T2K Oscillation Strategies

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on behalf of the T2K Collaboration

Neutrino Factories 2010
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The Actual Title

- After I arrived, I found out that my actual talk title was “Near to Far, T2K Style”

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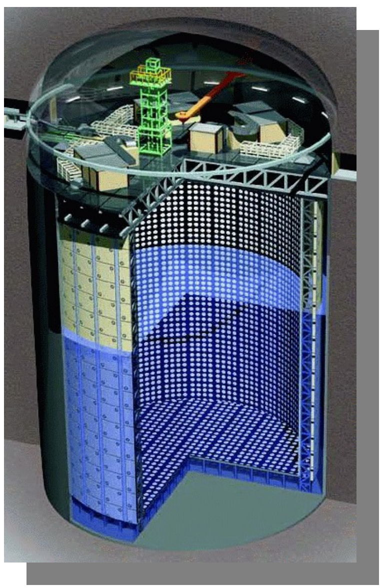
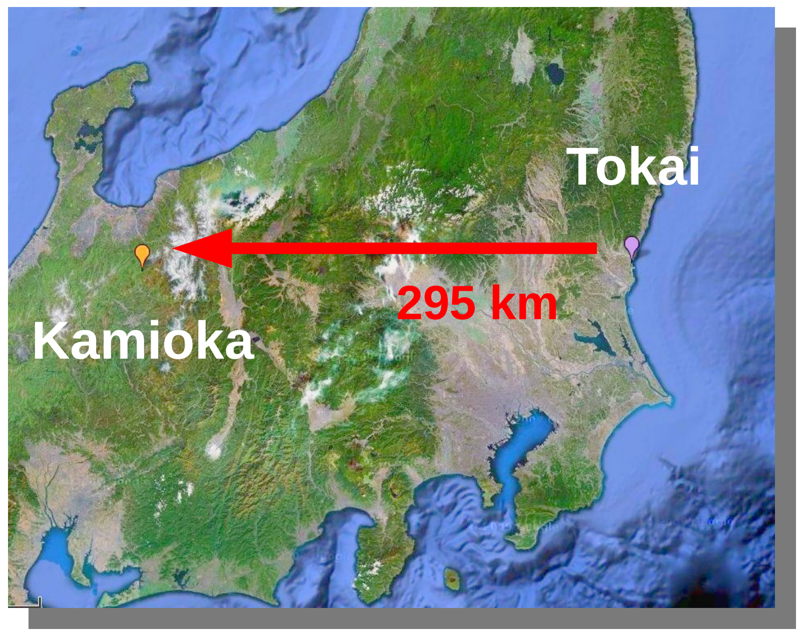
- This is all I could think of to fit that title. It's a long trip from near T2K to my far away home...

The T2K Experiment

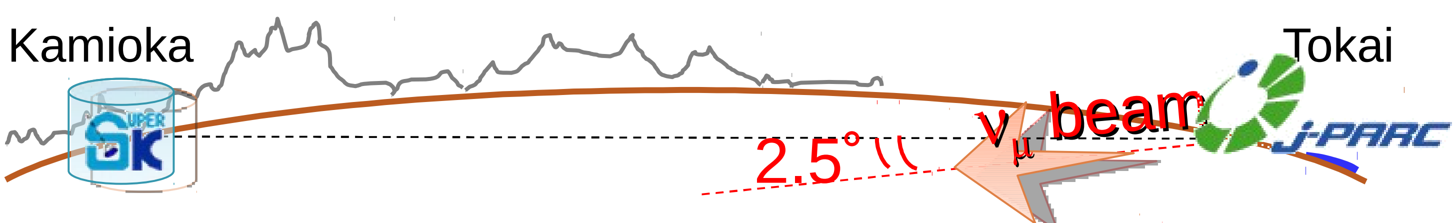
The T2K (Tokai to Kamioka) Experiment





Super-K
The Super-Kamiokande detector

JPARC
Japan Proton Accelerator Research Complex



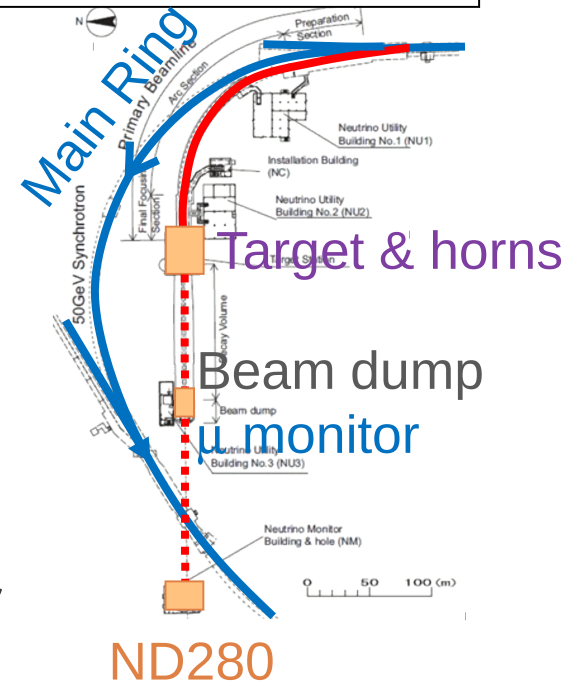
Characteristics of T2K

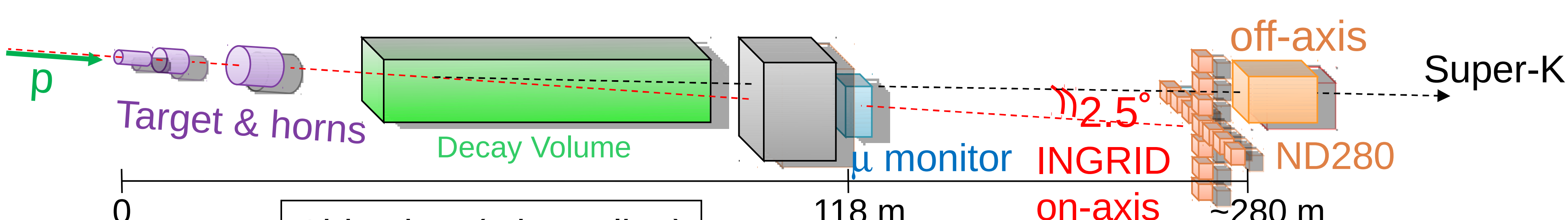
- High intensity beam
- Off-axis detectors:
  - The detectors are at 2.5° off-axis from the beam, which tunes the ν energy and shape.
- A massive, well understood, far detector SK.
- A complex suite of near detectors:
  - INGRID is on-axis for beam direction monitoring.
  - ND280 has multiple sub-detectors and regions, focused on specific backgrounds at SK.

JPARC Beam

- Protons collide with a graphite target, producing charged pions.
  - Design 30 GeV, 750 kW
- The positive pions are focused by horns, and enter the decay volume.
  - The decay produces ν_μ and μ^+
  - The length is tuned, to minimize the number of μ^+ that decay, producing anti-ν_μ.

Top view (ν beamline)

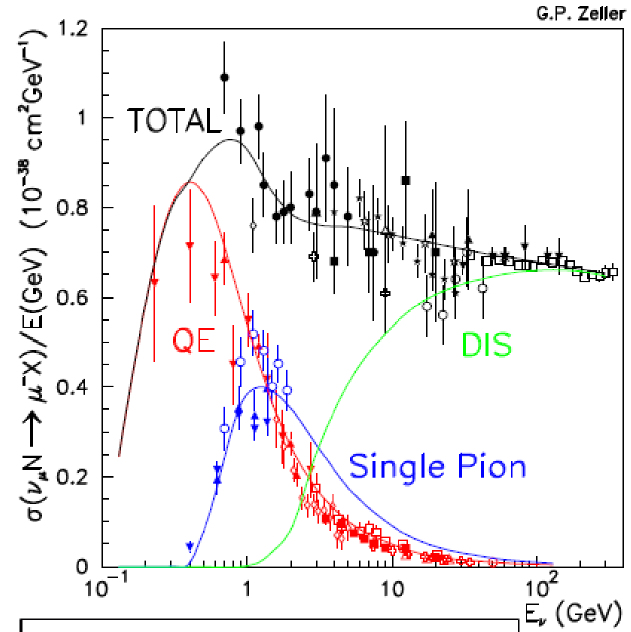


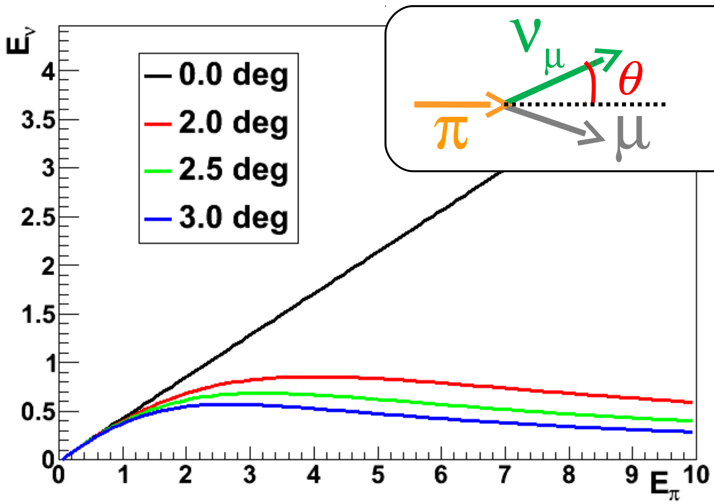


Side view (ν beamline)

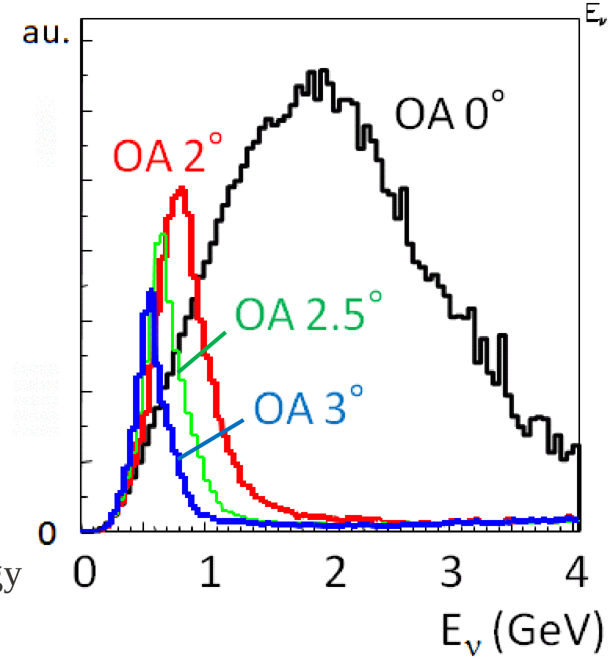
Off-axis Design

- The detectors are placed off-axis from the beam.
  - 1st oscillation maximum @ $E_\nu \sim 0.6$ GeV.
  - Beam peak ~ 0.7 GeV, CCQE interaction dominates, allows E reconstruction.
- The angle can be varied from 2.5° to 2.0° off-axis.





$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

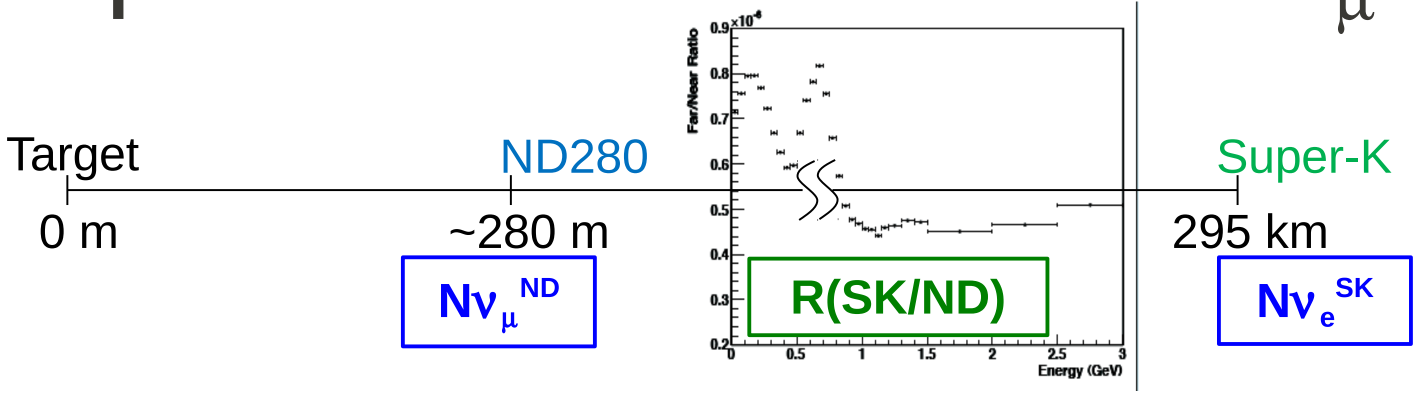


Goals of T2K

Oscillation Goals

- T2K will make two oscillation measurements
- ν_μ disappearance:
  - Observe a deficit of ν_μ in the beam at Super-K.
  - Improved measurements on θ_{23} and Δm^2_{32}.
- ν_e appearance:
  - Search for increased ν_e in the beam at Super-K
  - If found, would establish non-zero θ_{13}
  - With other measurements, may probe mass hierarchy and δ

Conceptual Measurement of $\nu_\mu \rightarrow \nu_e$



- # of observed events @ SK

$$N\nu_e^{SK} = P(\nu_\mu \rightarrow \nu_e) \times \Phi^{SK}(\nu_\mu) \times \sigma(\nu \text{ int. water})$$

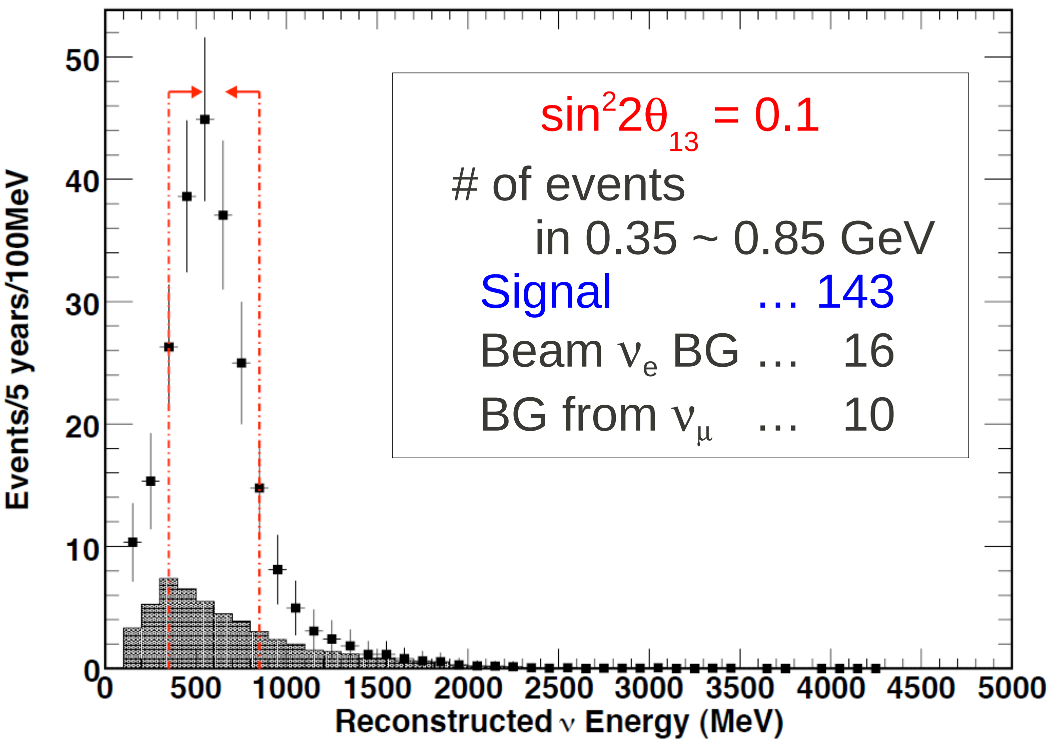
- $\Phi^{SK}(\nu_\mu) \times \sigma(\nu \text{ int.}) = R(SK/ND) \times \Phi^{ND}(\nu_\mu) \times \sigma(\nu \text{ int. water})$

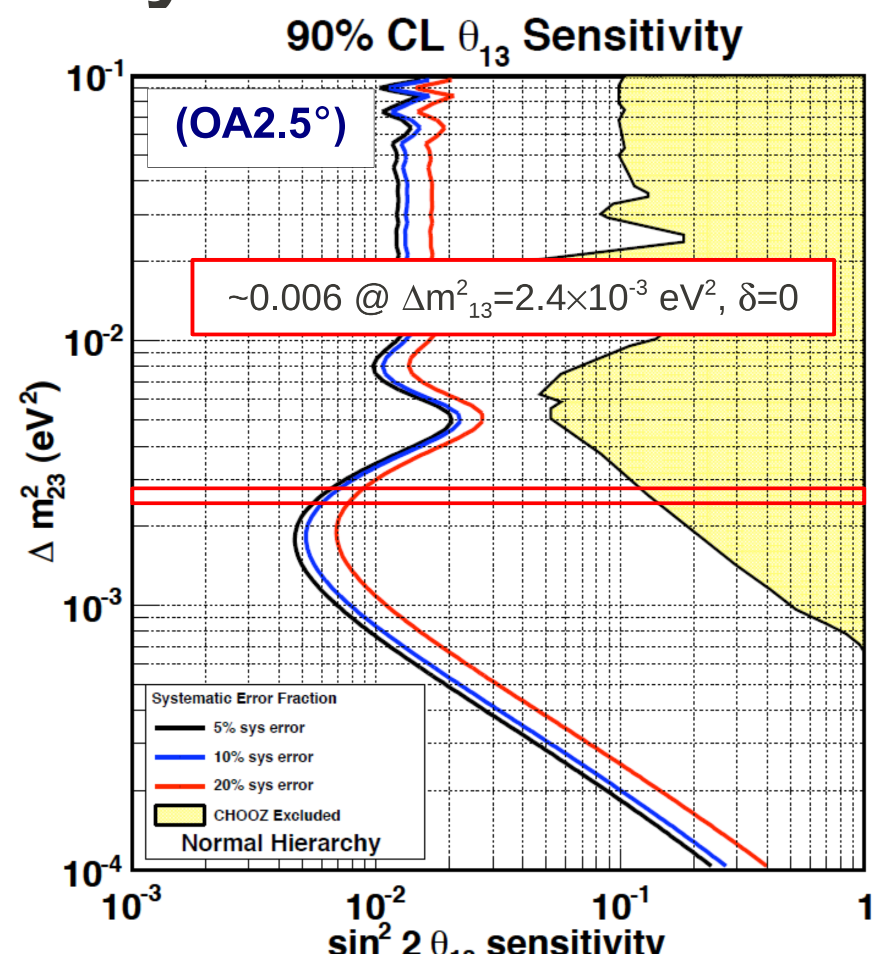
$$= R(SK/ND) \times N\nu_\mu^{ND}$$

← Near Detector Measurement

- R(SK/ND) : Far to Near flux ratio
  - Estimated from simulation, using measurements from beam monitors and CERN NA61.

Eventual ν_e Appearance Sensitivity





Note that eventual (3.75 MW-yr) sensitivity estimate has 90% CL limit at ~10 signal events

$\sin^2 2\theta_{23} = 1.0$ is assumed

8×10^{21} POT ~ 5 years @ 750 kW

Conceptual Measurement of $\nu_\mu \rightarrow \nu_x$

Disappearance measurement gives θ_{23}, Δm^2_{32}

$$P(\nu_\mu \rightarrow \nu_x) = N_\nu^{obs} / N_\nu^{null}(E_\nu) \approx \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32} L / 4E_\nu\right)$$

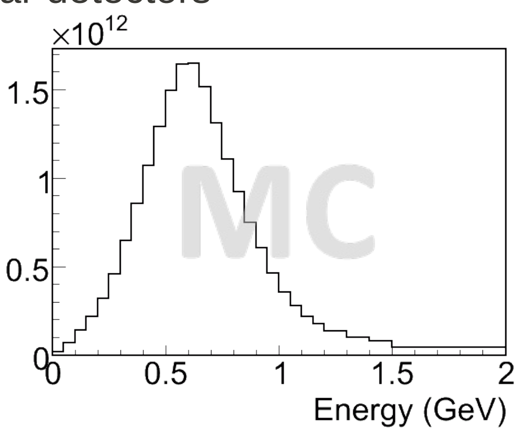
R(Far/Near)
Extrapolated from MC, verified by NA61

σ_ν^{water}
Measured by near detectors

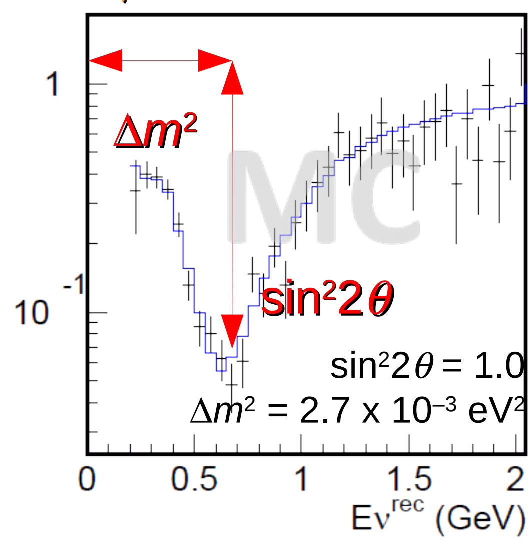
N_ν^{obs}

$$N_\nu^{null} = R \times \Phi_\nu^{ND} \times \sigma_\nu^{water}$$

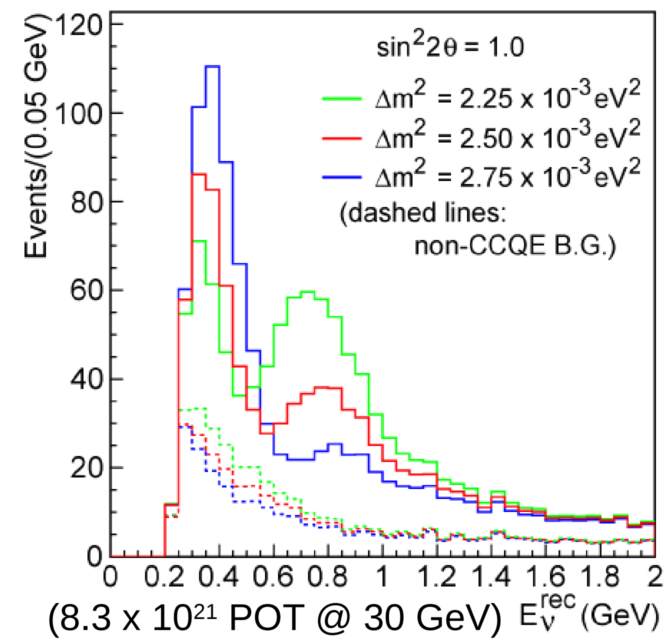
Φ_ν^{ND}
Measured by near detectors



$P(\nu_\mu \rightarrow \nu_x)$



Measured by Super-K



$(8.3 \times 10^{21}$ POT @ 30 GeV)

Statistical and Systematic Uncertainties

Anticipated Systematics $\nu_\mu \to \nu_e$

- Intrinsic ν_e in beam (60% of background)
- Fake e^- in far detector (e.g., NC π^0) (40% of background)
- If oscillation probability is large, will eventually limited by signal eff. (fiducial volume, energy reconstruction of ν_e events)
- S/N of 1:1 corresponds to $\sin^2 2\theta_{13}$~0.02
  - Analysis goal is to keep fractional uncertainty on each background source to 10%

Accepted ν_μ

beam ν_μ	Frac.
NC1π^0	77 %
NC1$\pi^\pm$	8.6 %
NC1γ	5.2 %
NC other	6.0 %
CC	3.8 %

Accepted Beam ν_e

beam ν_e	Frac.
1e	94.6 %
1e + 1p$^\pm$	2.6%
1e + 1P	0.4%
NC	2.4%

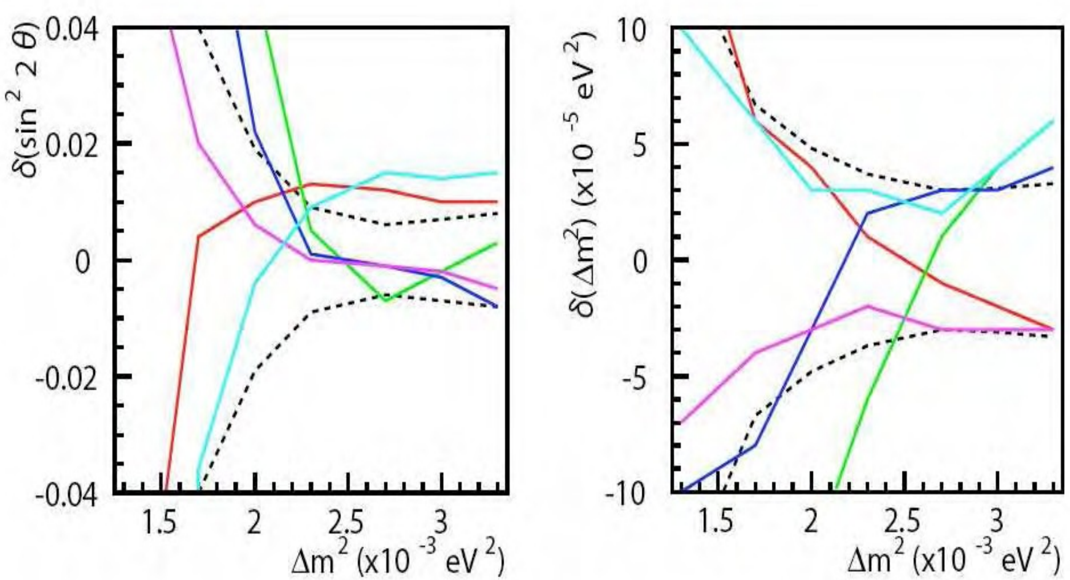
Signal ν_e

signal ν_e	Frac.
1e	98.5 %
1e + 1p$^\pm$	1.5 %

Systematic error of 1π^0 and 1e efficiencies are important

Anticipated Systematics $\nu_\mu \rightarrow \nu_\mu$

- Disappearance $\nu_\mu \rightarrow \nu_\mu$
  - Beam energy, normalization
  - Detector fiducial volumes and energy scales
  - Non-QE background in Super-K



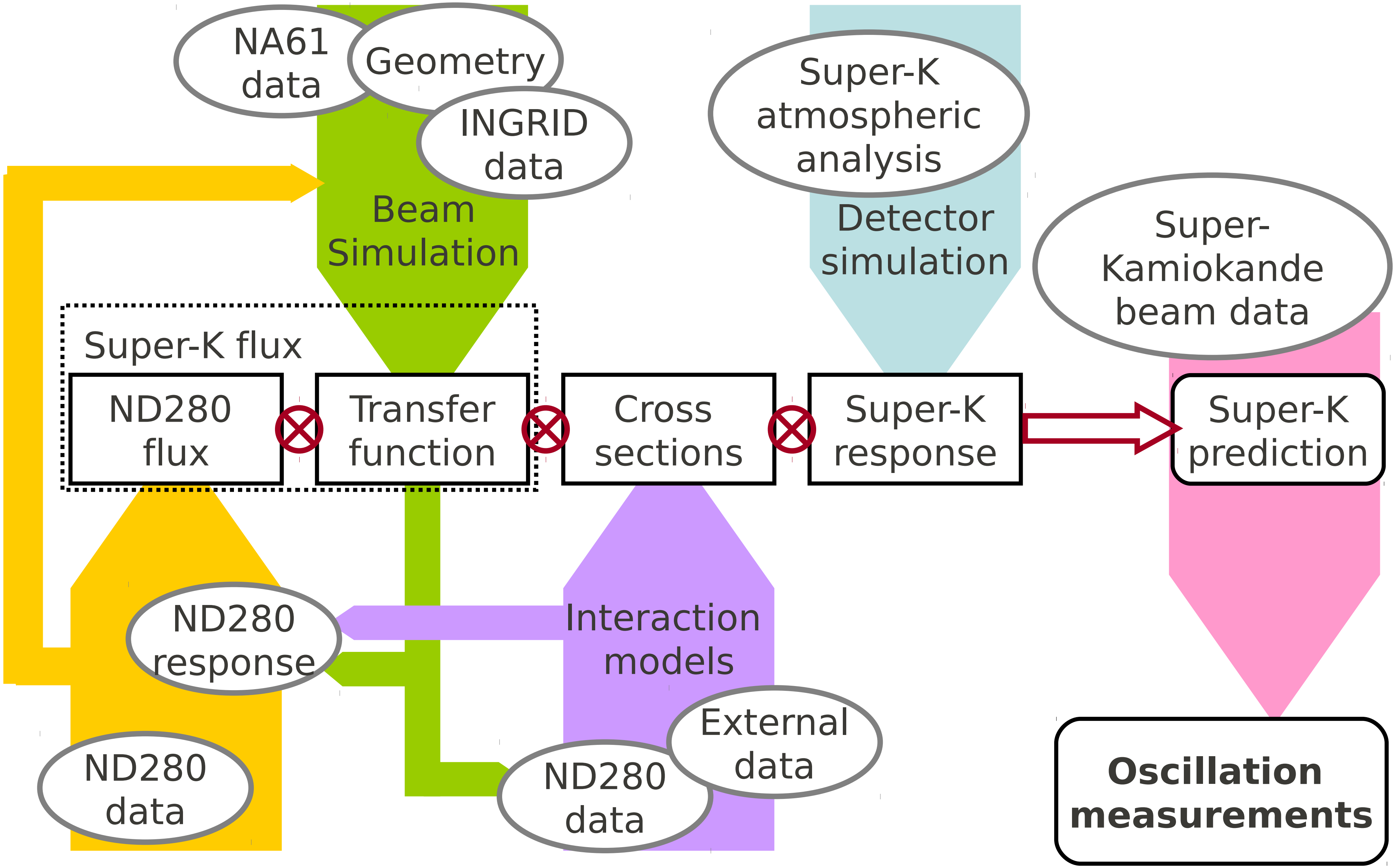
Design Report Era Systematics		
Event Normalization	Red	10%
Background (non-QE)	Green	20%
Energy Scale	Blue	4%
Spectrum Shape (linear)	Purple	20%
Spectrum Peak Width	Lt. Blue	10%

T2K Analysis Strategy

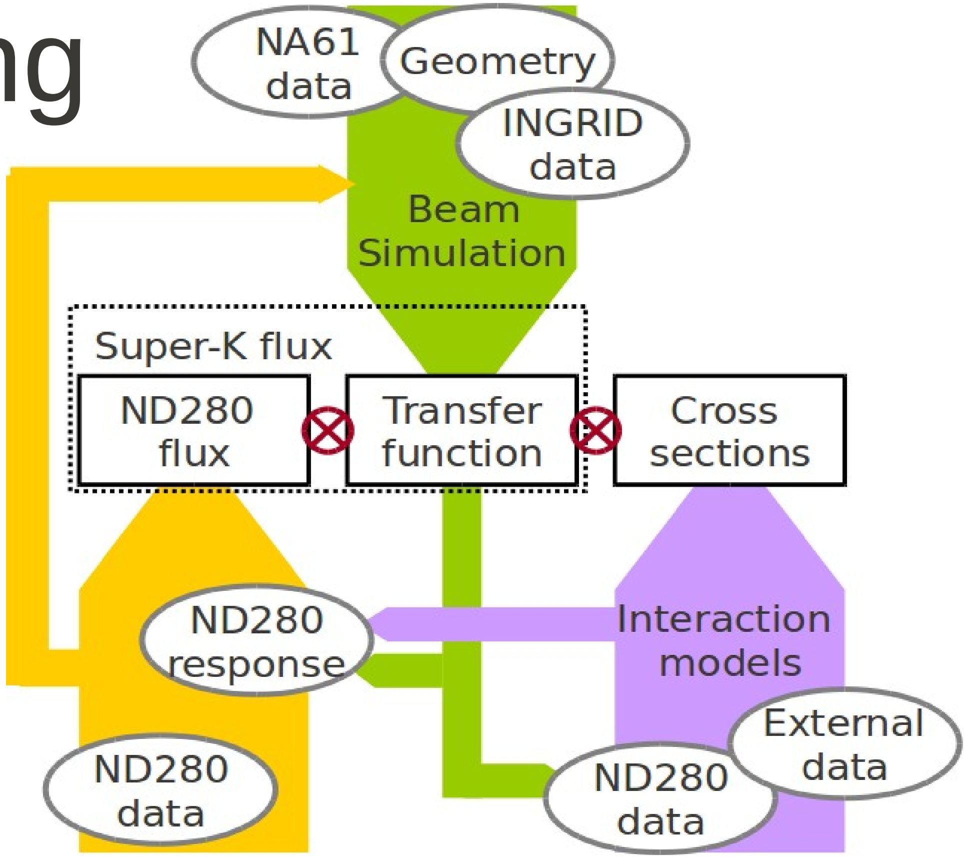
- We plan to bring overwhelming force on multiple fronts to beat down systematics, perhaps out of proportion to their actual impact

Systematic uncertainties place flowers in rifles of T2K Collaborators outside the US Pentagon (1967), (photo: Bernie Boston)

- Our tools of choice
  - Experimental design: primarily off-axis beam, partial cancellations from near-to-far comparisons
  - “Redundant” methods: build complete data-based models for beam, neutrino interactions, detectors to cross-compare and study systematics

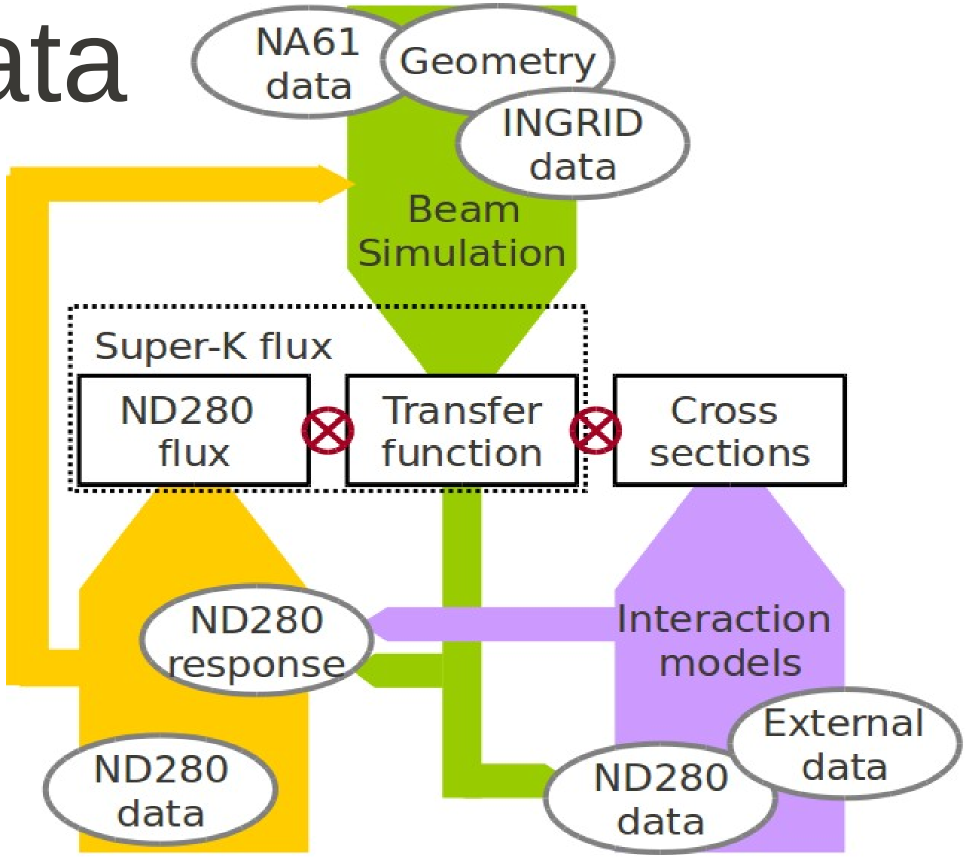

NA61 data
Geometry
INGRID data
Beam Simulation
Super-K atmospheric analysis
Detector simulation
Super-Kamiokande beam data
Super-K flux
ND280 flux
Transfer function
Cross sections
Super-K response
Super-K prediction
ND280 response
Interaction models
External data
ND280 data
ND280 data
Oscillation measurements

Example: Flux Tuning



- Beam simulation gives a prediction for flux
  - Protons monitors provide initial proton direction
  - Hadron production tuned for consistency with NA61 (T2K target replica) data
  - Muon monitor crosscheck
- INGRID (on axis) detector determines beam direction
  - Rate also constrains flux
- Off-axis near detector flux can be used with near/far ratio or "matrix method"
  - May also be used to tune beam simulation

Example: ND280 Data



- ND280 off-axis detectors measure NC π^0 and ν_μ CCQE on Water
  - Both of these can be predicted in an interaction model
  - Tune interaction model to reproduce observation in ND280
- Interaction model then gives a prediction for background with flux at Super-K
- Tuning of cross-sections will actually be much more comprehensive
  - ND280 can reconstruct a broad variety of final states

Summary

Prospects for 2011

- Next run starts Nov 2010
- We are planning for a run with 150 kW × 10^7s by July 2011
  - Sensitivity to $\sin^2 2\theta_{13}$ ~ 0.05
- The early appearance results are still statistics limited
  - Disappearance results will be more affected
  - We'll have time to explore these techniques and see which are the most effective