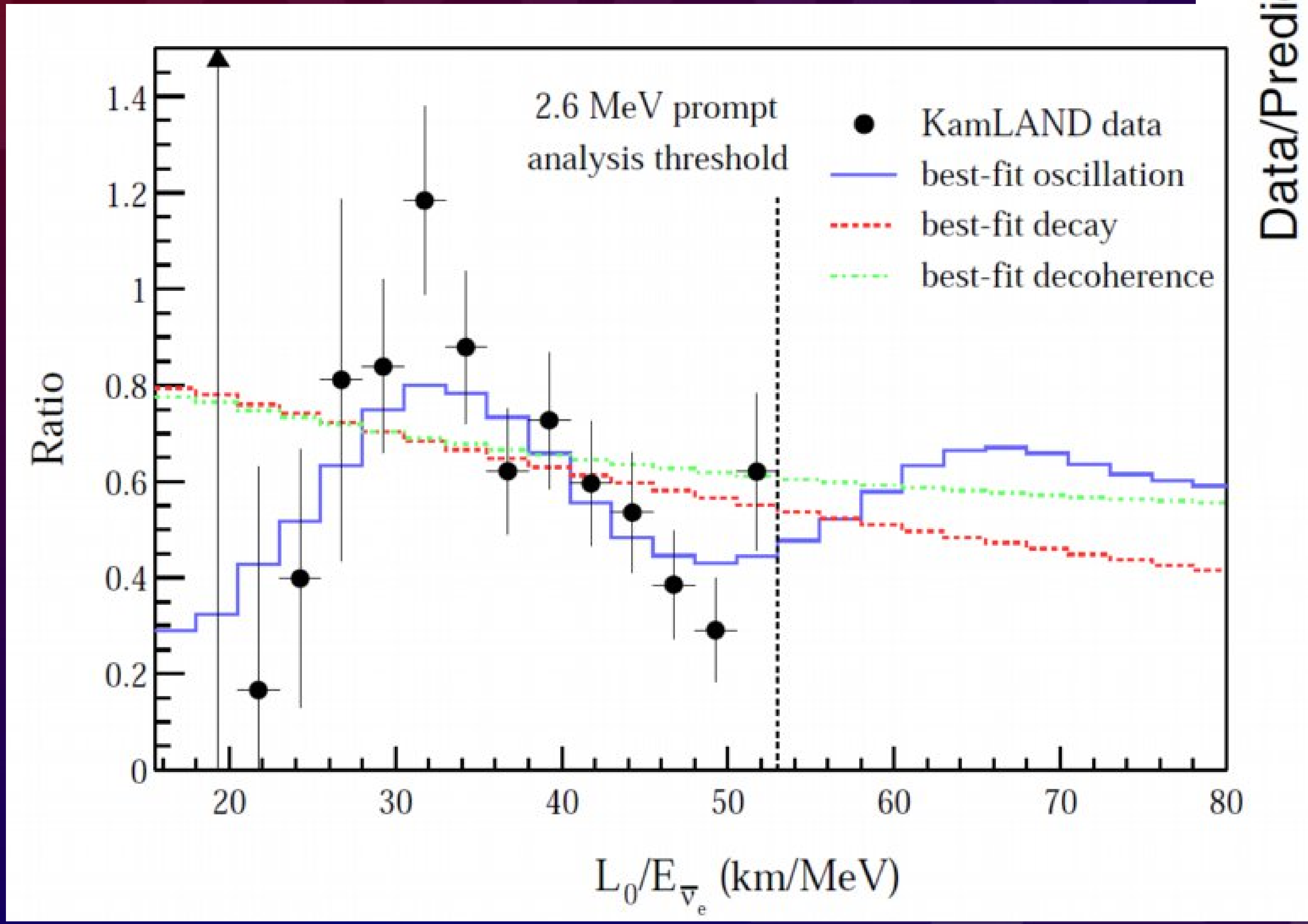
$$P_{\nu_i\rightarrow\nu_{j\neq i}}(L,E_\nu)=\sin^2 2\theta\times\sin^2\left(1.27\Delta m^2\frac{L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$



Neutrino Oscillation Signatures (ca. 2004)

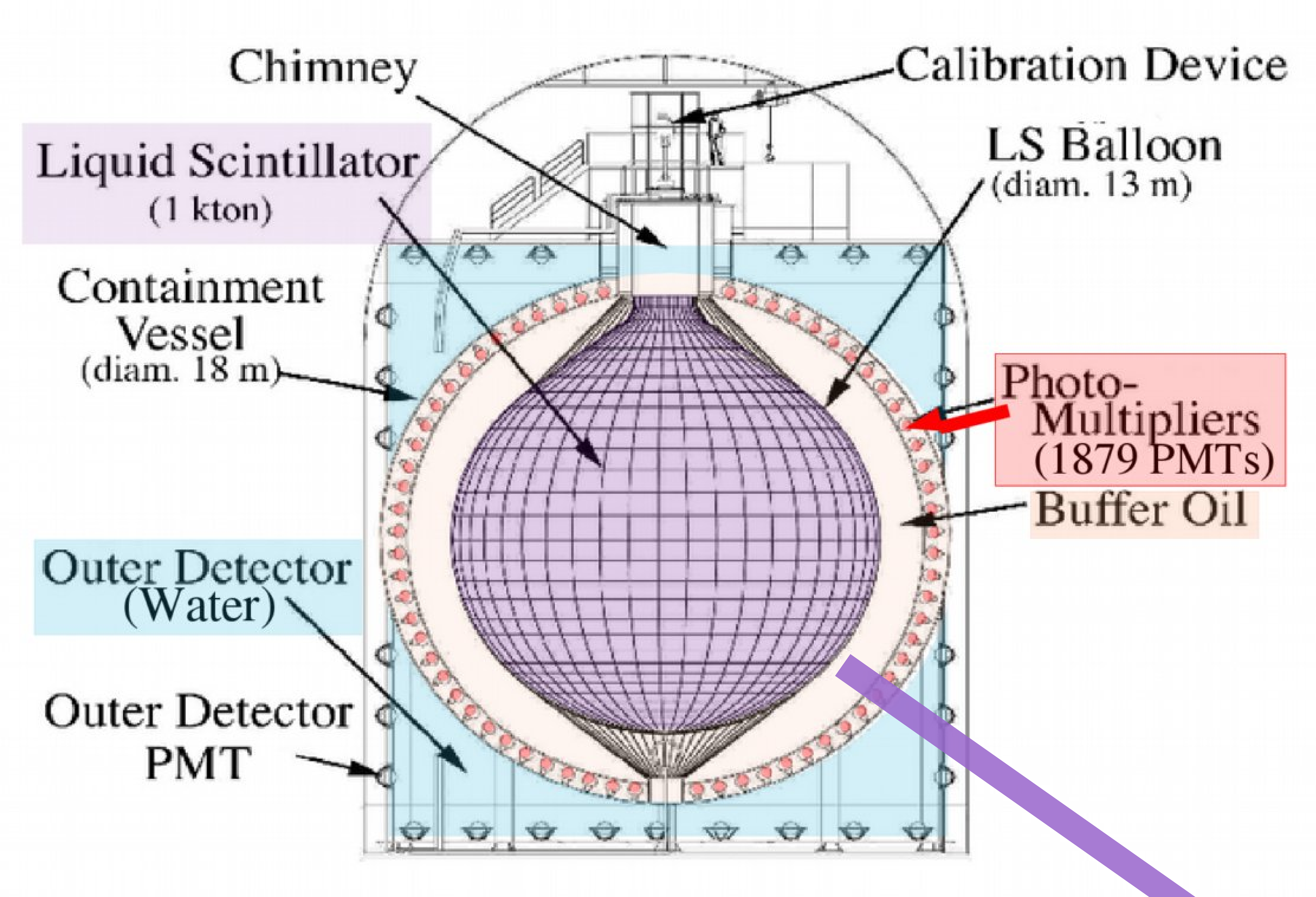


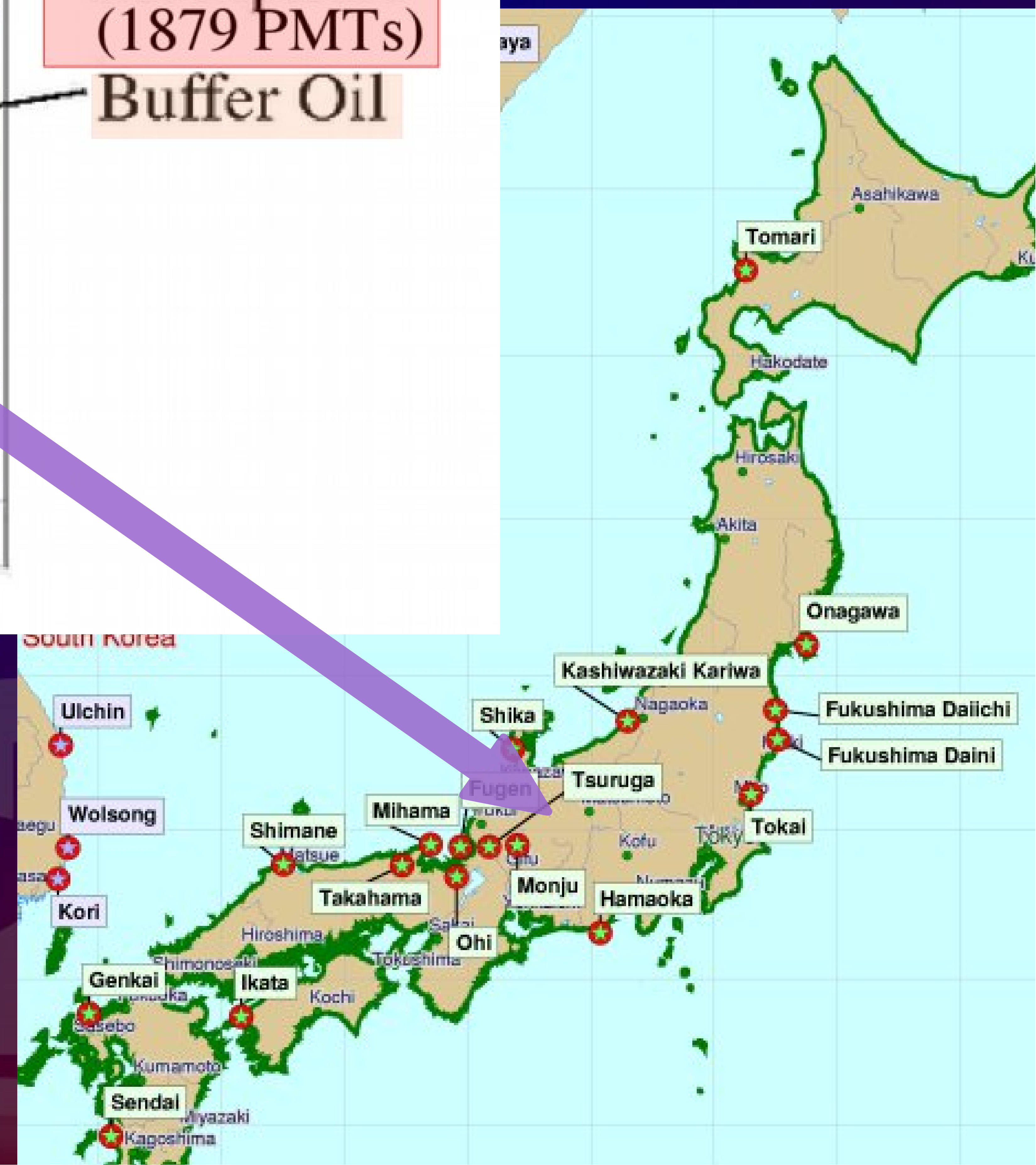
Super-K
(atmospheric neutrinos)



KamLAND
(reactor neutrinos at 180 km)

$$P_{\nu_i \to \nu_{j \neq i}}(L, E_\nu) = \sin^2 2\theta \times \sin^2\left(1.27 \Delta m^2 \frac{L[\text{km}]}{E_\nu[\text{GeV}]}\right)$$

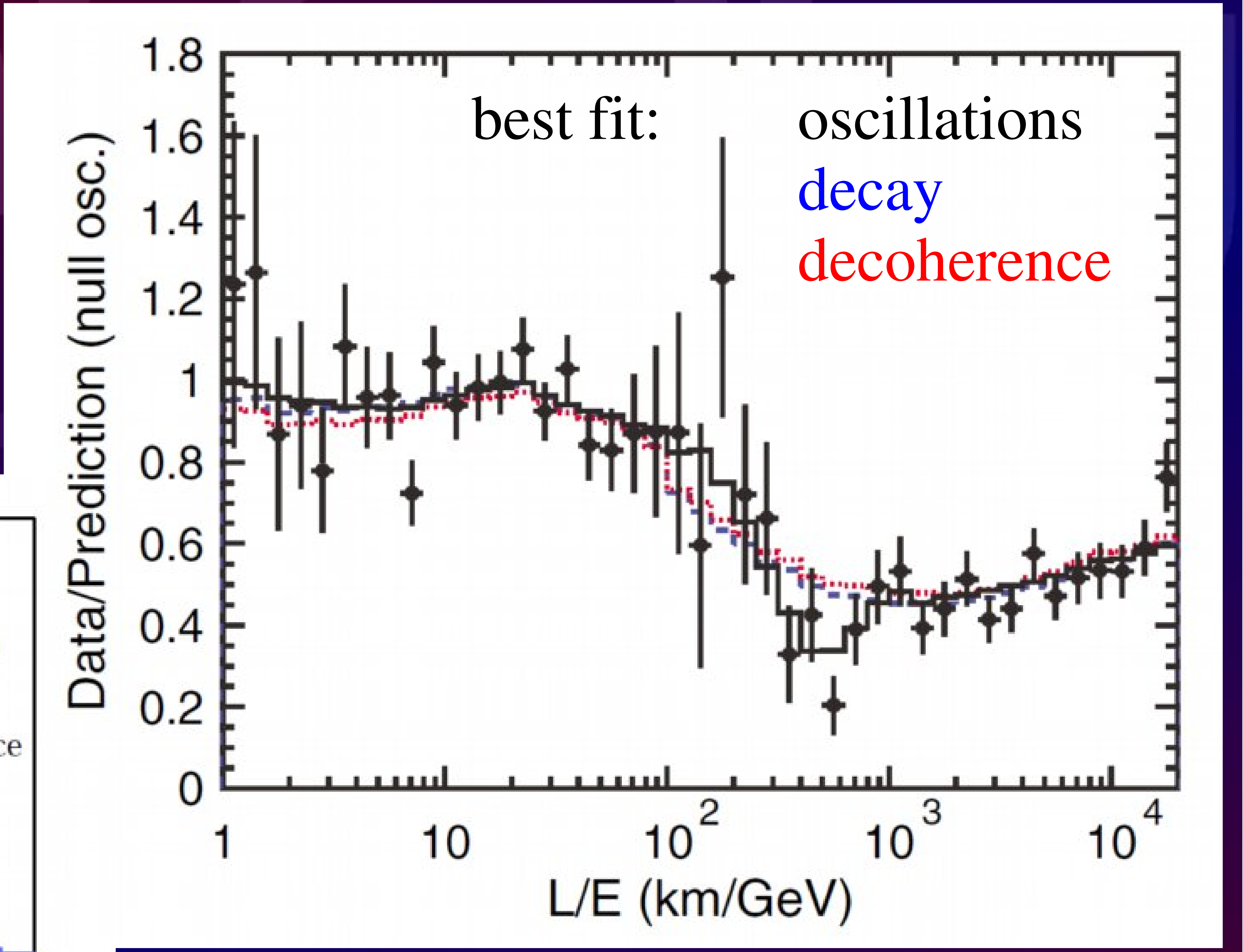




KamLAND — Reactor Neutrinos at 180 km

electron antineutrinos
from 3 to 10 MeV

Neutrino Oscillation Signatures (ca. 2004)



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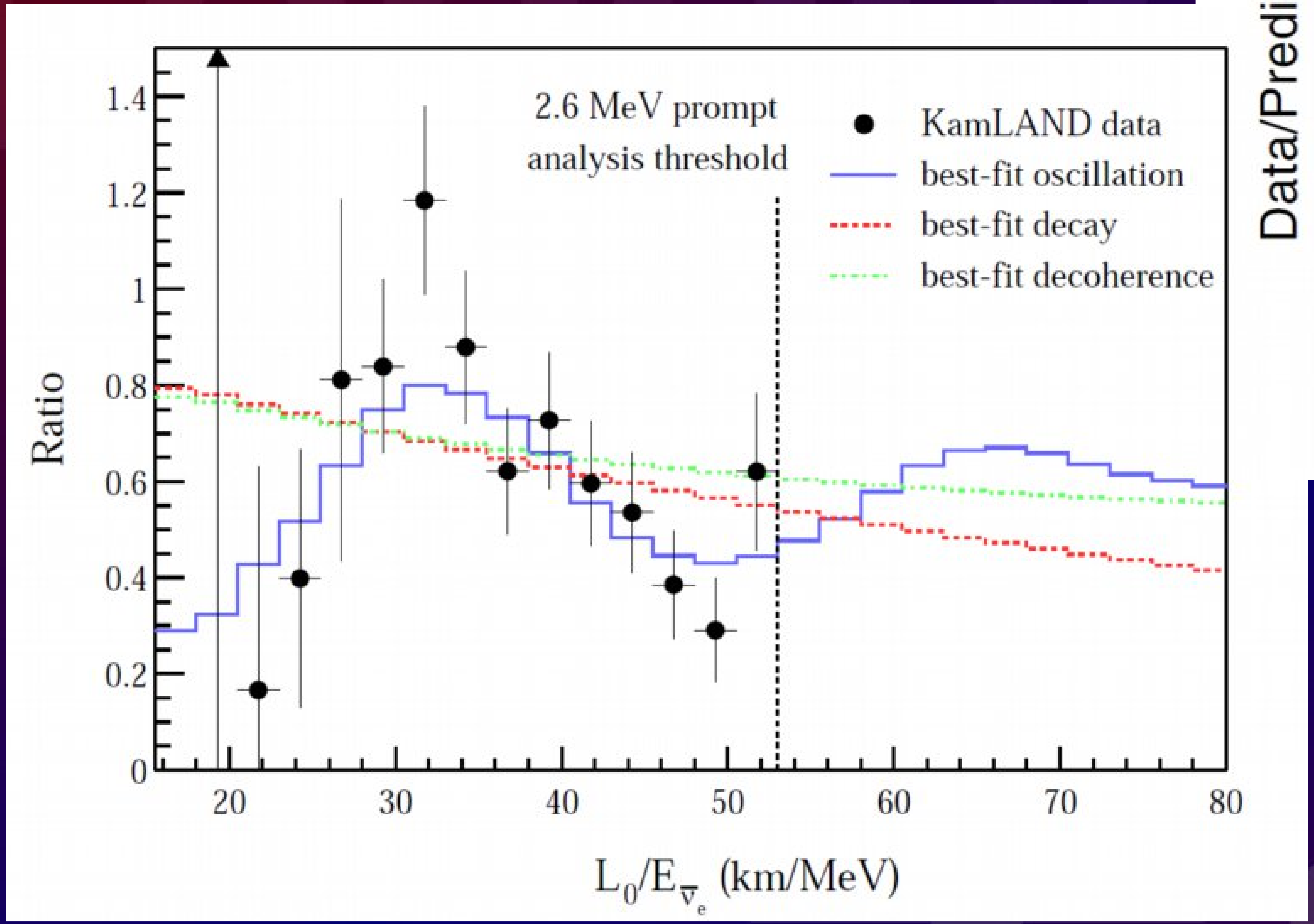

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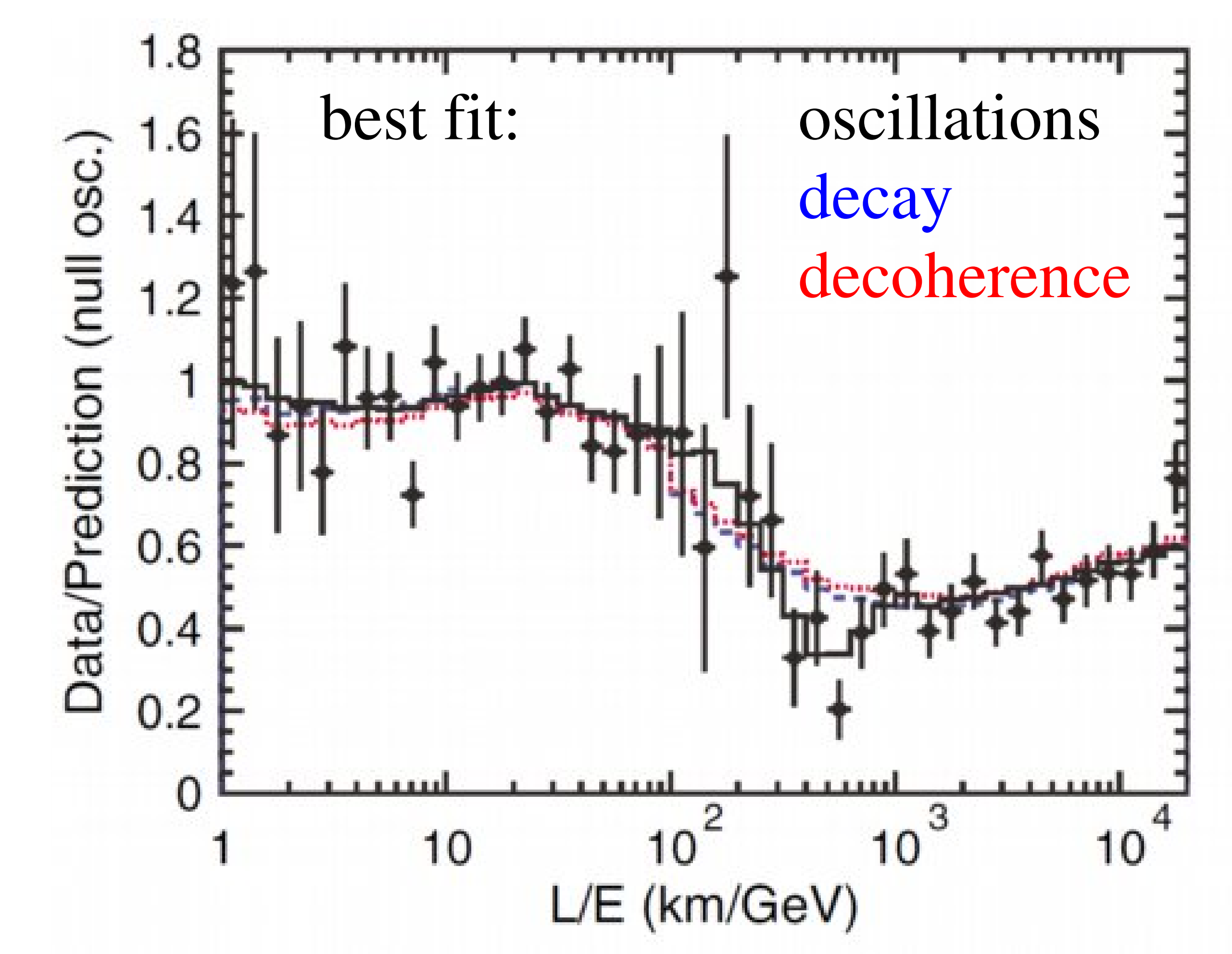
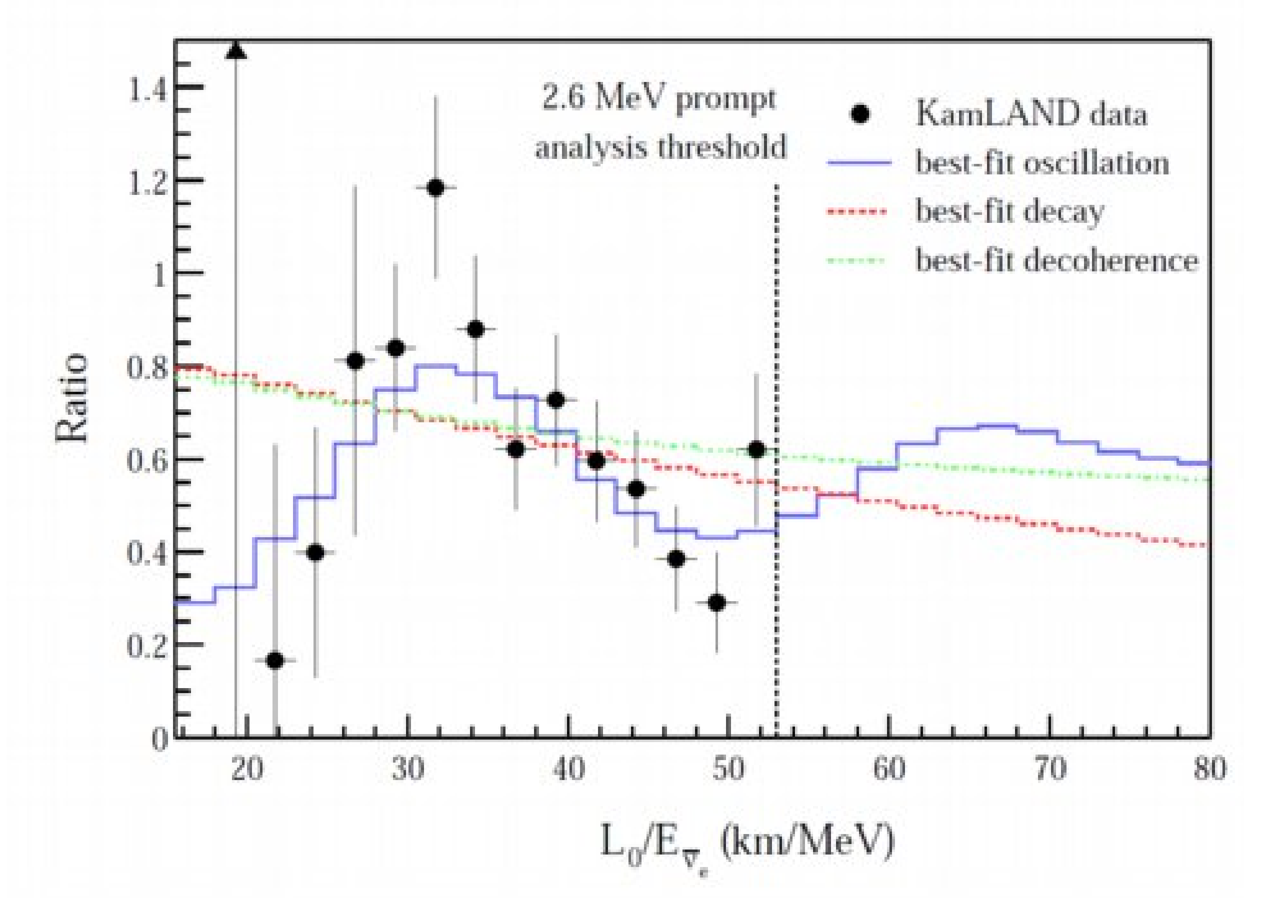
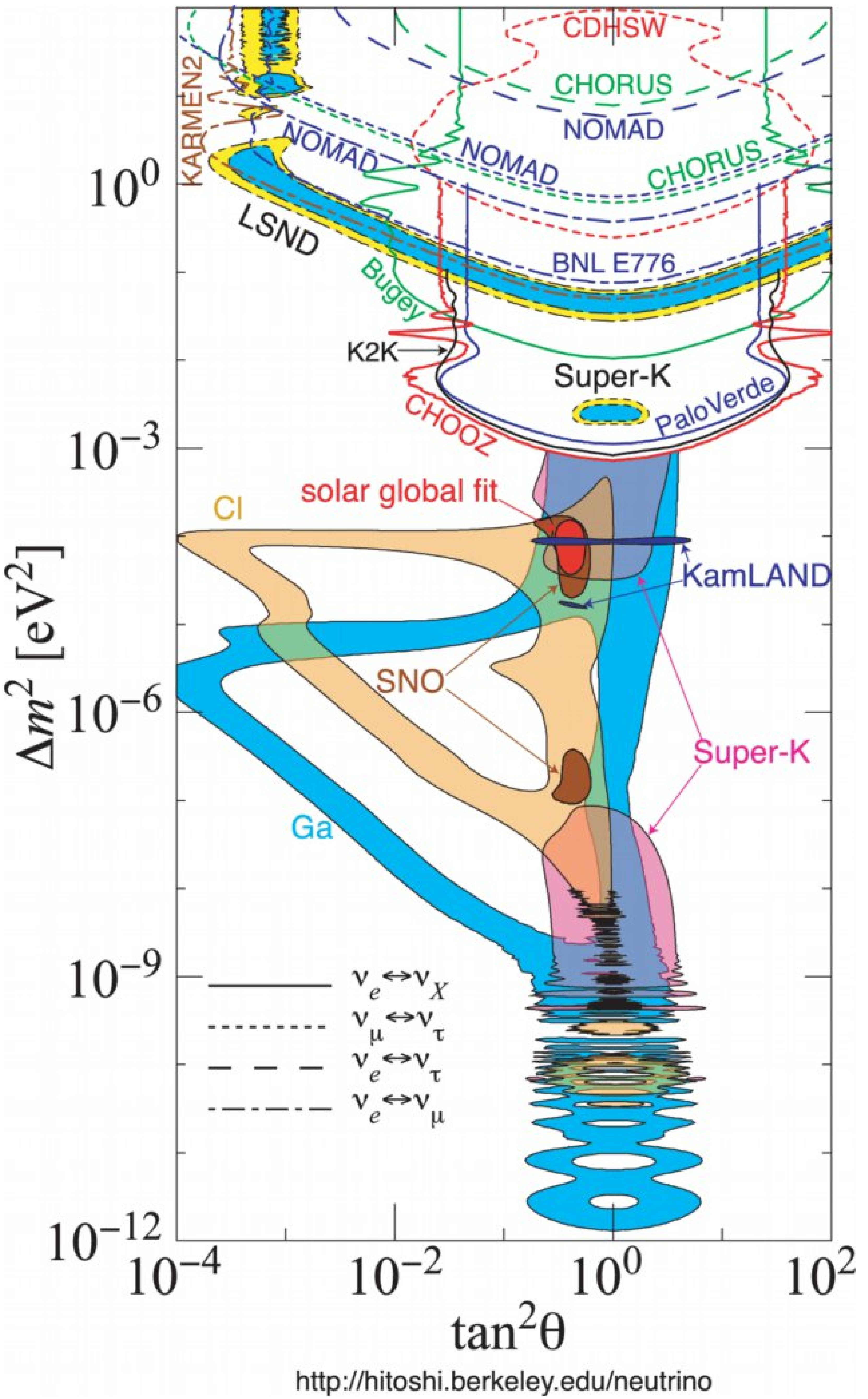
Neutrino Oscillation Signatures (ca. 2004)

Super-K
(atmospheric)



KamLAND
(180 km reactor)





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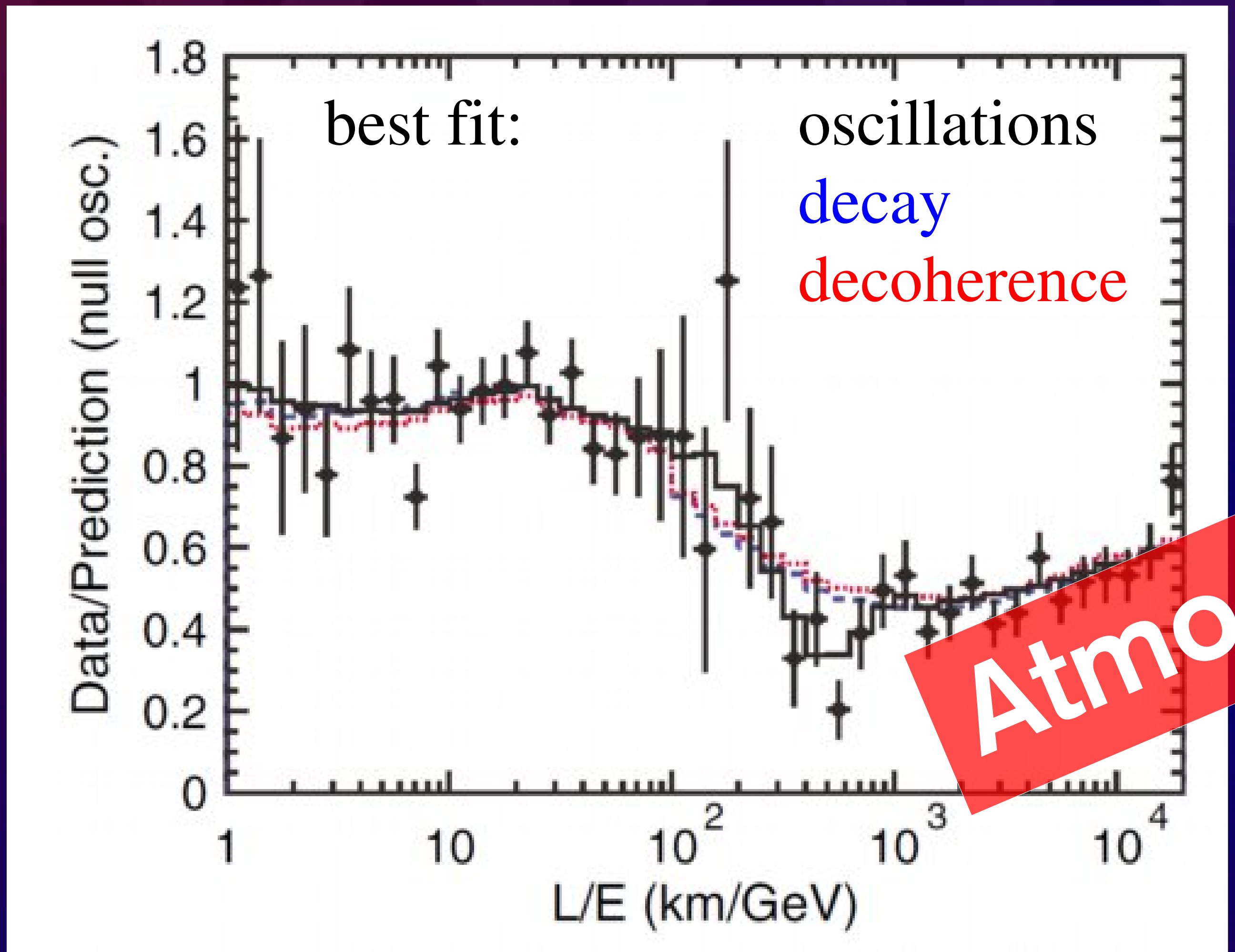

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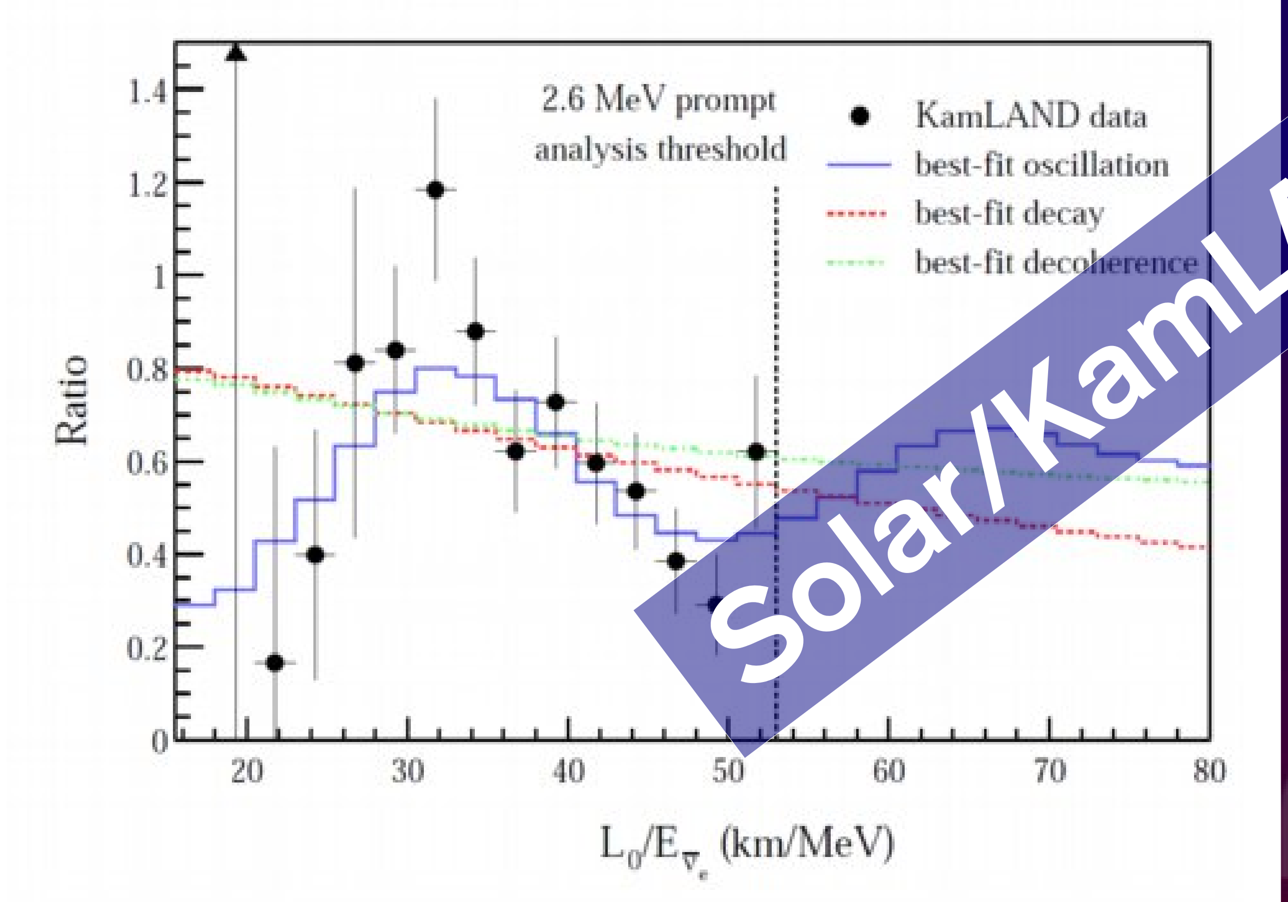
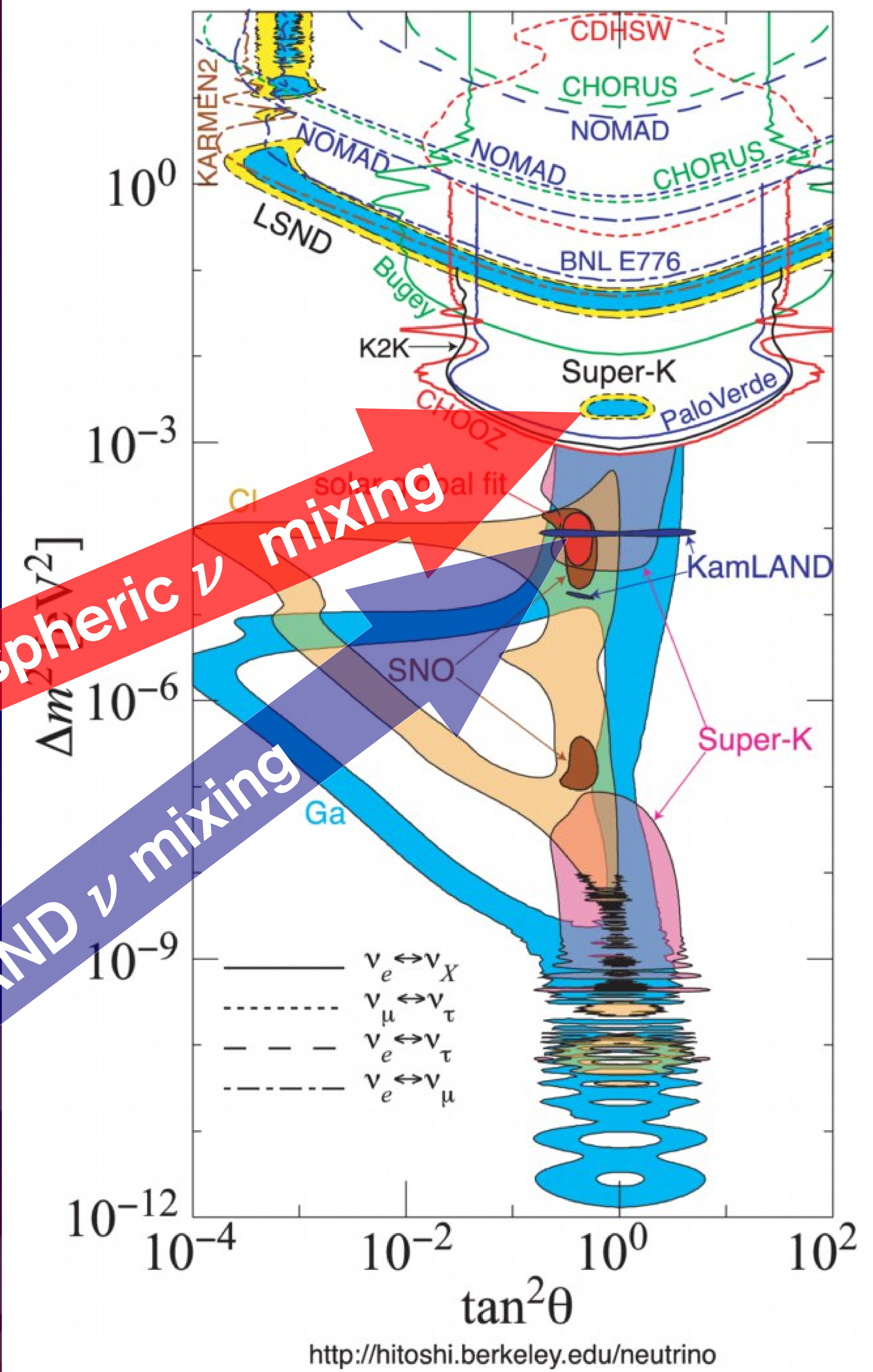
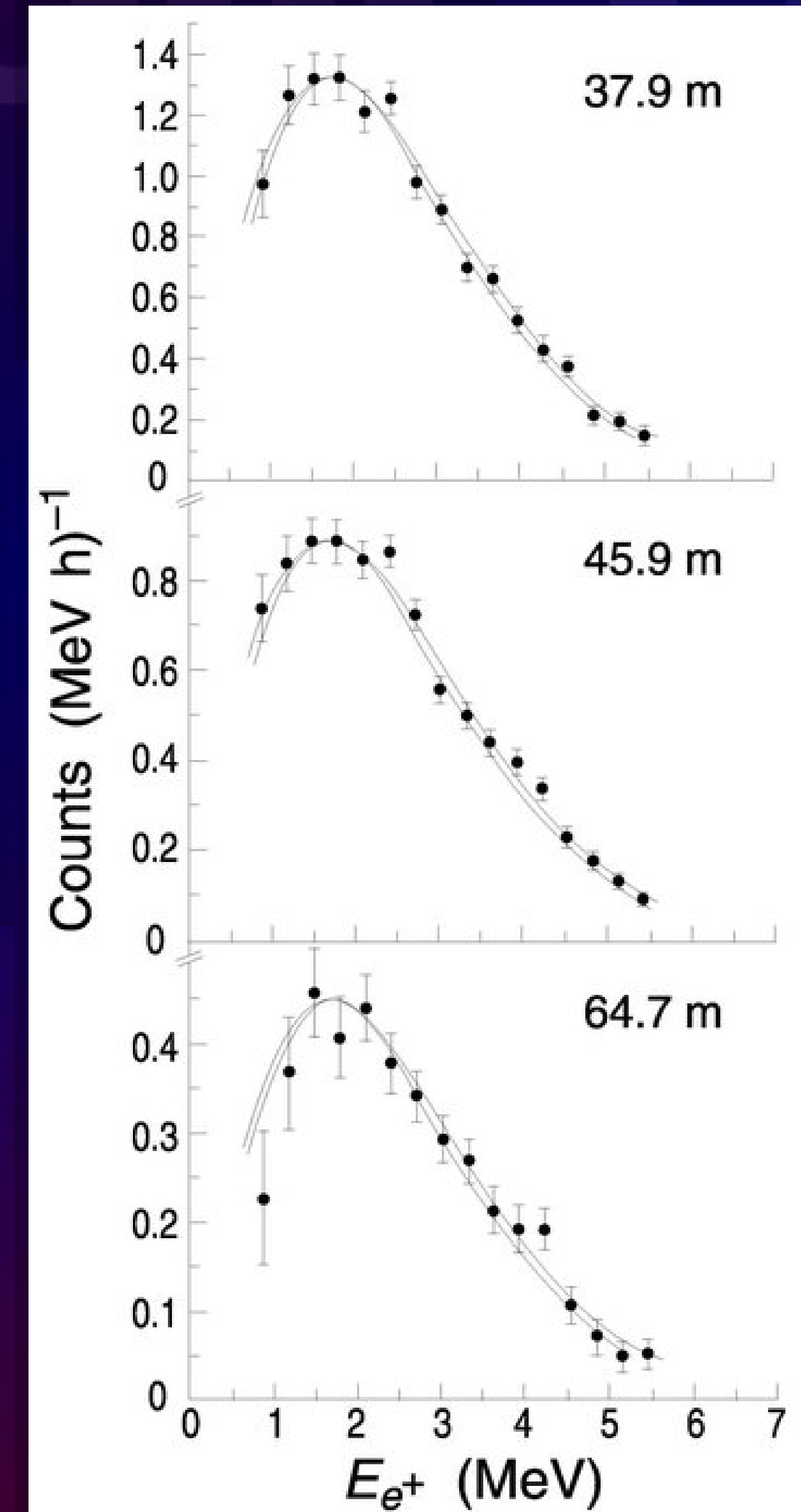


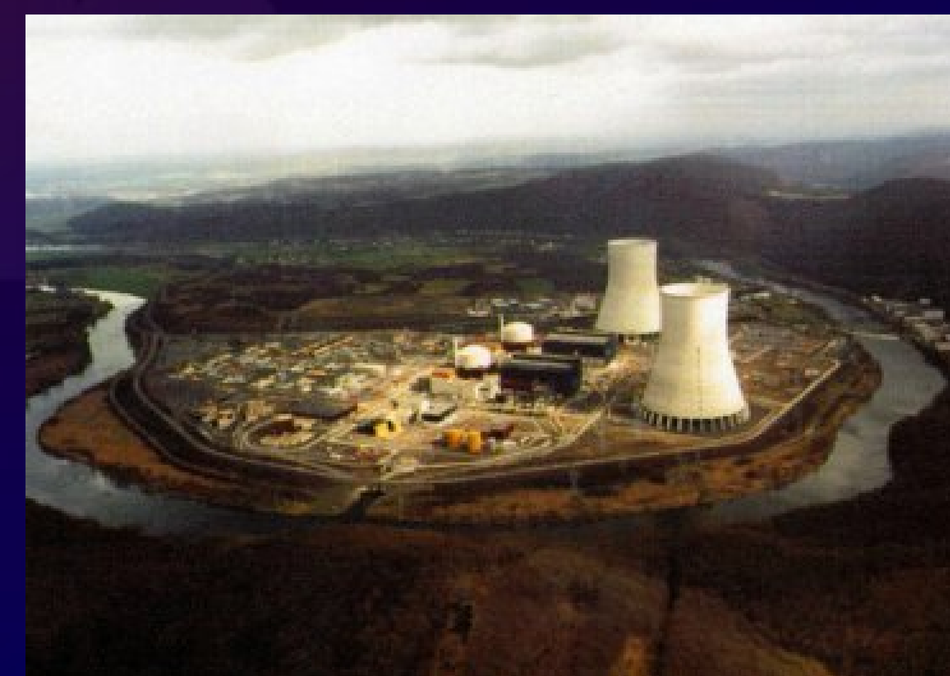


Short-Baseline Reactor Experiments

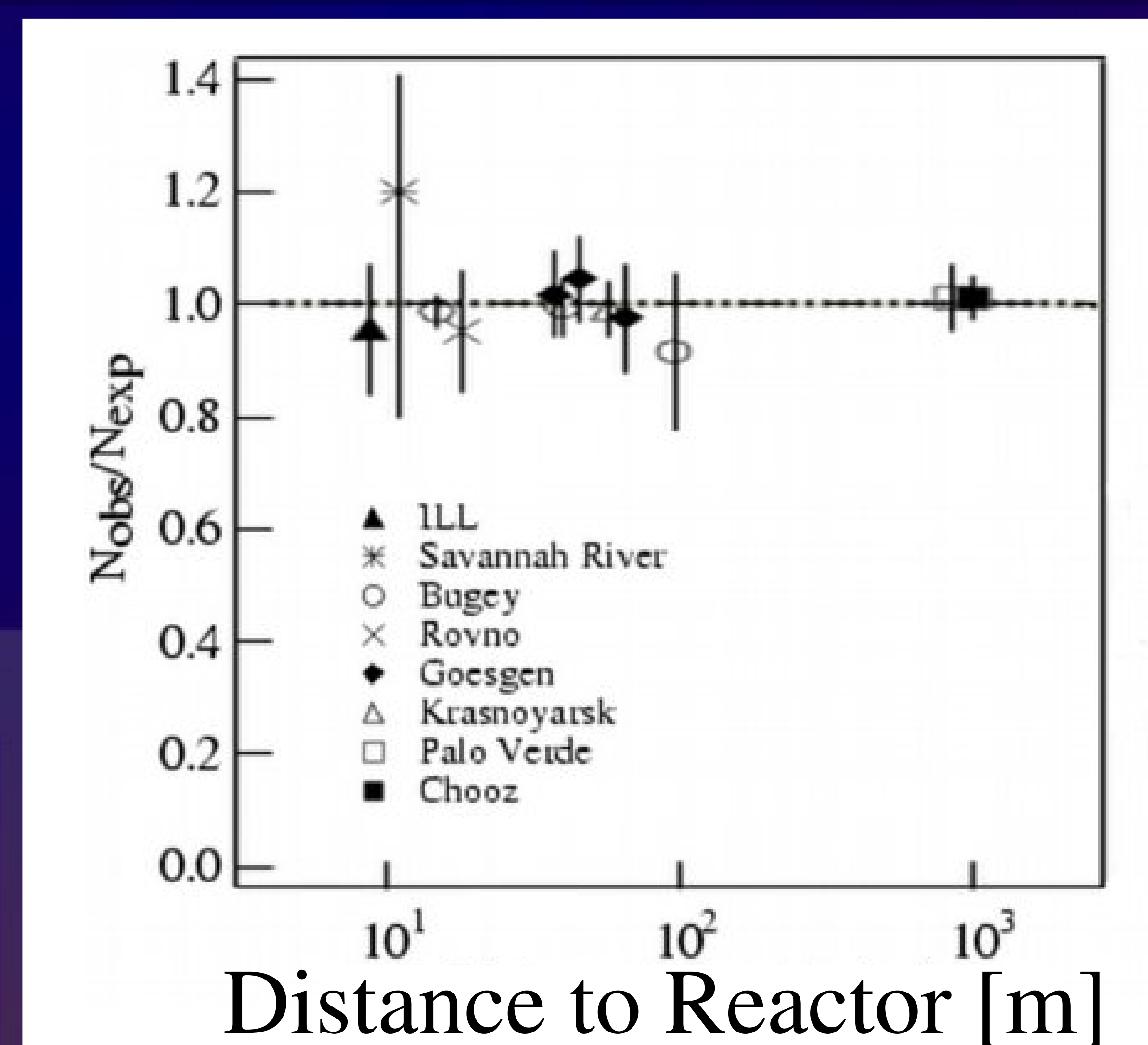
Palo Verde



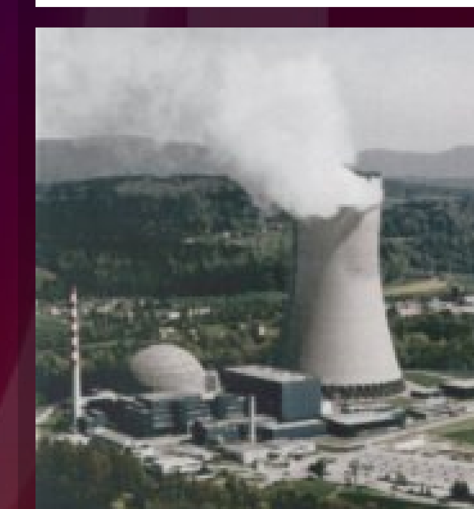
Chooz



- Chooz and Palo Verde experiments from the late 1990s
- the generation prior to Daya Bay, Double Chooz & RENO
- preceded by many **shorter-baseline reactor experiments**



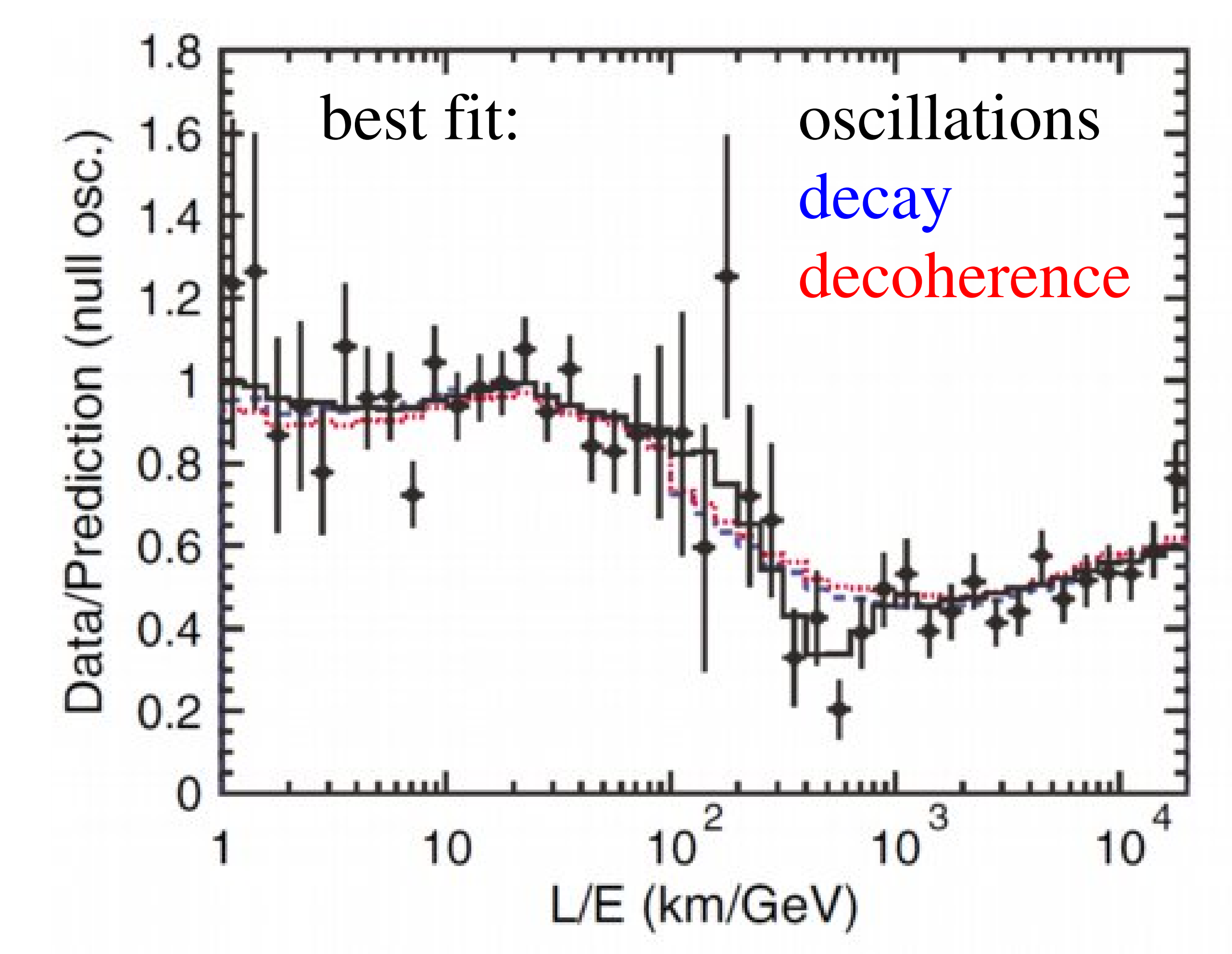
Goesgen



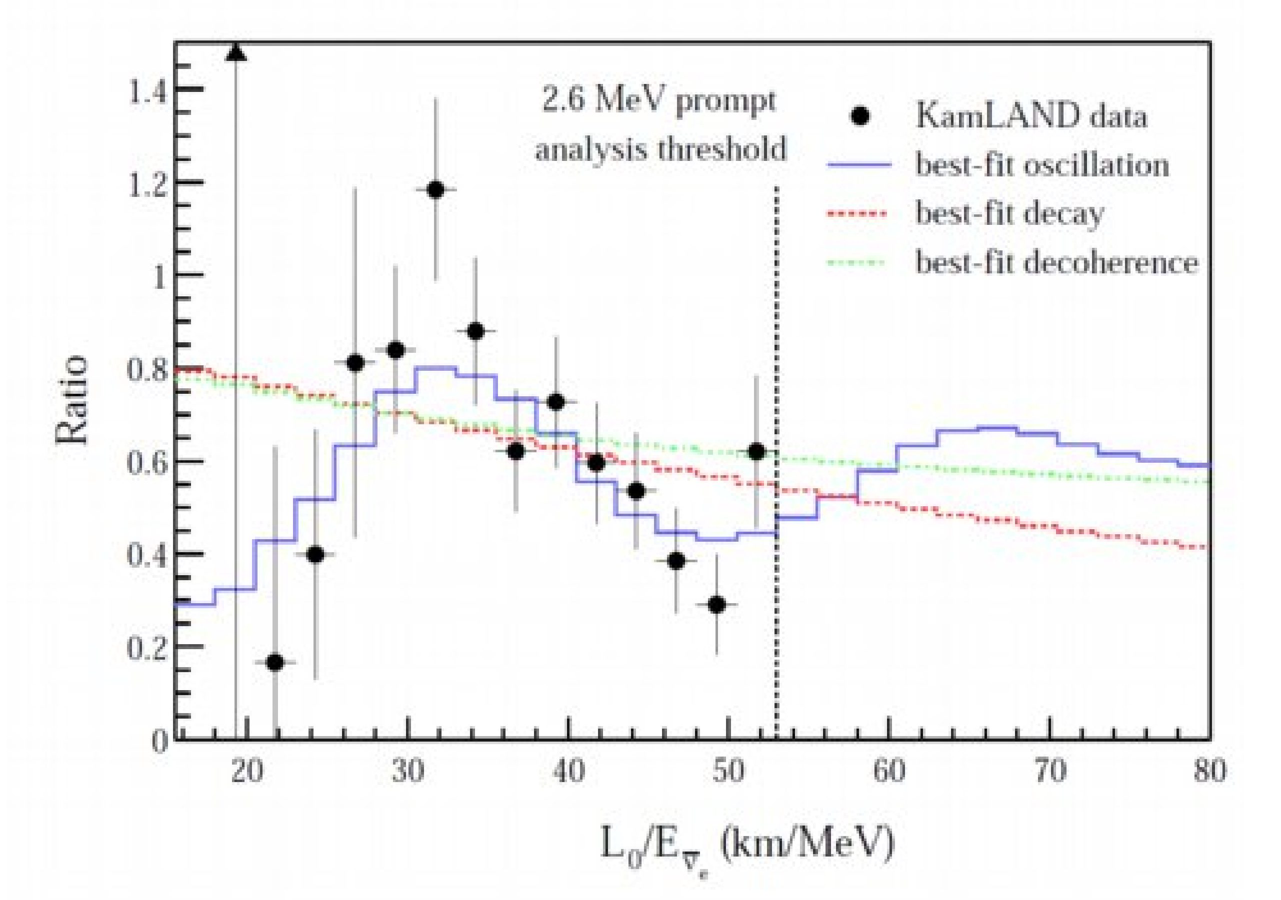
- **did not see any antineutrino deficit**

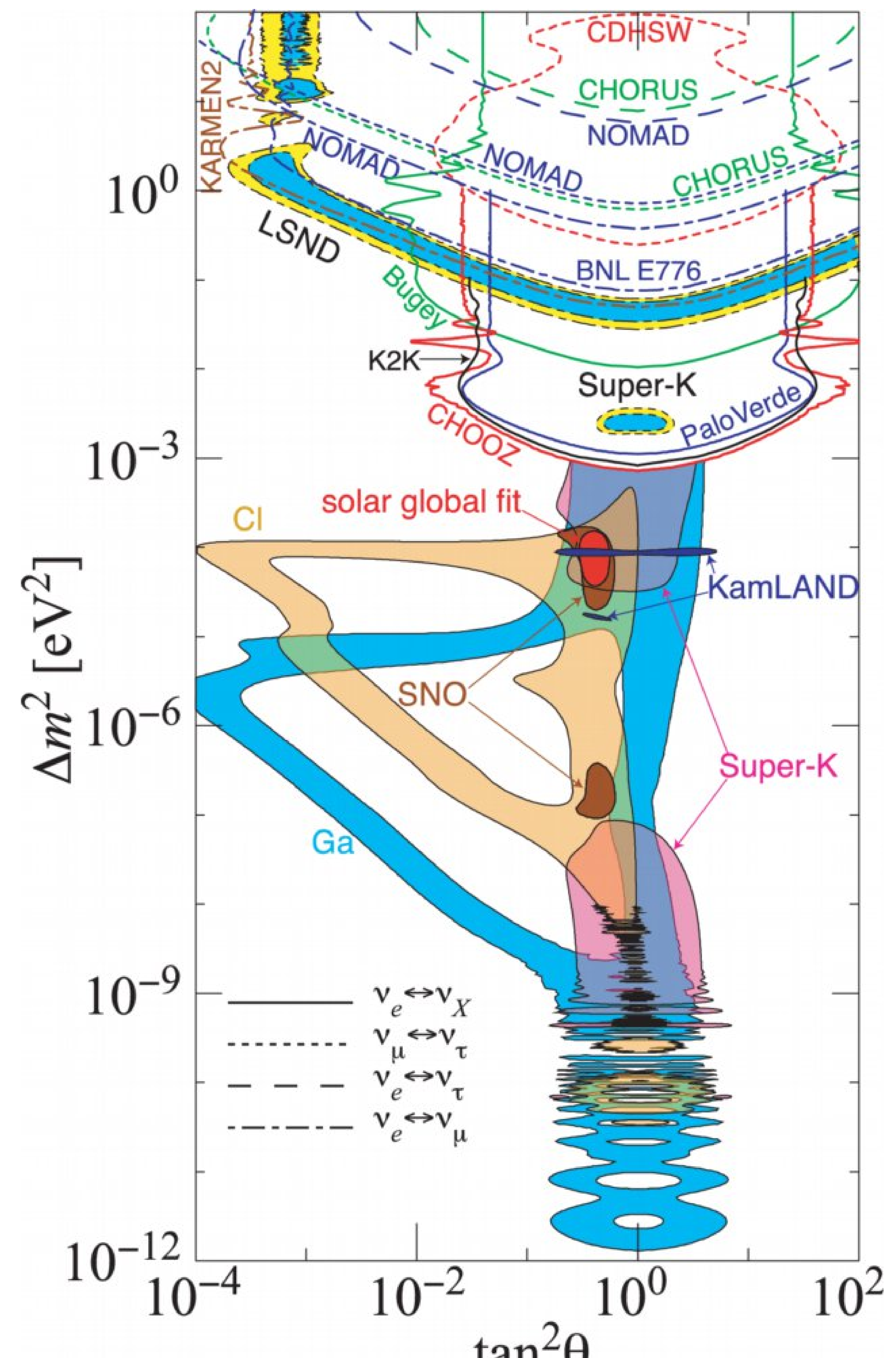
Neutrino Oscillation Signatures (ca. 2004)

Super-K
(atmospheric)



KamLAND
(180 km reactor)

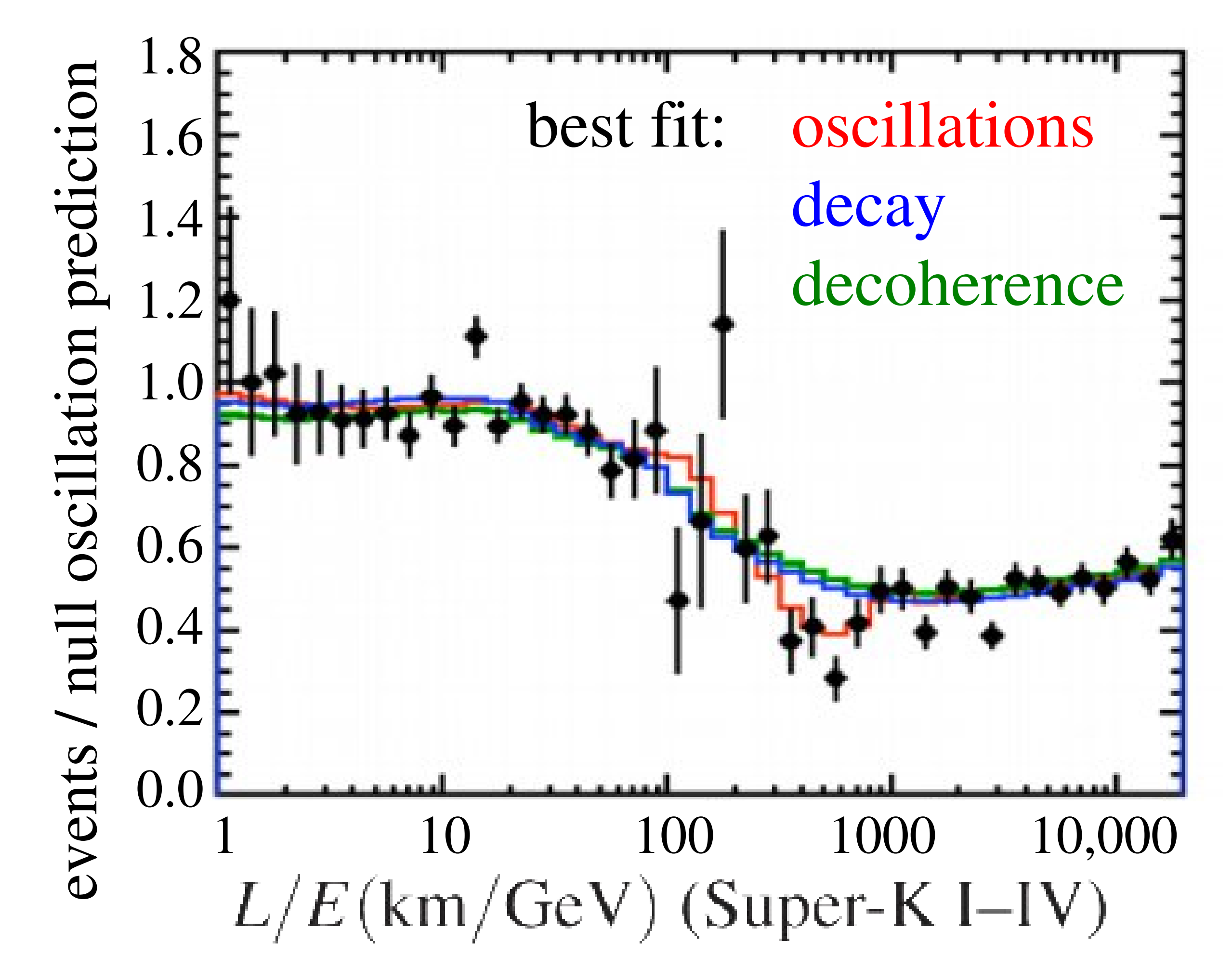




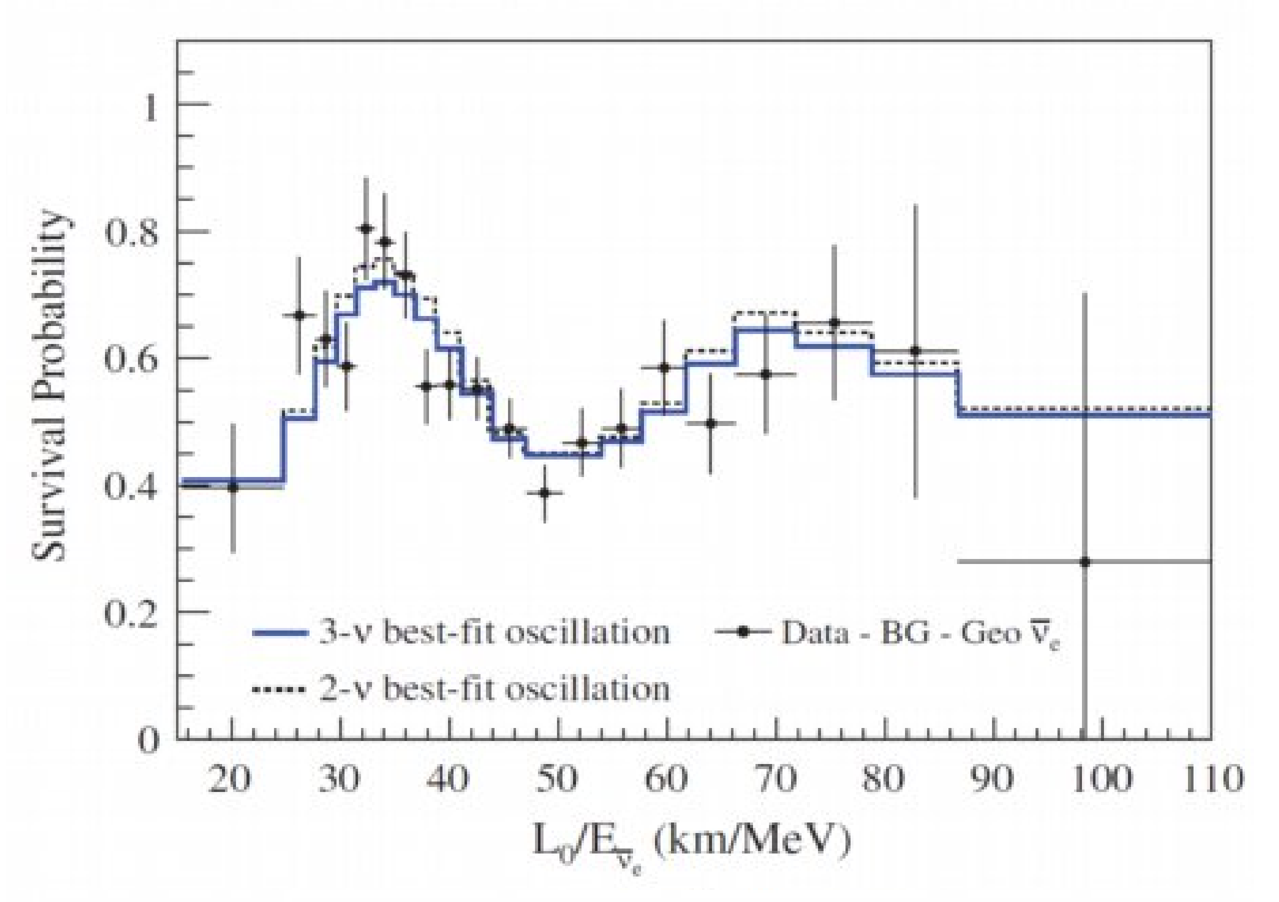
http://hitoshi.berkeley.edu/neutrino

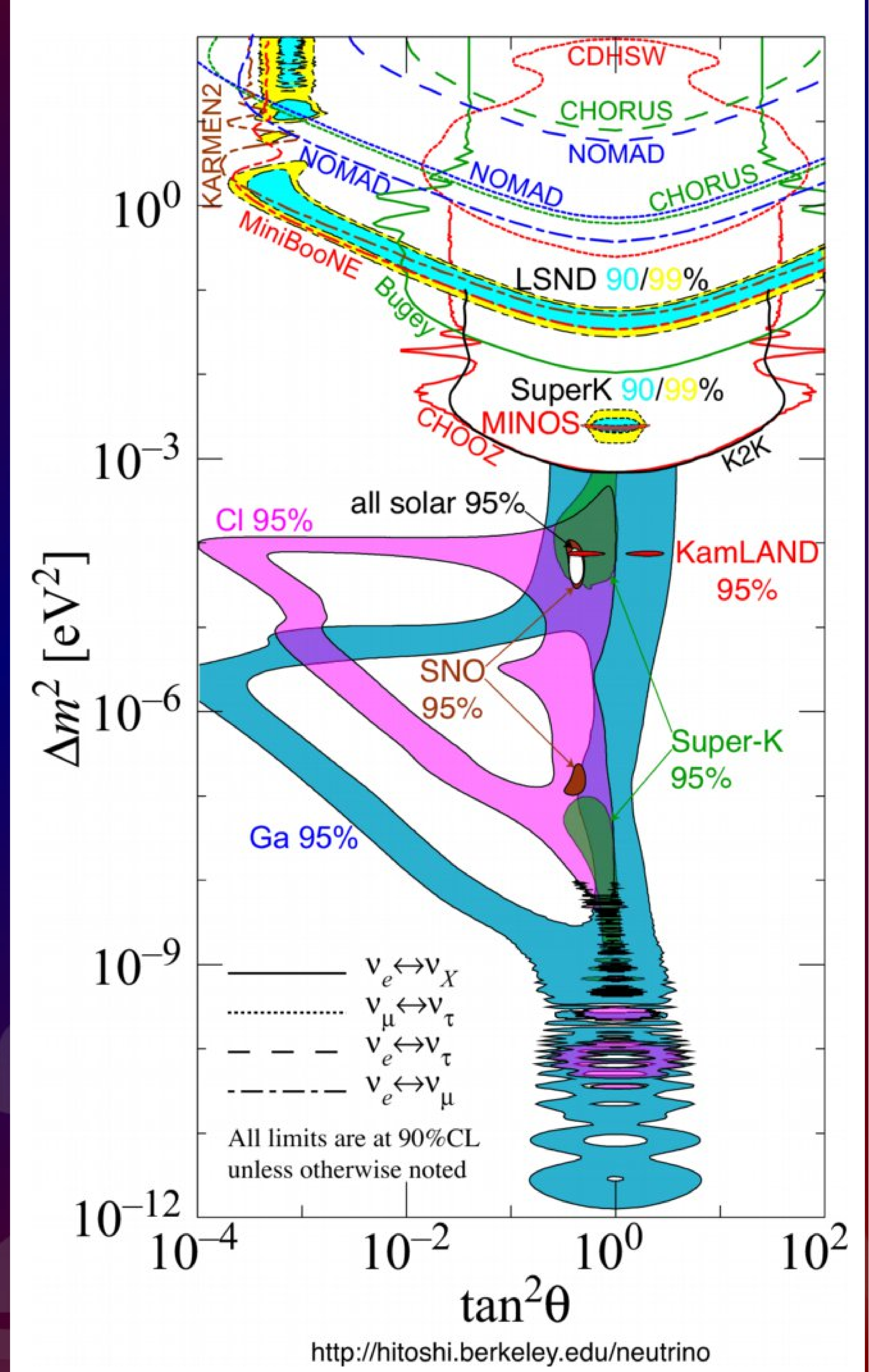
Neutrino Oscillation Signatures (2012)

Super-K
(atmospheric)



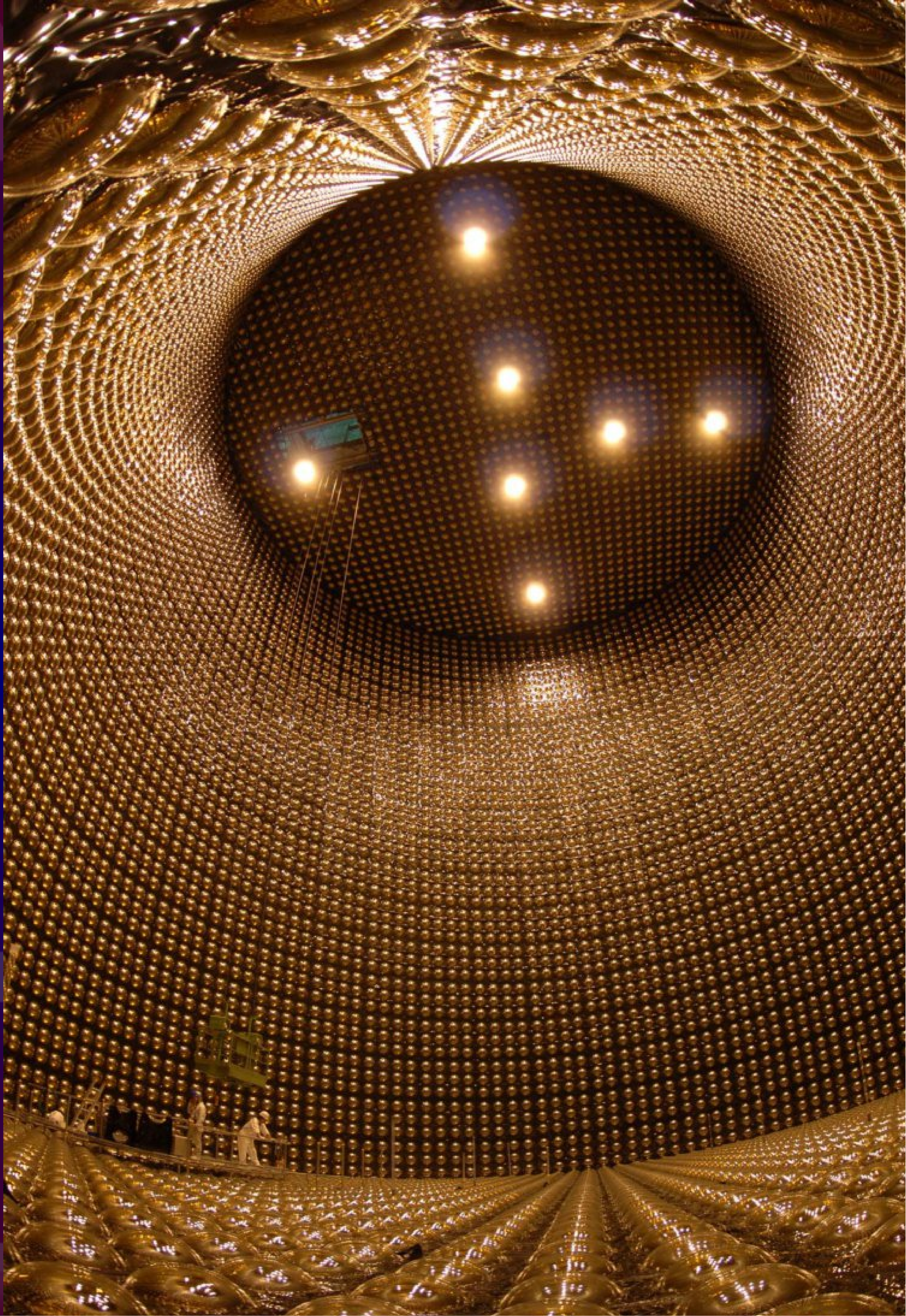
KamLAND
(180 km reactor)





Super-Kamiokande

- 40m × 40m cylindrical tank of pure water
- 1 km underground
- 11,146 phototubes in **Inner Detector** (visible in photograph)
- 1,885 phototubes instrument 2.5 metre-thick **Outer Detector**
- First data in 1996



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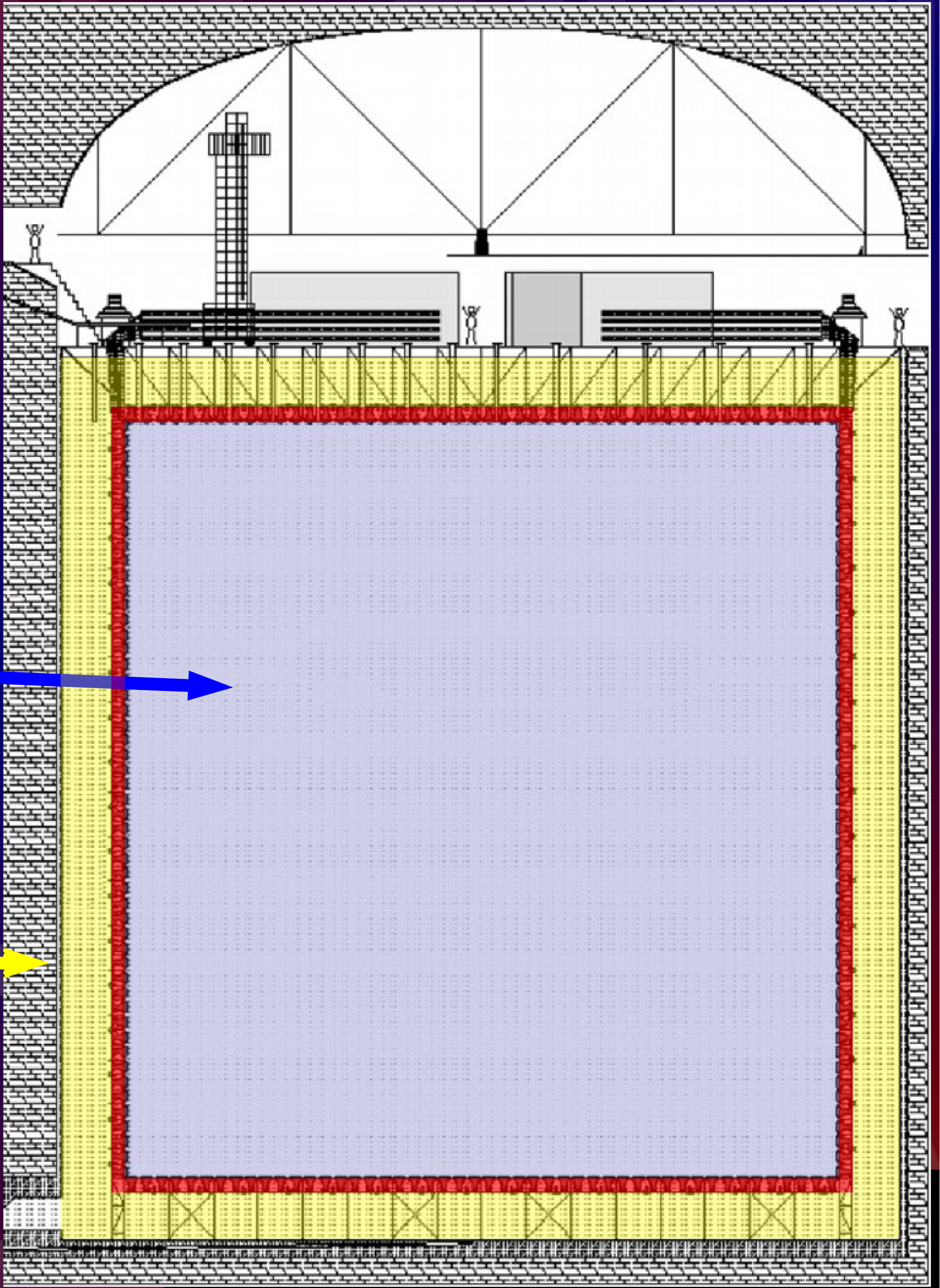
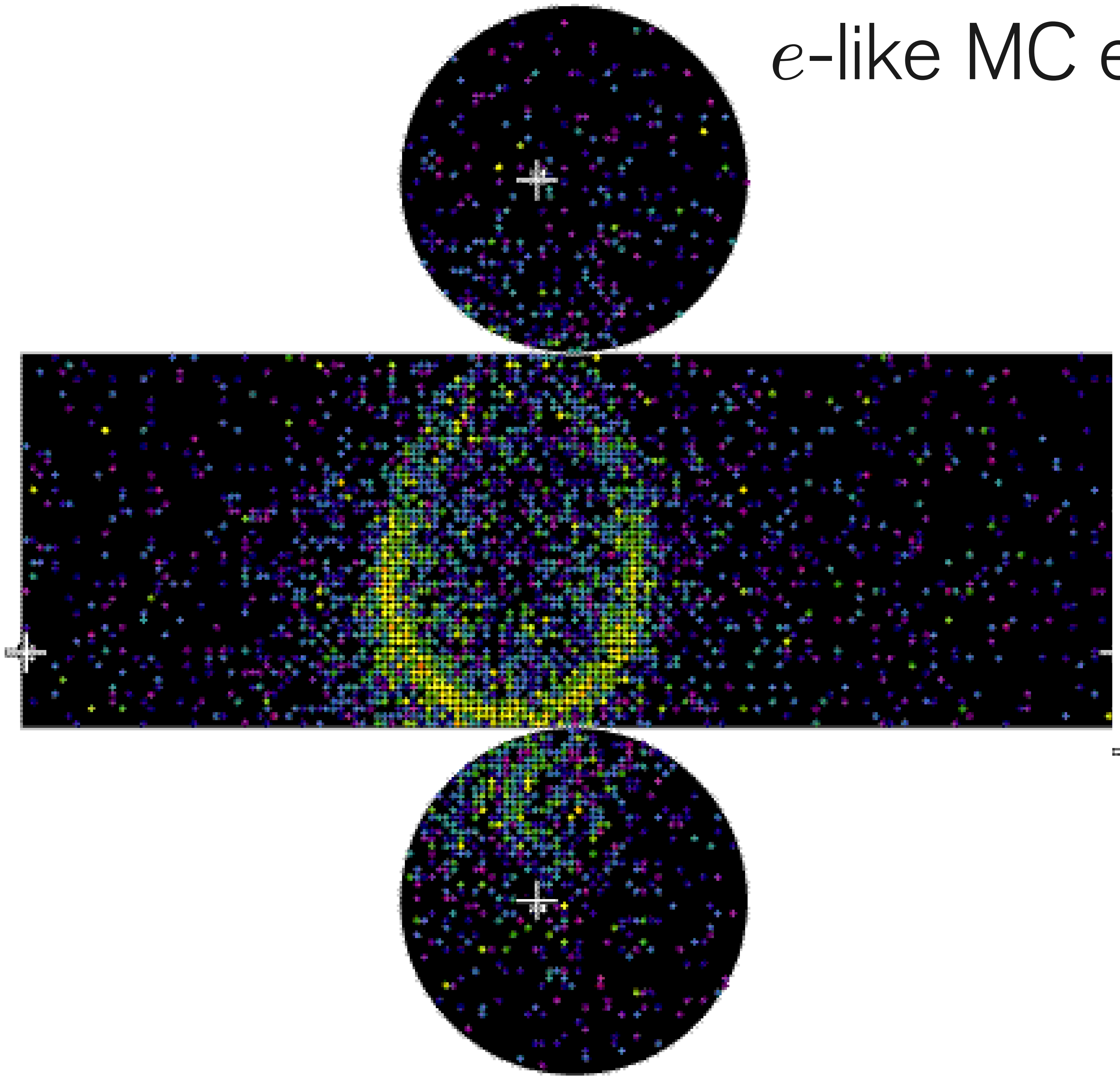
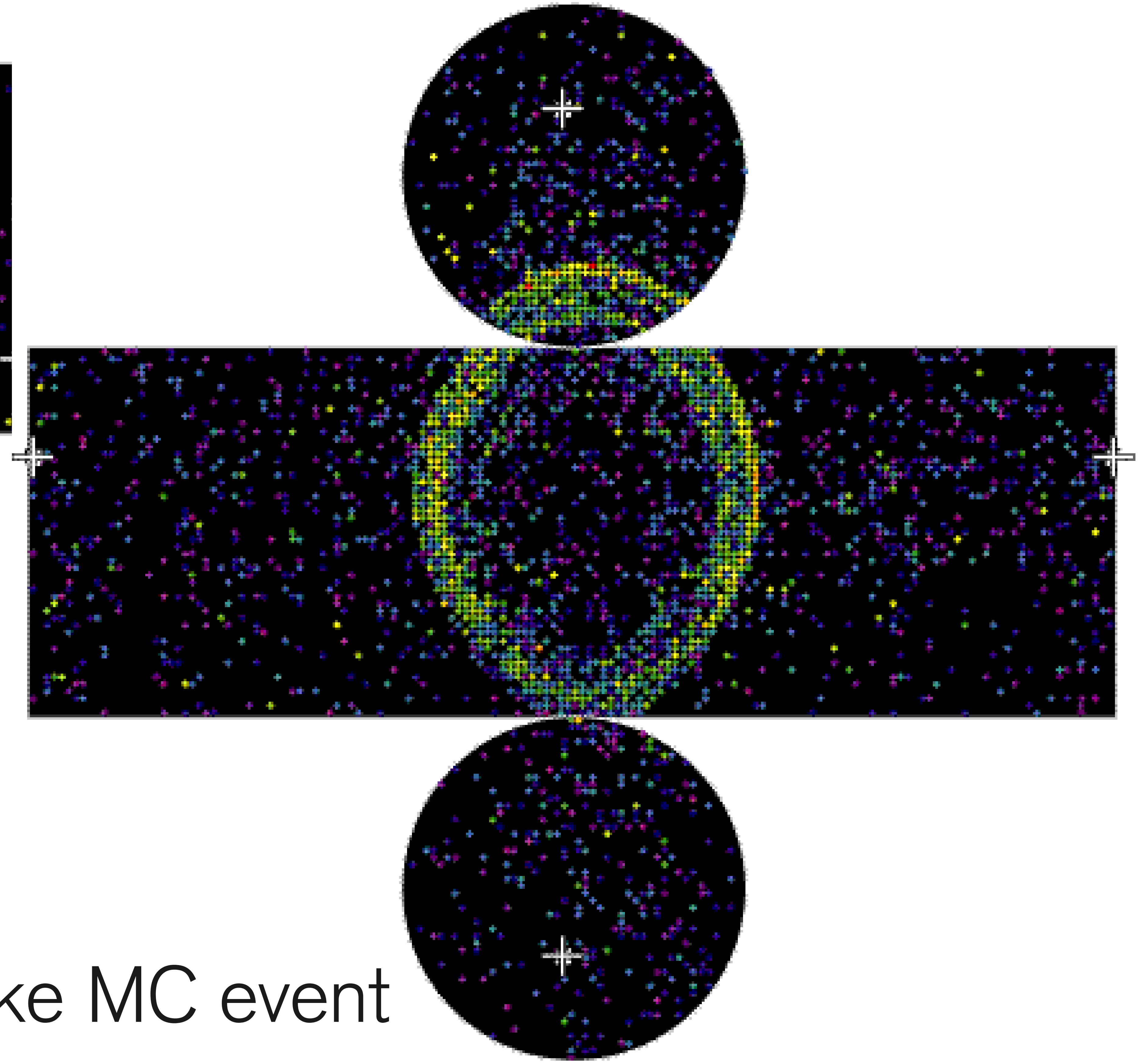


Particle ID at Super-K



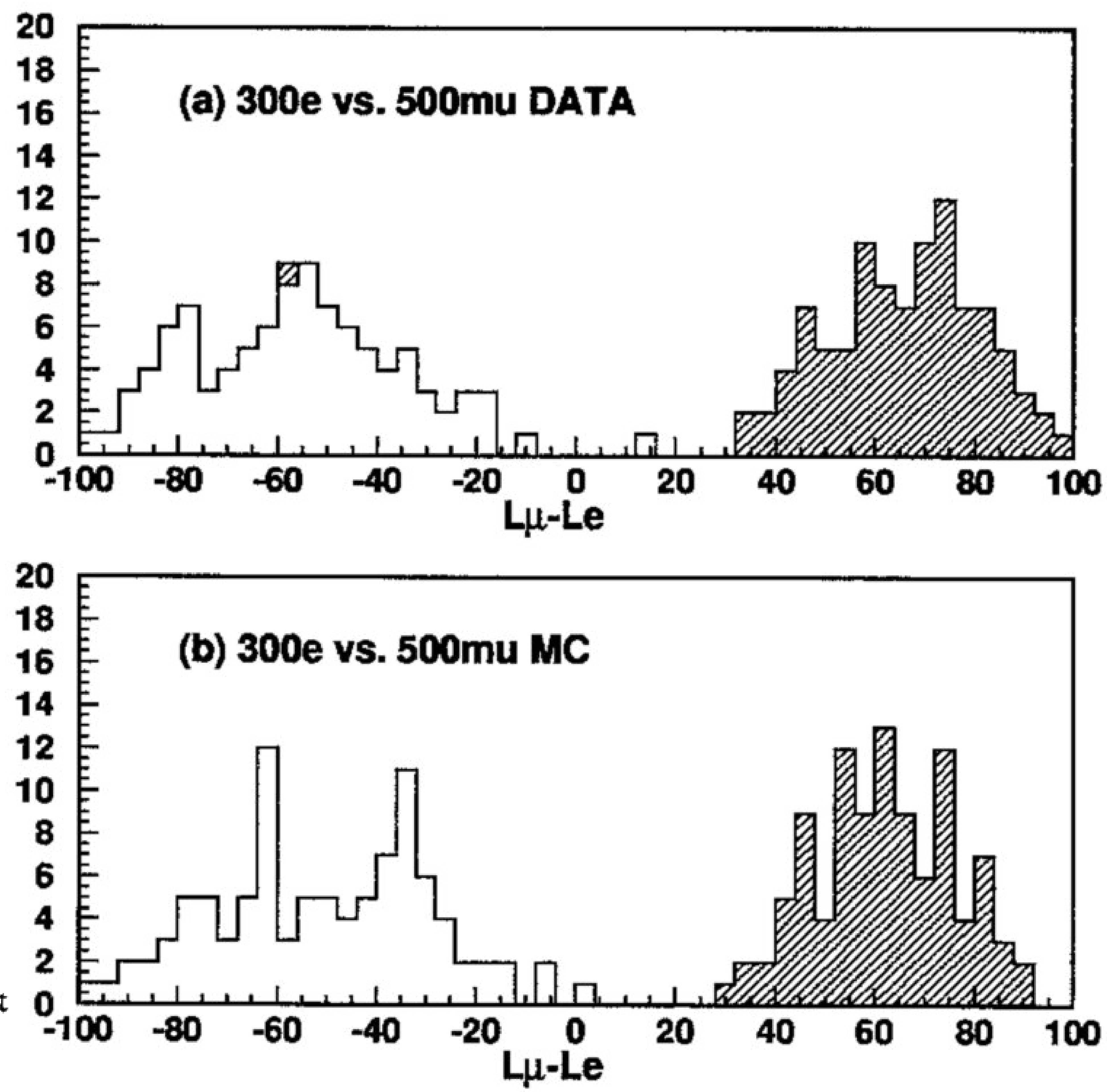
e-like MC event



μ-like MC event

Particle ID at Super-K

- PID capabilities originally shown in test beam in 1996 with a 1 kton model



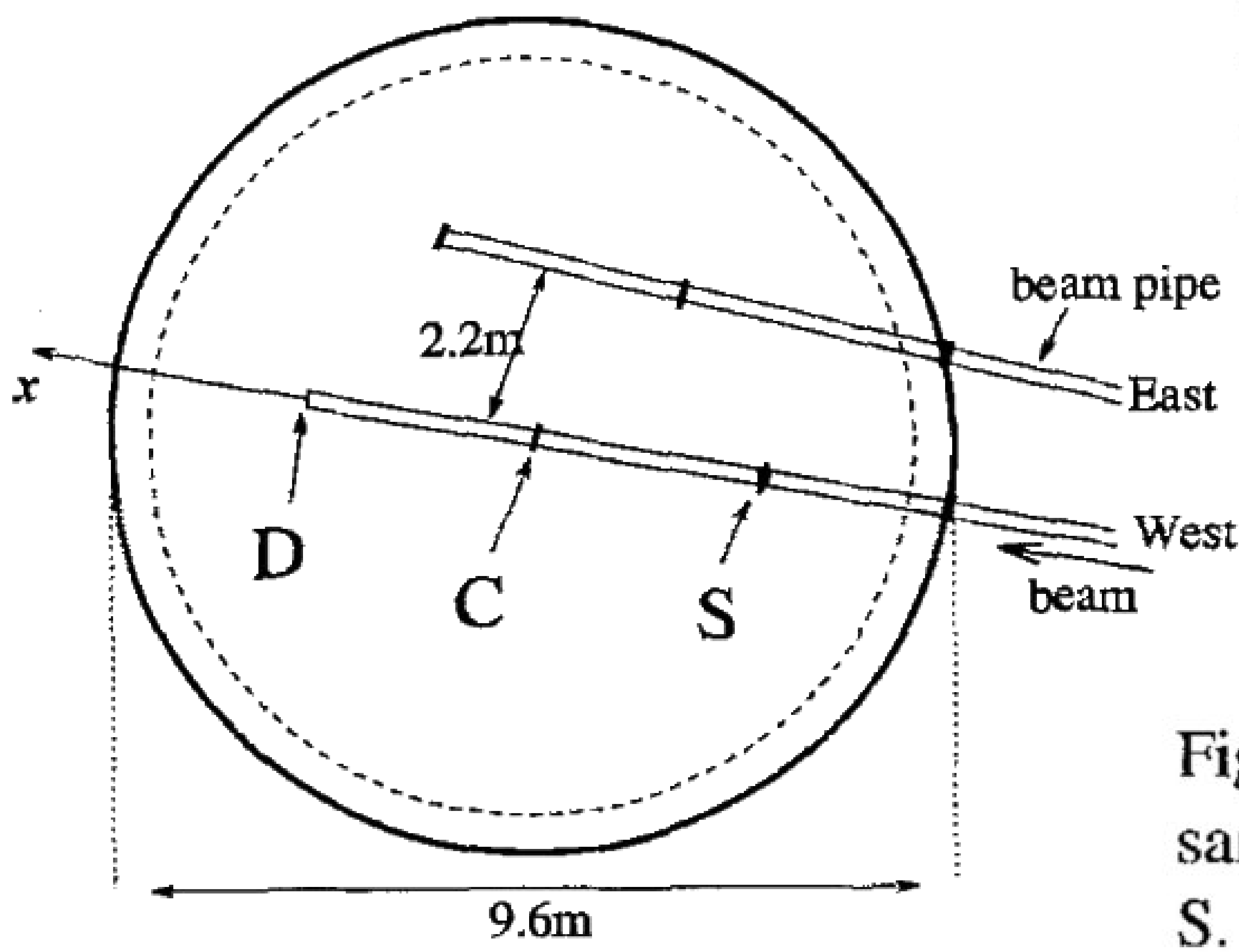
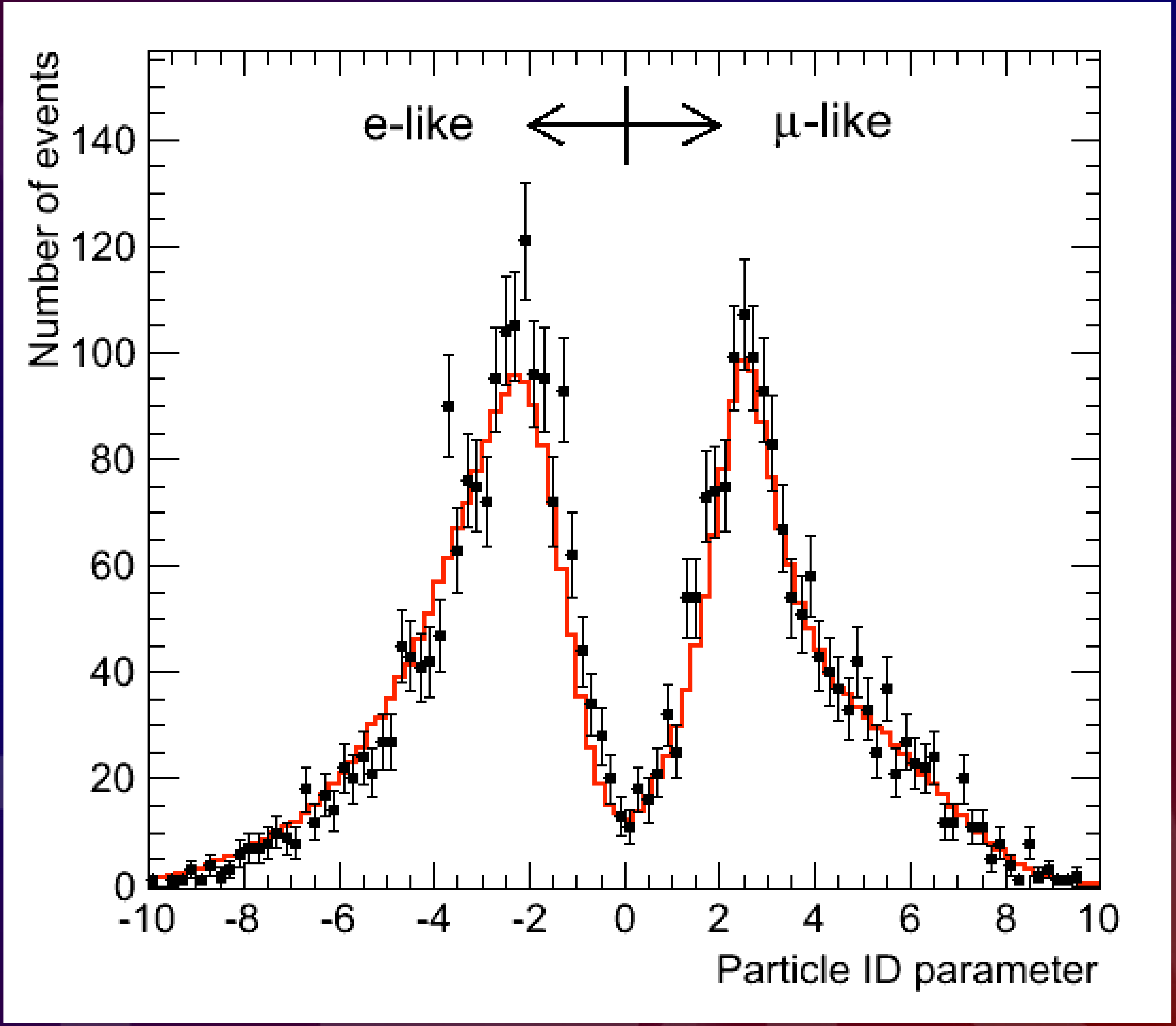


Fig. 2. The [L_μ–L_e] distribution of (a) data and (b) Monte Carlo samples for e (300 MeV/c) and μ (500 MeV/c) at the position S. The two data samples have about the same total-p.e.'s.

Particle ID at Super-K

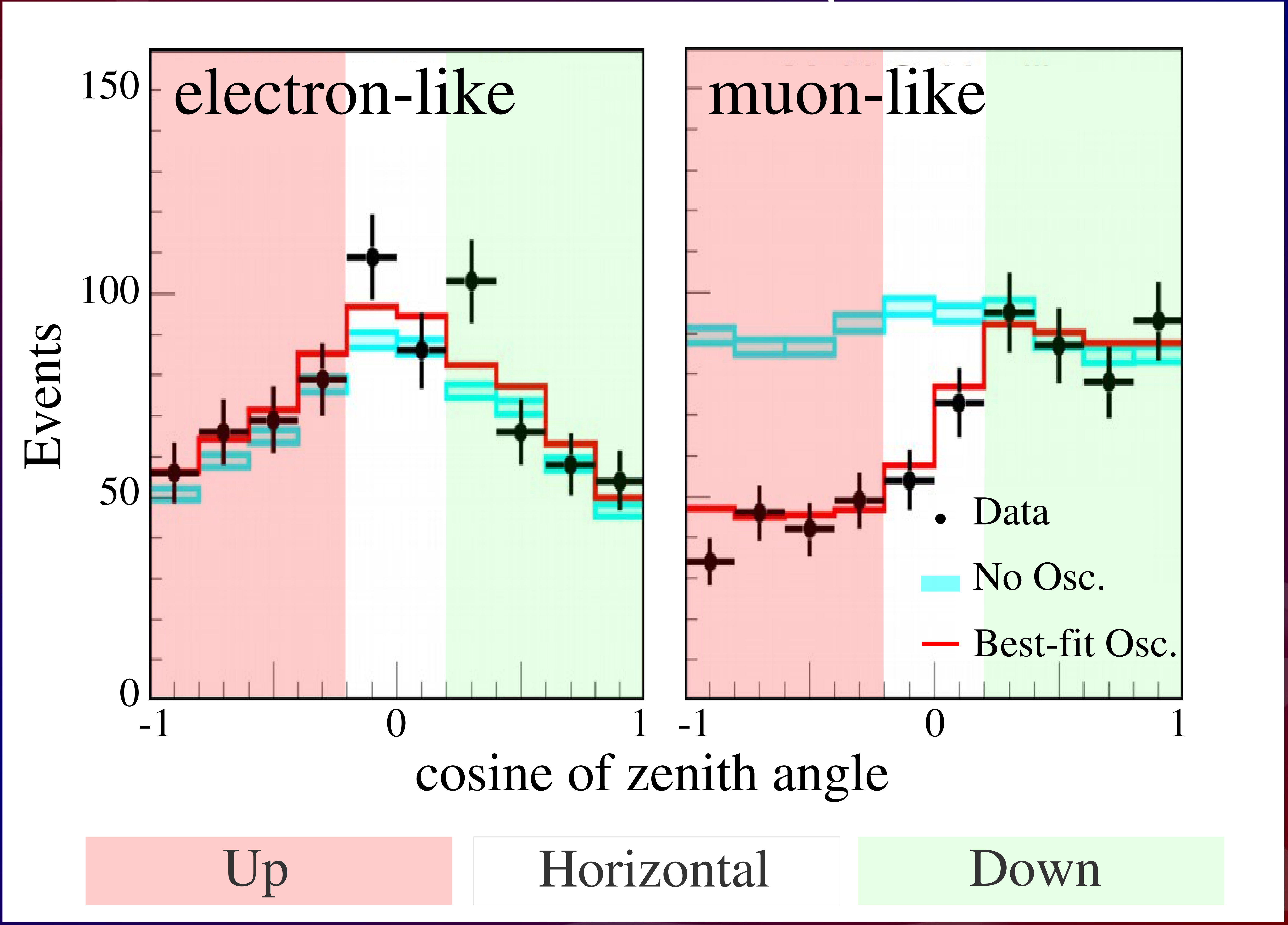
- PID capabilities originally shown in test beam in 1996 with a 1 kton model
- Muon mis-ID now at sub-percent level at Super-K



Atmospheric neutrino data and MC

Super-K Multi-GeV Atmospheric ν_e, ν_μ Events

1998

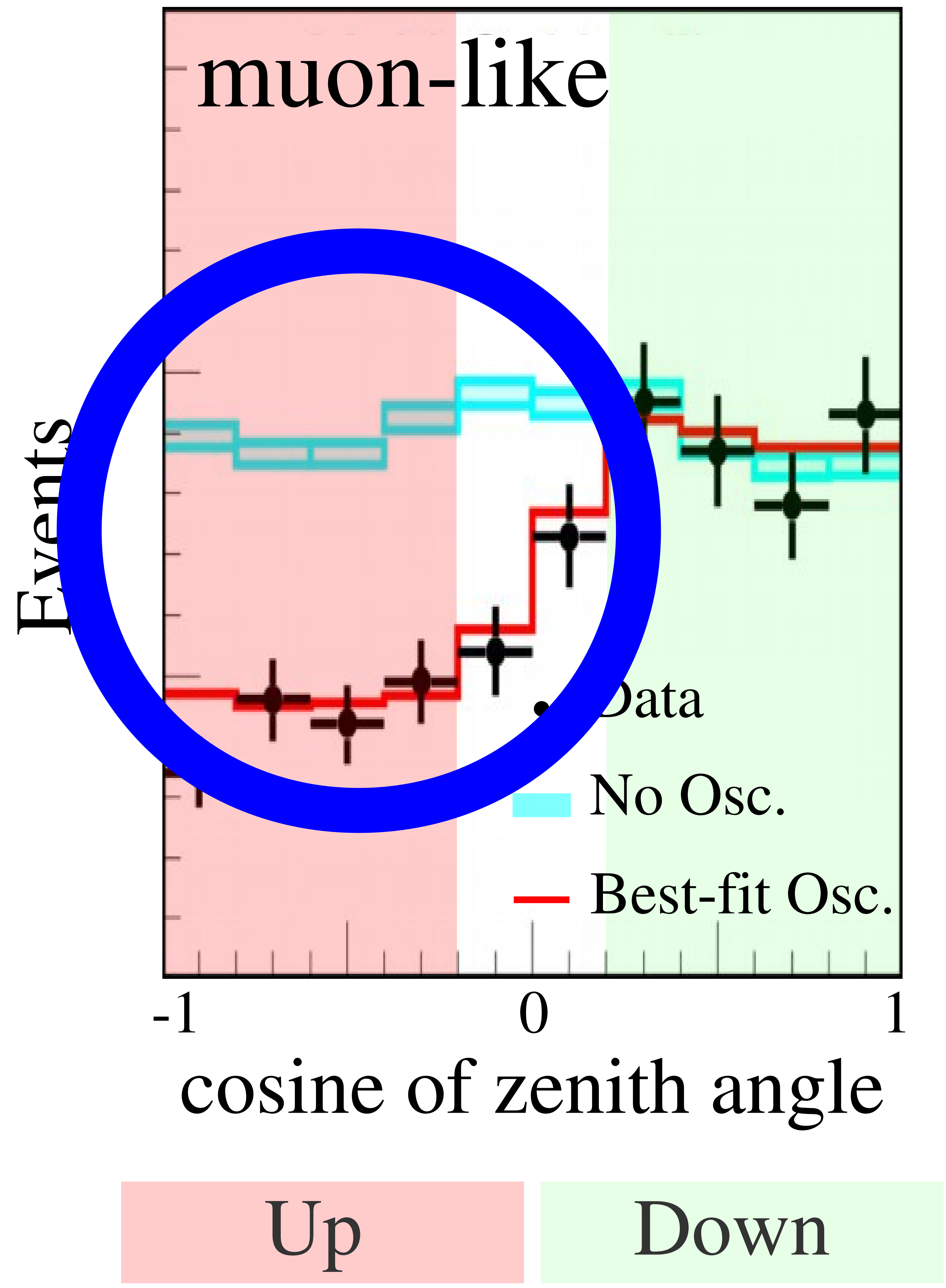


Super-K Multi-GeV ν_μ Events

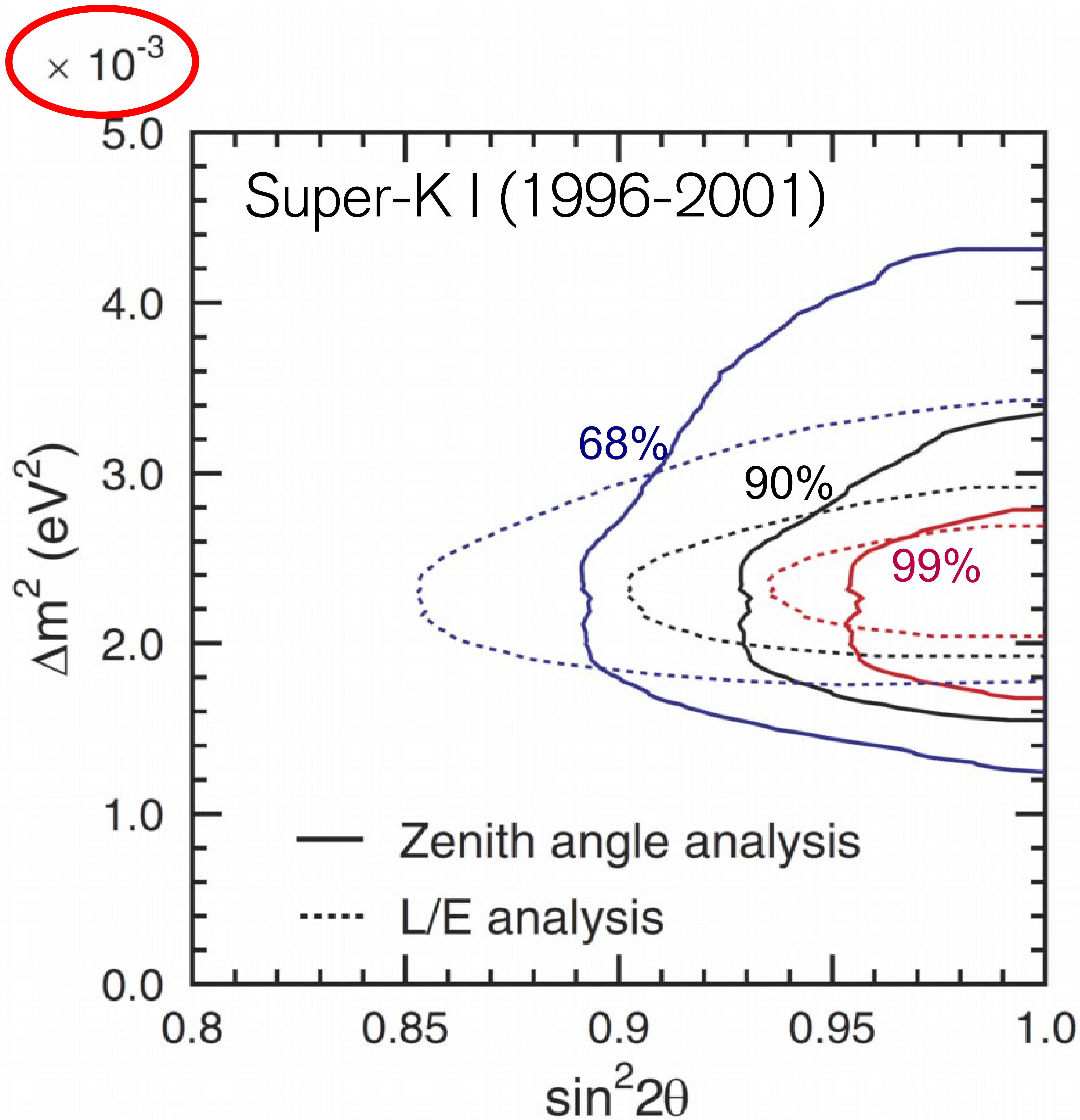
Evidence for neutrino flavour change, dependent on distance

⇒ neutrinos must have mass

Neutrino "oscillation" is the simplest model for neutrino flavour change that is consistent with these data



Atmospheric ν Deficits as Oscillations

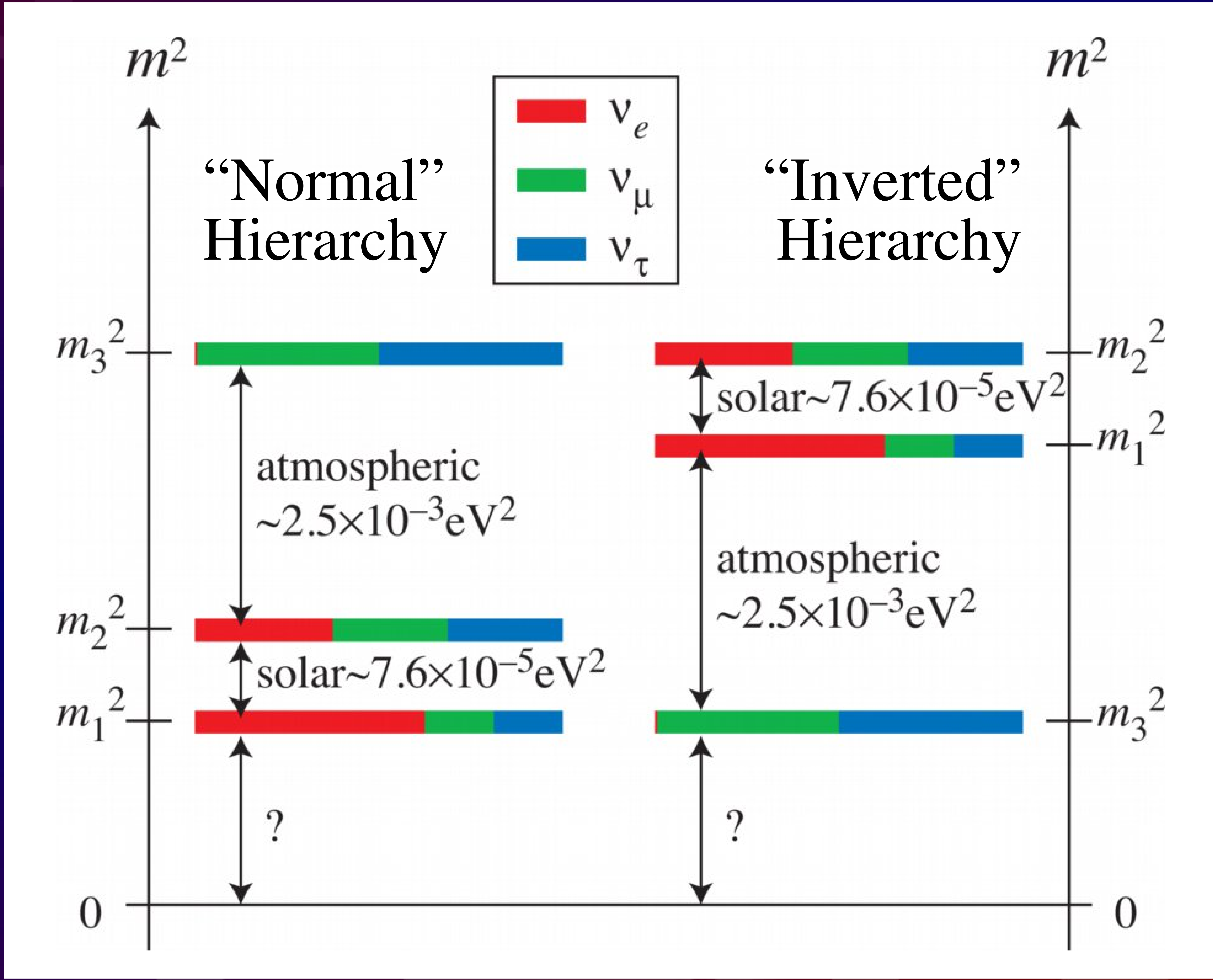


Atmospheric neutrinos at Super-K

Neutrino Mass Spectrum and Flavour Composition

Oscillation fits give Δm^2 and mixing angles:

- $\theta_{12} = 34^\circ \pm 3^\circ$
- $\theta_{23} = 45^\circ \pm 5^\circ$
  - consistent with "maximal" mixing



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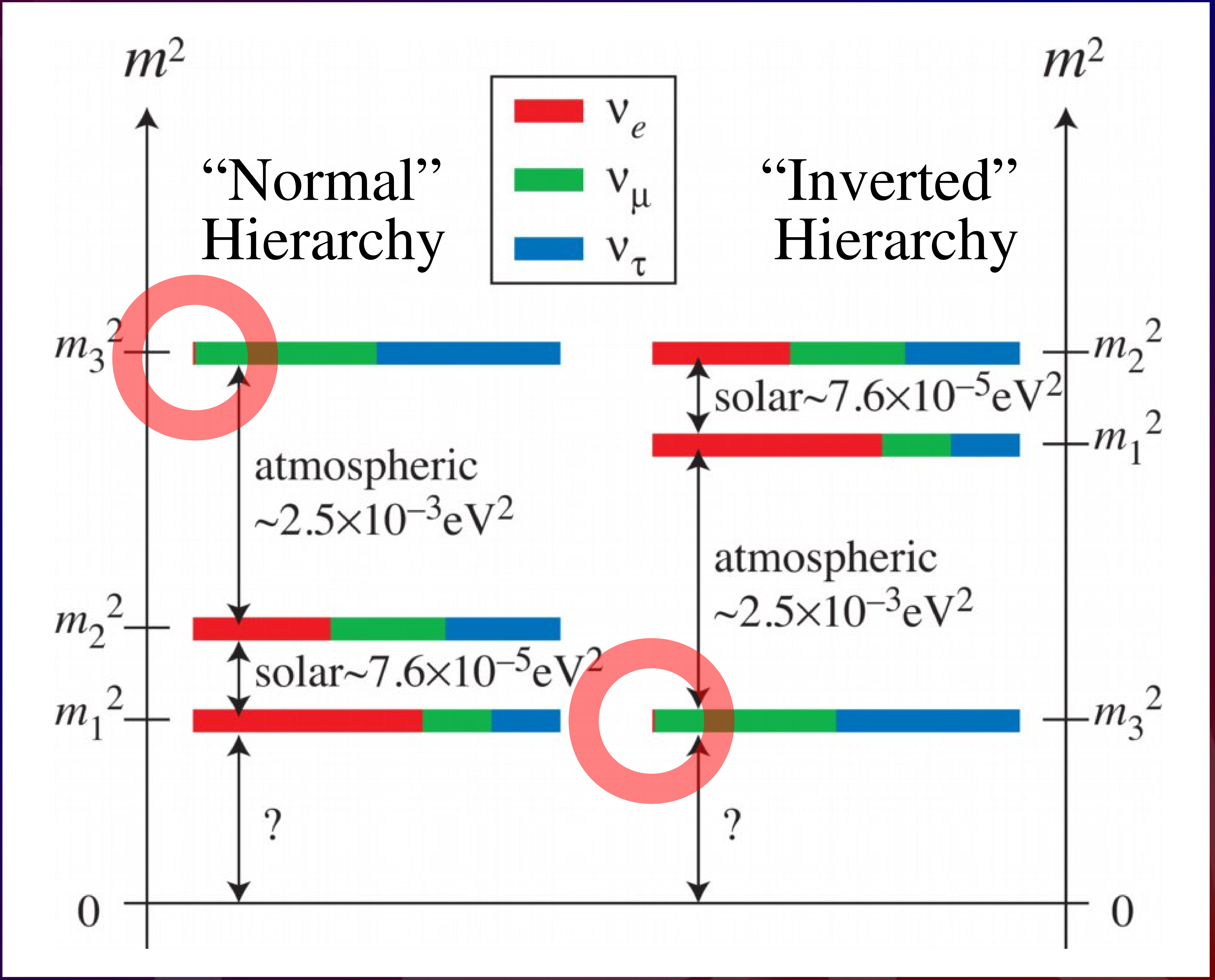

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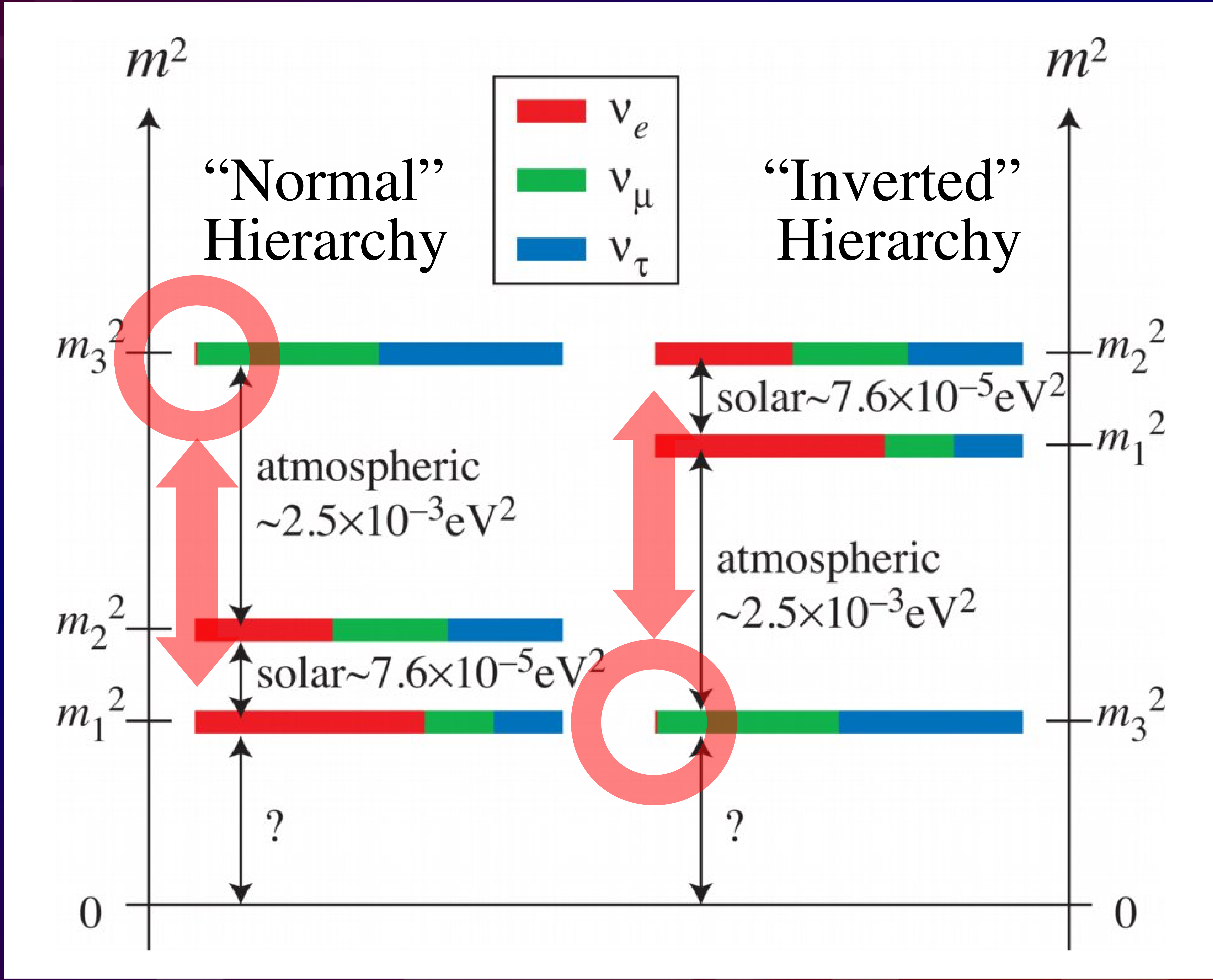
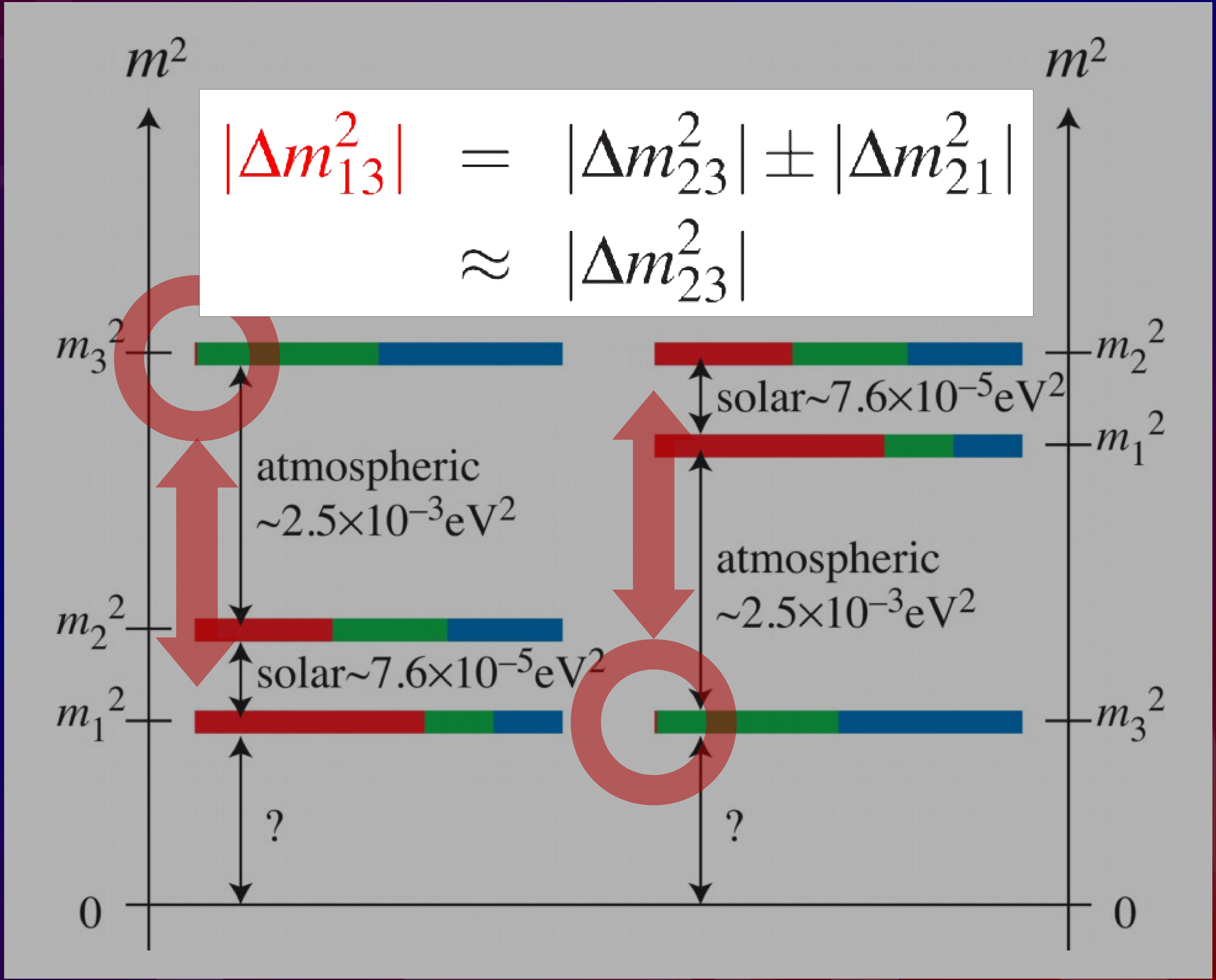


Neutrino Mass Spectrum and Flavour Composition

- Search for oscillations at $\Delta m^2 = \Delta m^2_{atm}$
  - disappearance
  - **appearance**



Three-Generational Mixing

Defining the mixing matrix such that

$\nu_l = U_{lj}\,\nu_j$ where $l = e, \mu, \tau$,

and $j = 1, 2, 3$ for the three mass eigenstates

$$U_{ij} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

Atmospheric oscillations

$$\times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Solar/KamLAND oscillations

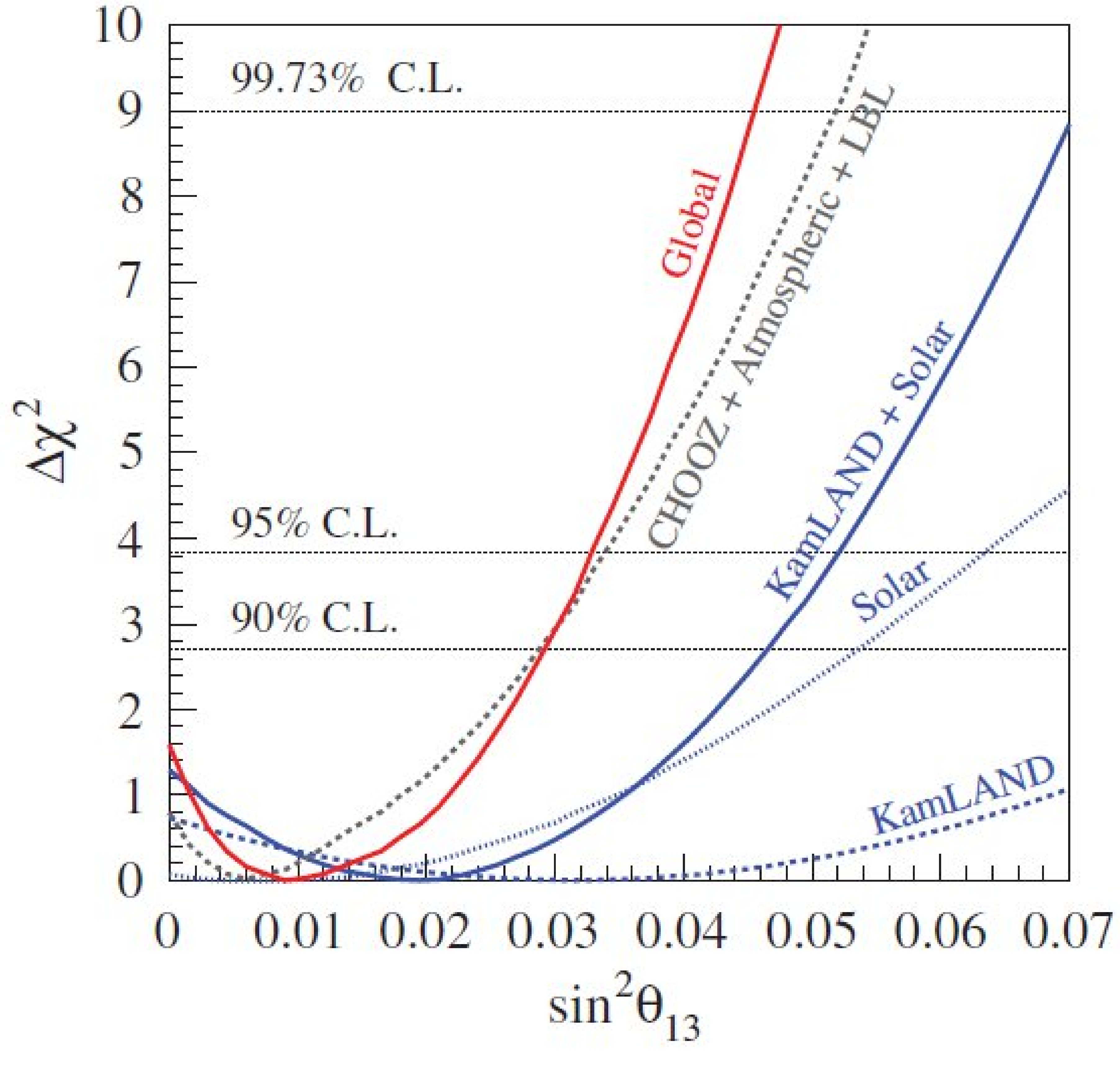
1-3 generation mixing: not observed (May 2011)

$$\times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \times e^{i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} \times e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix}$$

δ_{CP}: CP-violating parameter

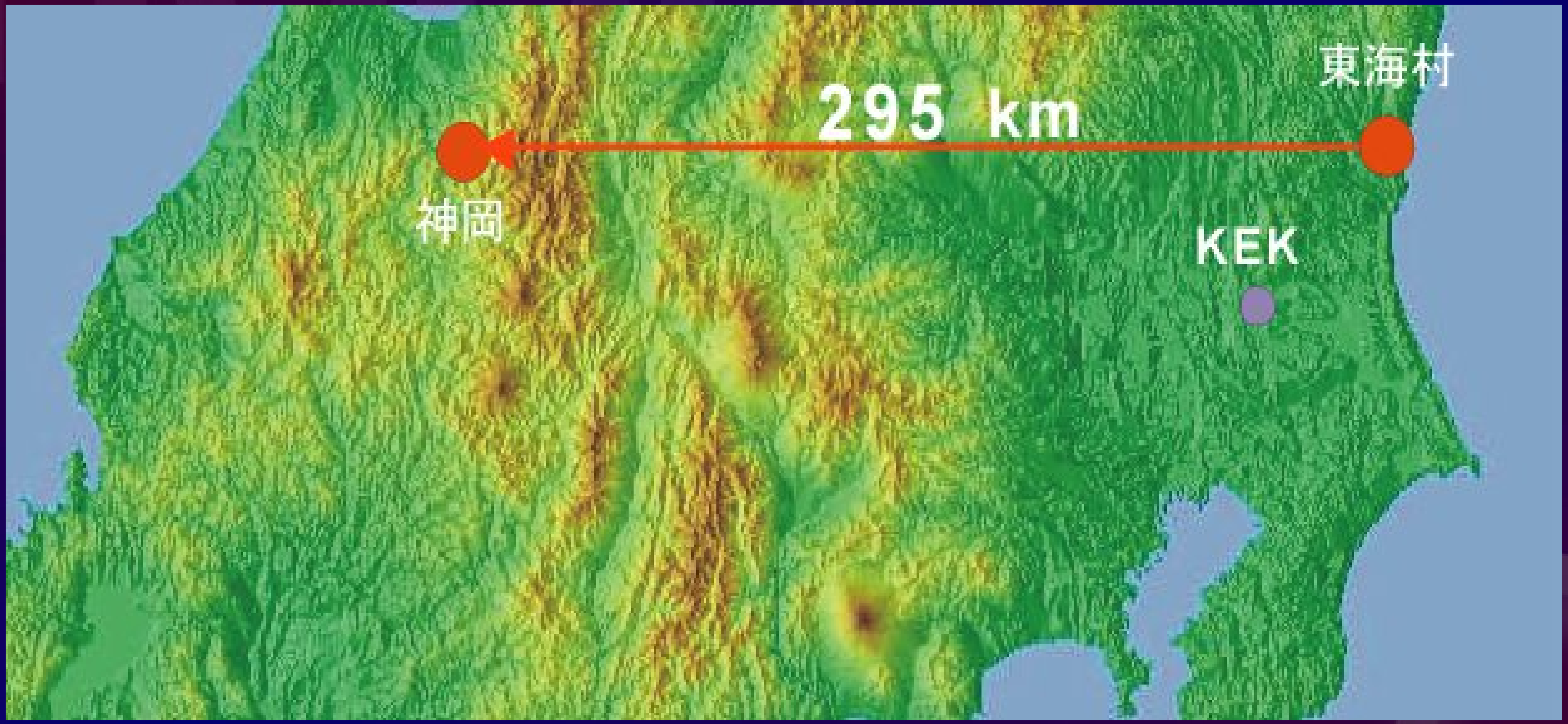
Hints of $\theta_{13} > 0$?

KamLAND 2011
and others



$\Delta\chi^2$-profiles projected onto the $\sin^2\theta_{13}$ axis for different combinations of the oscillation data floating the undisplayed parameters ($\tan^2\theta_{12}$, Δm^2_{21}).

T2K: The Tokai-to-Kamioka



Neutrino Oscillation Experiment

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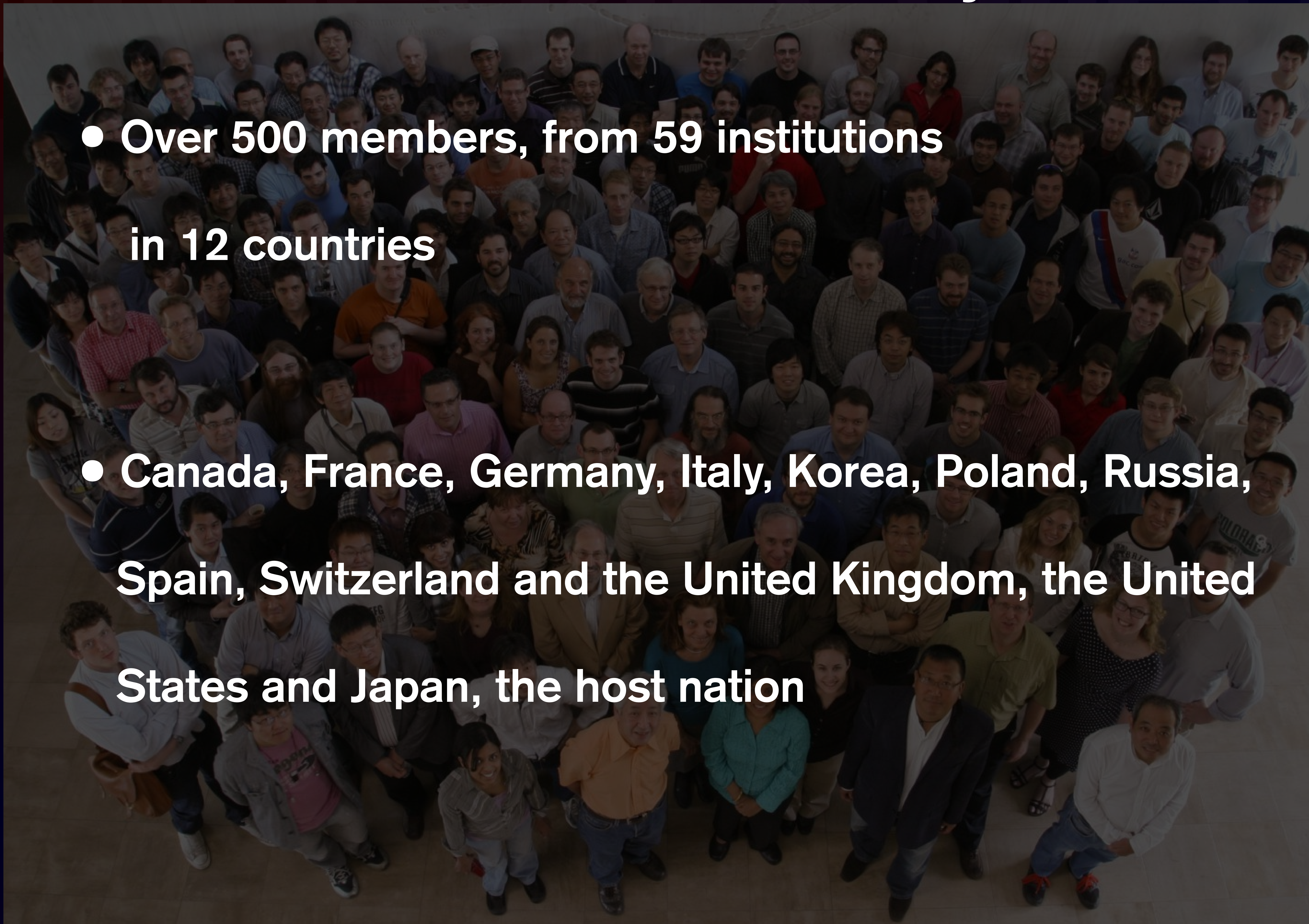
The purpose of T2K is to probe the Δm^2 region near 2 to 3 × 10^{-3} [eV^2] with a muon neutrino beam

The T2K Collaboration May 2011

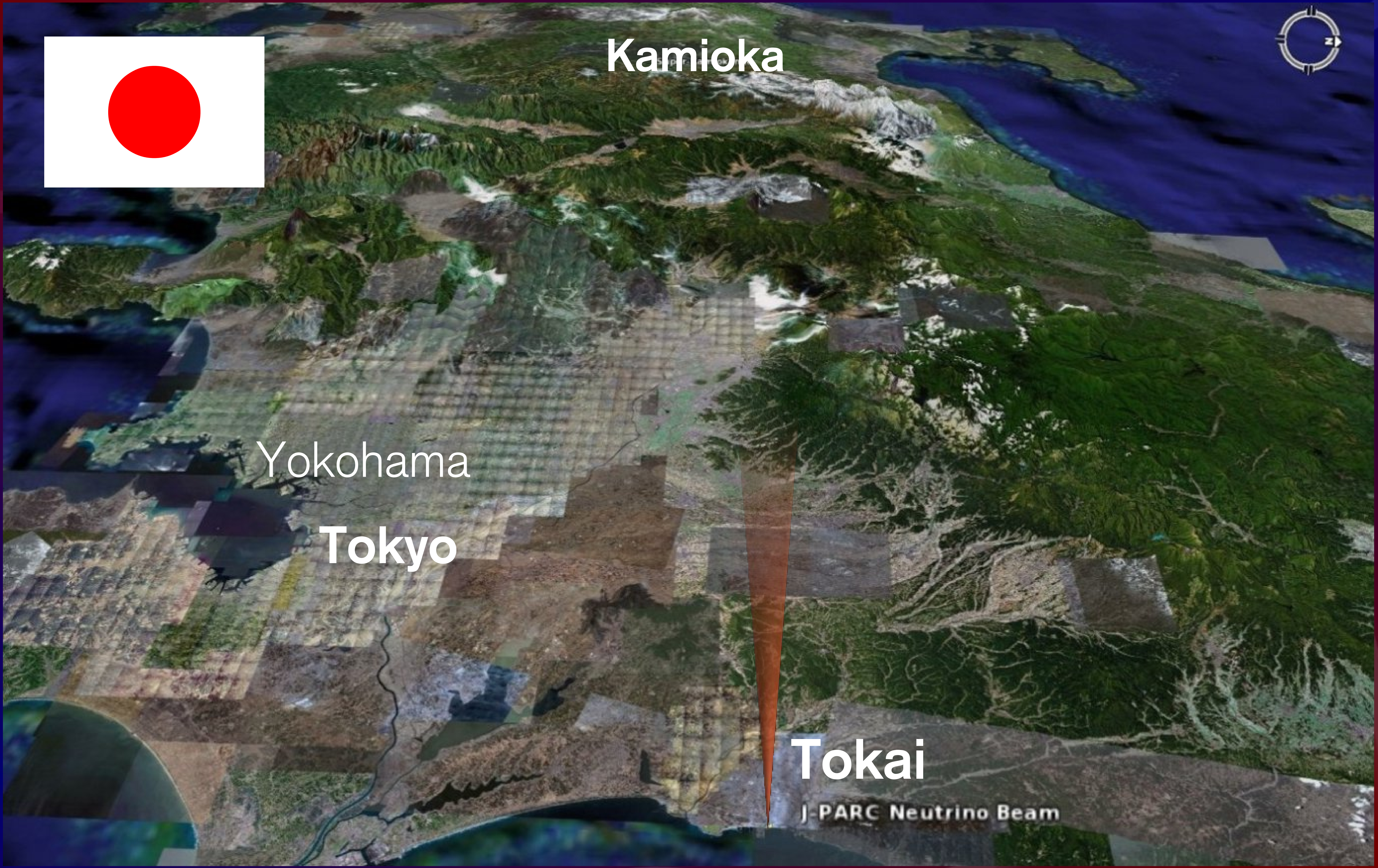
The T2K Collaboration May 2011



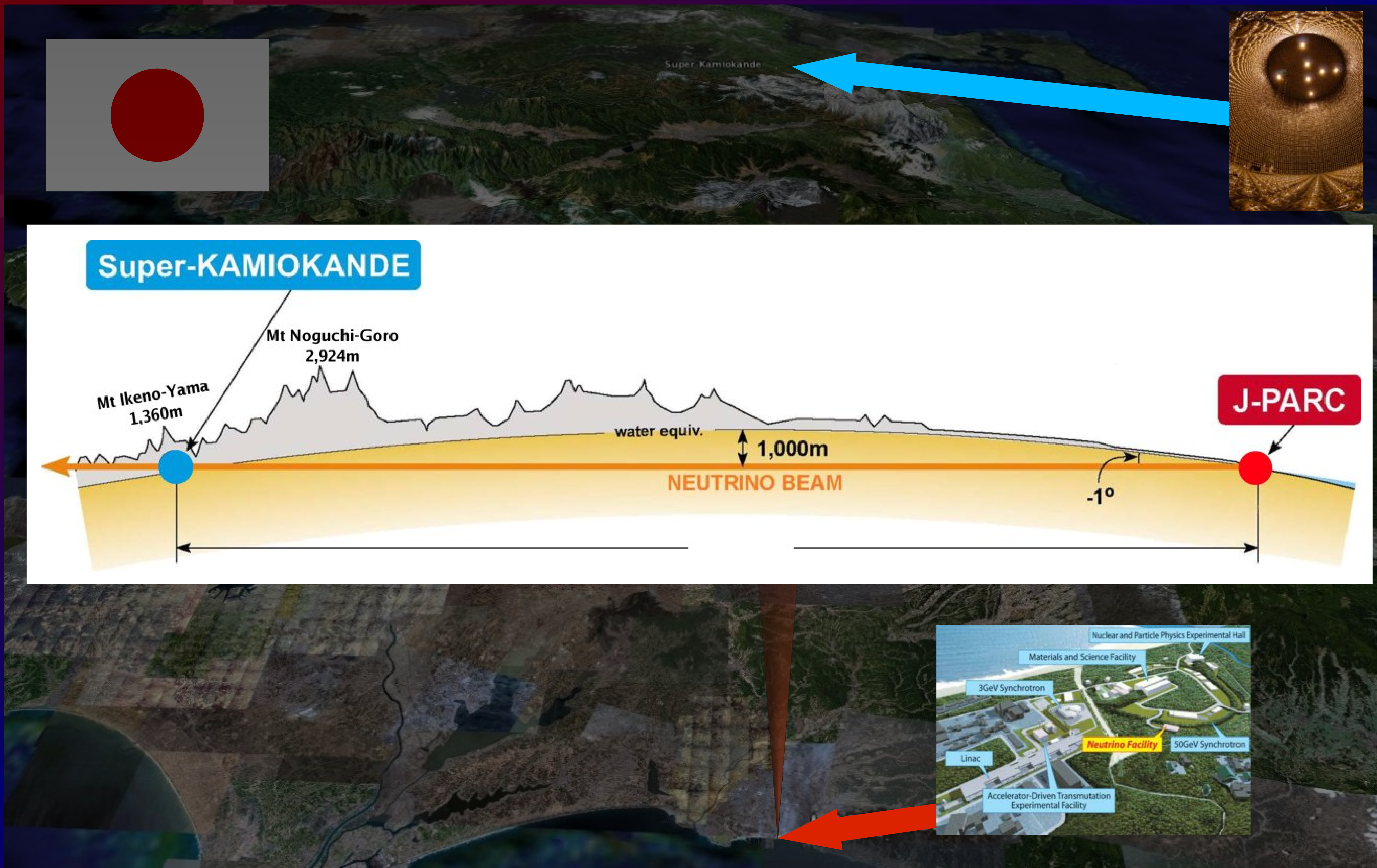
- Over 500 members, from 59 institutions in 12 countries
- Canada, France, Germany, Italy, Korea, Poland, Russia, Spain, Switzerland and the United Kingdom, the United States and Japan, the host nation

The T2K Collaboration May 2011

T2K: Tokai-to-Kamioka



T2K: Tokai-to-Kamioka



J-PARC

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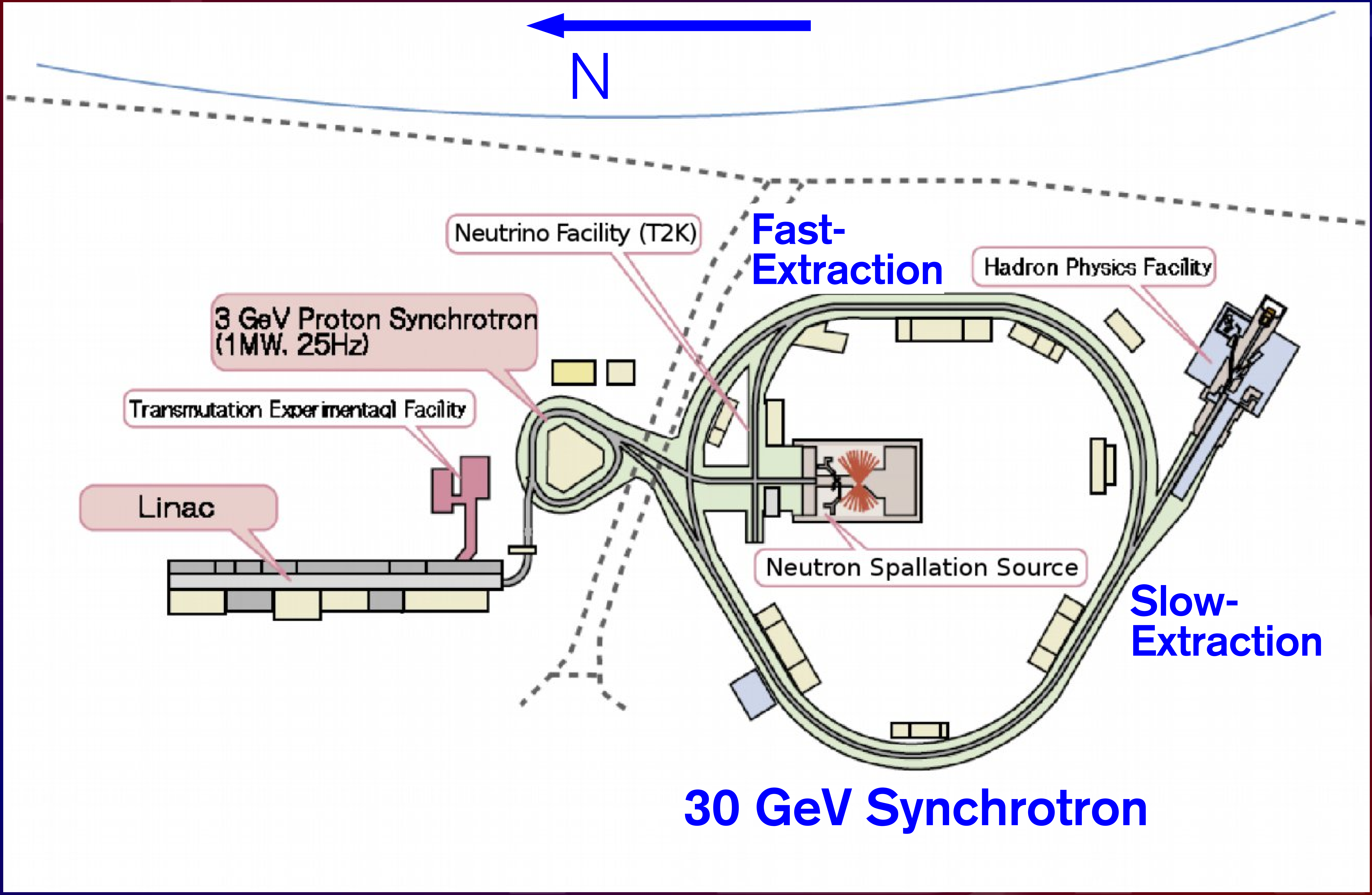
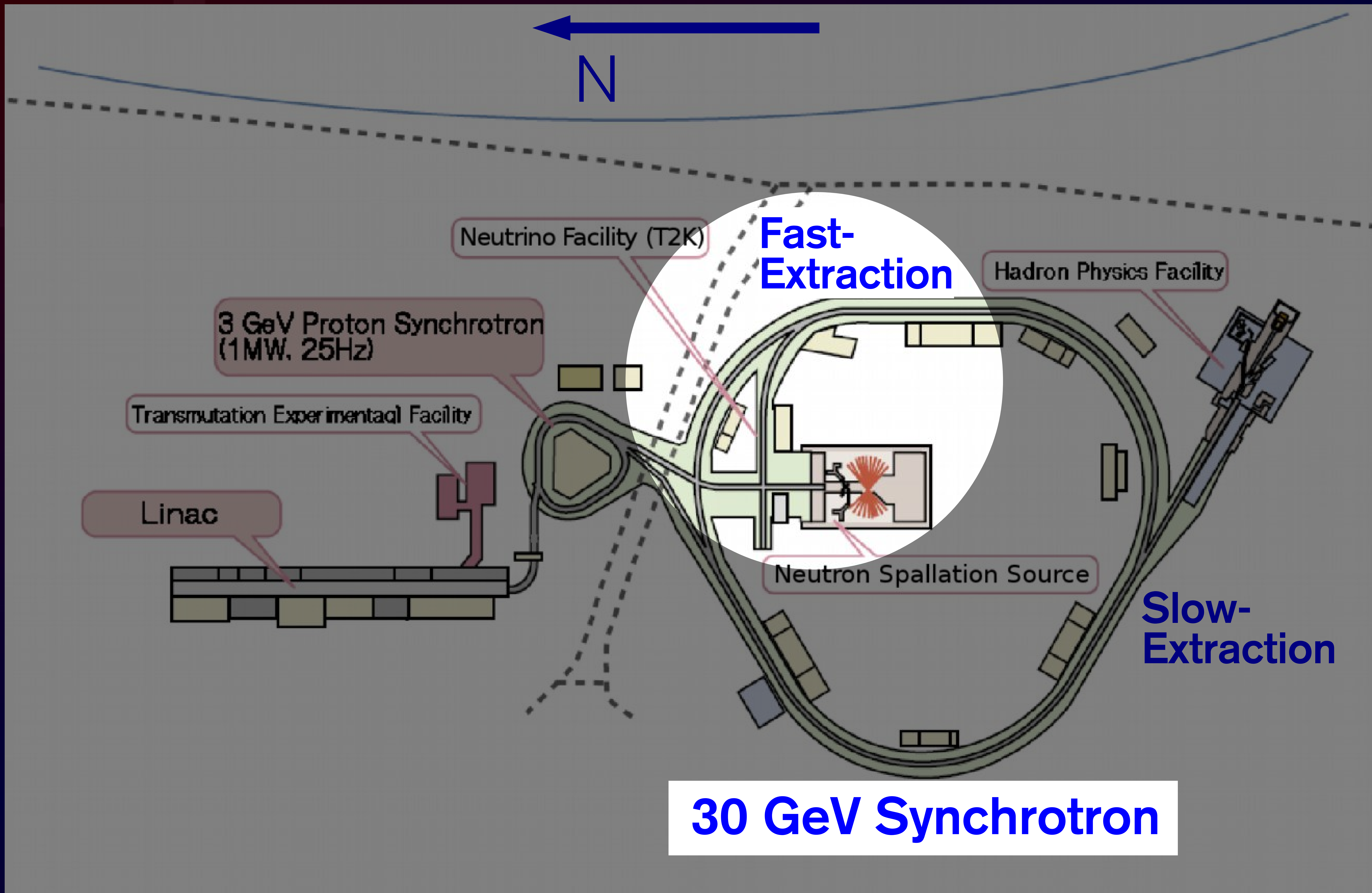


N
Neutrino Facility (T2K)
Fast-
Extraction
Hadron Physics Facility
3 GeV Proton Synchrotron
(1MW, 25Hz)
Transmutation Experimentaql Facility
Linac
Neutron Spallation Source
Slow-
Extraction
30 GeV Synchrotron

J-PARC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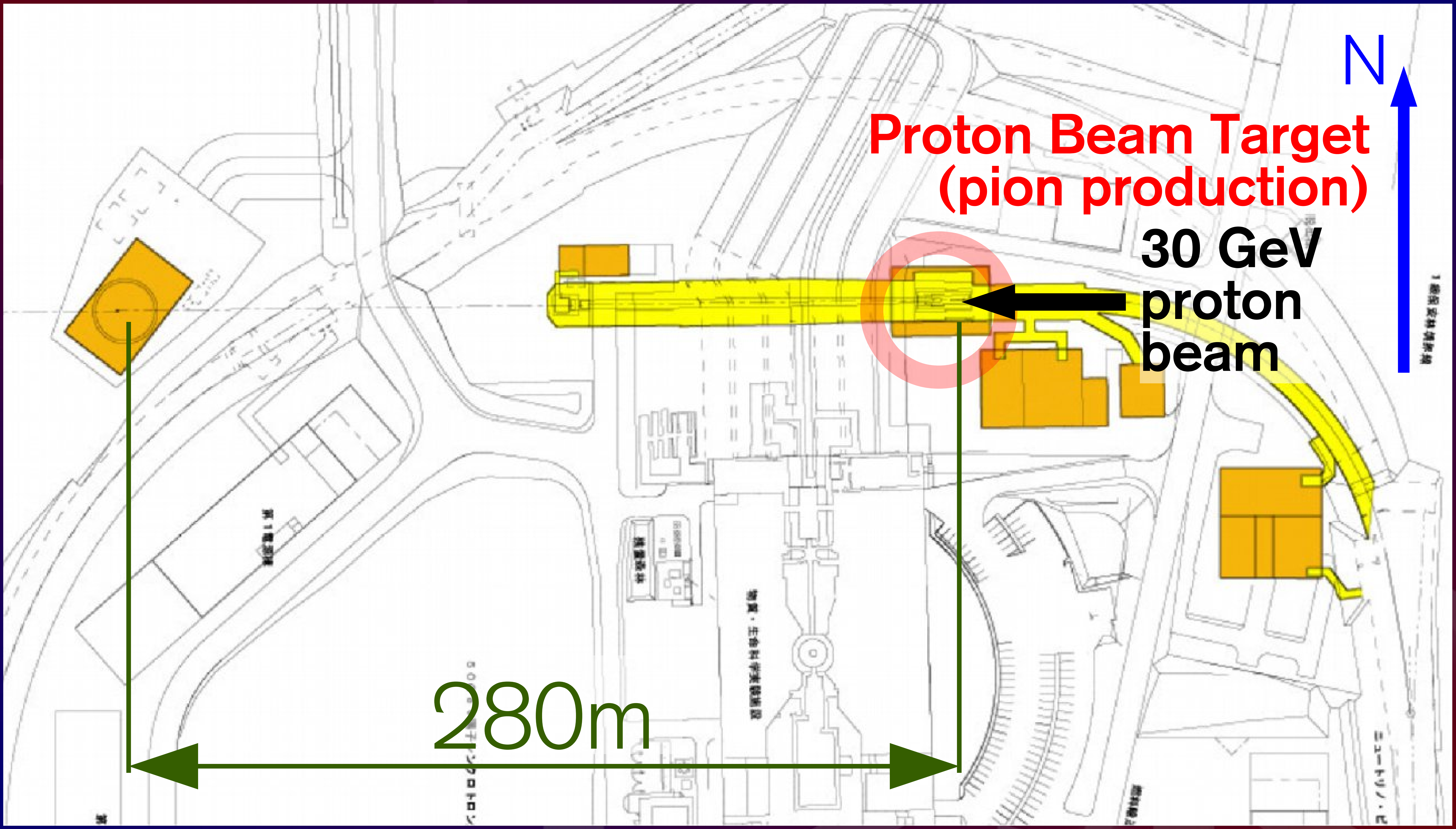
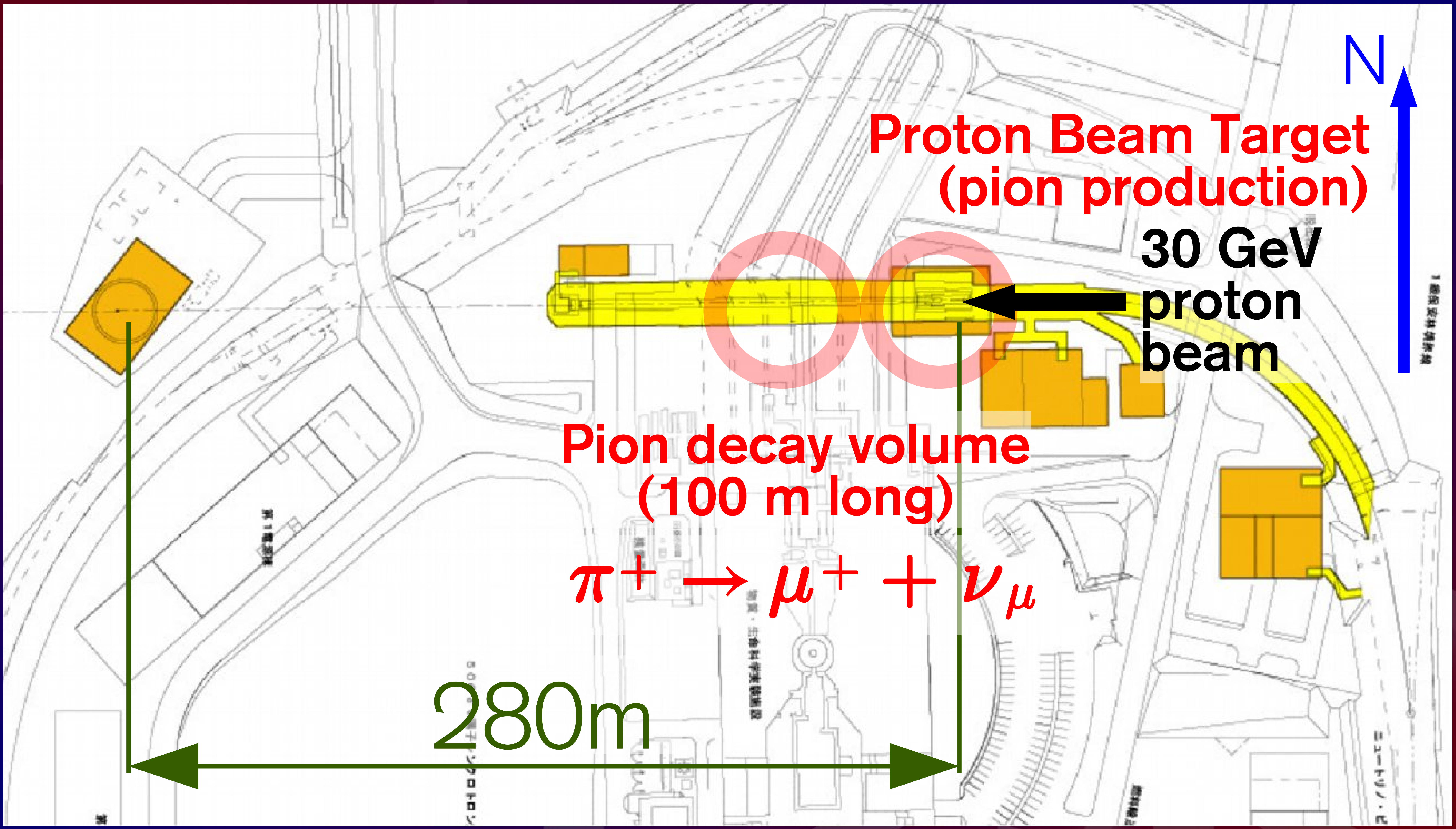
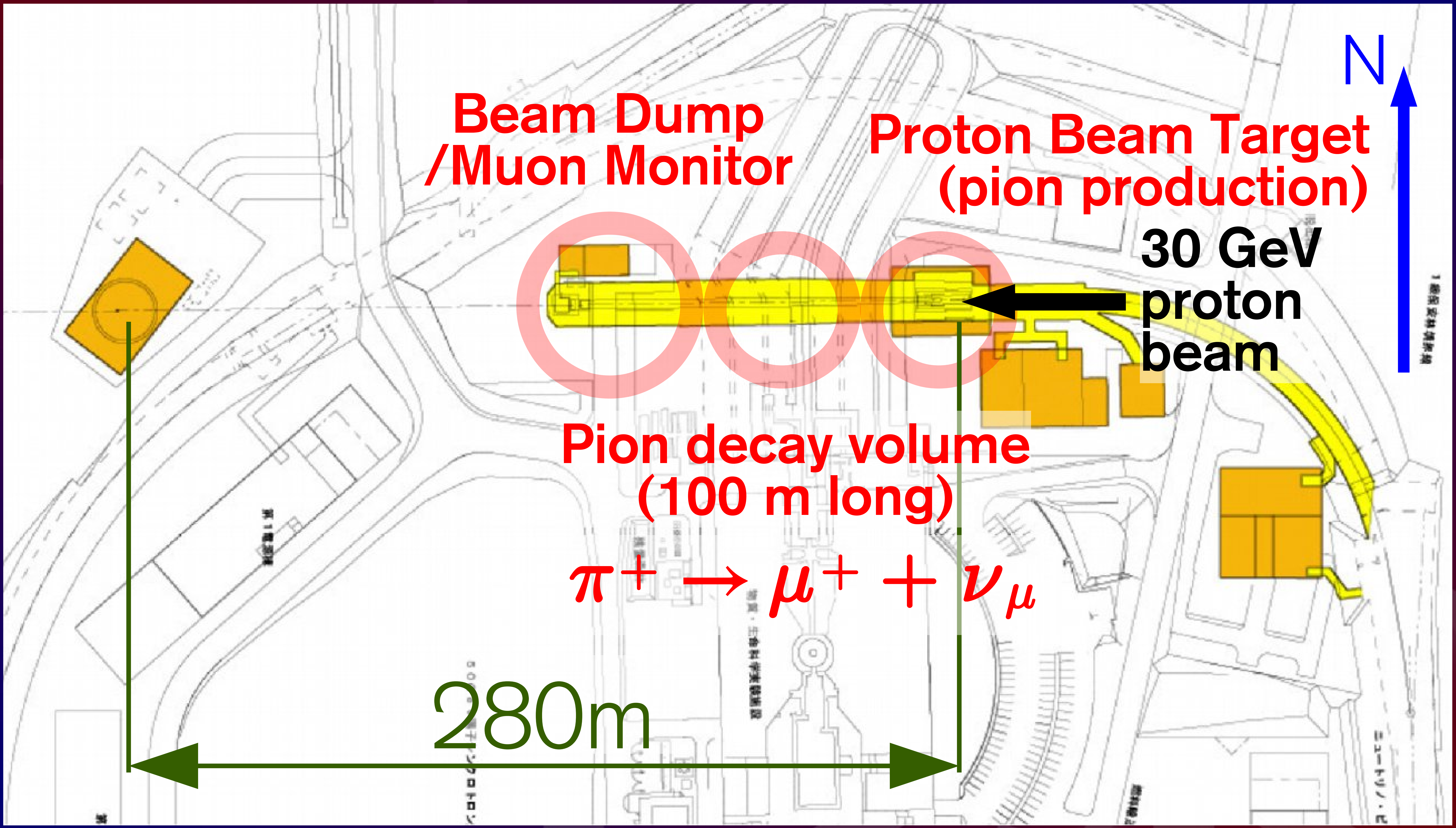
T2K Neutrino Beam Production



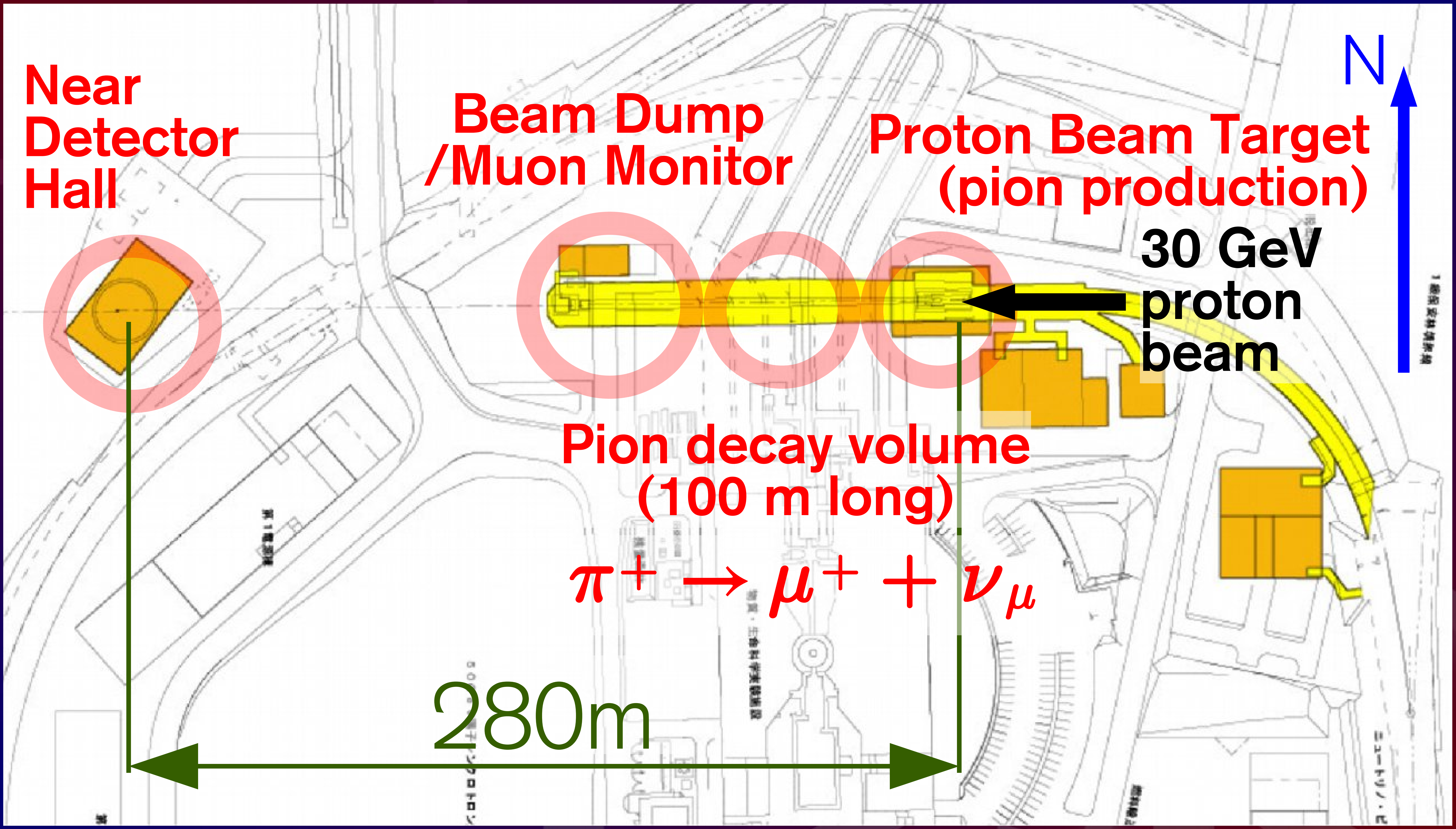
T2K Neutrino Beam Production



T2K Neutrino Beam Production



T2K Neutrino Beam Production



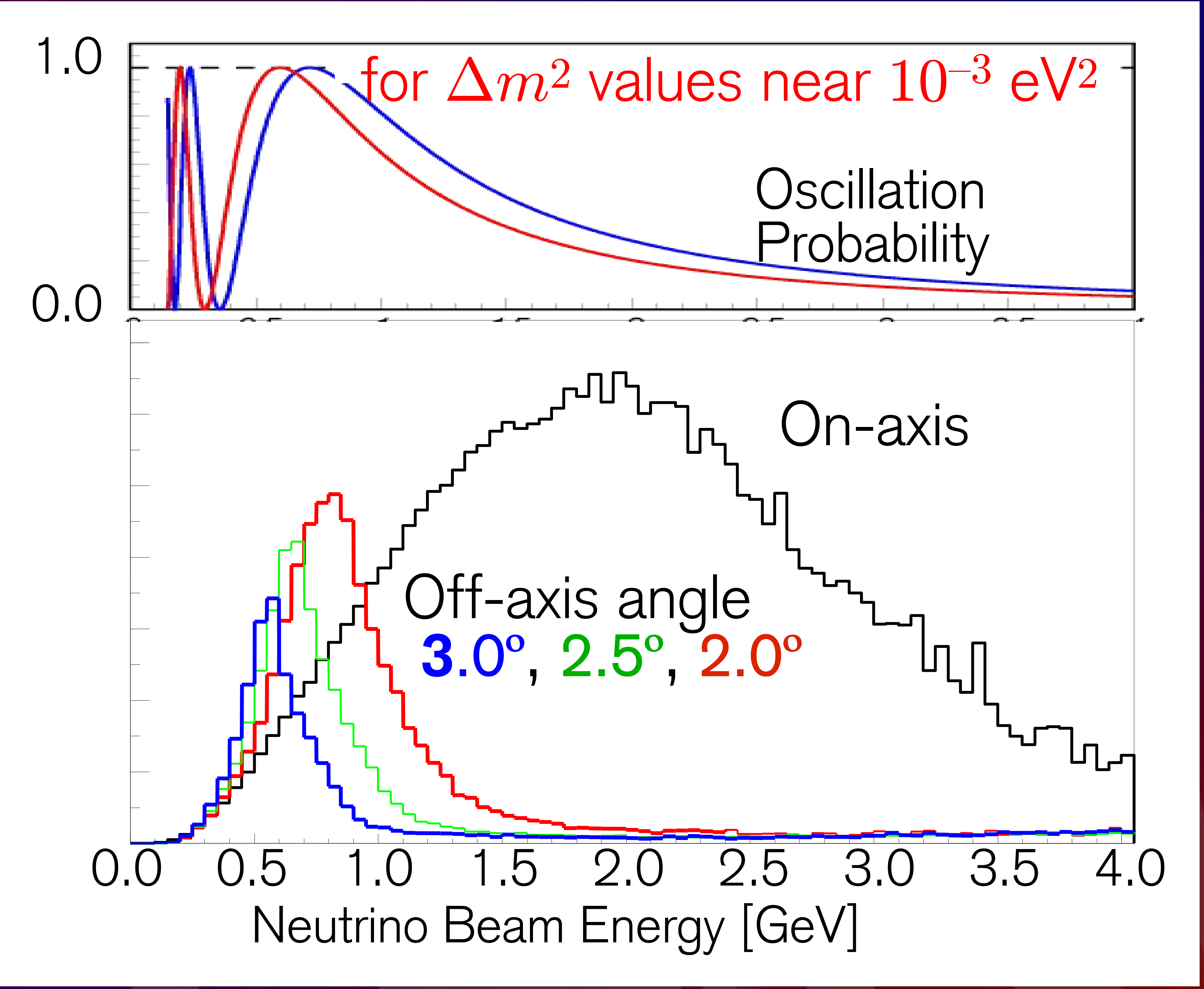
Off-Axis Neutrino Beam

Pion decay kinematics send lower energy neutrinos to higher off-axis angles

Can create a more intense low-energy beam

Idea originally from Brookhaven, but never implemented before

2.5 degree off-axis angle chosen for T2K



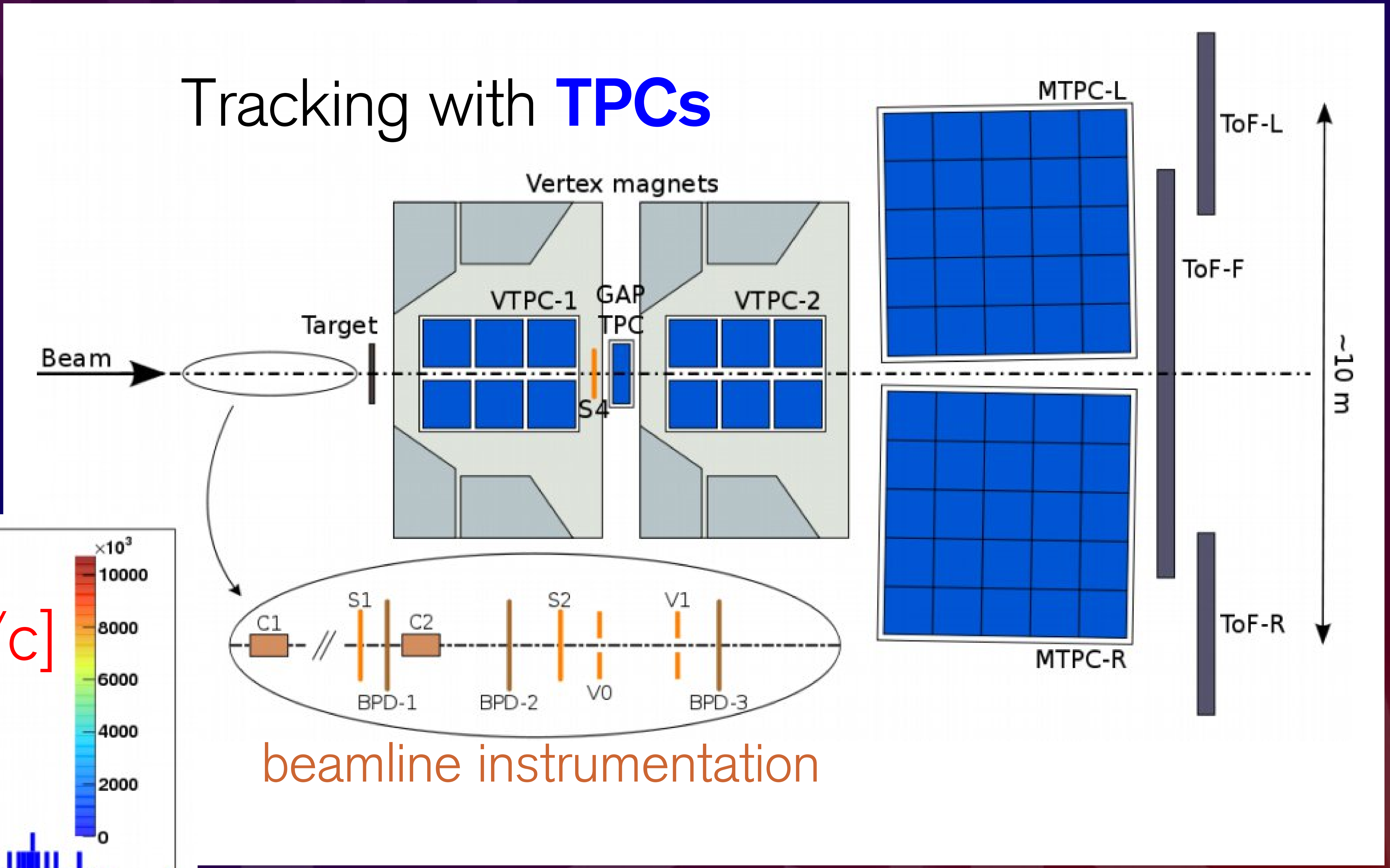
Hadron Production Studies

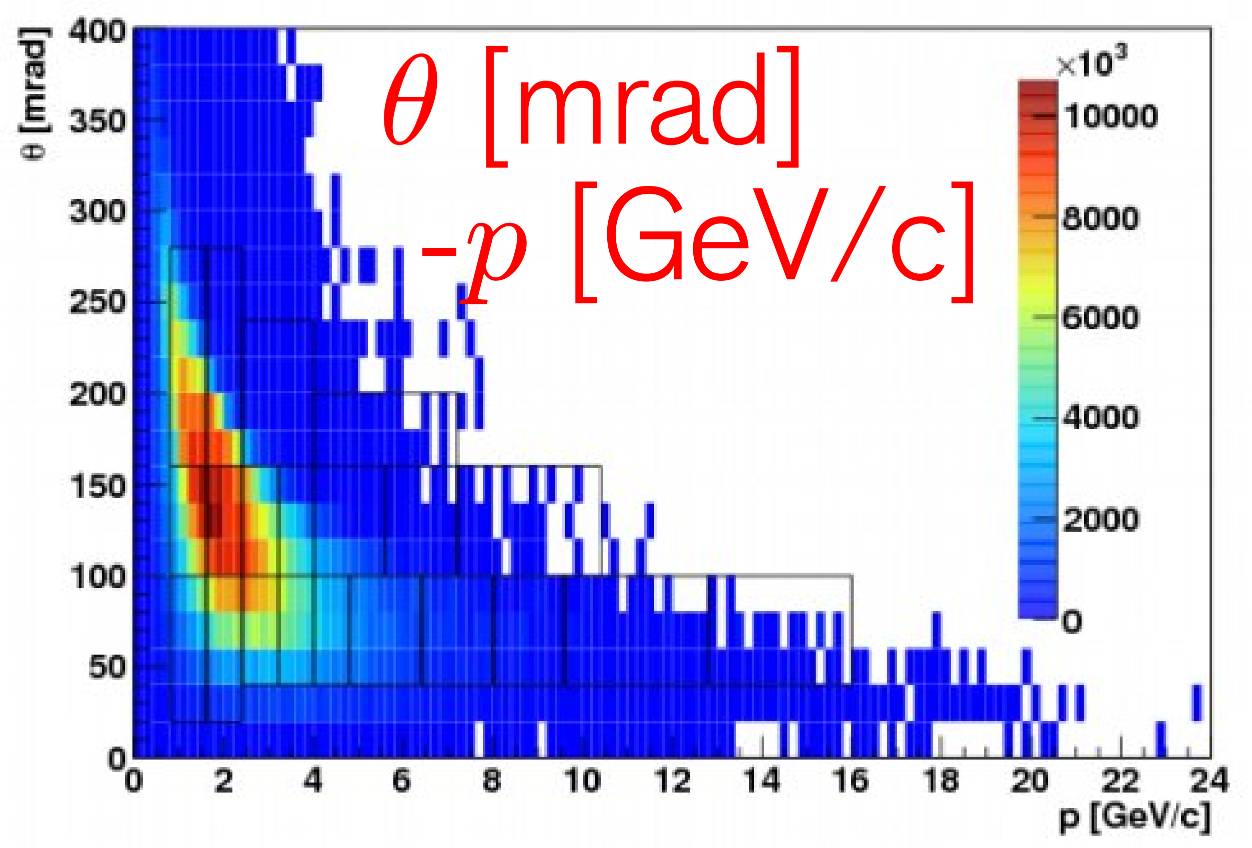
NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) at CERN

Proton beam interactions on T2K replica target & "thin" target

Data since 2007

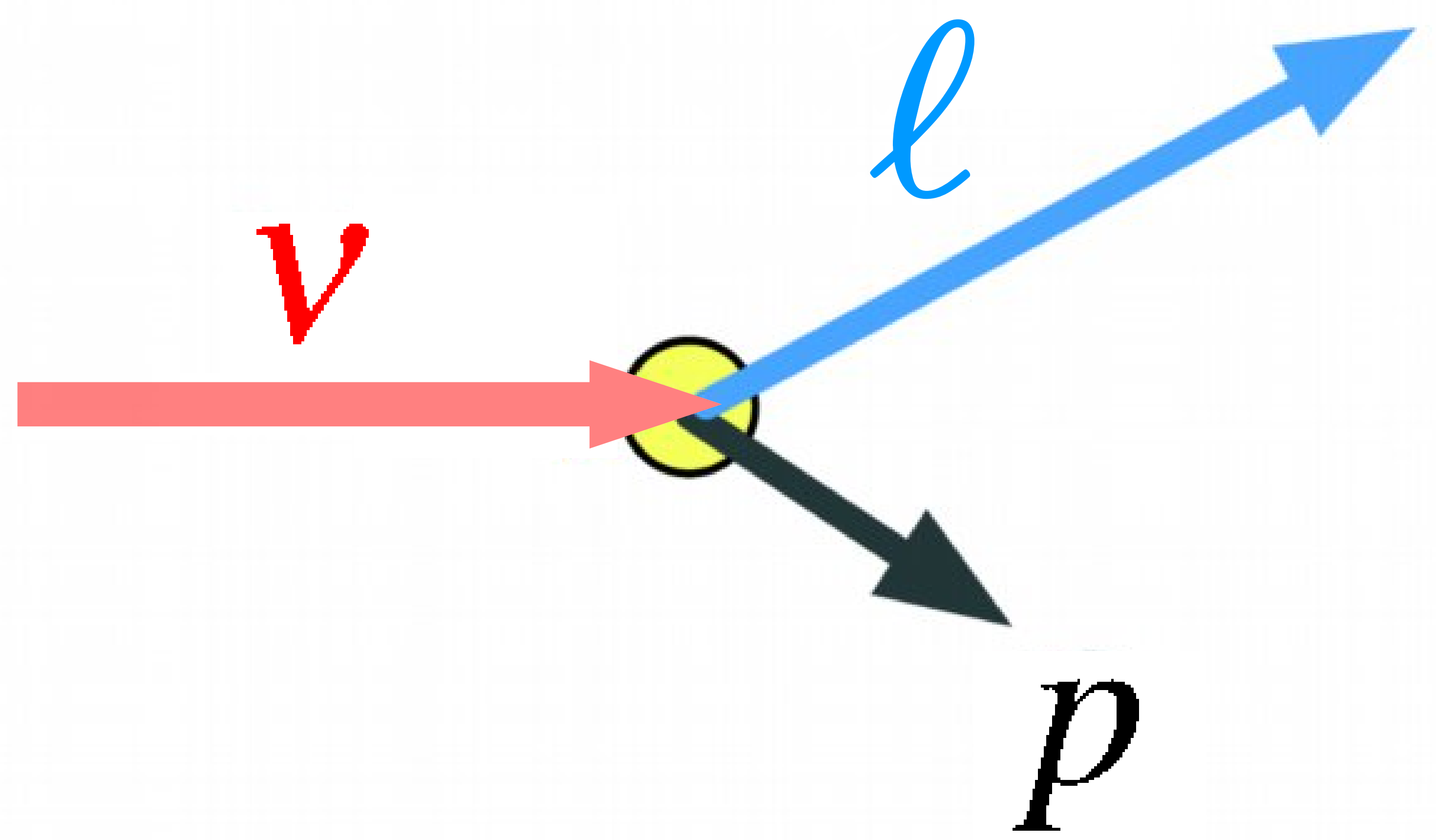
Kinematics of pions, Kaons and protons





⇒ input to T2K neutrino beam predictions

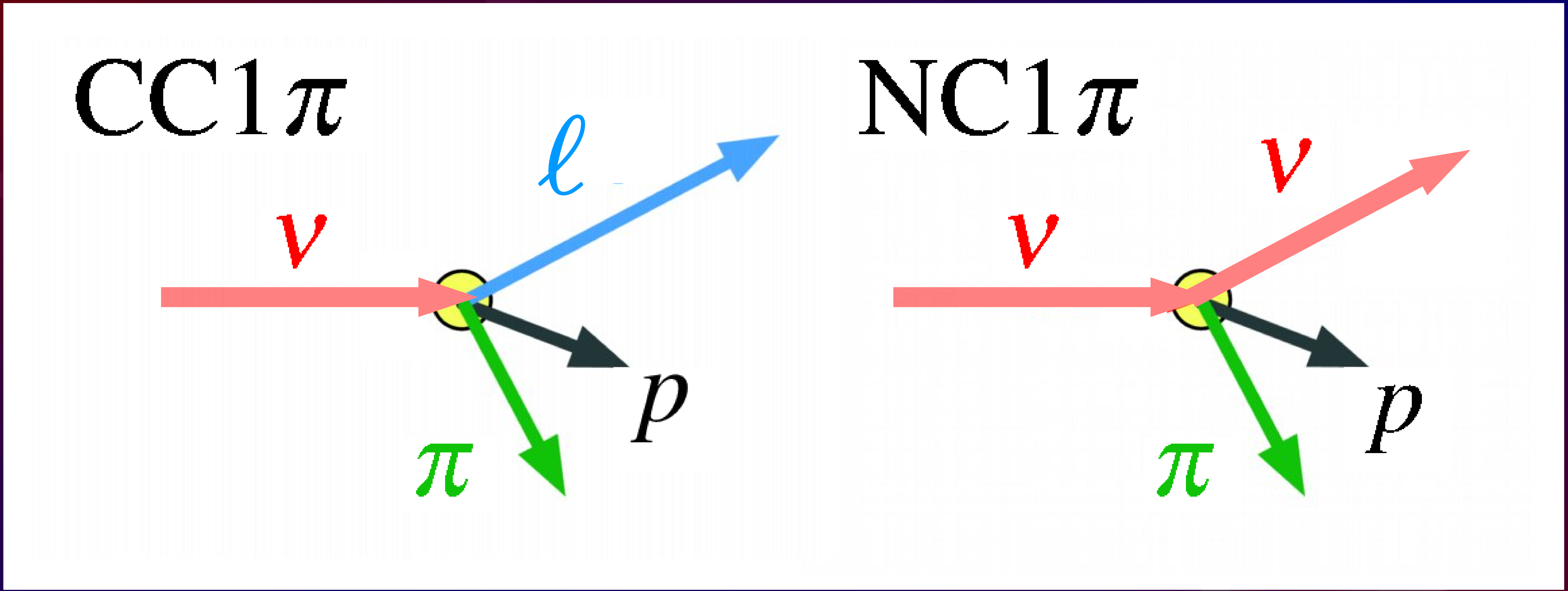
Charged Current Quasi-Elastic Neutrino-Nucleon Interactions



$$\text{CCQE} : \nu_\ell + n \rightarrow \ell + p$$

- Clean final state, can fully reconstruct neutrino energy and flavour from lepton ID and kinematics alone
- Main signal event category at T2K
- Complicated by nuclear effects (O, C etc)

non-CCQE Interactions



- CC1π: messy final state, more difficult to reconstruct in Water Cherenkov detectors such as Super-K
- NC1$\pi^{\pm}$: pion can mimic muons, little information on the neutrino
- NC1π^0: gamma from π^0 can be misidentified as electrons
- More particles produced at higher energies

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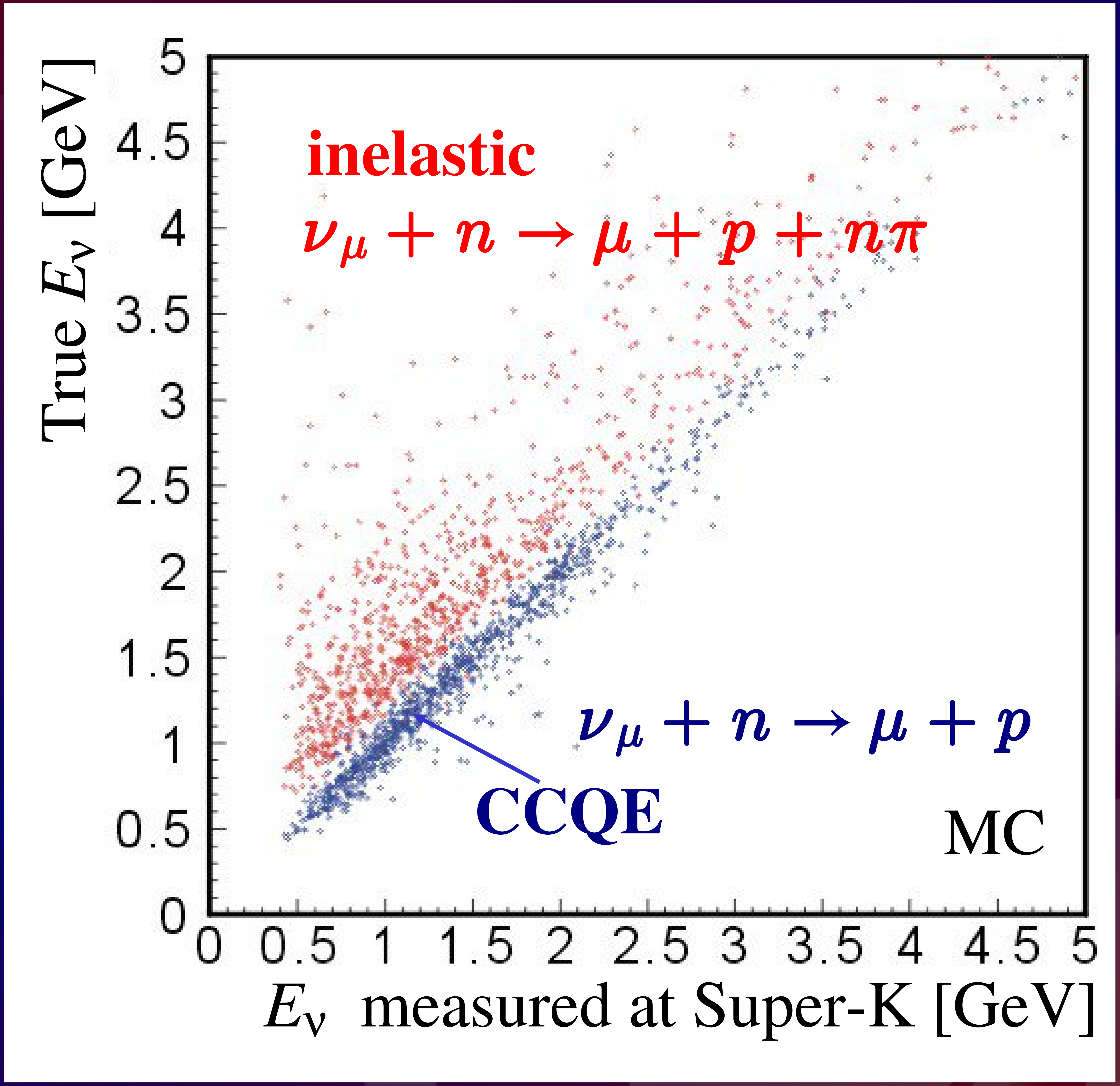
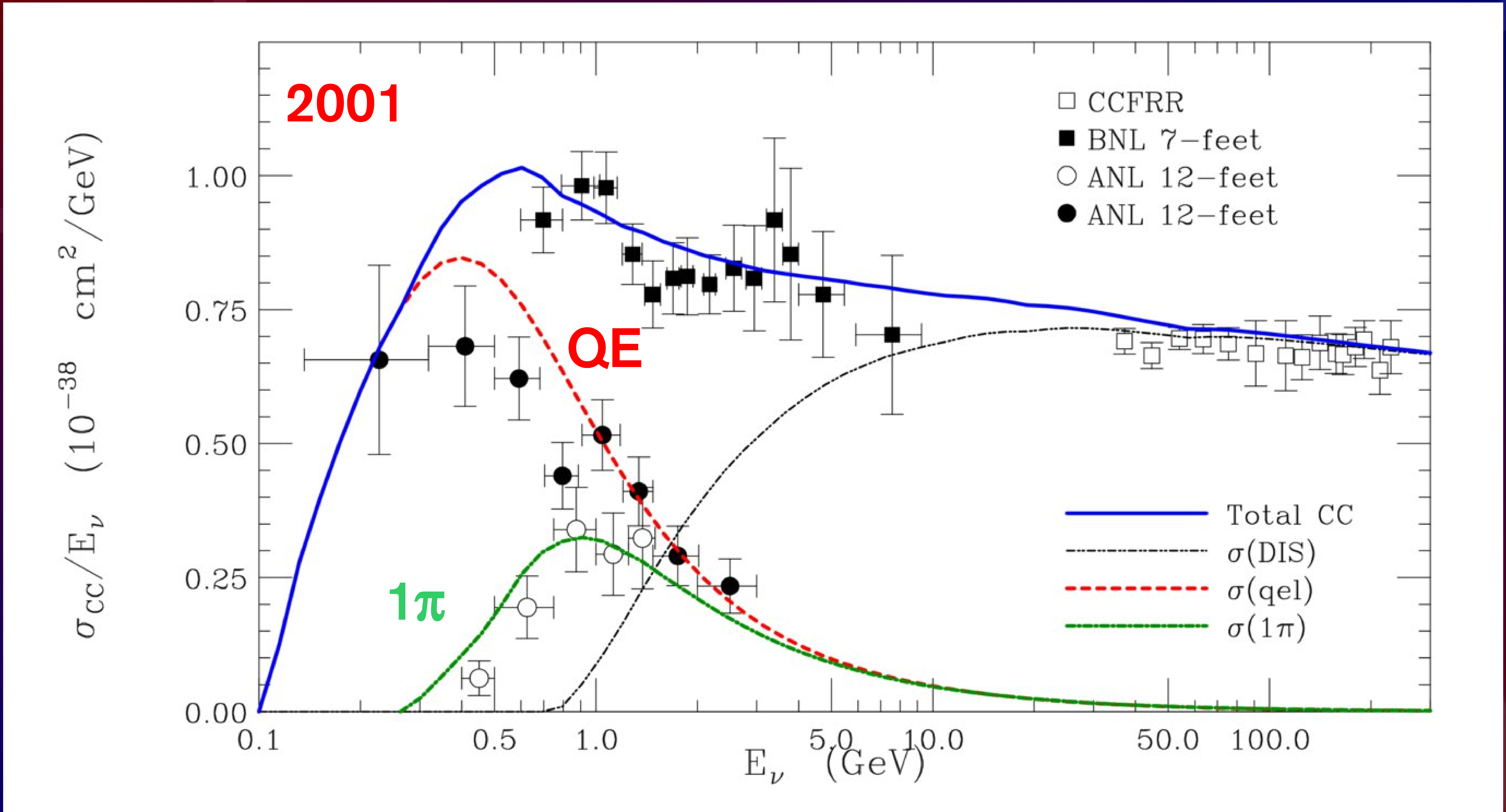
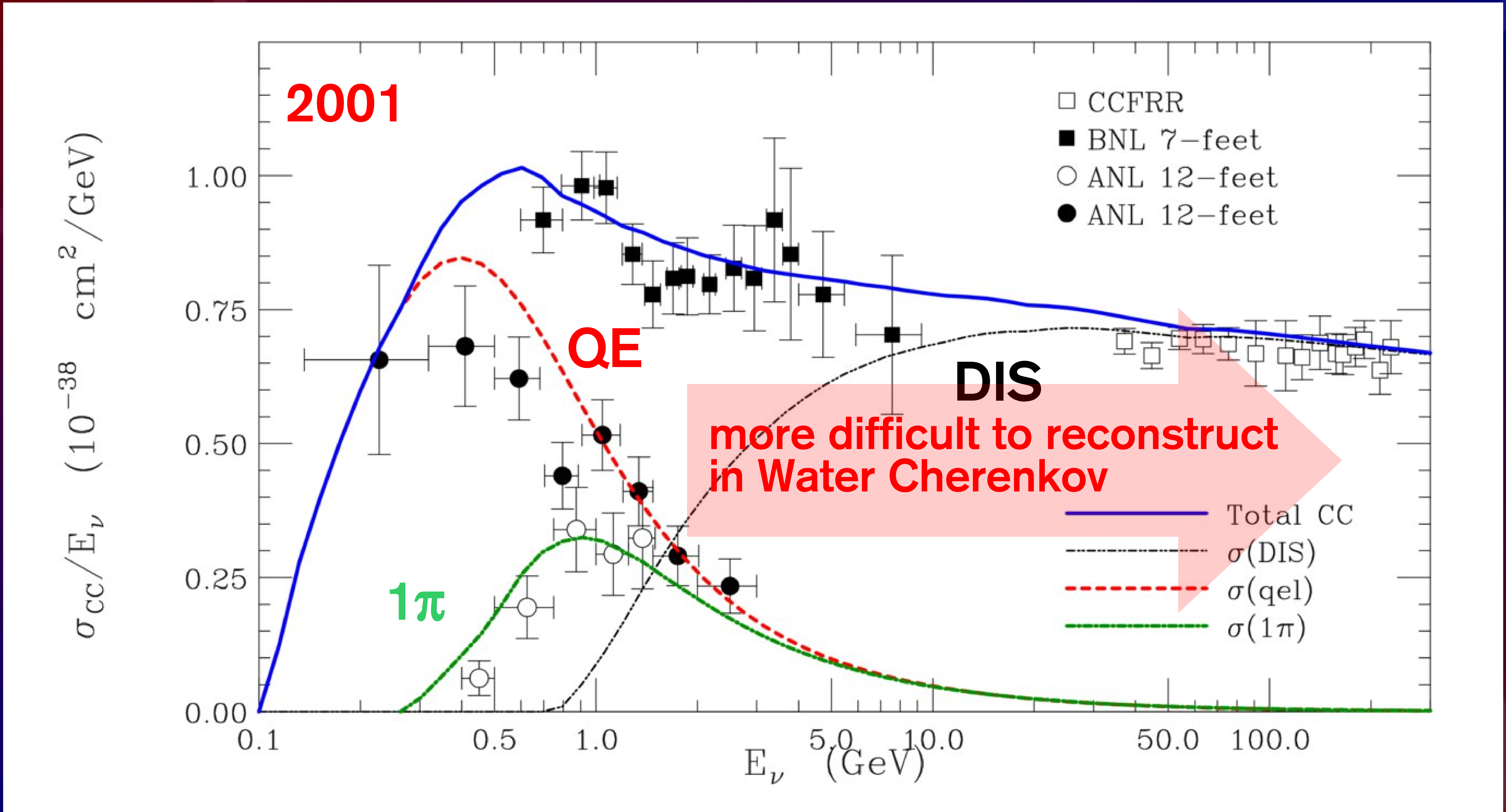
ν_μ Energy Reconstruction at Super-K



Neutrino Interactions Near 1 GeV



Neutrino Interactions Near 1 GeV



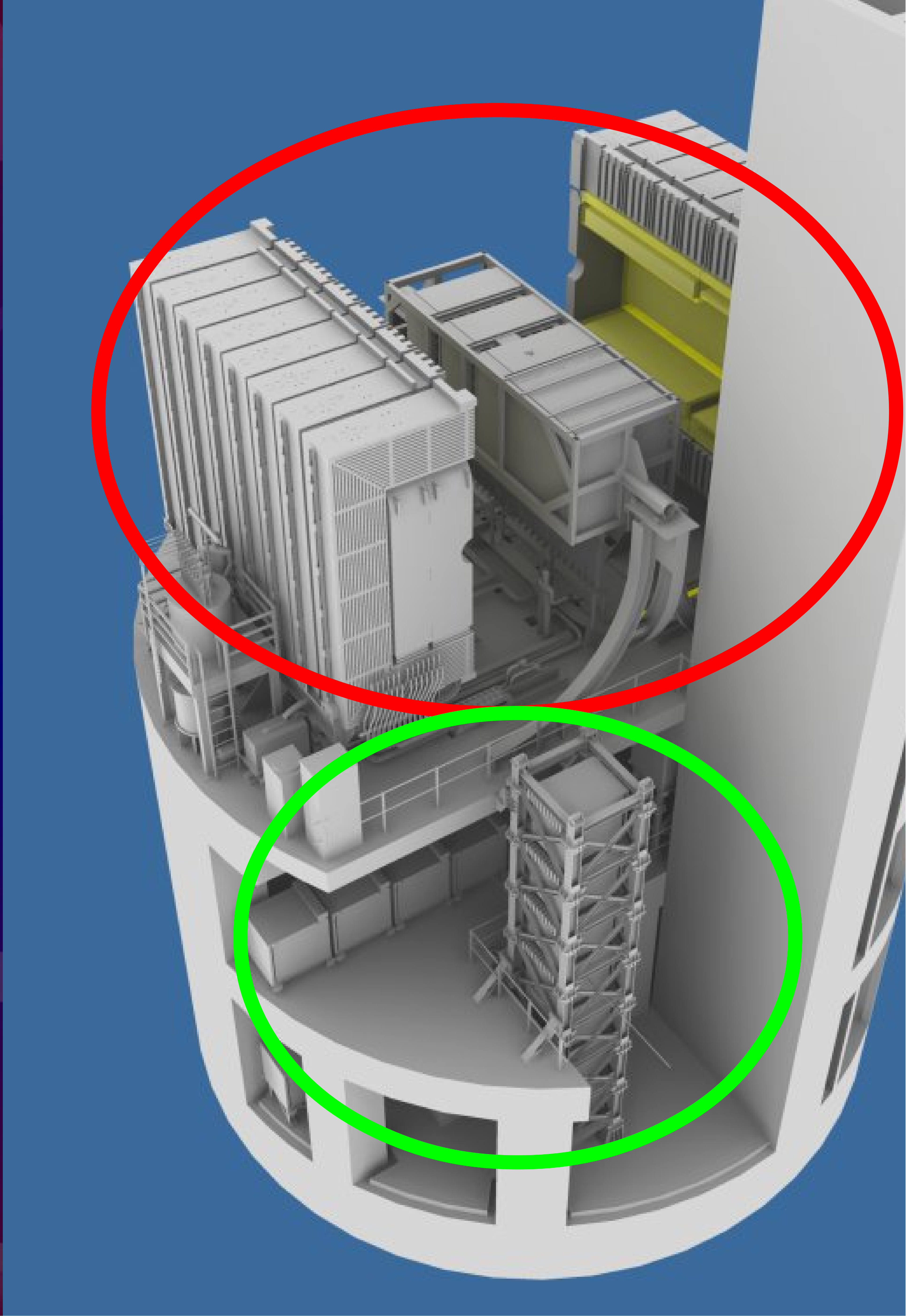
- Need to stay below a few GeV to reduce backgrounds
- Also need to learn more about neutrino cross sections

T2K Design Principles

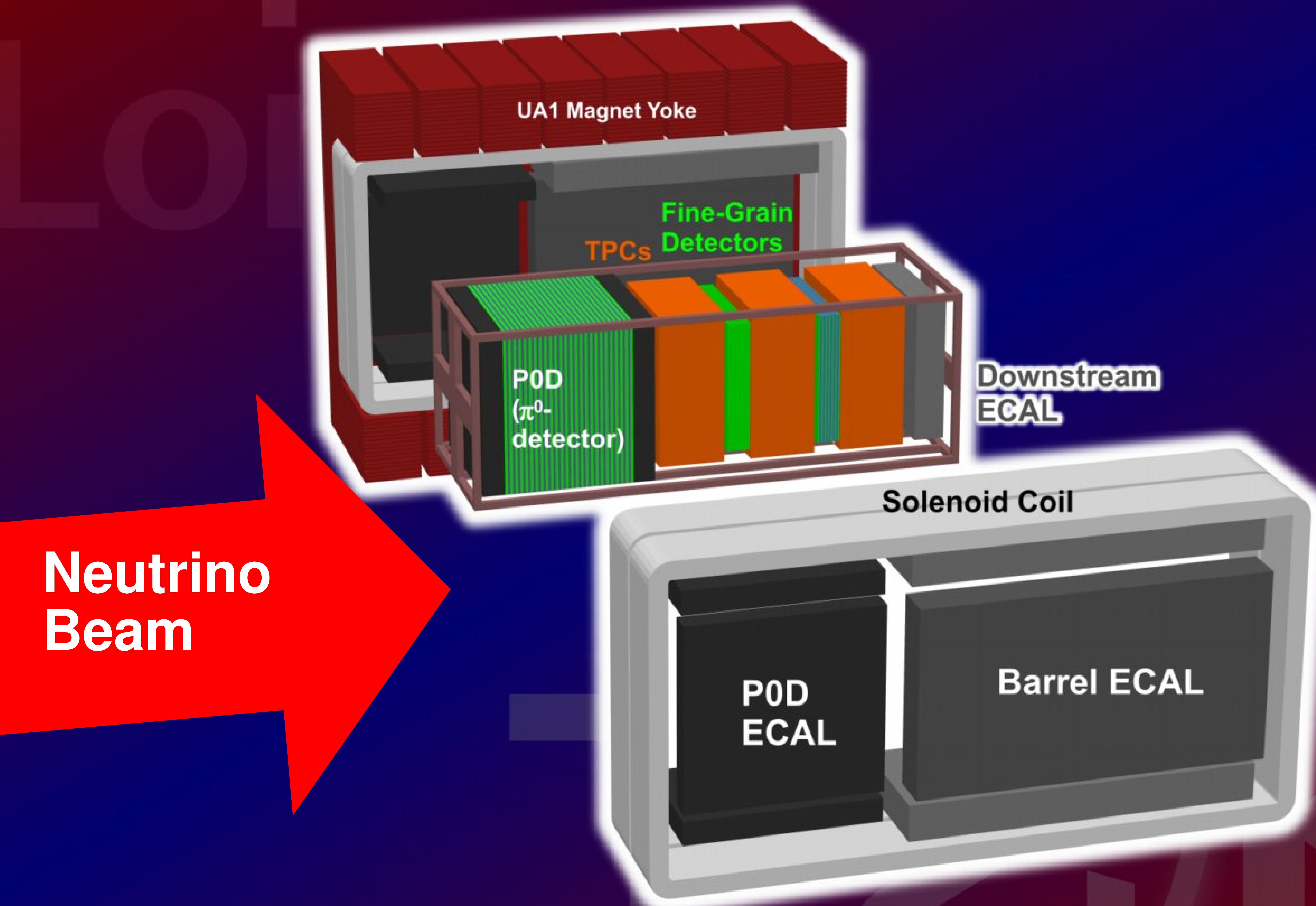
- **Large Water Cherenkov** Far Detector (Super-Kamiokande)
  - **proven, well-understood and calibrated detector** with excellent μ/e discrimination
  - large diameter: **excellent e/μ energy measurement up to several GeV**
- **Sub-GeV peak neutrino energy**
  - high fraction of clean CCQE events
- **High-power** neutrino beam of up to 750 kW
- **295 km baseline**
  - distance between J-PARC laboratory and Kamioka
- **Off-axis beam**
  - much reduced high-energy tail and ν_e contamination
- **“Near Detectors”** for Detailed beam characterisation
  - **dedicated ν detector for beam direction** and **sophisticated off-axis detector** for beam spectrum composition and interactions

T2K Near Detectors at J-PARC

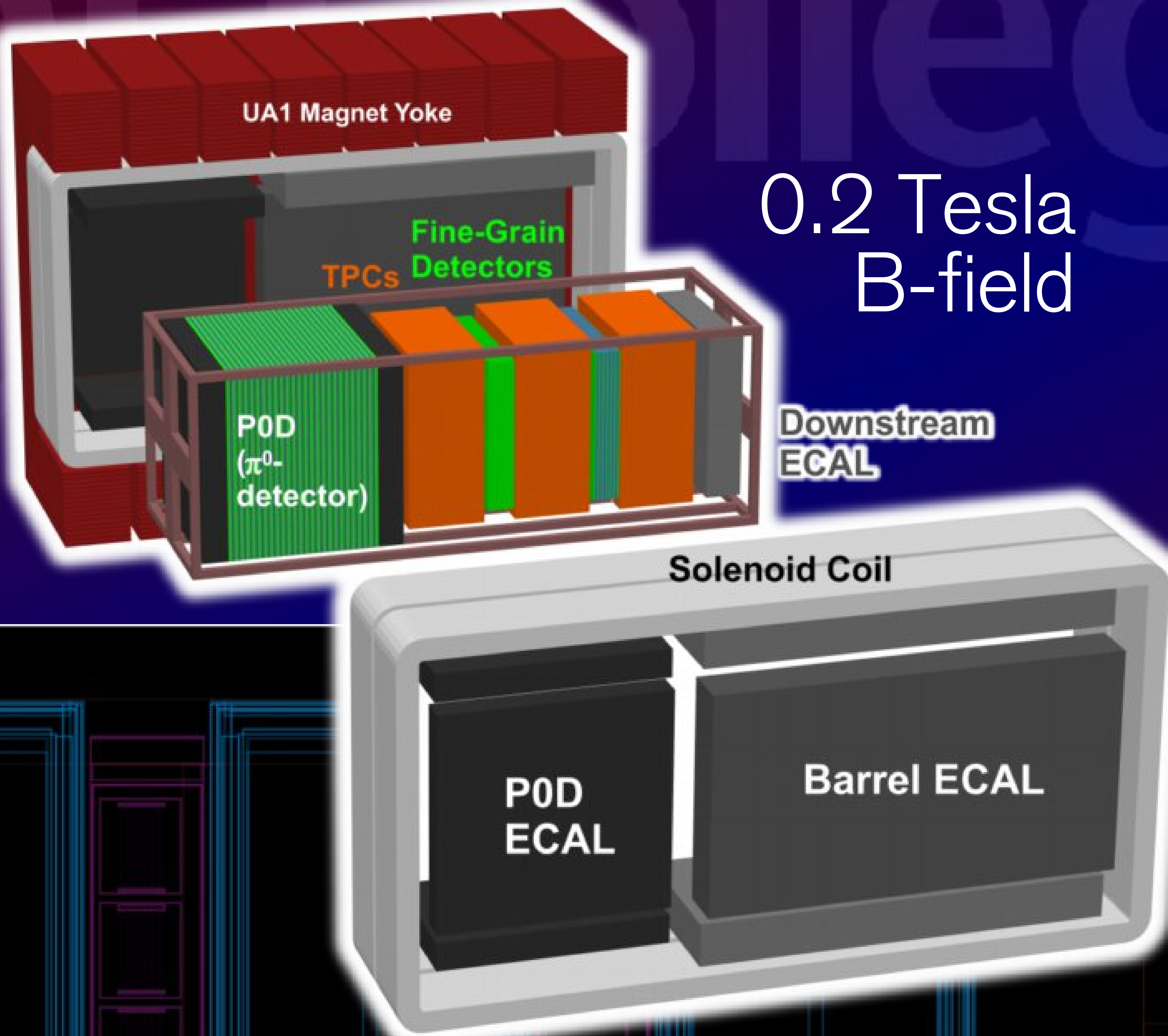
- 280m from proton beam target
- High-mass on-axis **INGRID** detector
  - "cross-hairs" target for neutrino beam
- Fully-instrumented, off-axis **ND280** detector



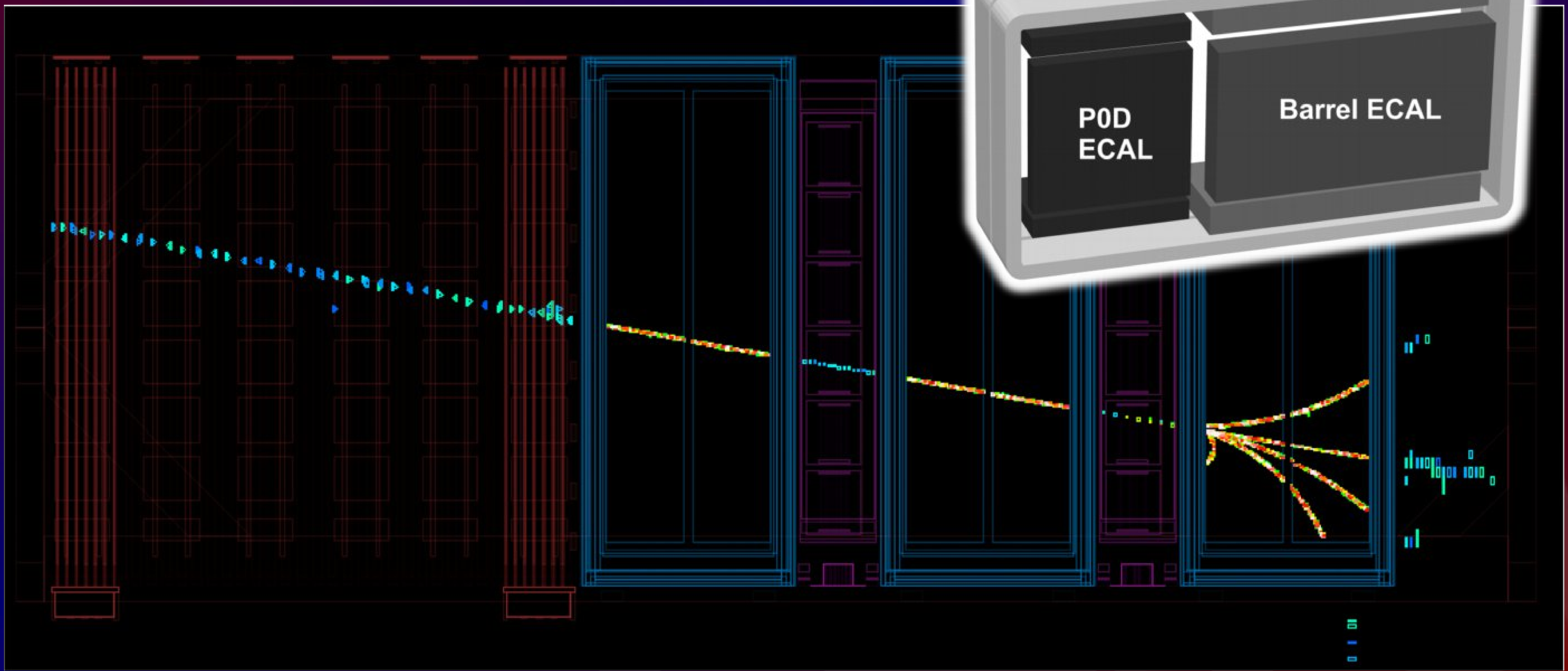
The Off-Axis ND280 Detector



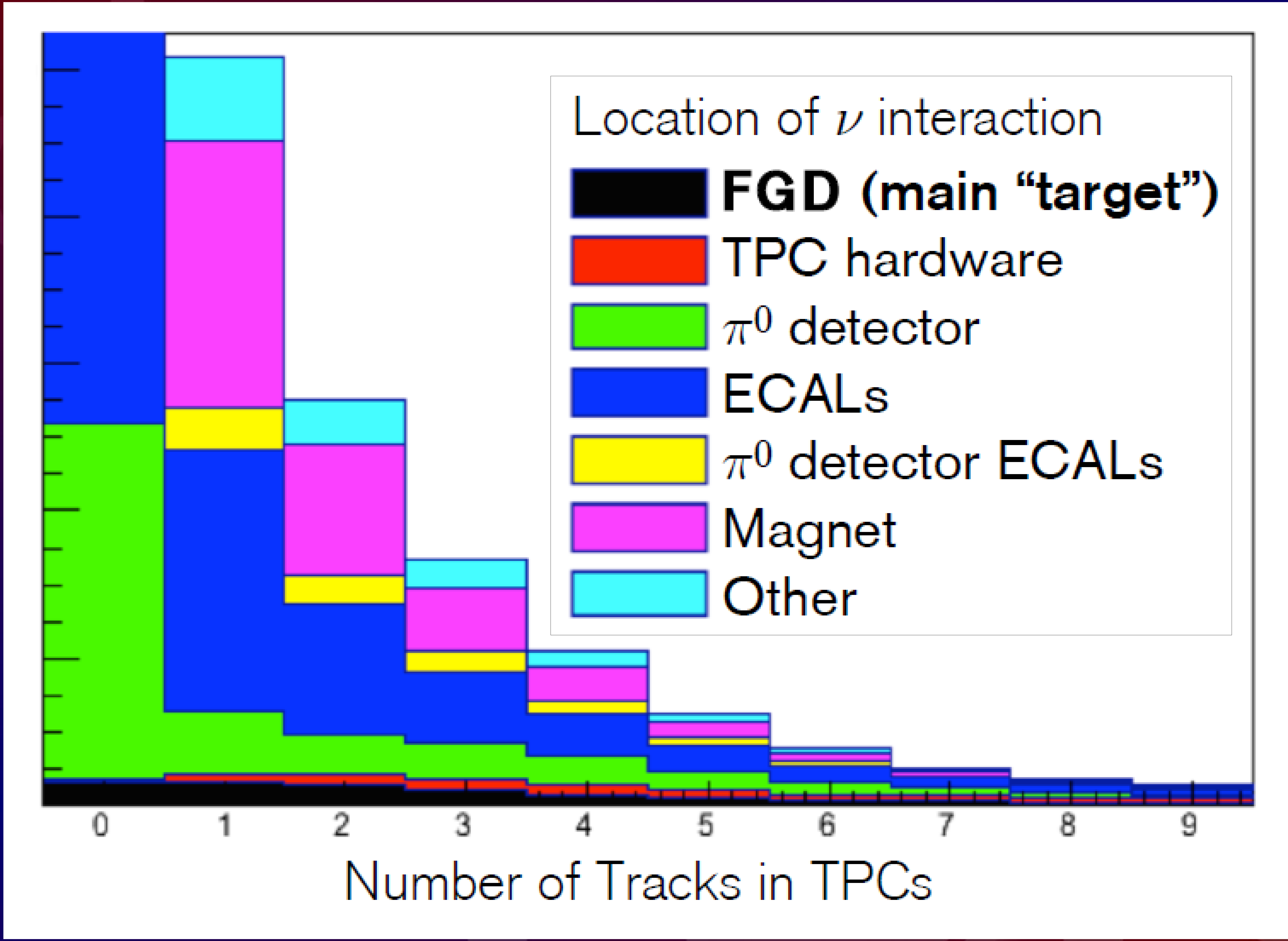
ND280 Detector Events



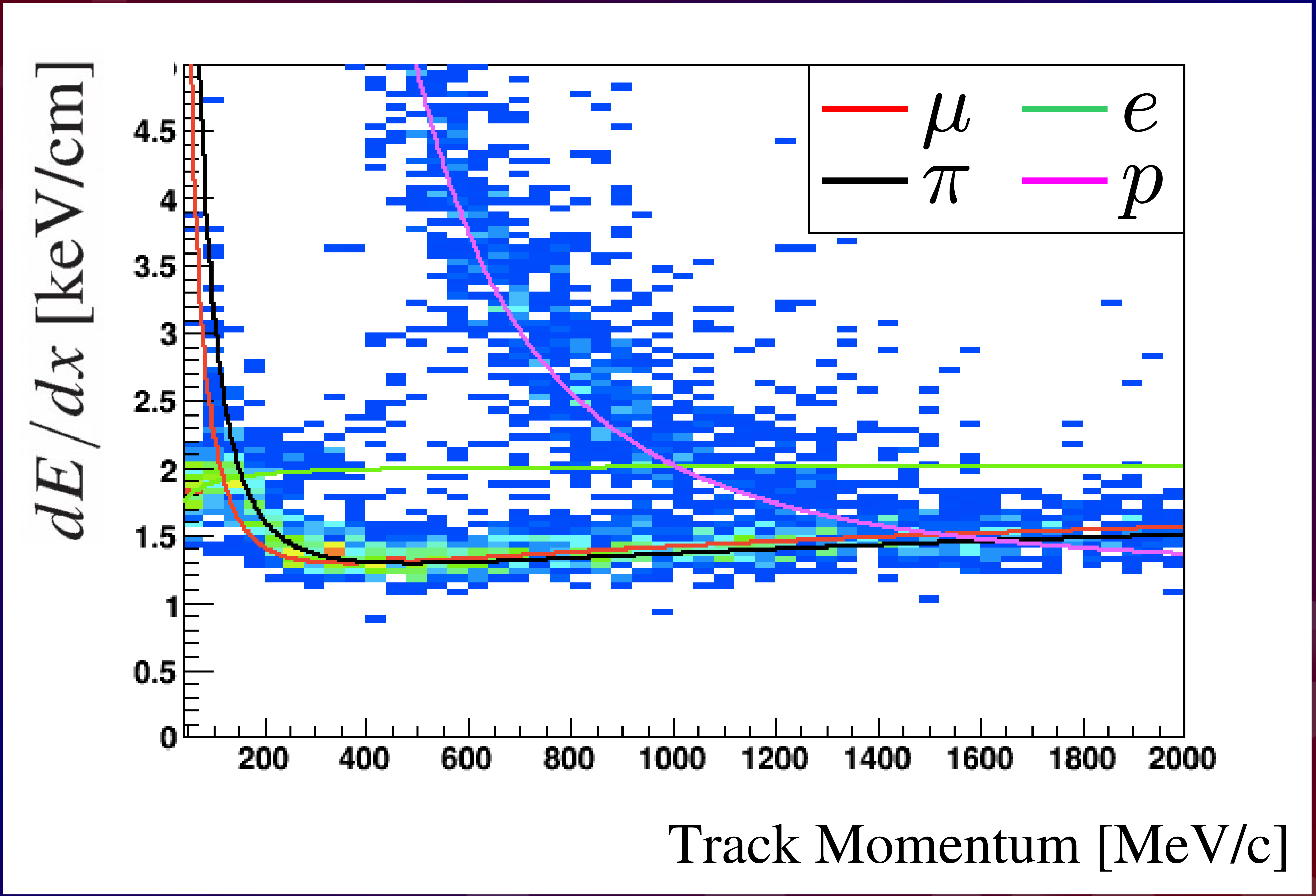
0.2 Tesla
B-field



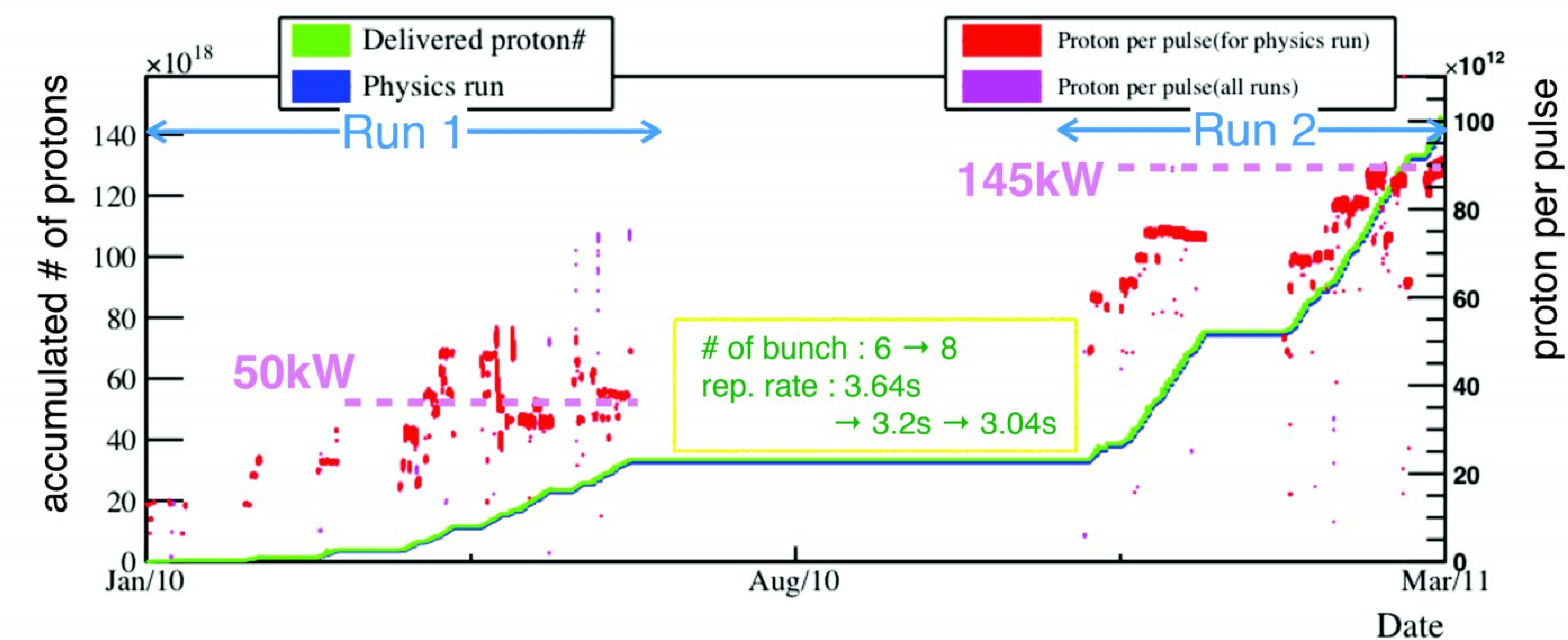
Origin of TPC Tracks (MC)



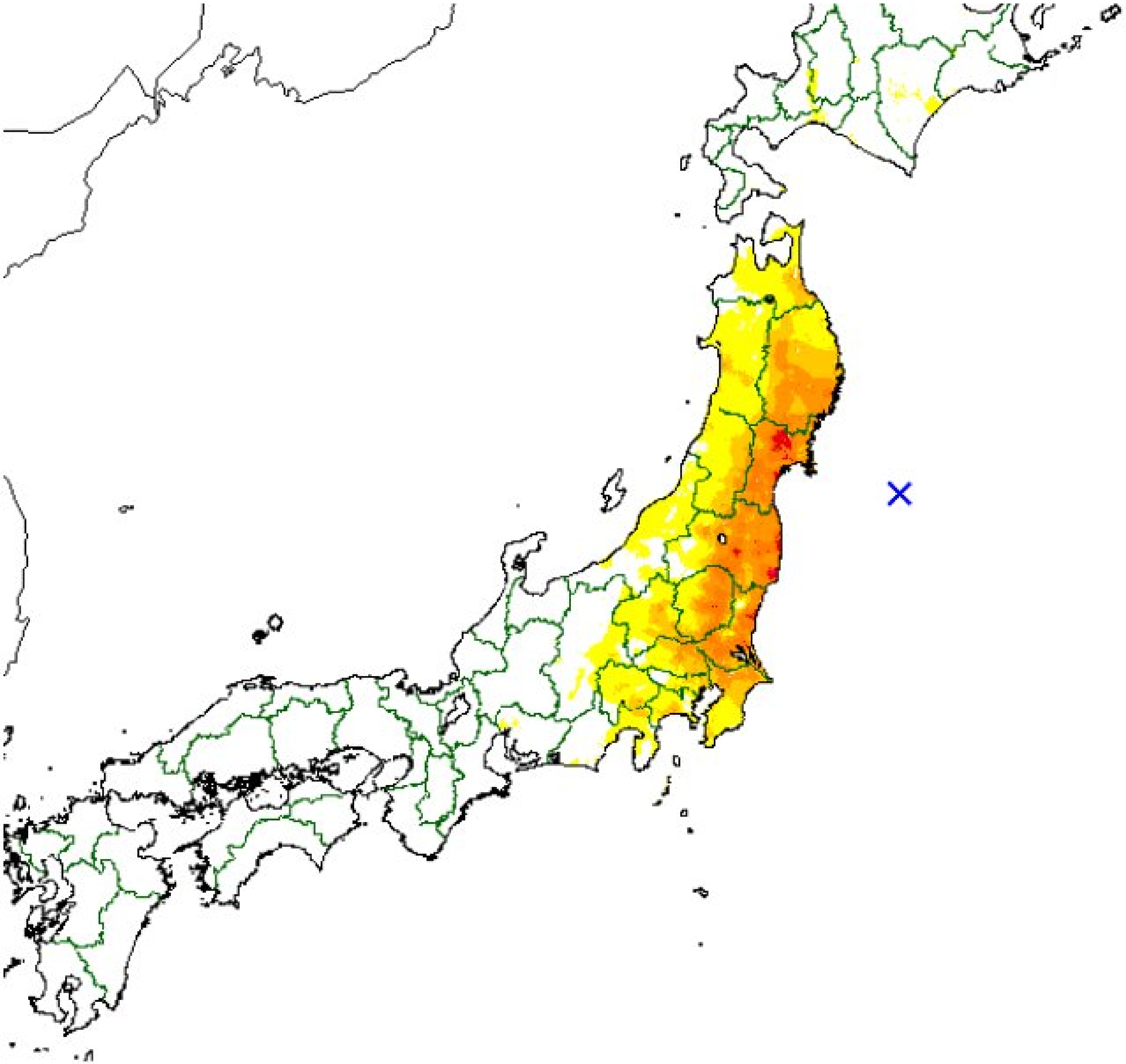
TPC dE/dx Particle ID (Positive Tracks)



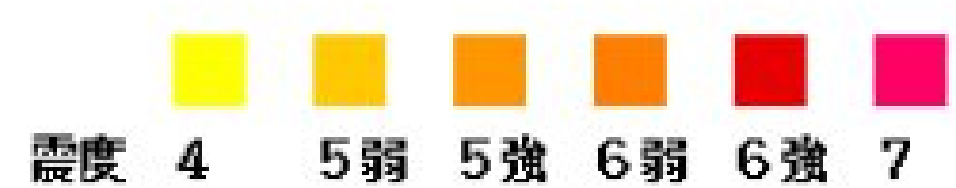
T2K Beam Performance to March 2011



Two major runs, increasing beam power
2% of total number of protons for T2K

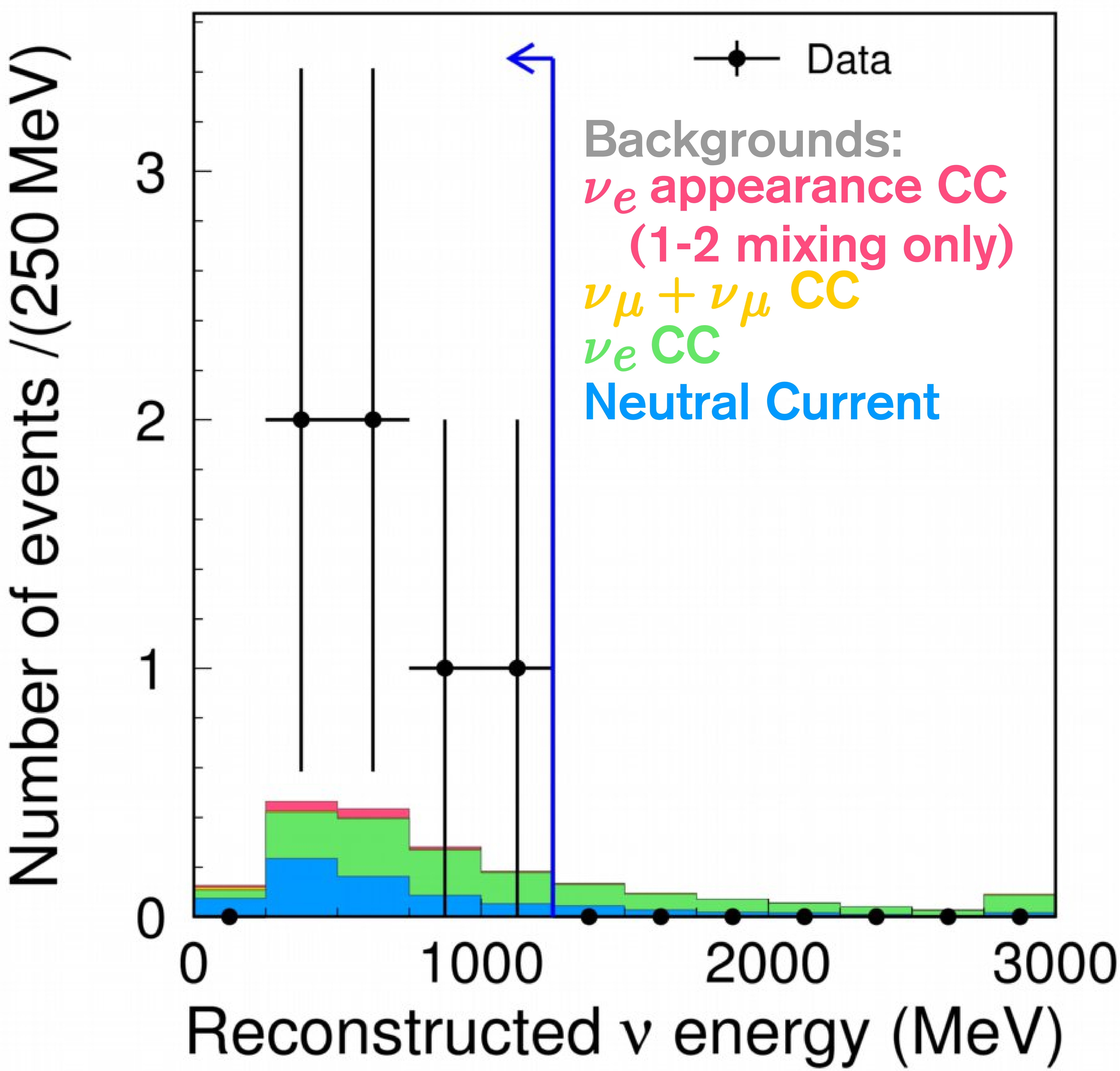


〔震源要素〕
２０１１年０３月１１日１４時４６分　三陸沖　　Ｍ７．９
〔情報時刻〕
２０１１年０３月１１日１５時０１分

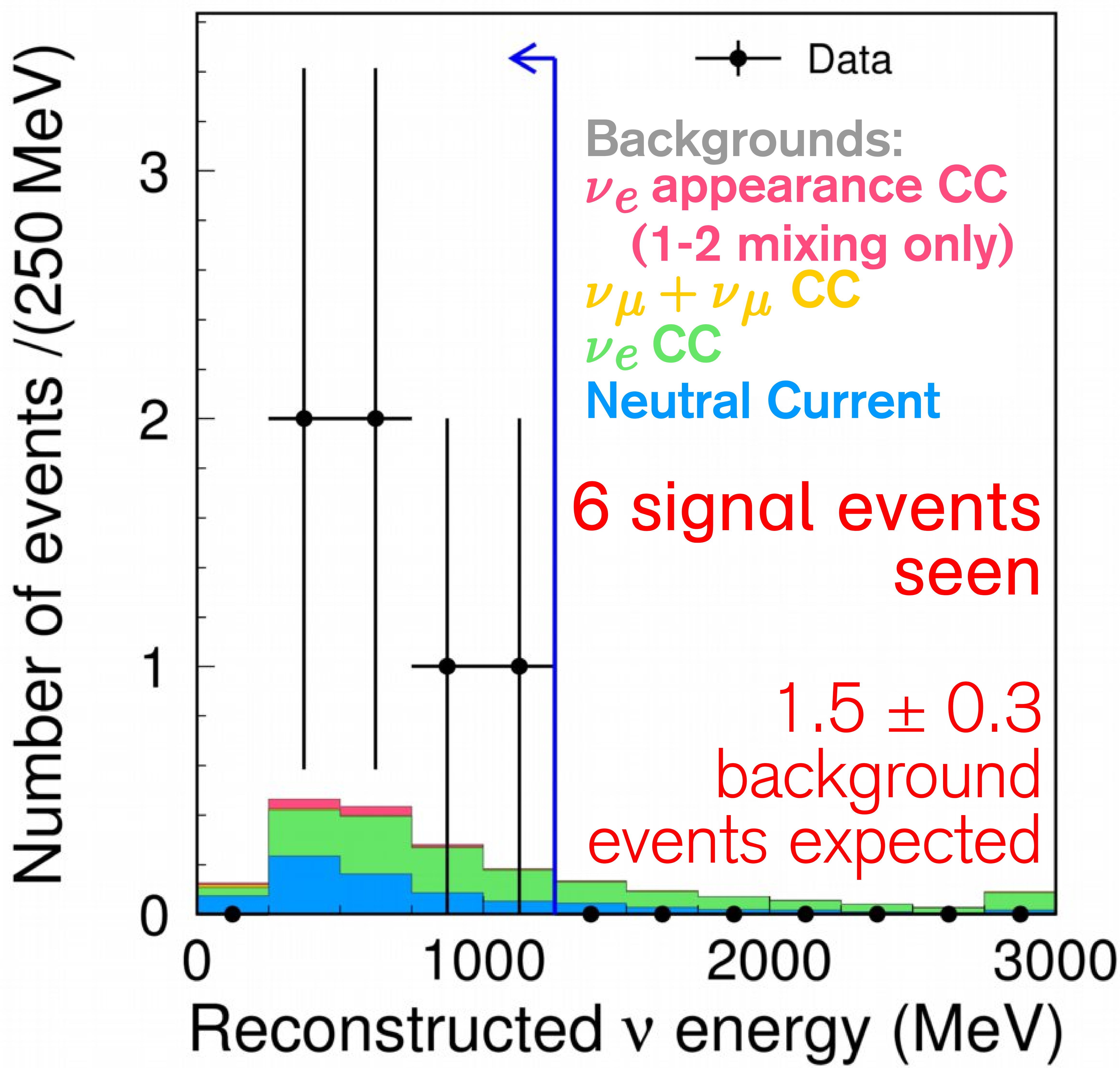


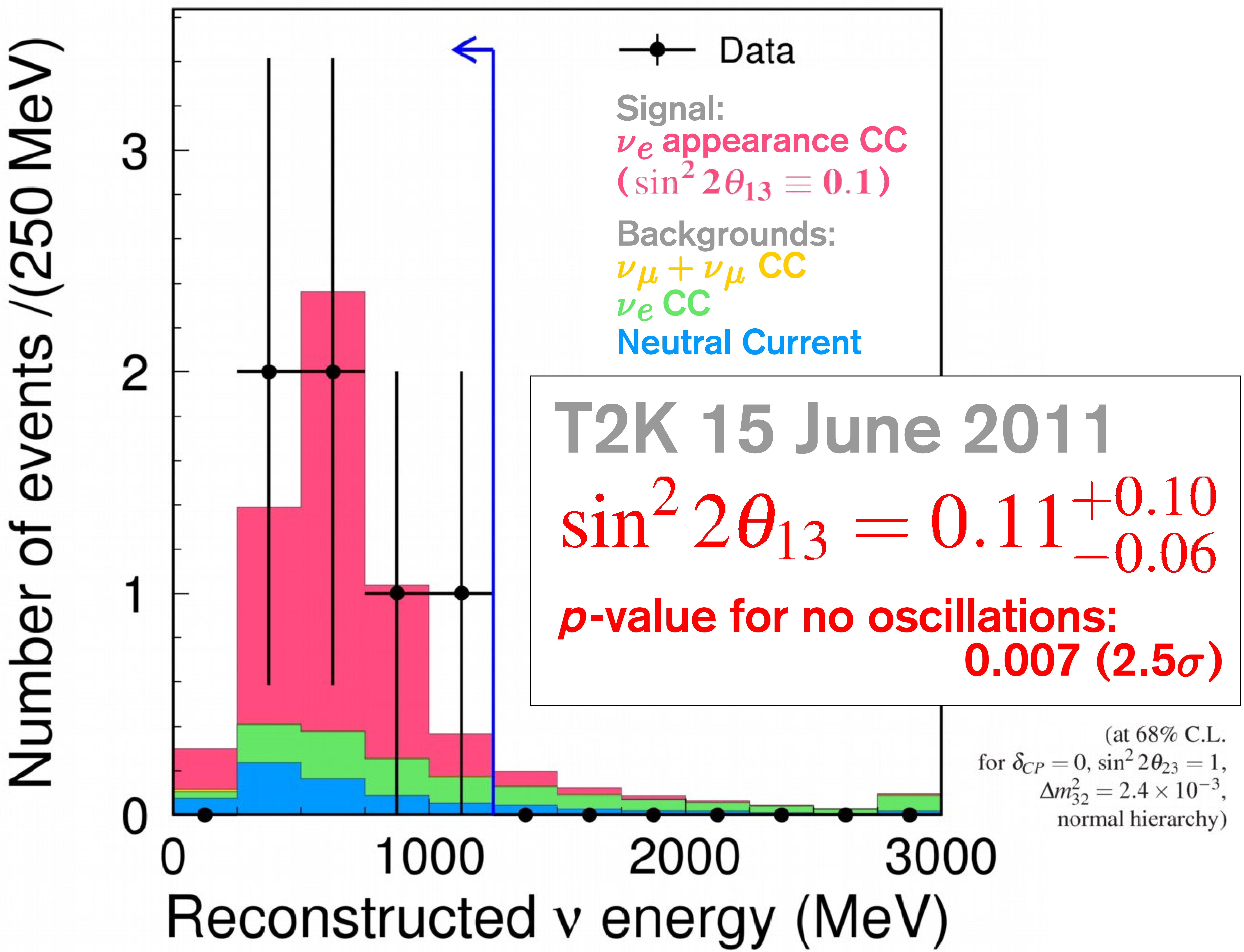
15 June 2011—First T2K ν_e Result

T2K July 2011: T2K ν_e Candidates



T2K July 2011: T2K ν_e Candidates





Number of events /(250 MeV)
0
1
2
3
0
1000
2000
3000
Reconstructed ν energy (MeV)
Data
Signal:
ν_e appearance CC
($\sin^2 2\theta_{13} = 0.1$)
Backgrounds:
$\nu_\mu + \nu_\mu$ CC
ν_e CC
Neutral Current
T2K 15 June 2011
$\sin^2 2\theta_{13} = 0.11^{+0.10}_{-0.06}$
p-value for no oscillations:
0.007 (2.5σ)
(at 68% C.L.
for $\delta_{CP} = 0$, $\sin^2 2\theta_{23} = 1$,
$\Delta m^2_{32} = 2.4 \times 10^{-3}$,
normal hierarchy)

T2K ν_e Appearance Status
Summer 2012

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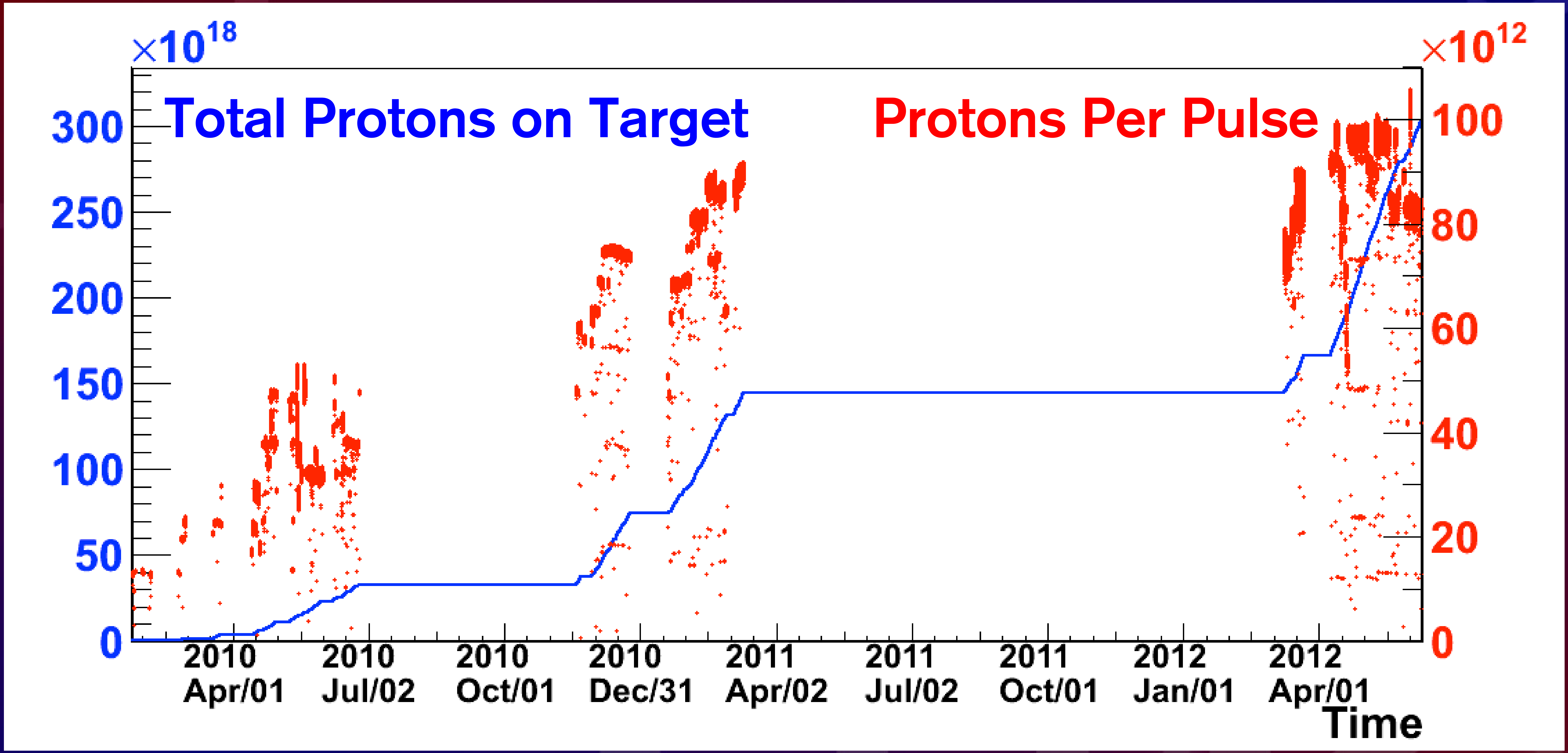
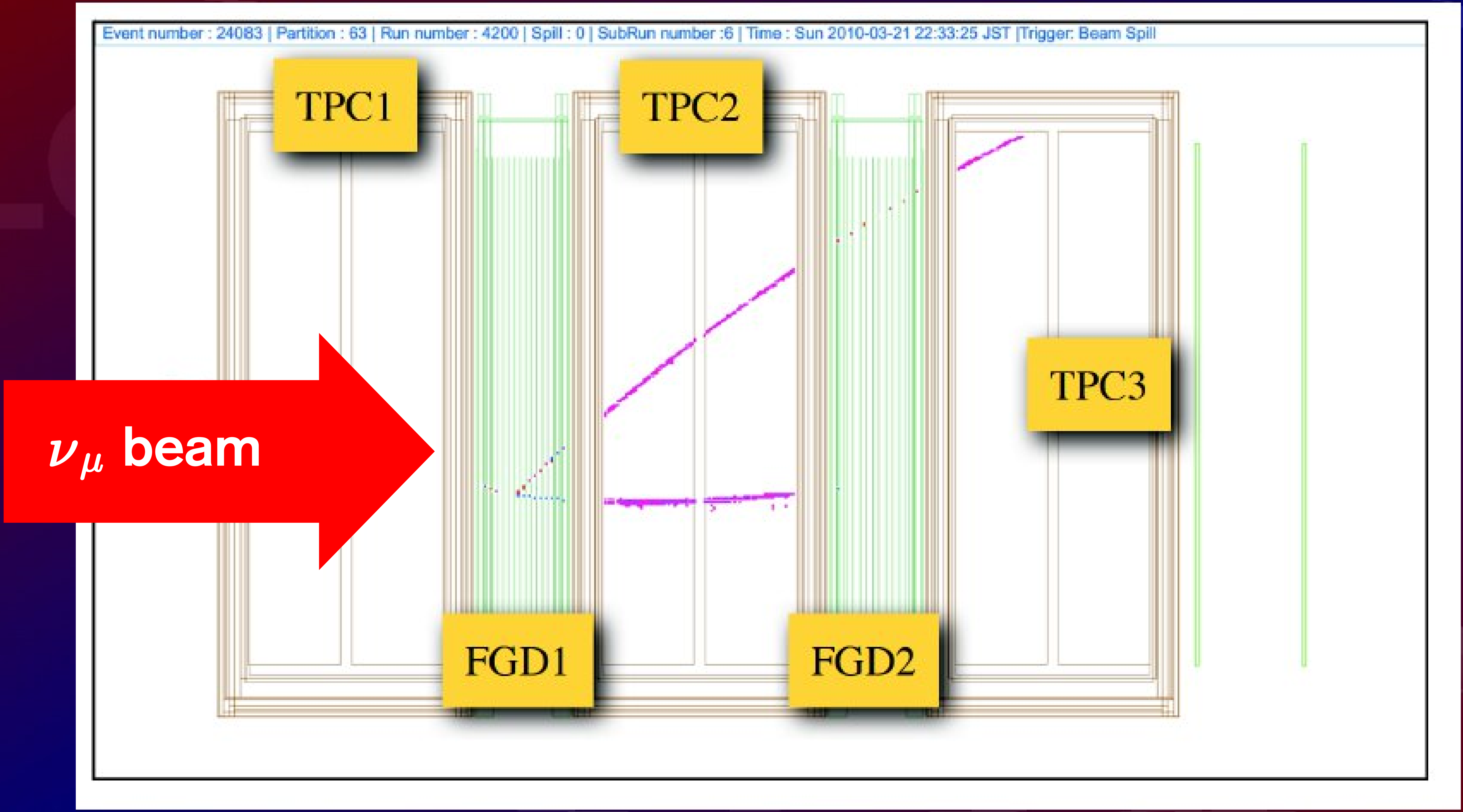
J-PARC T2K Beam Performance



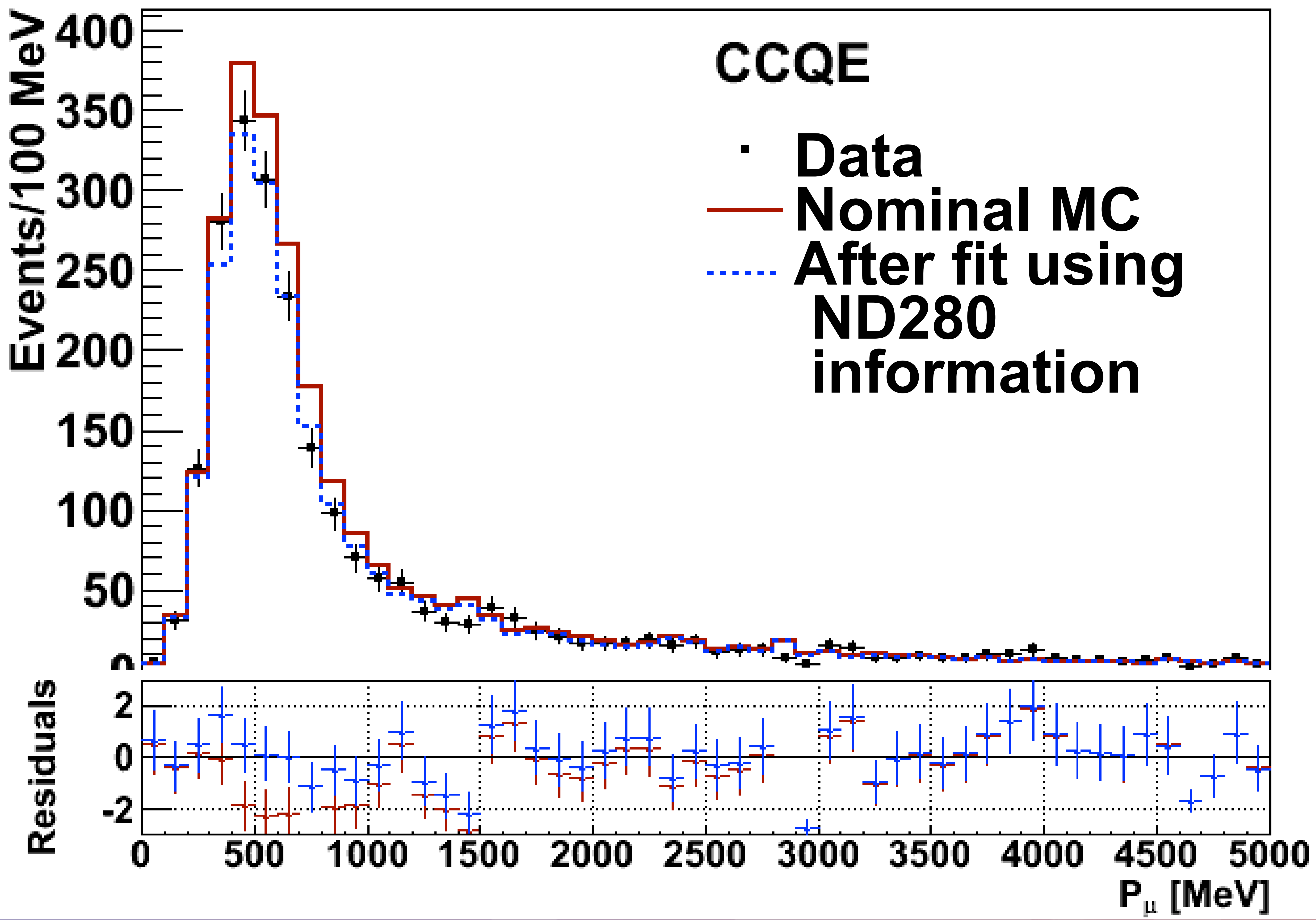
- Total 3.01×10^{20} protons on target (factor 2.1 over March 2011)
- **4% of total T2K dataset**
- Peak power: 200 kW

ν_μ Events at the Near Detector



90% selection efficiency for inclusive events, of which 50% are CCQE

Beam Prediction Fits to ND280 Data



Event Selection Cuts at the Far Detector

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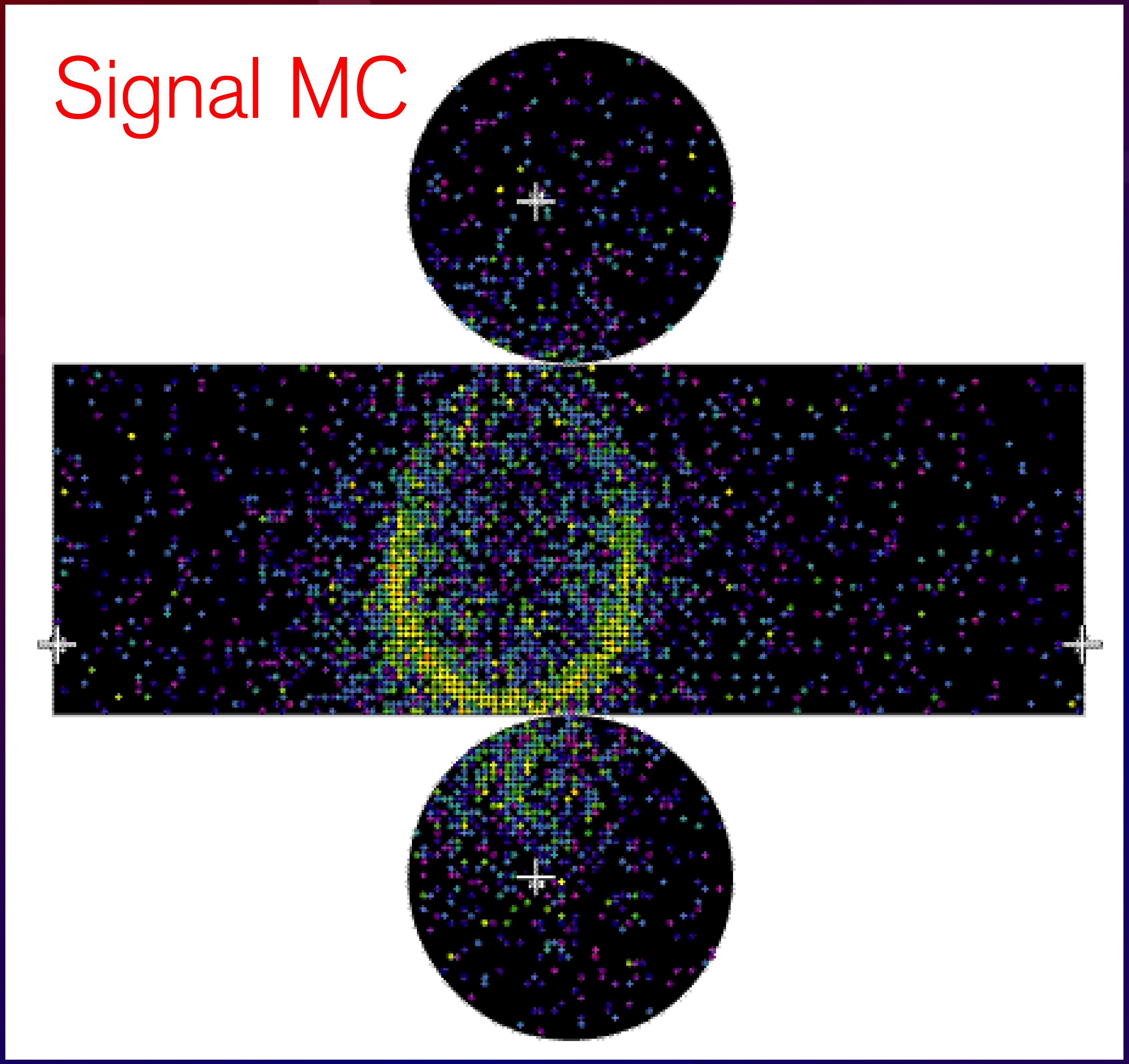
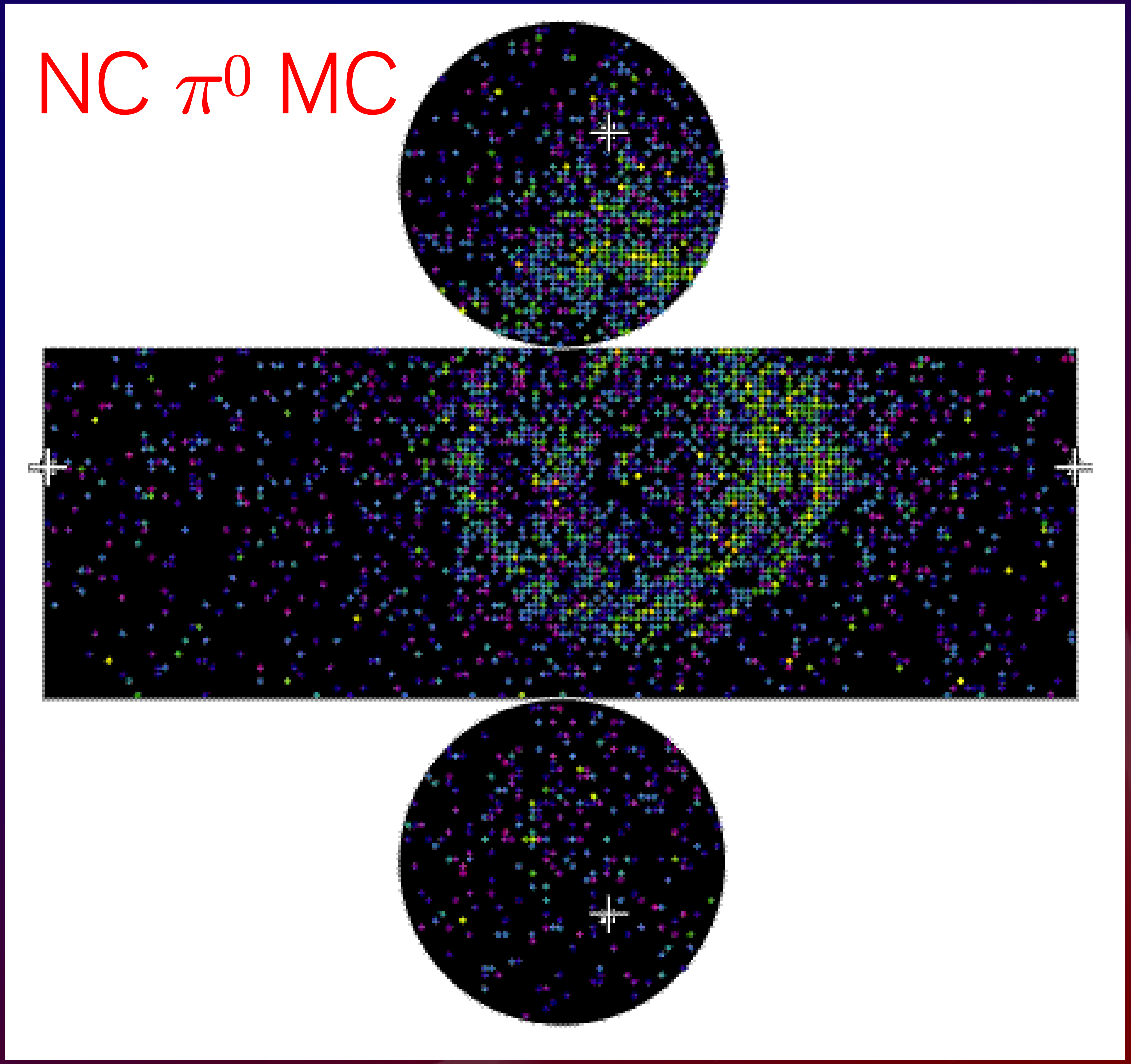
Signal and Background



Single CCQE electron ring



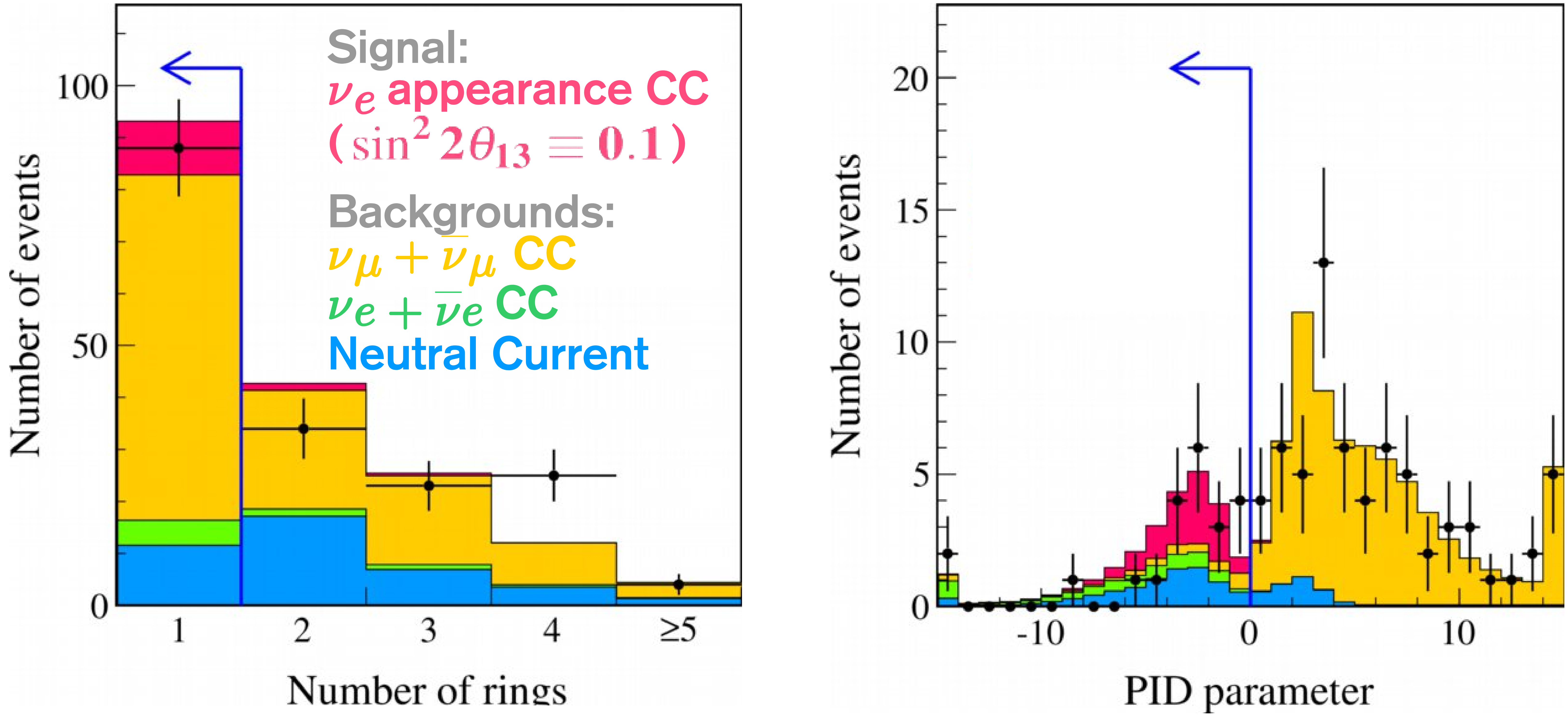
Two photons from neutral pions can mimic single EM shower

The event selection cuts at T2K were frozen before data taking commenced

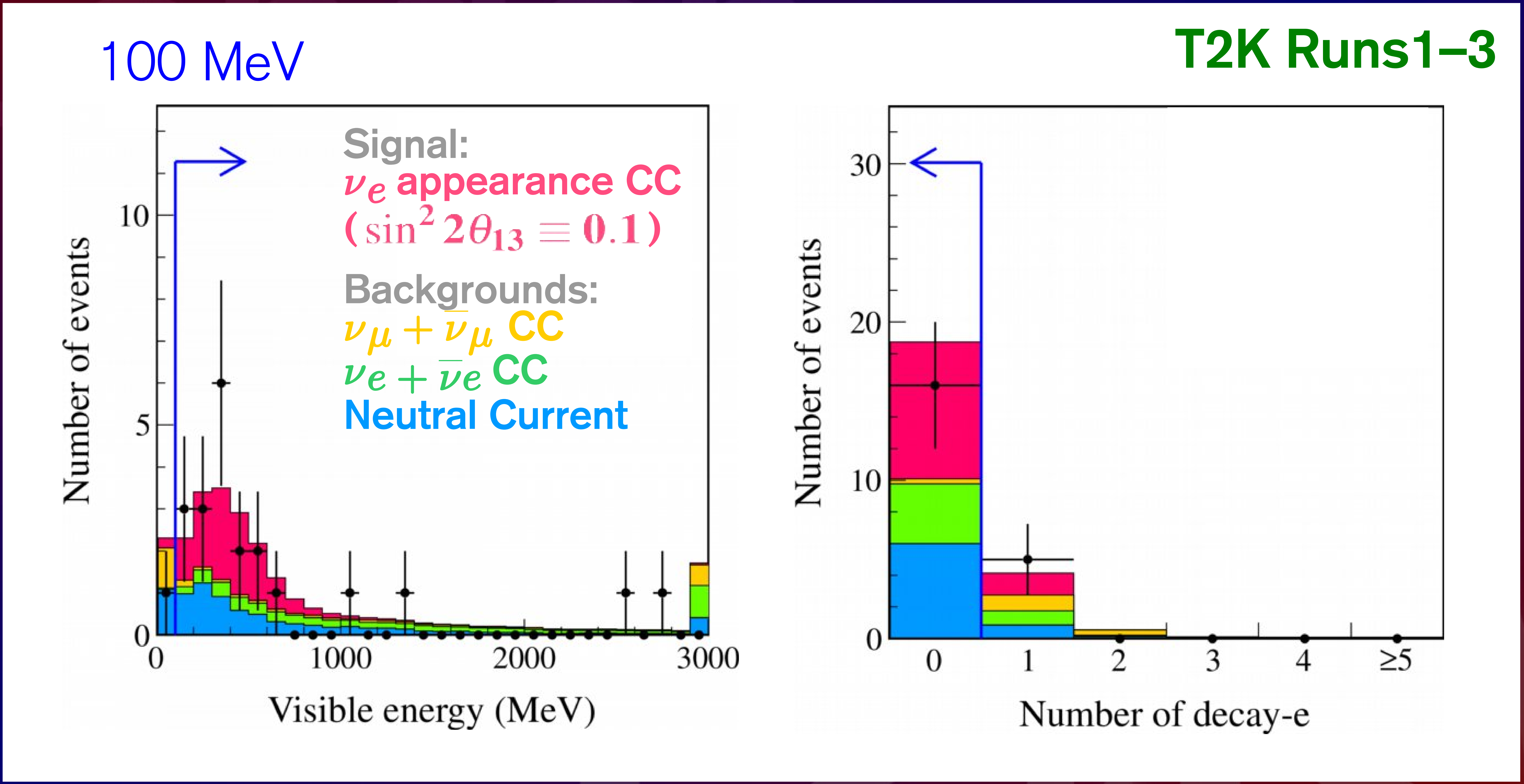
Single e-like Rings in the Detector

(after pre-selection for timing, containment etc)

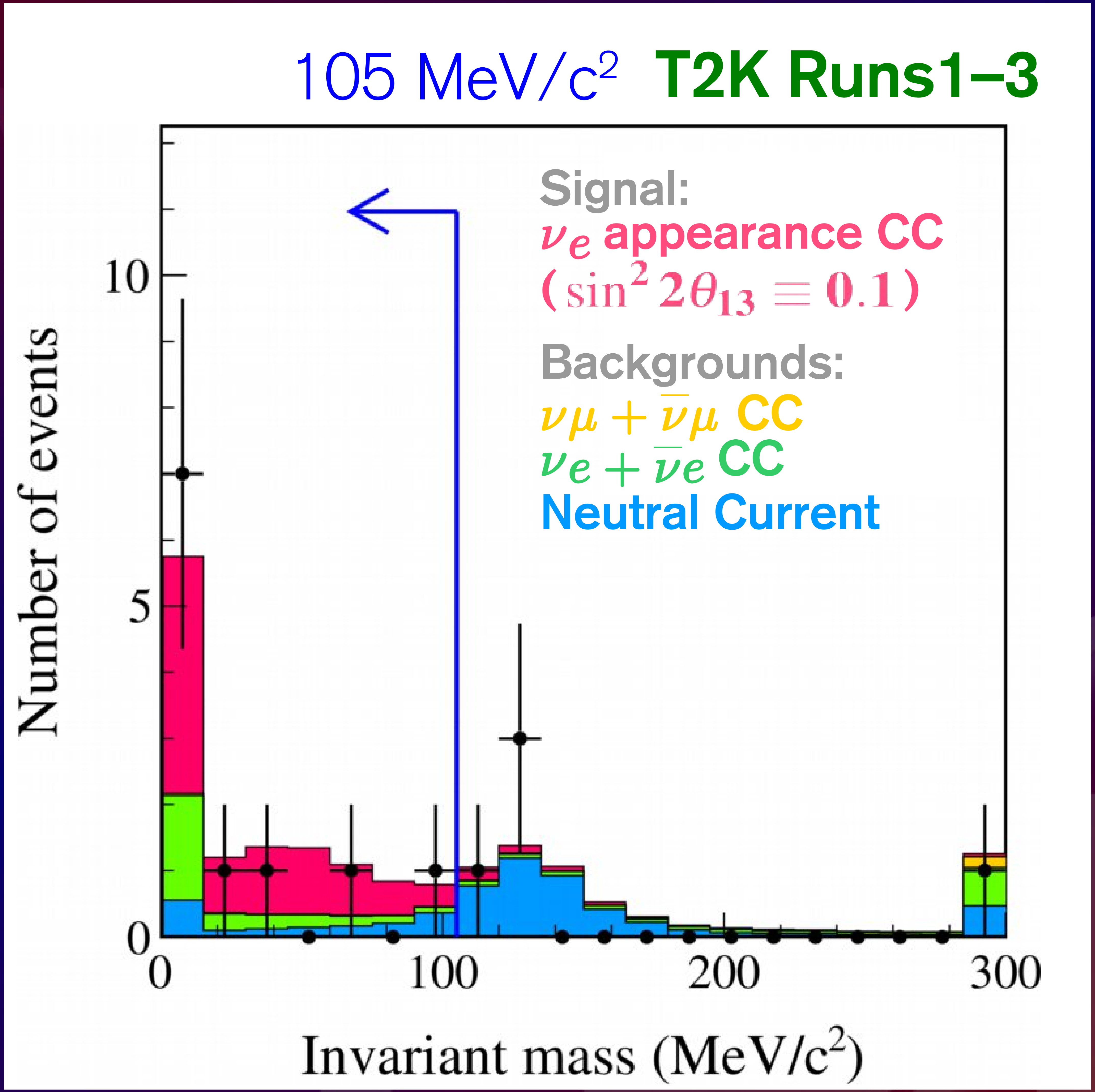
T2K Runs1–3



Background Reduction



“Forced” 2-EM Ring Invariant Mass

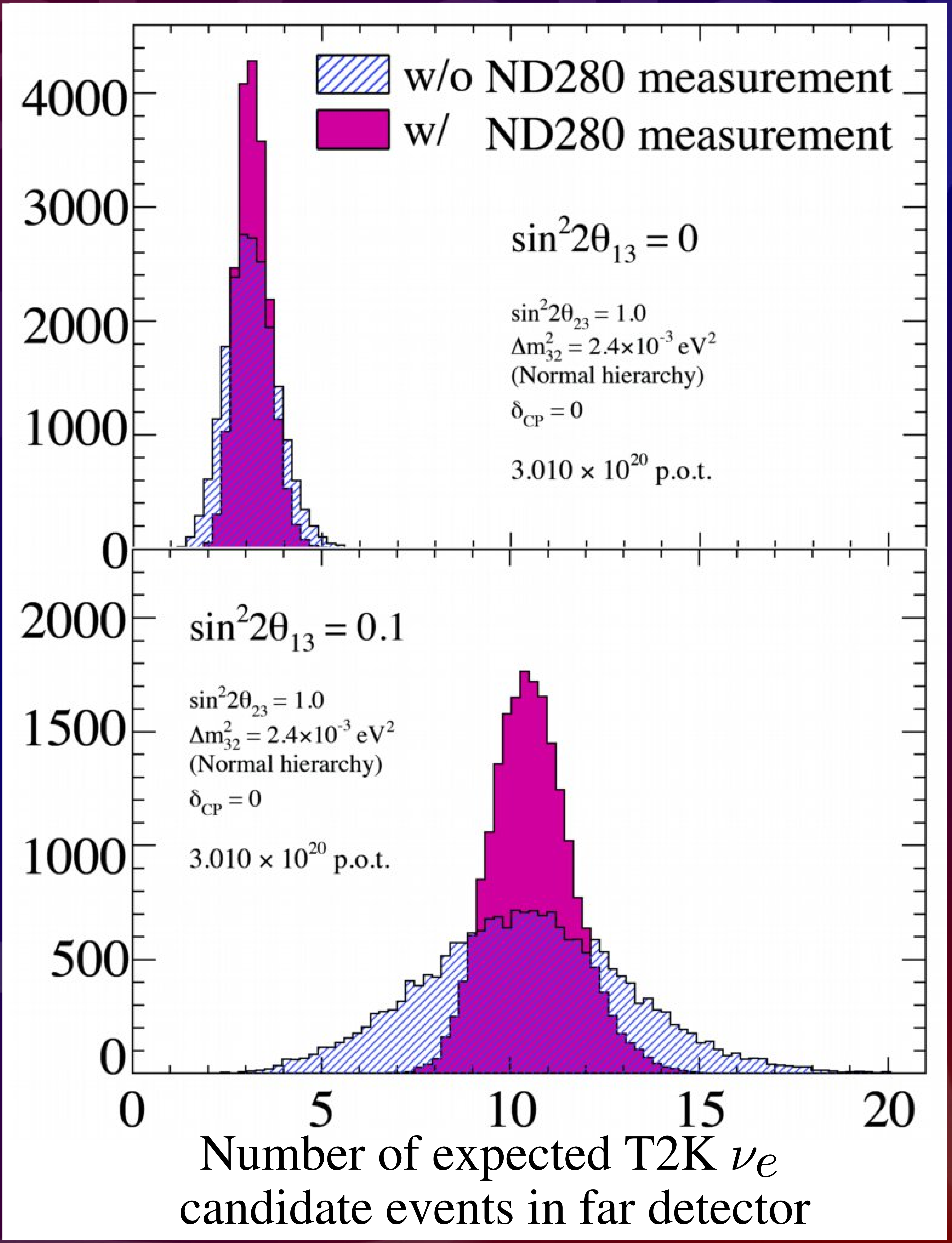


Reduce neutral pion backgrounds

Systematic Uncertainties (T2K 2012)

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux+ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %
(2011 values	23 %	18 %)

Impact of ND280 Constraints on ν_e Appearance Predictions (T2K 2012)



Selection Cuts Summary (T2K 2012)

Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22±0.43	10.71±1.10
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background	1.21	1.21
$\overline{\nu}_\mu + \overline{\nu}_e$ background	0.16	0.16

- Signal Efficiency

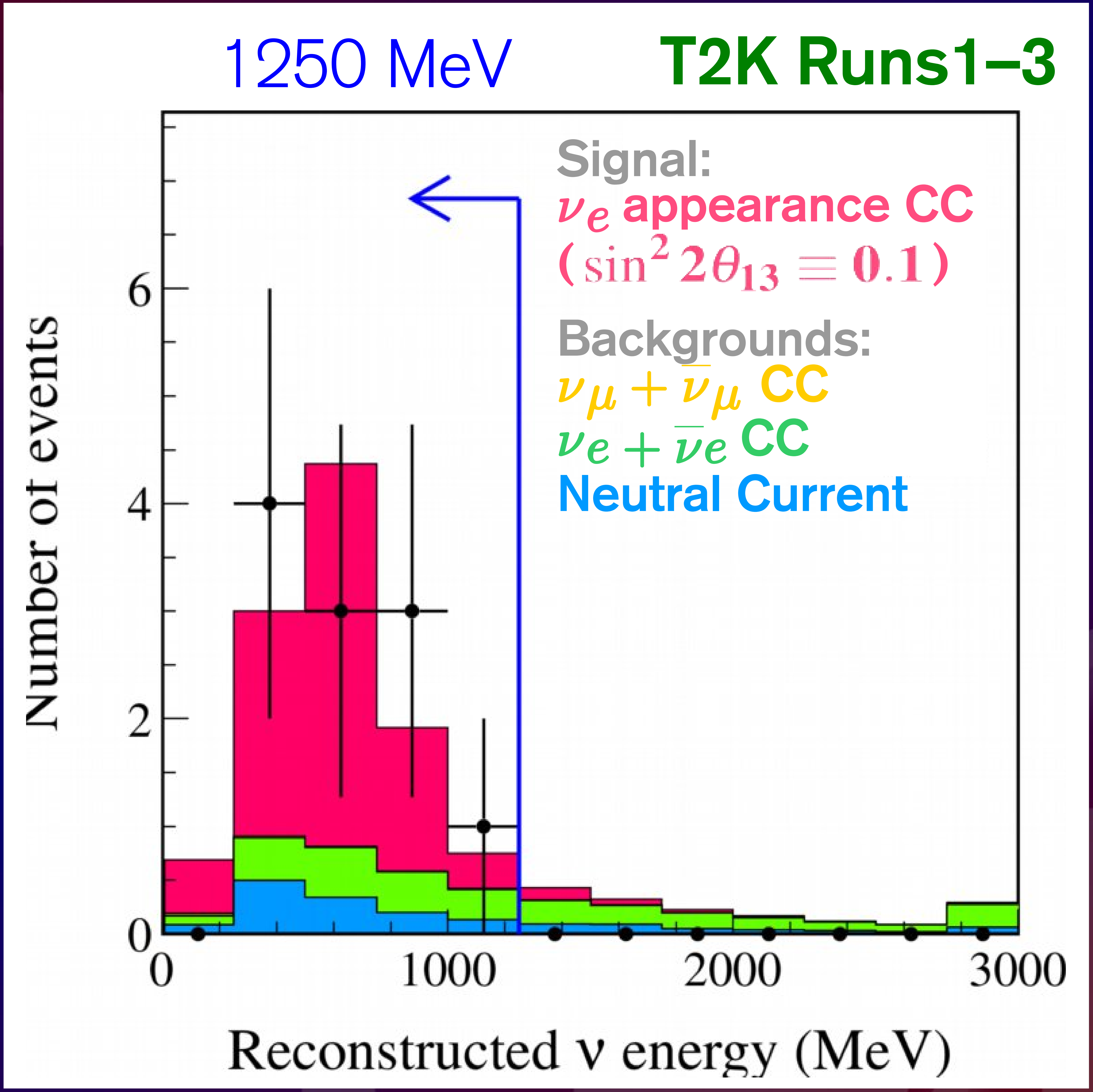
  61%

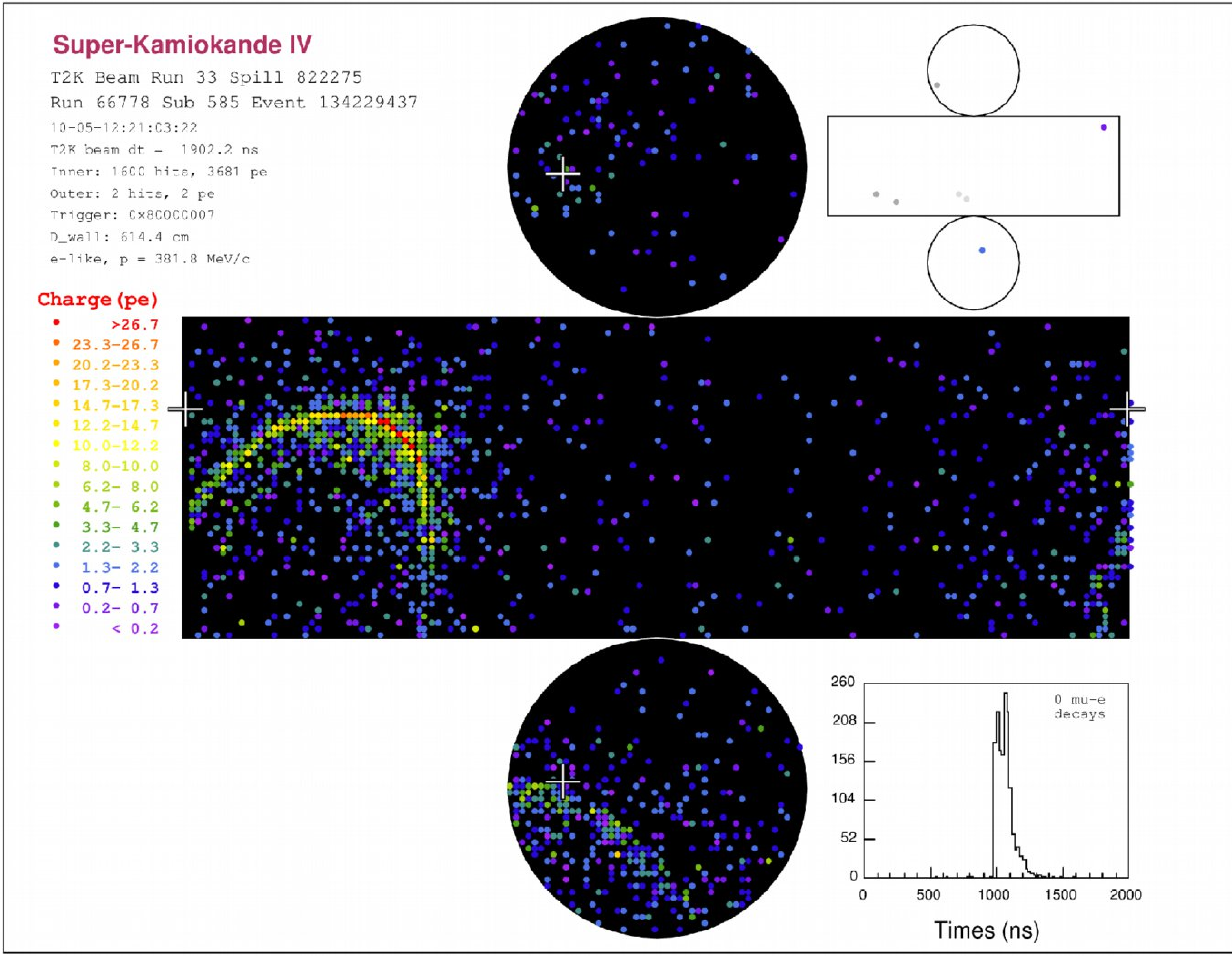
- Background Rejection

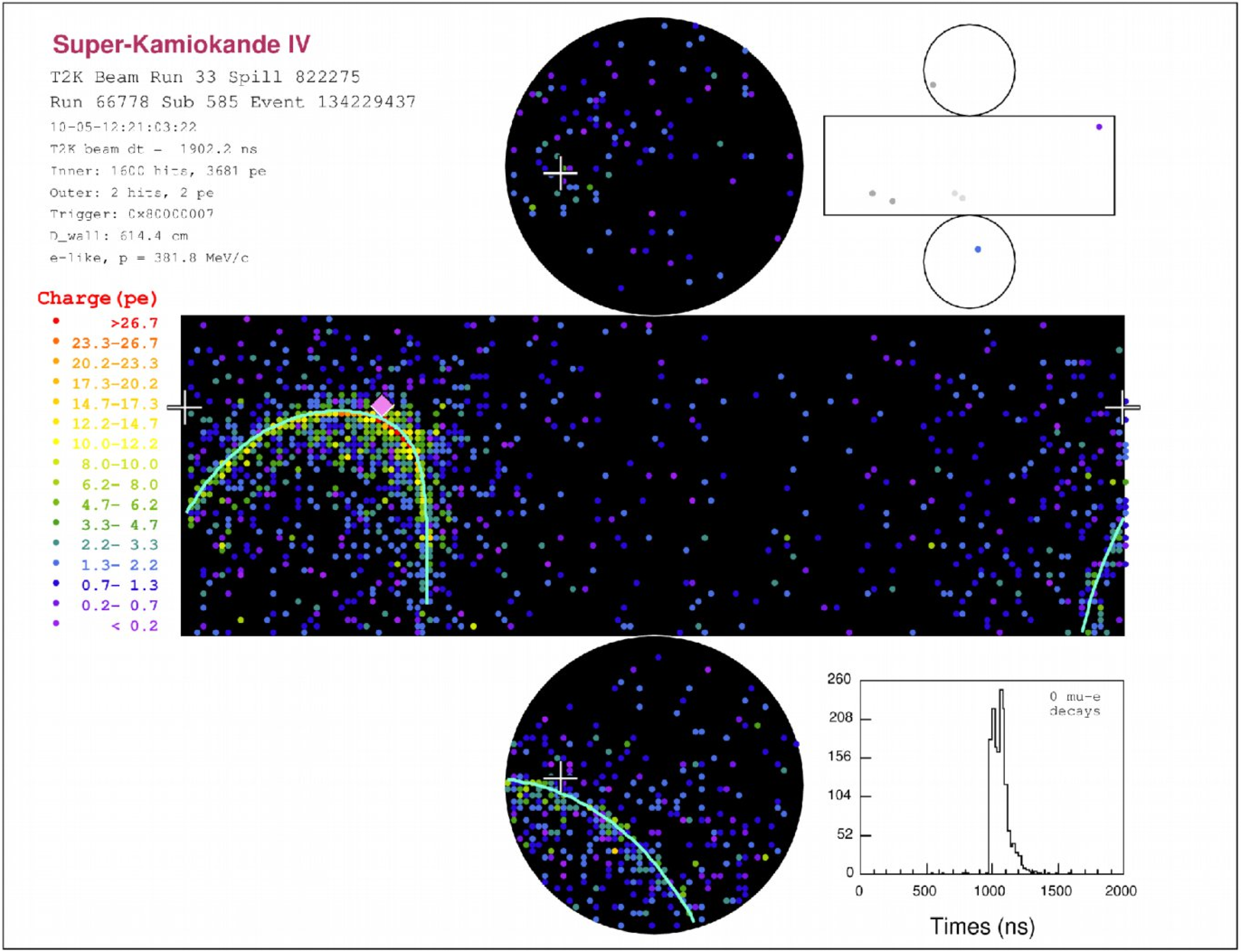
  80% for intrinsic beam ν_e

  99% for neutral current events

Final Selection




Super-Kamiokande IV
T2K Beam Run 33 Spill 822275
Run 66778 Sub 585 Event 134229437
10-05-12:21:03:22
T2K beam dt = 1902.2 ns
Inner: 1600 hits, 3681 pe
Outer: 2 hits, 2 pe
Trigger: 0x80000007
D_wall: 614.4 cm
e-like, p = 381.8 MeV/c
Charge (pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
260
208
156
104
52
0
0 mu-e decays
0
500
1000
1500
2000
Times (ns)



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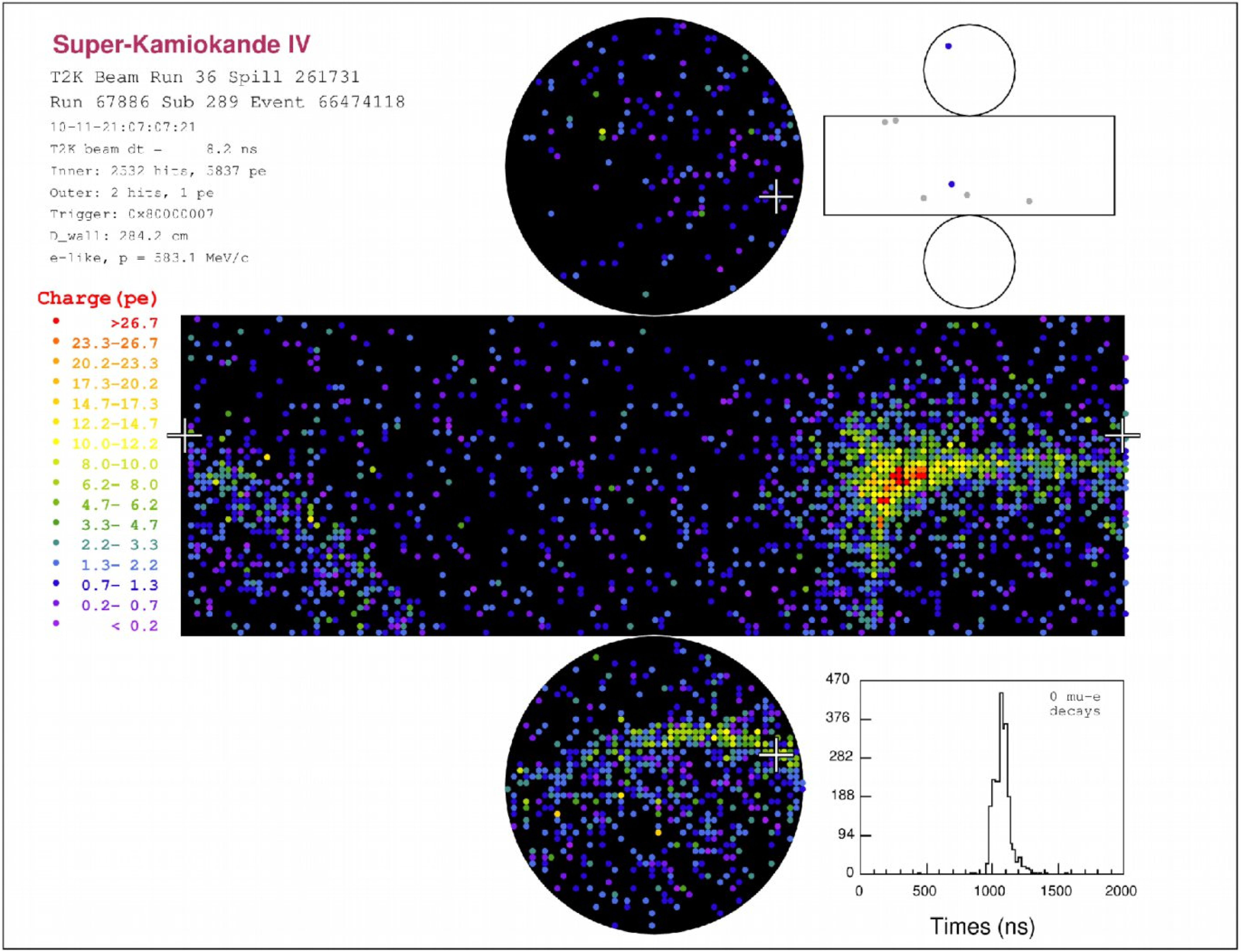
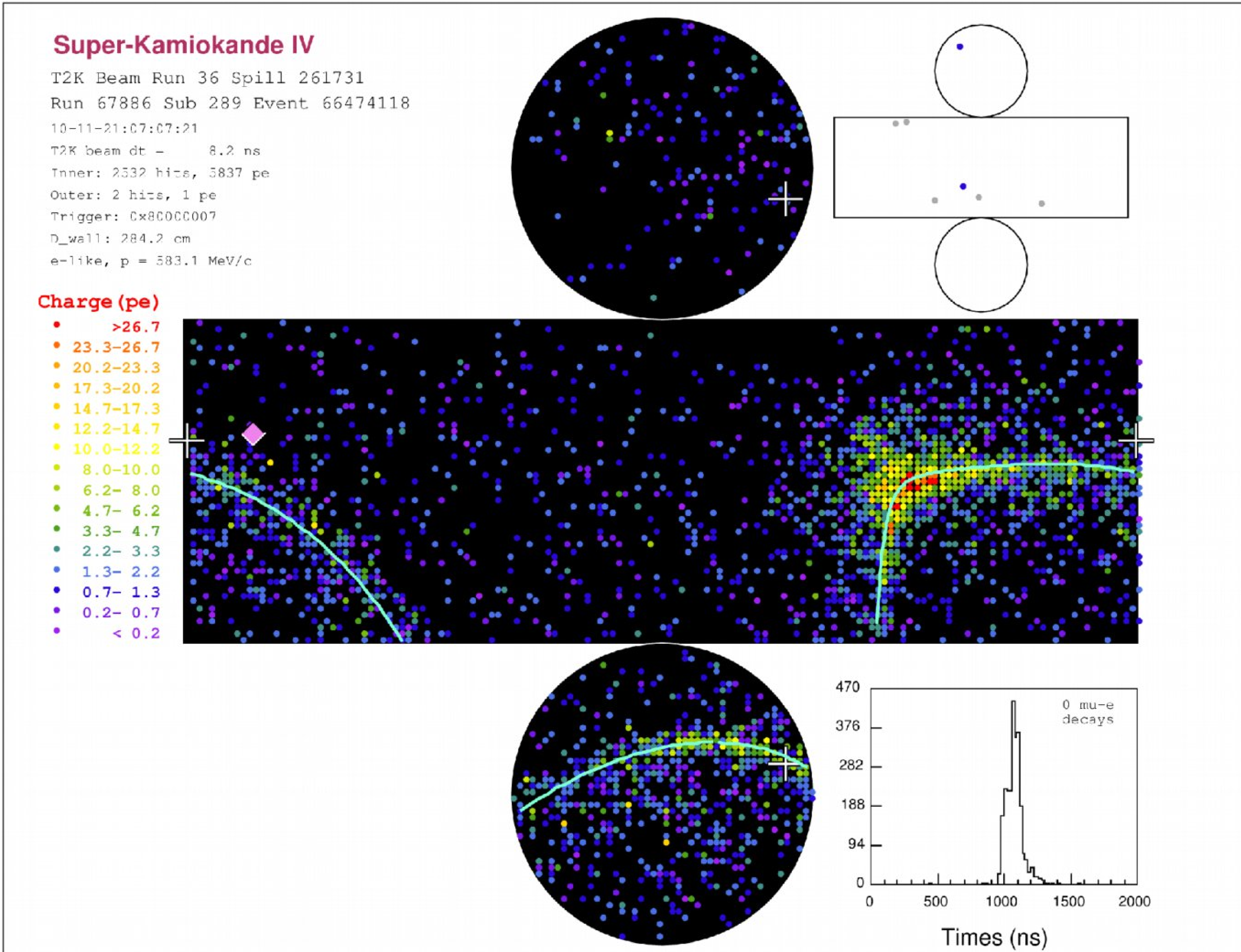
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
0 mu-e decays
260
208
156
104
52
0
0
500
1000
1500
2000
Times (ns)


Super-Kamiokande IV
T2K Beam Run 36 Spill 261731
Run 67886 Sub 289 Event 66474118
10-11-21:07:07:21
T2K beam dt = 8.2 ns
Inner: 2532 hits, 3837 pe
Outer: 2 hits, 1 pe
Trigger: 0x80000007
D_wall: 284.2 cm
e-like, p = 583.1 MeV/c
Charge (pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
0 mu-e decays
470
376
282
188
94
0
0
500
1000
1500
2000
Times (ns)


Super-Kamiokande IV
T2K Beam Run 36 Spill 261731
Run 67886 Sub 289 Event 66474118
10-11-21:07:07:21
T2K beam dt - 8.2 ns
Inner: 2532 hits, 5837 pe
Outer: 2 hits, 1 pe
Trigger: 0x80000007
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Charge (pe)
>26.7
23.3-26.7
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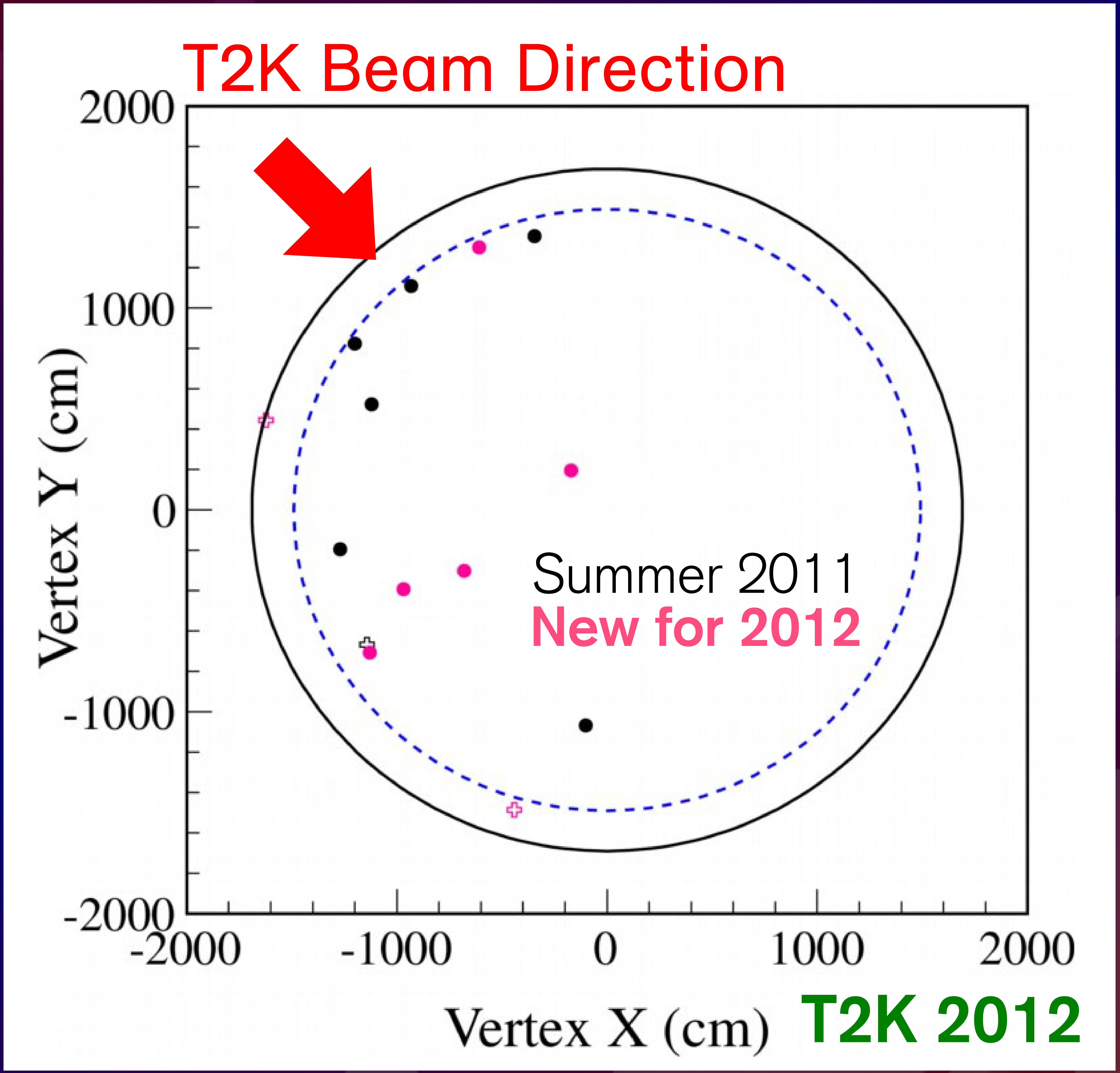
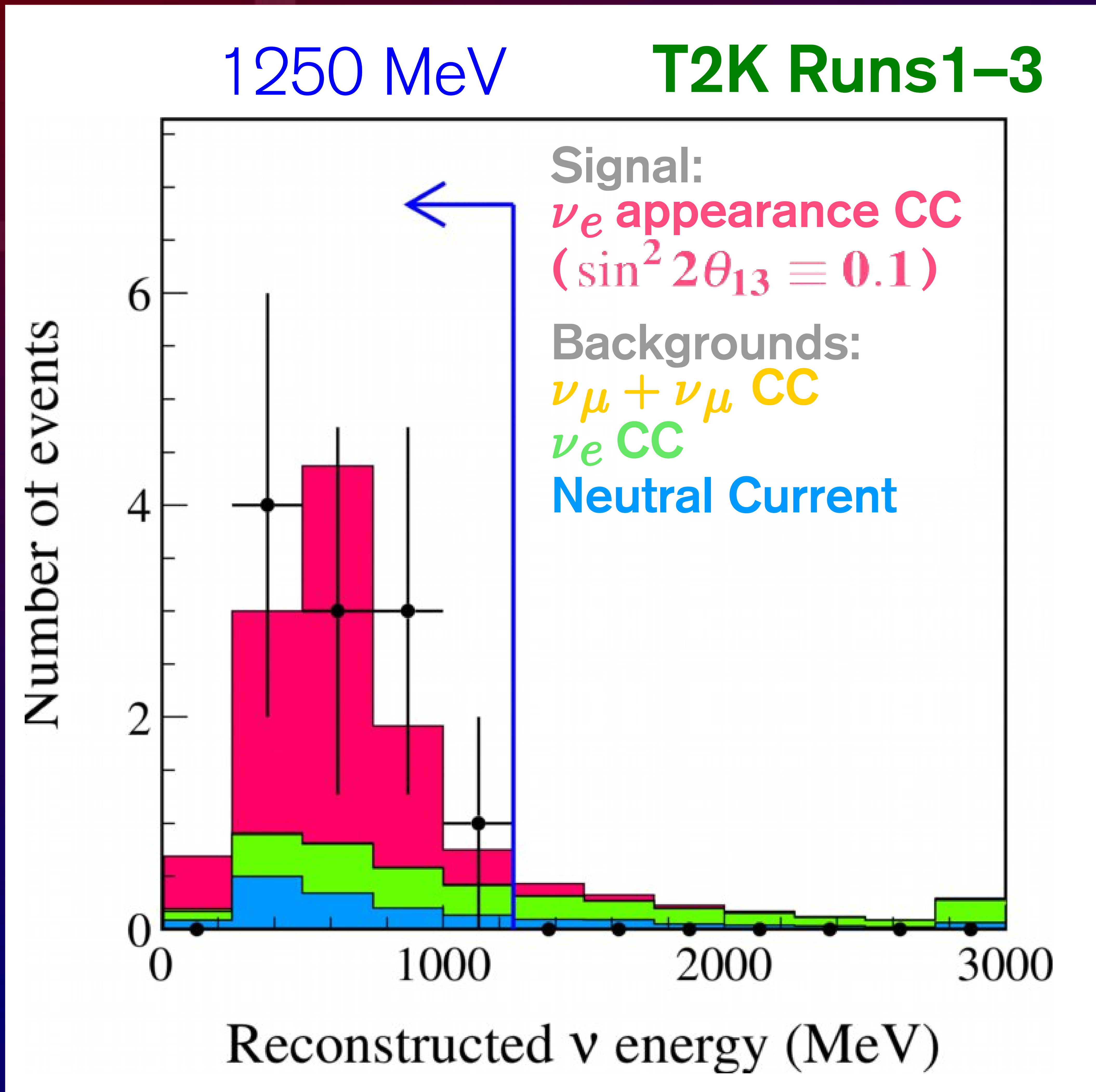
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
470
376
282
188
94
0
0 mu-e decays
0
500
1000
1500
2000
Times (ns)

Event Vertex Distributions

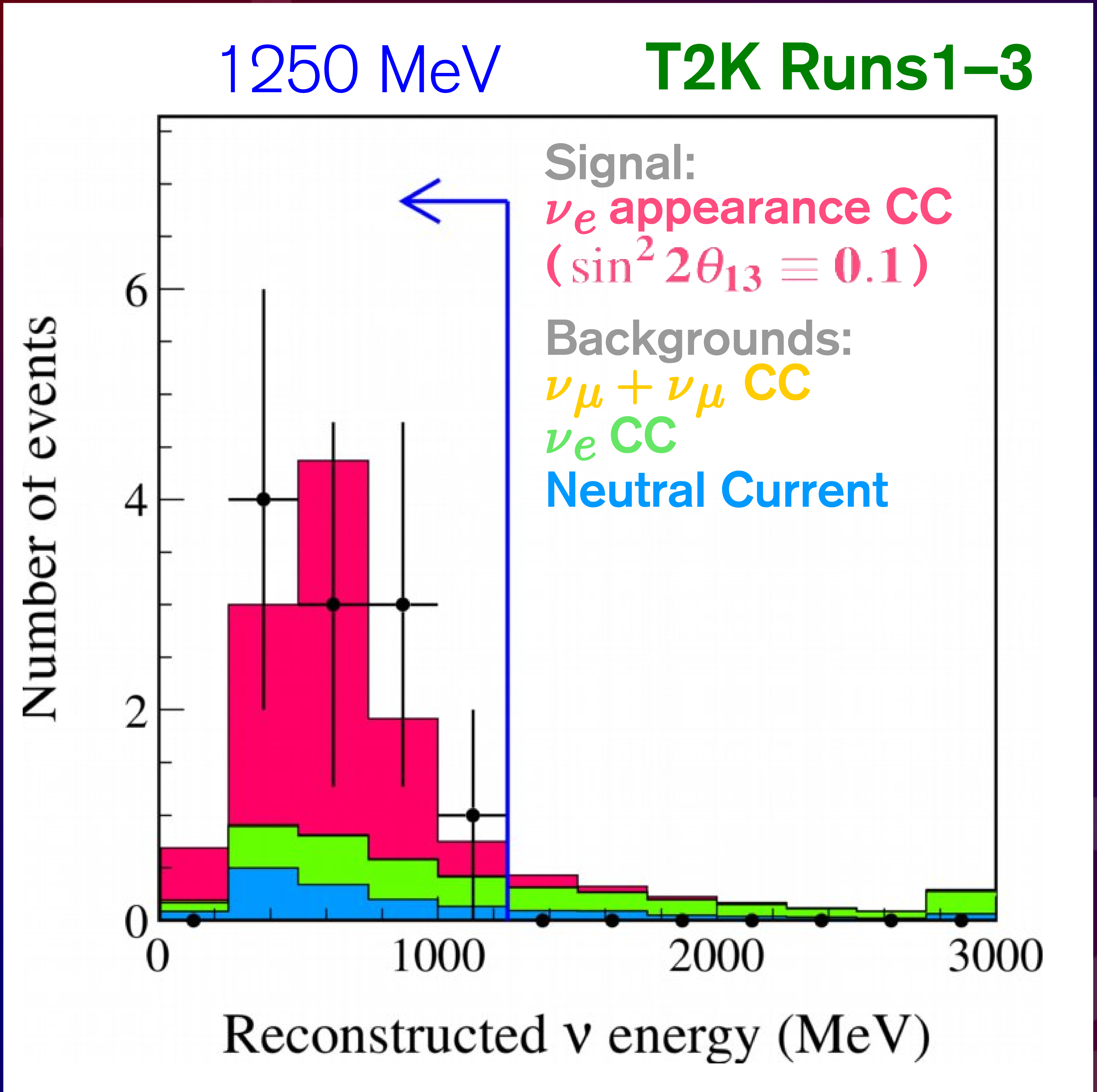
T2K ν_e candidates in Super-K



Final Selection



Final Selection



11 events observed

3.22±0.43 expected for $\theta_{13} = 0$

3.2 σ significance

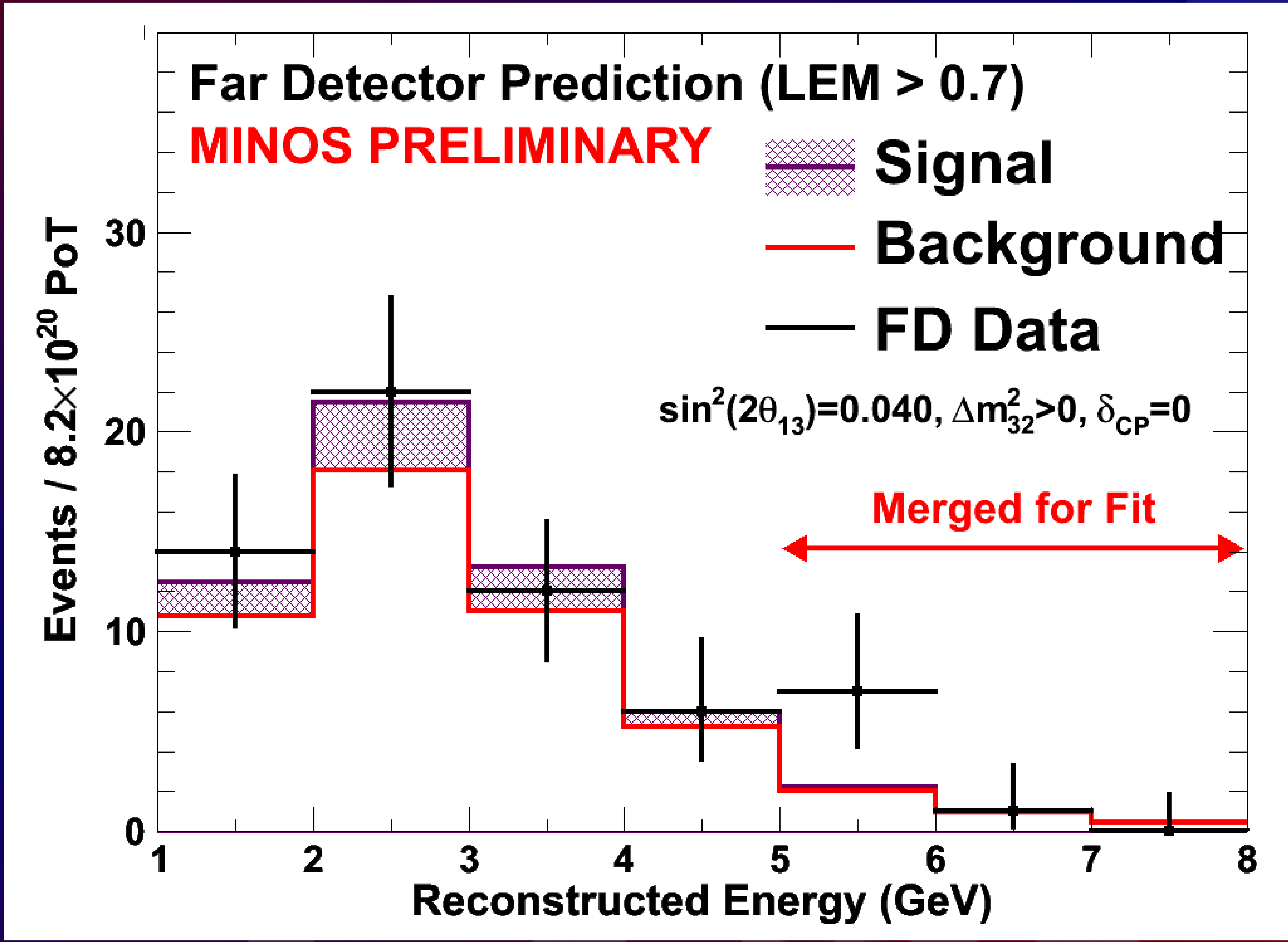
$0.033 < \sin^2 2\theta_{13} < 0.188$ (90% C.L.)

(fitting electron momentum and direction)

ν_e Appearance at MINOS (24 June 2011)

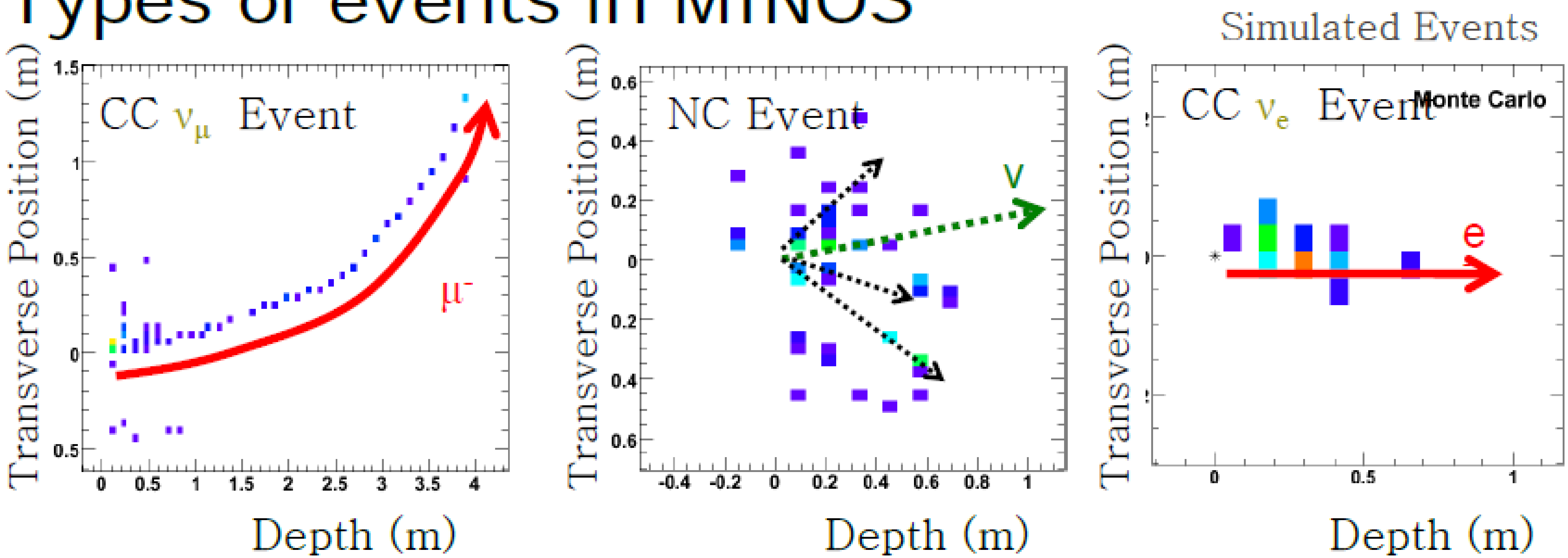
735 km baseline from Fermilab to Soudan

Identical iron sampling calorimeters near and far



Backgrounds (for $\theta_{13}=0$): 49.5 ± 2.8 ± 7.0 — **62 observed**

Types of events in MINOS



- Coarse detector granularity makes ν_e CC id challenging
  - Pattern recognition by finding closest matches with a library of MC events (comparing hit patterns in the two 2D views)
  - Discriminating variables from truth information from best-match library events. Combine into one (LEM) variable.
- Apply selection to ND for background determination
- Vary beam configuration to determine composition (because components extrapolate to FD differently)

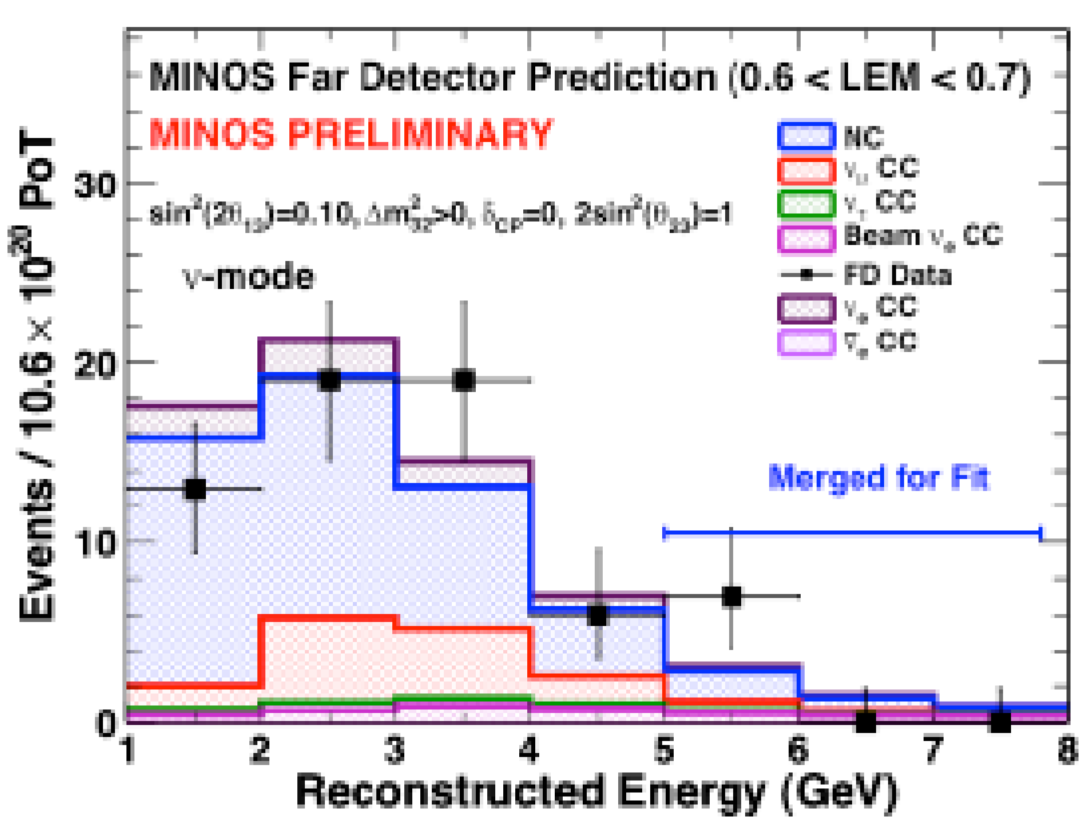
Recent MINOS ν_e Results

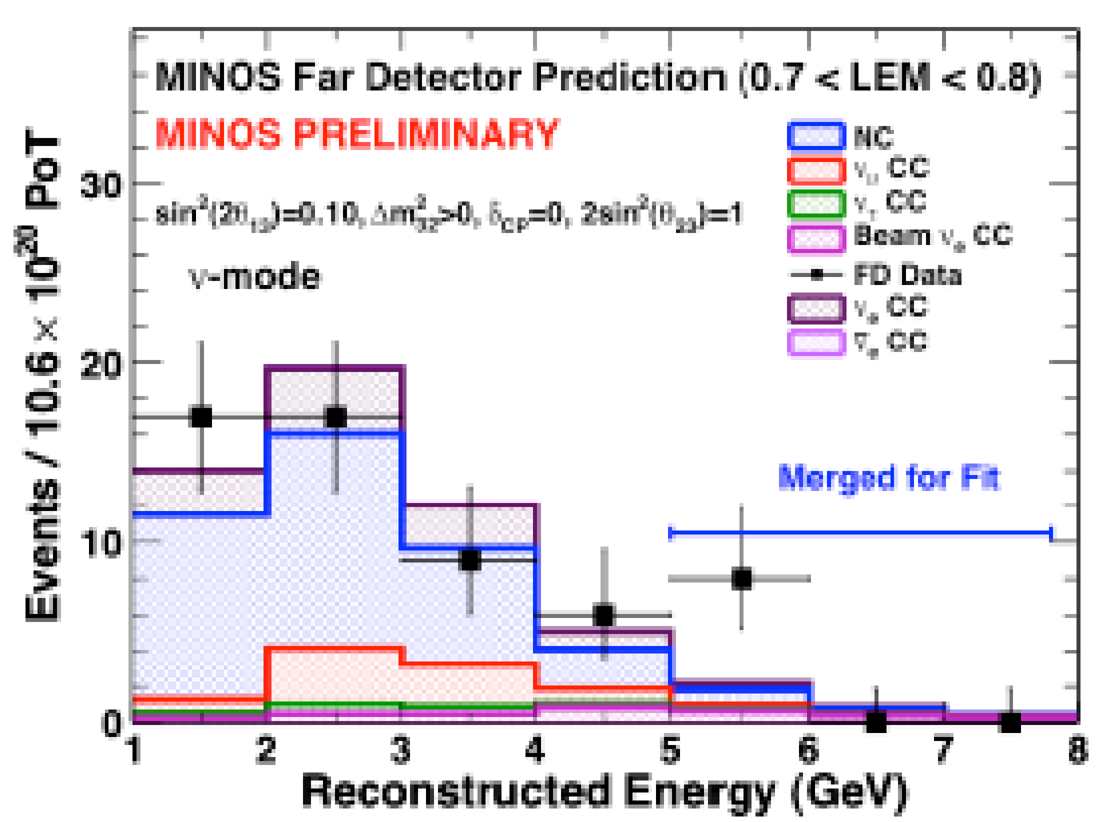
Neutrino running mode:

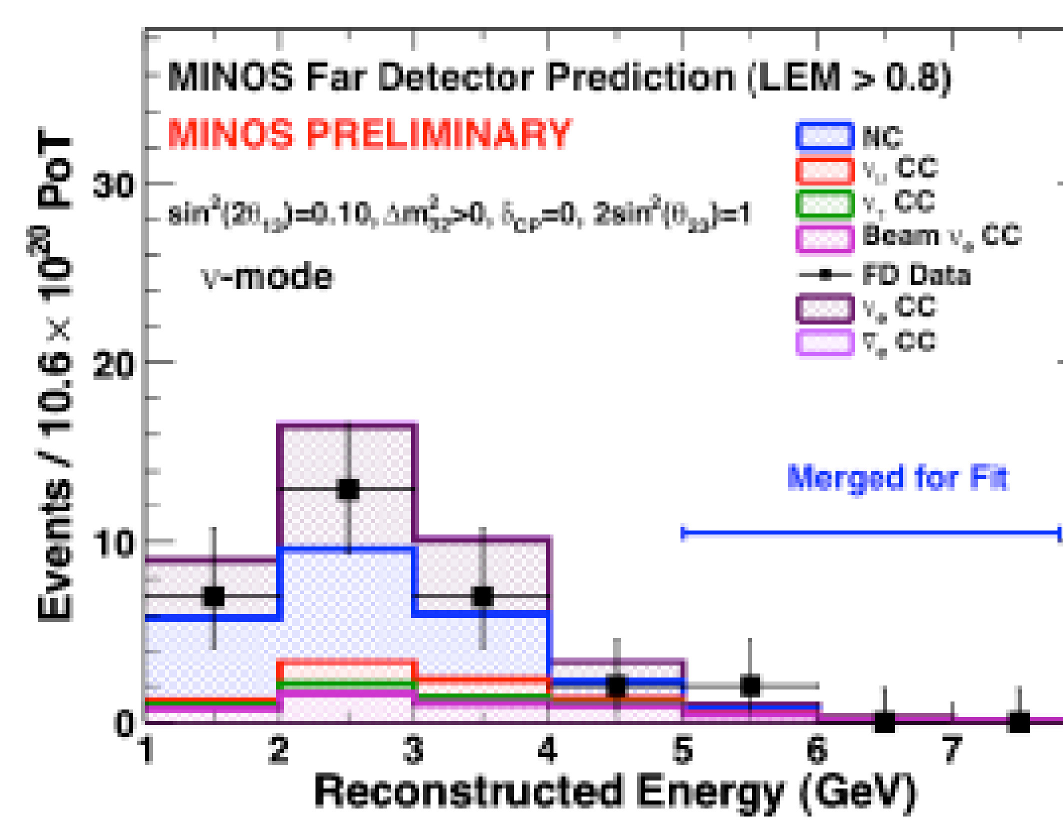
- Observe: 88 Events
  - If $\theta_{13}=0$: 69.1 bkgnd events
  - If $\sin^2(2\theta_{13})=0.1$: +26.0 events

Antineutrino running mode:

- Observe: 12 Events
  - If $\theta_{13}=0$: 10.5 bkgnd events
  - If $\sin^2(2\theta_{13})=0.1$: +3.1 events







ν_e Appearance in ν_μ Beams

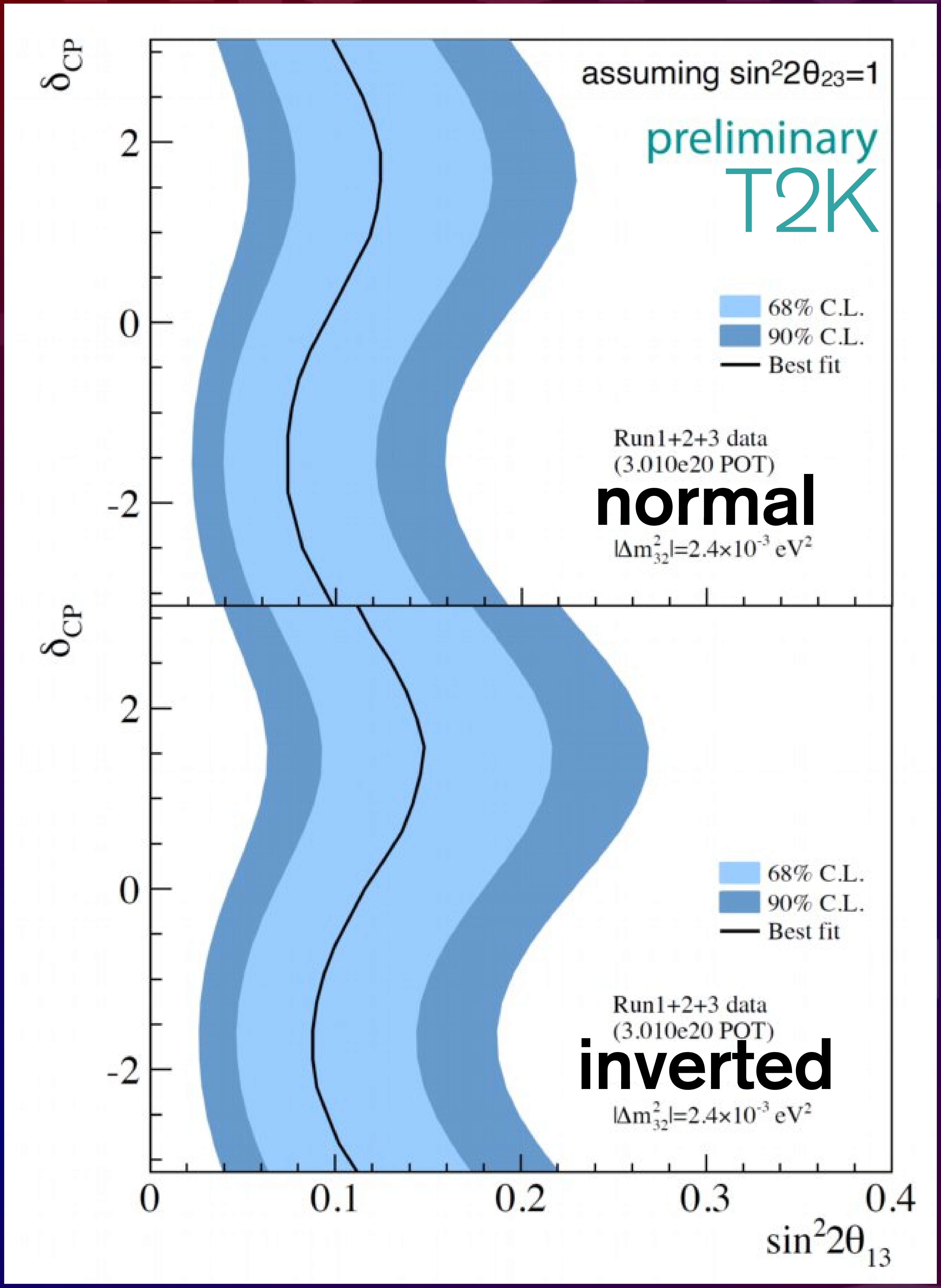
- Three-ν oscillation formula, expanded in $\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim 0.01$

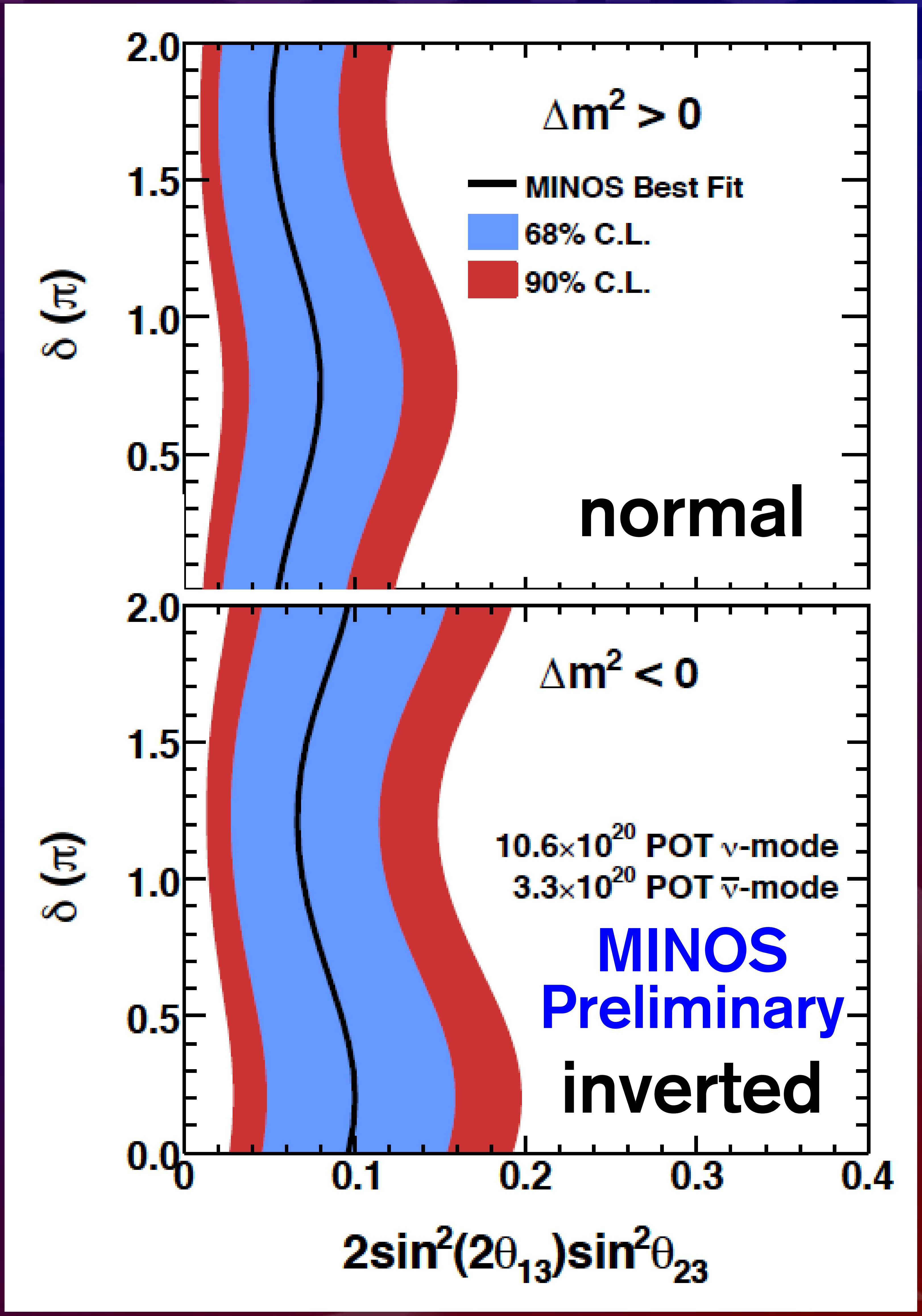
$$
\begin{aligned}
P_{\mu\to e} &= \sin^2 2\theta_{13} \sin^2 2\theta_{23} \frac{\sin^2 \hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2} \\
&+ \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \\
&\qquad \times \cos(\hat{\Delta} \pm \delta_{CP}) \frac{\sin \hat{\Delta}\hat{A}}{\hat{A}} \frac{\sin \hat{\Delta}(1-\hat{A})}{1-\hat{A}} \\
&+ \alpha^2 (\cdots)
\end{aligned}
$$

- where

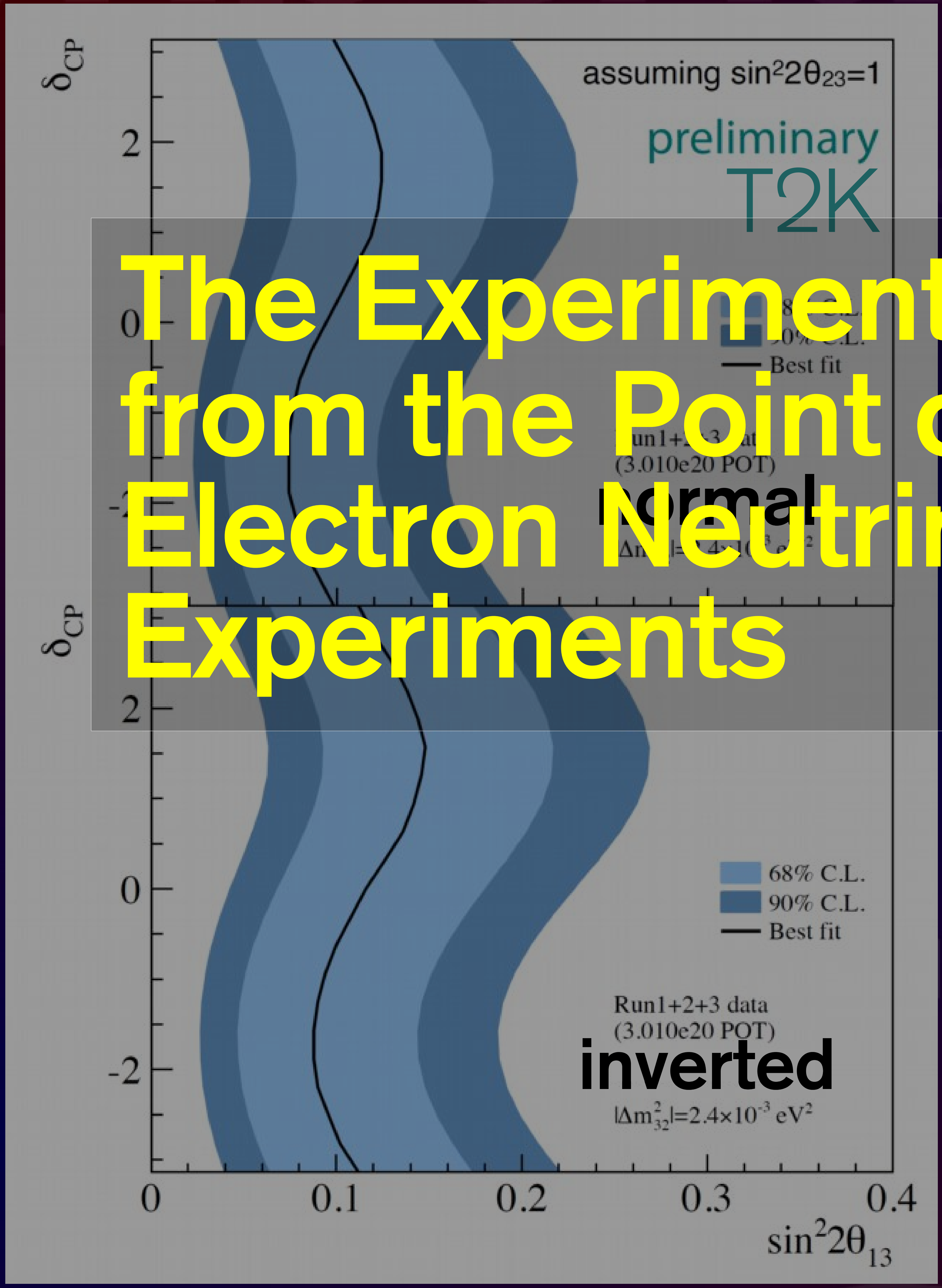
$$
\hat{\Delta} \equiv \Delta m^2_{31} \frac{L}{4E}, \qquad \hat{A} \equiv \pm 0.76 \times 10^{-4} \frac{\rho E [\mathrm{g \cdot cm^{-3} \cdot GeV}]}{\Delta m^2_{31} [\mathrm{eV}^2]}
$$

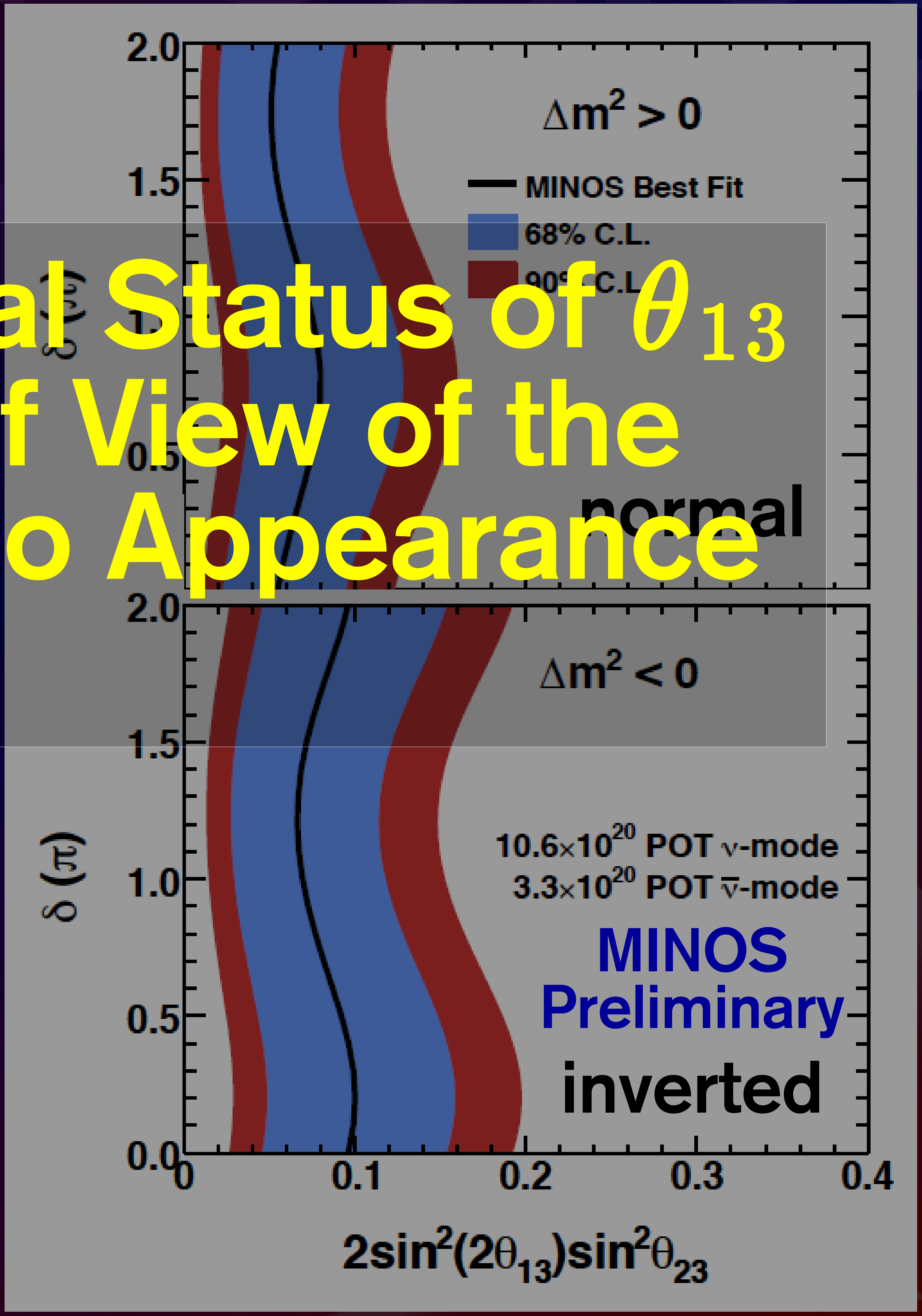
ν_e Appearance Oscillation Contours





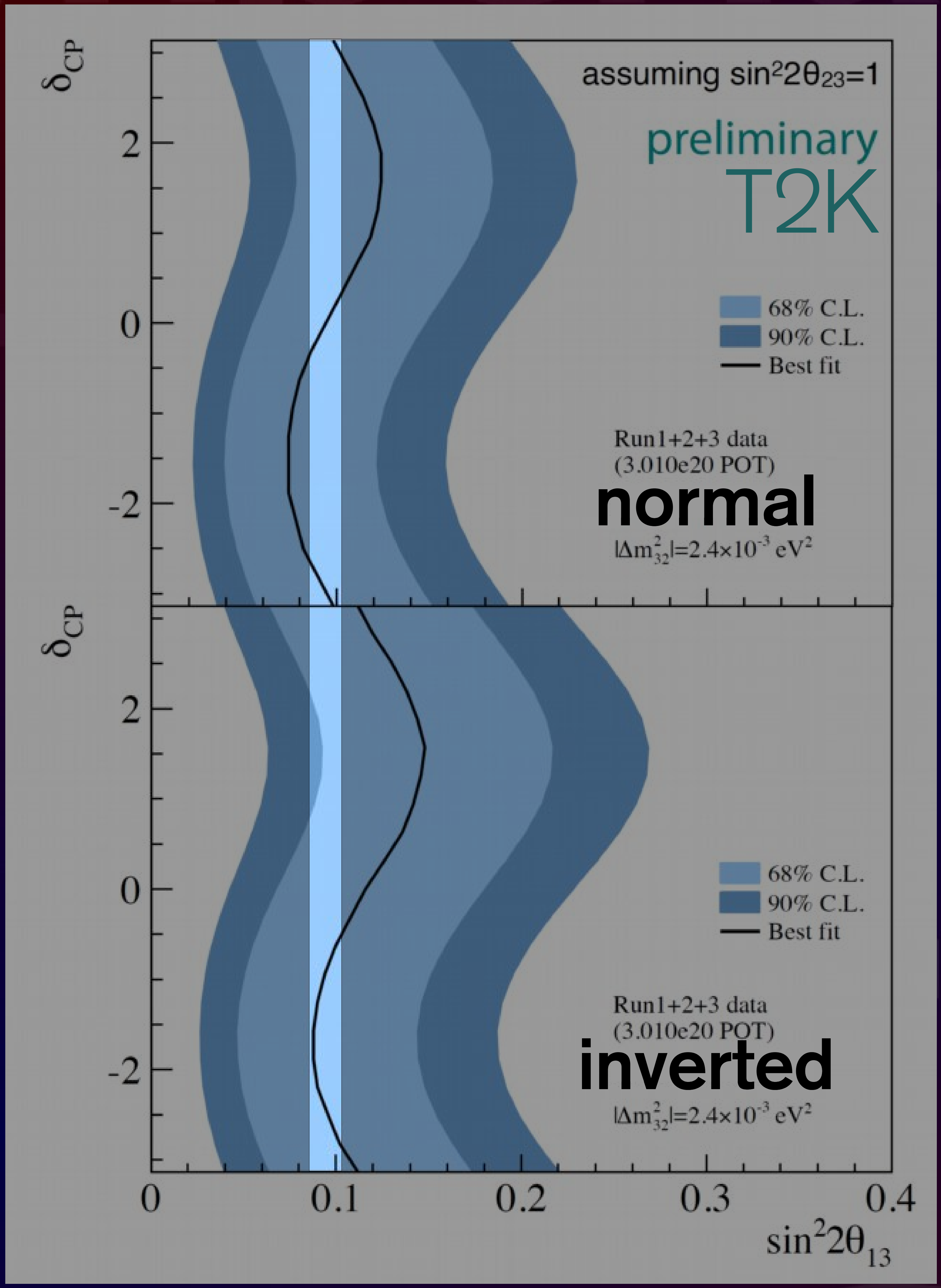
ν_e Appearance Oscillation Contours

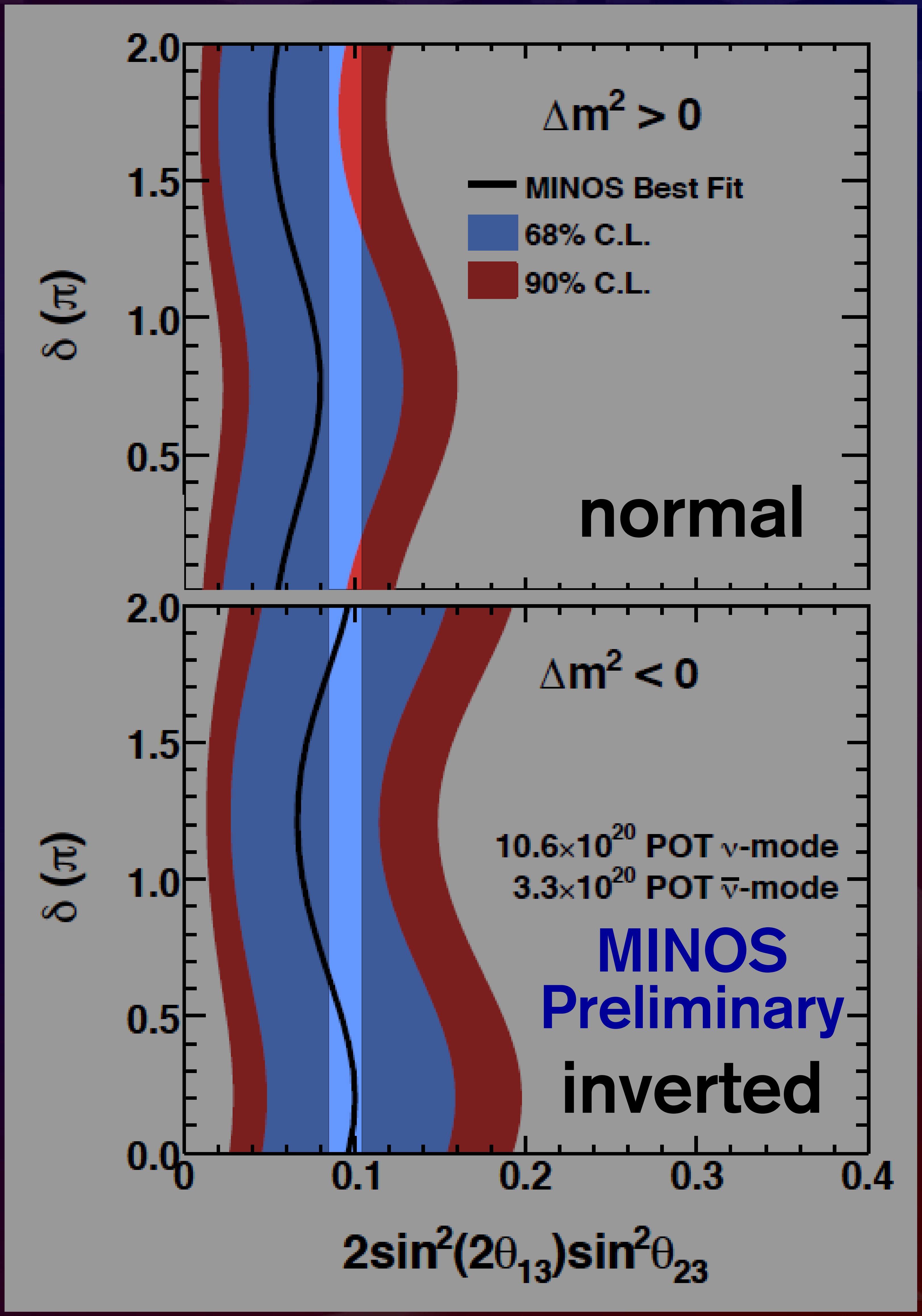




The Experimental Status of θ_{13} from the Point of View of the Electron Neutrino Appearance Experiments

ν_e Appearance Oscillation Contours





ν_e Appearance in ν_μ Beams

- Depends on (in addition to known values)
  - θ_{13} : the dominant mixing angle
  - θ_{23} : in particular the deviation from 45°
  - δ_{CP} : CP-violating mixing parameter
  - **sign(Δm^2_{31})** : the mass hierarchy

and **energy**, **distance**, and **matter density** and ν / $\bar{\nu}$ choice

- rich experimental phenomenology to explore
  - crucial input from our knowledge of θ_{13} from reactors
  - degeneracies need to be resolved
    - multiple long-baseline beam experiments

ν_e Appearance in ν_μ Beams

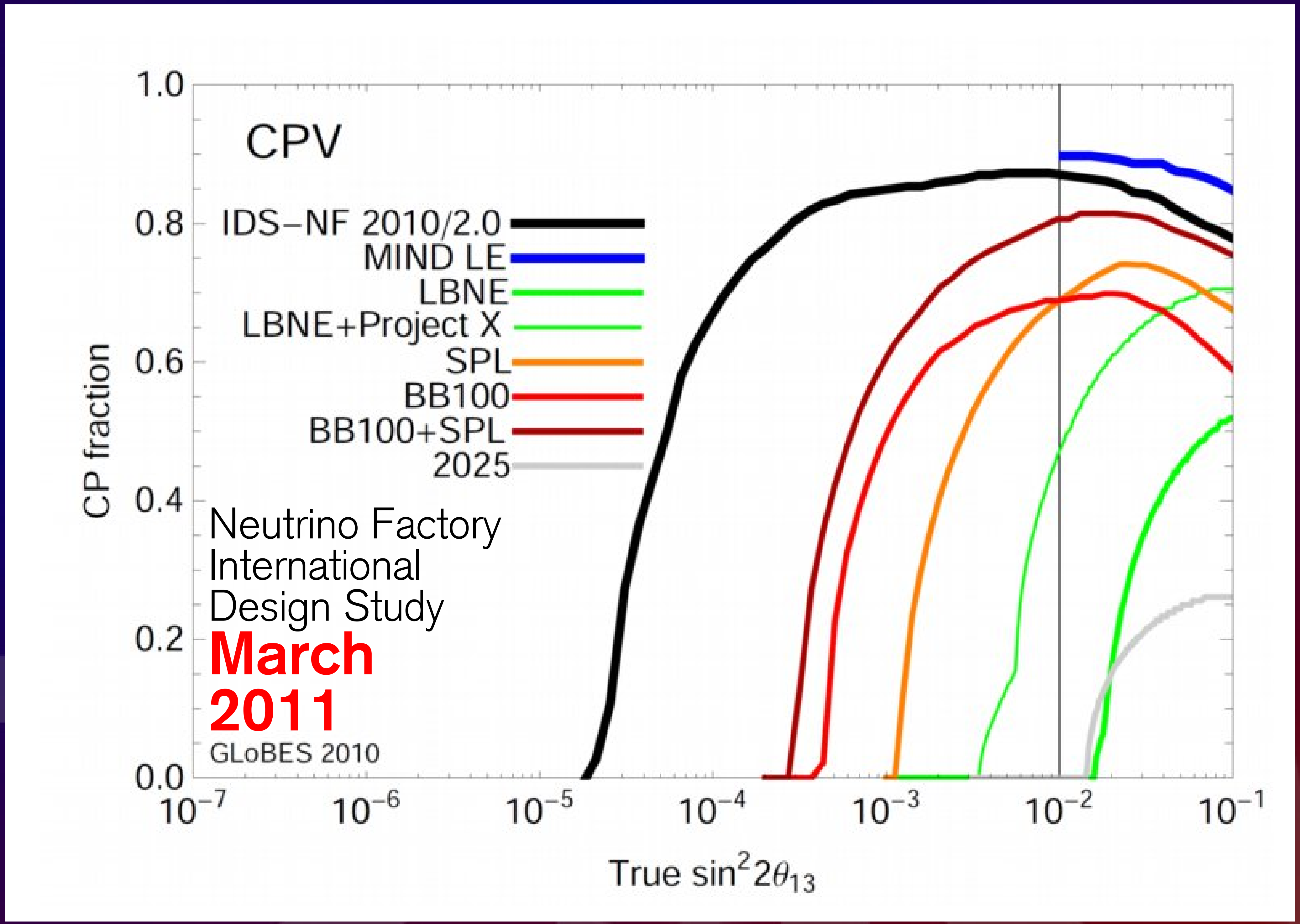
- Depends on (in addition to known values)
  - θ_{13} : the dominant mixing angle (now known)
  - θ_{23} : in particular the deviation from 45°
  - δ_{CP} : CP-violating mixing parameter
  - **sign**$(\Delta m^2{}_{31})$: the mass hierarchy

and **energy**, **distance**, and **matter density** and ν / $\overline{\nu}$ choice

- rich experimental phenomenology to explore
  - crucial input from our knowledge of θ_{13} from reactors
  - degeneracies need to be resolved
    - multiple long-baseline beam experiments

The Discovery of ν_e Appearance

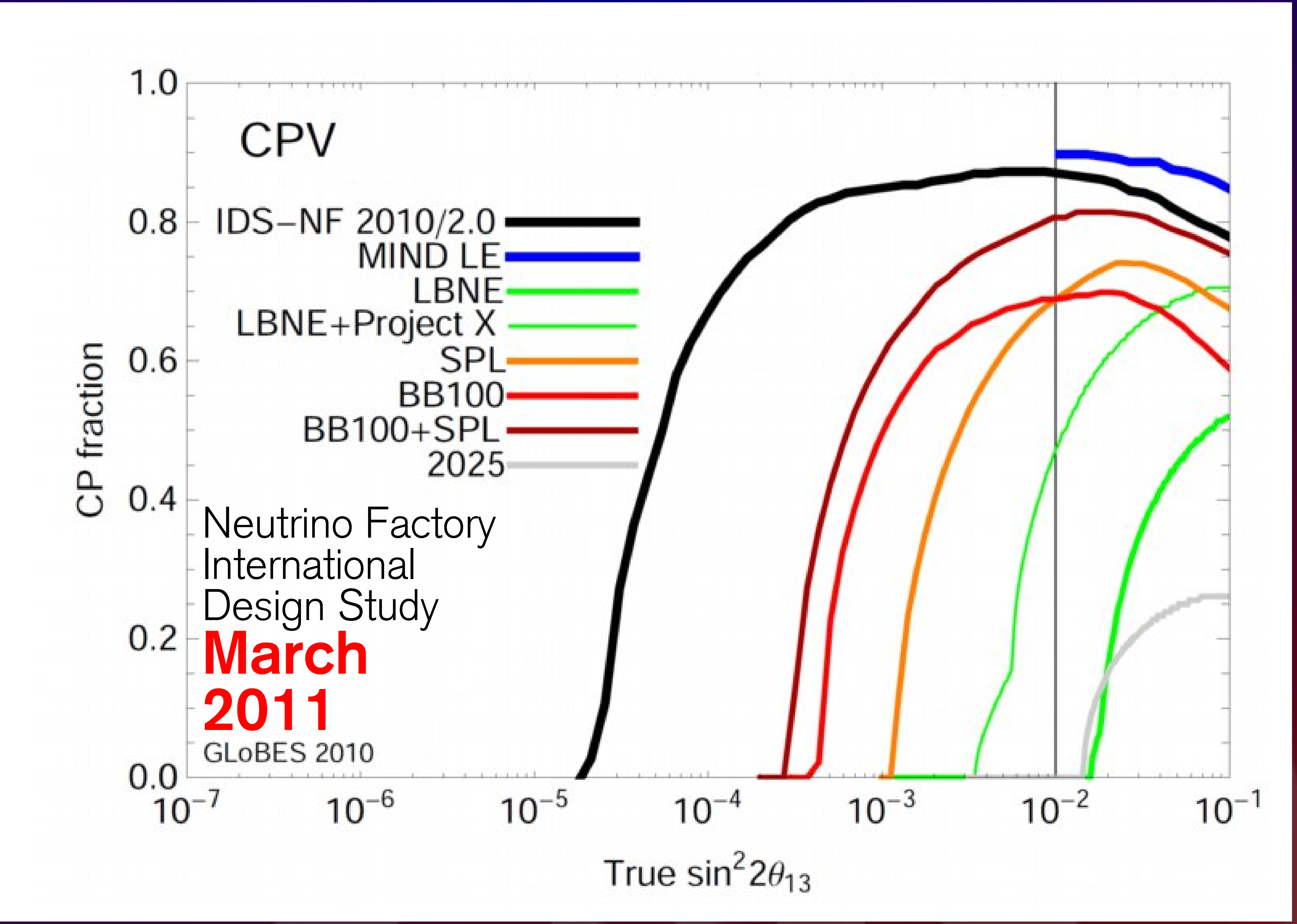
- **T2K has observed ν_e appearance** with a significance of 3.2 σ
- **θ_{13} must be non-zero** to observe ν_e appearance
- **Consistent with 1 km reactor $\overline{\nu}_e$ disappearance** results



Comparison of the **physics reach** of different future facilities for the discovery of **CP violation**

The Discovery of ν_e Appearance

- **T2K has observed ν_e appearance** with a significance of 3.2 σ
- **θ_{13} must be non-zero** to observe ν_e appearance
- **Consistent with 1 km reactor $\overline{\nu}_e$ disappearance** results
- However, these measurements are sensitive to **different properties of neutrinos**
  - **1 km reactor $\overline{\nu}_e$s effectively measure θ_{13} directly** (see previous talk)
  - accelerator ν_e appearance experiments measure a **combination of neutrino parameters**



Comparison of the **physics reach** of different future facilities for the discovery of **CP violation**

ν_e Appearance in ν_μ Beams

- Three-ν oscillation formula, expanded in $\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim 0.01$

$$P_{\mu\to e} = \sin^2 2\theta_{13} \sin^2 2\theta_{23} \frac{\sin^2 \hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2}$$
$$+ \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$
$$\times \cos(\hat{\Delta} \pm \delta_{CP}) \frac{\sin \hat{\Delta}\hat{A}}{\hat{A}} \frac{\sin \hat{\Delta}(1-\hat{A})}{1-\hat{A}}$$
$$+ \alpha^2 (\cdots) \qquad (\nu \,/\, \bar{\nu})$$

- where

$$\hat{\Delta} \equiv \Delta m^2_{31} \frac{L}{4E}, \qquad \hat{A} \equiv \pm 0.76 \times 10^{-4} \frac{\rho E [\mathrm{g \cdot cm^{-3} \cdot GeV}]}{\Delta m^2_{31} [\mathrm{eV}^2]}$$

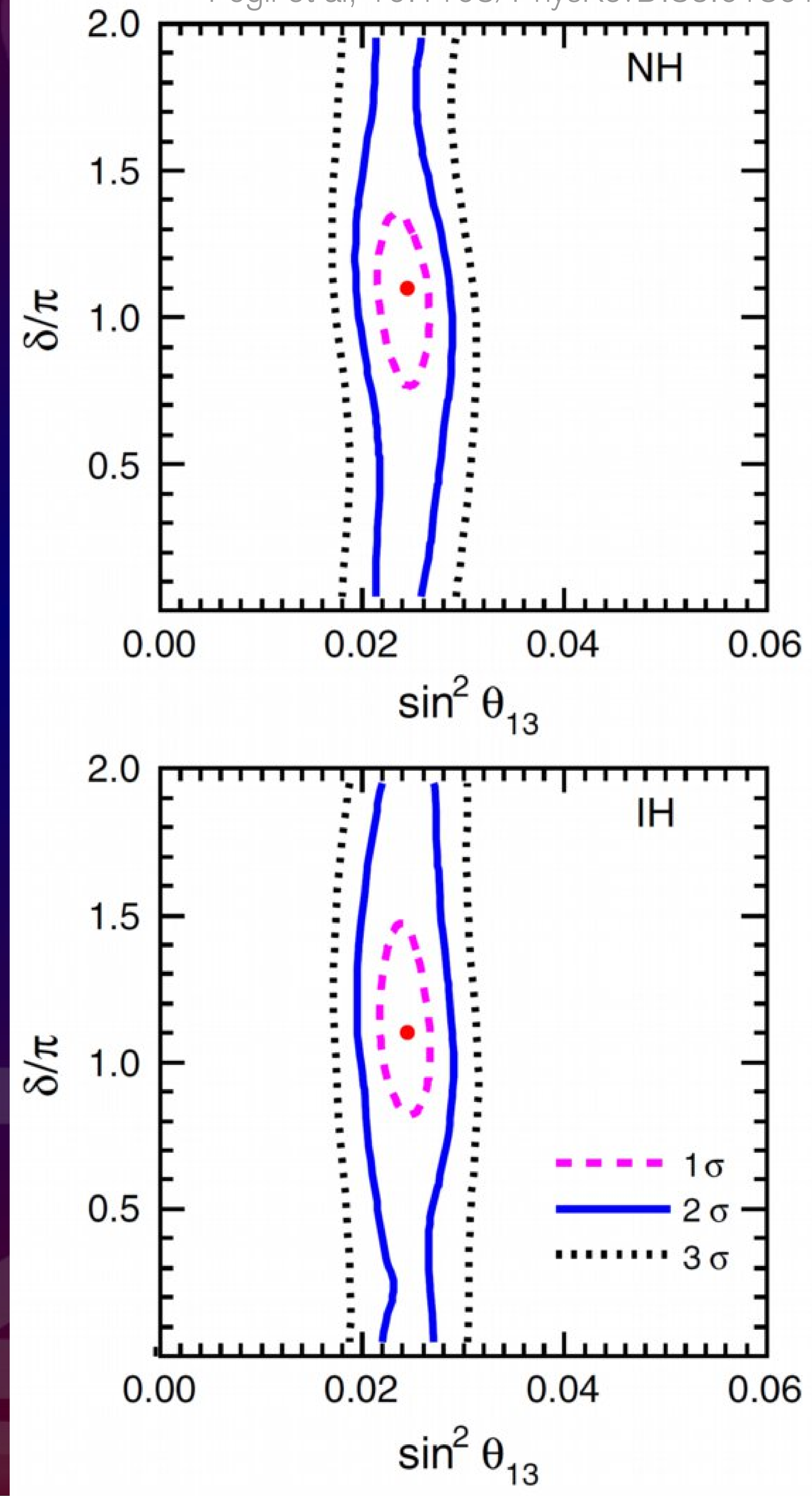
- Experiment-dependent quantities: L, E, ρ (matter density)

Global 3-Neutrino Oscillation Fits

Several groups demonstrating increasing ability of experimental evidence to constrain neutrino parameters

Fit for δ_{CP} including accelerator (K2K, MINOS, T2K), solar, KamLAND, 1 km reactor and Super-K atmospheric neutrinos

Fogli et al, 10.1103/PhysRevD.86.013012



The Immediate Future

T2K Beam Power Plans

The medium-term plan of the MR-FX until 2017

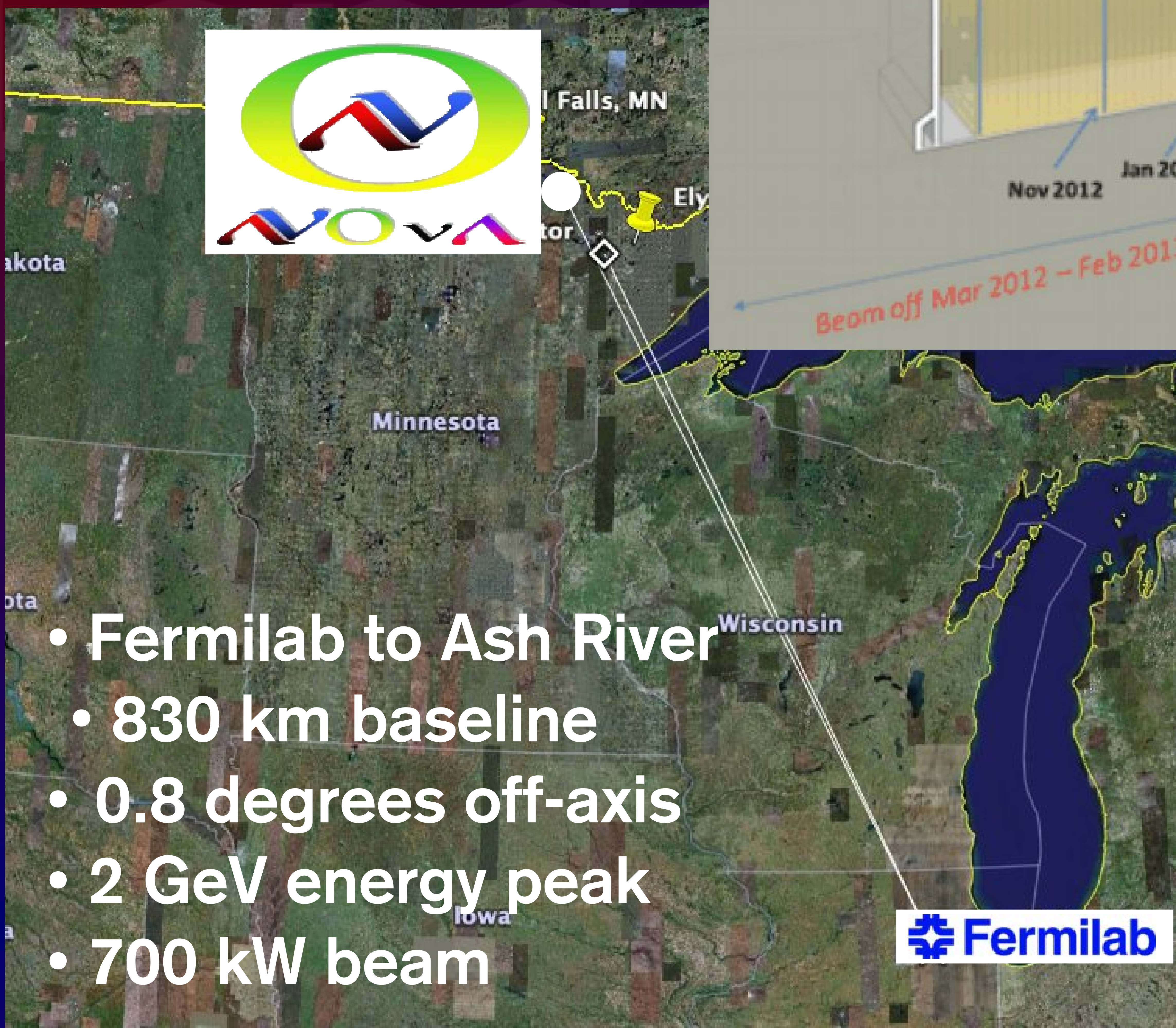
We adopt the high repetition rate scheme to achieve the design beam intensity, 750 kW.
Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's and RF cavities.

JFY	2011	2012	2013	2014	2015	2016	2017
			Li. upgrade				
FX power [kW]	150	200	300	400			750
Cycle time of main magnet PS **New magnet PS for high rep.**	3.04 s	2.56 s R&D	2.4 s		Manufacture installation/test		1.3 s
Present RF system **New high gradient rf system**	Install. #7,8	Install. #9 R&D			Manufacture installation/test		
Ring collimators	Additional shields	Add.collimators and shields (2kW)	Add.collimators (3.5kW)				
Injection system **FX system**	New injection kicker	Kicker PS improvement、Septum 2 manufacture /test LF septum, PS for HF septa manufacture /test					

NOνA (2013—)

NuMI Off-Axis ν_e Appearance

Far detector projected progress



- Fermilab to Ash River
  - 830 km baseline
- 0.8 degrees off-axis
- 2 GeV energy peak
- 700 kW beam

- Large far detector (14 kt)
- Optimised specifically for ν_e appearance
- Larger matter effects (distance & energy) than T2K

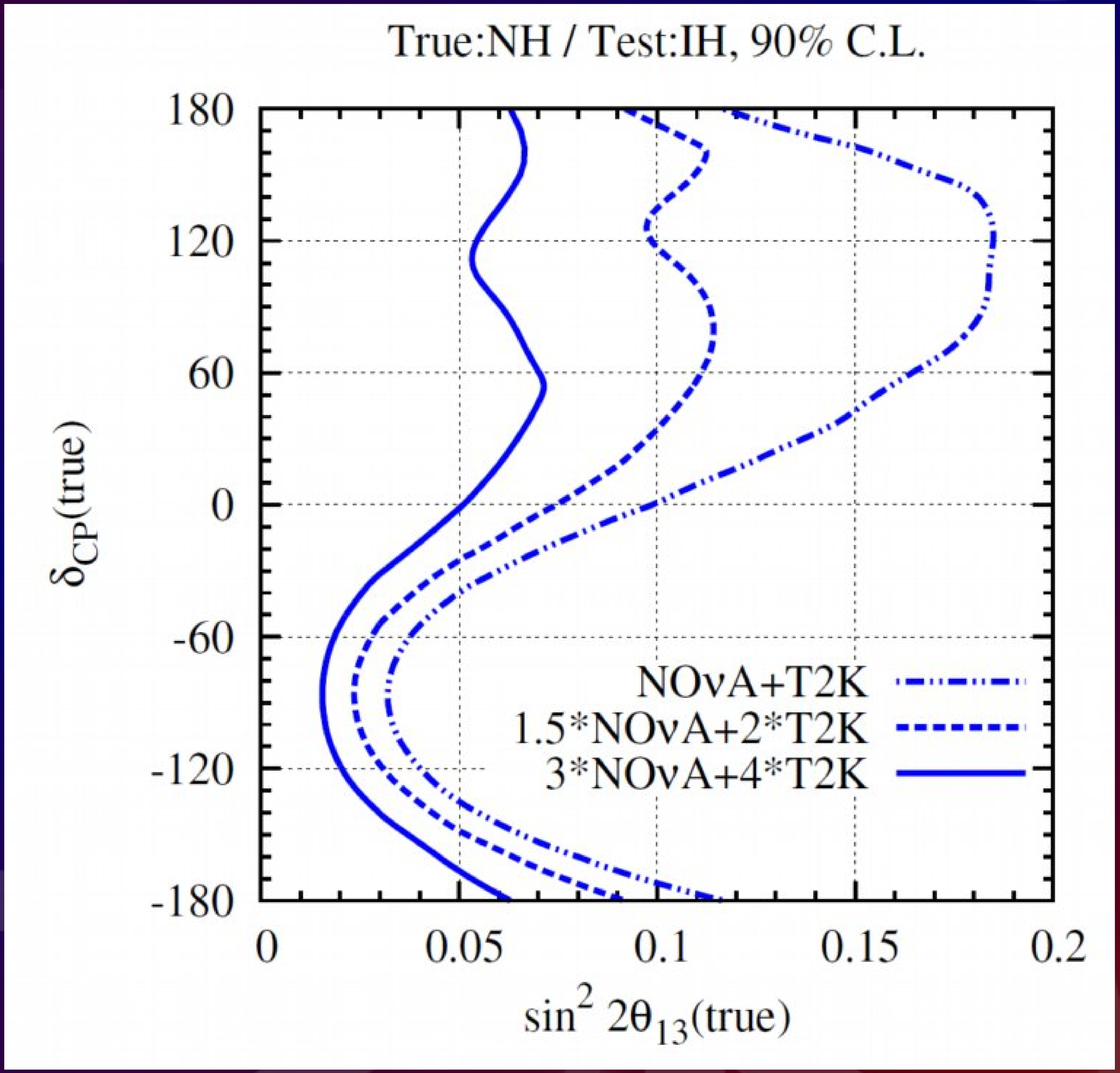
NOνA (2013—)

NuMI Off-Axis ν_e Appearance

Far detector site

Combining T2K and NOνA

- Several variables
  - beam intensity / detector construction time profile
  - ν / $\bar{\nu}$ running fractions
  - true values of oscillation parameters
- Many phenomenological studies ongoing



Example: T2K+NOνA combinations to test for the mass hierarchy

The Next Generation(s)

this a very active area—hence no intention
to present a comprehensive survey today

Design Considerations

Event rate

Oscillation phase

CP violation

Cross sections

Matter effects

Beam composition

Design Considerations

Event rate
$\propto$ intensity $\times$ cross sections
$\times$ detector mass $\div$ distance

Oscillation phase
$\propto$ distance $\div$ energy

CP violation
ν and $\bar{\nu}$
matter effects

Cross sections
high for ν
low for $\bar{\nu}$
CCQE/CCnπ/DIS

Matter effects
$\propto$ density $\times$ distance
$\times$ energy

Beam composition
pion decay
stored muon decay
beta decay

Design Considerations

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$\propto$ intensity $\times$ cross sections
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Matter effects
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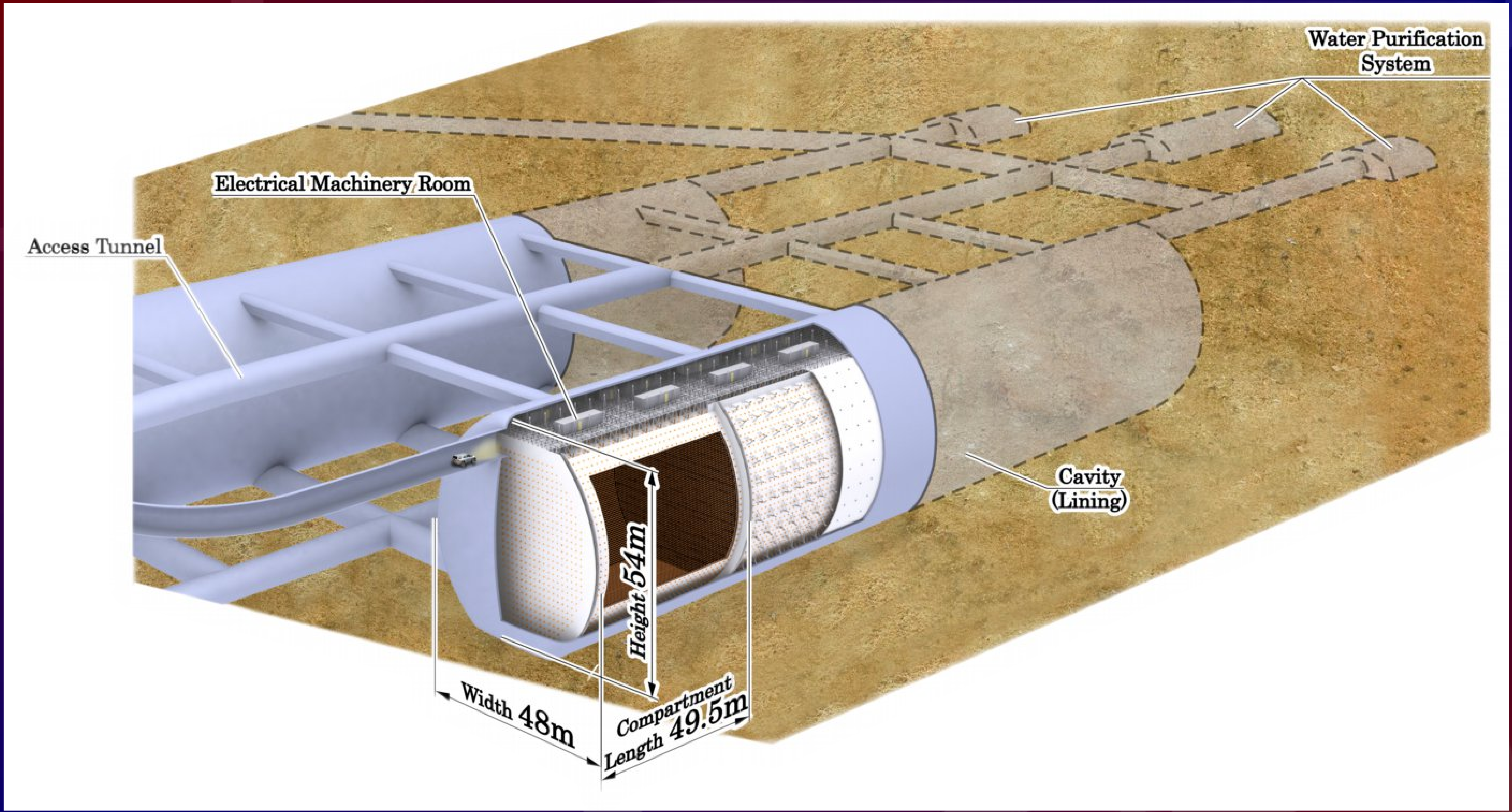
Beam composition
pion decay
stored muon decay
beta decay

...and of course **cost**. Many large-scale studies under way and concrete proposals

Hyper-Kamiokande



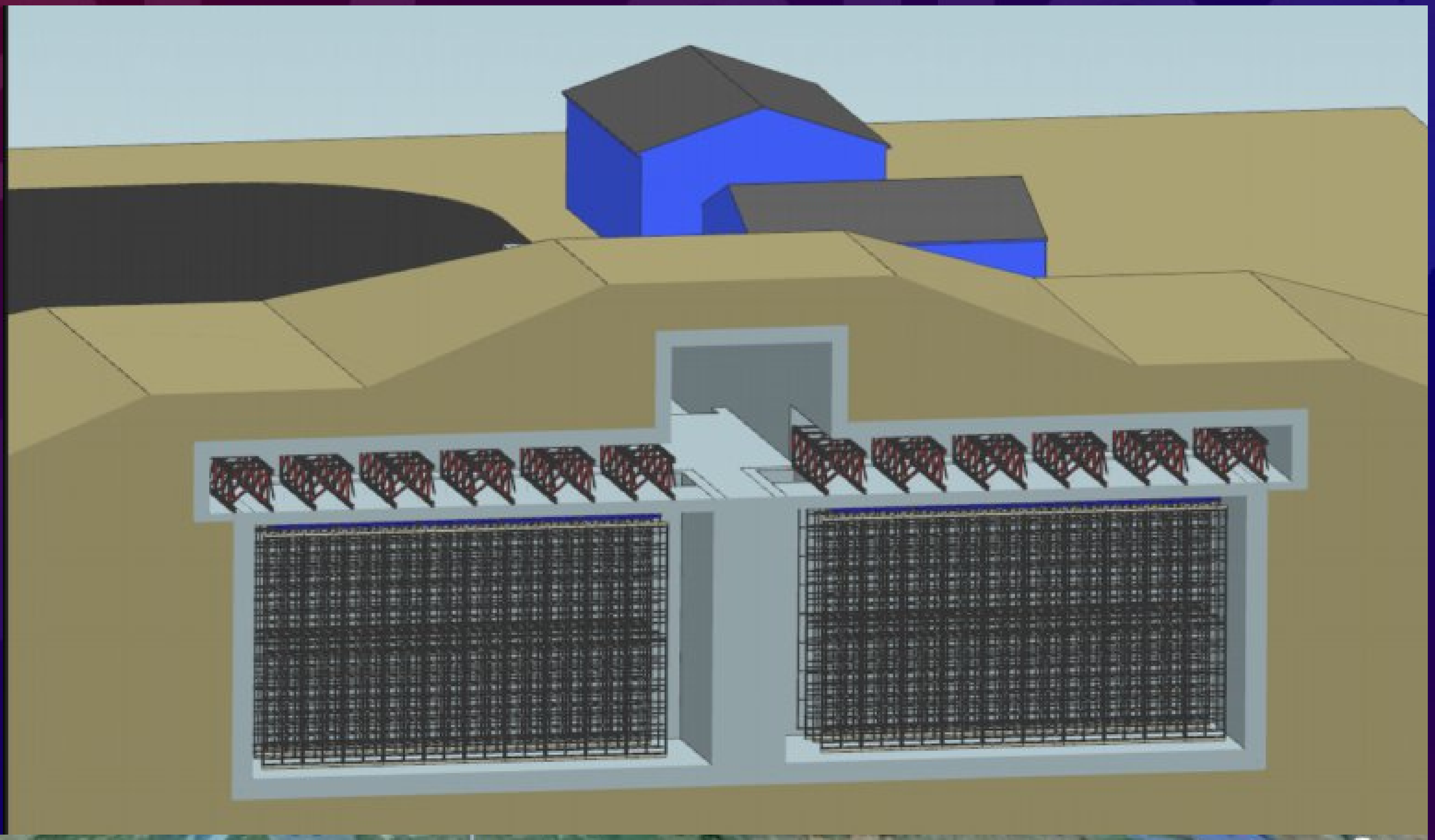
- 0.56 Mt (Super-K × 25), 750 kW from J-PARC over 295 km
- Okinoshima island (Sea of Japan) with Liquid Argon also an option

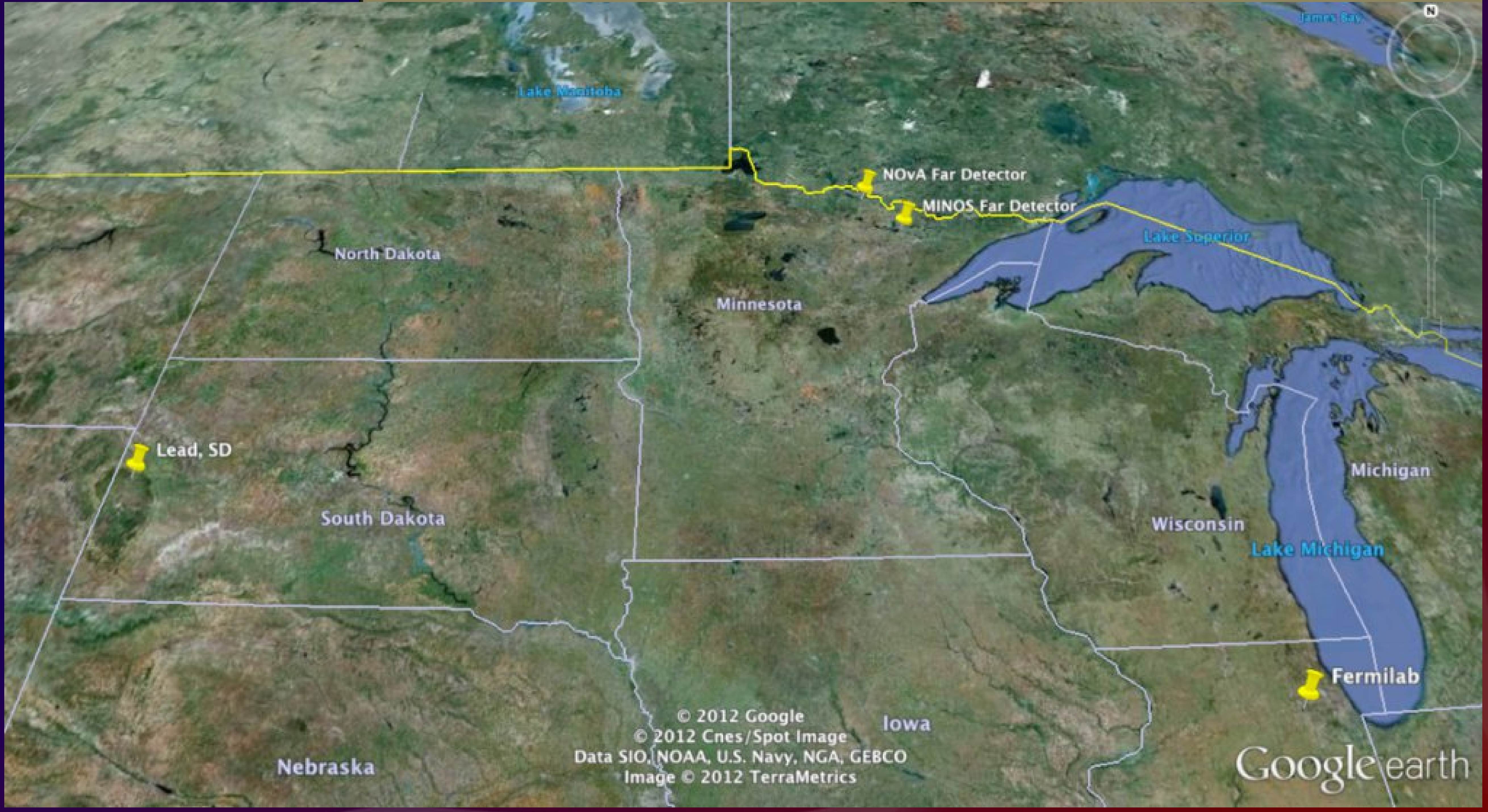
LAGUNA-LBNO

- CERN to Pyhäsalmi mine (Finland)
- 2300 km baseline
- Detectors:
  - 100 kt Liquid Argon
  - 50 kt Magnetised Iron

LBNE

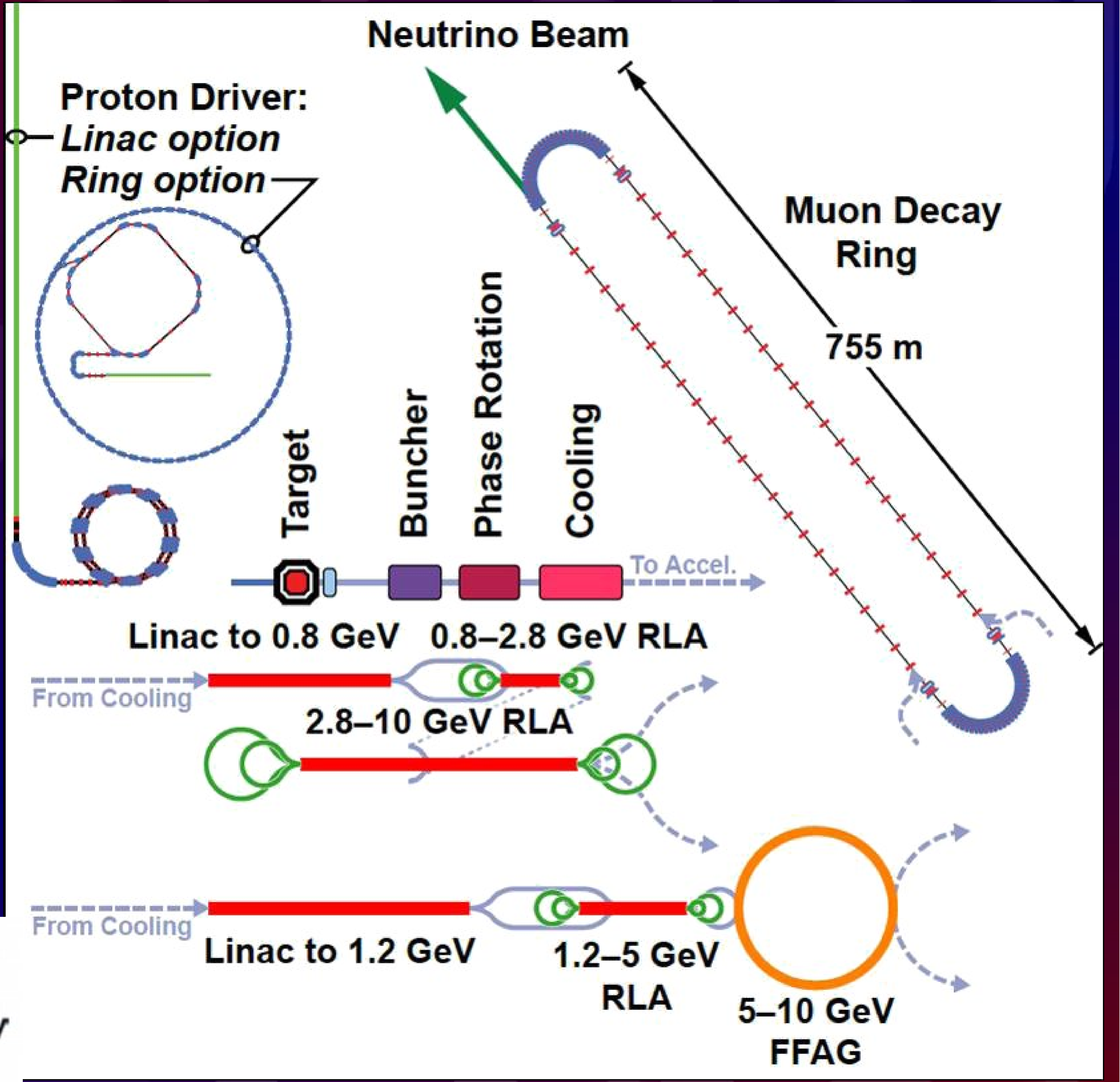
- Fermilab to Homestake
  - 1300 km baseline
- New neutrino beamline
- Recently settled on 10 kton Liquid Argon TPC detector at the surface
- Potentially up to 2.2 MW with Project-X

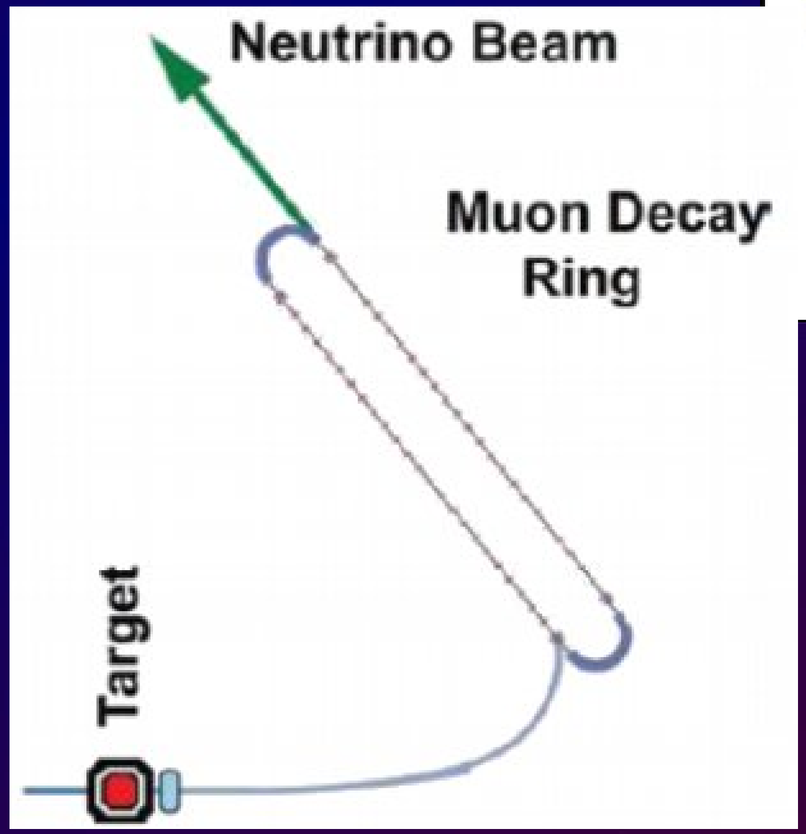




Neutrino Factory

- Neutrino beam from muon storage beam
  - pure muon decay neutrino products
  - excellent beam definition
- Staging plan being developed
  - nuSTORM:



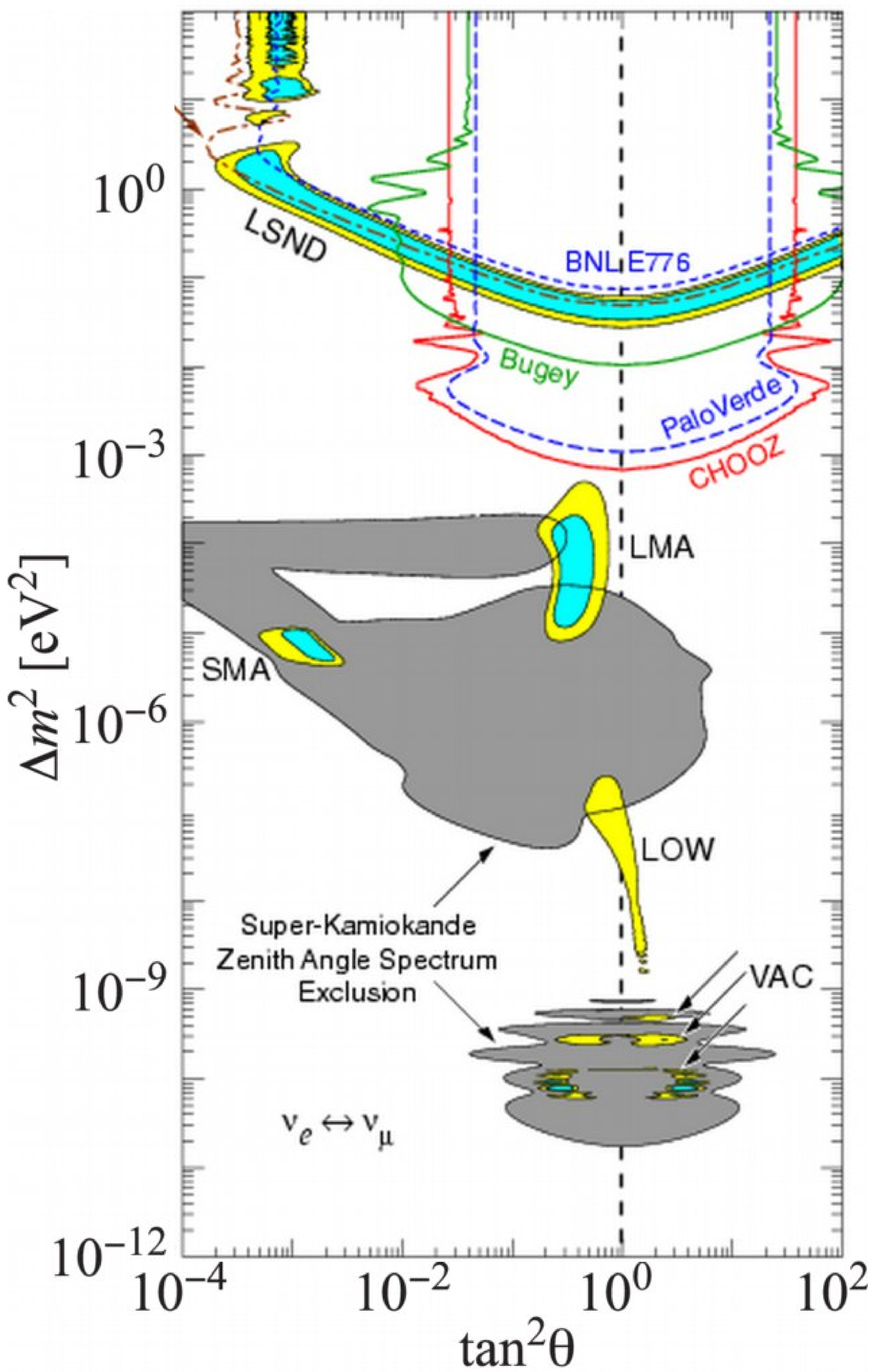


Conclusions

- Neutrino mass is the only well-established observation that lie Beyond the Standard Model
- With θ_{13}, all "standard" mixing angles and Δm^2 s observed
- We learn by combining reactor and accelerator results
- Rates for oscillation processes now calculable
- Test for
  - deviation of θ_{23} from maximal, the mass hierarchy, CP-violation in leptons, and the unexpected
- The effort to exploit the θ_{13} discovery is under way
  - Near future: T2K & NOνA
  - Next generation: currently undergoing intense study

End of Talk—Spare Slides Follow

ν_μ and ν_e Oscillations (2001)



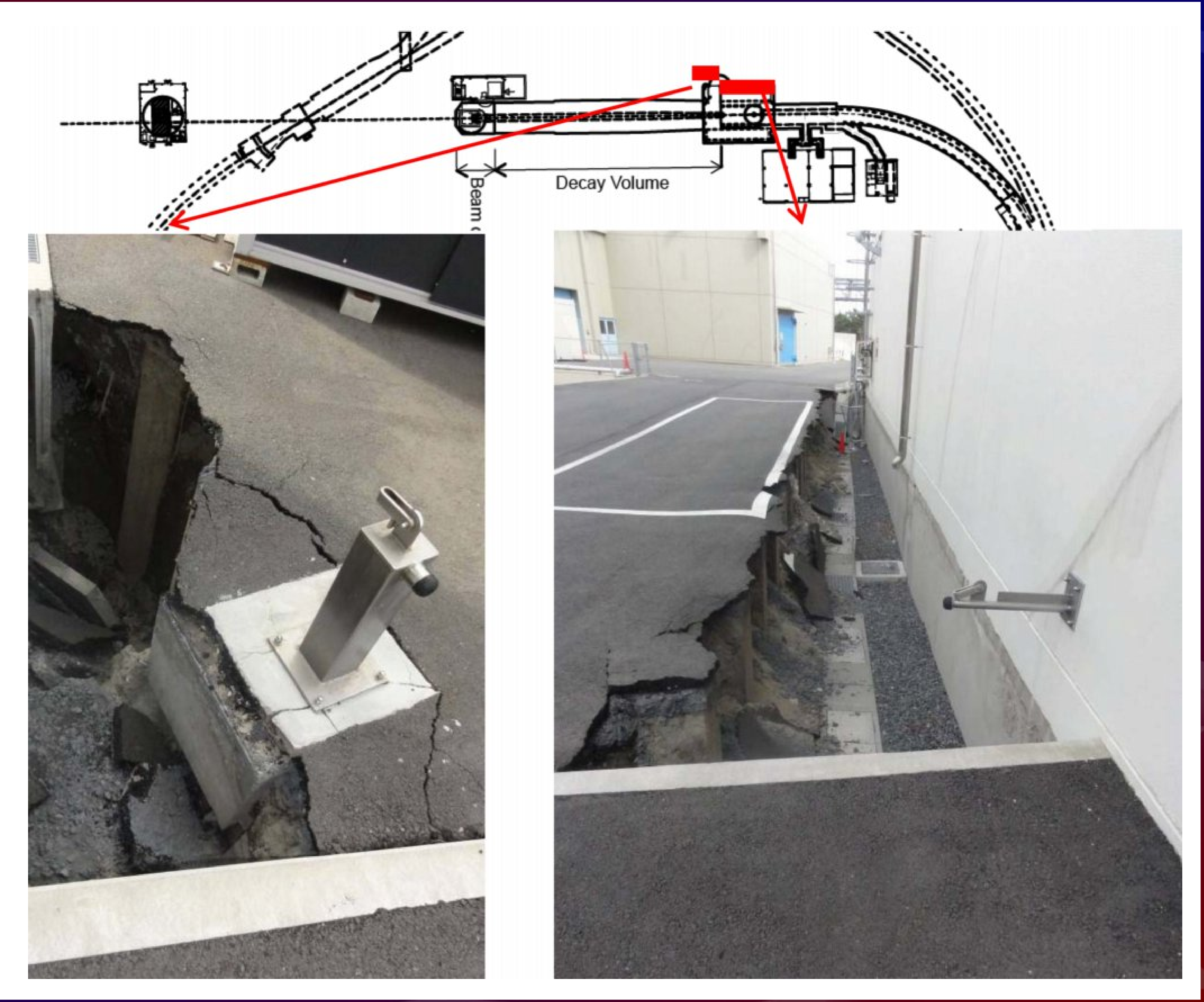
http://hitoshi.berkeley.edu/neutrino

The 11 March Earthquake

LINAC building entrance

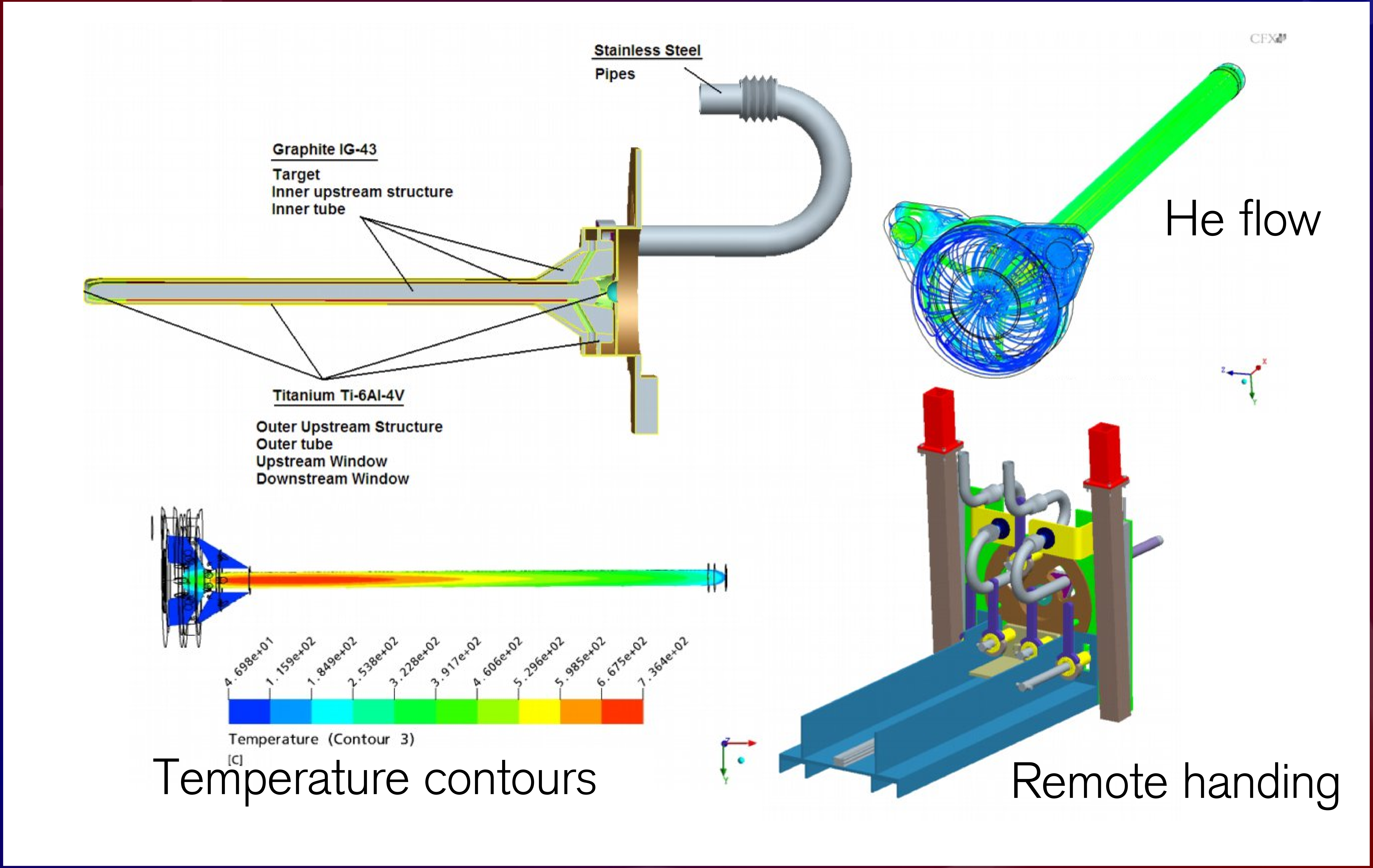
3 GeV Ring
Condenser Bank

The 11 March Earthquake

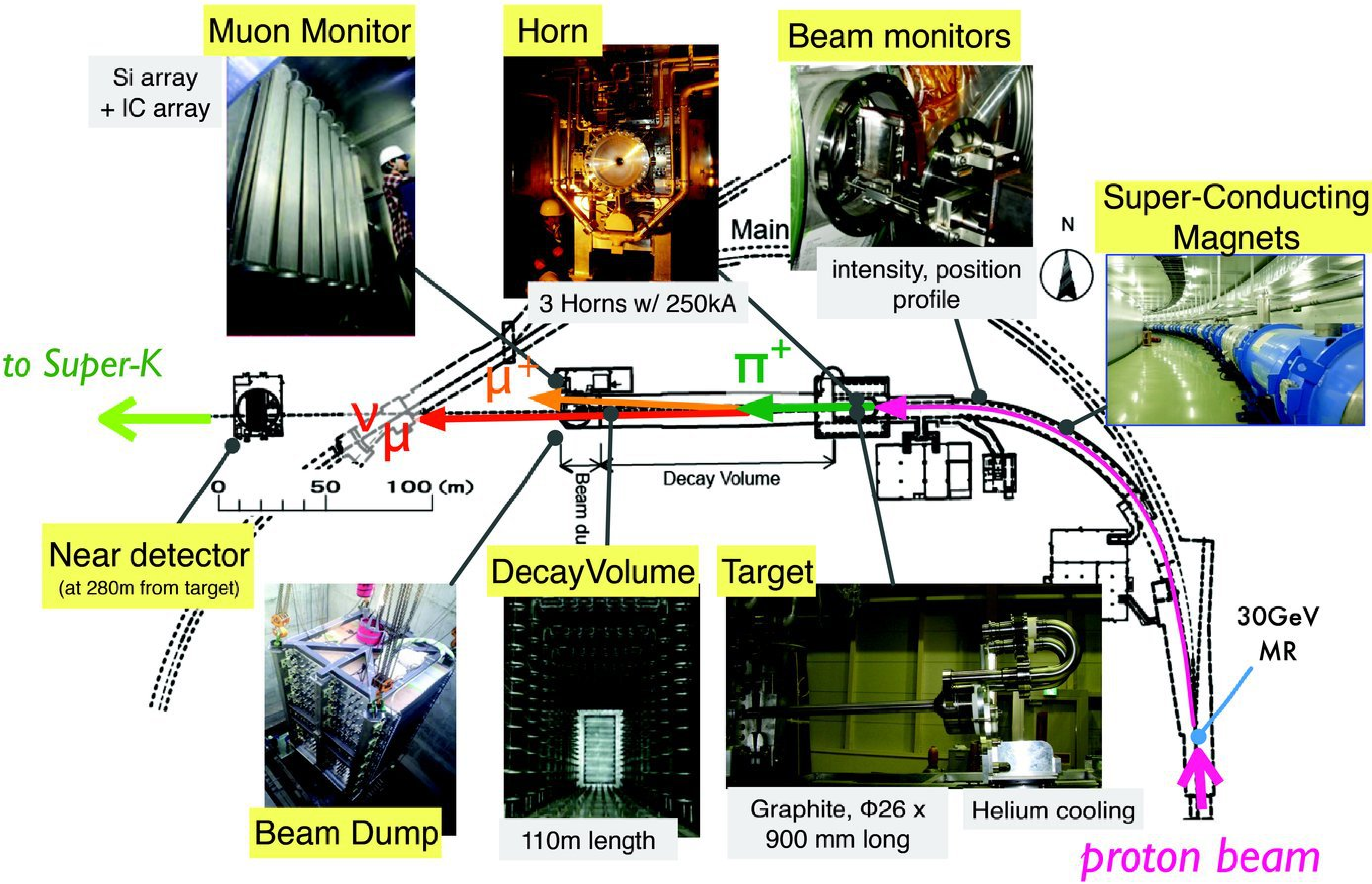


Neutrino Target Building Area

Proton Beam Targetry

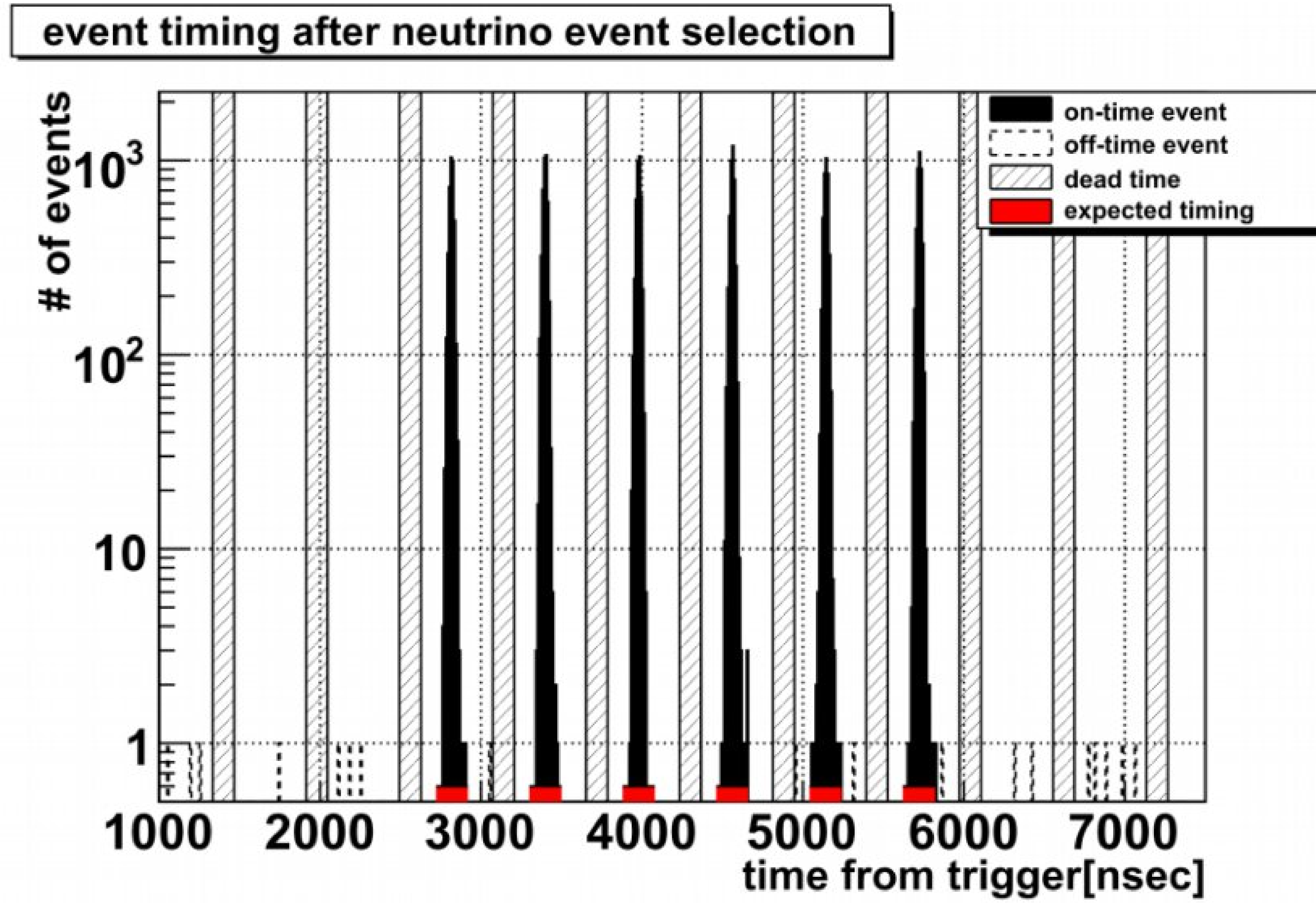


Neutrino Production at J-PARC

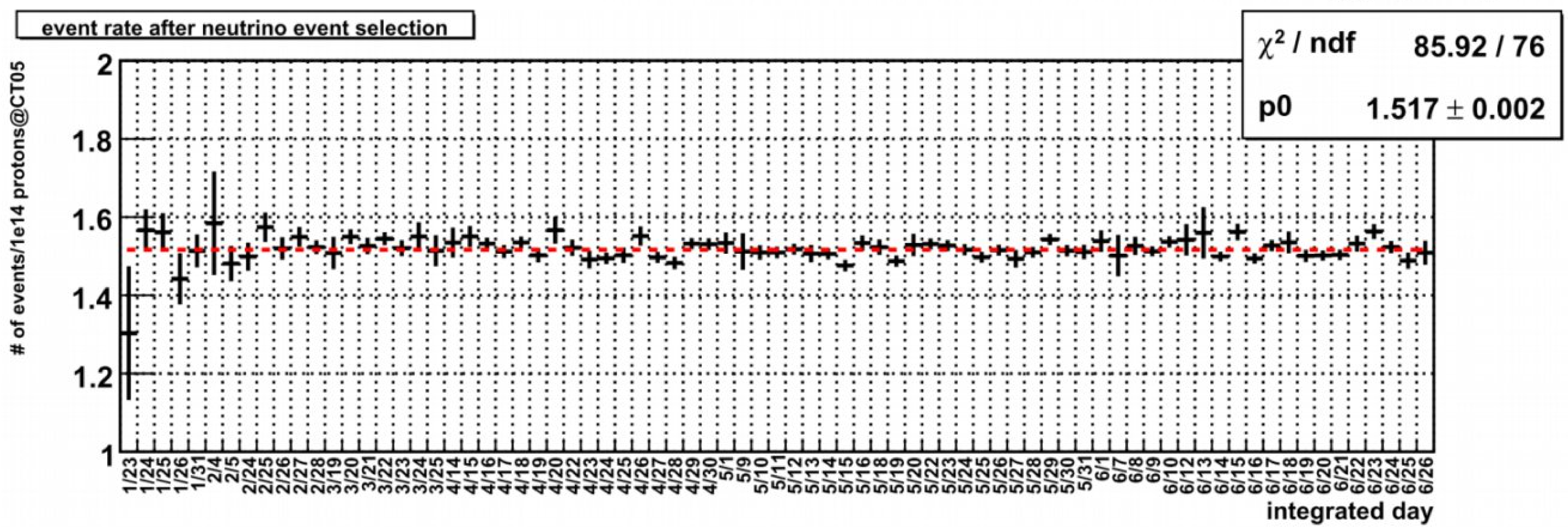


Measurements at INGRID

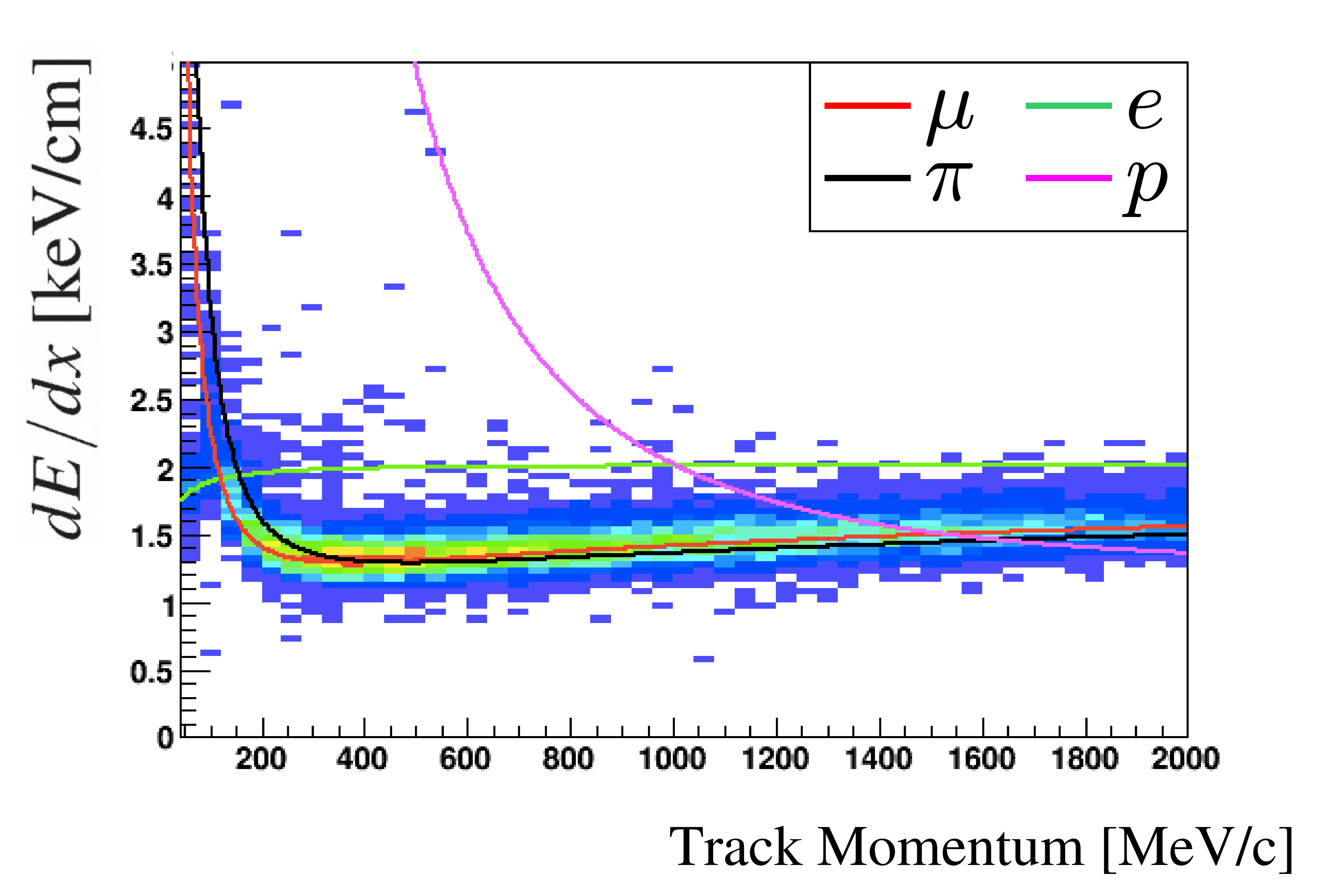
Bunch timing from neutrinos



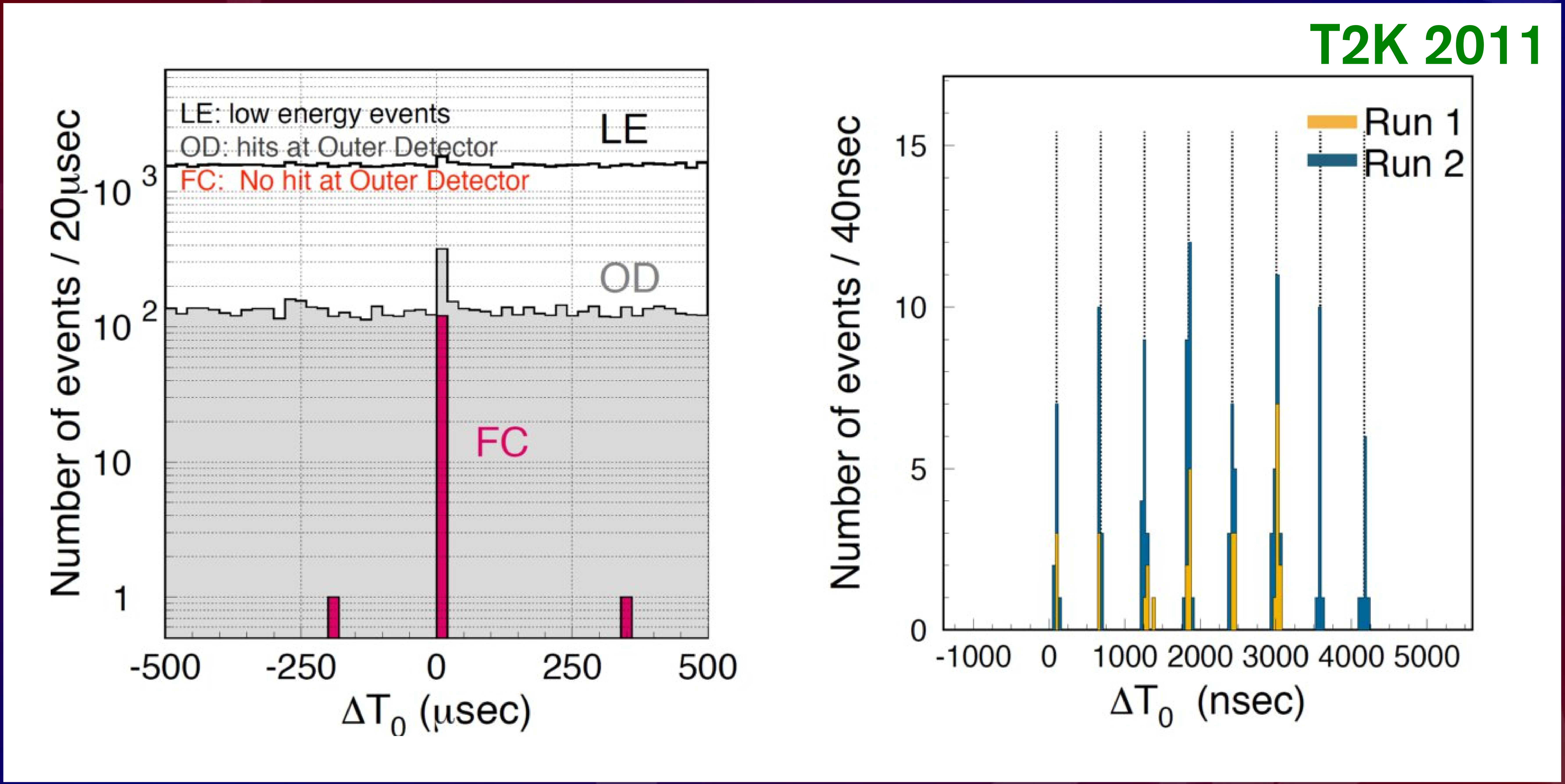
Daily number of neutrino events per number of protons



TPC dE/dx Particle ID (Negative Tracks)



T2K Far Detector Beam Event Timing

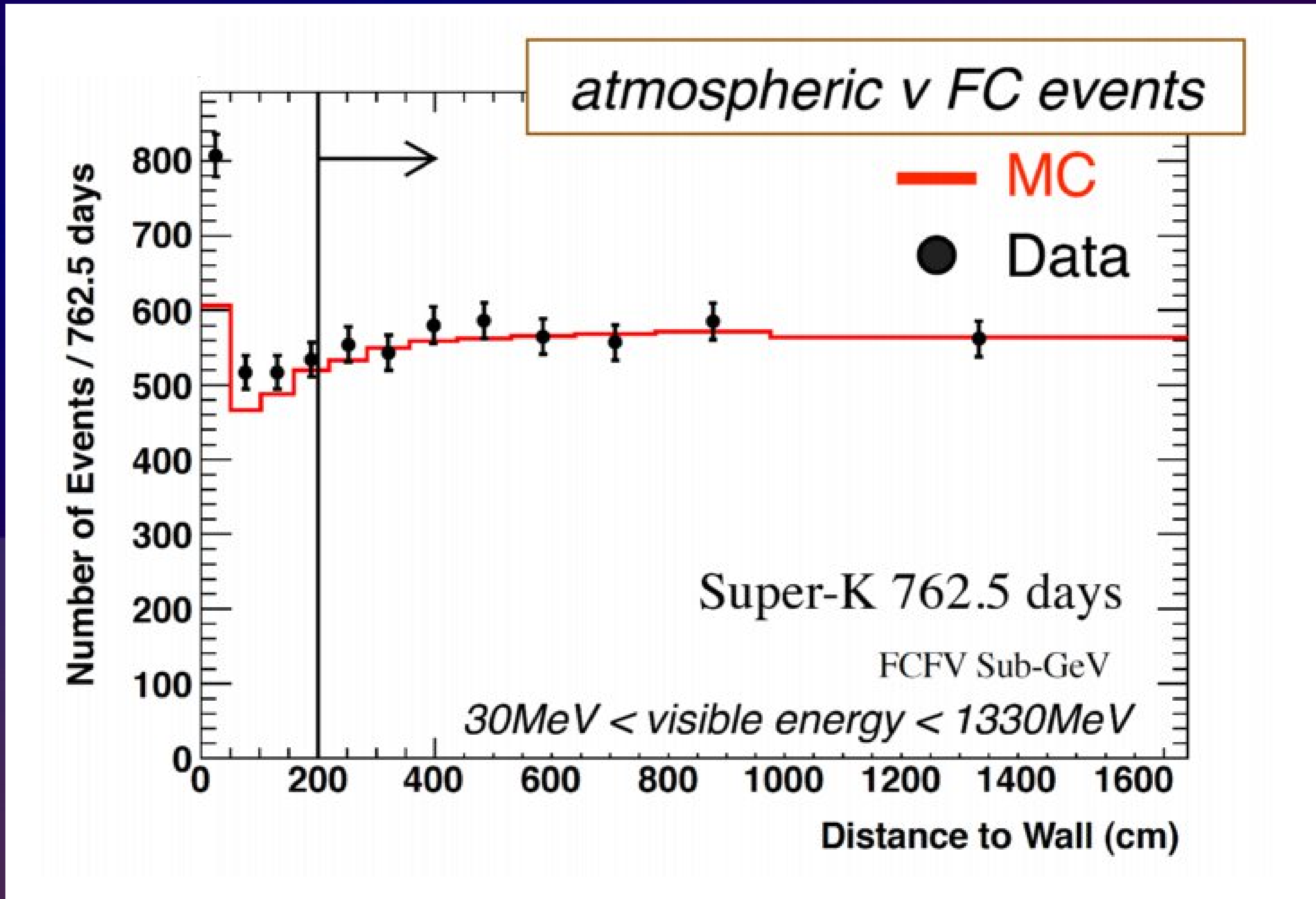


121 events survive timing cut (between –2 and +10 μs)

0.023 estimated background

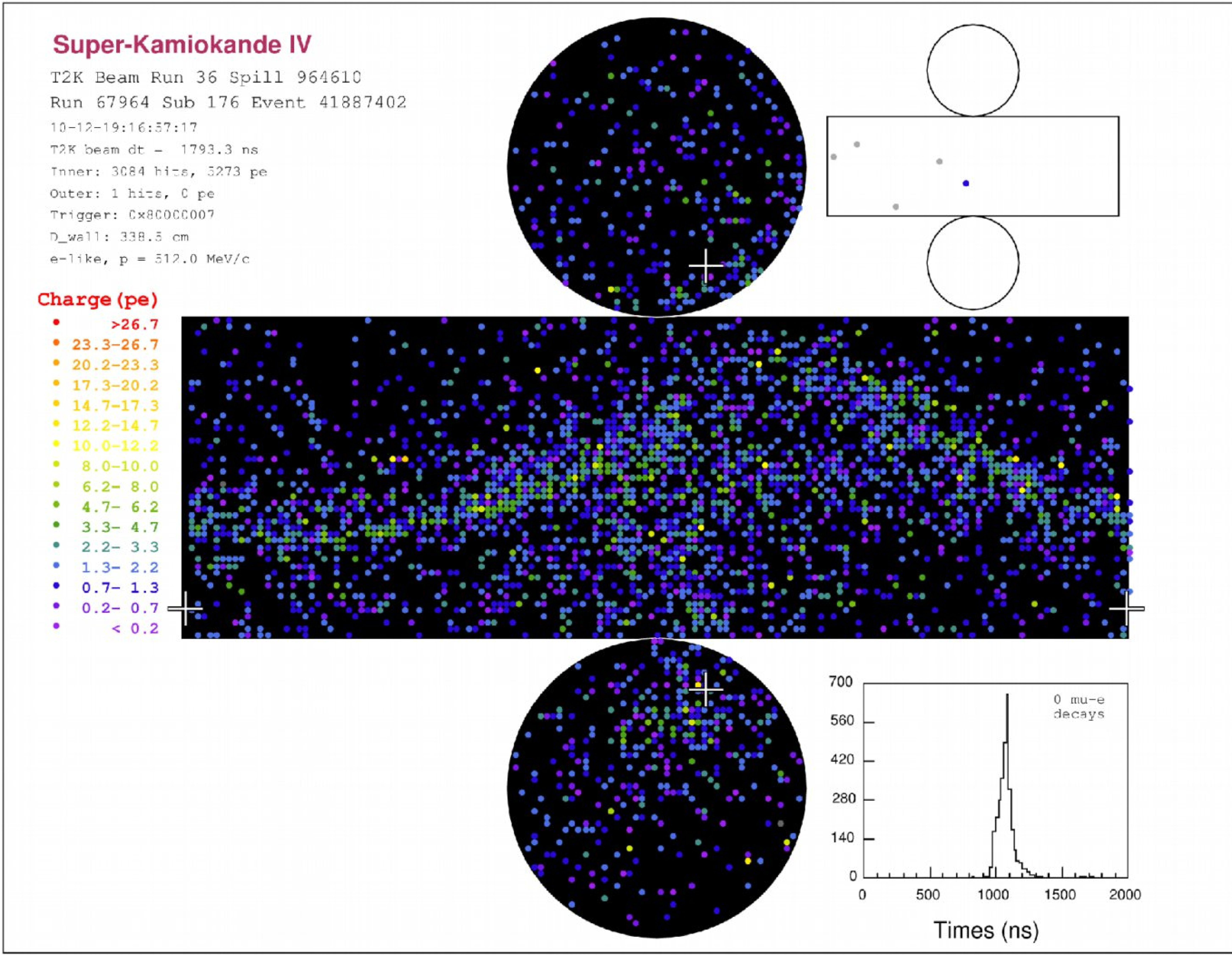
Pre-Selection Cuts

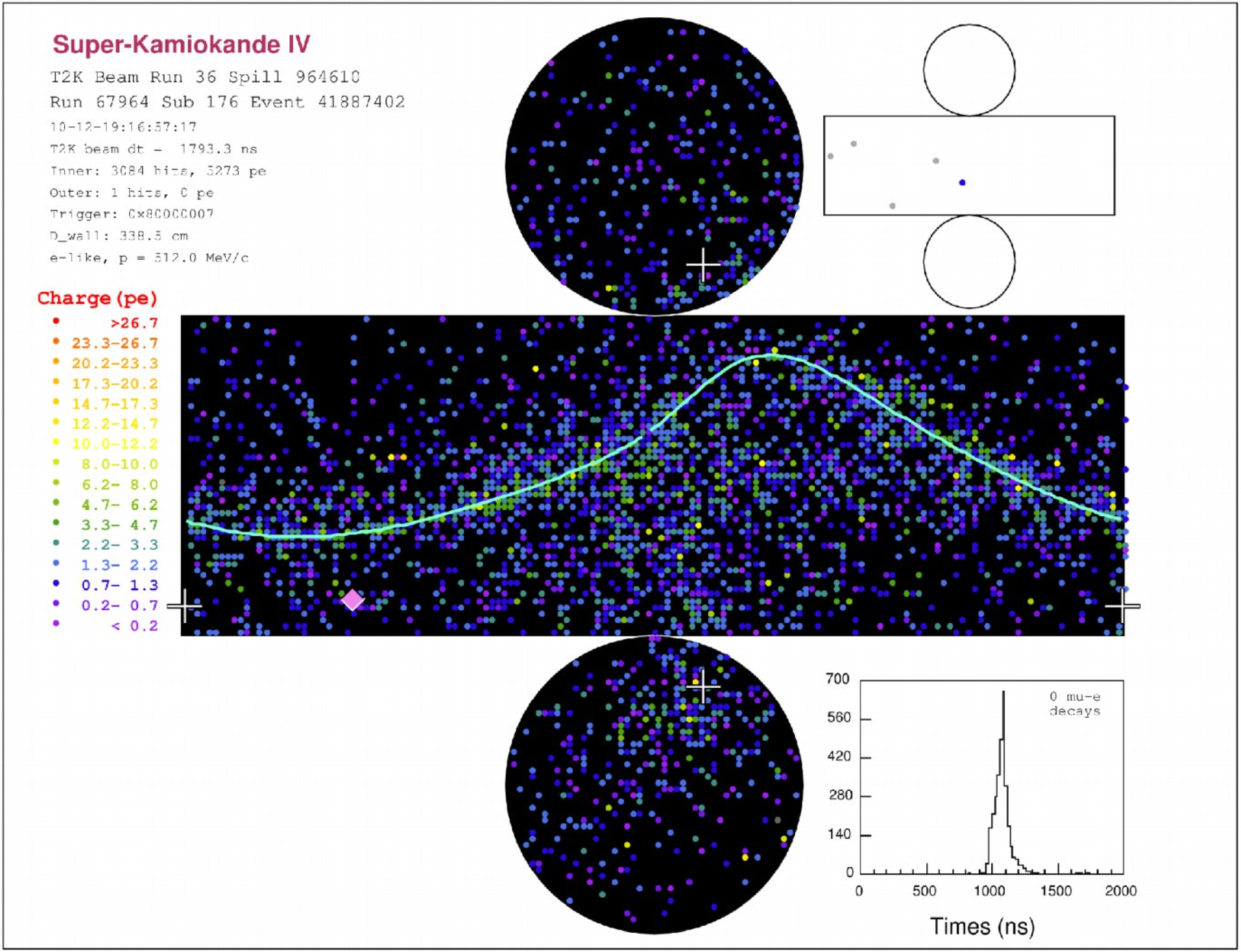
- T2K beam timing cut
  - data taken with GPS-synchronised threshold-free trigger
- Fully contained event cut
  - no activity in the Outer Detector
  - no incoming activity
    ⇒ neutrino
  - no outgoing activity
    ⇒ no energy escape
- Fiducial Volume Cut
  - 2 metres from wall



Event Selection Summary

RUN1+2+3 3.010x10^{20}POT	MC Expectations w/ $\sin^2 2\theta_{13}$=0.1					Data
	$\nu_\mu+\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$ CC	NC	BG total	Signal	
True FV	154.54	8.03	132.89	295.46	12.86	-
FCFV	117.33	7.67	40.48	165.47	12.35	174
One-ring	66.41	4.82	11.55	82.78	10.39	88
e-like	2.72	4.79	8.10	15.60	10.27	22
E_{vis}>100MeV	1.76	4.75	7.01	13.53	10.04	21
No decay-e	0.33	3.76	6.00	10.09	8.63	16
POLfit mass	0.09	2.60	1.64	4.32	8.05	11
E_ν^{rec}<1250MeV	0.06	1.61	1.25	2.92	7.81	11
Efficiency [%]	0.0	20.0	0.9	1.0	60.7	-


Super-Kamiokande IV
T2K Beam Run 36 Spill 964610
Run 67964 Sub 176 Event 41887402
10-12-19:16:57:17
T2K beam dt = 1793.3 ns
Inner: 3084 hits, 5273 pe
Outer: 1 hits, 0 pe
Trigger: 0x80000007
D_wall: 338.5 cm
e-like, p = 512.0 MeV/c
Charge (pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
700
560
420
280
140
0
0
500
1000
1500
2000
Times (ns)
0 mu-e decays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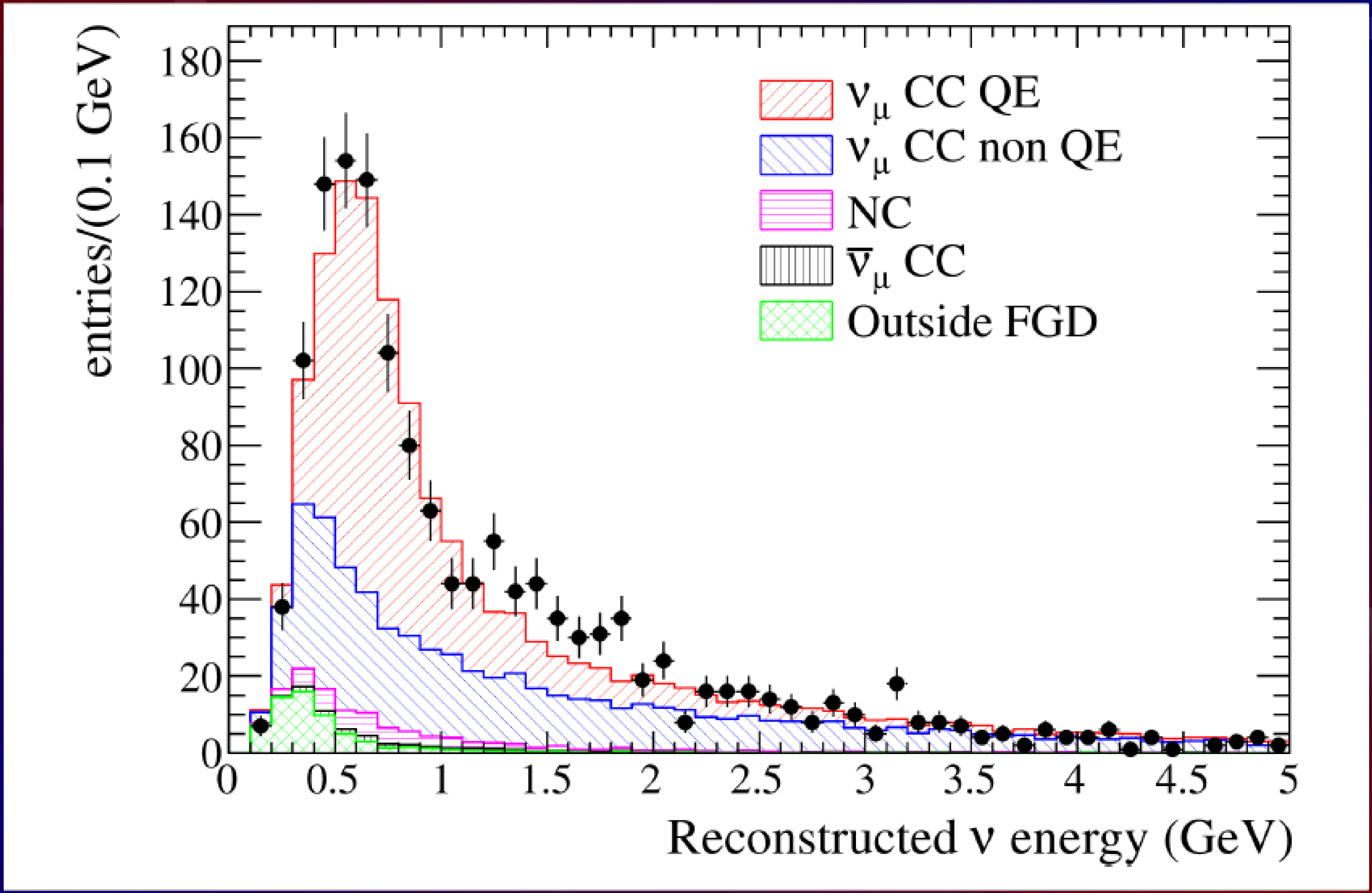
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
0 mu-e decays
700
560
420
280
140
0
0
500
1000
1500
2000
Times (ns)

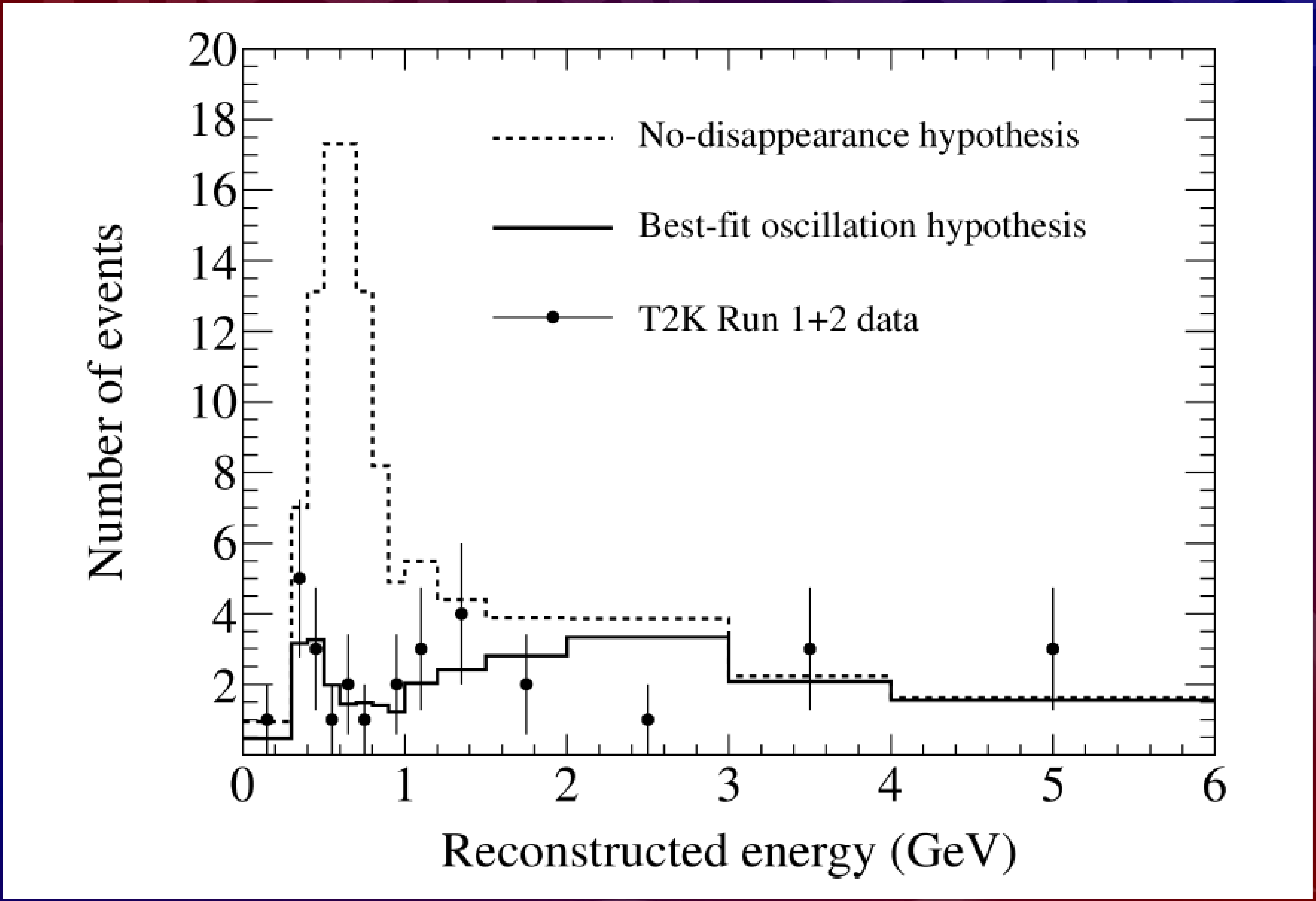
ν_μ Disappearance at T2K

—published December 2011—

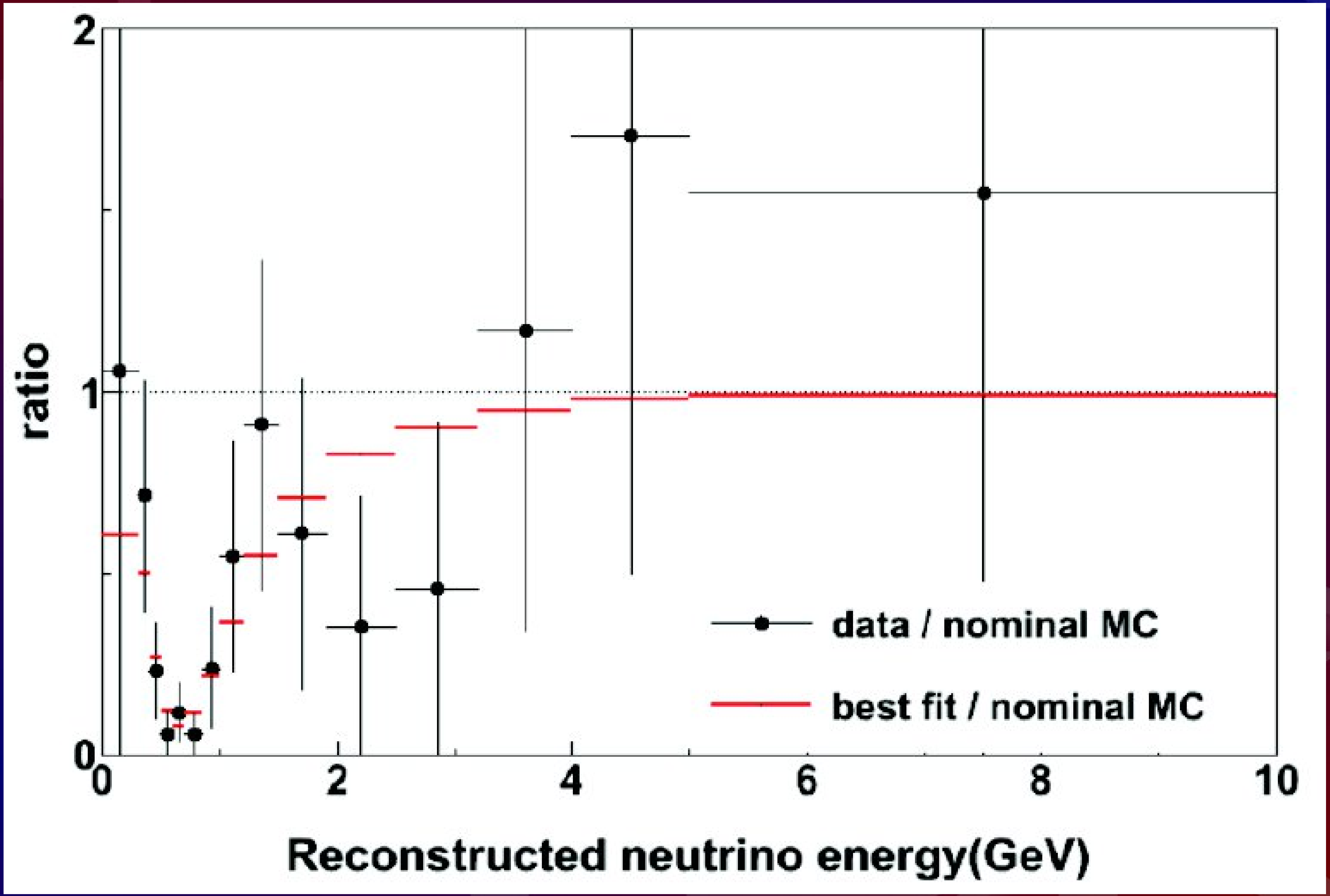
ν_μ Events at ND280



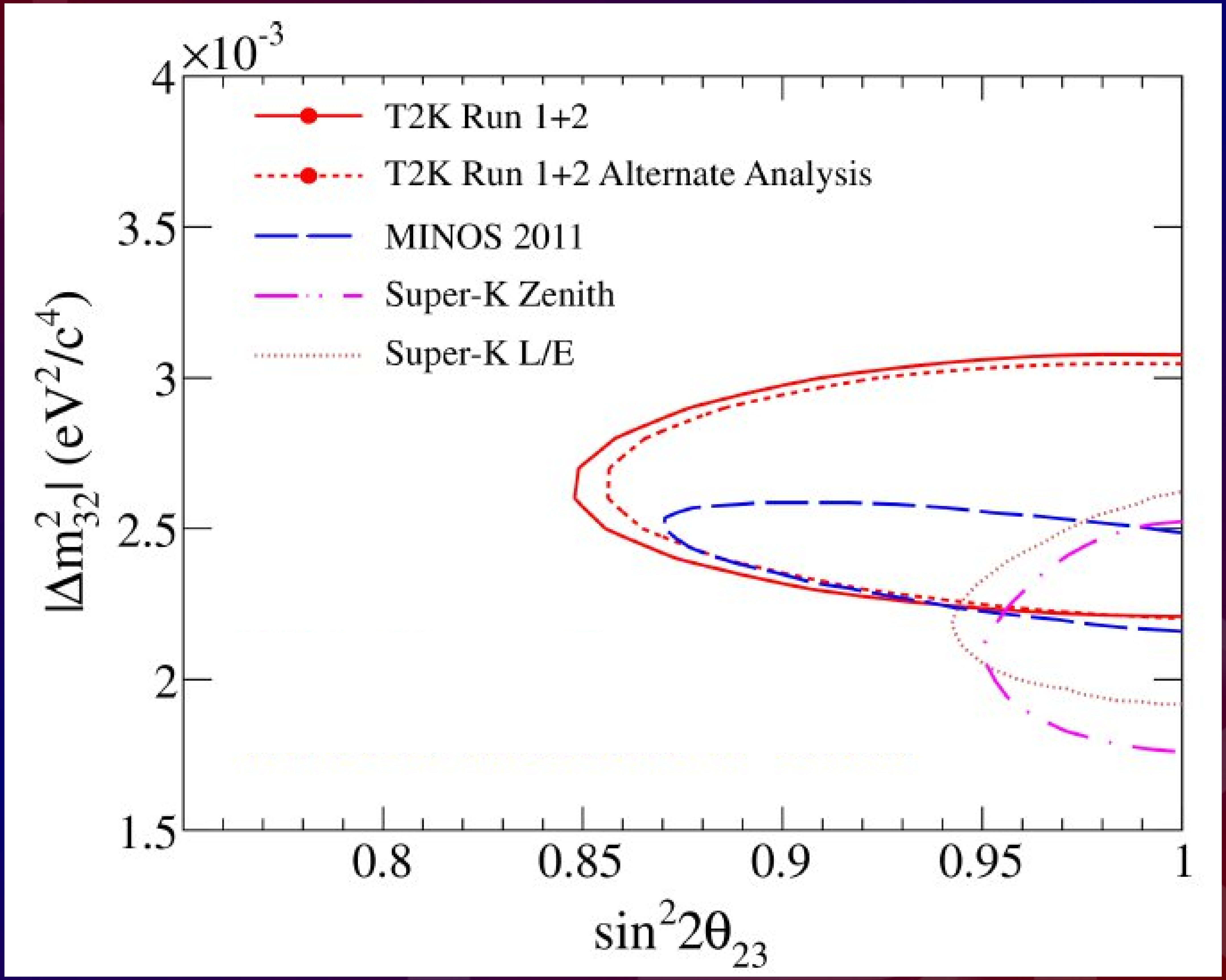
Far Detector Event Spectrum



Data / Unoscillated Prediction



Oscillation Parameter Contours



KamLAND should see

86.8 ± 5.6

(0.94 ± 0.85 background)

events if all antineutrinos travel to KamLAND from reactors without loss

KamLAND should see

86.8 ± 5.6

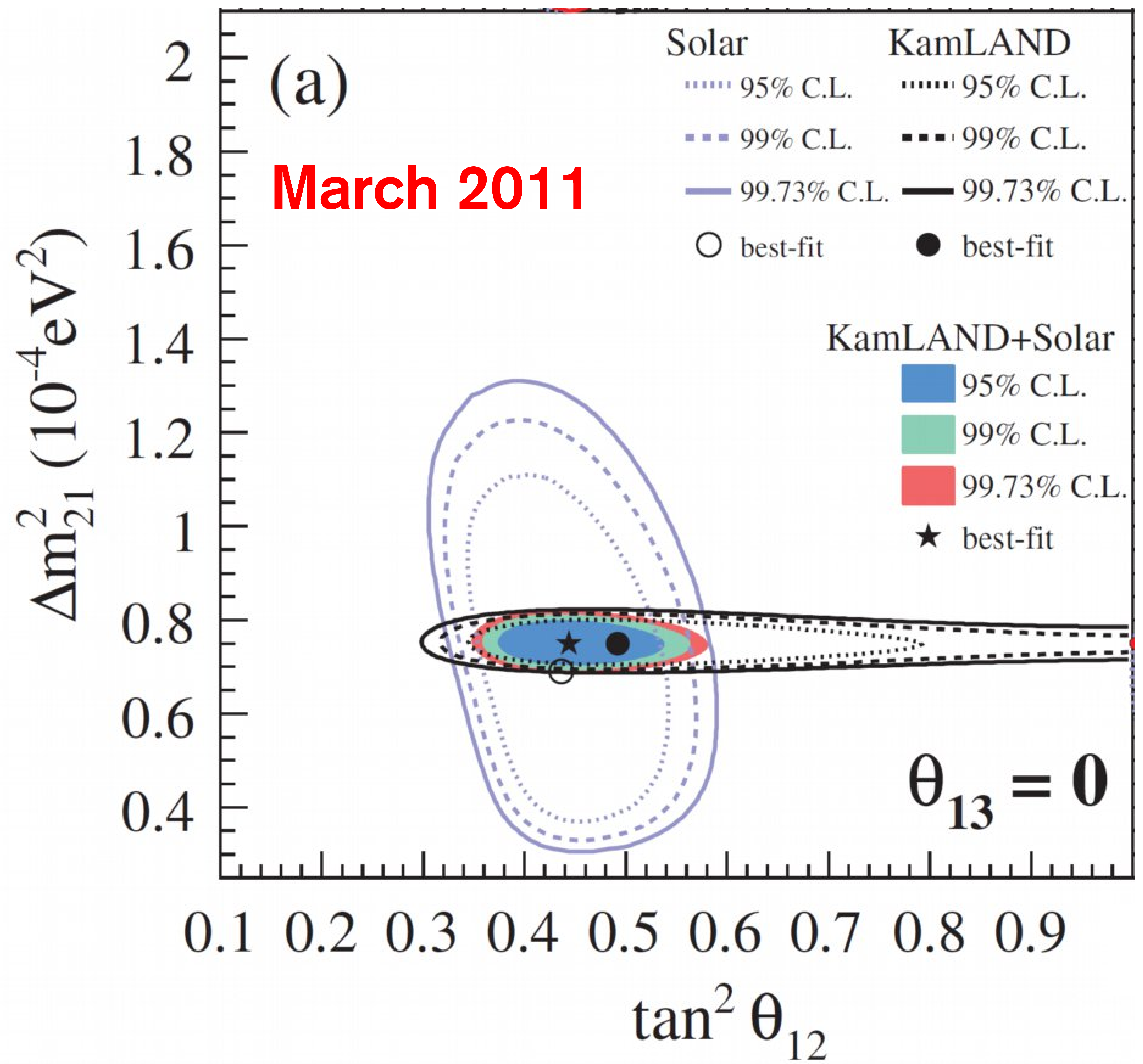
(0.94 ± 0.85 background)

events if all antineutrinos travel to KamLAND from reactors without loss

---

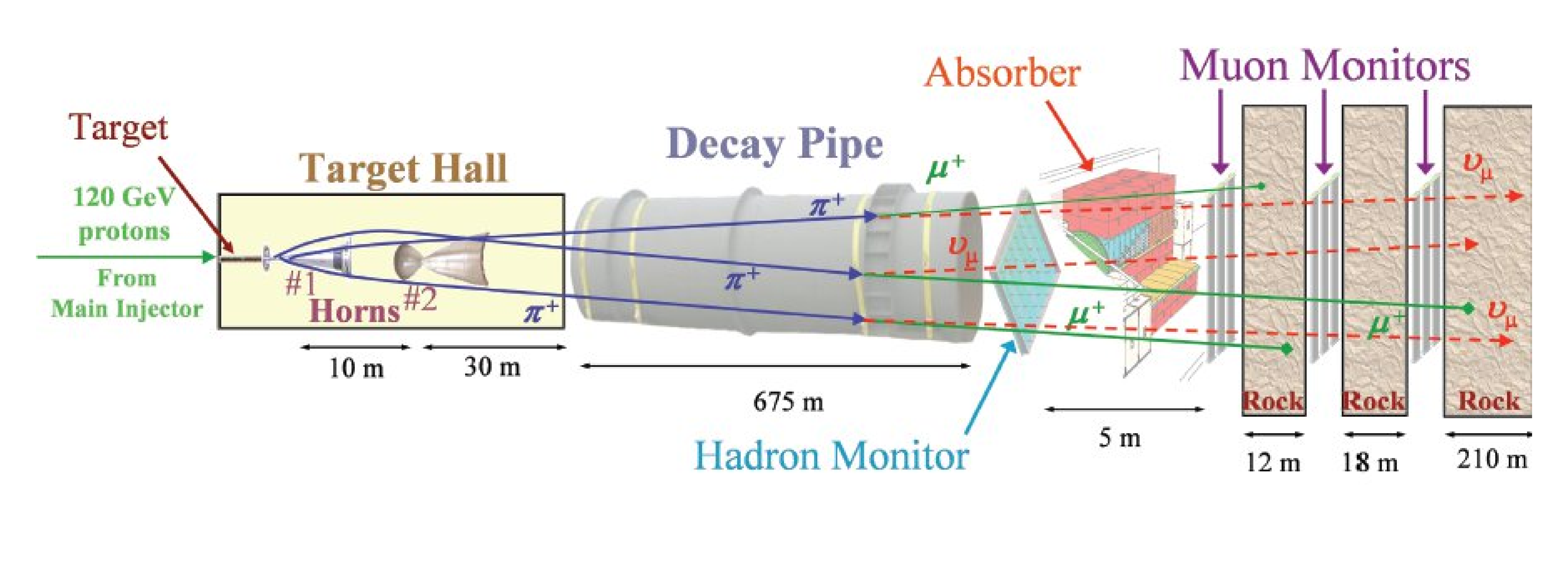
54 events seen

Solar and KamLAND Two-Generation Oscillation Results

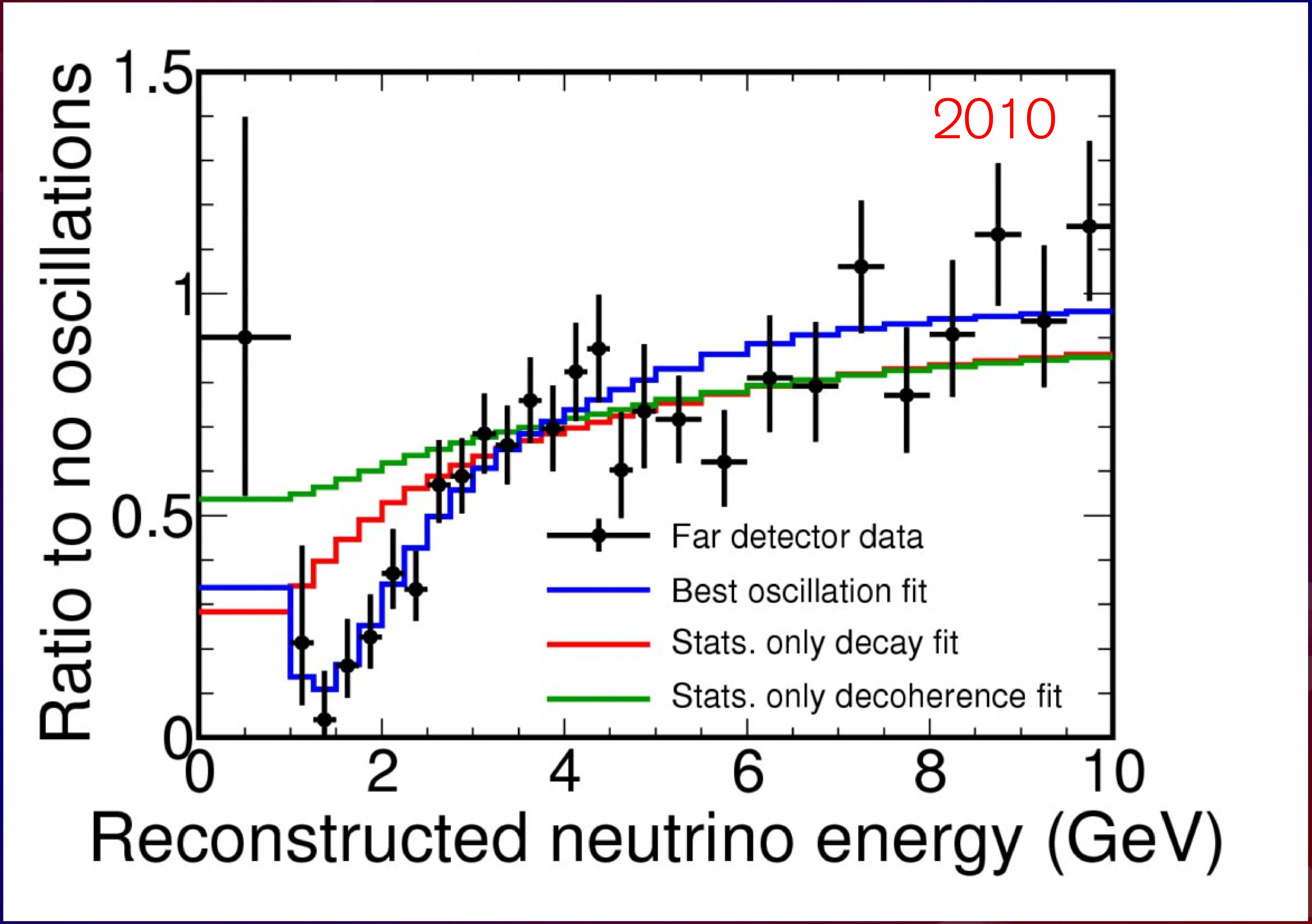


$$\Delta m^2_{21} \sim 7.5 \times 10^{-5} \text{eV}^2$$

The MINOS Neutrino Beam



Oscillation Signature in ν_μ Deficit at MINOS



ν_μ Disapperance

Governed by the quantity

$$\begin{aligned}\Delta m^2_{\mu\mu} &= \Delta m^2_{31} \\ &\quad -(\cos^2\theta_{12} - \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}) \\ &\quad \times \Delta m^2 21\end{aligned}$$

CP Violation in Neutrino /Antineutrino Oscillations

Governed by the quantity

$$J_{CP} = \sin\delta \times \frac{1}{8}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$$

CP-violating term δ accessible to experiment if θ_{13} is not too small (future T2K, Neutrino Factory etc)