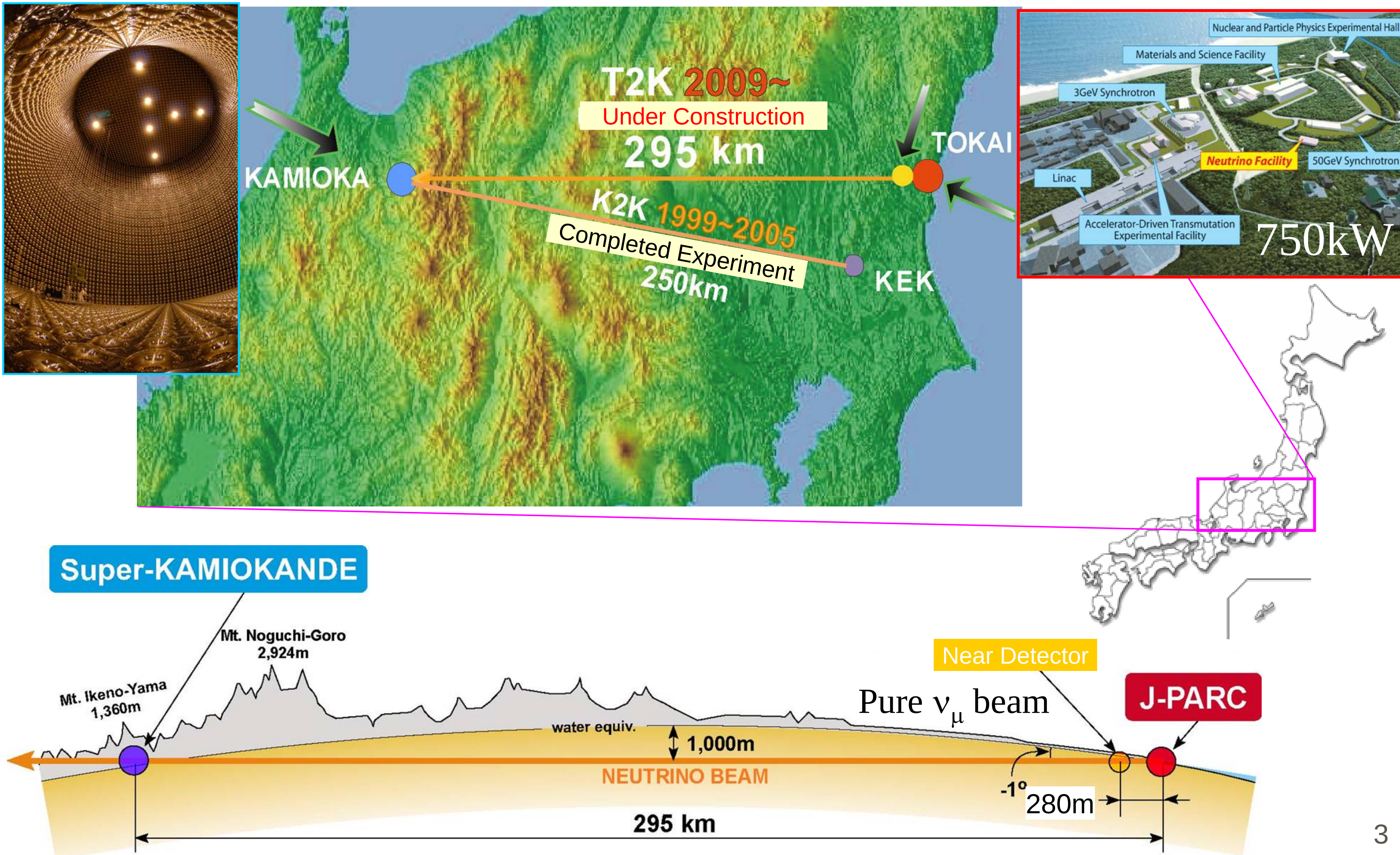
K2K, T2K
および
将来のニュートリノ実験

T. Nakadaira
(KEK)
For T2K collaboration

Neutrino 2006 Talks on Oscillation exp.

- K2K (1999 - 2005)
  "K2K Cross Section Measurements", R. Gran
- T2K (2009 -)
  "T2K and beyond", T. Nakadaira
- CNGS (2006 -)
  "CNGS", C. Sirignano
- Noνa (*2010/2011?* -)
  "Future Experiments (NOVA)", P. Shanahan
- *Other future experiments*
  "Superbeams (physics and expts)", B. Marciano
  "Neutrino Factories & Beta Beams", L. Camillieri
- c.f.
  "Secondary Production (HARP, MIPP, E910)", G. Mills

K2K & T2K LBL ν experiment



K2K Cross Section Measurements

Rik Gran
U. Minnesota Duluth, U. Washington

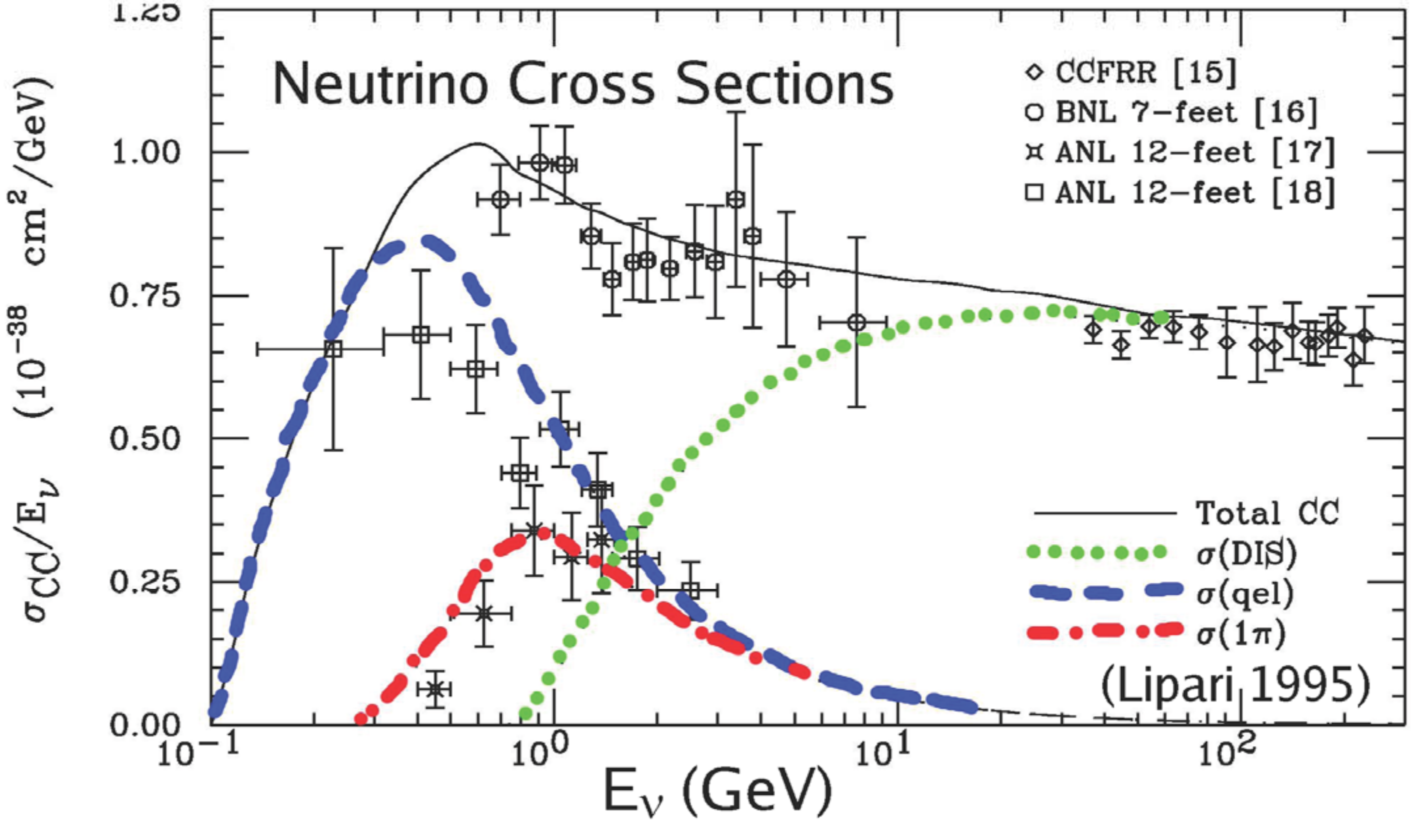
For the K2K collaboration

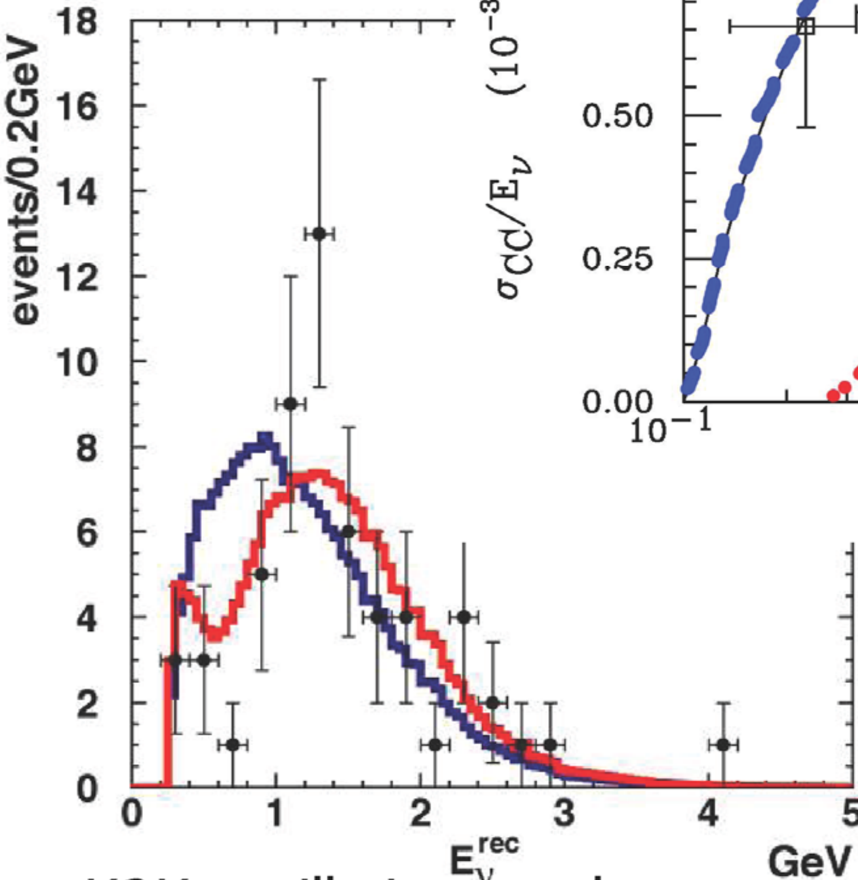
1. NC single π^0/(All CC) in 1KT Cherenkov detector
2. CC-Coherent Pion Production in SciBar detector
3. MA-QE from shape fit to SciFi detector data

(4. Final results from mu-disappearance and e-appearance)

Motivations

Improve knowledge of Cross Sections





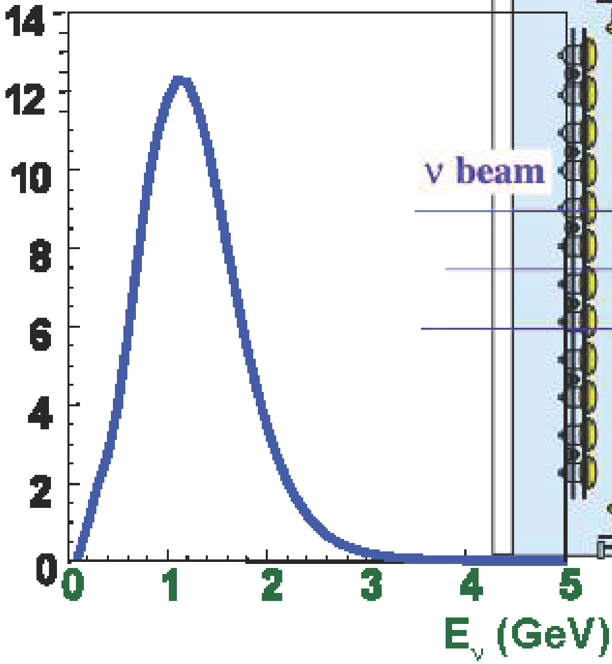
K2K oscillation result

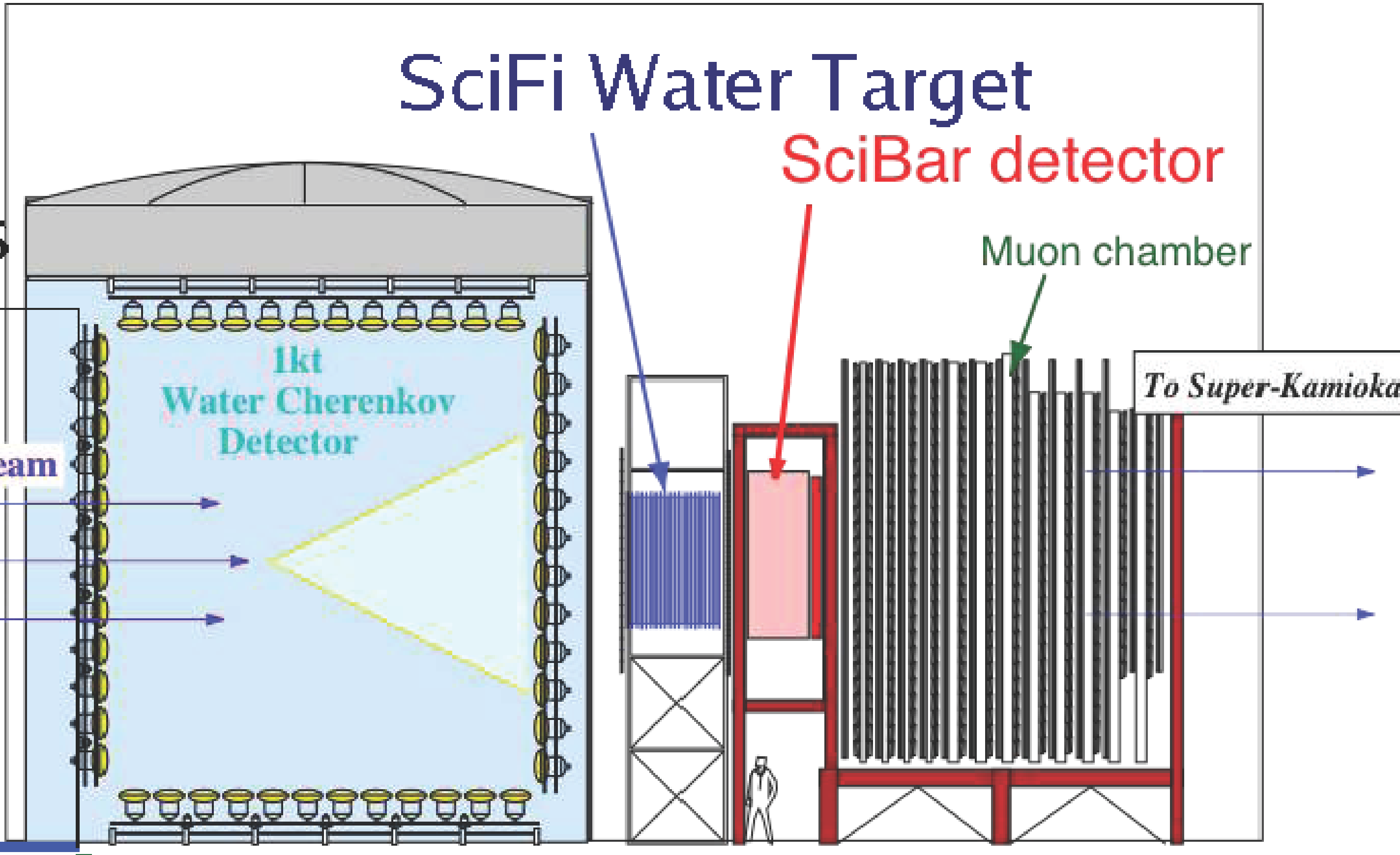
Cross Sections and Nuclear Effects are important for extracting oscillation parameters from nu-mu disappearance nu-e appearance experiments.

K2K beam and near detectors

98% pure ν_μ beam   target materials: H_2O, HC, Fe

ν_μ energies at the K2K near detectors



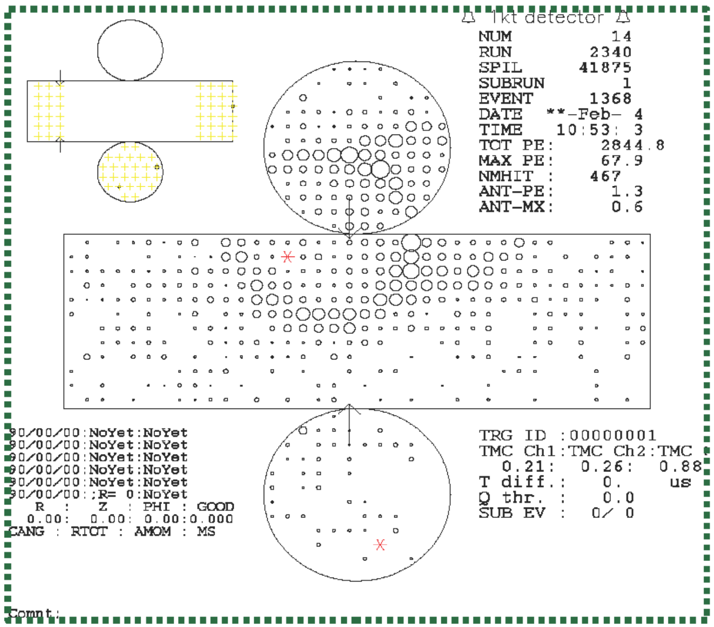


NC single π^0 in the water Cherenkov detector

$$\nu + N \rightarrow \nu + N + \pi^0$$

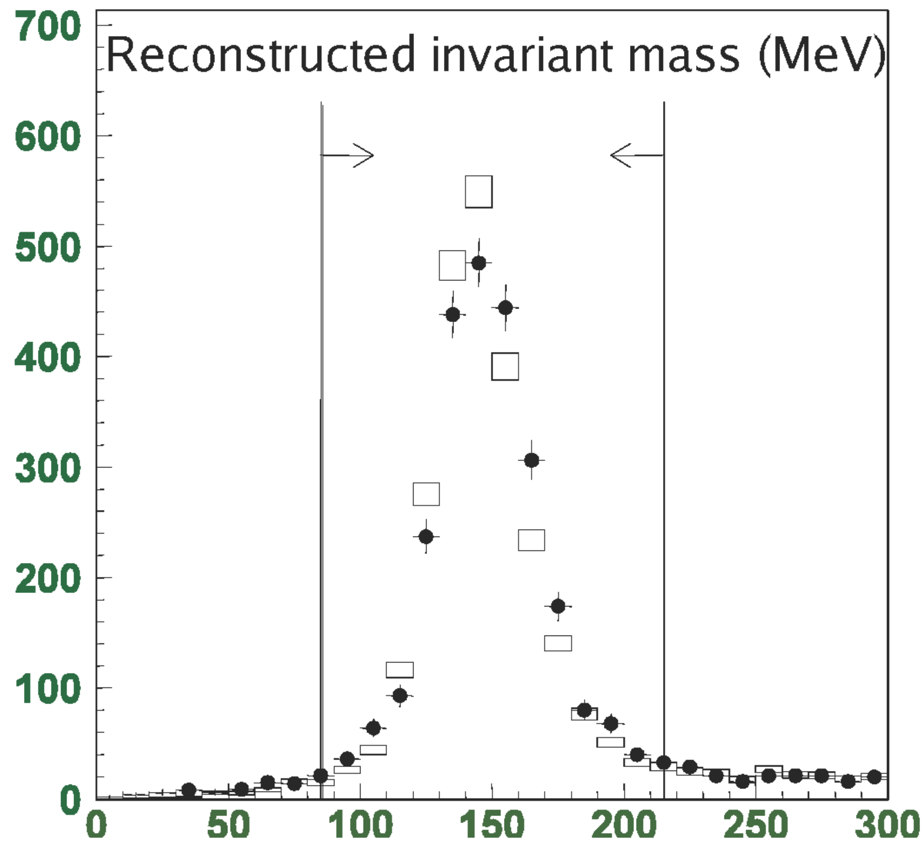
Neutral Current (no muon),

recoil proton below 1 GeV/c threshold (no proton)



Typical π^0 candidate

has two electron-like rings



with the right invariant mass

NC single π^0 fraction result

After efficiency and background corrections

Create ratio with single-ring muon-like events as the reference.

$$\frac{\text{signal in 25 ton fiducial volume} \quad (3.61 \pm 0.07 \text{ stat} \pm 0.36 \text{ syst}) \times 10^3}{\text{all muon-like in 25t fiducial volume} \quad (5.65 \pm 0.03 \text{ stat} \pm 0.26 \text{ syst}) \times 10^4}$$

NC1π^0/μ ratio at <Eν> ~ 1.3 GeV

= 0.064 $\pm$ 0.001 stat $\pm$ 0.007 syst.

(Prediction from our MC = 0.065)

Major sources of systematic error:

DIS model dependence 5.6% NC/CC cross section 3.2%

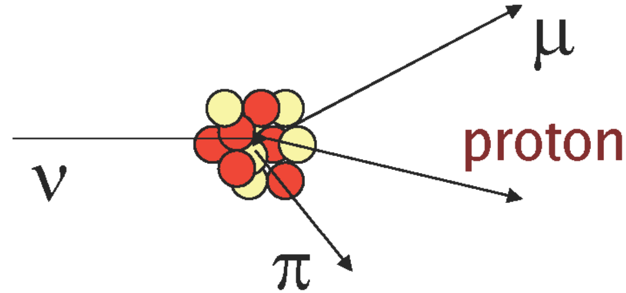
Ring counting 5.4% e-like ring particle ID 4.2%

(In mu-like denominator only: vertex reconstruction 4%)

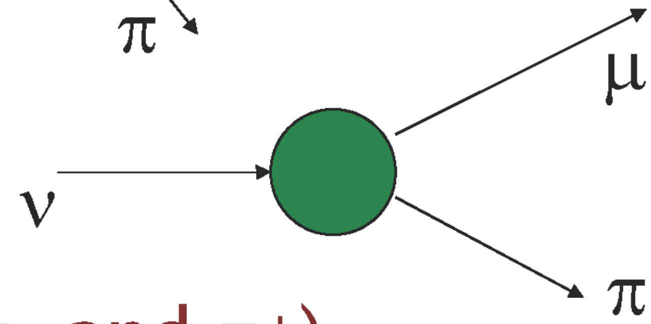
S. Nakayama, et al., Phys. Lett. B 619 (2005)

CC coherent pion selection

Resonant pion production
is scattering from nucleon



Coherent pion scatters
from entire nucleus.



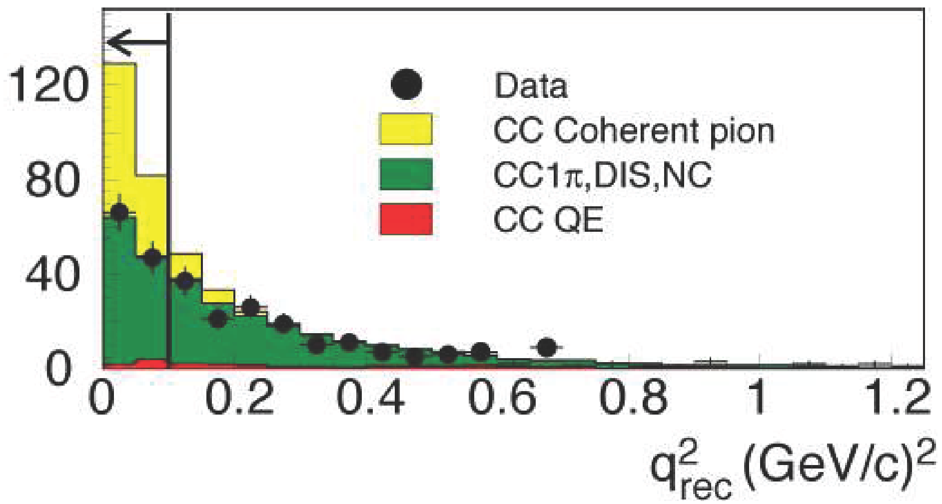
No recoil nucleon (see only μ^- and π^+)
Very low momentum transfer (low Q^2, low angle).

Several recent experiments see disagreement
between data and expectation in very low Q^2 region.

Does CC coherent pion contribute to disagreement?

CC coherent pion results

M. Hasegawa, et al., Phys. Rev. Lett. 95 (2005)



Select the 113 events with $Q^2_{rec} < 0.1$ (GeV/c)2

Coherent Pion content expected
21.1% efficiency 47.1% purity

Mesurement relative to all CC events

$$\frac{\sigma_{CCcoh\pi}}{\sigma_{All\ CC}} = (0.04 \pm 0.29\ \text{stat}\ ^{+0.32}_{-0.35}\ \text{syst}) \times 10^{-2}$$

Compute upper bound

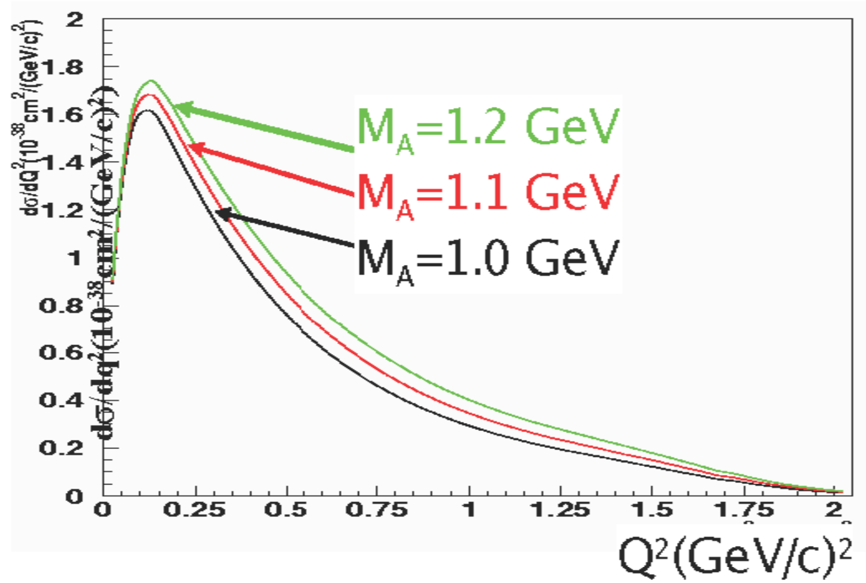
$$\frac{\sigma_{CCcoh\pi}}{\sigma_{All\ CC}} < 0.60 \times 10^{-2}\ \text{(at 90\% CL)}$$

This is ~30% of Rein-Sehgal model

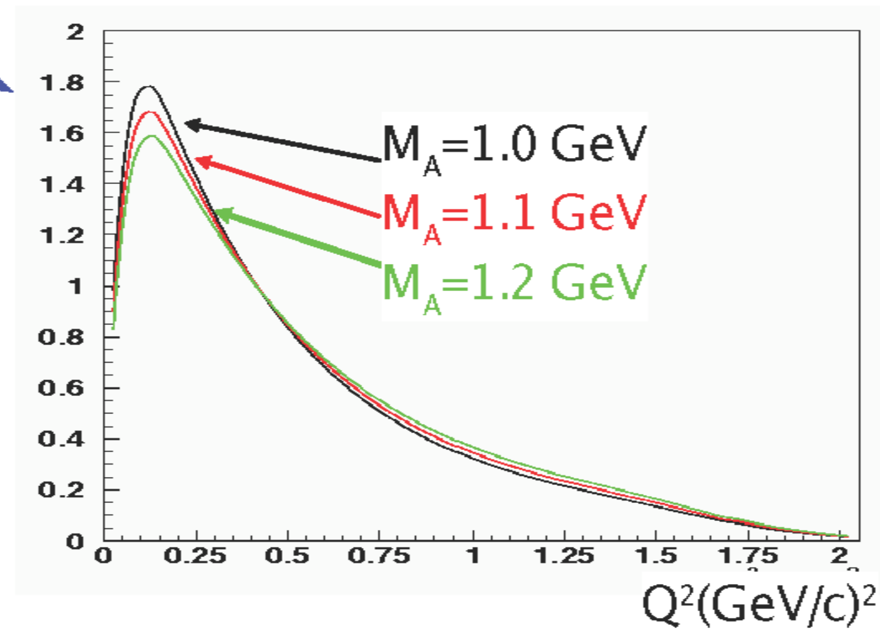
Largest systematics: $\sigma_{\text{Resonant Pion}}$ and pion reinteractions in carbon

Axial mass and shape of Q^2 distribution

Absolute
Quasi-elastic
Cross section
(includes normalization)



This analysis: Shape Only

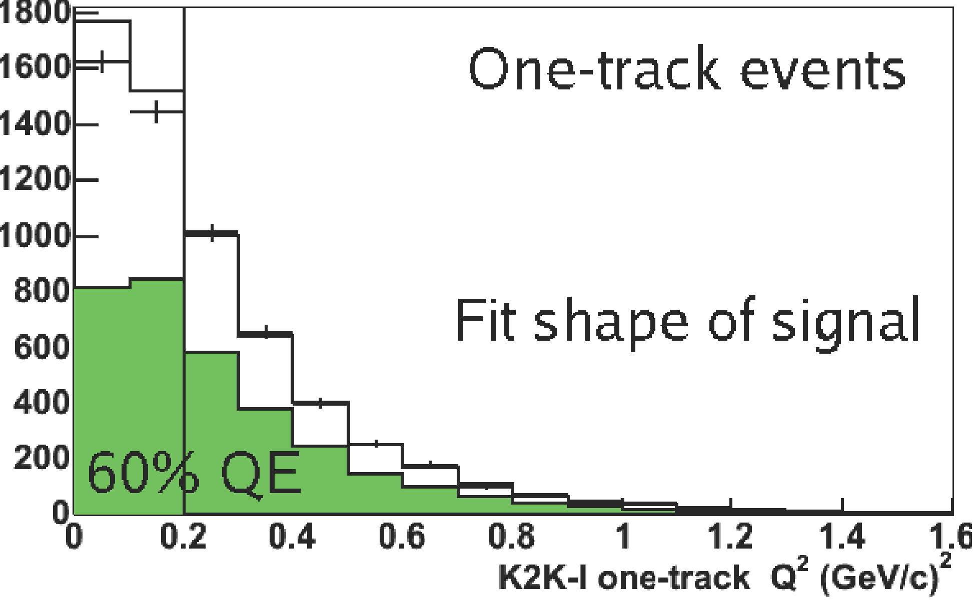


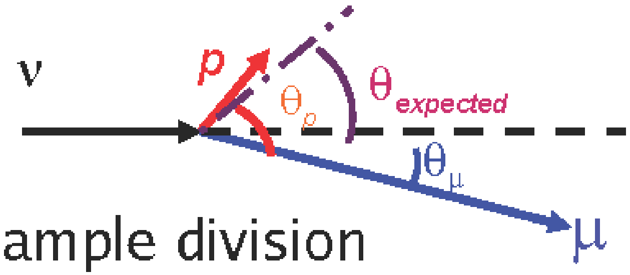
Measure Q^2 for each event
still assuming QE interaction

$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

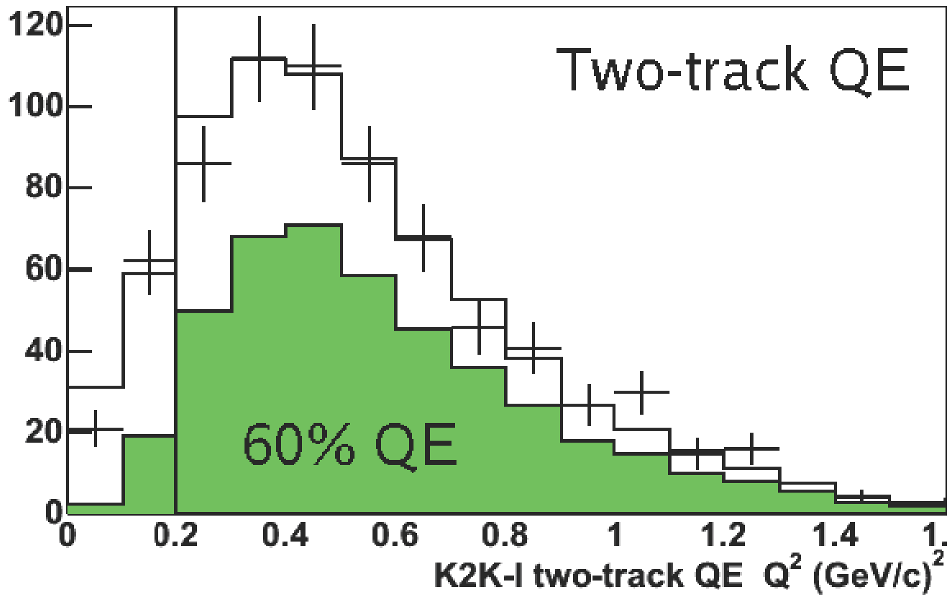
$$Q^2 = -2E_\nu (E_\mu - p_\mu \cos\theta_\mu) + m_\mu^2$$

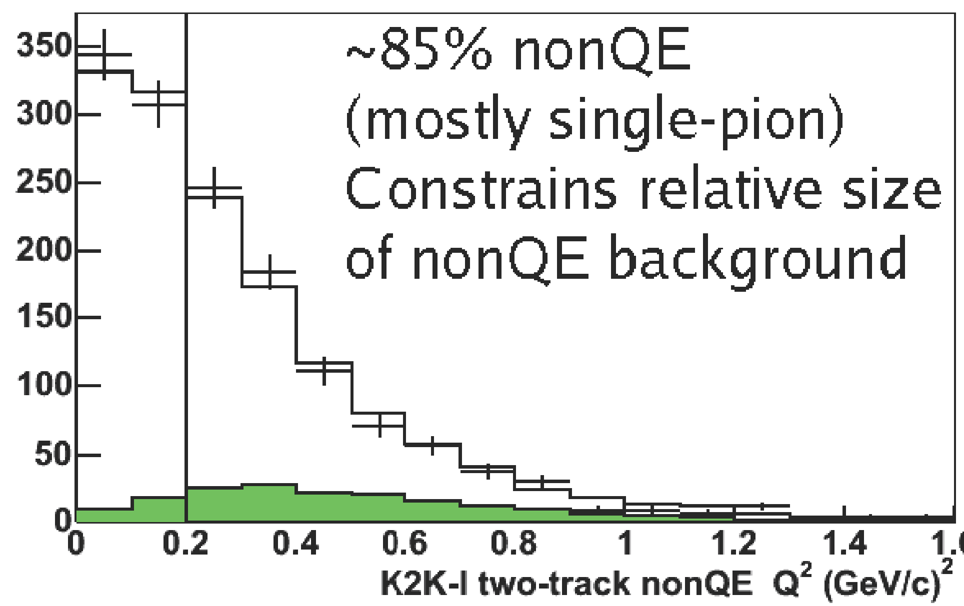
Reconstructed Q^2 for subsamples (after fitting)





Subsample division
(as in slides 9 and 10 but no PID)





Results for effective Quasi-elastic M_A on Oxygen

M_A = 1.20±0.12 GeV (χ^2 = 261/235 dof) shape only

Can be compared with Deuterium bubble chamber results (primarily also shape fits) with older vector form factors
K2K result M_A = 1.23±0.12 Deuterium M_A ~ 1.03±0.03

Most significant errors:	
Muon momentum scale	0.07
Relative flux and normalization	0.06
MA 1π	0.03
relative nonQE fraction	0.03
Nuclear rescattering	0.03
Statistics only	0.03

Our data has a flatter Q^2 spectrum than MC prediction

K2K default MC uses M_A=1.1 GeV dipole vector form factors

RG, Jeon, et al., submitted to PRD, hep-ex/0603034

Final neutrino oscillation results using the K2K data

- ν_μ disappearance (hep-ex/0606032)

HARP hadron measurements
for new far/near extrapolation

Updated Super-Kamiokande reconstruction

- Electron neutrino appearance analysis now uses entire data set.

→ “K2Kにおける電子ニュートリノ出現の探索”, 山本真平

(Other smaller refinements)

A Review of Secondary Production Measurements for ν Flux Determination: *E910, HARP, and MIPP*

Motivations

Experiments

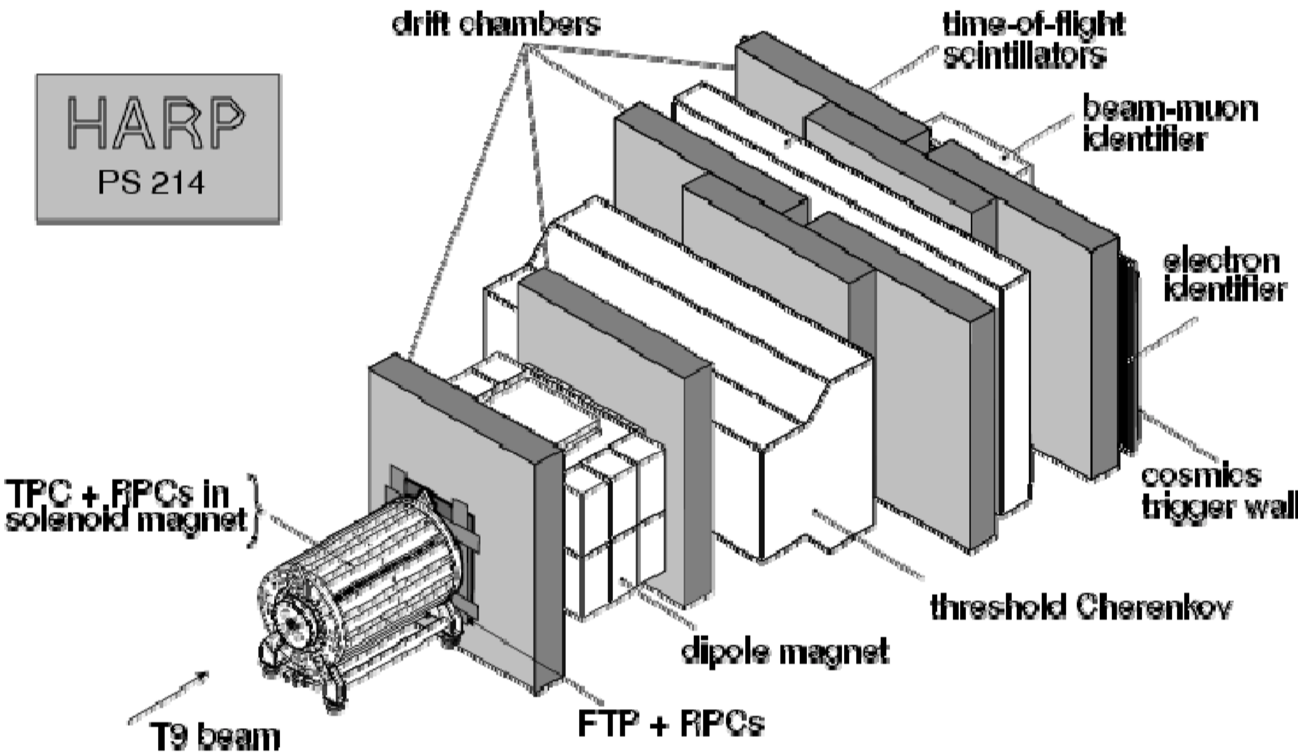
Results & Implications

Outlook

Geoffrey Mills
Los Alamos National Laboratory

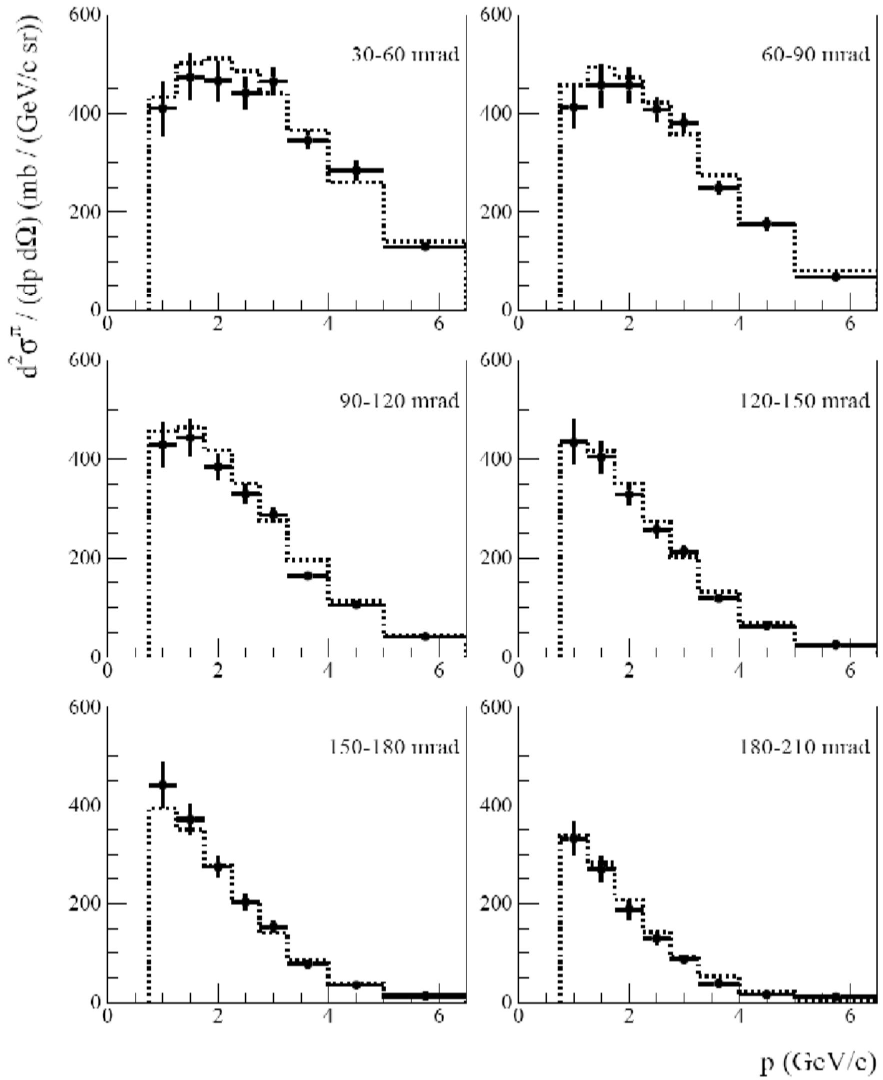
CERN/HARP Apparatus

400 M Triggers 1.5/**3**/**5**/**8**/8.9/**12**/12.9/**15 GeV/c Beam**
H/D/Be/C/N/O/Al/Cu/Sn/Ta/Pb Targets (5%,100%)
plus MiniBooNE and K2K runs



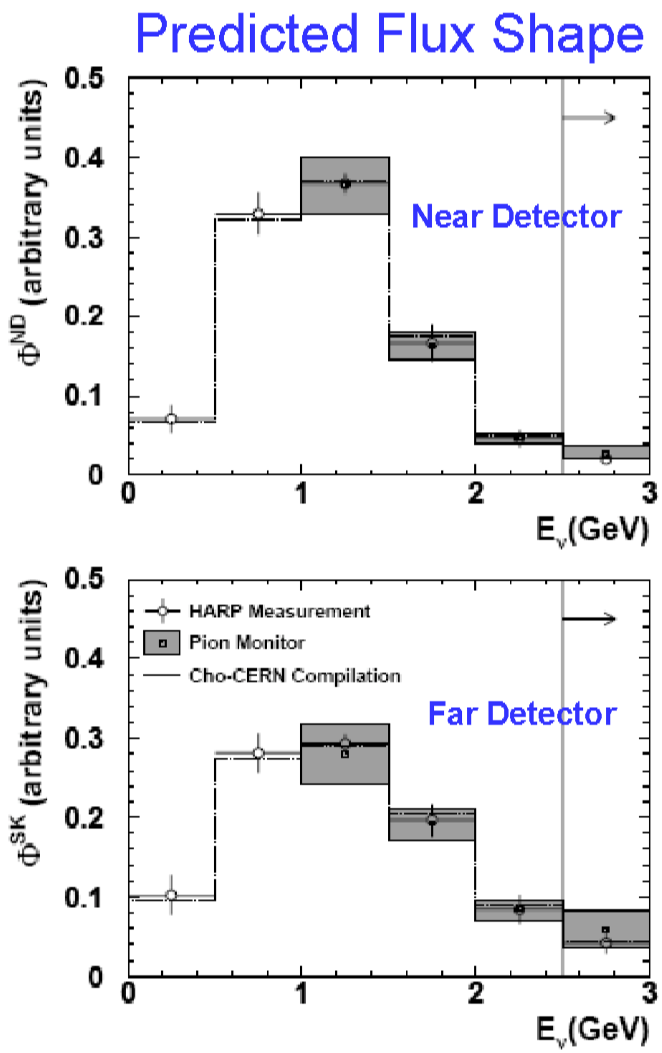
HARP Results: 12.9 GeV/c Al Thin Target Data

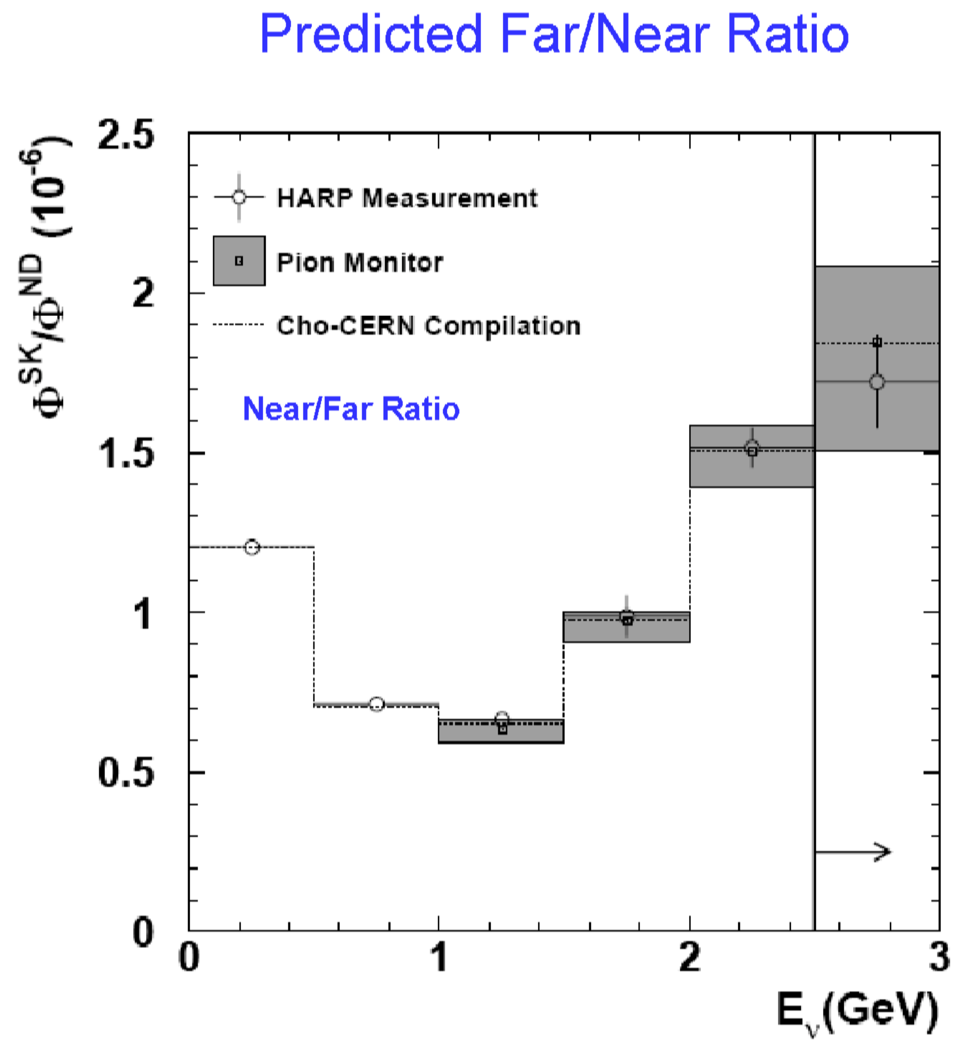
- Directly applicable to K2K's results (See Richard Gran's talk)
- K2K's oscillation result is mostly insensitive to this because they measure a *near/far ratio*



Nucl.Phys.B732:1-45,2006
hep-ex/0510039

K2K Near/Far Ratio

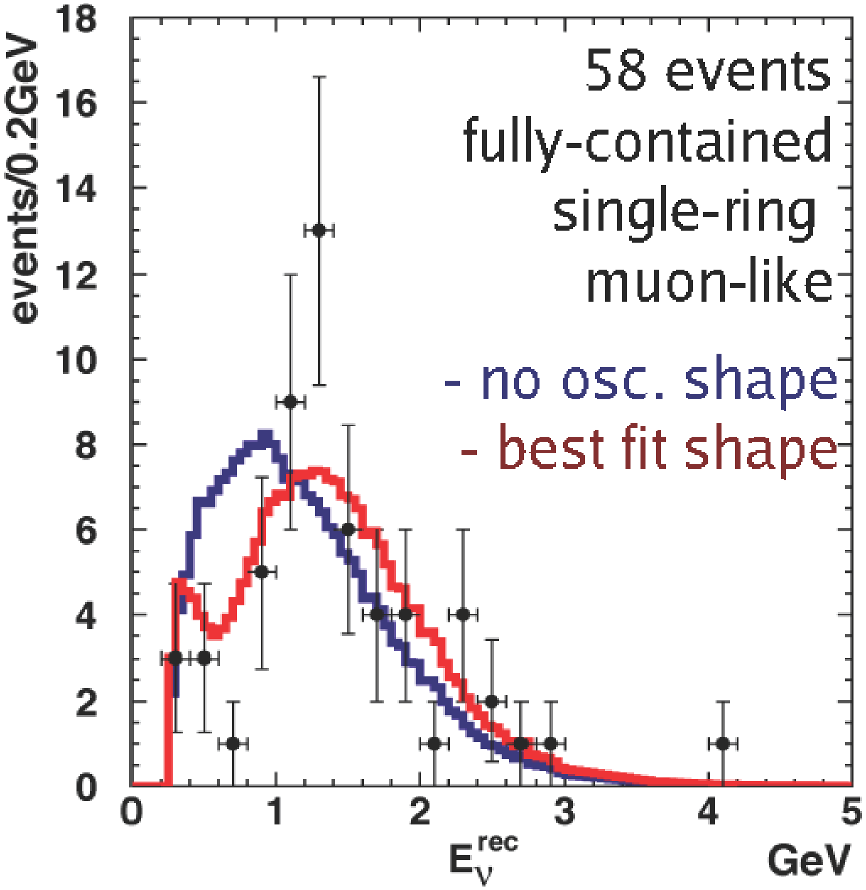




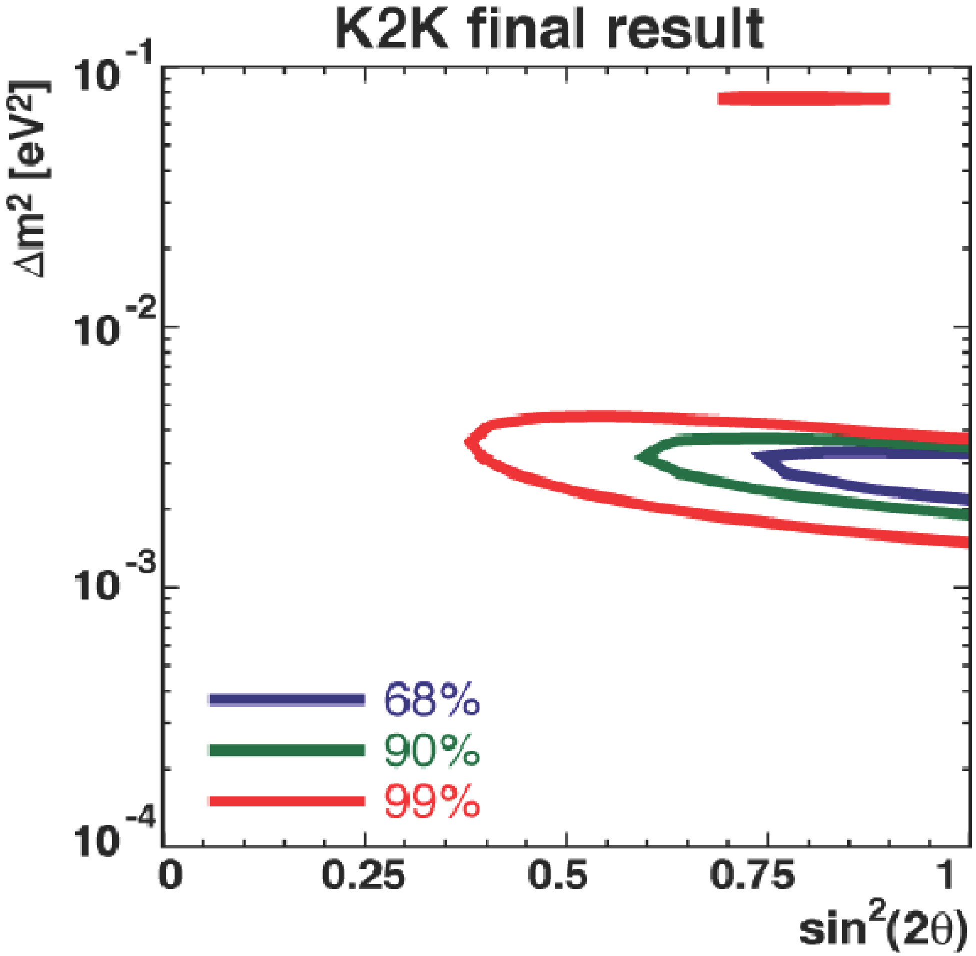
Near/far ratio errors are greatly reduced with the inclusion of Harp Data

Final ν_μ disappearance result

All neutrino events in SuperK
Observed 112, expected 158 $^{+9.2}_{-8.6}$



Ahn, et al. sub. to PRD hep-ex/0606032



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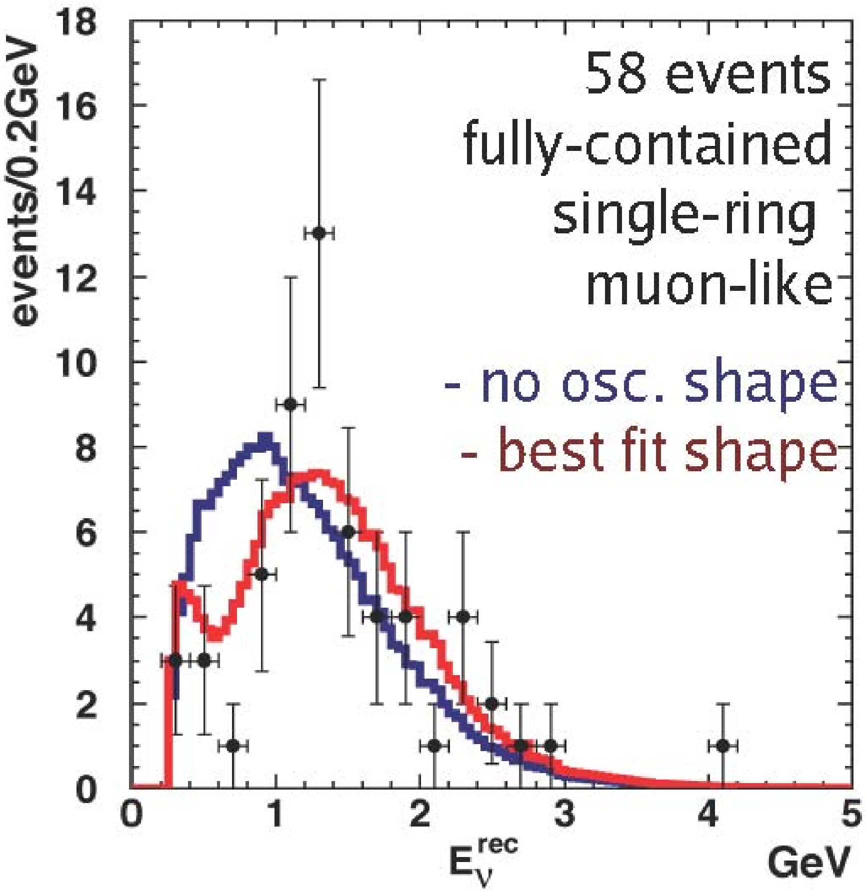

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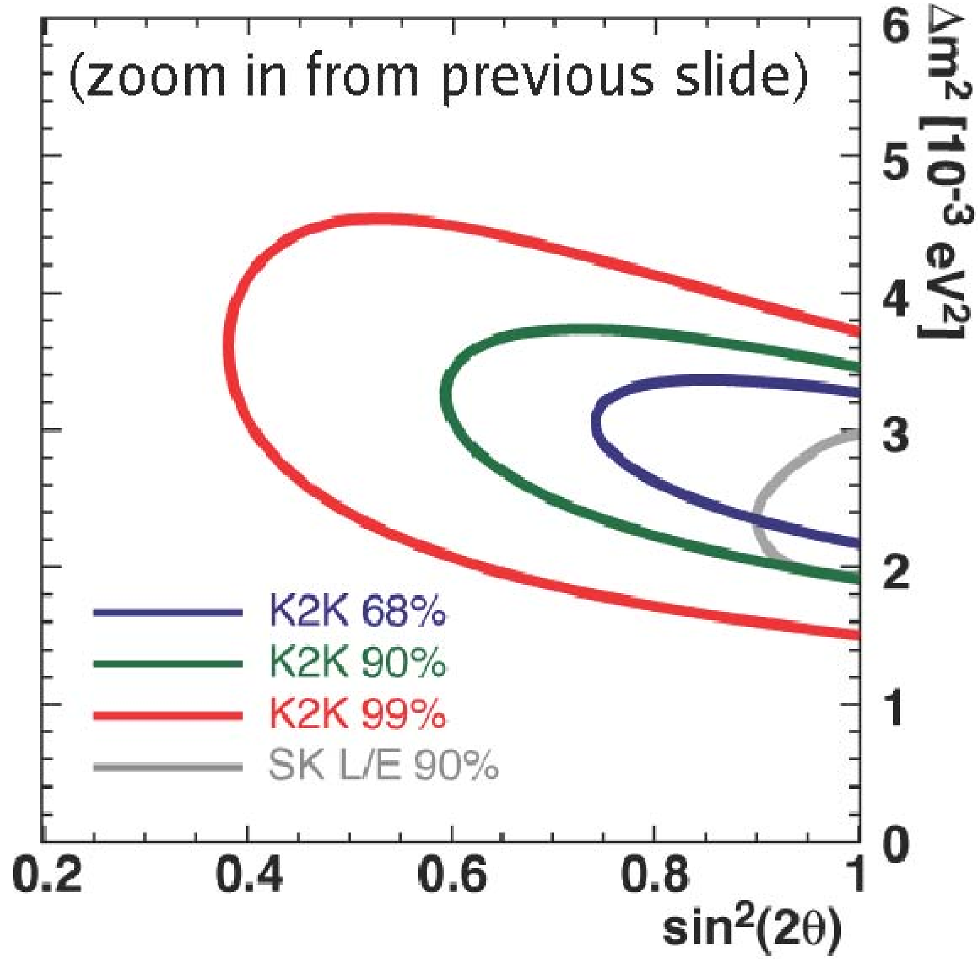


Maximal mixing 90% CL
$1.9 \times 10^{-3} < \Delta m^2 < 3.5 \times 10^{-3}$ eV^2
Best fit in physical region 2.8×10^{-3}

T2K and beyond

T. Nakadaira

(KEK)

For T2K collaboration

Physics @ T2K PHASE-I

- ν mixing matrix: $\theta_{13} \ll \theta_{12}, \theta_{23}$

Flavor eigenstate

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

Mass eigenstate

SK Atm., K2K, MINOS
$\theta_{23} \sim 45°$
$\Delta m^2_{23} \sim 2.5 \times 10^{-3}$ [eV^2]

θ_{13}, δ are still unknown.

Solar, KamLAND
$\theta_{12} \sim 34°$
$\Delta m^2_{12} \sim 8 \times 10^{-5}$ [eV^2]

- T2K-I searches for $\nu_\mu \rightarrow \nu_e$.

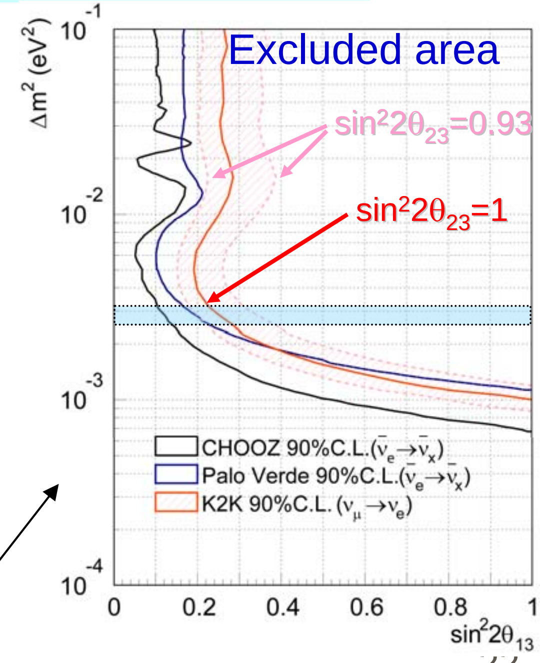
$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\Delta m^2_{31} L/4E\right)$$
$$\mp 4J_r \sin\delta\left(\Delta m^2_{21}L/2E\right)\sin^2\left(\Delta m^2_{31}L/4E\right) + \ldots$$

– for ν
+ for $\bar{\nu}$

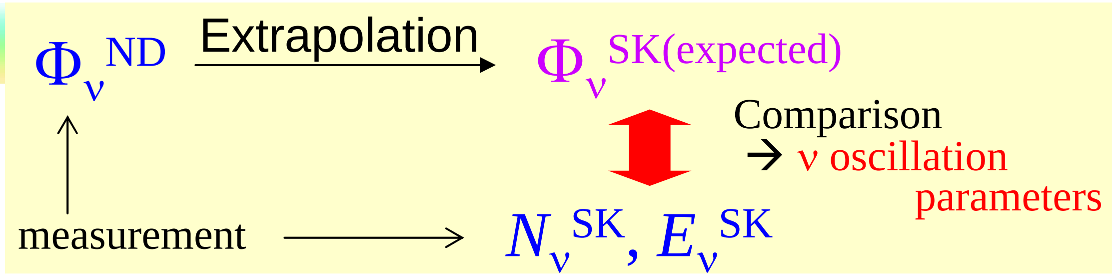
(Approximation @ $\Delta m^2_{31}L/4E \sim \pi/2$, $\Delta m^2_{32} \sim \Delta m^2_{31}$)

$$J_r \equiv \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}$$

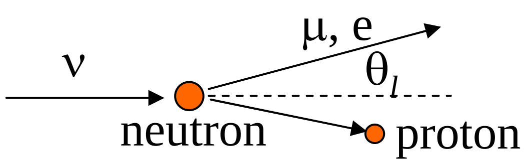
- Size of *CP* asymmetry depends on θ_{13}!!
  - *Matter effect is small in (E_ν, L) in T2K.*
  - $\Delta m^2_{13} = \Delta m^2_{23} - \Delta m^2_{12} \sim 2.5 \times 10^{-3}$ [eV^2] → $\sin^2 2\theta_{13} < 0.15$



Principle of T2K … Quite similar to K2K

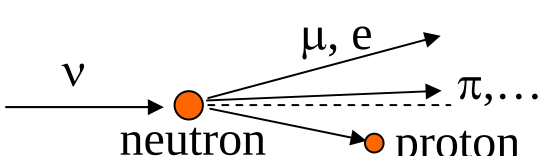


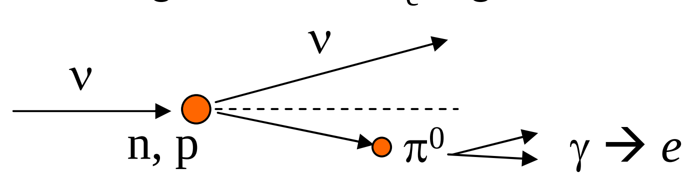
- Δm^2 = ~2.5x10^{-3}[eV^2], L=295km
  →1st Oscillation max. @ E_ν ~ 0.6 GeV
- Use Sub-GeV ν_μ beam
  - CC-QE is dominant process in ν-N interactions.
  - Neutrino Energy reconstruction by CC-QE kinematics … δE/E ~ 10%



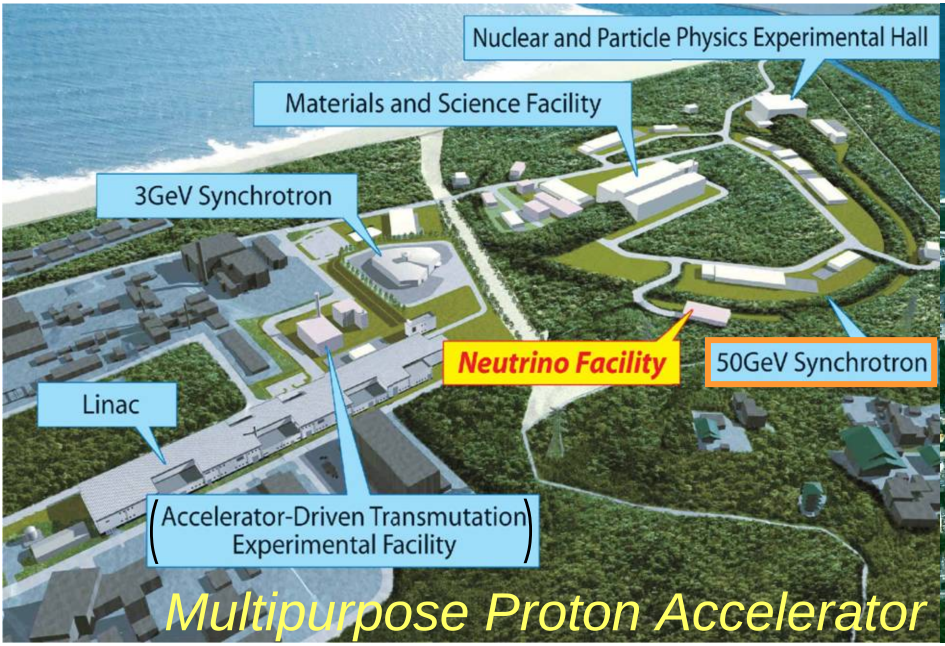
$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos\theta_l}$$

  - Fraction of high energy ν (Eν ~ a few GeV) is required to be small.
    - CC-non QE events are background for Eν reconstruction.
    - π^0 from NC events are dominant background for ν_e signal.





Japan Proton Accelerator Research Complex

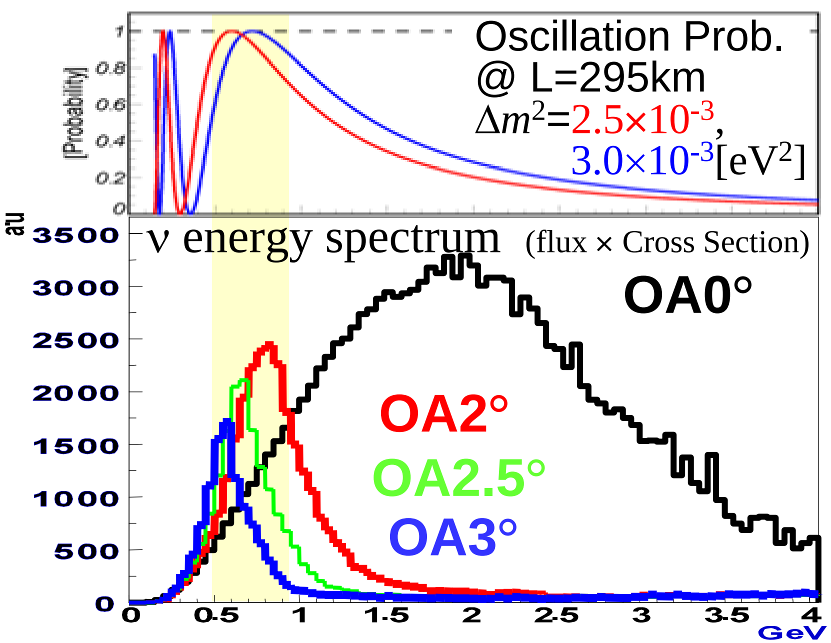


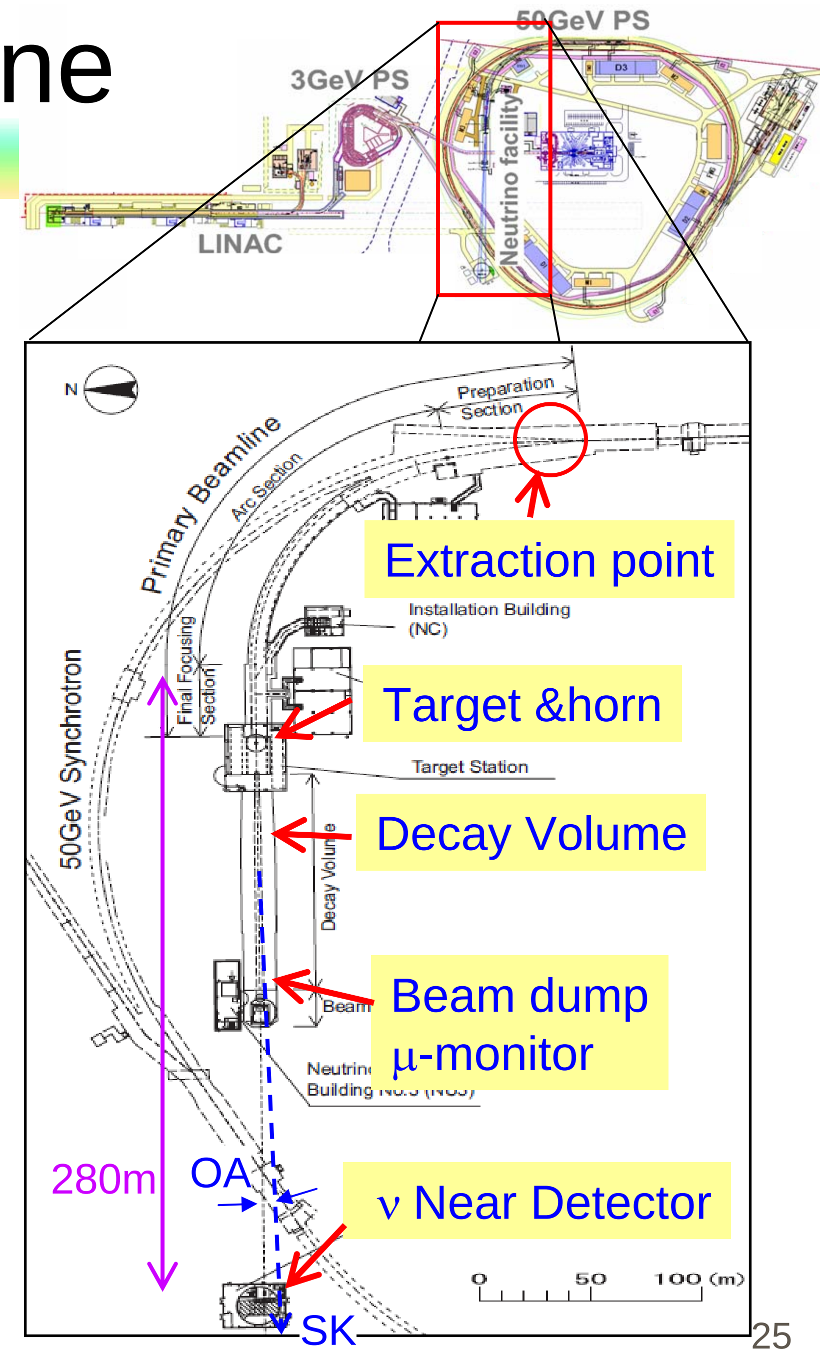
- 400MeV LINAC (200MeV@T=0)
  → 1MW 3GeV RCS
  → 0.75MW 50GeV MR (30GeV @ T=0)
  1×10^{21} protons/year (130days) [in 50GeV operation.]
  c.f. K2K: ~1×10^{20} POT(6 years including 1 year interruption)

Joint project by JAEA (former JAERI) and KEK

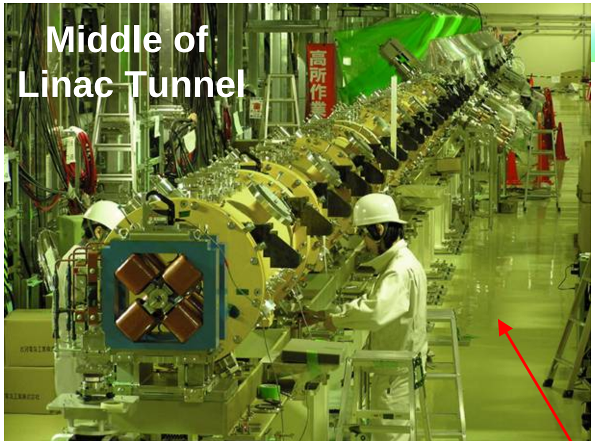
J-PARC ν-beam line

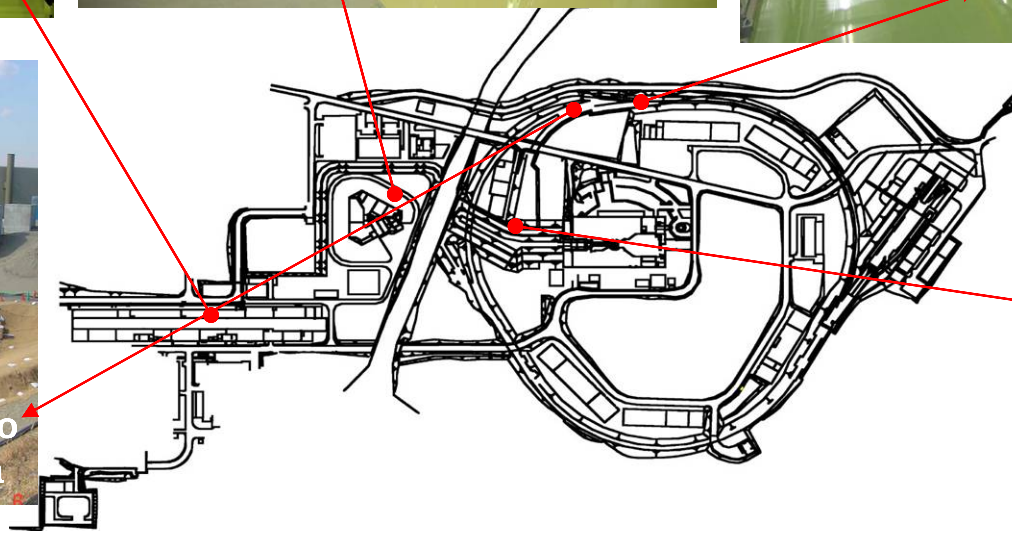
- Conventional ν_μ beam:
  - protons + Graphite target $\rightarrow$ pions
  - π^+ or π^- is focused selectively by 3 electromagnetic horns.
    $\pi^+ \rightarrow \mu^+ + \nu_\mu$ or $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$
- Pseudo-Monochromatic beam by Off-Axis method: (OA = 2° ~ 2.5°)
  - Set peak of (flux × σ_{CC}) @ oscillation max.
  - Fraction of high energy neutrino is small.

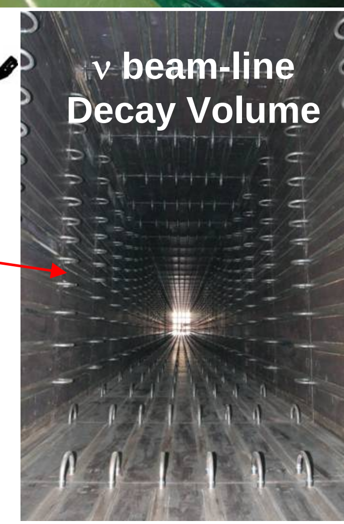




Accelerator construction status







Problem in RF system for MR:

Some of the RF cores discharges with 15kV/gap in long term tests.

← The failure components have already been identified.

* The MR commissioning will start with current RF system on schedule in low power.
* The parallel R&D work is in progress aiming to replacing RF system around 2010.

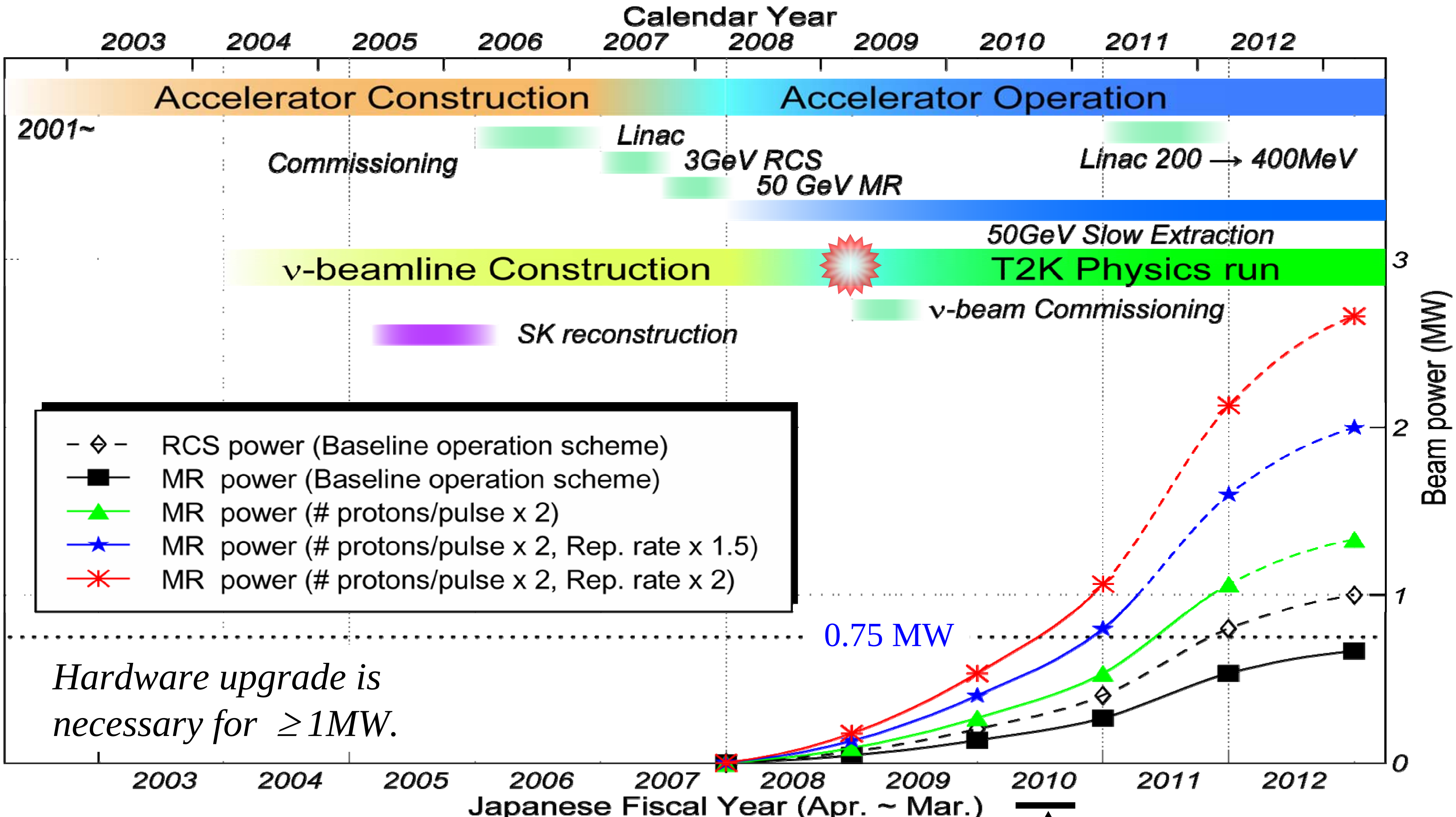
ν beam-line Construction is going well !

- Superconducting combined function magnet for Proton beam line.
  - First module of production version
  - Cool down test (4.6 K)
  - Excited to 7728A (50GeV operation+5% margin.) w/o quench.

- Mechanical Prototype of Graphite Target
  - Enough thermal shock resistance against 0.75MW beam.
  - He-gas cooling system is constructed.

- Prototype of 1^{st} Horn
  - Test operation with 250kA current
  - So far, There is no problem up with this test.

J-PARC schedule & Beam Power estimation

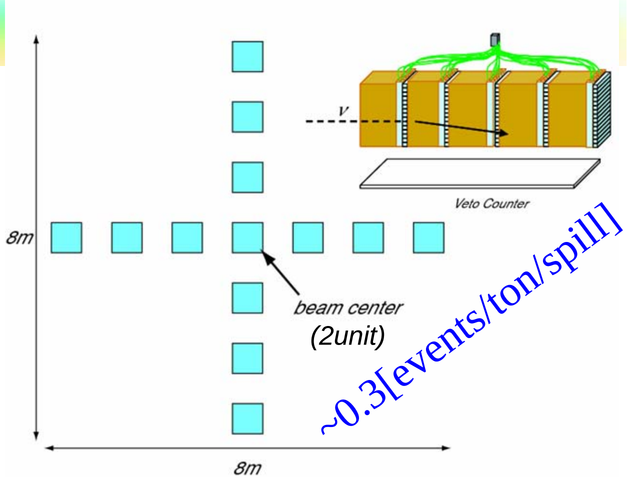


Hardware upgrade is necessary for $\geq$ 1MW.

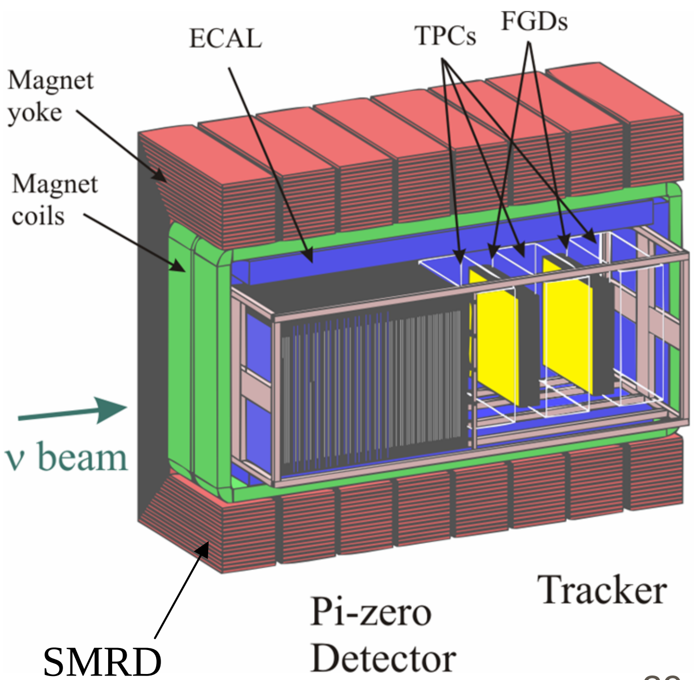
Target date for new RF system installation.

ν Near Detector @ 280m

- On-axis detector
  - Measure ν-beam profile
    → ν-beam direction at 1mrad precision.
  - iron - scintillator stacks × 14 units



- Off-axis detector: In Magnet (*B=0.2T*)
  - Measure ν-flux in SK direction : $\Phi_\nu^{ND}(E_\nu)$.
    - Measure ν_μ, $\overline{\nu}_\mu$ and $\nu_e+\overline{\nu}_e$ fluxes separately.
    - Neutrino Energy ← CC-QE kinematics.
  - Cross sections of ν interactions
    - CC-1π/CC-QE … BG for E_ν reconstruction
    - NC-π^0 production … BG for ν_e detection

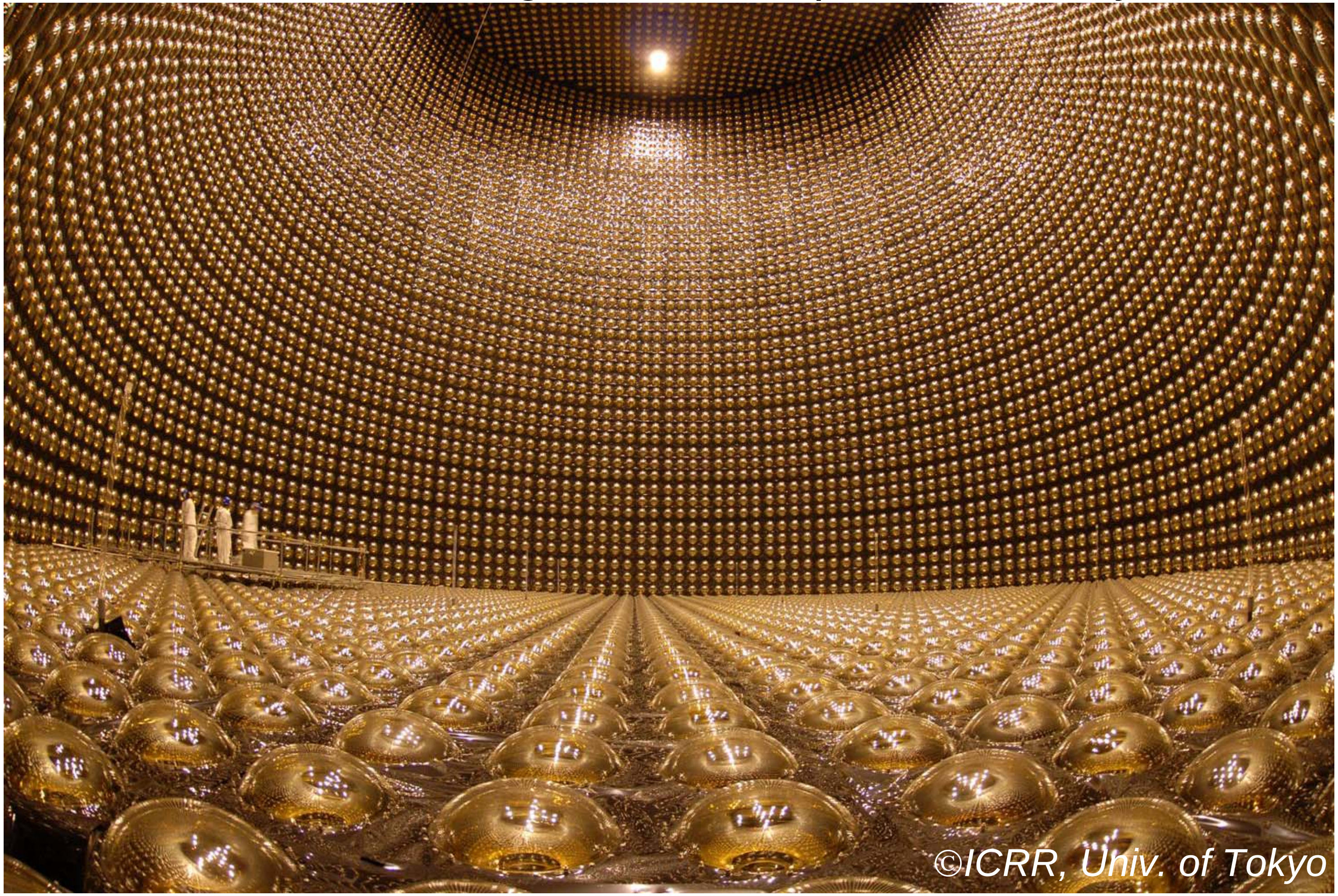


Reuse of UA1 magnet

Far Detector: SK-III

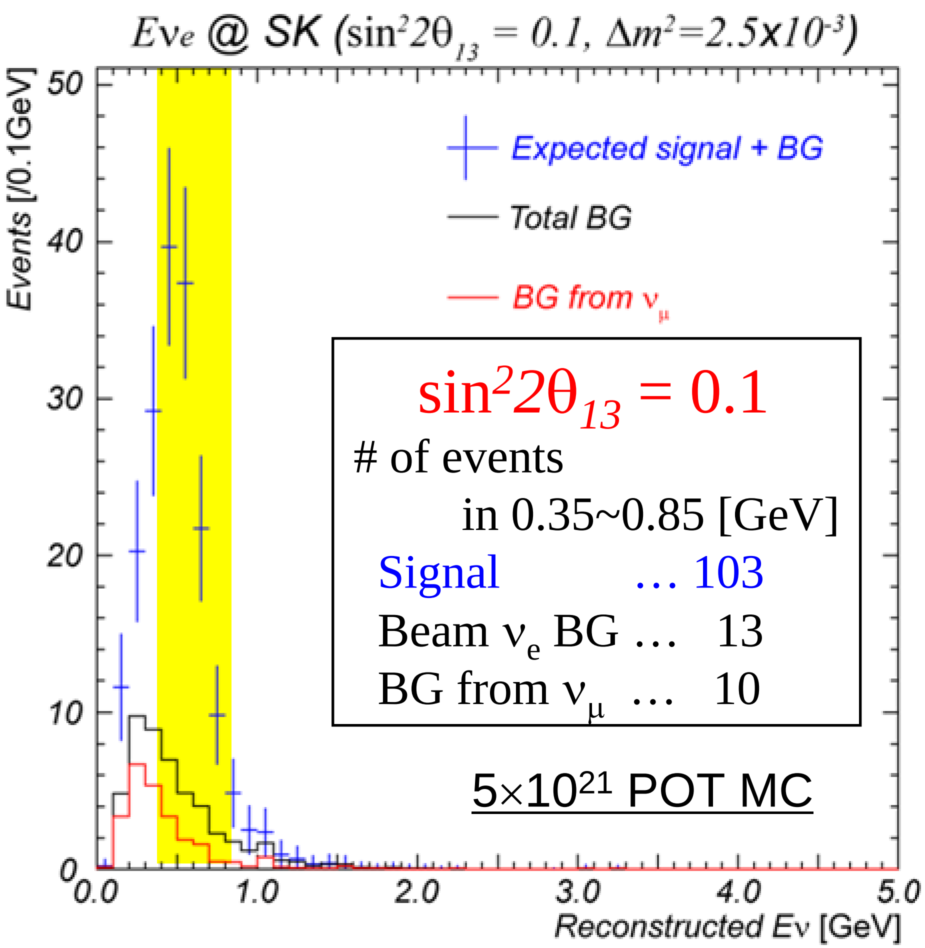
Ready for T2K !!!

- 50kt Water Cherenkov detector
- SK reconstruction is completed in Apr. 2006.
  → Back to 40% Photo coverage. Start full operation in July, 2006



Prospects in T2K Phase-I

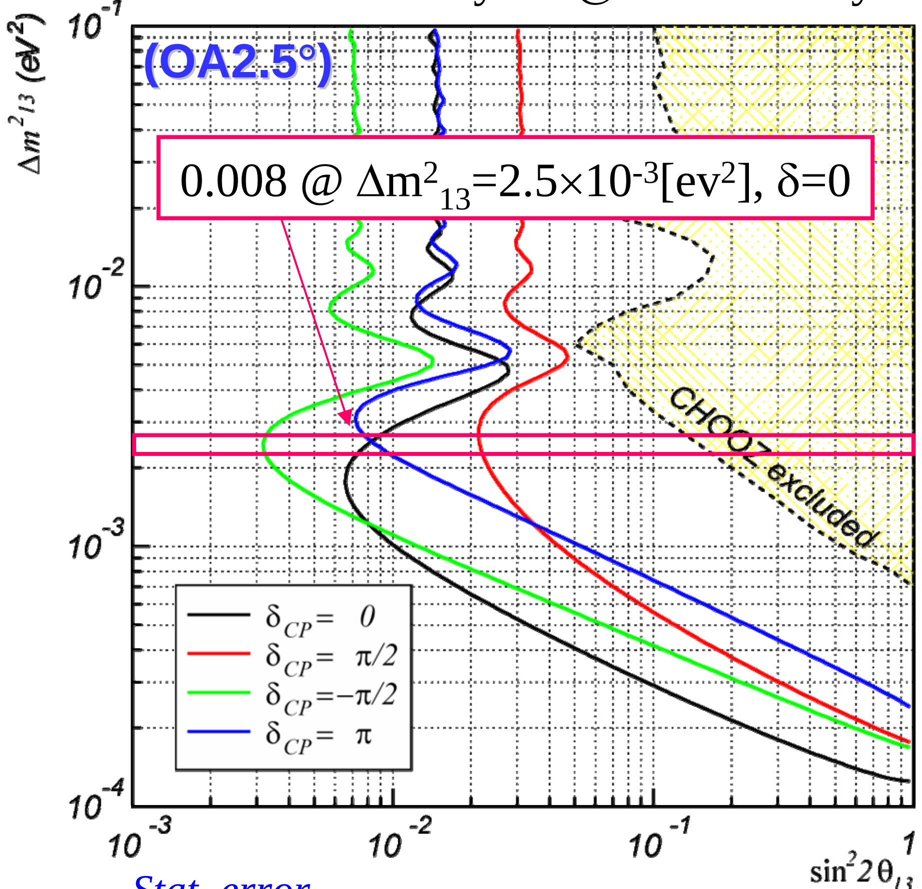
- ν_e appearance



T2K 90%CL sensitivity

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

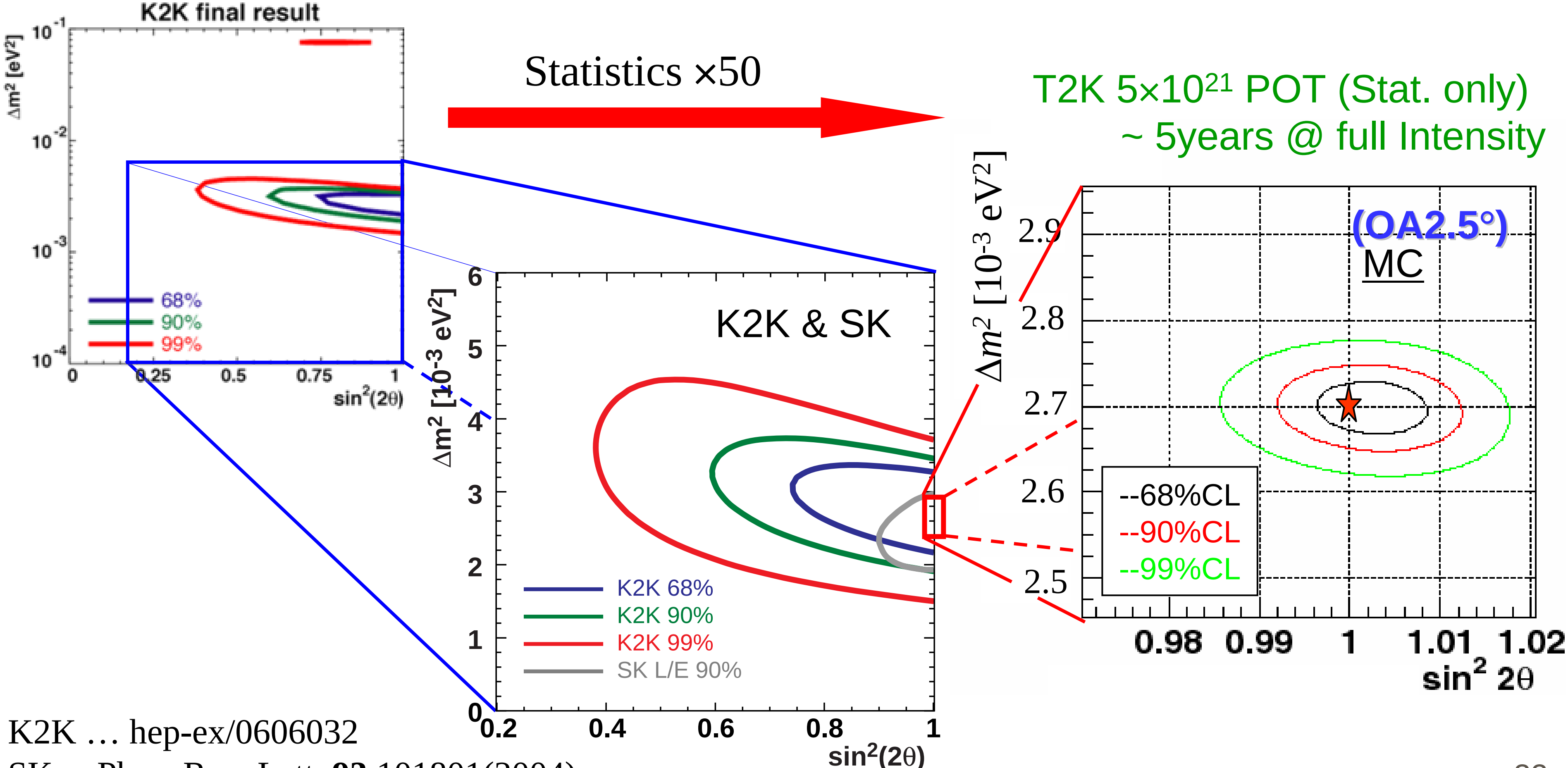
5×10^{21} POT ~ 5 years@ full intensity



Stat. error
+ Syst. error for BG subtraction (10%)

Prospects for T2K Phase-I (Cont'd)

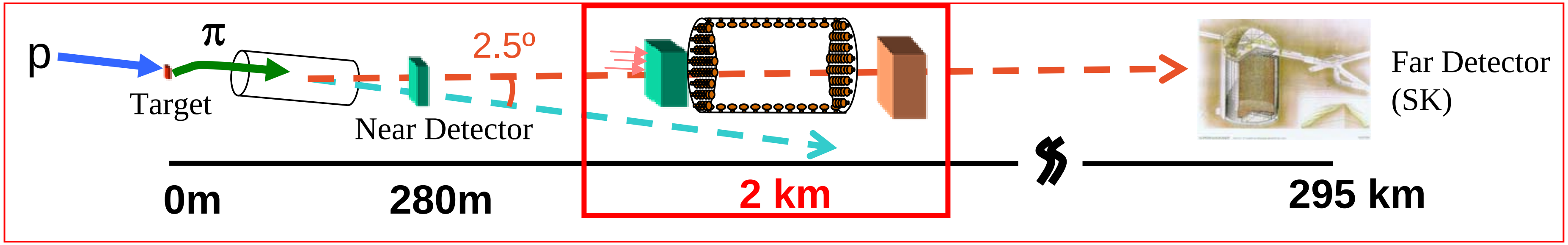
- ν_μ disappearance : $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2\theta_{23}\sin^2(1.27\,\Delta m^2_{23}L/E)$
  - Goal : $\delta(\sin^2 2\theta_{23}) \sim 0.01$, $\delta(\Delta m^2_{23}) < 1\times10^{-4}$ [eV^2]



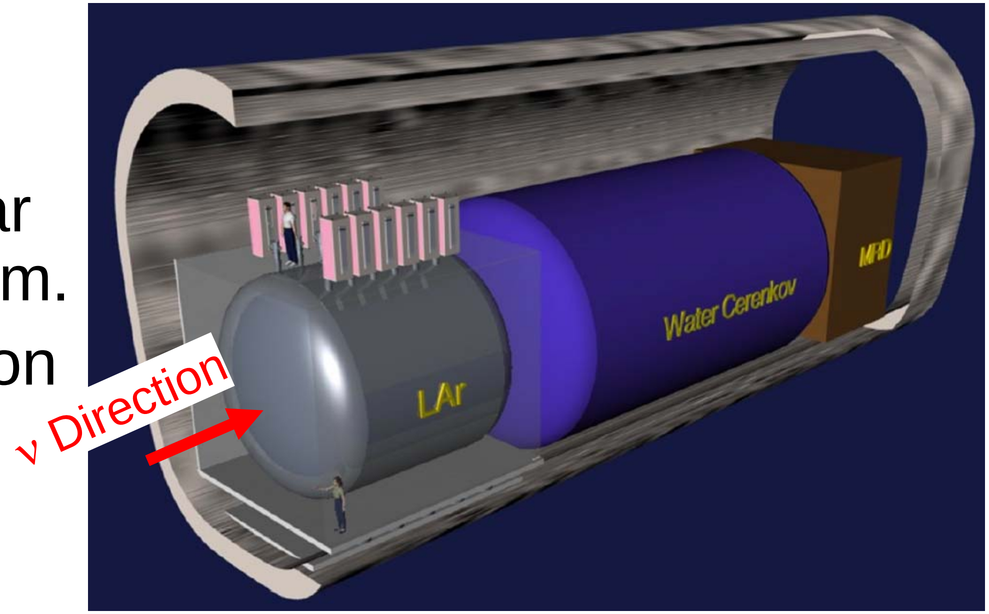
K2K … hep-ex/0606032

SK… Phys. Rev. Lett. **93**,101801(2004)

Intermediate detector @ 2km



- E_ν spectrum @ 2km ~ E_ν spectrum @ SK w/o oscillation → Uncertainties from Far/Near ratio is smaller than ND@280m.
- Possible Detector configuration
  - Liquid Ar TPC
  - Water Cherenkov
    - Same target & ν reconstruction algorithm as SK
  - Muon Range Detector



Facilities for 2km is to be requested in Japan after the commissioning of J-PARC facilities.

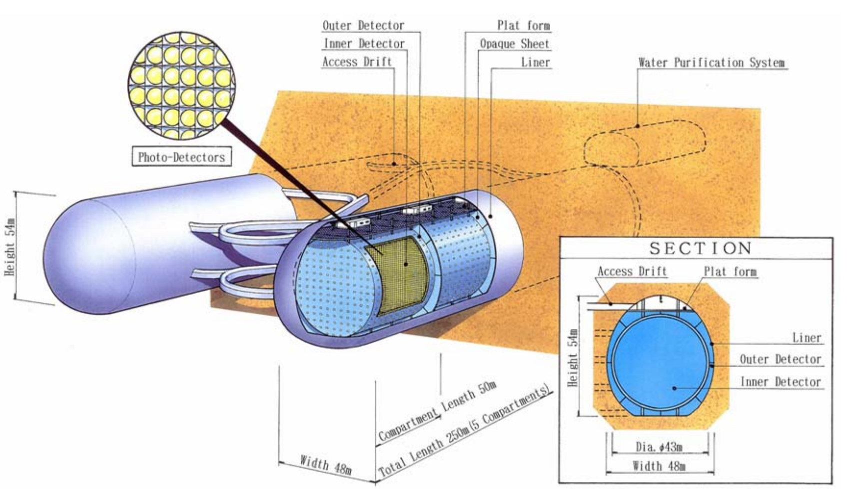
Beyond T2K-I

Possible upgrade: T2K Phase-II

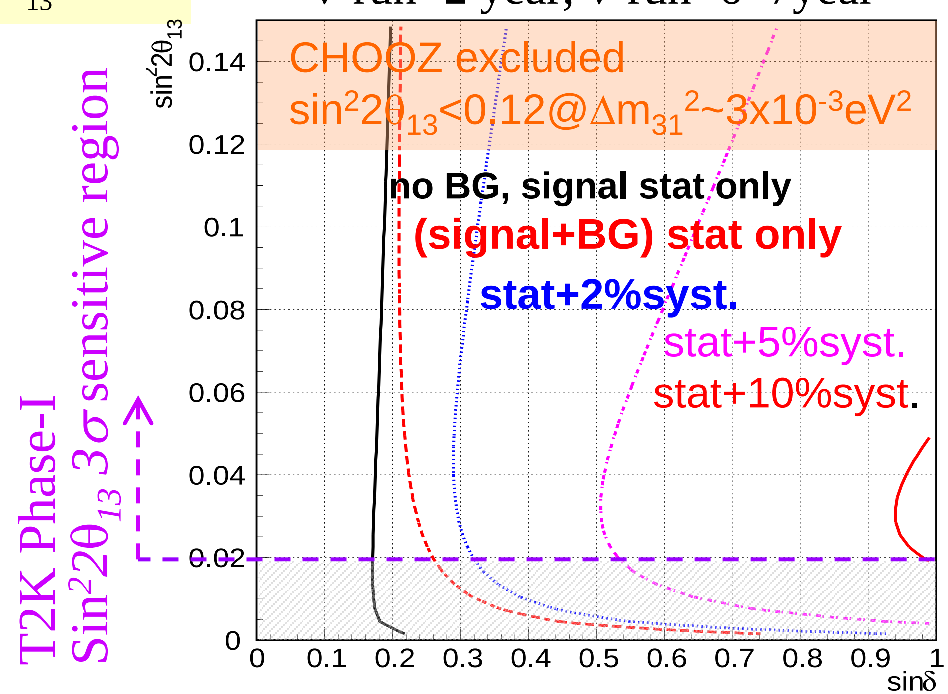
- If $\sin^2 2\theta_{13}$ measured @ T2K-I $\underline{> 0.01}$, it paves the way for ν *CP*-violation search.
  - J-PARC upgrade: *0.75MW* → ***4MW***
  - SK (*50kt*) → Hyper Kamiokande (HK): ***~1Mt***
    - Proton decay search: test of GUT.
- Comparison between ν_μ and Anti-ν_μ beam.

Assumptions:
$\Delta m_{21}^2 = 6.9\times10^{-5}\,eV^2$
$\Delta m_{32}^2 = 2.8\times10^{-3}\,eV^2$
$\theta_{12} = 0.594, \theta_{23} = \pi/4$

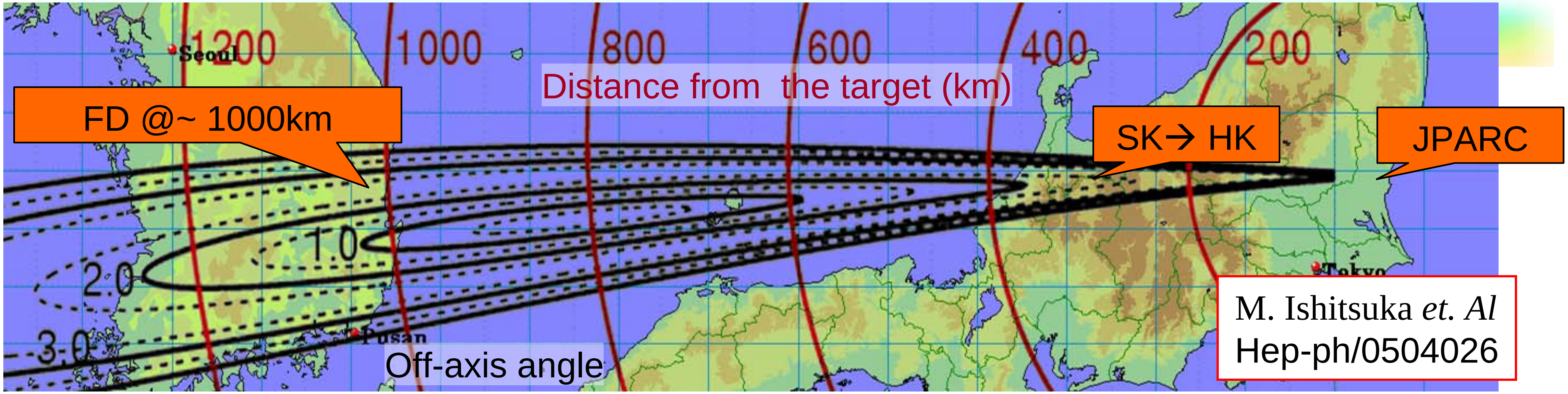
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m_{12}^2 L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin\delta$$



3σ sensitivity (4MW,540kt)
ν-run=2 year, $\bar{\nu}$-run=6~7year

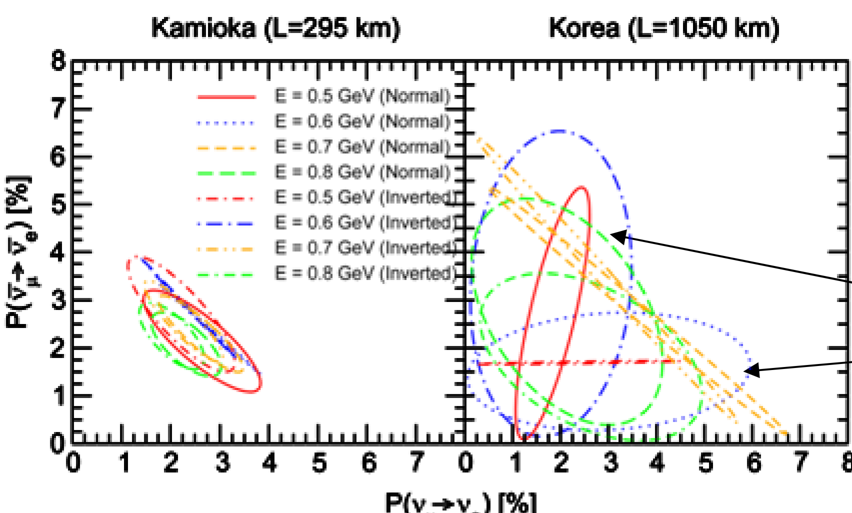


T2KK … Another far detector @ Korea



- Far detector identical with (SK)/HK @ 2nd Oscillation Maximum point.
  - Contribution of CP asymmetric term: ×3 compared to SK position.
  - Matter effect become significant. → Possibility to resolve mass hierarchy

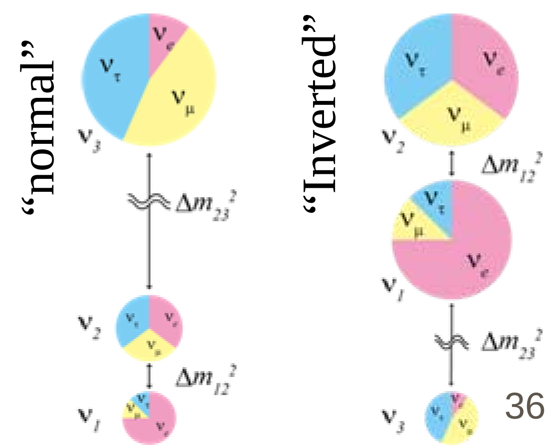
$$CPV \text{ term} \approx \mp 4J_r \sin\delta\left(\Delta m^2_{21}L/2E\right)\sin^2\left(\Delta m^2_{31}L/4E\right)$$



$\sin^2 2\theta_{13}=0.05$

δ … $0\sim2\pi$

If δ is suitable, it may possible to distinguish.



Status and Prospects of the NOνA Experiment

Peter Shanahan - Fermilab

Neutrino 2006

June 17, 2006 - Santa Fe

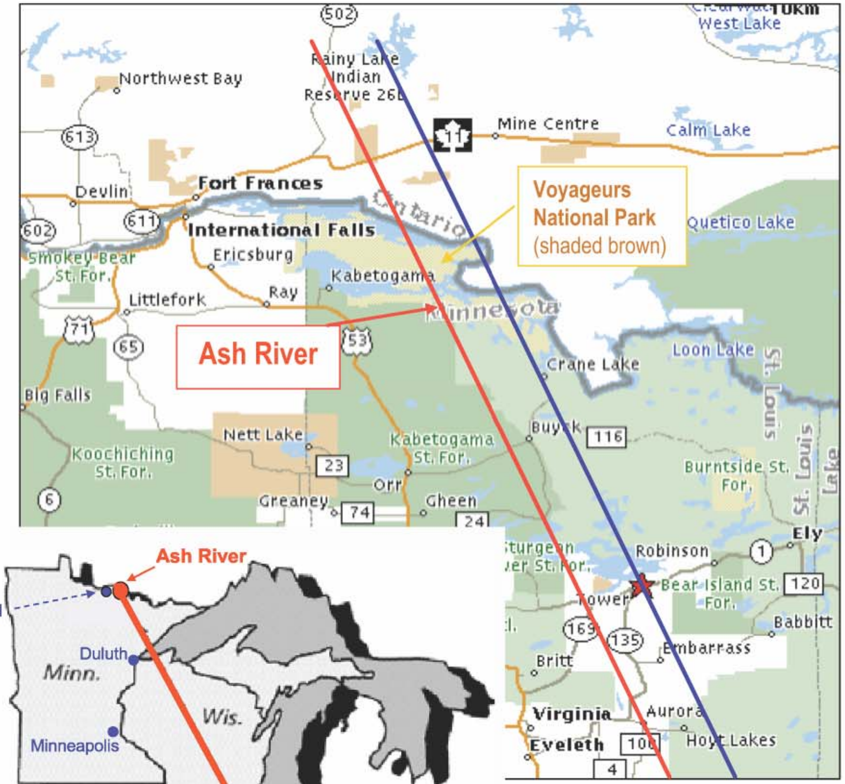
For the Collaboration

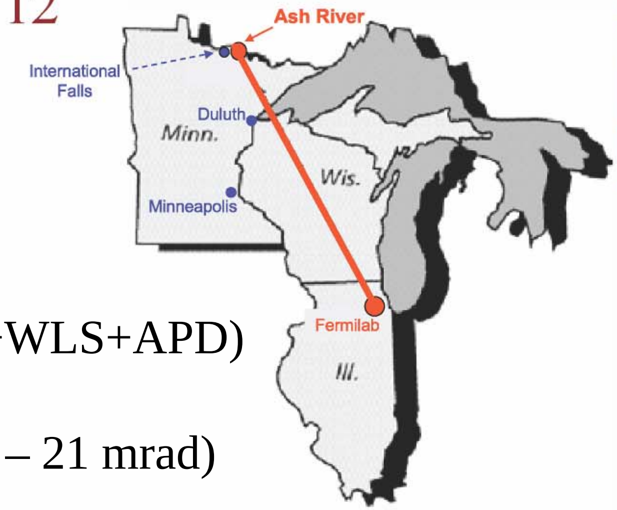
Introduction

- NOνA: NuMI Off-Axis ν_e Appearance
- Study $\nu_\mu \rightarrow \nu_e$:
  - search for $\sin^2(2\theta_{13})$ with a sensitivity a factor of ~14 beyond current limits
  - sensitivity to Mass Hierarchy for a significant fraction of parameters,
  - search for effect of CP violating phase δ
- Two detectors with a 810 km baseline using the NuMI Neutrino Beam from Fermilab
- Near and Far Detectors optimized for ν_e charged-current detection
- Located Off the Beam Axis for Background Suppression

Location

- Optimization: Maximize sensitivity to Mass Hierarchy
  - Maximize baseline within U.S. - 810 km from Fermilab
  - Optimize off-axis location: 12 km from beam axis
  - Ash River, MN





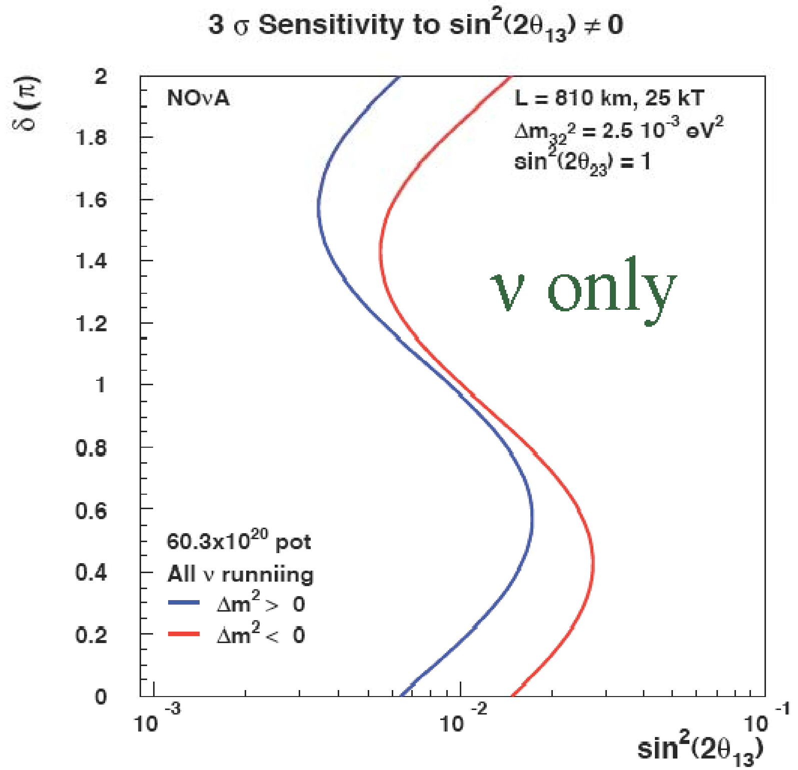
Far Detector: 25kT [15.7×15.7 × 110 m^{3}]
(18.25kT Liquid Scintillator in PVC cells+WLS+APD)
Near Detector:
Liquid Scintillator + Muon Catcher (OA 4 – 21 mrad)

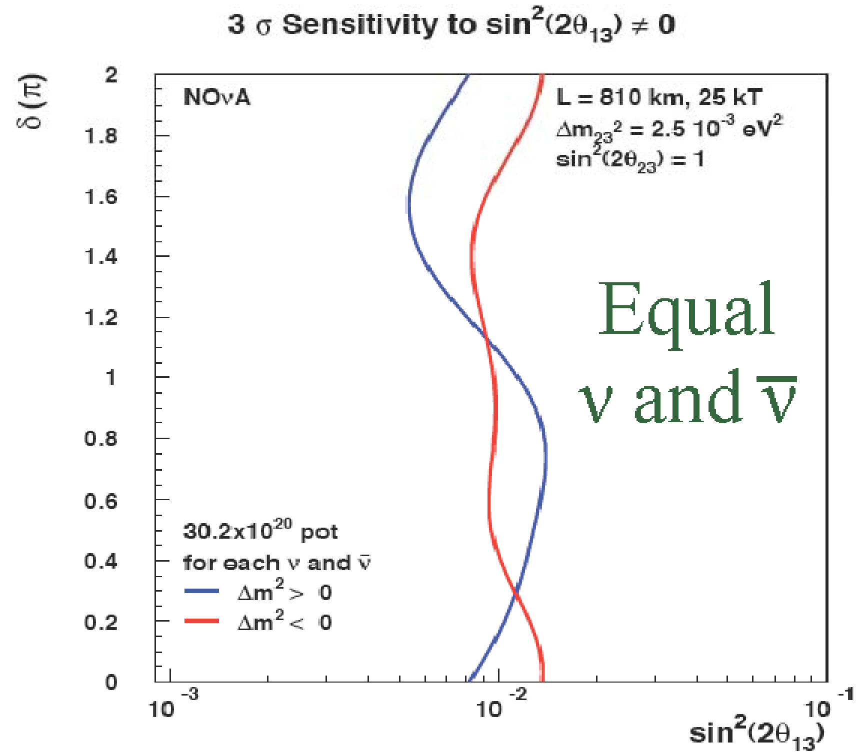
History/Schedule

- April 2005: Fermilab PAC approval
- April 2006: DOE CD-1 recommendation
  - "Approve Preliminary Baseline Range"
  - Conceptual Design Report
- Upcoming Reviews:
  - Late 2006/Early 2007: Review for CD-2 ("Approve Performance baseline")/ Technical Design Report
  - by Oct 2007: Reviews for CD-3 ("Approve start of construction")
- Detector construction and running
  - Start Far Detector Assembly in late 2009- start data taking with first 5 kT in late 2010 complete in late 2011

3σ Sensitivity to $\sin^2(2\theta_{13})\neq 0$

- Advantage to equal $\nu/\bar{\nu}$ running:
  - More consistent reach in $\sin^2(2\theta_{13})$ vs. δ and mass hierarchy

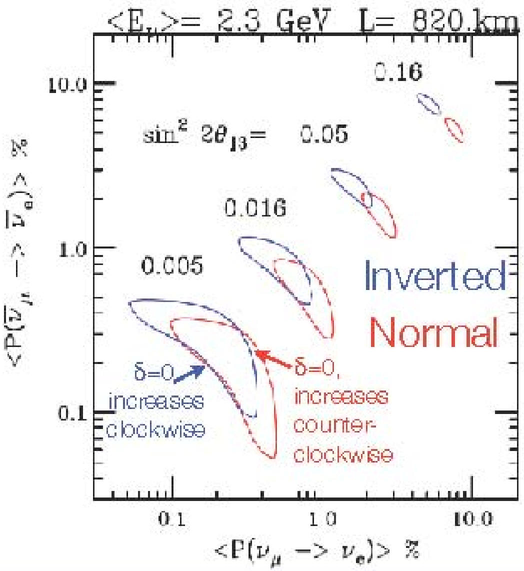




6×10^{21}POT: 6year, 25kT, 1MW beam

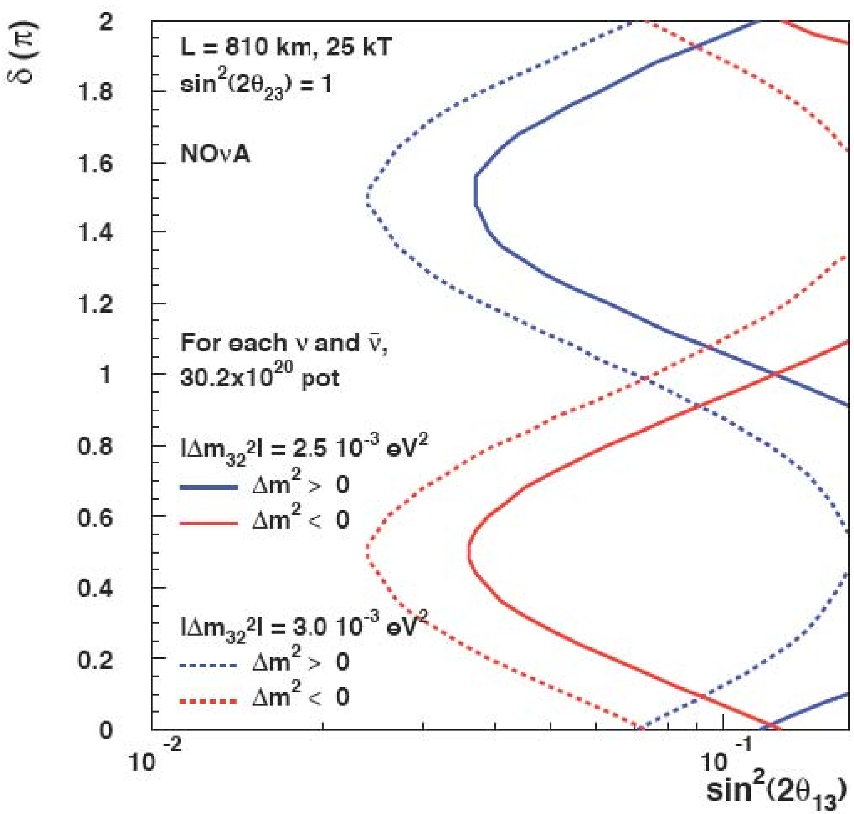
Mass Hierarchy

Reminder:
Matter effects enhance (decrease) ν oscillations for normal (inverted) MH, vice-versa for $\bar{\nu}$



Effect at a fixed L/E is proportional to baseline: unique reach for NOvA

95% CL Resolution of the Mass Hierarchy



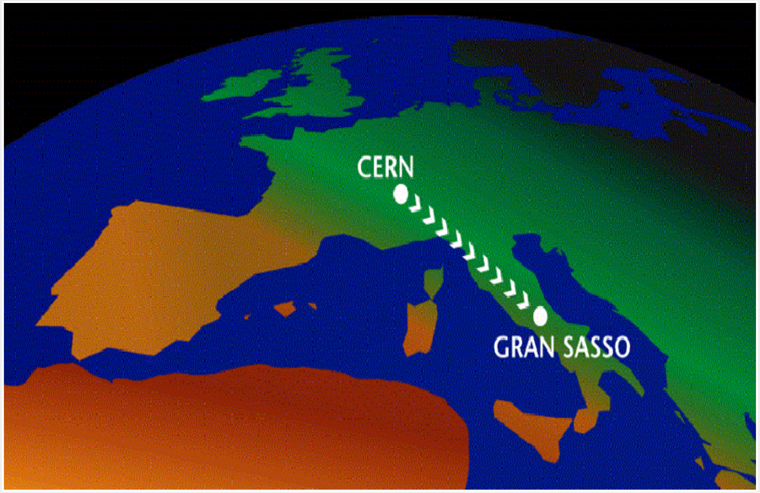
The CNGS project and OPERA experiment at LNGS

Chiara Sirignano (Salerno University)

for the OPERA Collaboration

Oscillation Project with Emulsion tRacking Apparatus

International Collaboration (Europe + Japan)



- IIHE (ULB-VUB), Brussels
- Sofia
- IHEP Beijing, Shandong
- IRB Zagreb
- LAPP Annecy, IPNL Lyon, LAL Orsay, IRES Strasbourg
- Berlin Humboldt, Hagen, Hamburg, Münster, Rostock
- Technion Haifa
- Bari, Bologna, LNF Frascati, L'Aquila, LNGS, Napoli, Padova, Roma La Sapienza, Salerno
- Aichi, Kobe, Nagoya, Toho, Utsunomiya
- INR Moscow, ITEP Moscow, JINR Dubna, Obninsk
- Bern, Neuchâtel, Zurich
- METU Ankara

- **Long baseline experiment**
- **CNGS pure ν_μ beam, <L> = 732 km, <E> = 17 GeV**
- **Appearance signal $\nu_\mu \rightarrow \nu_\tau$ (by product $\nu_\mu \rightarrow \nu_e$)**
- **Hybrid setup (Nuclear Emulsions + electronics)**
- **Atmospheric neutrino data allowed region oscillation search**

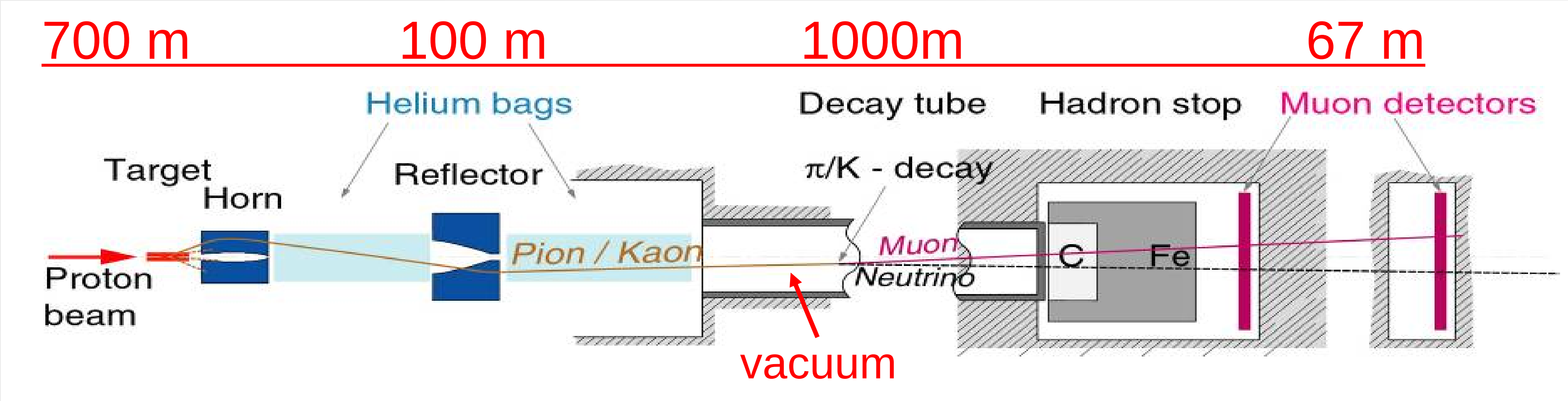
$\nu_\mu \rightarrow \nu_\tau$ oscillation search

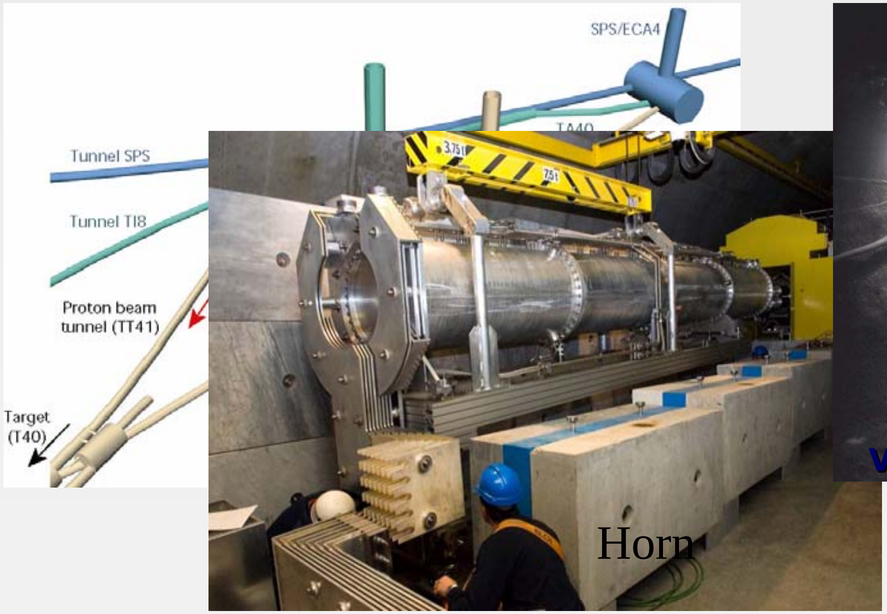
τ decay channel	Signal		Background
	$\Delta m^2 = 2.4 \times 10^{-3}$ eV^2	$\Delta m^2 = 3.0 \times 10^{-3}$ eV^2	
$\tau \rightarrow \mu$	3.6	5.6	0.23
$\tau \rightarrow e$	4.3	6.7	0.23
$\tau \rightarrow h$	3.8	5.9	0.32
$\tau \rightarrow 3h$	1.1	1.7	0.22
ALL	12.8	19.9	1.0

full mixing, 5 years run @ 4.5×10^{19} pot / year

Main background sources:

-charm production and decays
- hadron re-interactions in lead
- large-angle muon scattering in lead





Civil engineering completed (June ’03)

Hadron stopper and decay tube installed (June ’04)

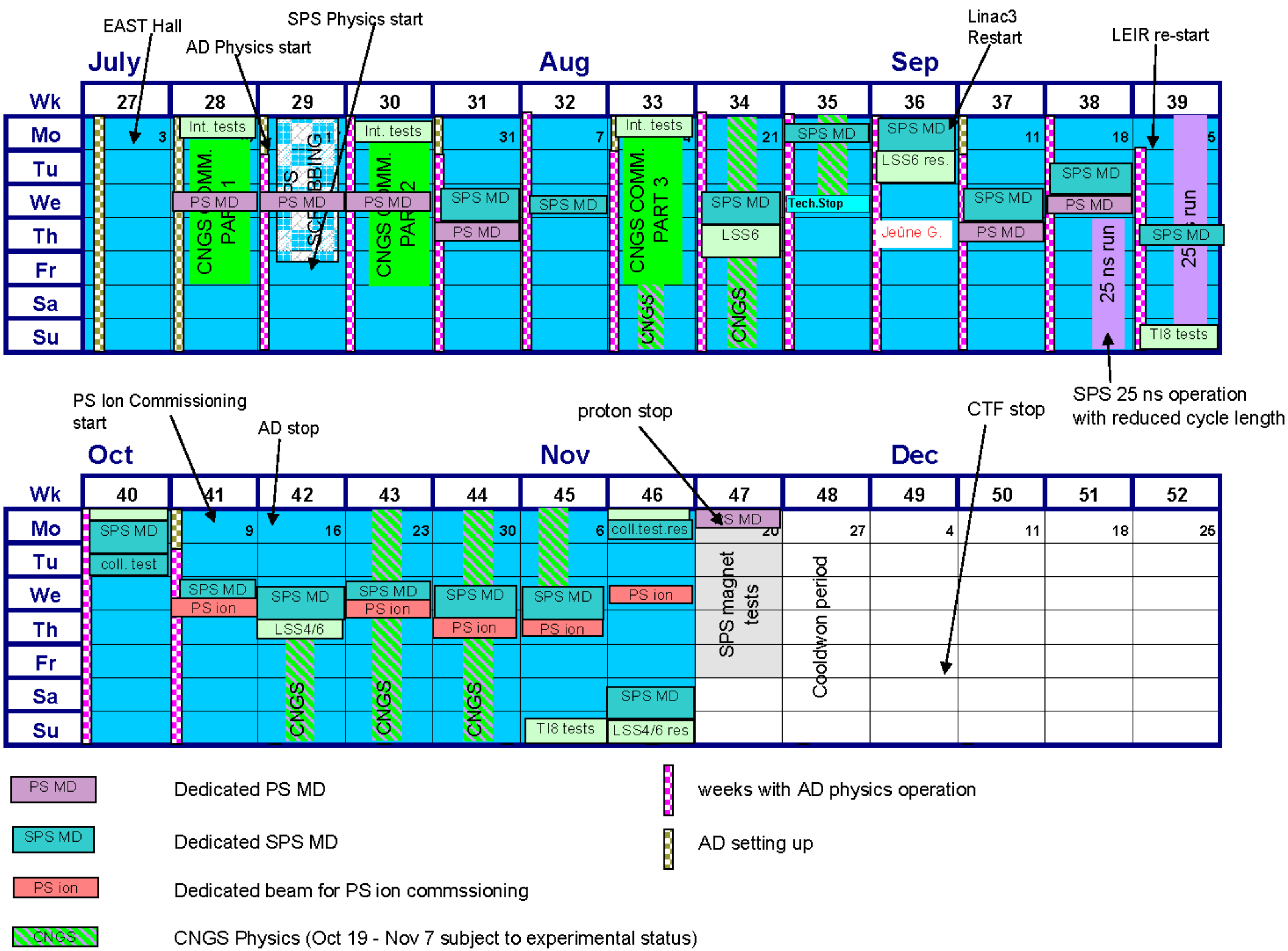
Target section completed (commissioning July ‘06)

GA/PC/CR

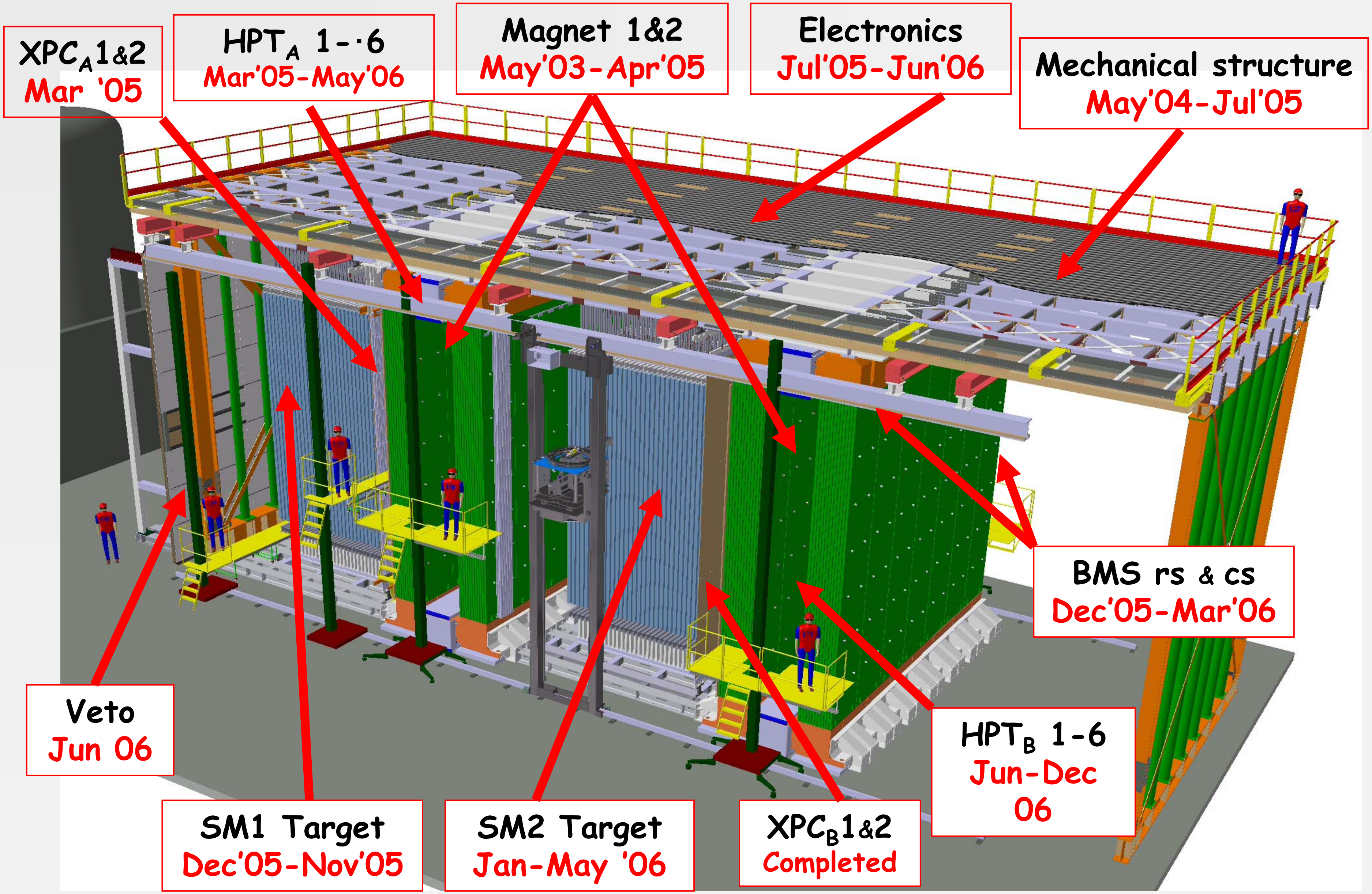
6/8/06

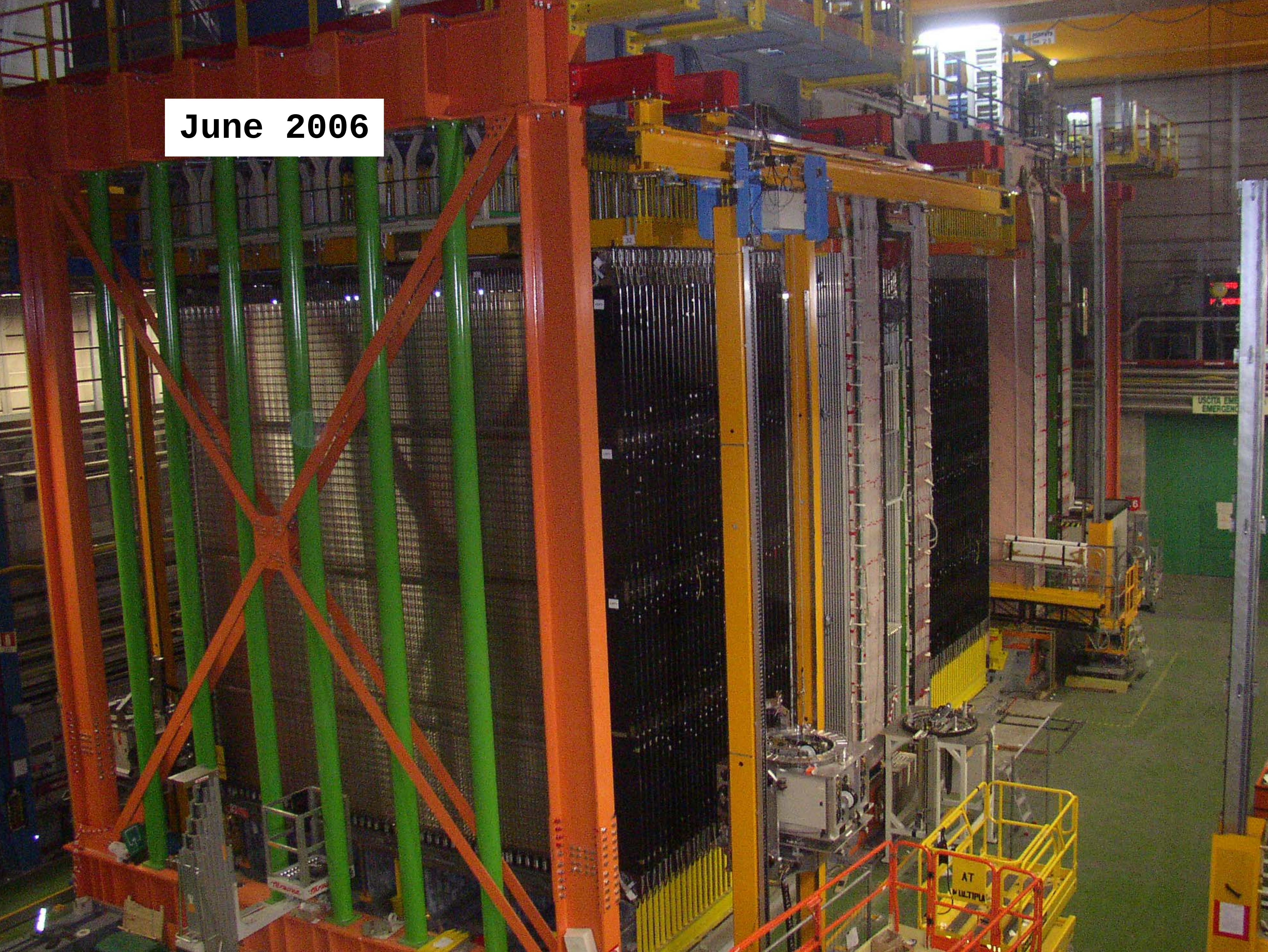
2006 Revised Accelerator Schedule

Approved by Research Board 7th June 2006



Detector construction status




June 2006