Muon neutrino disappearance at T2K

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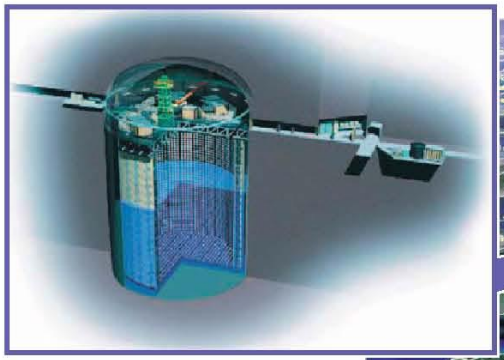
IOP HEPP, April 2013

Outline

The T2K experiment

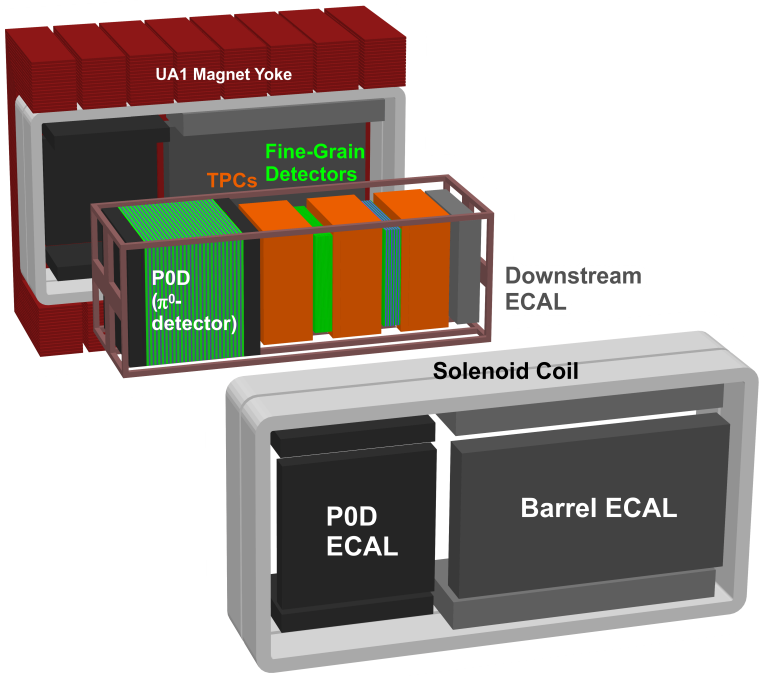


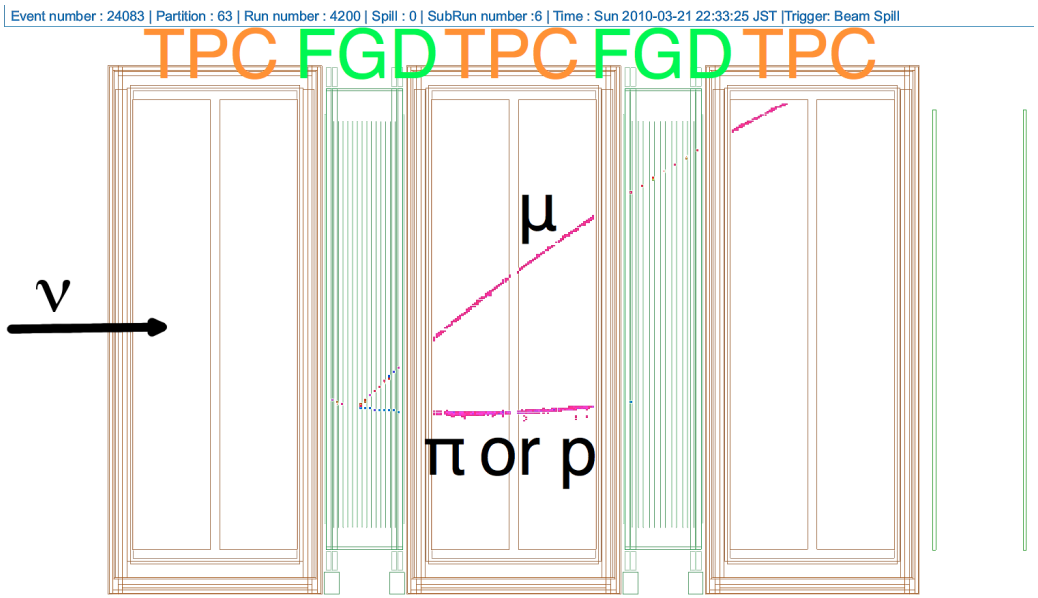
Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

- 30 GeV proton beam running up to ∼250 kW (design 750kW), producing ν_μ beam
- Far (& one near) detector 2.5° off-axis
- 3.010 $\times 10^{20}$ protons on target used in this analysis (data up to June 2012)
  - 2011 analysis used 1.431 $\times 10^{20}$ protons on target

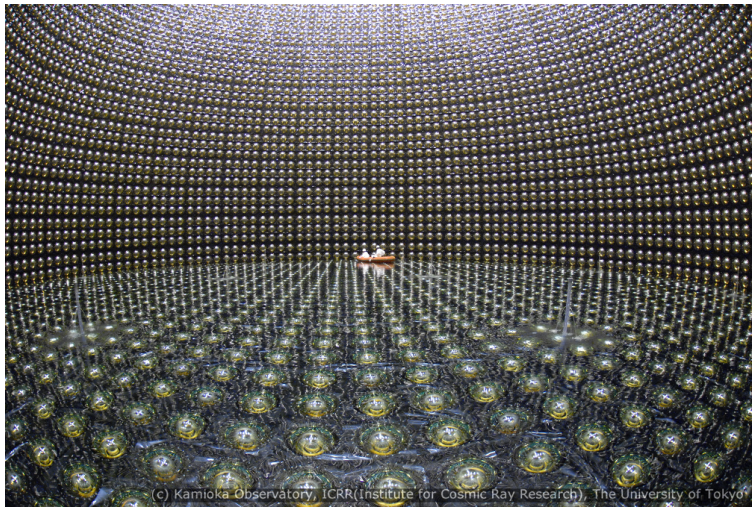
ND280

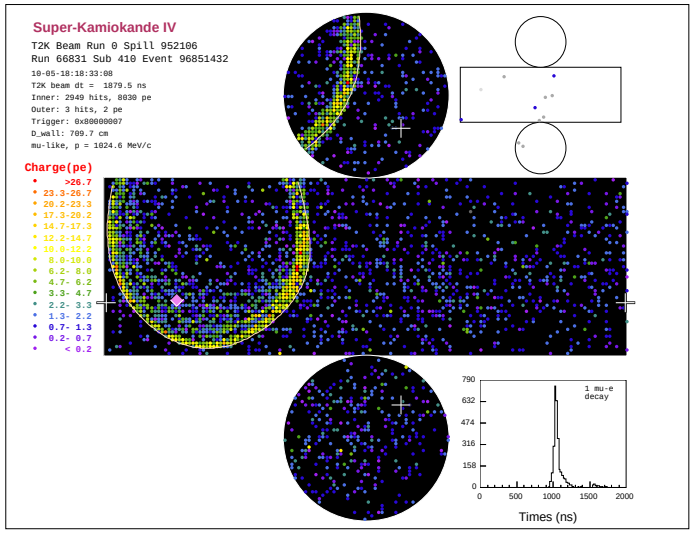




- Analysis shown in this talk uses the 'tracker' region
  - Fine-Grain Detector
    - ★ Excellent vertexing
  - Time Projection Chambers
    - ★ Excellent momentum resolution & particle identification

Super-Kamiokande





- 22.5 kton fiducial cylindrical water Čerenkov detector
  - Charged particles travelling faster than the speed of light in a dielectric medium emit Čerenkov light in a cone
  - ν interactions in Super-Kamiokande can produce such particles
  - Particle identification possible by *fuzziness* of ring
    - ★ $e^{\pm}$ shower & scatter more $\rightarrow$ fuzzy ring
- Outer detector used as veto

ν_μ disappearance physics

$$\overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}^{\text{Atmospheric}} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \overbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\text{Solar}}$$

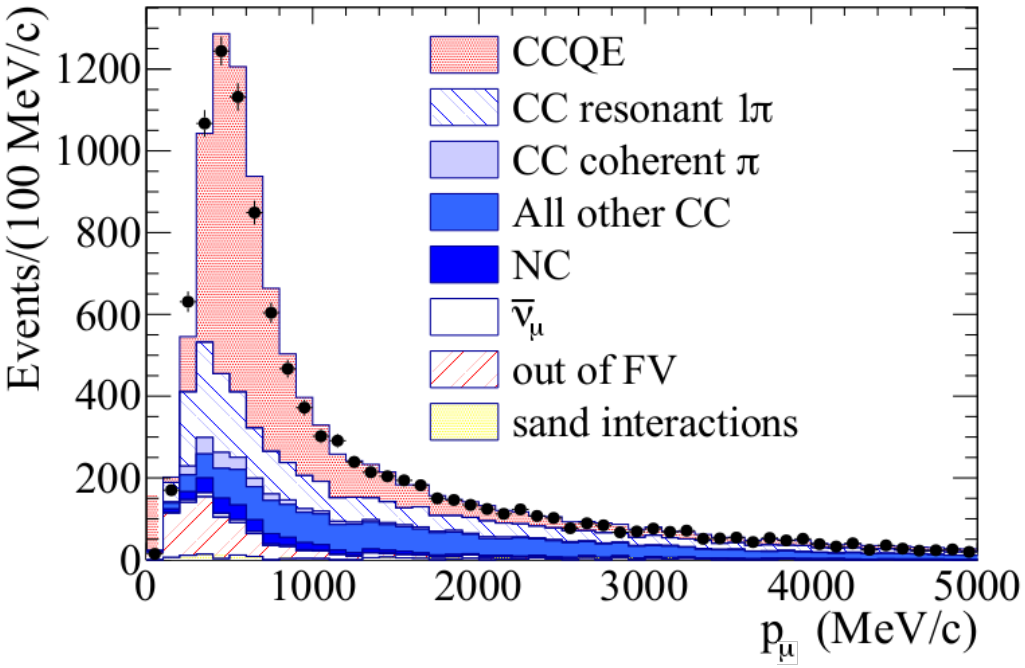
- Neutrino oscillations parameterised by:
  - PMNS matrix
    - ★ Relates neutrino mass eigenstates to neutrino flavour eigenstates
    - ★ Analogous to quark CKM matrix
  - Terms like: $\sin^2(\frac{1.267\Delta m^2(\mathrm{eV}^2)\mathrm{L(km)}}{E(GeV)})$
- "L/E" of experiment determines which oscillations dominate
  - Super-Kamiokande sits on the *atmospheric* Δm^2_{32}

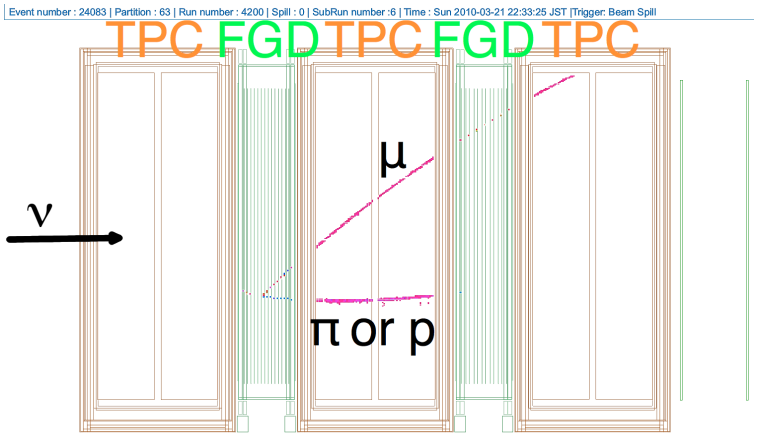
ν_μ disappearance physics

$$\overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}^{\text{Atmospheric}} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \overbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\text{Solar}}$$

- ν_μ disappearance @ T2K $\rightarrow \theta_{23}$, $|\Delta m^2_{32}|$
- $P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2(\frac{1.267\Delta m^2_{32}(\mathrm{eV}^2)\mathrm{L(km)}}{E(GeV)})$
- θ_{23} is close to 45° - maximal mixing
  - Points at an underlying symmetry
  - Hint of non-maximal mixing from MINOS
    - $\sin^2(2\theta_{23}) = 0.96^{+0.04}_{-0.04}$
- Mass hierarchy (sign of Δm^2_{32}) unknown; combinations with other experiments can lead to discovery

ND280 ν_μ CC selection



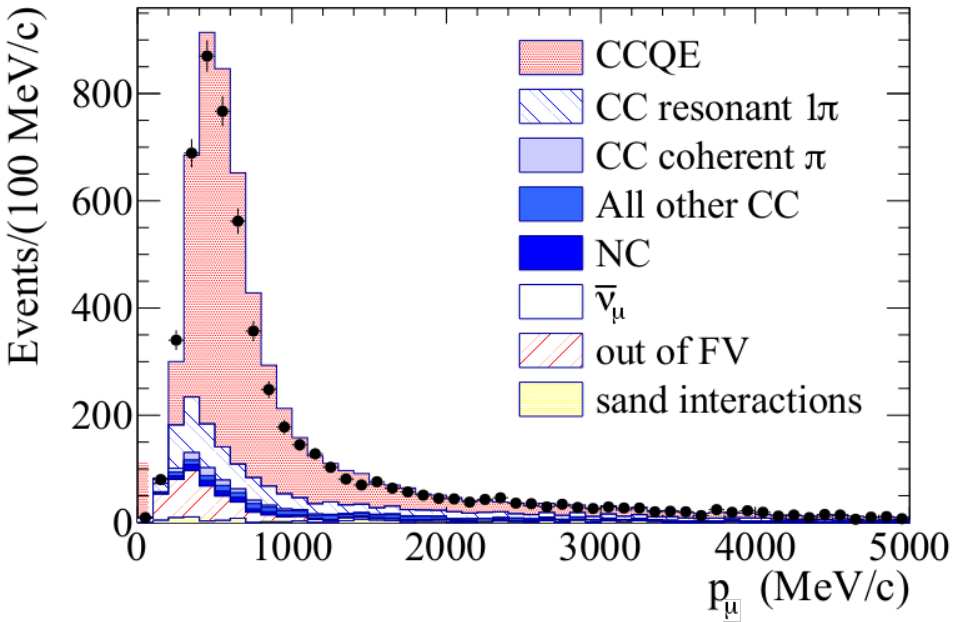


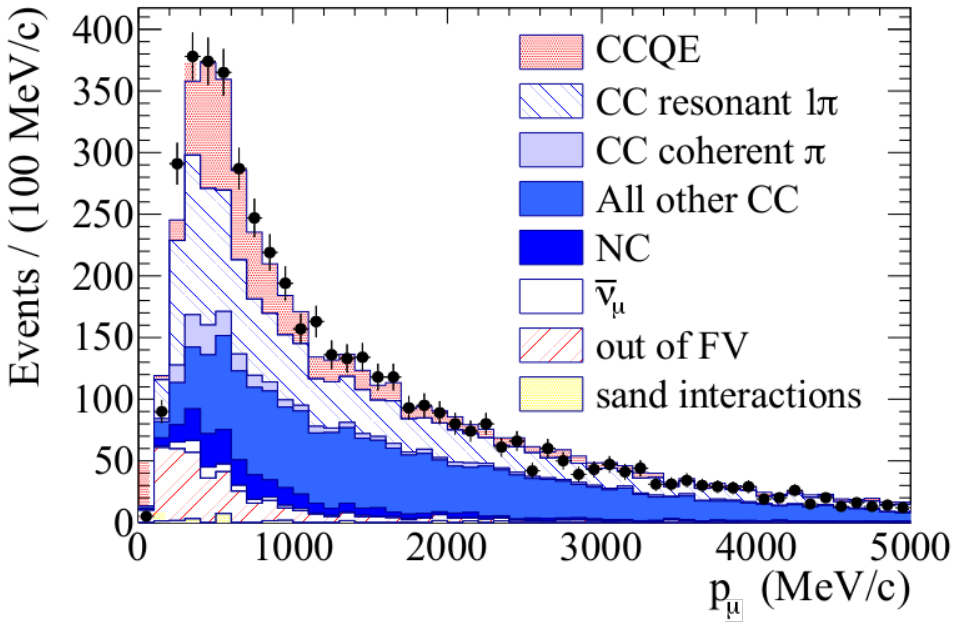
- Start with a ν_μ CC inclusive selection
  - Vertex in FGD fiducial volume
  - Highest momentum negative track downstream
  - Energy loss consistent with muon
  - Veto upstream tracks

ND280 ν_μ CC selection

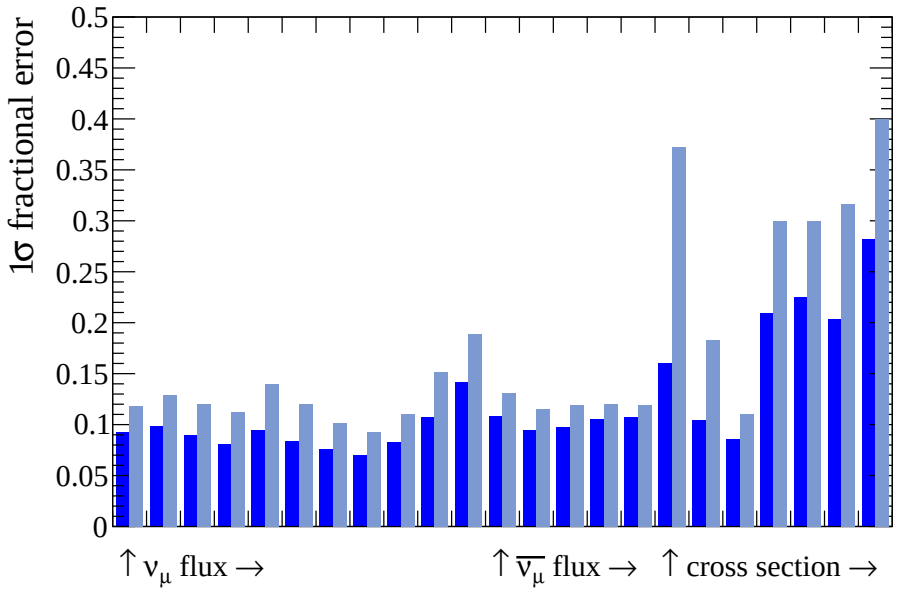
Split the sample

- CCQE-enhanced
  - No extra TPC-FGD matched tracks
  - No delayed electron from $\pi^\pm \to \mu^\pm \to e^\pm$
- CCnQE-enhanced
  - Everything else





ND280 ν_μ CC selection fit



- Fit ND280 ν_μ CC selection to constrain flux prediction & some cross section parameters
  - Flux prediction comes from Monte Carlo & hadron production experiments (mainly NA61/Shine)
  - Cross section errors come from fits to external data (mainly MiniBooNE)
- Used to tune Super-Kamiokande Monte Carlo expectation

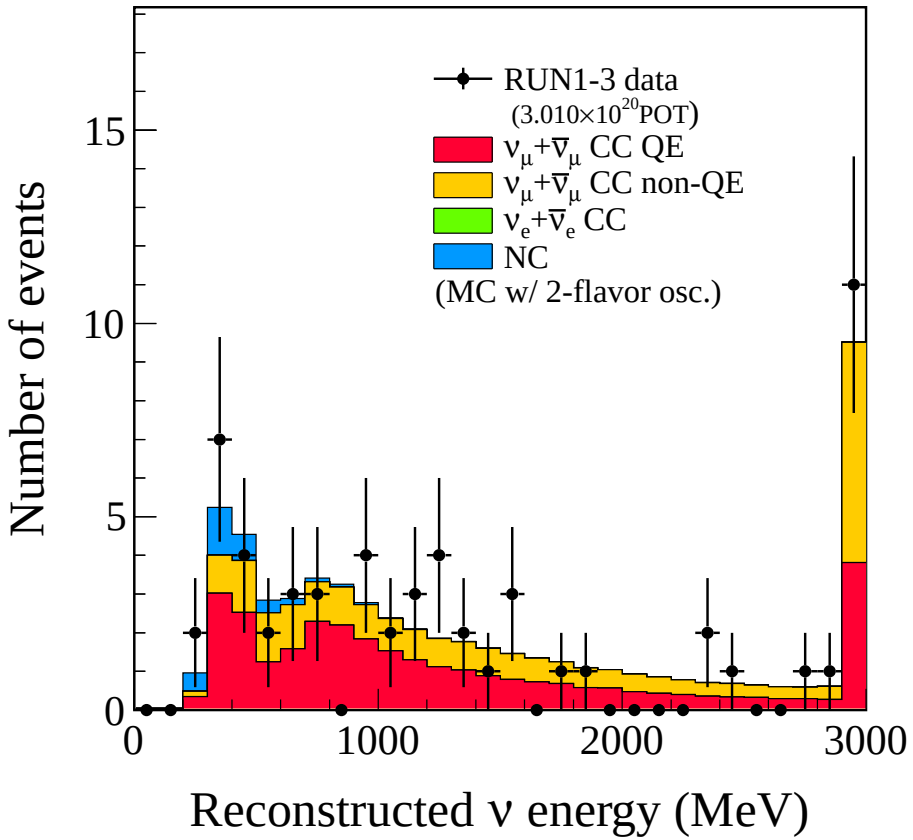
Super-Kamiokande: ν_μ selection

- Fully contained event, fiducial volume vertex
- Exactly 1 Čerenkov ring, with μ-like PID
- ≤ 1 reconstructed decay electrons
- Minimum energy & momentum cuts

58 events pass all cuts

Expectation with 2ν oscillations:
$\sin^2(2\theta_{23}) = 1.0$
$\Delta m^2_{32} = 2.4 \times 10^{-3}\,\mathrm{eV}^2$
57.78 events

Expectation with no oscillations:
196.22 events



Super-Kamiokande: Prediction

- Use MC tuned with ND280 fit
- Parameterise uncertainties with 48 systematics
- ND280 fit results in smaller uncertainties
  - 1σ errors at $\sin^2(2\theta_{23}) = 1.0$ and $\Delta m^2_{32} = 2.4 \times 10^{-3}\,\mathrm{eV}^2$

Source of uncertainty	$\delta n^{\mathrm{exp}}_{\mathrm{SK}}$	/ $n^{\mathrm{exp}}_{\mathrm{SK}}$
Super-Kamiokande detector	10.1%	
Flux & ND280-correlated cross section	4.1%	(21.8%)
ND280-uncorrelated cross section	6.3%	
Final- and secondary-state interactions	3.5%	
Total	13.0%	(25.1%) before ND280 fit

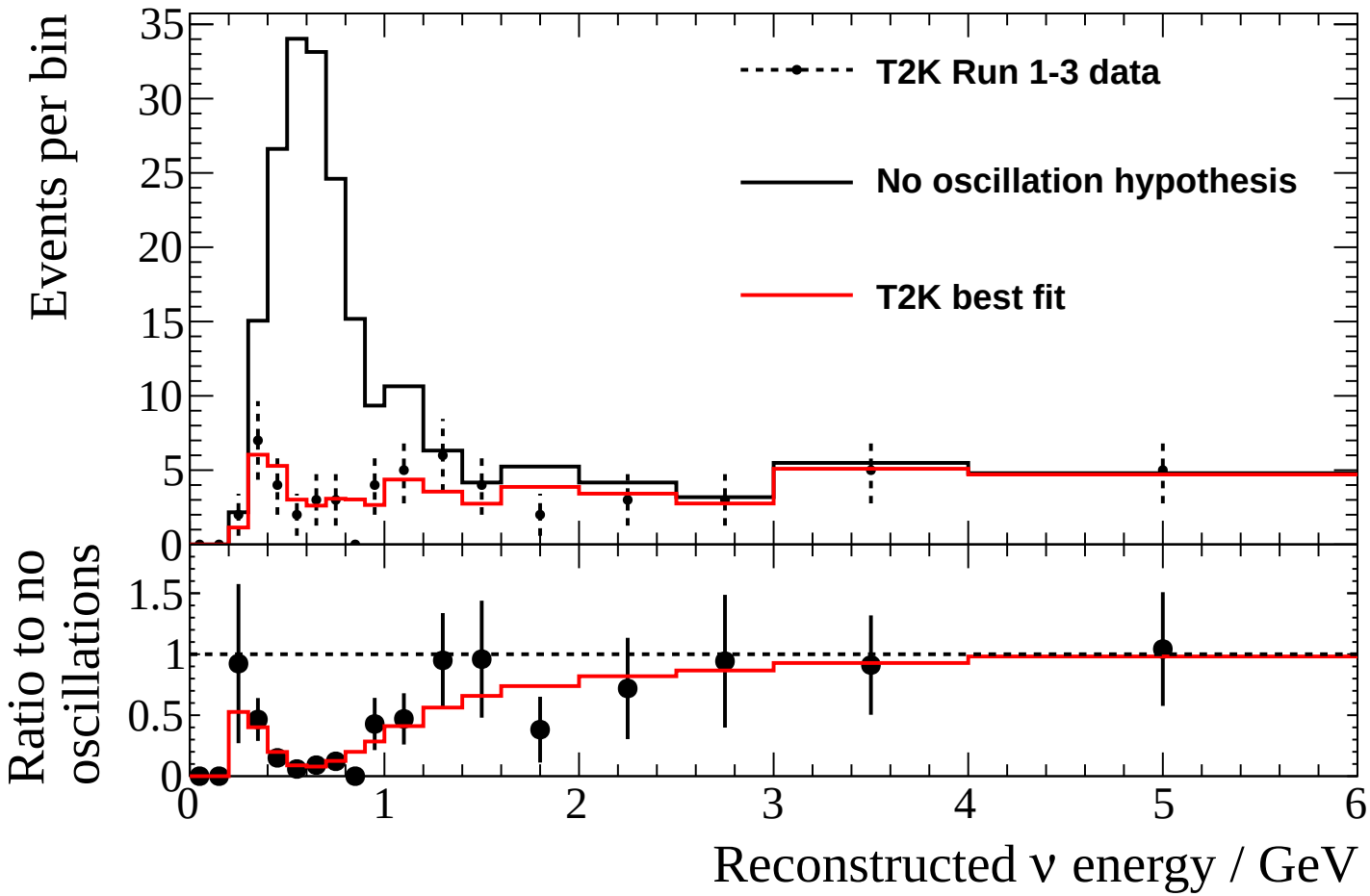
Oscillation fit

$$\chi^2(\sin^2(2\theta_{23}), \Delta m^2_{32}; \mathbf{f}) = 2 \cdot \sum_{i=0}^{N-1} \left(n_i^{\text{obs}} \cdot ln(n_i^{\text{obs}} / n_i^{\text{exp}}) + (n_i^{\text{exp}} - n_i^{\text{obs}}) \right) + (\mathbf{f} - \mathbf{f_0})^T \cdot \mathbf{C}^{-1} \cdot (\mathbf{f} - \mathbf{f_0})$$

- Likelihood-ratio method, fitting for all systematics
- Incorporates matter effects
- Assumes mixing between 3 active ν flavours

Parameter	Fixed at (2012 PDG best fit)
Δm^2_{21}	7.5×10^{-5} eV^2
$\sin^2(2\theta_{12})$	0.857
$\sin^2(2\theta_{13})$	0.098
δ_{CP}	0

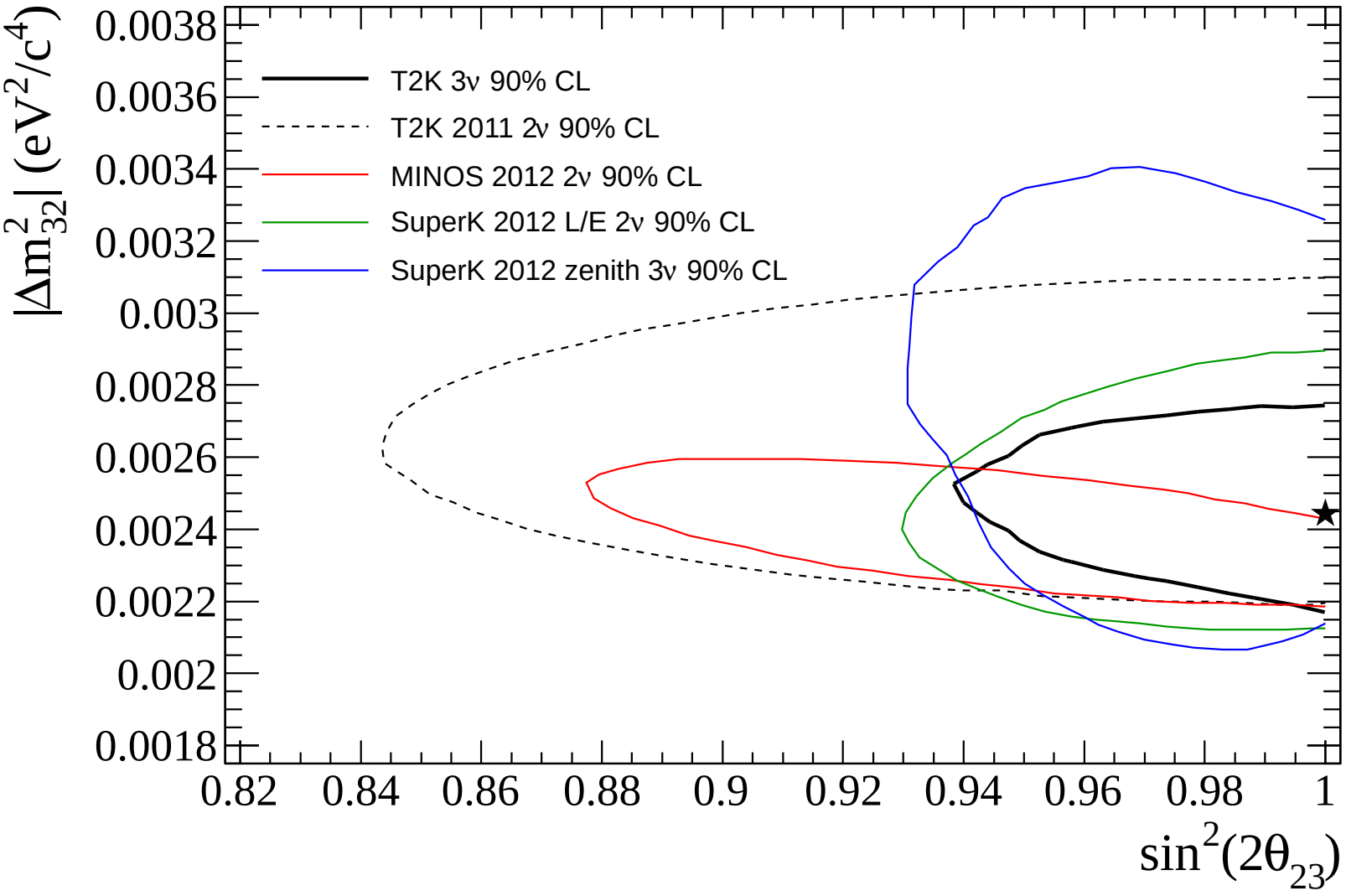
Result: spectrum



Best fit: $\sin^2(2\theta_{23}) = 1.00$, $|\Delta m^2_{32}| = 2.44 \times 10^{-3}\,\mathrm{eV}^2$

p-value of fit: 0.83

Result: contour

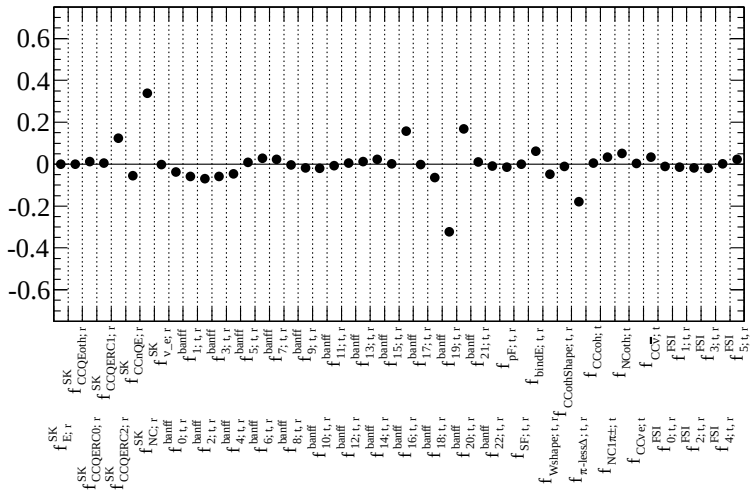


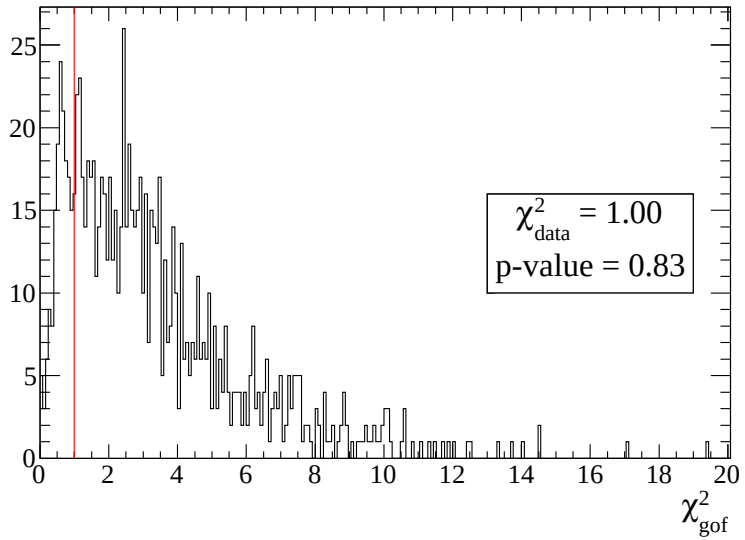
Summary

- T2K has a world leading result, using just 4% of final POT
  - Expecting to more than double data set by August 2013
- It is the first long-baseline ν_μ disappearance measurement using a 3ν-flavour analysis
- $\sin^2(2\theta_{23}) = 1.00$, $|\Delta m^2_{32}| = 2.44 \times 10^{-3}\,\mathrm{eV}^2$
  - Maximal mixing - new symmetry?

Backups

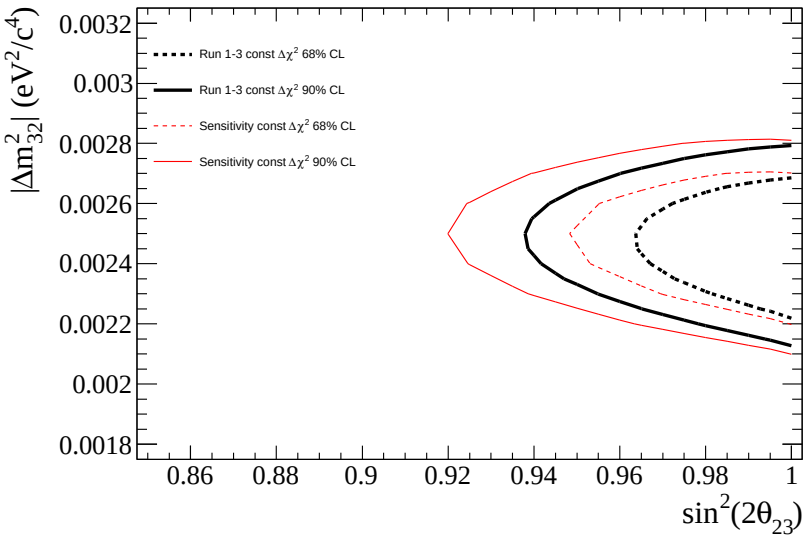
ν_μ disappearance: fit quality

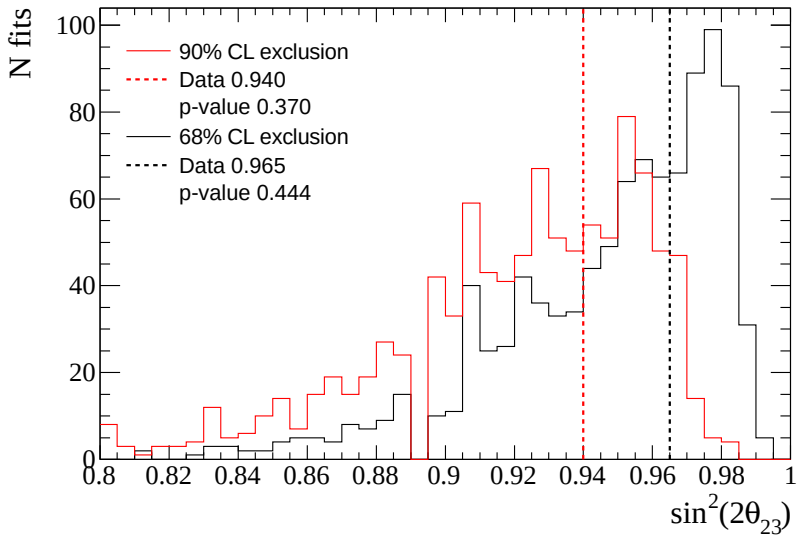




- Left: fitted pulls $(\text{pull} = \frac{f - f_0}{\sigma_{fit}})$ of the systematic parameters
  - Pulls close to 0 due to fit penalty term & most systematics having small effect on reconstructed energy spectrum
- Right: χ^2 at the best fit point for many toy experiments, with the value for data highlighted

ν_μ disappearance: sensitivity

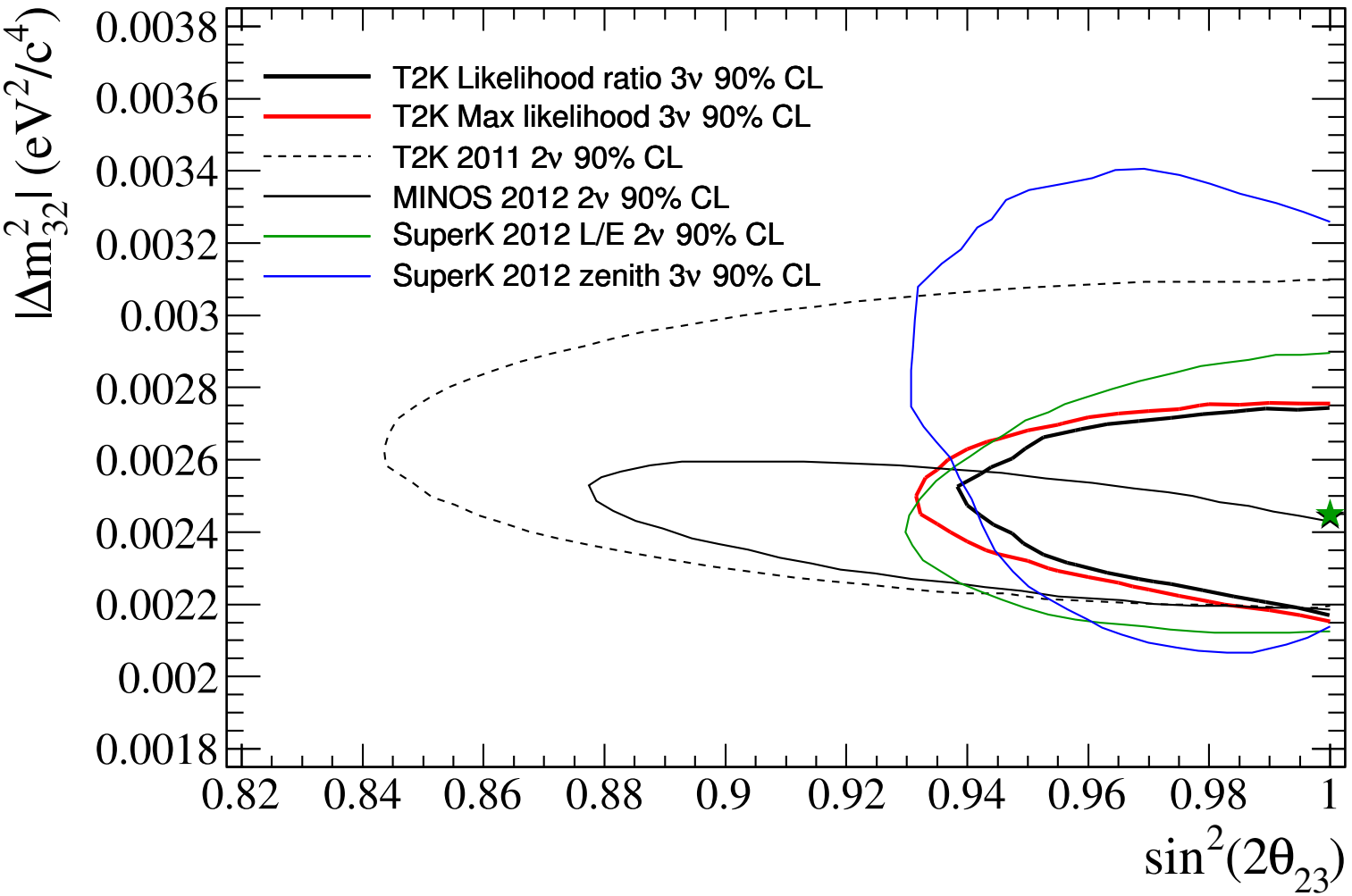




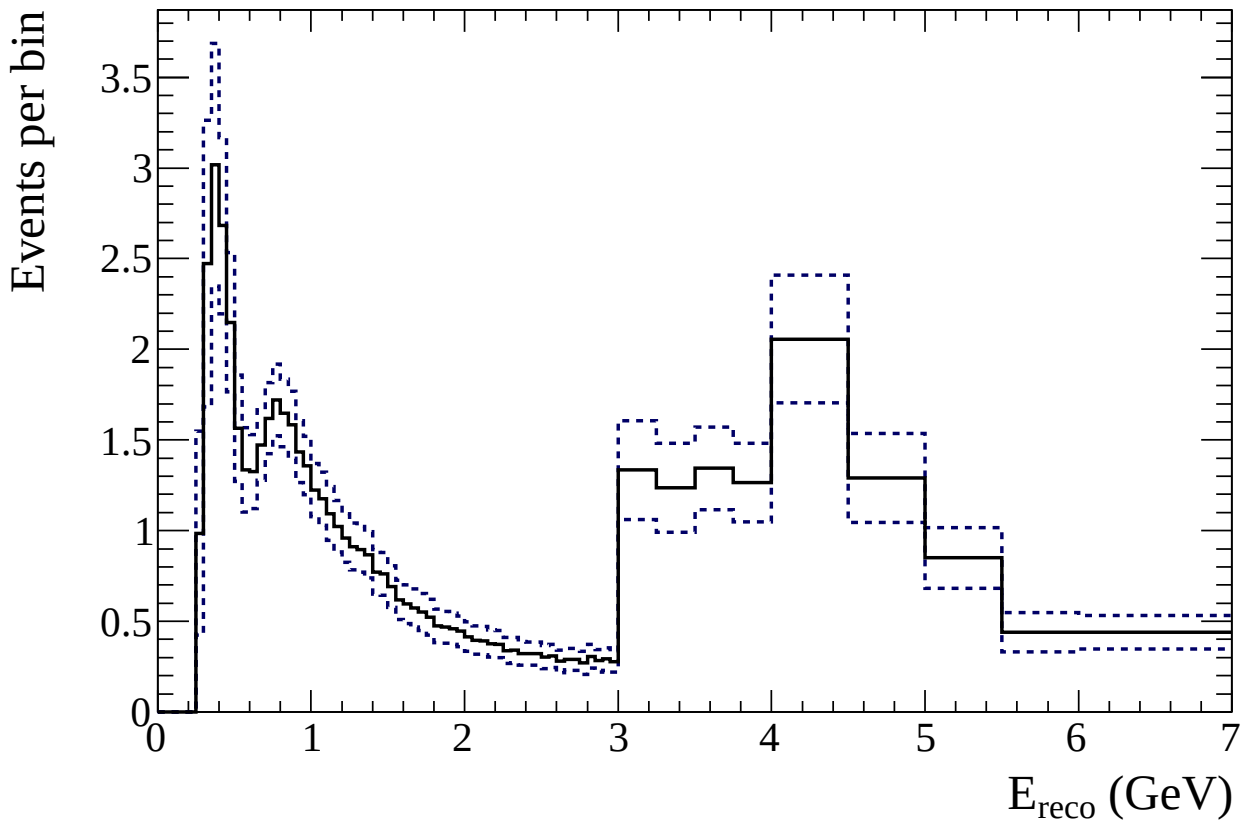
- Uses different fit method: only fit for the (8) systematics that are non-negligable, compared with statistical error
  - Gives equivalent result
- Right shows that even though we've performed better than the sensitivity, it's not unexpected

Alternative ν_μ disappearance: max likelihood

$$\mathcal{L} = \mathcal{L}_{norm}(\sin^2(2\theta_{23}), \Delta m^2_{32}, \mathbf{f}) \cdot \mathcal{L}_{shape}(\sin^2(2\theta_{23}), \Delta m^2_{32}, \mathbf{f}) \cdot \mathcal{L}_{syst}(\mathbf{f})$$

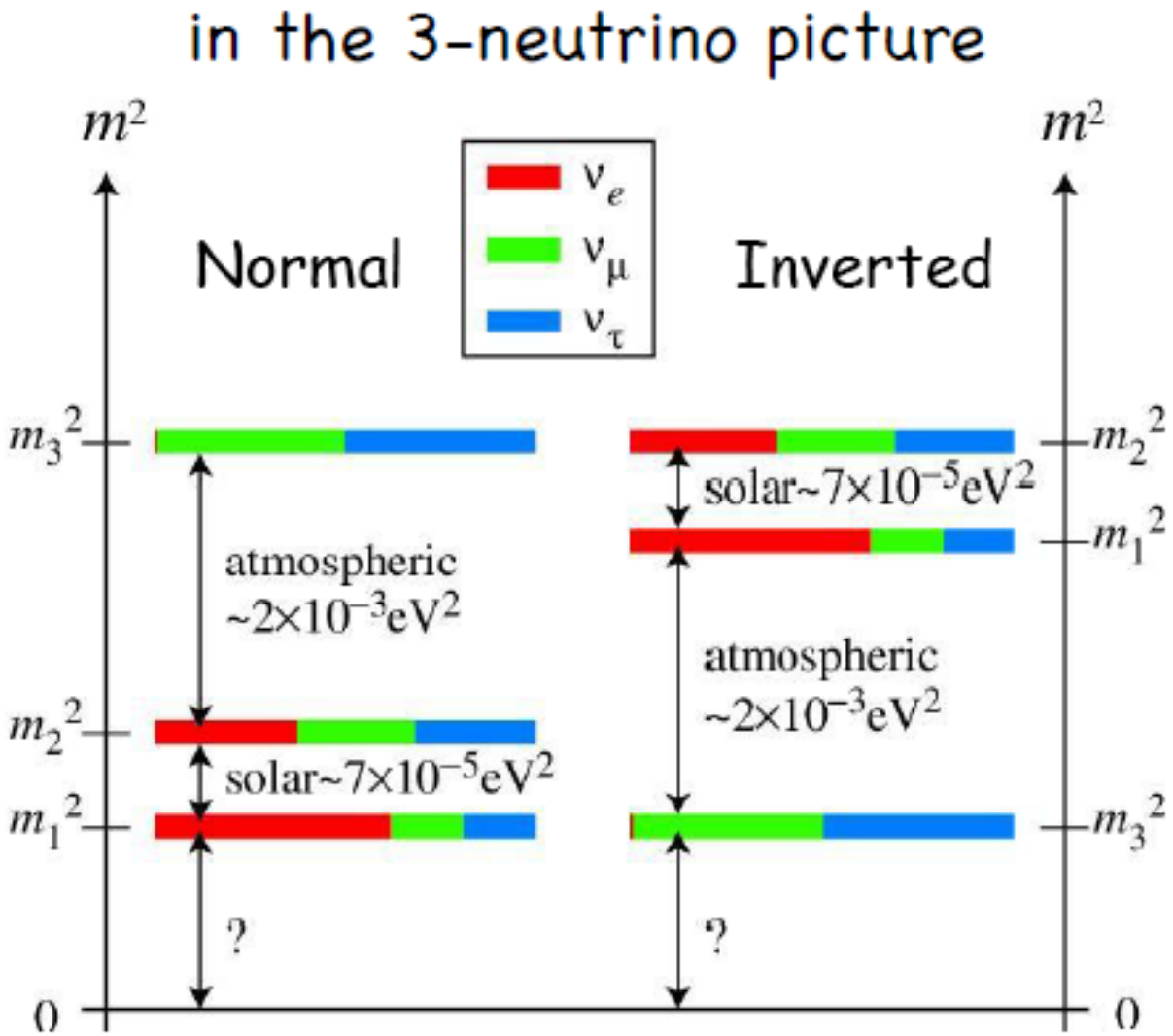


ν_μ disappearance: prediction error envelope

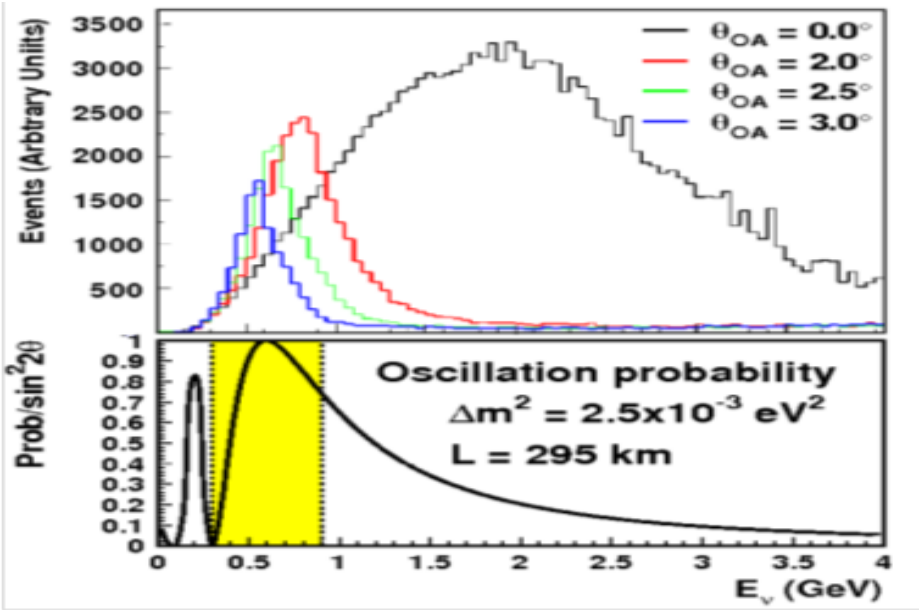


- Error envelope for all 48 systematic parameters
- Total effect on number of events at Super-Kamiokande is 13.0%

3-ν flavour oscillations

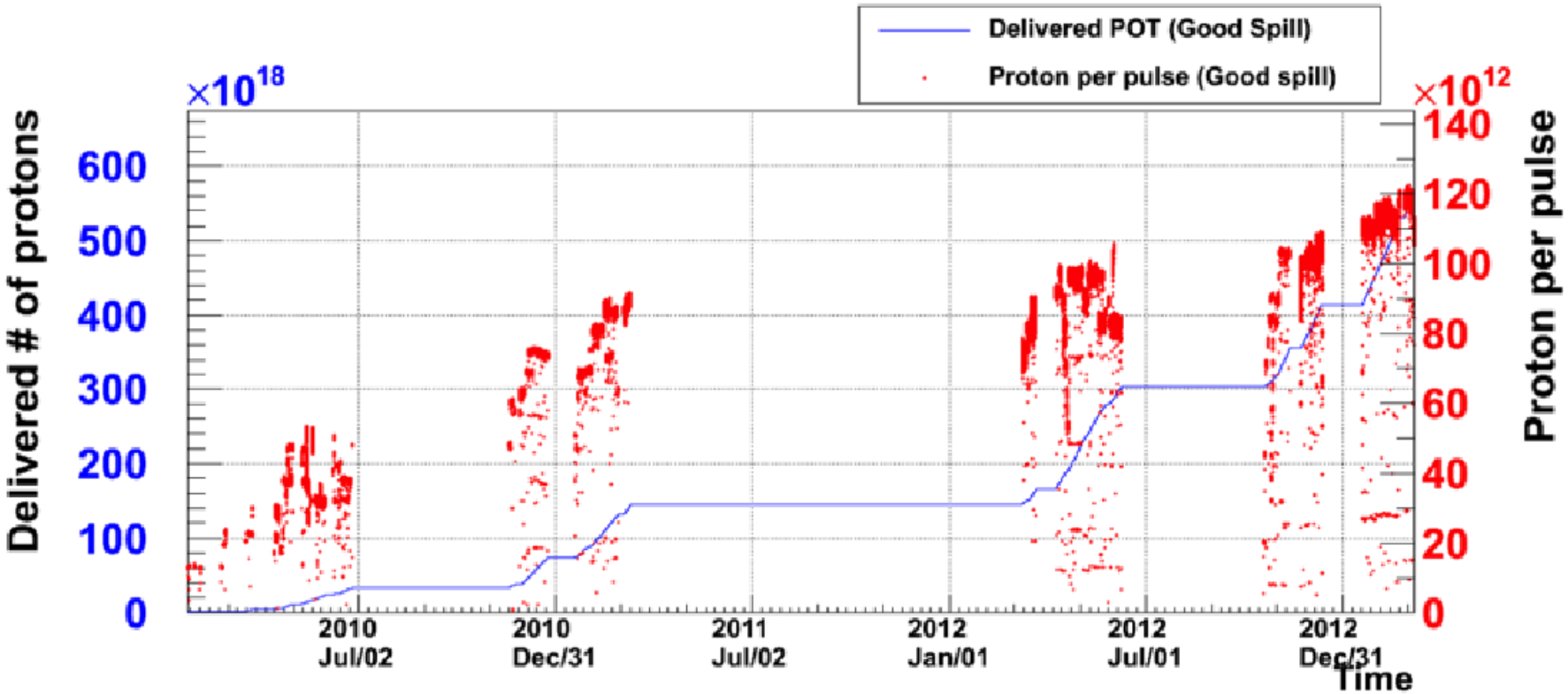


T2K: an off-axis experiment



- Super-Kamiokande & ND280 are 2.5° off-axis, giving narrow-band beam
  - Narrow ν energy range, focussed at ~ 0.6 GeV
  - Same place as the oscillation dip

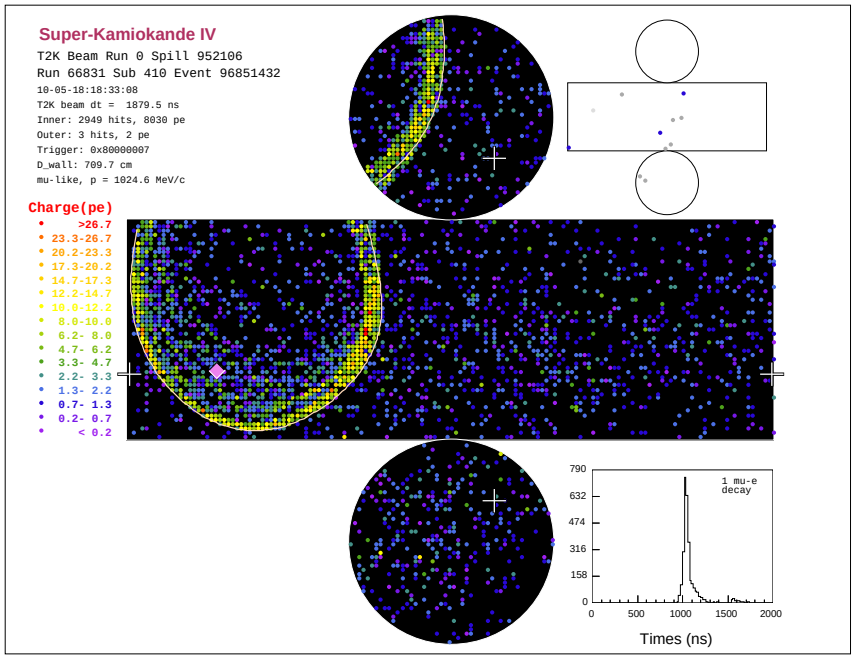
T2K: run status



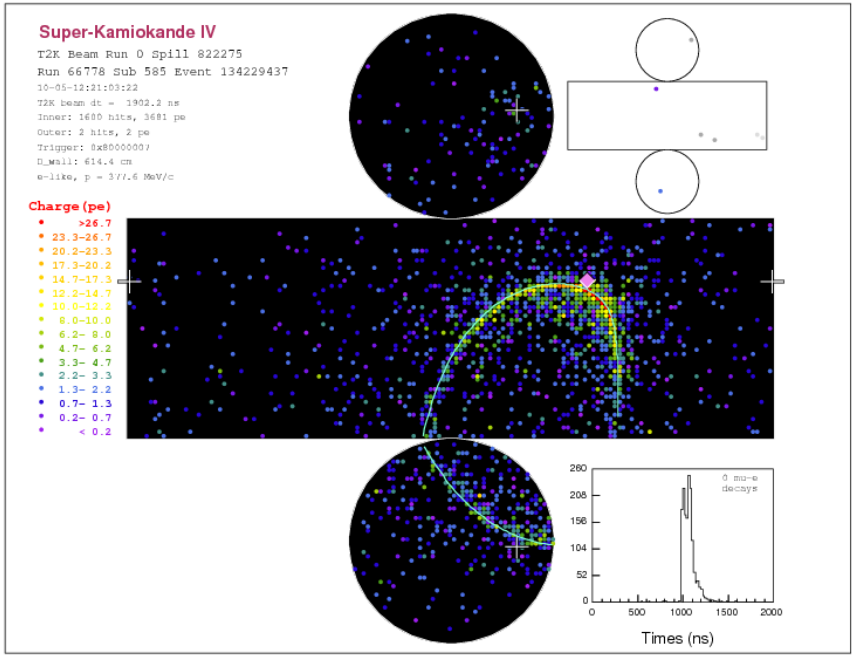
- 3.01×10^{20} POT recorded by July 2012
- Currently taking more data
- $\sim 7.5 \times 10^{20}$ POT expected by July 2013

Super-Kamiokande events

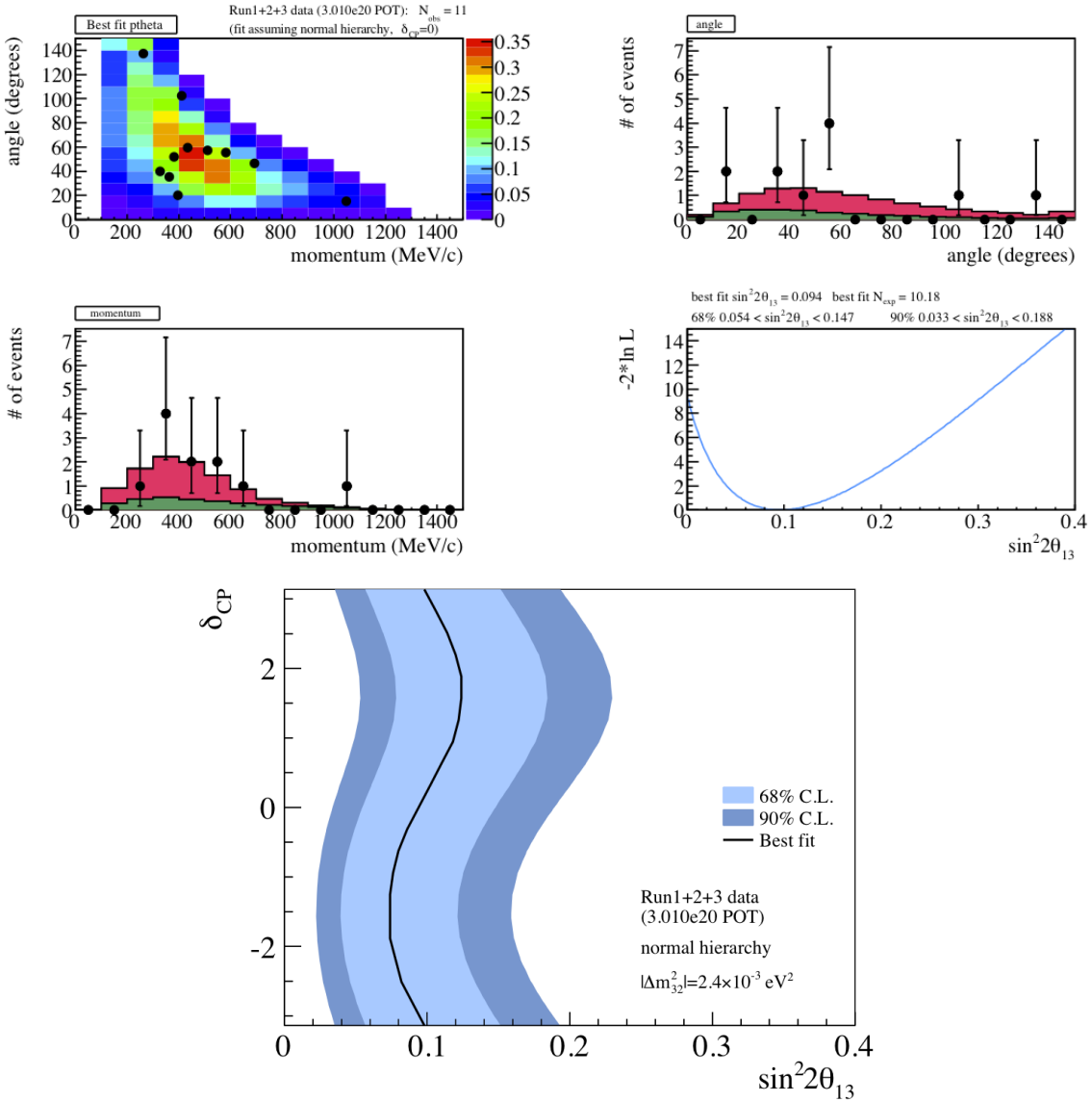
ν_μ candidate



ν_e candidate



ν_e appearance result (normal hierarchy)



ν_e appearance result (inverted hierarchy)