Neutrino Oscillation Experiment at J-PARC
-Our approach for the future-

Second International Workshop on
Neutrino Oscillations in Venice
December 3-5,2003

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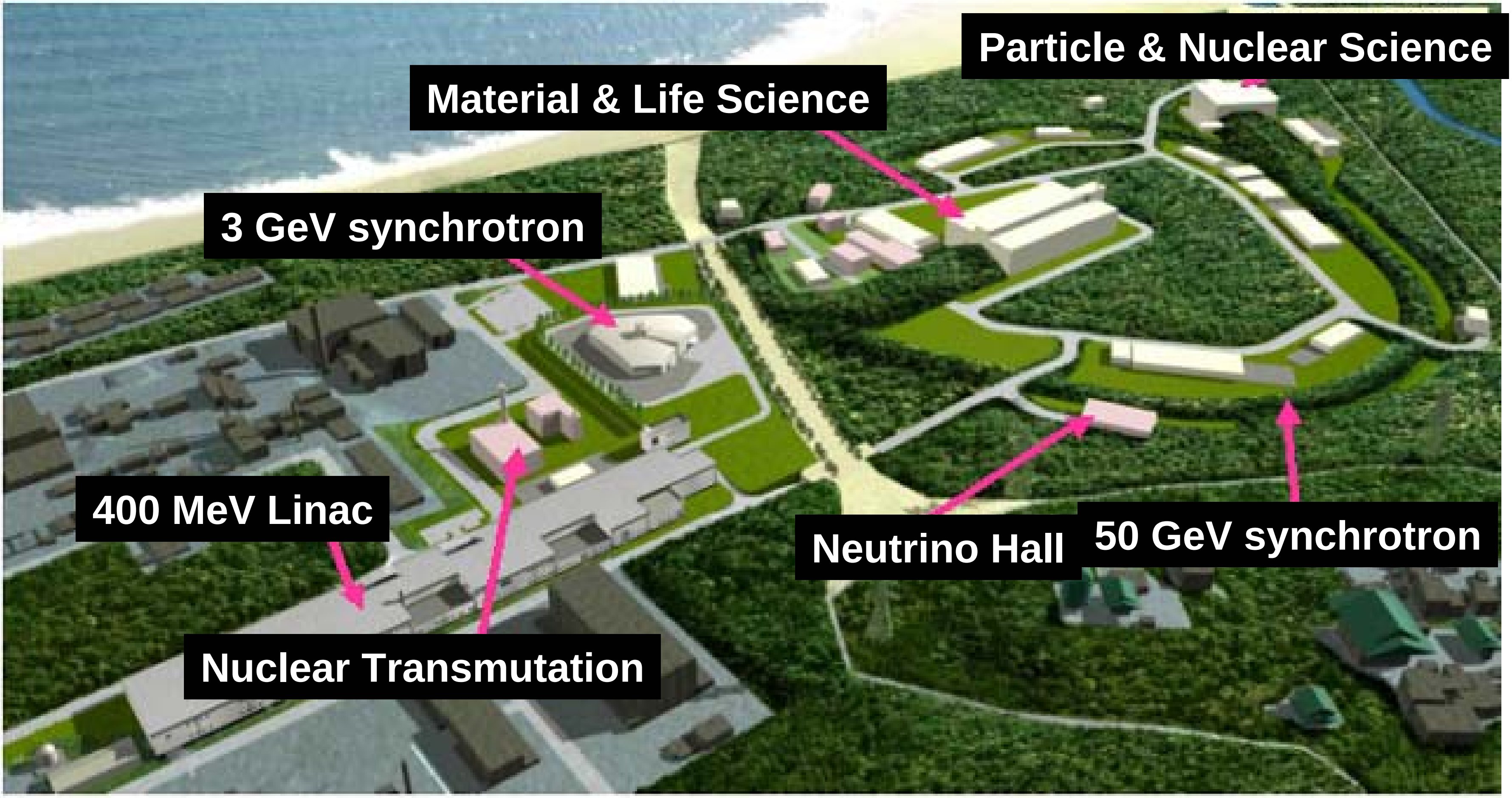
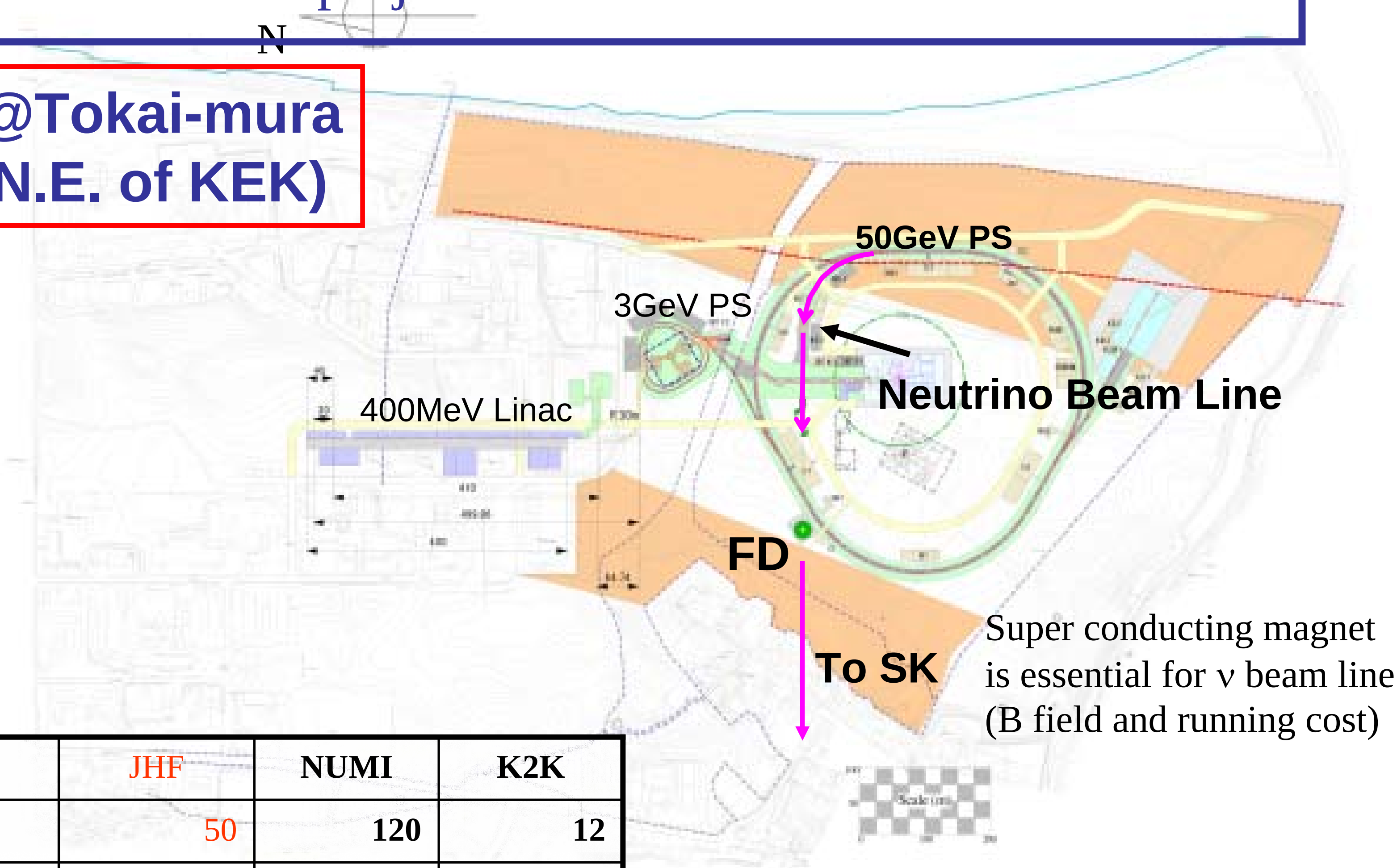
J-PARC (Japan Proton Accelerator Research Complex)：
2001-2007 MW 3 GeV & MW 50 GeV PS



J-PARC project and neutrino beam line

JAERI@Tokai-mura (60km N.E. of KEK)



Super conducting magnet is essential for ν beam line (B field and running cost)

	JHF	NUMI	K2K
E(GeV)	50	120	12
Int.(10^{12}ppp)	330	40	6
Rate(Hz)	0.292	0.53	0.45
Power(MW)	0.77	0.41	0.0052

10^{21}POT(130day) ≡ "1 year"


ν

JPARC-Kamioka Project

Phase-I (0.75MW + Fully reconstructed Super-K)~K2K x 100

Phase-II (4MW+Hyper-K) ~ Phase-I ×100

Past, Present and Future

- 1999-00 : **<u>Neutrino Working Group</u> formed**
  Physics goals identified
  (ICRR/KEK/Kyoto/Kobe/Tohoku/TRIUMF)
- Dec.2000 : Original LOI
- Dec.2002 : LOI submitted J-PARC office
  45 physicists from Japan, 110 physicists from Canada, China, France, Italy, Korea, Poland, Russia, Spain, Switzerland, UK and USA
- Mar. 2002,2003 : IAC endorsed neutrino exp. to be 1st priority
- Oct.2003 : Criticism from Council of Sci. & Tech.
- Nov. 2003 : New review organized by MEXT(Ministry of Edu, Sci & Tech) reported 'Neutrino should start in 2004'
  Decision by Ministry of Finance by the end of 2003

- Jan.11,12, 2004 :Meeting at KEK
- April 2004 : Start construction (?)
- 2008 : Commissioning

Physics Motivations

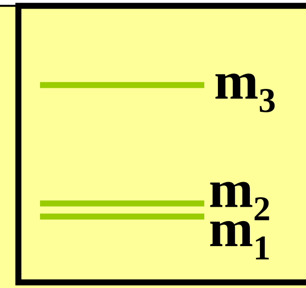
- **The mixing angles θ_{12}, θ_{23}, θ_{31}, δ ?**
  - **Symmetry of 2nd and 3rd generation?**
    - How close θ_{23} to $\pi/4$?
  - **How small the mixing of 1st and 3rd generation?**
    - $\nu_\mu \rightarrow \nu_e$ exist – Does ν_e contain ν_3?
  - **How large is the phase δ?**
    - CP violation in lepton?
  - **Is sterile neutrino exist?**
    - Fraction in disappearance of ν_μ

- **Look for un-expected with good resolution**

Measurements

Oscillation Probabilities when

$$\Delta m^2_{12} << \Delta m^2_{23} \approx \Delta m^2_{13}$$
$$\Delta m^2_{ij} = m^2_j - m^2_i$$



- ν_μ disappearance

$$P_{\nu\mu \to \nu\mu} \approx 1 - \cos^4\theta_{13} \sin^2 2\theta_{23} \cdot \sin^2\left(1.27\,\Delta m^2_{23} L / E_\nu\right)$$

≈

- ν_e appearance

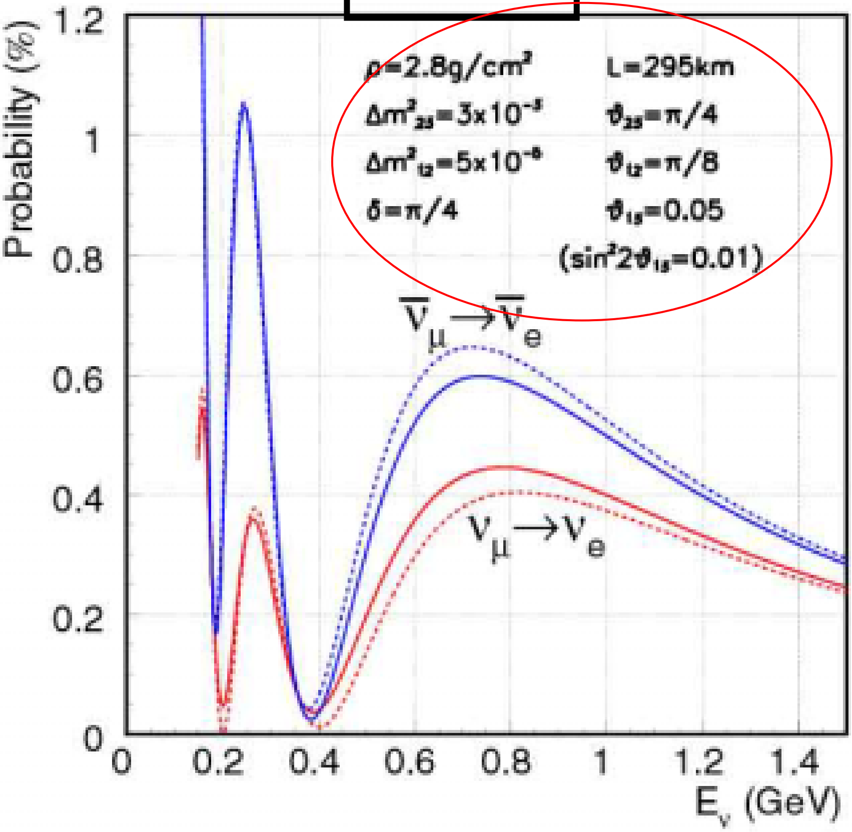
$$P_{\nu\mu \to \nu e} \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\,\Delta m^2_{13} L / E_\nu\right)$$

- δ: ~~CP~~ in ν_e appearance

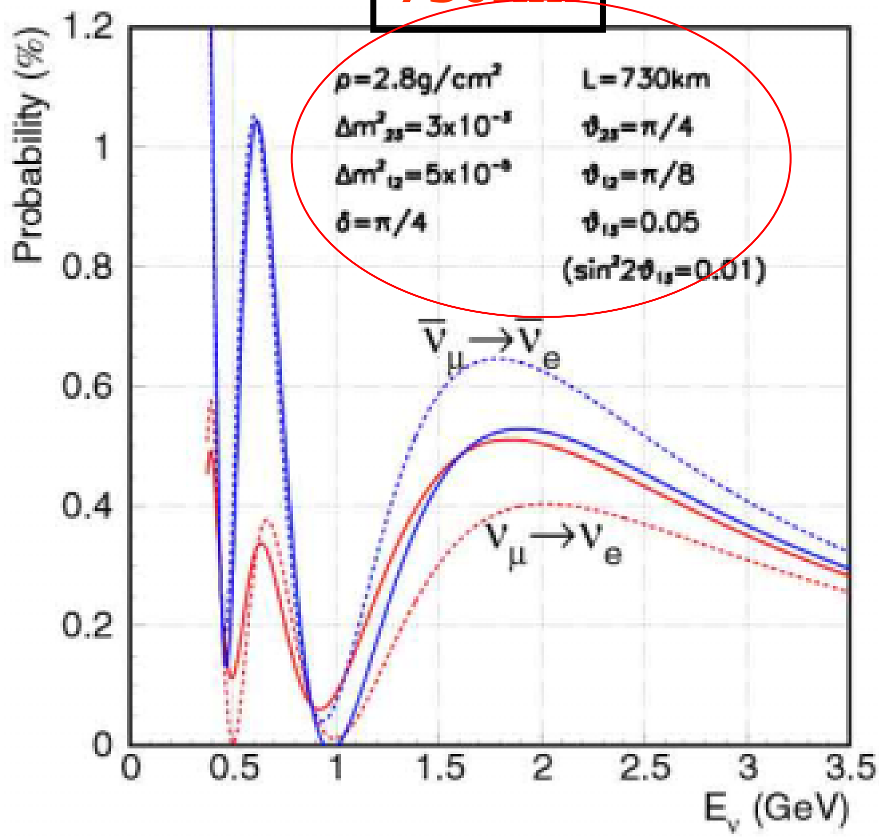
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m^2_{12}}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

Matter effect vs CP violation

295km



730km



Solid line: w/ matter
Dashed line: w/o matter

At oscillation maximum (L/E~π/2)
matter effects scale as $\theta_{13}^2 E$ or $\theta_{13}^2 L$
Chosen an experiment with smallest matter effect

Strategy

- **High statistics by high intensity ν beam**
- **Set $E\nu$ at oscillation maximum**
- **Sub-GeV ν beam suited for Water Cherenkov, dominated by $\nu_\mu + n \rightarrow \mu + p$: $E\nu$ reconstruction**
- **Narrow band beam to reduce BG**

0.75MW 50GeV-PS

Off-Axis ν beam

Super-Kamiokande

Experiment with low energy beam with water Cherenkov detector

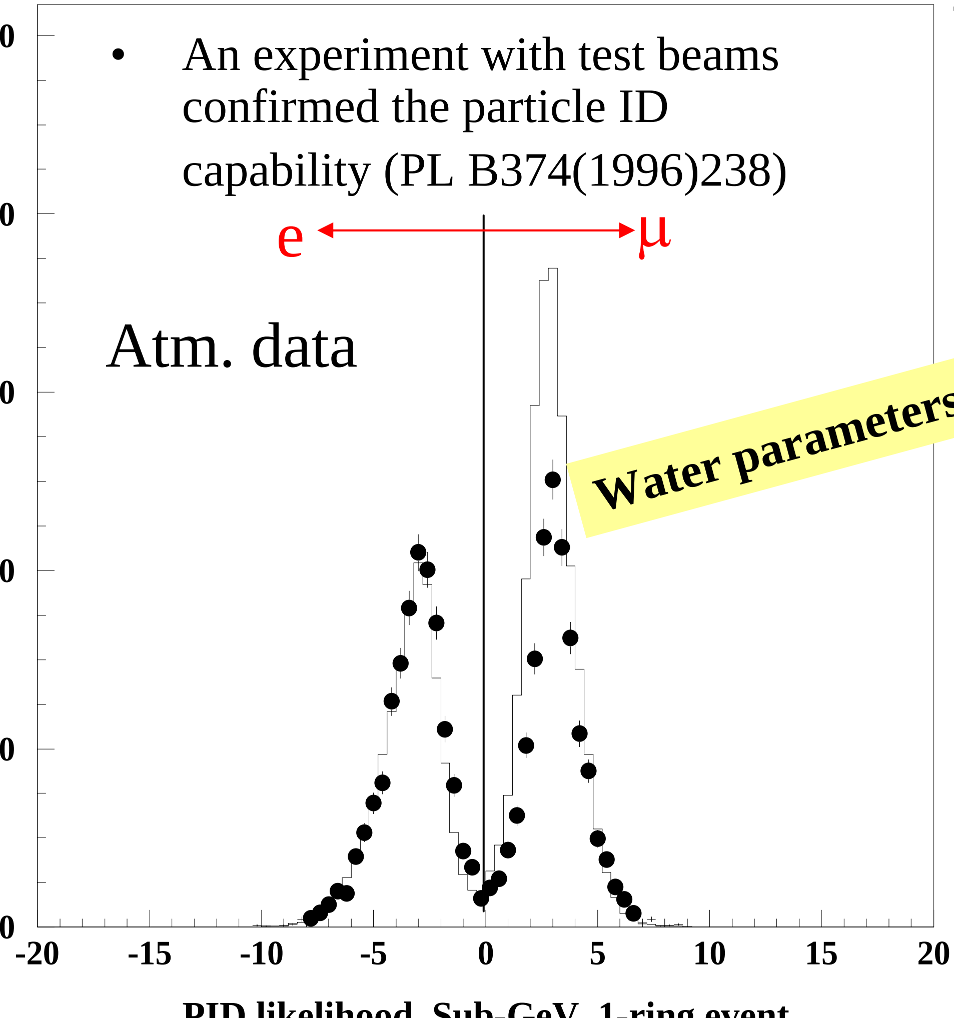
1. Neutrino oscillation is the oscillation between different flavors - PID
   - e, μ identification by charged current interactions
   - single particle prefered in water Cherenkov (CCQE)
2. Only Flux(Eν) x σ(Eν) will be measured
   - Eν, (L) must be known event-by event to get Δm^2
   - Only CCQE process and measure at two location
3. E_ν reconstruction resolution

$$N_{obs} = F(E_\nu)\cdot P(\nu_\alpha \to \nu_\beta)\cdot \sigma(E_\nu)$$

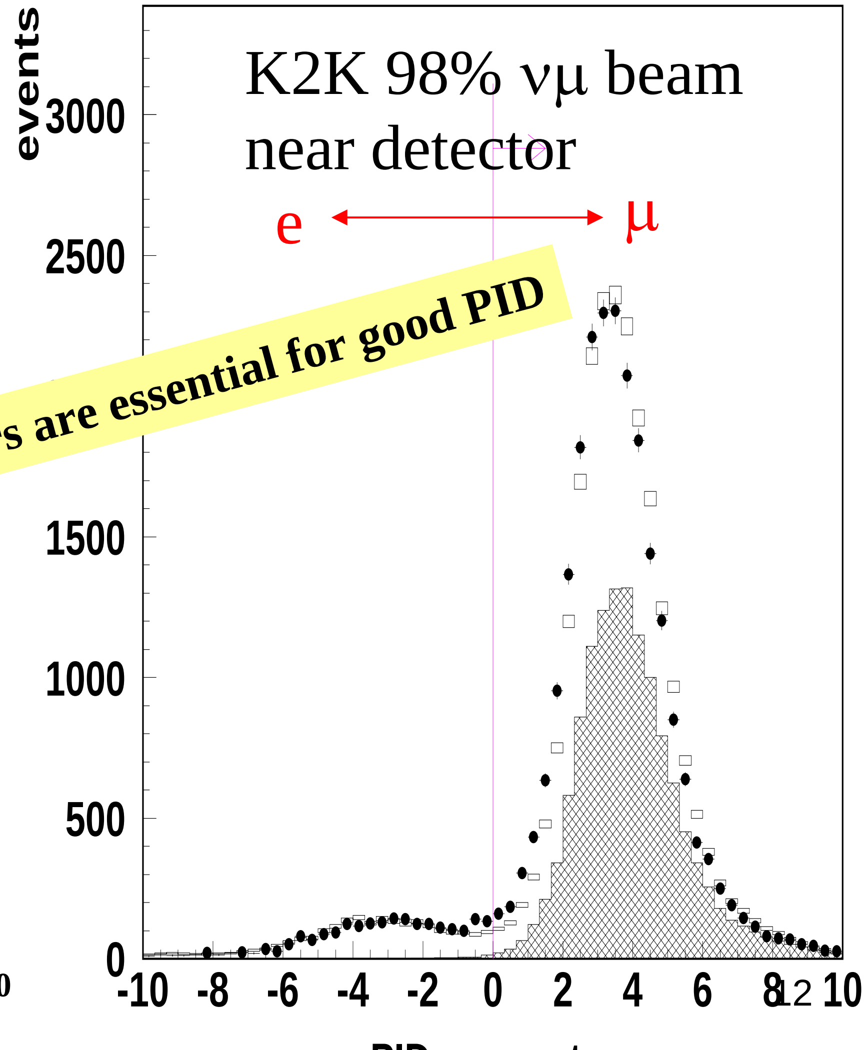
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \cdot \sin^2 \frac{1.27\Delta m^2(eV^2)L(km)}{E_\nu(GeV)}$$

1. Particle ID (e & μ) (in single ring events)

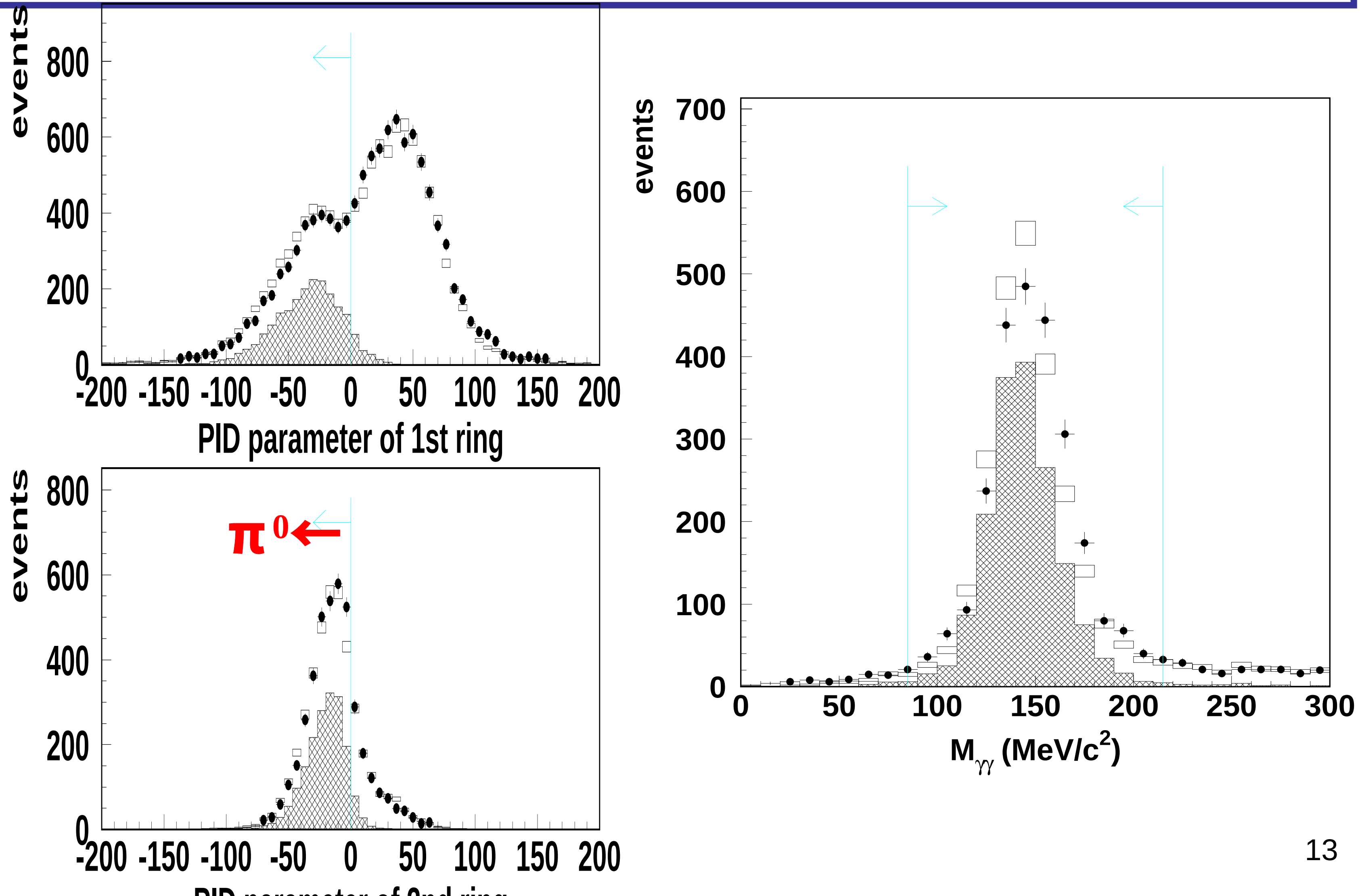
- An experiment with test beams confirmed the particle ID capability (PL B374(1996)238)



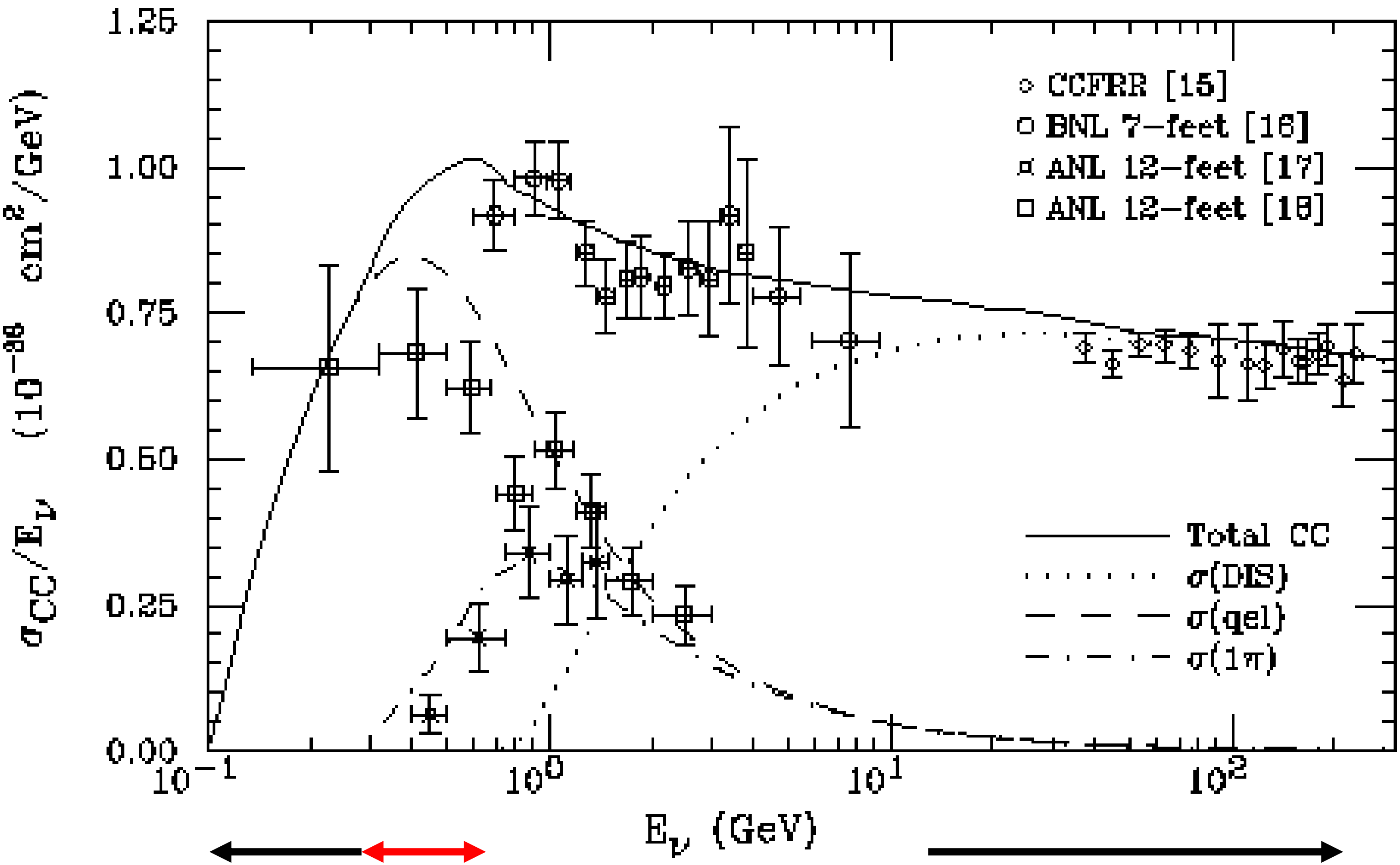
Water parameters are essential for good PID



Particle ID in multi ring events (π^0 selection)



2. Neutrino CC process

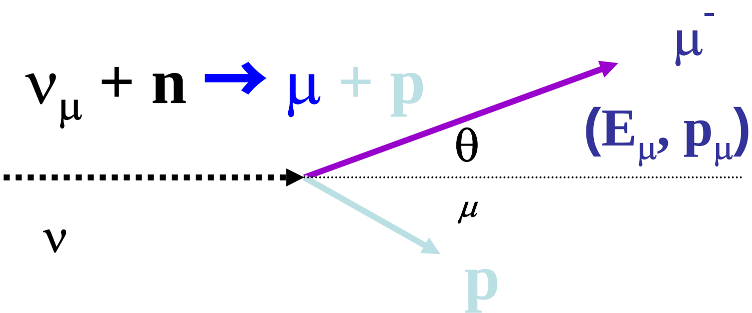


Pauli Blocking

L/E ⇒ L>1000km

3. E_ν reconstruction

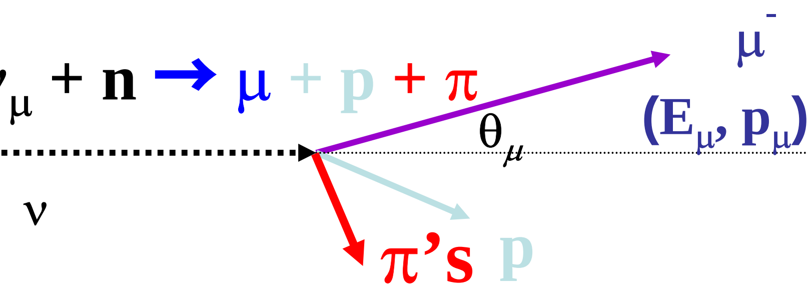
$$P = \sin^2 2\theta \cdot \sin\left(\frac{1.27\Delta m^2 \cdot L}{E_\nu}\right)$$



✧ CC QE

✧can reconstruct Eν ←(θ_μ,p_μ)

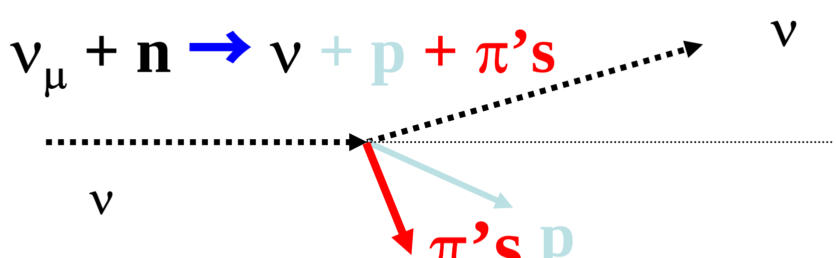
$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$



✧ CC nQE

✧Bkg. for E_ν measurement

p,n no signal in W-C
E_{had} measurement!

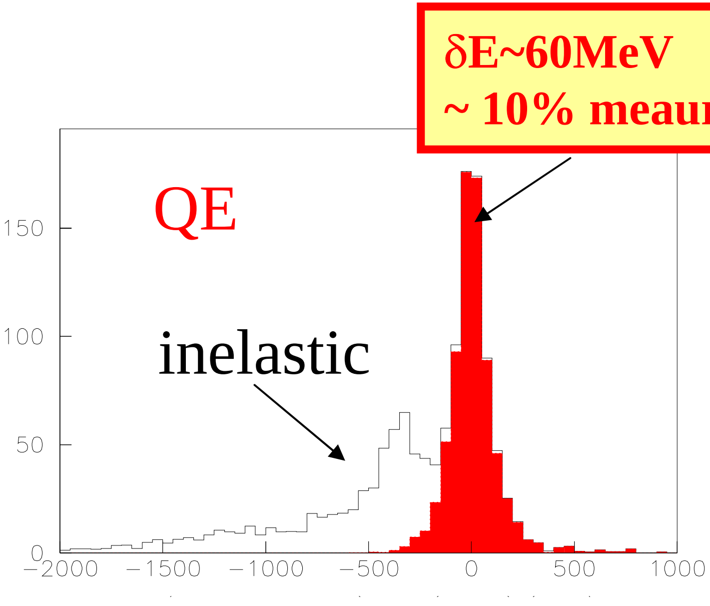


✧ NC

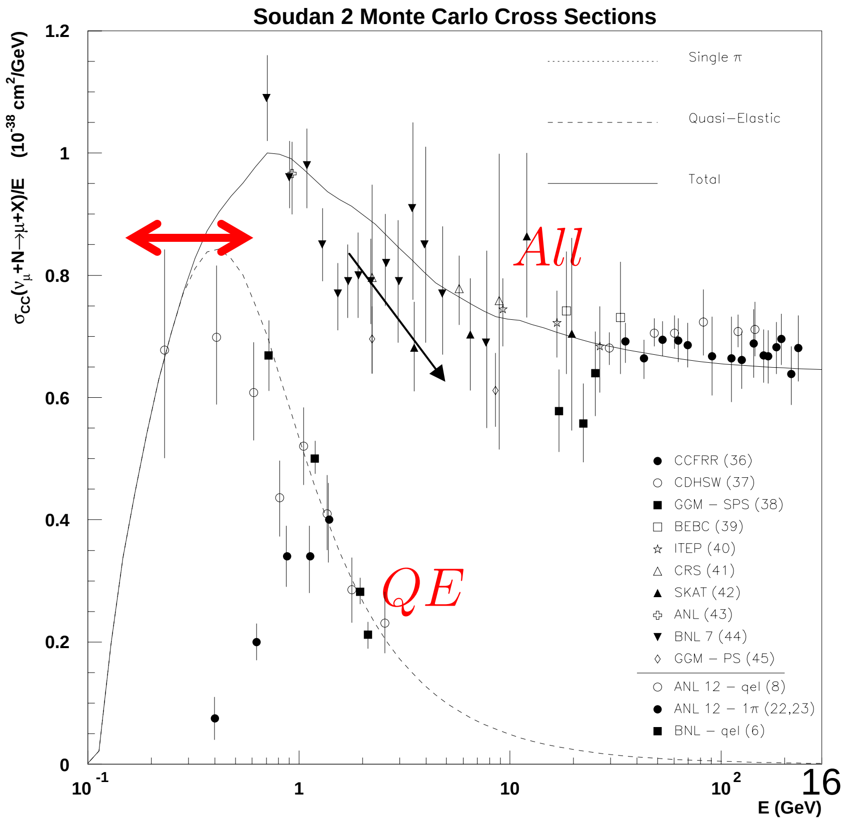
✧main Bkg. for electron appearance

E_ν reconstruction resolution

- Large QE fraction for <1 GeV
- Knowledge of cross sections
- Beam with small high energy tail
- Multiplicity

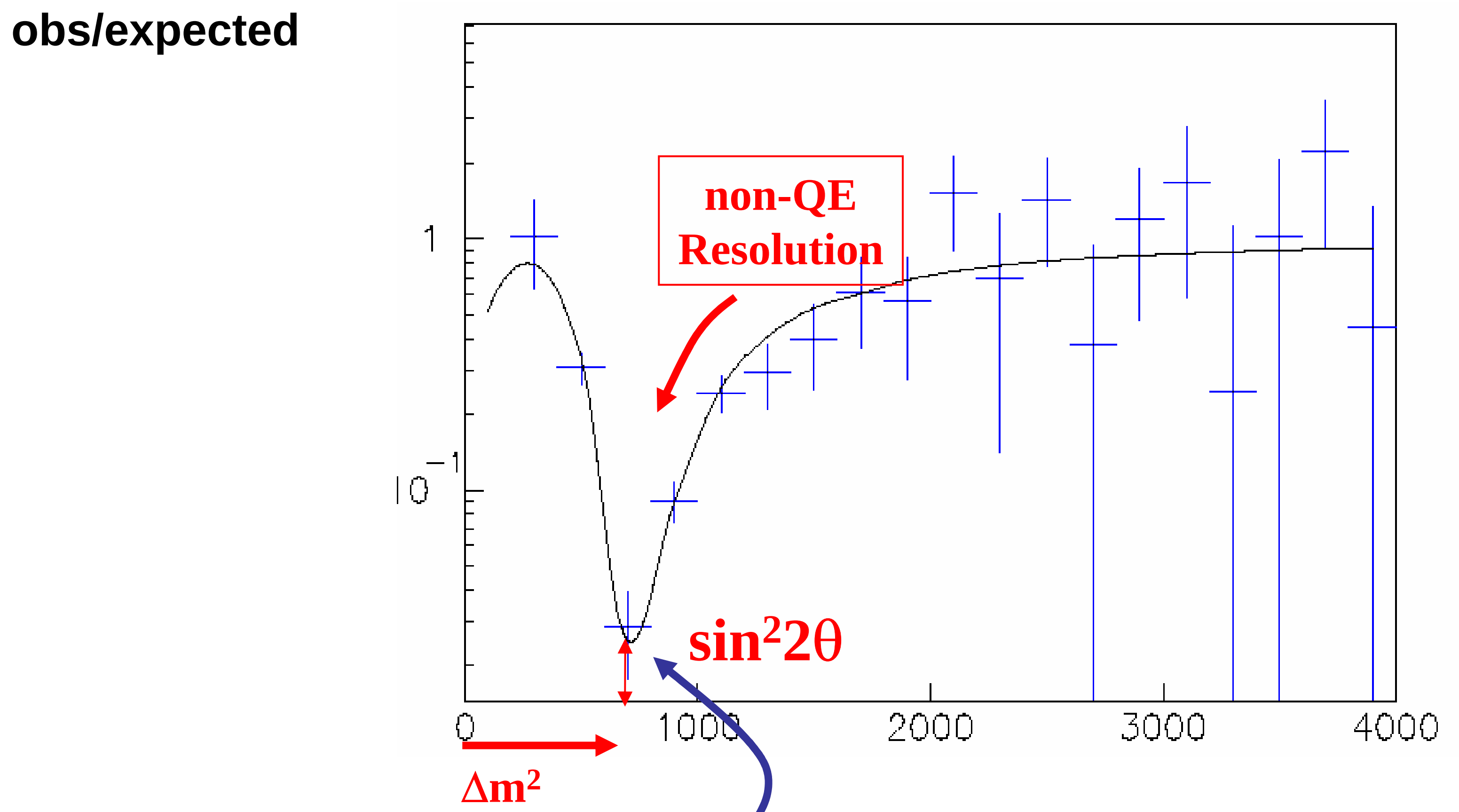


E_ν (reconstructed) – E_ν (true)



✓ No $\nu_\mu - \nu_\tau$

Measurement of θ_{23}



$\pm$ 10% bin P(disappearance)~0.01 x $\sin^2 2\theta$
High resolution : less sensitive to systematics

Neutrino beam concept

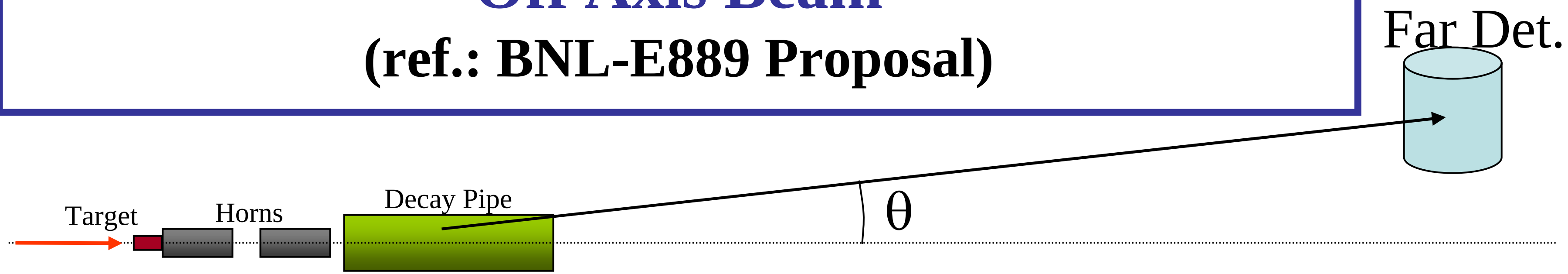
- **Highest possible intensity at relevant energy region**
  - **oscillation maximum at sub-GeV**

- **ν beam suitable for water Cherenkov detector**
  - **good PID with single particle final state**
  - **μ–e decay rejection (ν_e + n → e + p)**

- **Narrow band beam to reduce BG**
  - **Small high energy tail**
  - **CCQE cross section to obtain neutrino spectrum**
  - **Neutrinos from main part of π**

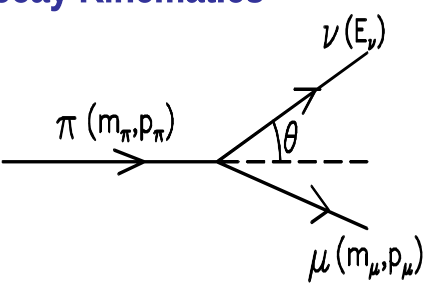
Off Axis Beam

(ref.: BNL-E889 Proposal)

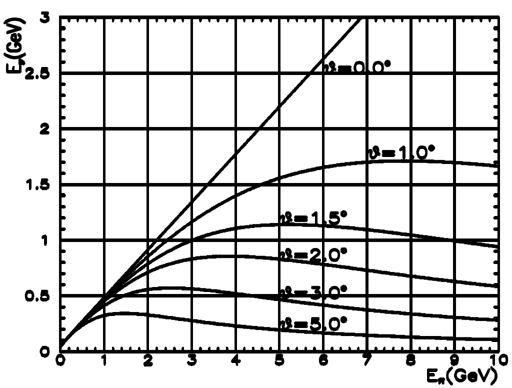


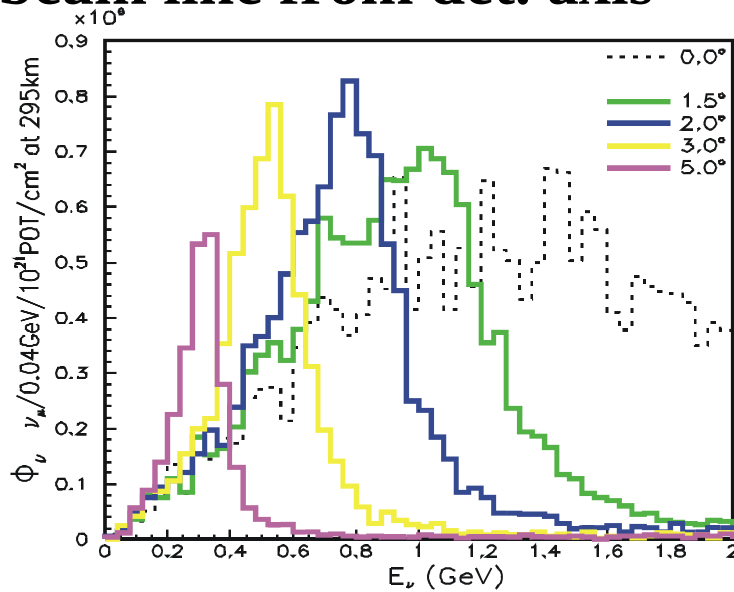
WBB w/ intentionally misaligned beam line from det. axis

ecay Kinematics



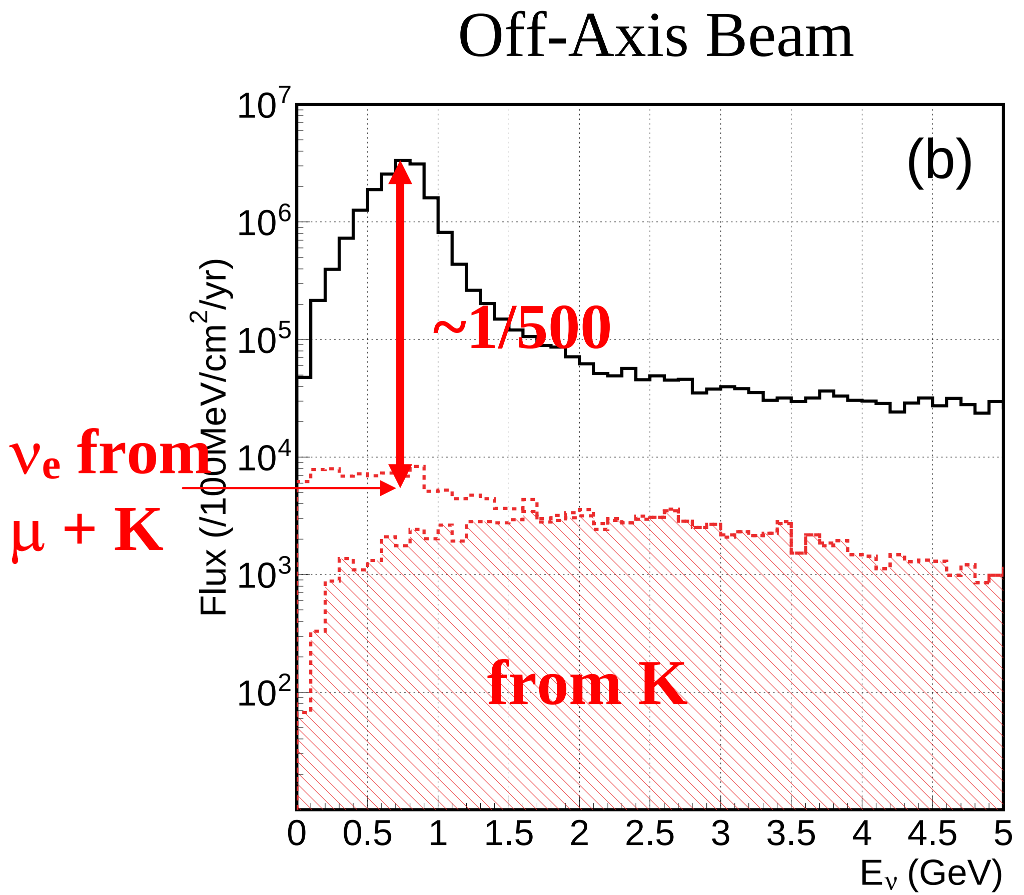
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$



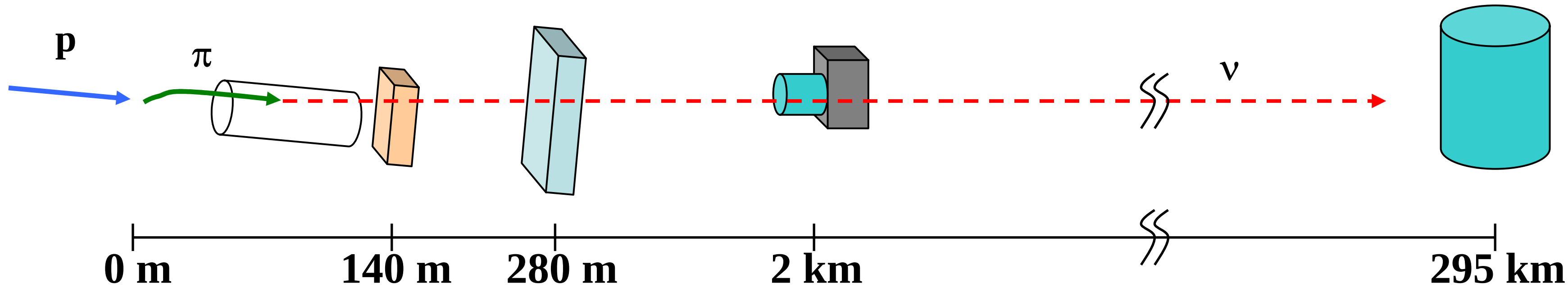


- **Highest intensity at low energy 4500 int./22.5kt/year (10^7 sec.)**
- **Contamination ν_e:0.8%(0.2% @ peak)**
- **Low Eν from main part of pion production**

Extra handle in ν_e appearance search



Intrinsic background: ν_e / ν_μ (peak) ~ 0.002



Muon monitors @ ~140m

– spill-by-spill monitoring of π–beam direction/intensity

First Front detector @280m

– 0 degree definition
– E_ν, π^0 production to ~10%

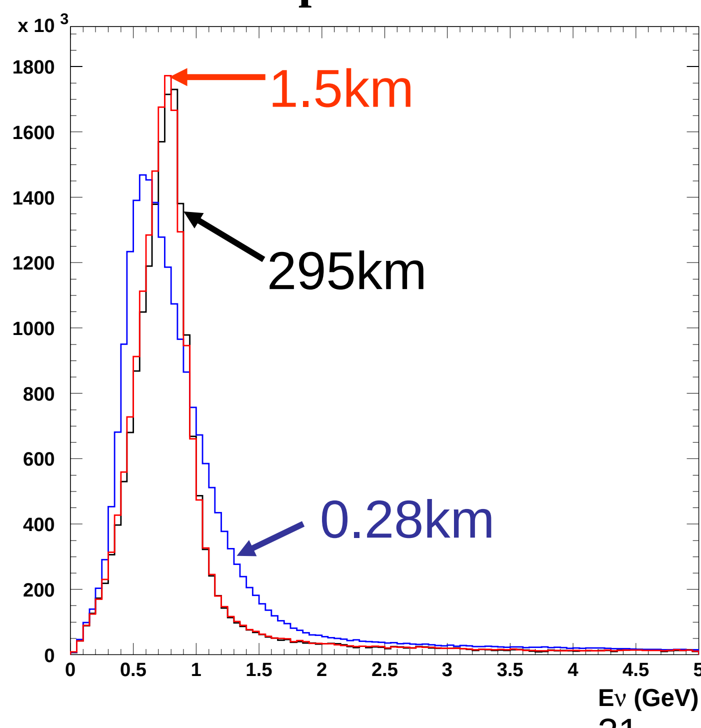
Second Front Detector @ ~2km

– Ultimate systematics

Far detector @ 295km

– Super-Kamiokande (50kt)

Neutrino spectra at diff. dist



dominant syst. in K2K

Measurement of $\sin^2 2\theta_{23}$, Δm^2_{23}

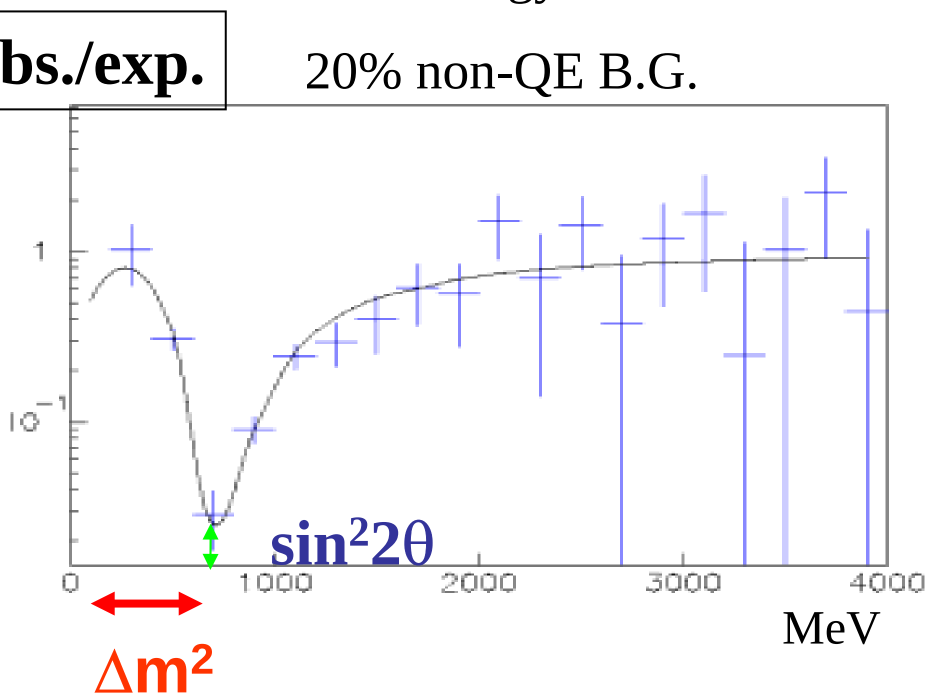
ν_μ disappearance: How close to the maximal mixing?

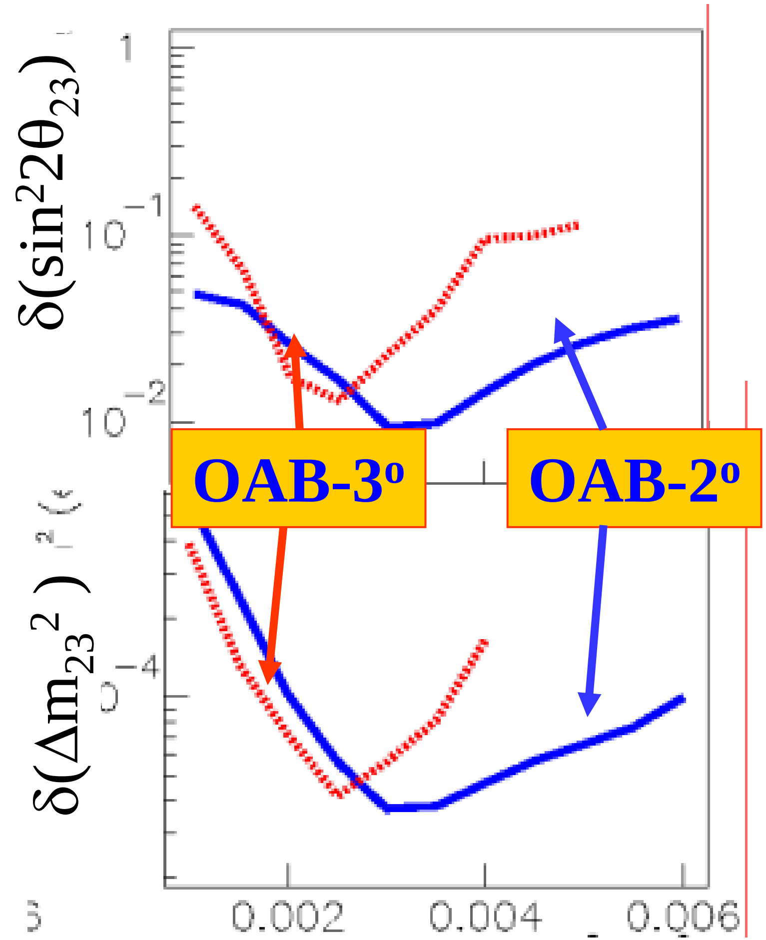
FC, 1-ring, μ-like events

Sys. error 10% for near/far

4% energy scale

20% non-QE B.G.





$\delta(\sin^2 2\theta)\sim 0.01$ $\delta(\Delta m^2)$ $\sim< 1 \times 10^{-4}$

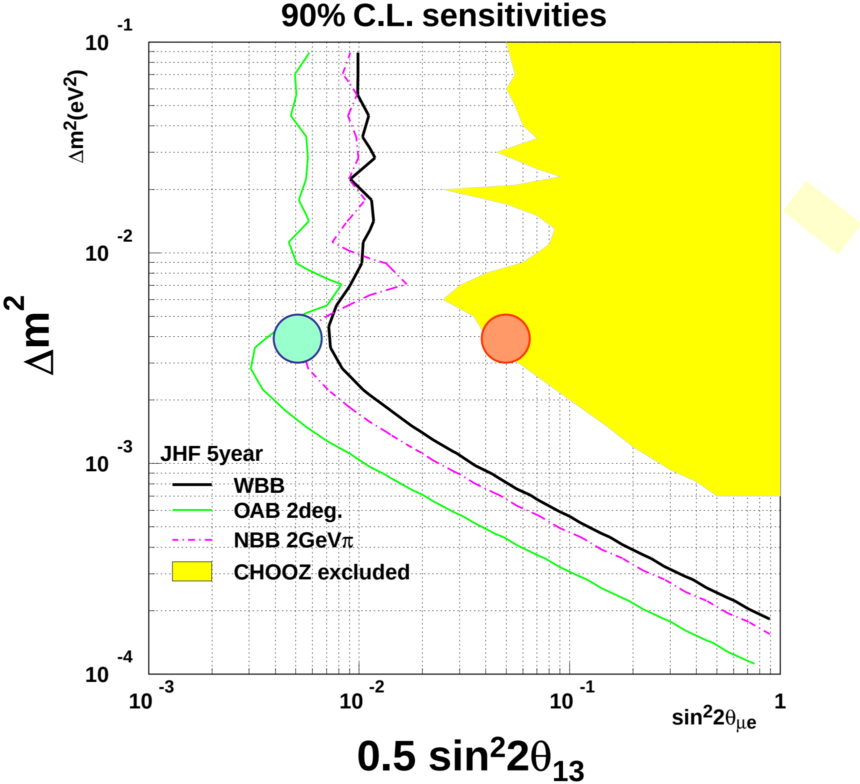
True Δm_{23}^2 (eV^2)

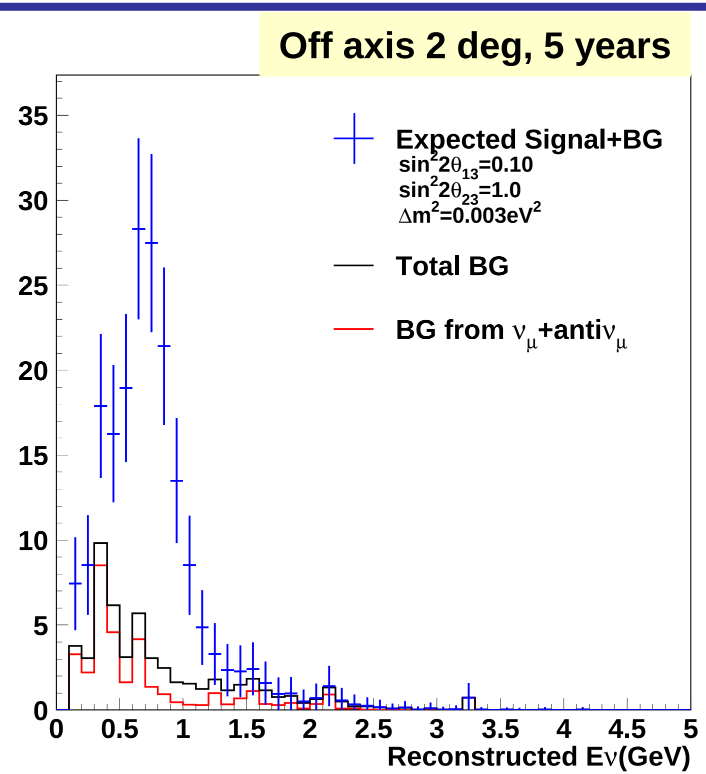
ν_e appearance search

- Selection of ν_e events
  - 1 ring e-like
  - No decay electrons
  - Visible Energy > 100 MeV
  - Tight e/π^0 separation
  - Reconstructed $E\nu$ cut
  - Background Subtraction

  - Correct matter effect, difference of ν spec., cross section, and detection eff. to θ_{13}

$\sin^2 2\theta_{13}$ from appearance experiment $\nu_e + n \rightarrow e + p$



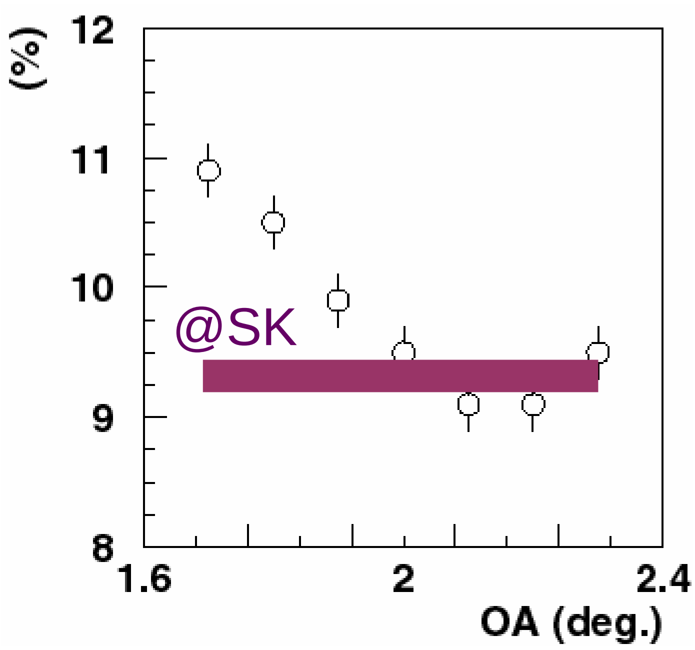


$\sin^2 2\theta_{13}$	Background in Super-K					Signal	Signal + BG
	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$	total		
0.1	12.0	10.7	1.7	0.5	24.9	114.6	139.5
0.01	12.0	10.7	1.7	0.5	24.9	11.5	36.4

Off axis 2 deg, 5 years

NC-π^0 / CC ratio at 280m position

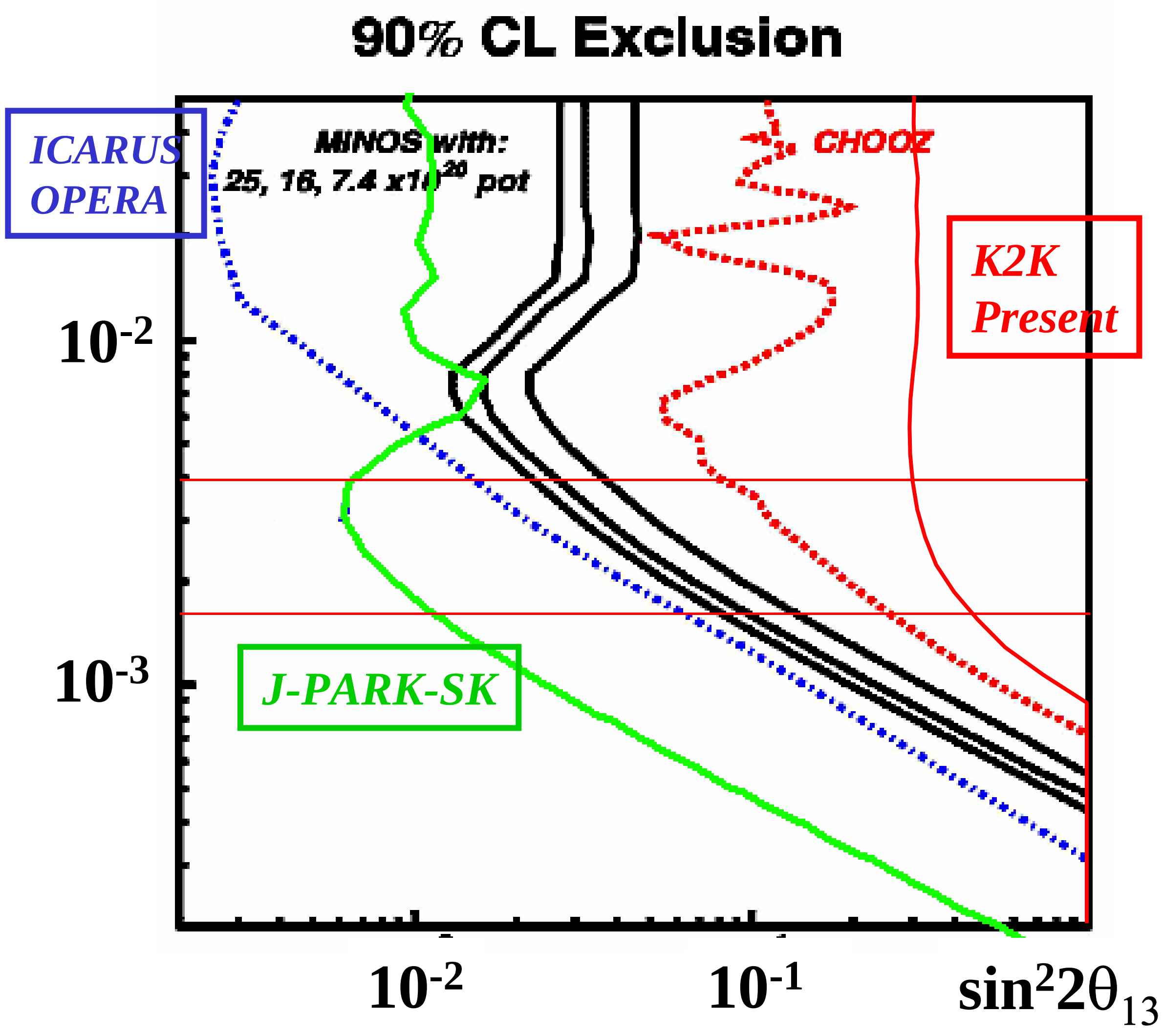
Beam OA2.5deg



10% determination of NC-π^0 background can be negligible

The best position is OA2.0~2.3deg

Expected 90% CL sensitivity on θ_{13} in this decade



Summary of Phase-I

★**Precision measurement of neutrino mixing matrix**

$\delta(\sin^2 2\theta_{23})$ ••• 1% (factor 8 improvement)

$\delta(\Delta m^2_{23})$ ••• a few % (factor 10 improvement)

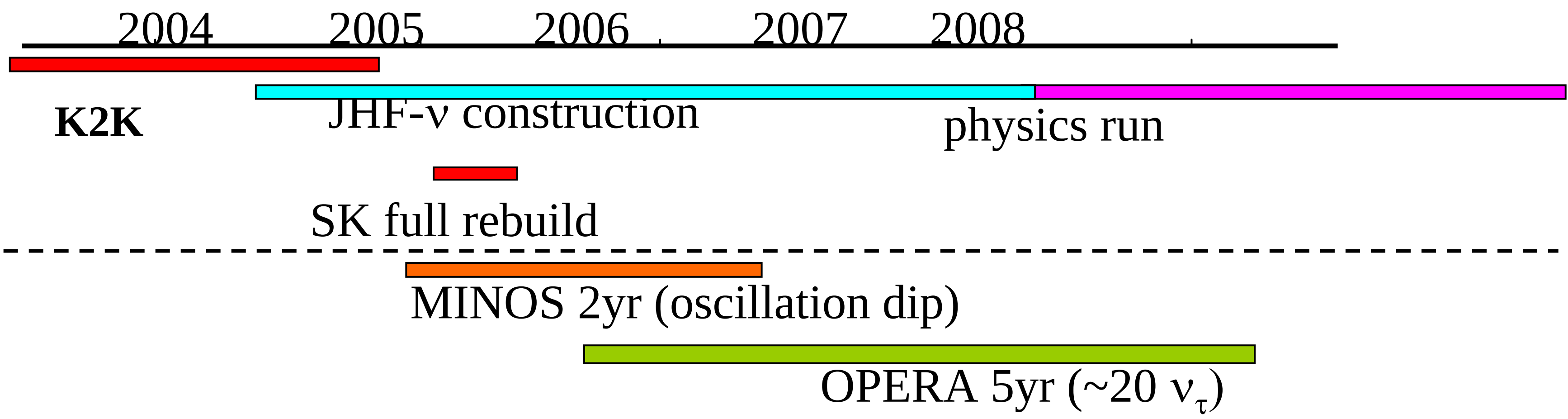
★**Discovery and measurement of non-zero θ_{13}**

$\sin^2 2\theta_{13}$ ••• > 0.006 (factor 20 improvement)

1st Evidence of 3-flavor mixing !

1st step to CP measurement

Schedule & Summary



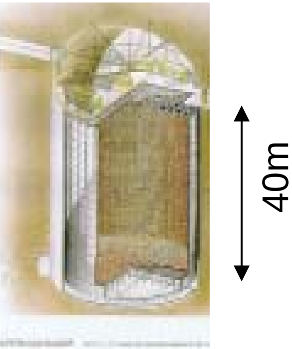
- **Beyond the 'confirmation' of neutrino oscillation**
- **Best possible measurements of neutrino oscillation with present technology**
- **World-wide interests to join the experiment**

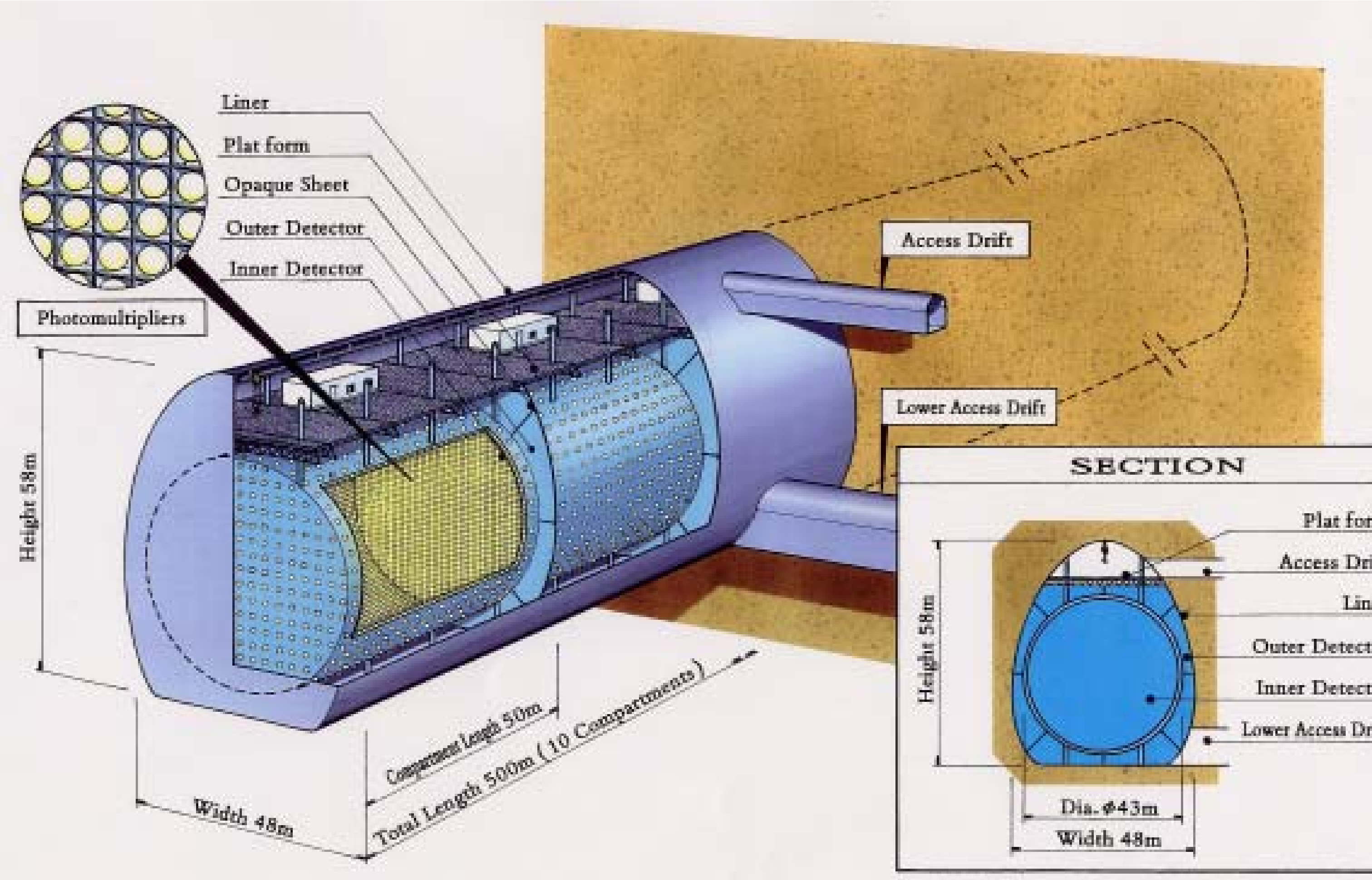
- **Possible upgrade in future**
  - **4MW Super-JHF + Hyper-K (1Mt water Cherenkov)**
  - **CP violation in lepton sector**

Future upgrade

Schematic drawing of Hyper-Kamiokande

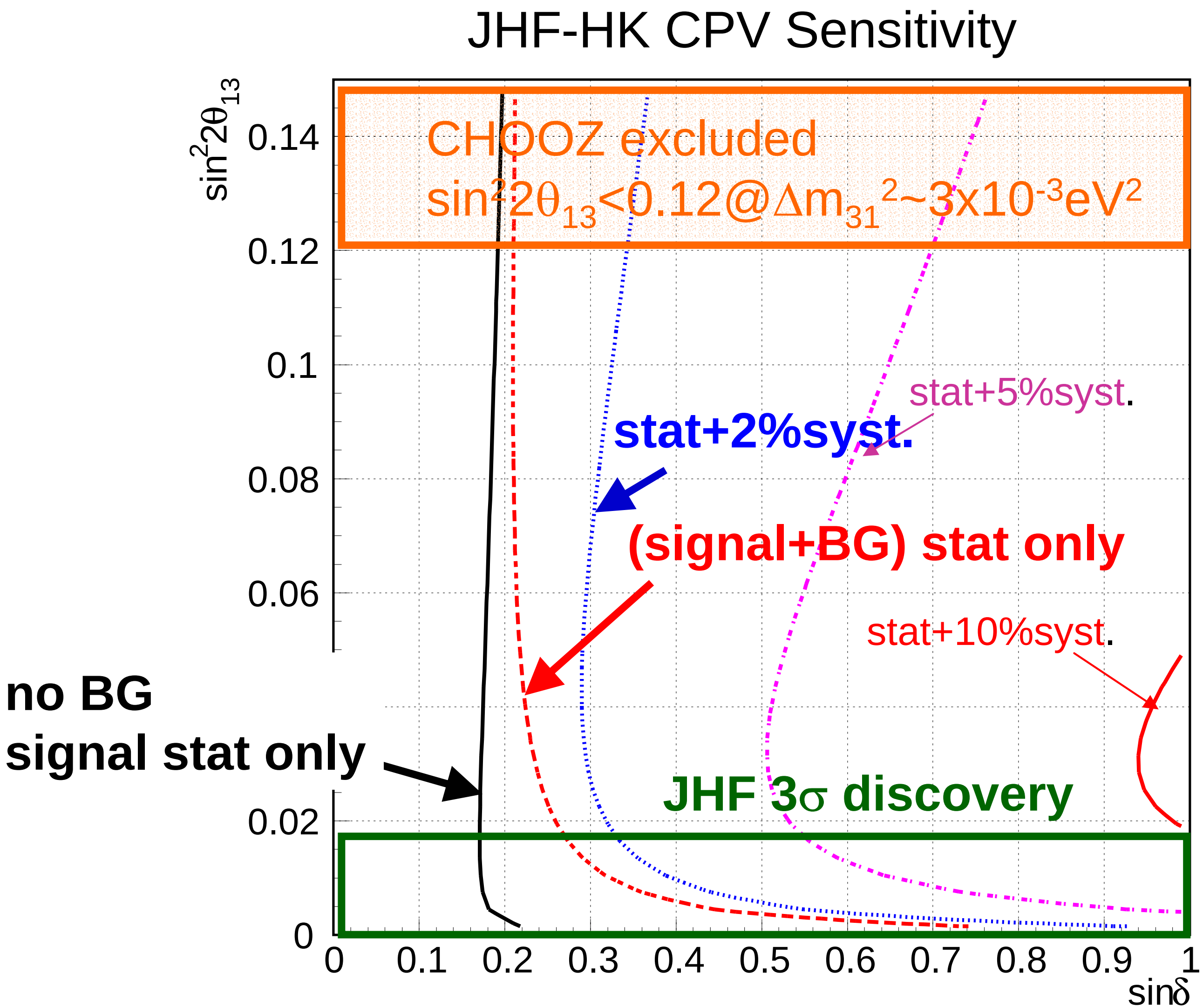
Super-K





1 Mton (fiducial) volume: Total Length 400m (8 Compartments)

~~CP~~ sensitivity (3σ)



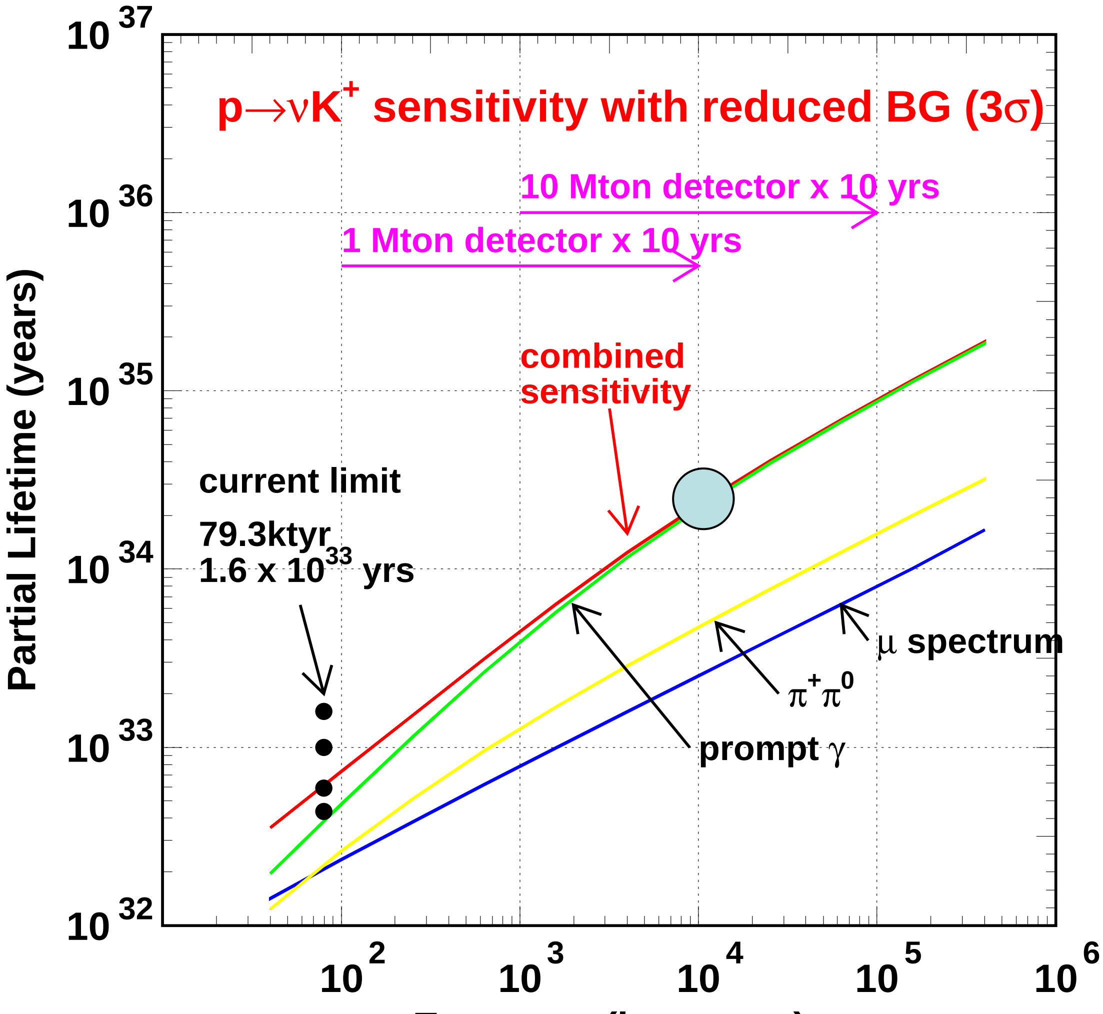
3σ CP sensitivity : |δ|>20° for $\sin^2 2\theta_{13}$>0.01 with 2% syst.

Sensitivity limit of p→νK^+ in HK

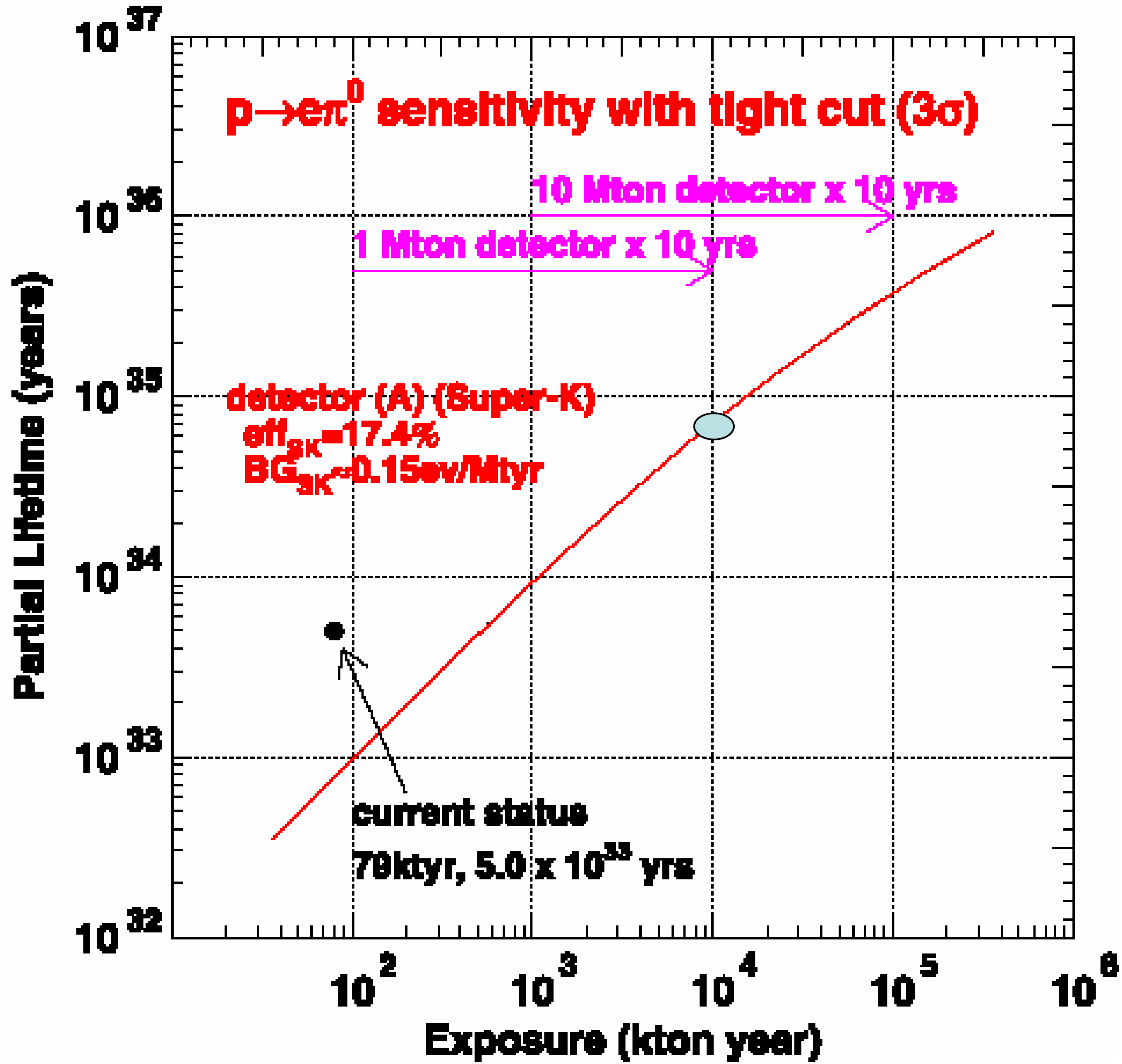
$^{16}O \rightarrow {}^{15}N^* + \nu + K^+$

↓ γ(6MeV, prompt)

$K^+ \rightarrow \nu + \mu^+$ (12ns delay)



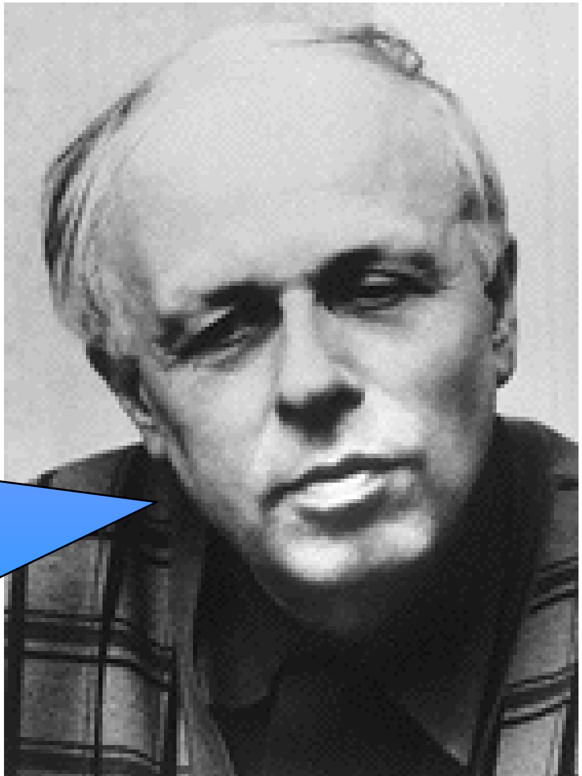
Sensitivity limit of p→eπ^0 in HK



$B > \bar{B}$ Universe

1967 Saharov

1. Violation of Baryon number
2. P and CP violation
3. Non thermal equibrium



Summary

- **Precise observations of solar and atmospheric neutrinos over the last 10 years**
- **Deficits of solar ν_e and of atmospheric ν_μ revealed the existence of two types of neutrino oscillations**
- **Underlying parameters were determined with rather poor accuracies**
- **Hierarchical masses $(m_3>m_2>m_1)$:**
  - **$m_3 \sim 0.04 – 0.06$ eV**
  - **$m_2 \sim 0.005 – 0.01$ eV**
    - All 90% C.L.

Degenerate masses $(m_3 \sim m_2 \sim m_1)$:

$m_e < 2.2$ eV

$\Sigma m_i < 6.6$ eV

(95% CL)

- **Neutrinos**
  - **$\sin^2 2\theta_{12} = 0.6 – 0.9$**
  - **$\sin^2 2\theta_{23} = 0.92 – 1.0$**

Quarks

$\sin^2 2\theta_{12} = 0.188 \pm 0.007$

$\sin^2 2\theta_{23} = 0.0064 \pm 0.0010$

cont1

- **Values of θ_{13} and CP phase δ are still unknown**
- **Toward near GUTs**
  - **New experiments are proposed:**
    - MINOS at Fermi Lab
    - CNGS (CERN to Gran Sasso)
    - J-PARC-Kamioka
    -
    -