New Results from the T2K Experiment:

ν_e Appearance in a ν_μ Beam

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(on behalf of the T2K Collaboration)

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Neutrino Mixing

- Neutrinos have mass!

Flavour eigenstates: ν_e, ν_μ, ν_τ
(interaction)

Mass eigenstates: ν_1, ν_2, ν_3
(propagation)

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

1998 onwards:
Probed with atmospheric neutrinos, long baseline accelerator neutrinos (SK, K2K, MINOS)

2001 onwards:
Probed with solar neutrinos, long baseline reactor neutrinos (SK, SNO, KamLAND)

First measured last year!
Short baseline reactor neutrinos (Daya Bay, RENO, DoubleChooz);
Long baseline accelerator neutrinos (T2K, MINOS, NOvA)

Experimental Probes

- For Dirac neutrinos, standard parameterization of the PMNS matrix U_{li} (for Dirac neutrinos) has:

  3 mixing angles, 2 mass square differences, 1 CP phase

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

$\sin^2(2\theta_{23}) > 0.95$ (90% C.L.)
$\Delta m^2_{32} = 2.43 \pm 0.13 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2(2\theta_{12}) = 0.857 \pm 0.024$
$\Delta m^2_{12} = 7.59 \pm 0.20 \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$

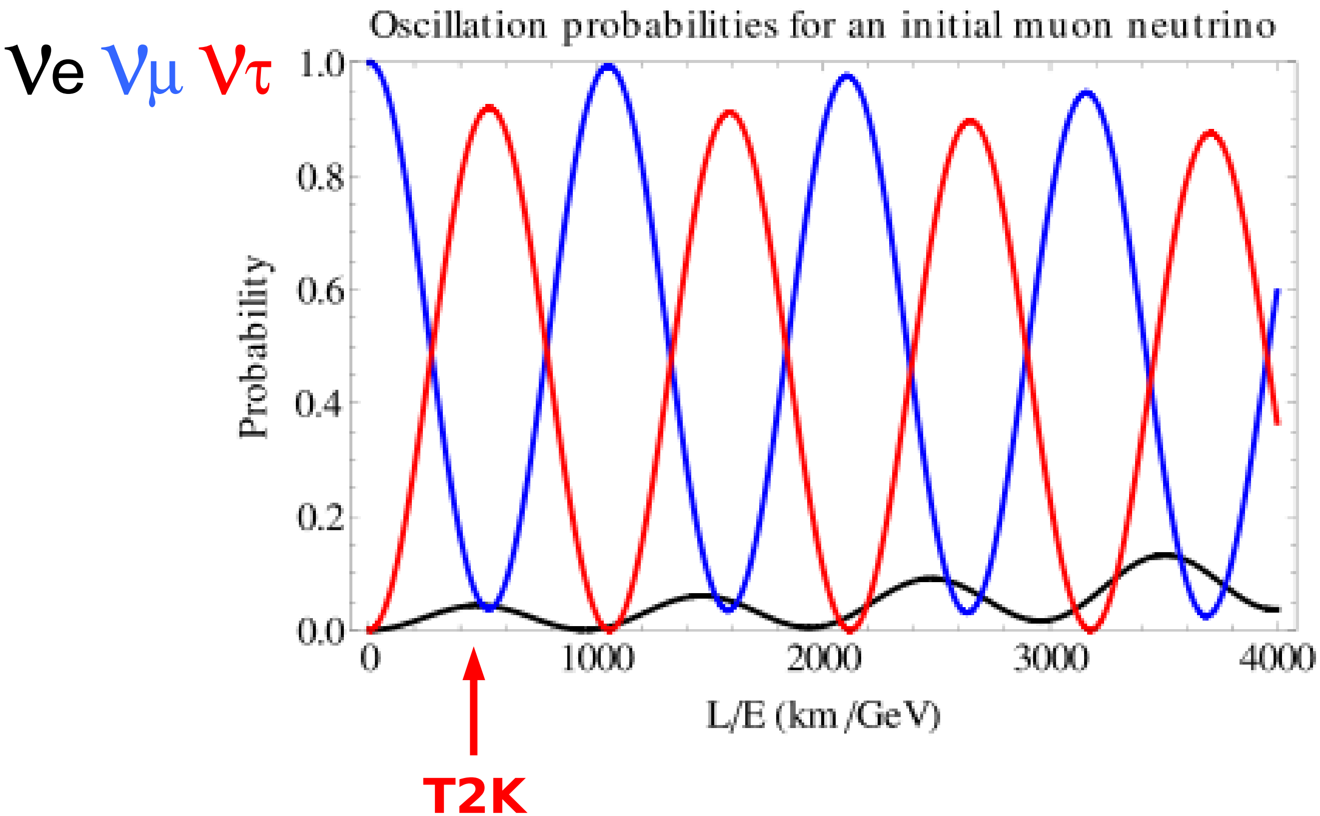
What is the CP violating phase δ?

What is the mass hierarchy?

Oscillation @Accelerators

Long baseline accelerator:

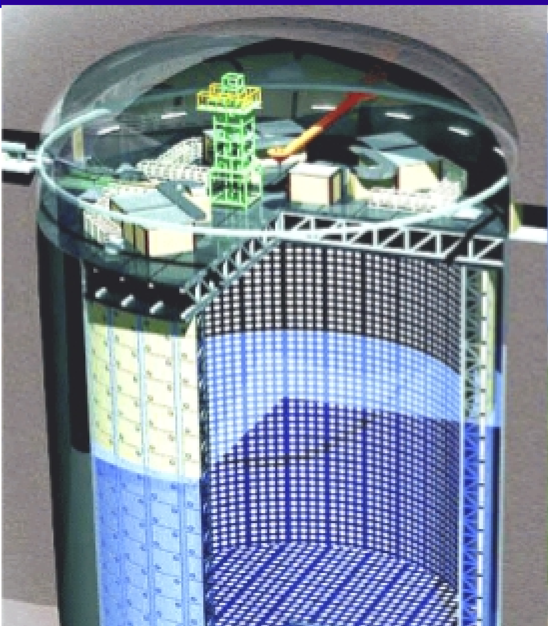
- Search for ν_e appearance
- Sensitive to θ_{13}, δ, mass hierarchy



$$P_{\mu\rightarrow\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P_{\mu\rightarrow e} \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

Tokai to Kamioka (T2K)



Super-Kamiokande
22.5 kton (fiducial)
water cherenkov
detector at 295 km

J-PARC: 30 GeV proton
beam, design power of
750 kW

- Experimental goals:
  - **Search for ν_e appearance (focus of this talk)**
  - Precision ν_μ disappearance (new results coming soon!)
  - Other (ν cross sections, sterile ν searches, etc.)

T2K Collaboration

~ 500 members, 59 Institutes, 11 countries

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
Aachen U.

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 Metropolitan U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia

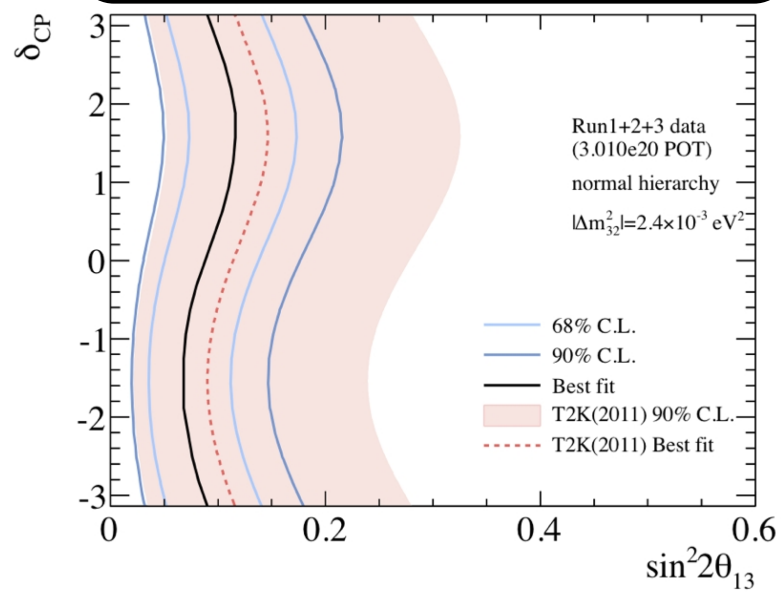
Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial C. London
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

Previous T2K ν Osc. Results

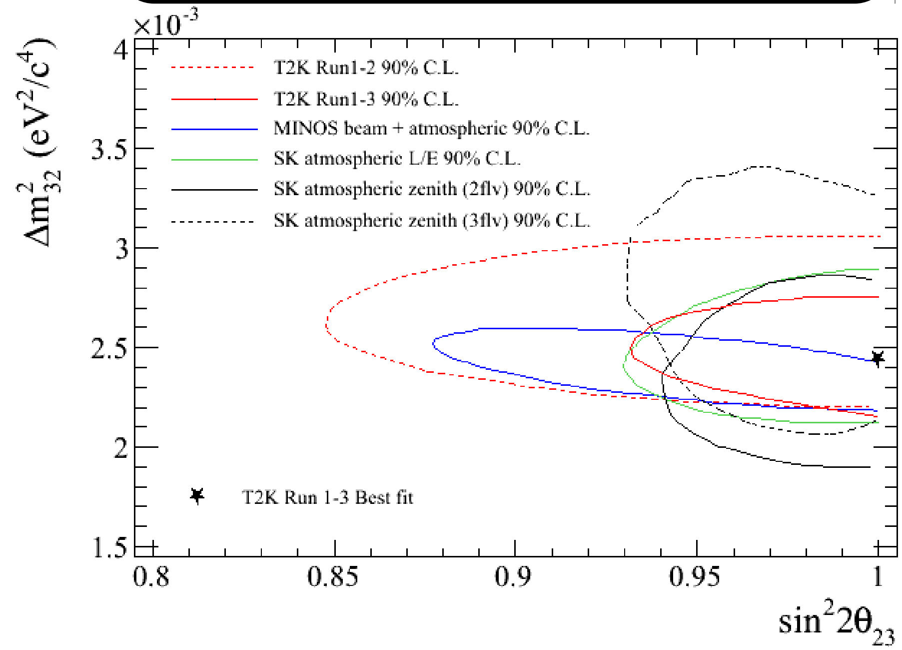
2012 ν_e Appearance



2011: Observe 6 evts (w/ BG 1.5 ± 0.3)
First indication of non-zero θ_{13}
(2.5σ significance)
Phys. Rev. Lett. **107:041801** (2011)

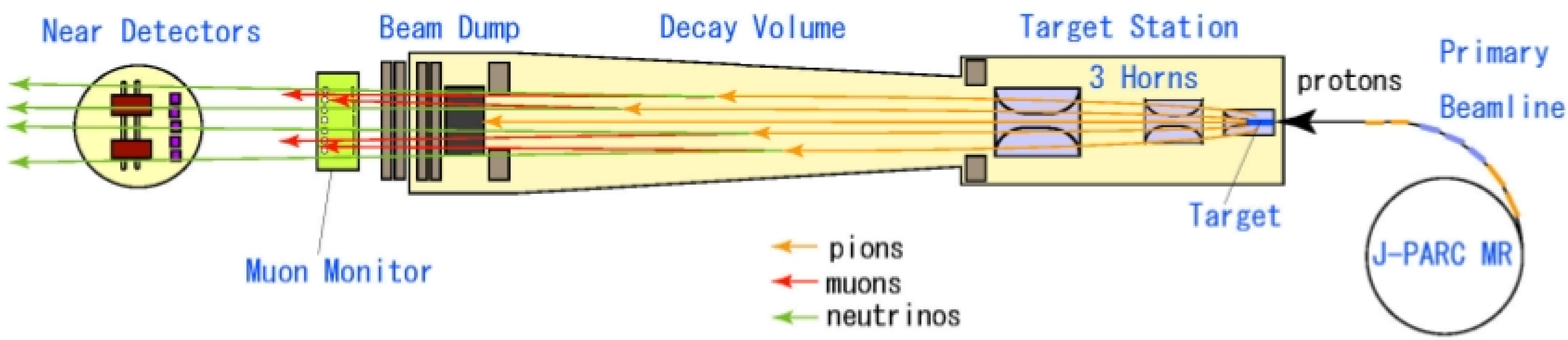
2012: Observe 11 evts (w/ BG 3.3 ± 0.4)
3.1σ evidence for non-zero θ_{13}
Phys. Rev. D **88:032002** (2013)

2013 ν_μ Disappearance



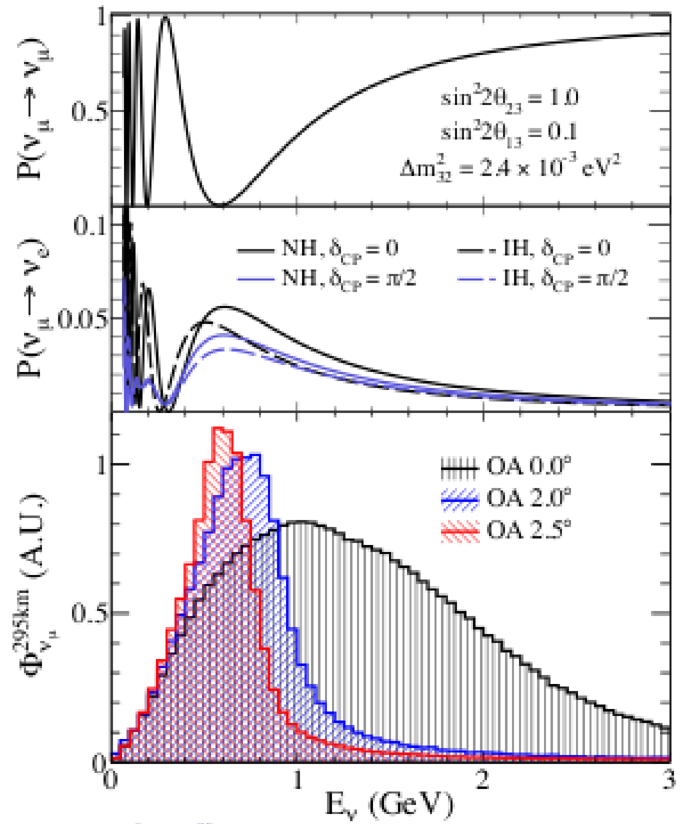
2013: Competitive measurement of θ_{23}
Submitted to Phys. Rev. Lett.
arXiv: 1308.0465

Neutrino Beam

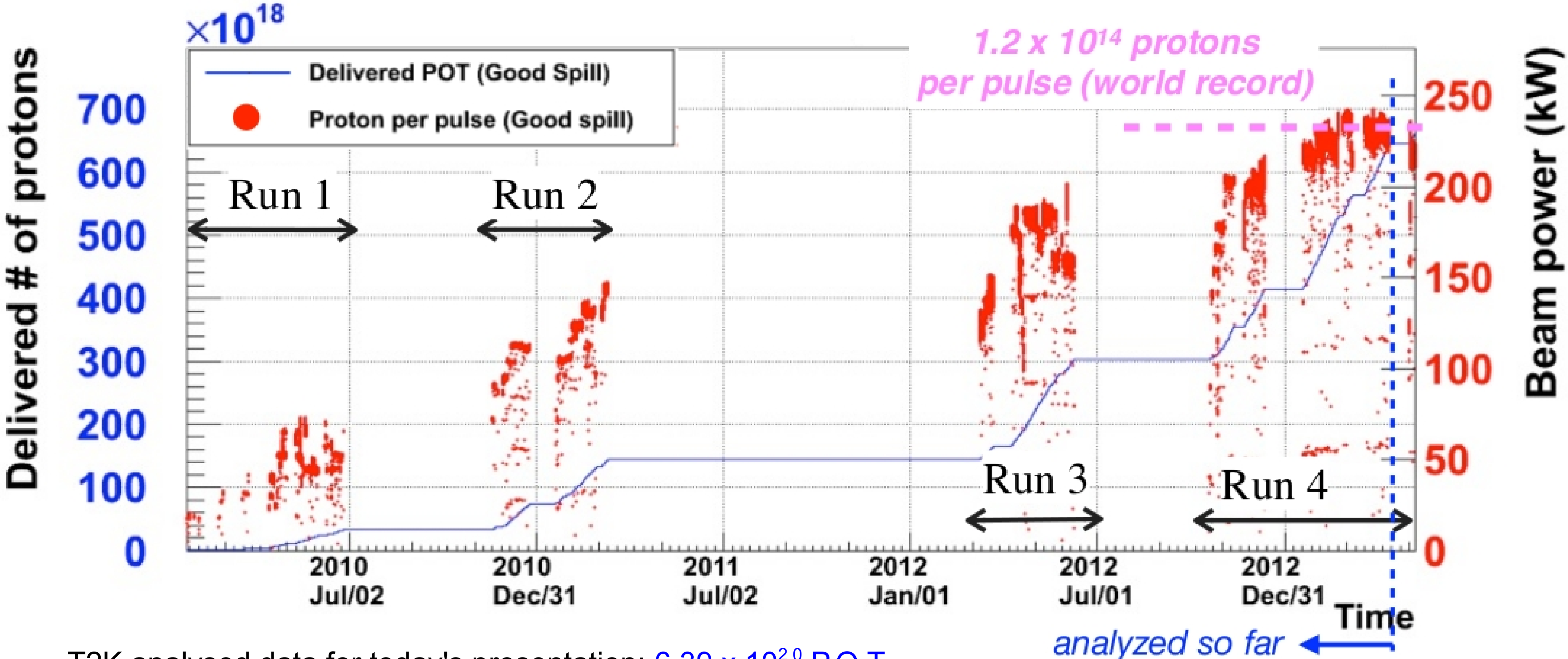


T2K is the first experiment to use an **off-axis** neutrino beam:

- Enhances signal at oscillation maximum
- Reduces backgrounds from other energies
  - – *e.g.*, π^0 BG greater at higher Eν



T2K Data Taking

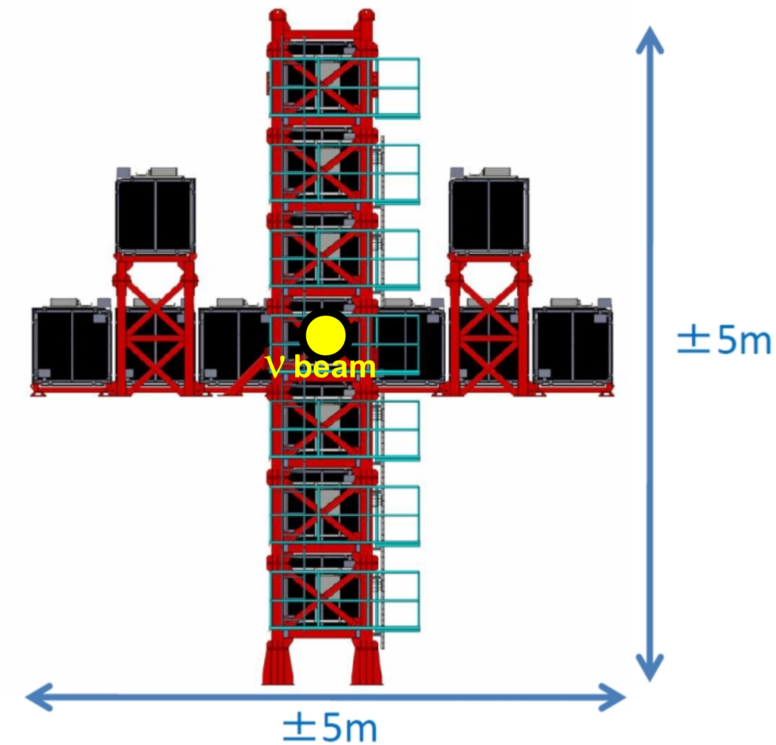


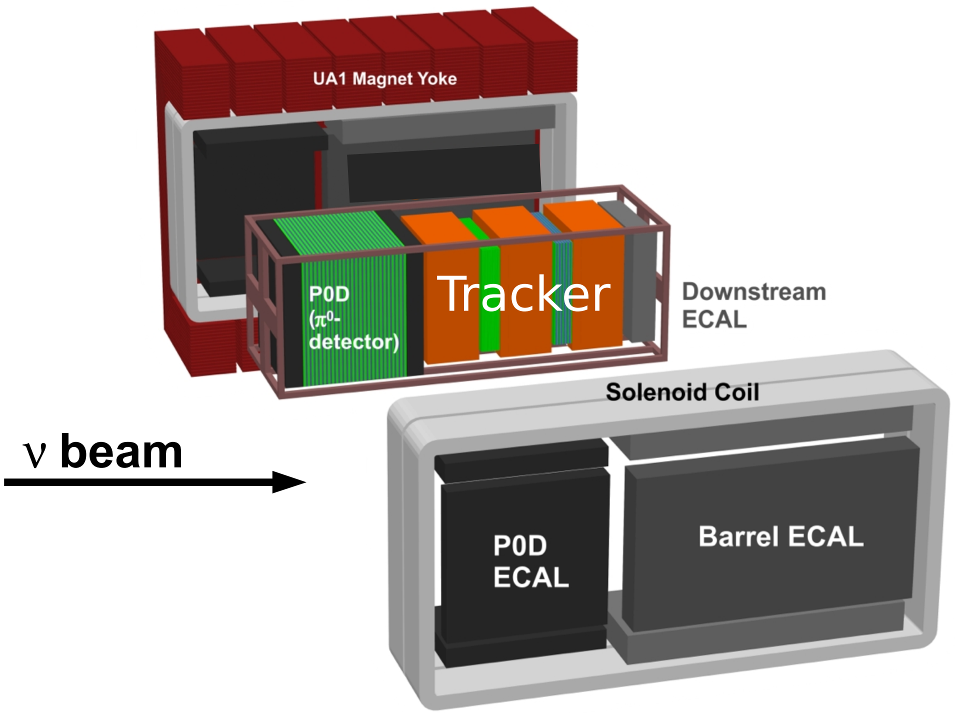
- T2K analysed data for today's presentation: 6.39×10^{20} P.O.T.
  - We have accumulated 6.63×10^{20} P.O.T. to date
  - Previous ν_e appearance result (2012) used 3.01×10^{20} P.O.T. → Statistics increased by factor >2!
- Thus far, ~8% of the total data has been collected (assuming design goal)
- Instantaneous luminosity of 220 kW (1.2×10^{14} protons per pulse) → **World record!**
- **Many thanks to the J-PARC accelerator division for their efforts and much hard work**

Near Detector Suite

INGRID (On-axis)

- 16 modules of iron and scintillator
  - 14 in "cross" configuration
- Monitors stability of neutrino beam:
  - Direction: Off-axis angle determines narrow-band beam energy
  - Event rate: To confirm targeting efficiency





ND280 (Off-axis)

- Sits in 0.2 T magnetic field
- Tracker comprised of:
  - 2 Fine-Grain Detectors (FGDs)
    - → 1.6 t plastic scintillator primary target
    - → Detailed vertex information
  - 3 Time Projection Chambers (TPCs)
    - → Track momentum from curvature
    - → Particle identification from dE/dx

Near Detector Constraint

GOAL: Constrain neutrino flux & cross section parameters used for oscillation prediction (via MC) at T2K far detector

Error on Far Detector ν_e Prediction
(After Near Detector Constraint)

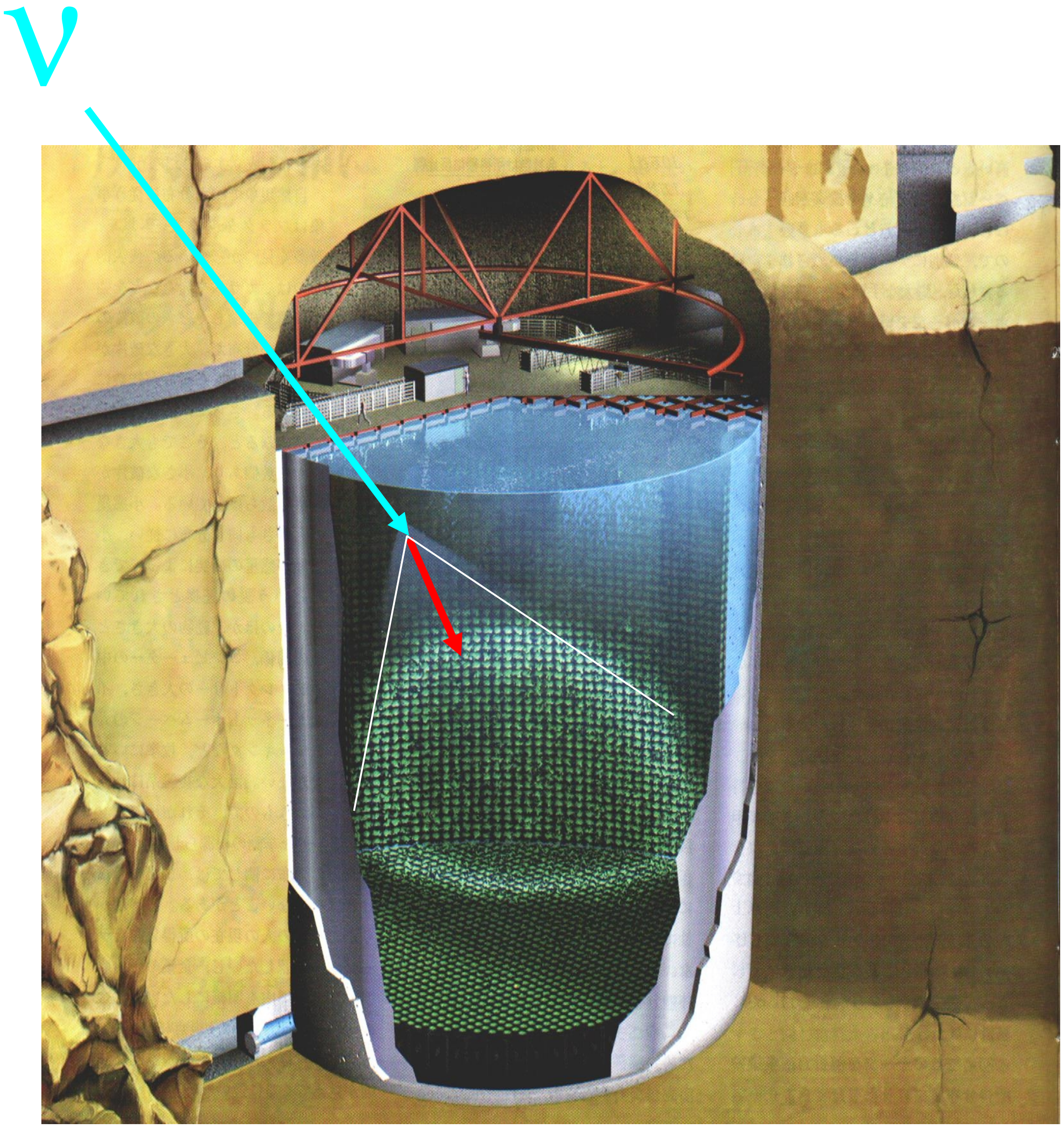
	Runs 1-3 (2012)	Runs 1-3 (2013)	Runs 1-4 (2013)
$\sin^2 2\theta_{13}=0.1$	4.7%	3.5%	3.0%
$\sin^2 2\theta_{13}=0.0$	6.1%	5.2%	4.9%

Error on Cross Section Parameters
(After Near Detector Constraint)

Parameter	Runs 1-3 (2012)	Runs 1-4 (2013)
M_A^{QE} (GeV/c²)	1.27 ± 0.19	1.22 ± 0.07
M_A^{RES} (GeV/c²)	1.22 ± 0.13	0.96 ± 0.06
CCQE Norm.	0.95 ± 0.09	0.96 ± 0.08
CC1π Norm.	1.37 ± 0.20	1.22 ± 0.16

- Significant reduction for event rate errors at the far detector
- Uncertainties on the *cross section & flux* parameters have been reduced

Super-Kamiokande (far)



- 50,000 tonne water Chereknov detector
- 22.5 kton fiducial mass
- Inner Detector (ID) has 11,129 inward facing 50cm PMTs for ~40% photocathode coverage
- Outer Detector (OD) has 1885 20cm PMTs; OD used as passive shielding + active veto
- Stable operation for many years
- Good reconstruction in energy range of T2K beam
- Well-understood particle identification (see next slide)

SK Particle Identification

Muons:

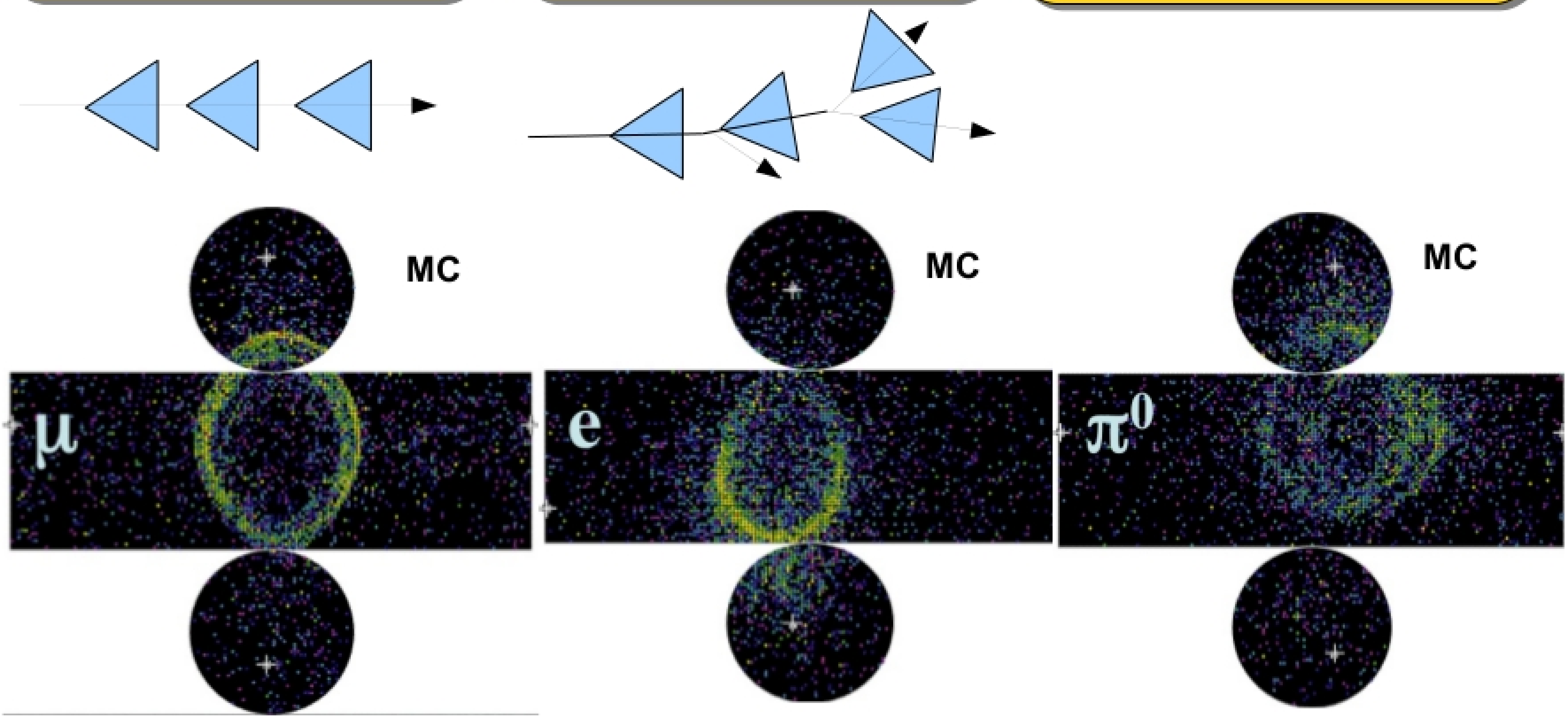
- Minimal scattering
- Ring has sharp edges

Electrons

- Electromagnetic shower
- EM scattering makes a "fuzzy" ring

Neutral Pions

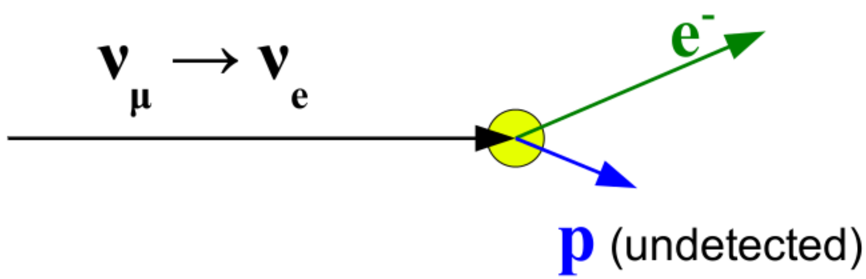
- γs from π^0 decays shower and look like electrons



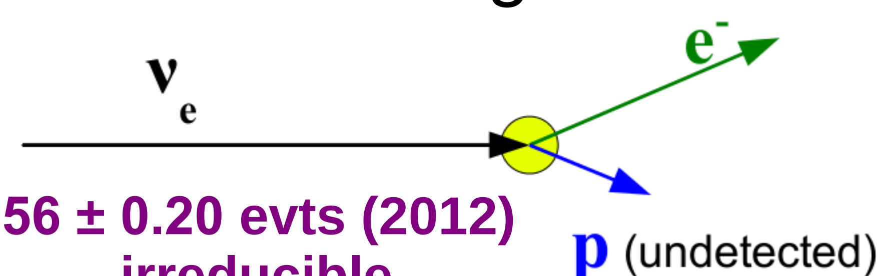
- Reliable PID particularly crucial to ν_e appearance analysis
- PID well-established at KEK beam test (1kton tank) in 1990s

T2K ν_e Signal & BG

- Oscillation signal:



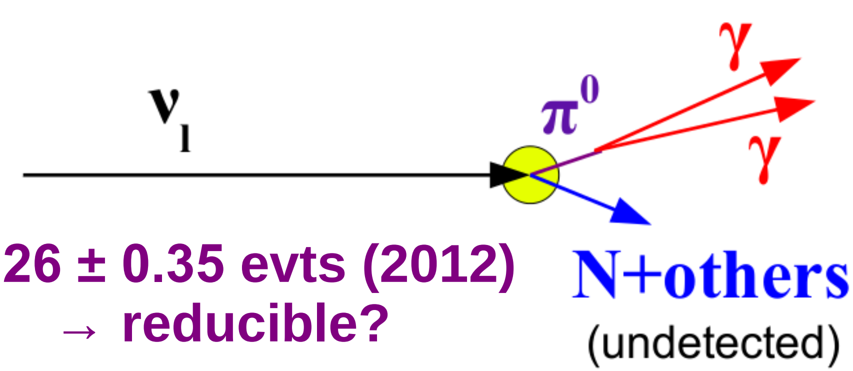
- Beam ν_e background:



1.56 ± 0.20 evts (2012)
→ irreducible

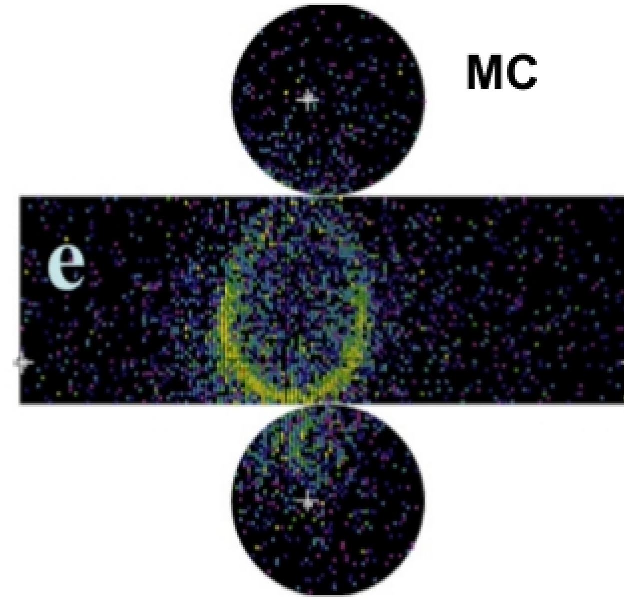
Beam background has harder energy spectrum

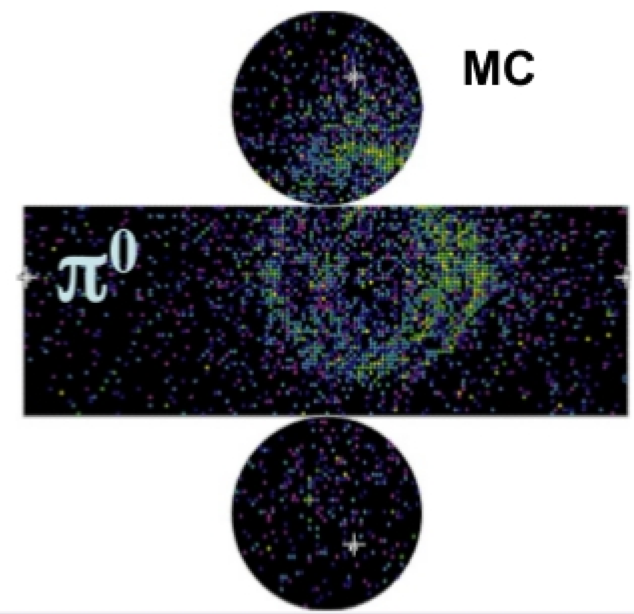
- Neutral current π^0 background:



1.26 ± 0.35 evts (2012)
→ reducible?

Can be removed by identifying second photon ring

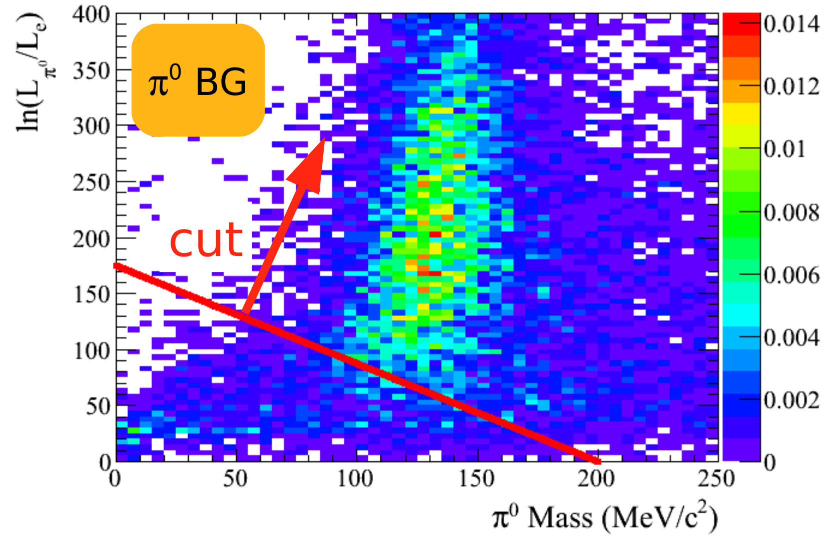


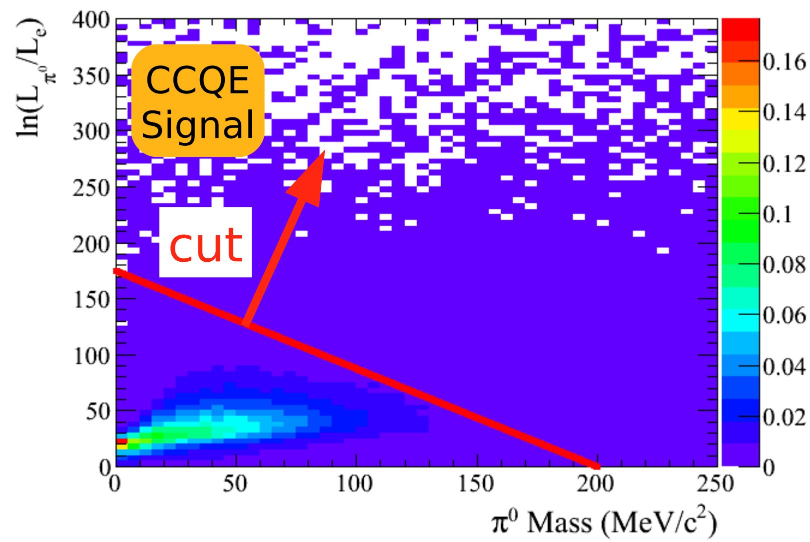


Improved π^0 Rejection

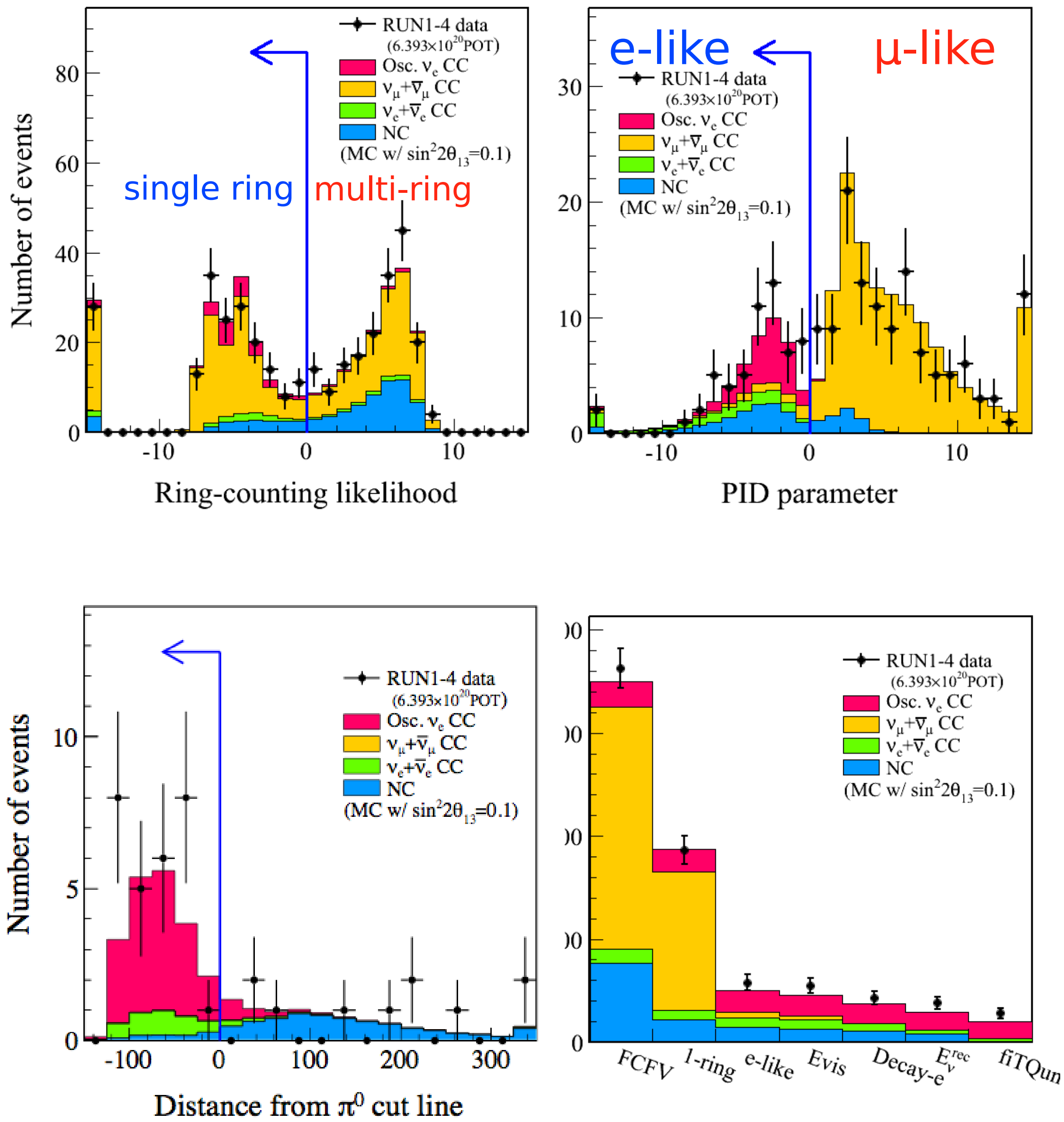
- New likelihood fitter used to distinguish electrons from π^0
- Assumes two electron-like rings produced at a common vertex
- Uses 12 parameters in fit:
  - Vertex (X, Y, Z, T)
  - Directions (θ_1, φ_1, θ_2, φ_2)
  - Momenta (p_1, p_2)
  - Conversion lengths (c_1, c_2)
- This 2D cut **removes 70% of the π^0 background remaining** after previous selection applied (for same signal efficiency)
- Total background is reduced by 27%
- 6.36 BG events → 4.64 BG events expected (in full Run 1 – 4 dataset)

Likelihood Ratio vs π^0 Mass (T2K Monte Carlo)





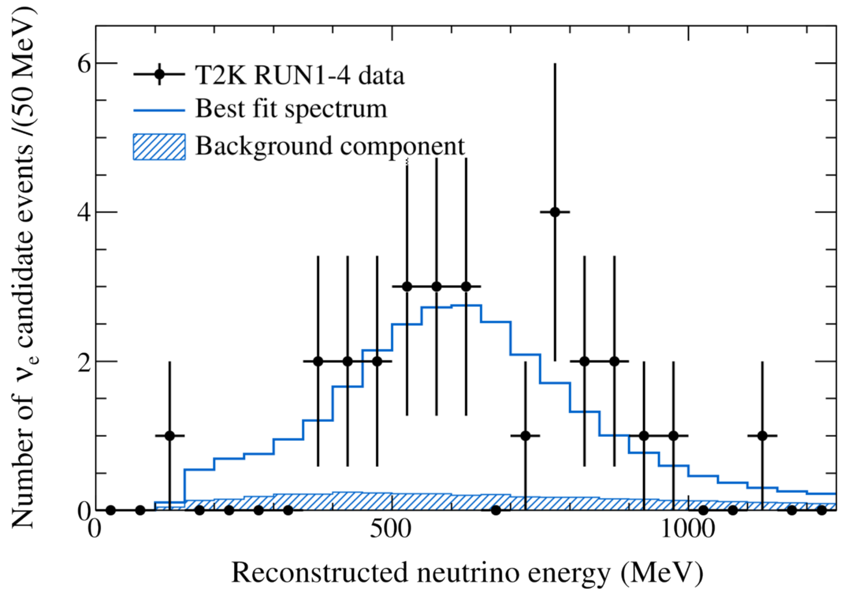
T2K ν_e Event Selection

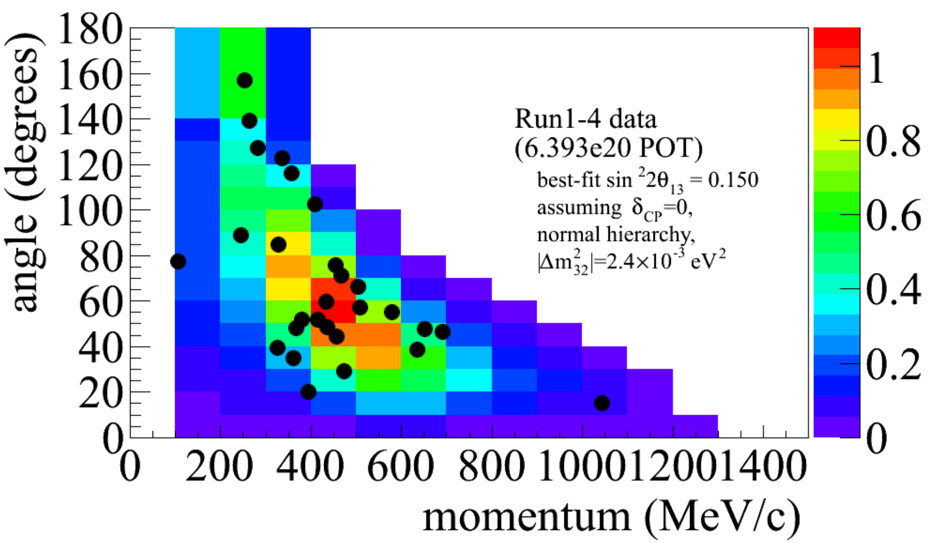


ν_e Selection Criteria

- \# clustered veto hits < 16
- Distance to wall > 200 cm
- \# of rings = 1
- PID of ring is e-like
- Visible energy > 100 MeV
- no Michel electrons
- New likelihood π^0 cut
- $0 < E\nu < 1250$ MeV

ν_e Appearance Analysis





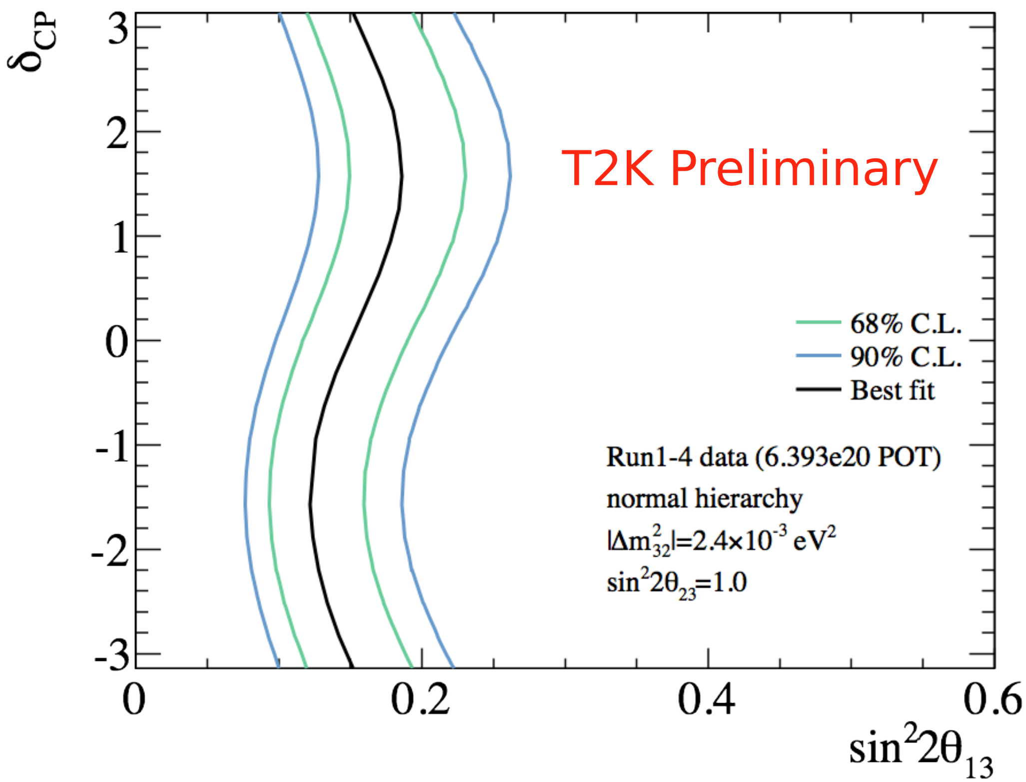
- Expected background:
  - 4.64 ± 0.53 events
- With the following assumptions:
  - $\sin^2(2\theta_{13}) = 0.1$
  - $\sin^2(2\theta_{23}) = 1$
  - $\delta_{CP} = 0$
  - normal mass hierarchy

  the expected signal is:
  - 20.4 ± 1.8 events
  - **5.5σ sensitivity to exclude $\theta_{13} = 0$**
- Oscillation parameters were extracted with two parallel analyses:
  - Using the 1D Eν distribution (top)
  - Using the 2D p-θ distribution (bottom)

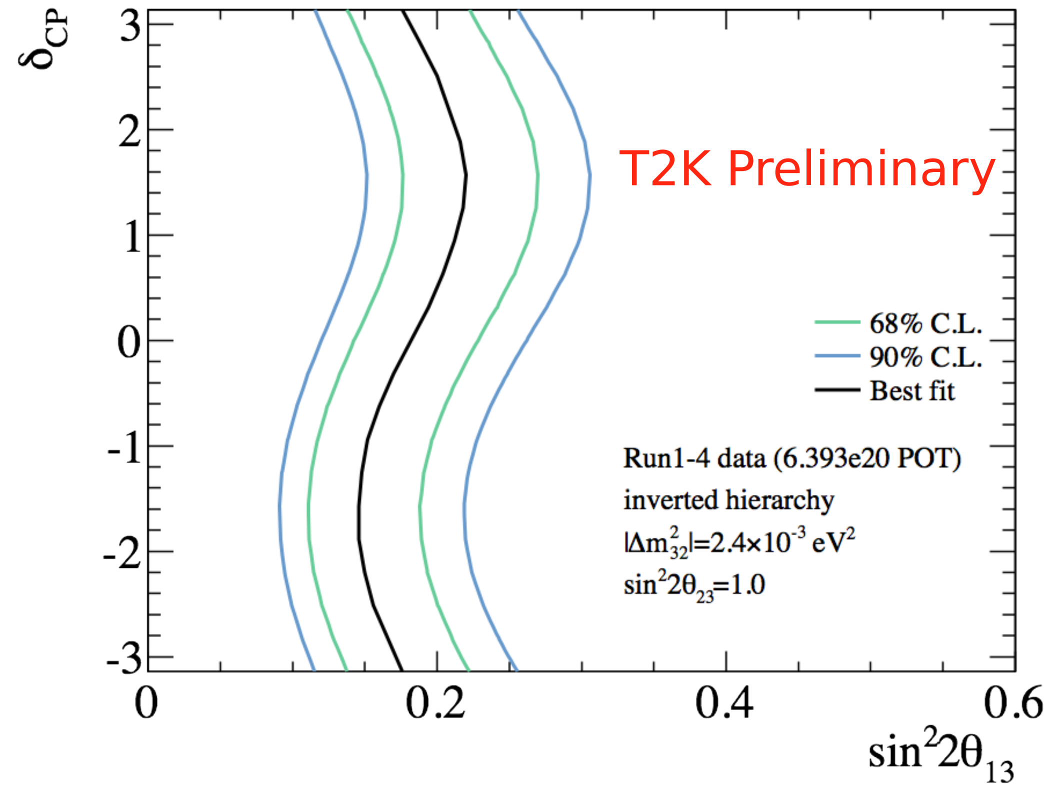
ν_e Appearance Results

- **28 ν_e events observed** (recall 20.4 ± 1.8 expected for $\sin^2(2\theta_{13}) = 0.1$)
- Comparison to null hypothesis gives 7.5σ significance for $\theta_{13} \neq 0$

T2K δ_{CP} vs $\sin^2 2\theta_{13}$ (Normal Hierarchy)



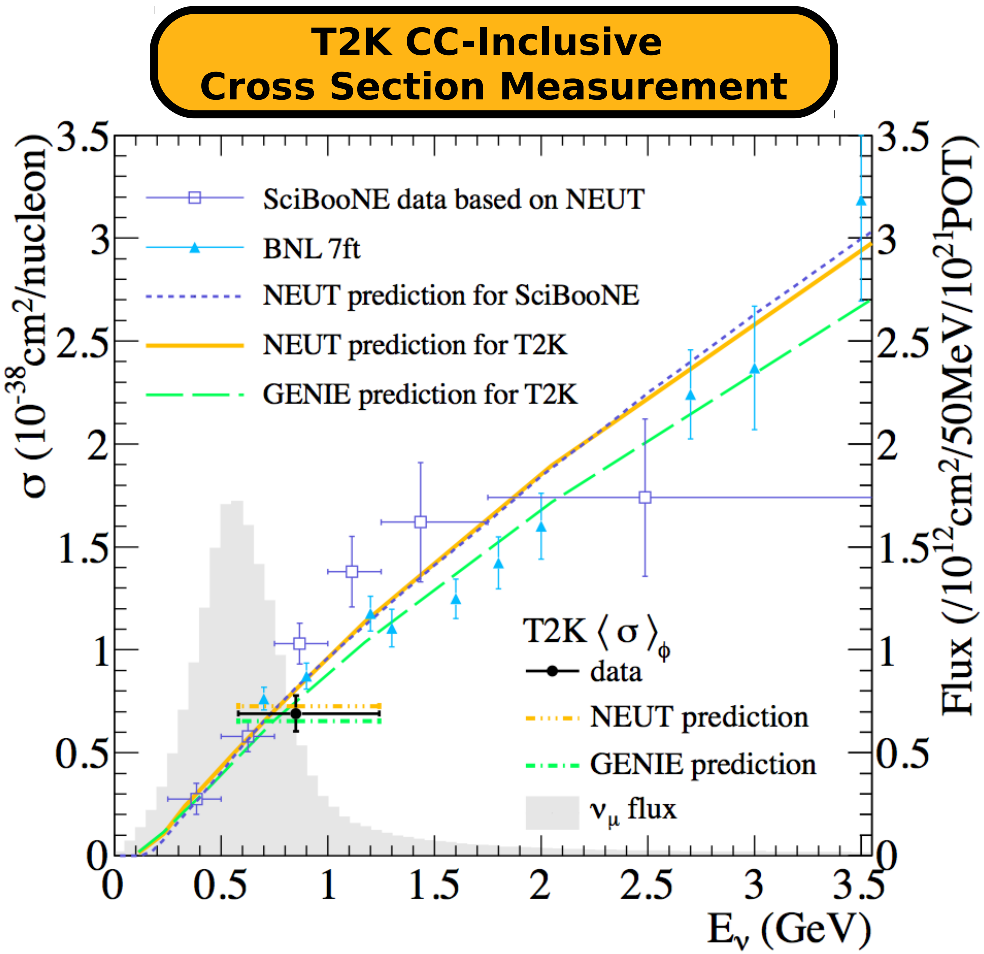
T2K δ_{CP} vs $\sin^2 2\theta_{13}$ (Inverted Hierarchy)



First direct observation (>5σ) of a ν appearance channel!

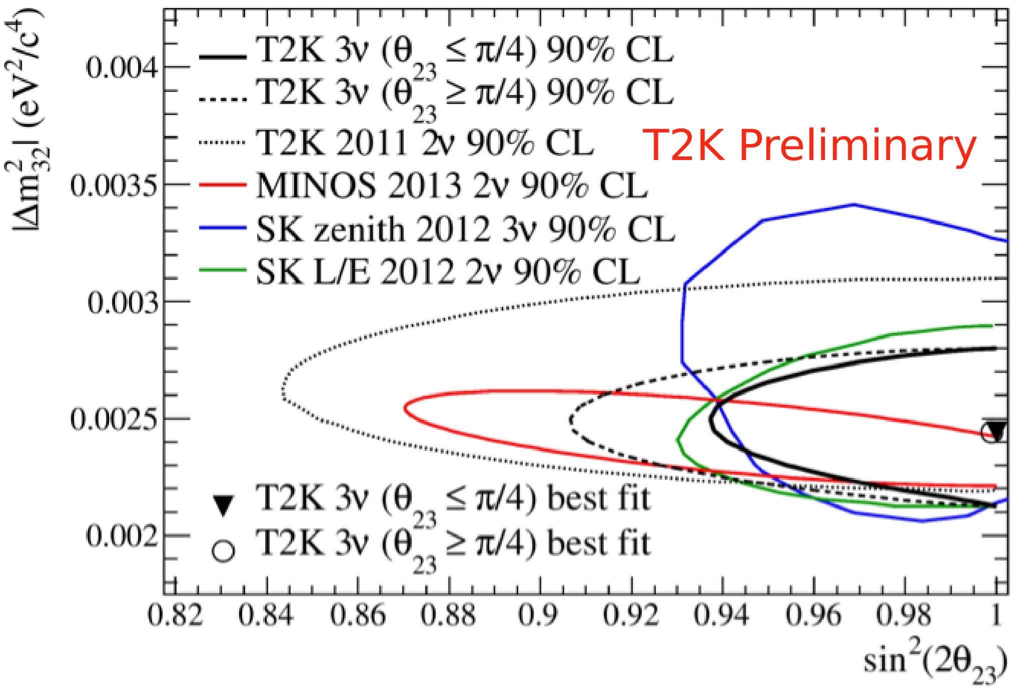
(N.B. These are 1D contours for various values of δ_{CP} **not** 2D contours)

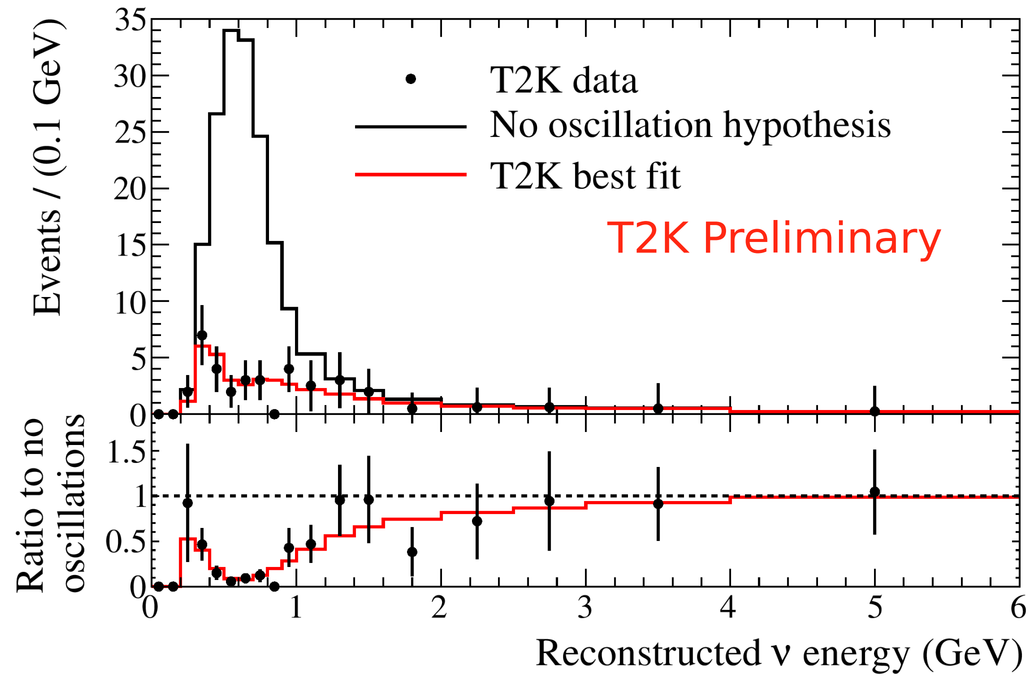
Other T2K Results: Cross Sections



- The near detectors can also be used to make cross section measurements
- The T2K charged current inclusive cross section measurement was published earlier this year:
  - Phys. Rev D **87:092003** (2013)
  - Uses same near detector event selection as 2012 osc. analysis
- The CCQE sample from the 2012 osc. analysis has been used to measure $\sigma_{CCQE}(E\nu)$
- Additional cross section results expected soon...

Other T2K Results: ν_μ Disappearance





- Preliminary results using Run 1 – 3 data (3.01×10^{20} P.O.T.) were first shown earlier this year
- Contours for both octants ($\theta_{23} < \pi/4$ and $\theta_{23} > \pi/4$) now provided (above)
  - Previously, only first octant ($\theta_{23} < \pi/4$) reported
- New ν_μ disappearance results coming soon
  - Future results will be reported as $\sin^2(\theta_{23})$ NOT $\sin^2(2\theta_{23})$ to remove octant ambiguity

Summary & Conclusions

- **First observation of electron neutrino appearance!**
  - T2K has measured ν_e appearance in a ν_μ beam
  - $\theta_{13} = 0$ is excluded at the 7.5σ level (assuming $\delta_{CP} = 0$ and $\theta_{23} = 45°$)
- Neutrino beam at J-PARC achieved stable operation with a 220 kW beam power
- A total exposure of 6.39×10^{20} P.O.T. has been collected & analysed to 2013-Apr-12, more than doubling the data sample used for the previous (2012) analysis
  - A total of 6.63×10^{20} P.O.T. has been accumulated
- Near detector CC-inclusive cross section measurement has been published; other cross section measurements are on the way
- Many other exciting results to come:
  - A new ν_μ disappearance measurement will be out soon
  - Combined $\nu_\mu + \nu_e$ joint analysis is underway
  - Comparison of accelerator results from T2K with reactor anti-neutrino results (measuring only θ_{13}) may provide insight to δ_{CP} and mass hierarchy

Supplemental Slides

Open Questions

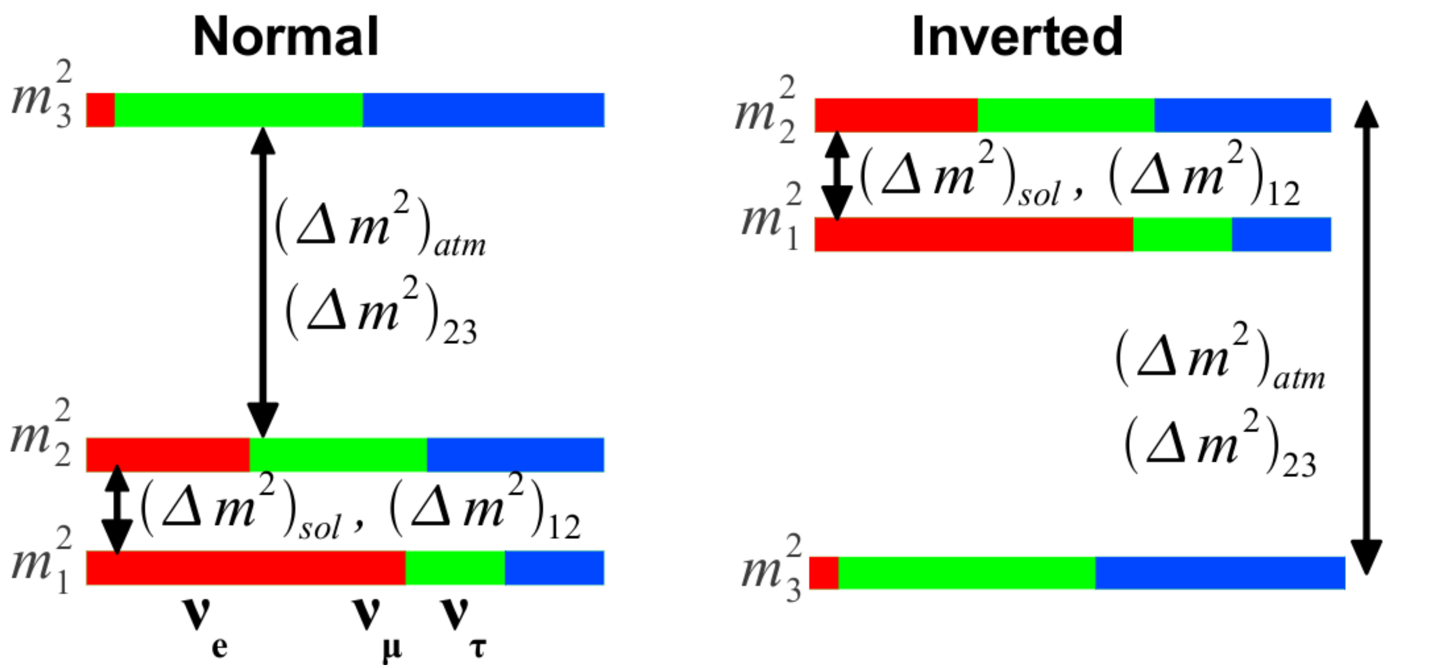
- **Q:** What do we still need to know?
- **A:** Two big questions in front of us now:

1) What is the CP violating phase δ?
2) What is the mass hierarchy?

Ambiguity in sign of

$$m_3^2 - m_2^2$$

Two possible mass hierarchies



⟶ Electron neutrino appearance can help answer both questions!

Oscillation Probabilities

T2K

Long baseline accelerator: Sensitive to θ_{13}, δ, mass hierarchy

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = \; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

CP violating (flips sign for anti-ν)

Solar

Matter

where:

$C_{ij} = \cos(\theta_{ij})$

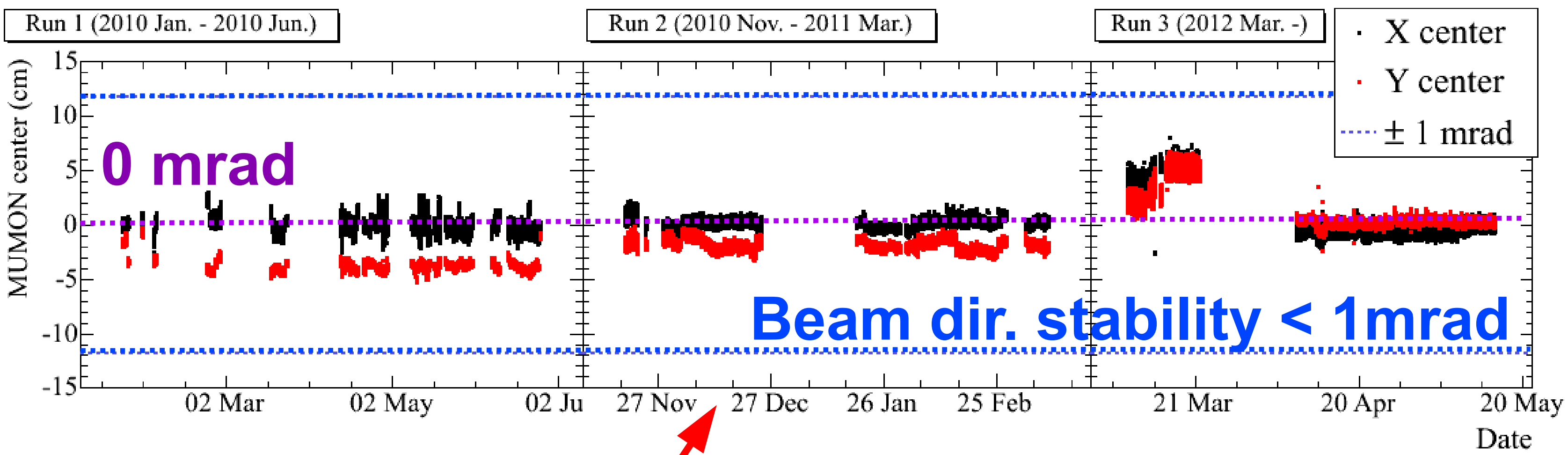
$S_{ij} = \sin(\theta_{ij})$

$\Delta_{ij} = \Delta m_{ij} (L/4E)$

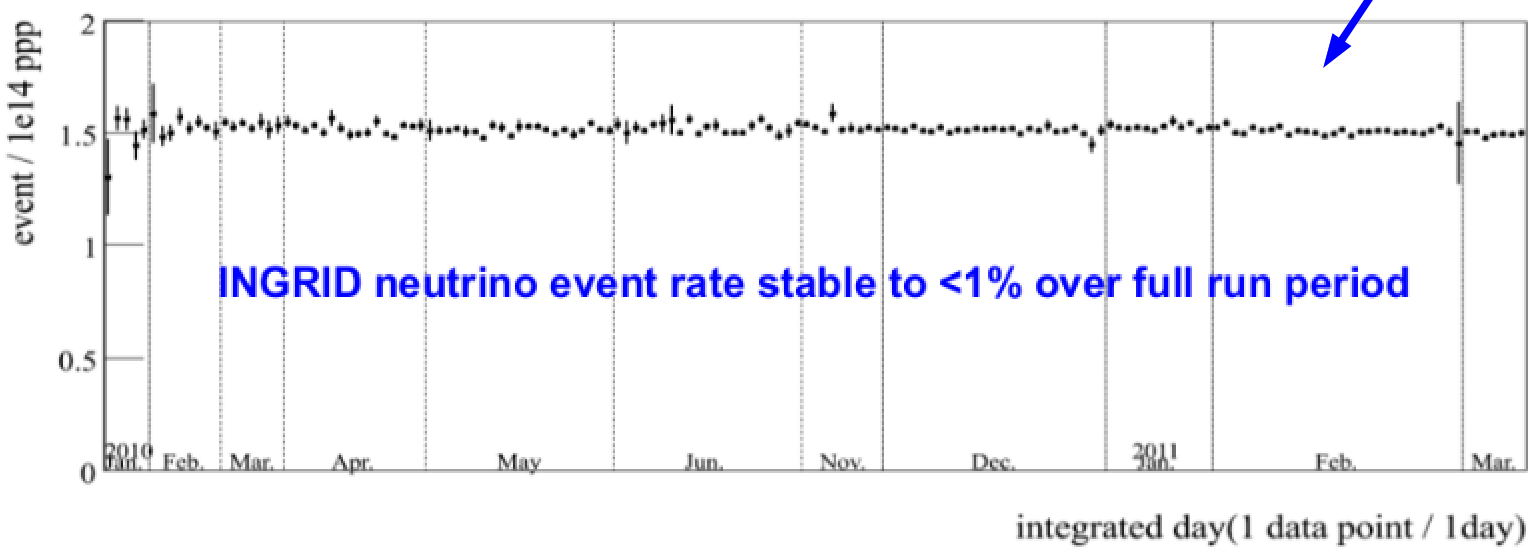
Short baseline reactor: Sensitive only to θ_{13}

$$P_{\text{sur}} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m_{31}^2 L/E)$$

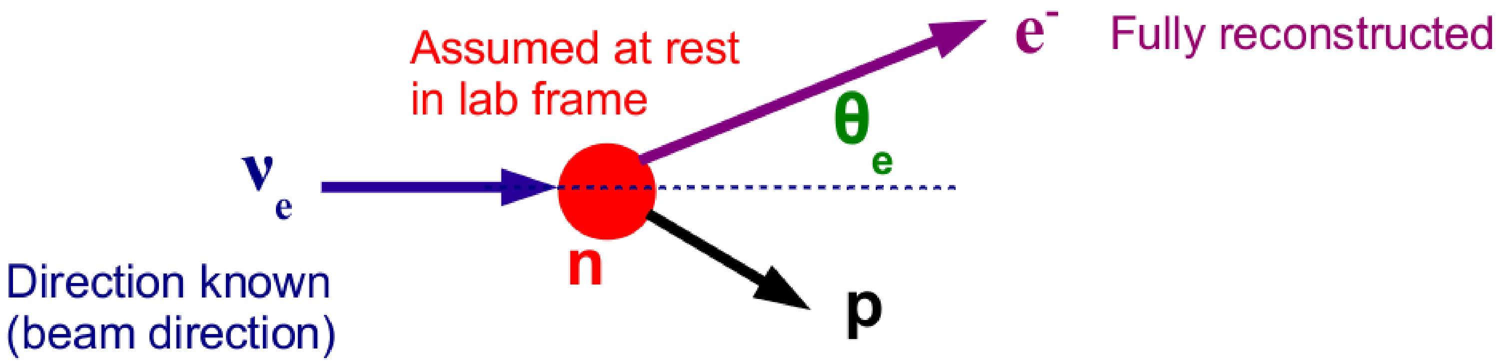
Beam Stability: Rate & Direction



Beam is quite stable in **space** (1 mrad tolerance) and **time** (within 1%)



Reconstructing ν Energy

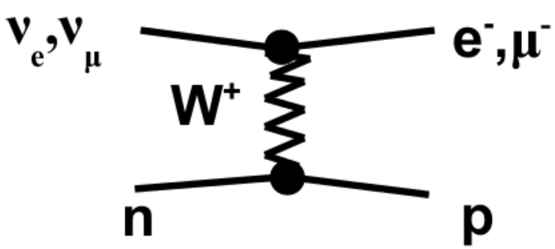


$$E_\nu^{QE} = \frac{2M_n E_e - (M_n^2 + m_e^2 - M_p^2)}{2[M_n - E_e + \sqrt{E_e^2 - m_e^2}\cos\theta_e]}$$

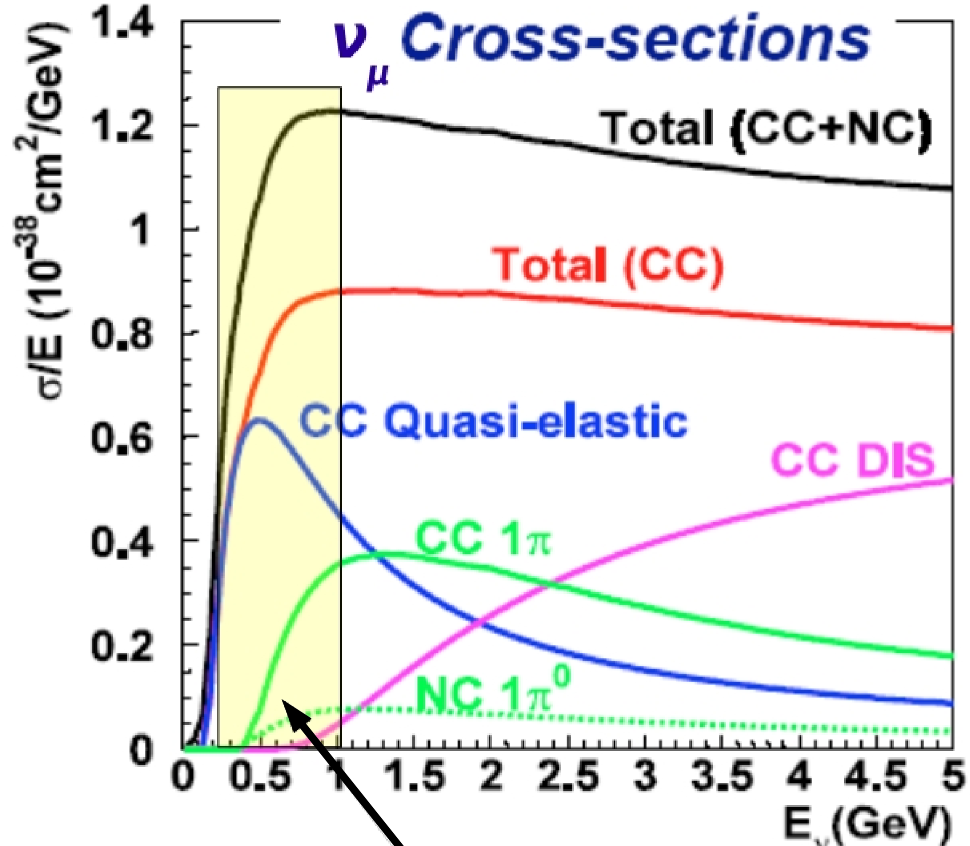
- Only final state lepton is reconstructed
- Neutrino energy can be determined with certain assumptions:
  - Neutrino direction is known (beam direction)
  - Recoil nucleon mass is known (use neutron mass)
  - Target nucleon is at rest (not quite true; introduces smearing)

Neutrino Interactions

- In the region of interest for T2K, large contribution from charge current quasi-elastic scattering:



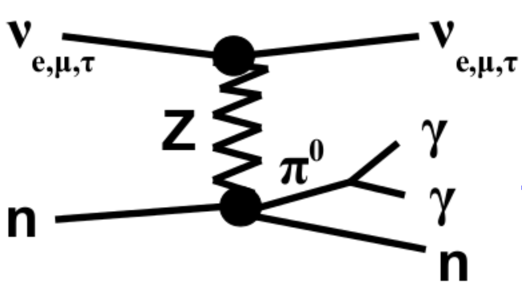
T2K signal at SK



T2K beam peak energy

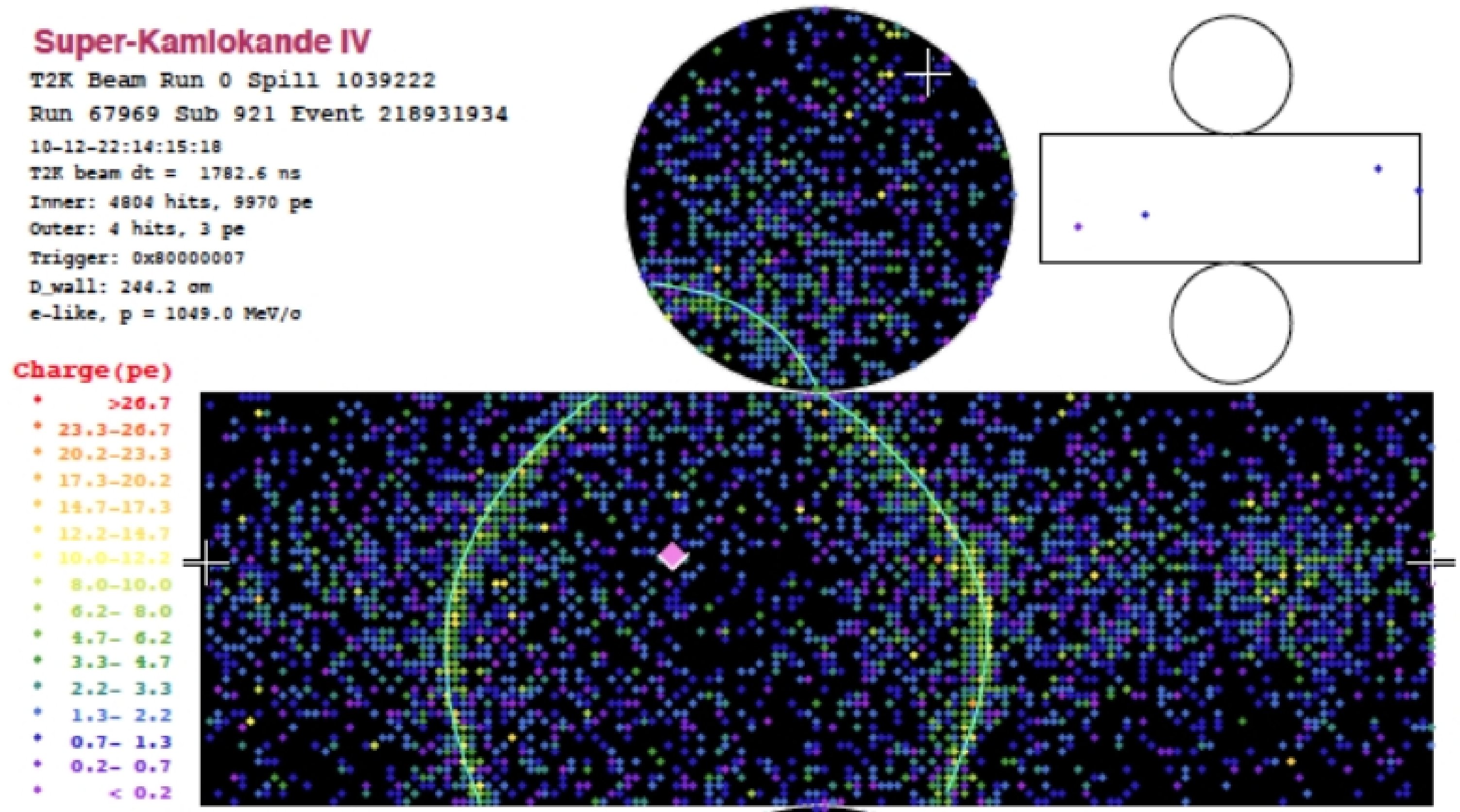
- Also significant CC contribution with pion in final state

- NCπ^0 is a major background mode from electron appearance:

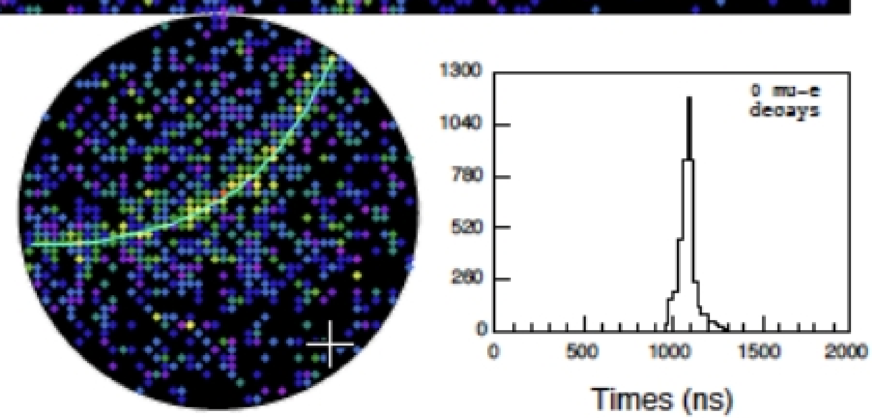


Photons from π^0 can fake electron signal

A Typical ν_e Candidate

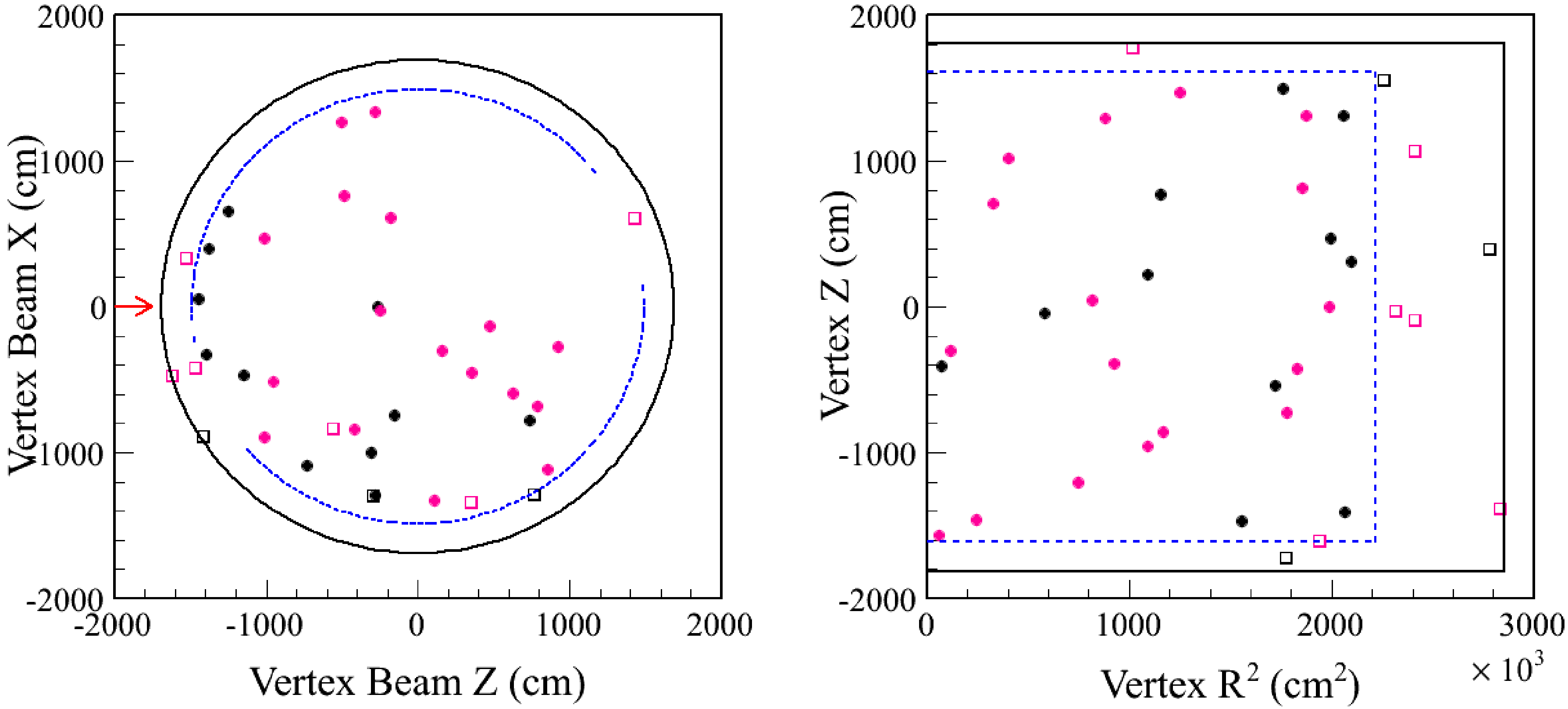


visible energy : 1049 MeV
# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c²
recon. energy : 1120.9 MeV



Vertex Distributions

Vertex distributions for νe candidates at the far detector:



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