# Oscillation Physics with Superbeams

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# Long-Baseline Experiments Today

| Experiment | Source | Baseline (km) | ↑$E_\nu$⇧ (GeV) | Power (MW) | Rate ($\mathrm{yr}^{-1}$) |
|---|---|---|---|---|---|
| K2K | KEK | 250 | 1 | 0.005 | 50 |
| MINOS | FNAL | 732 | 3 | 0.4 | 1000 |
| CNGS | CERN | 730 | 17 | 0.17 | 3700 |

Note: "1 year" is defined as $10^7$ seconds

# View from the Crystal Ball

- Near-term long-baseline experiments focused on dominant $\nu_\mu \rightarrow \nu_\tau$ channel
  - Expect ~few percent measurements
  - Possible direct observation of $\nu_\tau$ appearance
  - Sensitivity to $\sin^2 2\theta_{13}$ around few % level
  - Sensitivity of all limited if $\Delta m_{23}^2$ small
- Kamland, Borexino should determine solar solution
  - LMA solution critical to CP violation searches
- Mini-BOONE will test LSND
  - Precision mixing measurements imperative if confirmed

# Next Generation Goals

- Precision measurement of dominant oscillation $\nu_\mu \rightarrow \nu_\tau$ channel
- Sensitivity to sub-dominant $\nu_\mu \leftrightarrow \nu_e$ channel at 1‰ level
- Determine sign of $\Delta m_{13}^2$
- Sensitivity to $\delta_{CP}$
  - "Phase 2" goal, after $\theta_{13}$
    - Requires upgraded beams, larger detectors
  - Dependent on solar neutrino solution

# Neutrino Factories

- The ultimate tool for probing neutrino oscillation
  - Enormous luminosity
  - Exceptional purity
  - Perfect knowledge of spectrum
  - Flavor of initial neutrino tagged by charge
- Caveats:
  - Technical challenges to muon acceleration
  - Cost
- Not considered here

# Superbeams

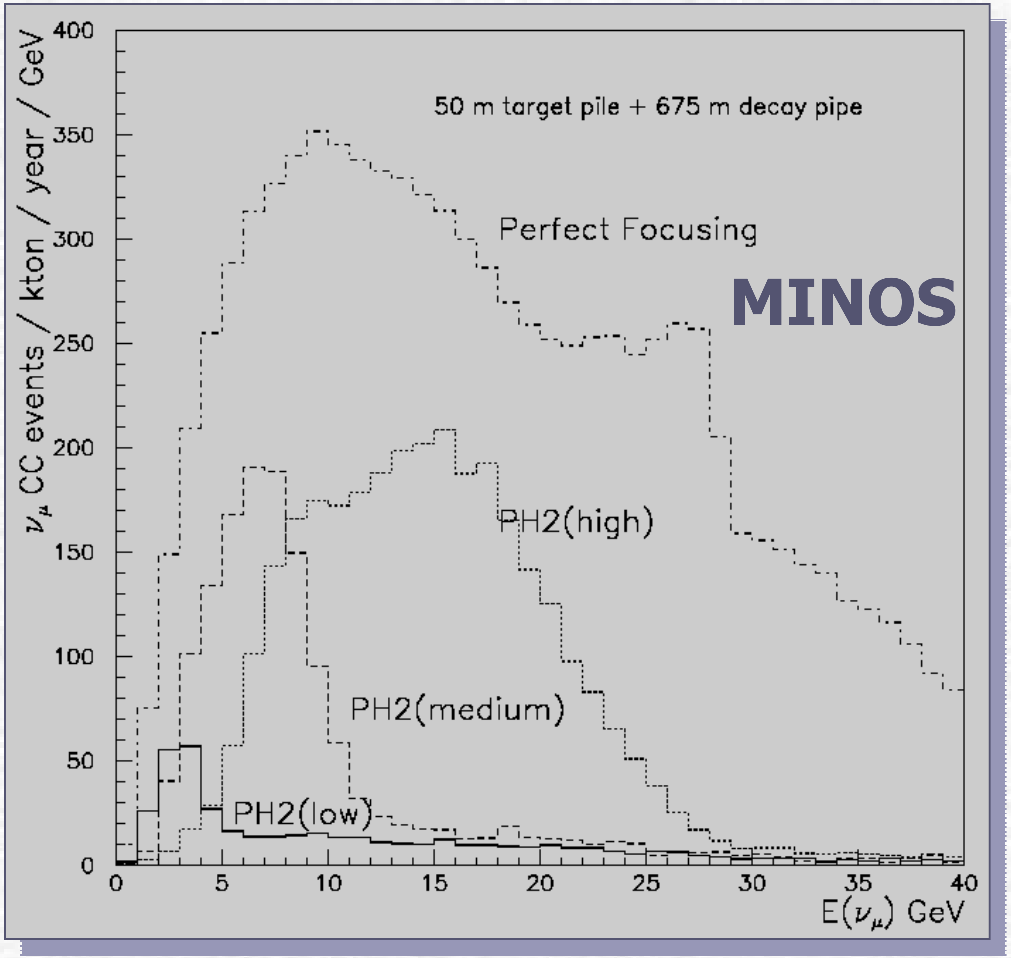
- Exploit extremely intense proton sources to produce beam from $\pi$-decay
- Intermediate step to neutrino factory
  - $\pi$ beam necessary for $\mu$ beam
- Sensitivity intermediate between near-term experiments and neutrino factory
- Cost also intermediate
- Technical hill less steep to climb
  - Proton drivers essentially designed (or existing)
  - Radiation damage near target station may be important

# Possible Future Proton Drivers

| Source | Location | Proton Energy (GeV) | Power (MW) |
|---|---|---|---|
| Upgraded Booster | FNAL | 16 | 1? |
| Upgraded NUMI | FNAL | 120 | 1.6 |
| 50 GeV PS | JHF | 50 | 0.77 (→4) |
| SPL | CERN | 2.2 | 4 |

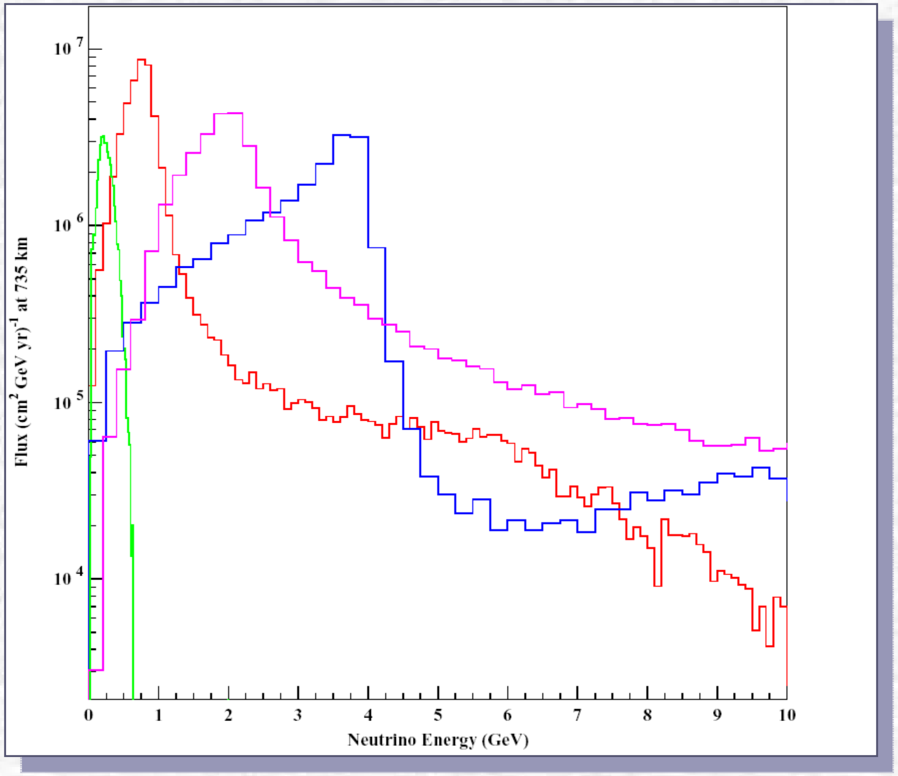
# Upgraded NUMI Beams

- Expect four-fold luminosity increase of MINOS neutrino beam
- $\nu_e$ contamination: 0.5%
- Beam direction fixed by existing MINOS experiment
- Go off-axis to suppress high-energy tail?



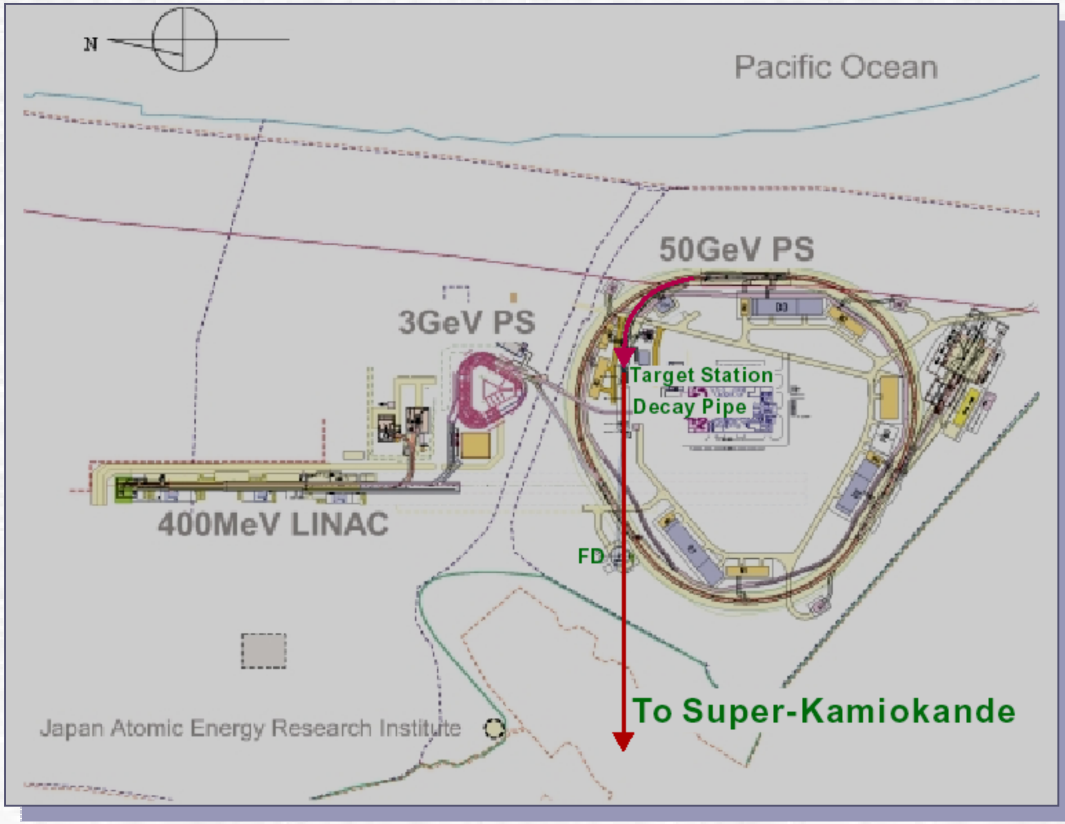
# Off-axis/Dipole NUMI beams

- Variations on NUMI:
  - Off-axis detector with MINOS low-energy beam? (D. Harris)
  - Use dipole after second horn? (F.DeJongh)
- Higher energy implies matter effects



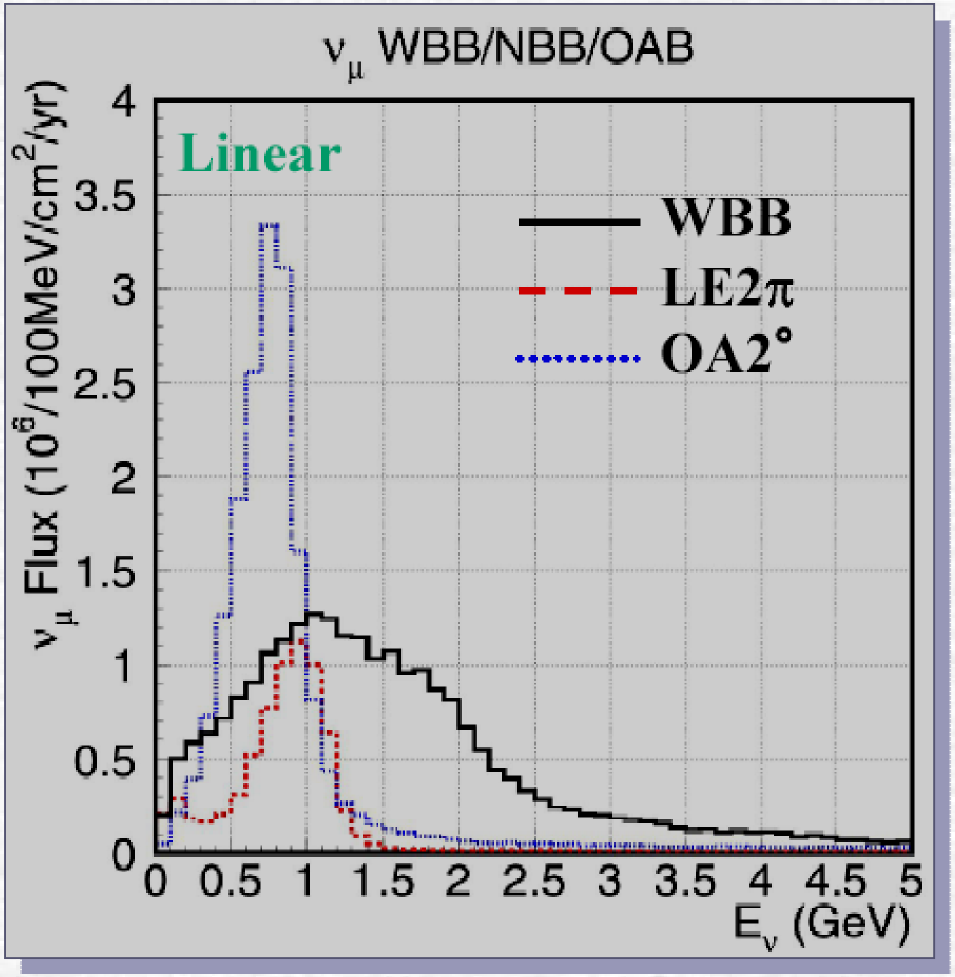
# JHF 50 GeV PS

- Approved:
  - 50 GeV PS
  - 0.77 MW
- Proposed:
  - Neutrino beamline to Kamioka
  - Upgrade to 4 MW
- Outlook:
  - Completion of PS in 2006/2007



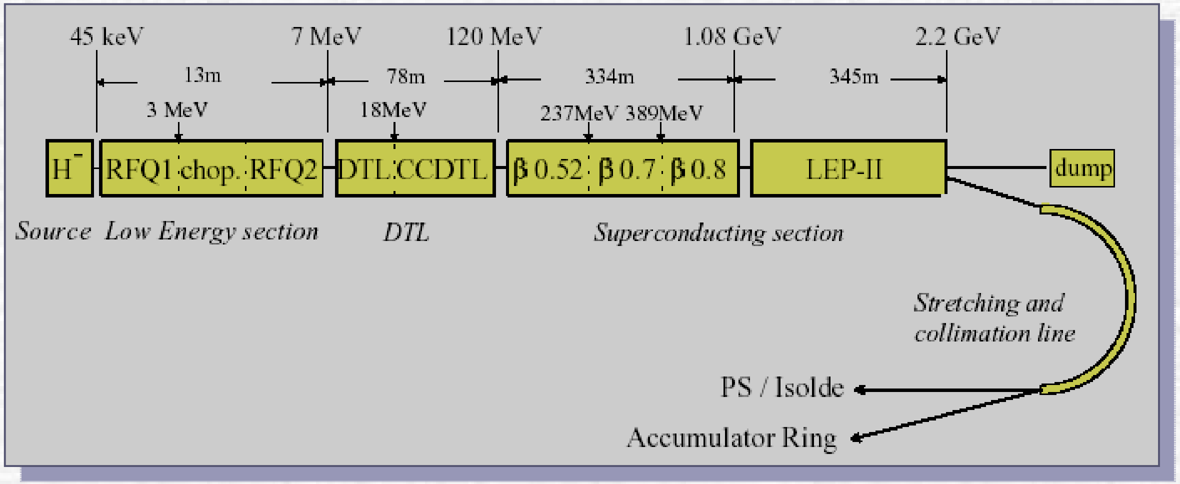
# JHF Neutrino Beams

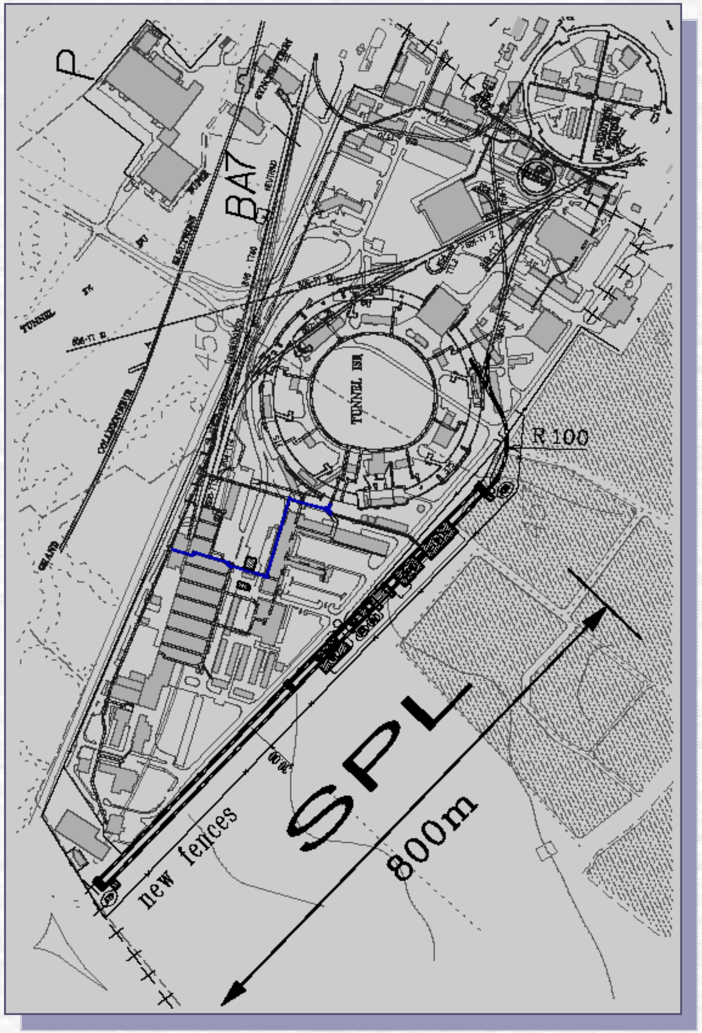
- Wide-band beam
  - Horn-focusing only
  - Long high-energy tail
- Narrow-band beam
  - Pions momentum-selected with dipole
  - Lower intensity
- Off-axis beam
  - Intense, narrow
  - Less tail than WBB
  - 0.2% $\nu_e$ around peak energy



# CERN/SPL

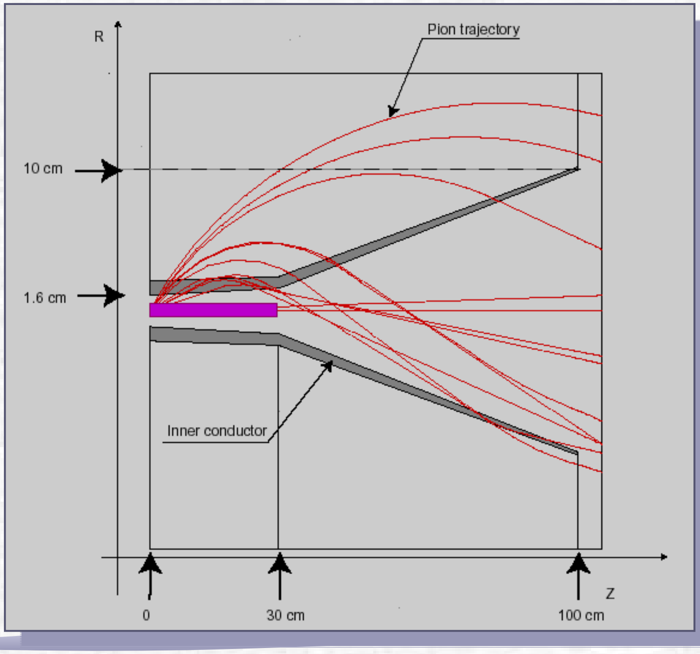
- Proposed:
  - Recycle LEP RF cavities into proton linac
  - Proton kinetic energy: 2.2 GeV
  - Power: 4 MW
- Outlook:
  - Not yet approved
  - Recommendation by ECFA considered likely

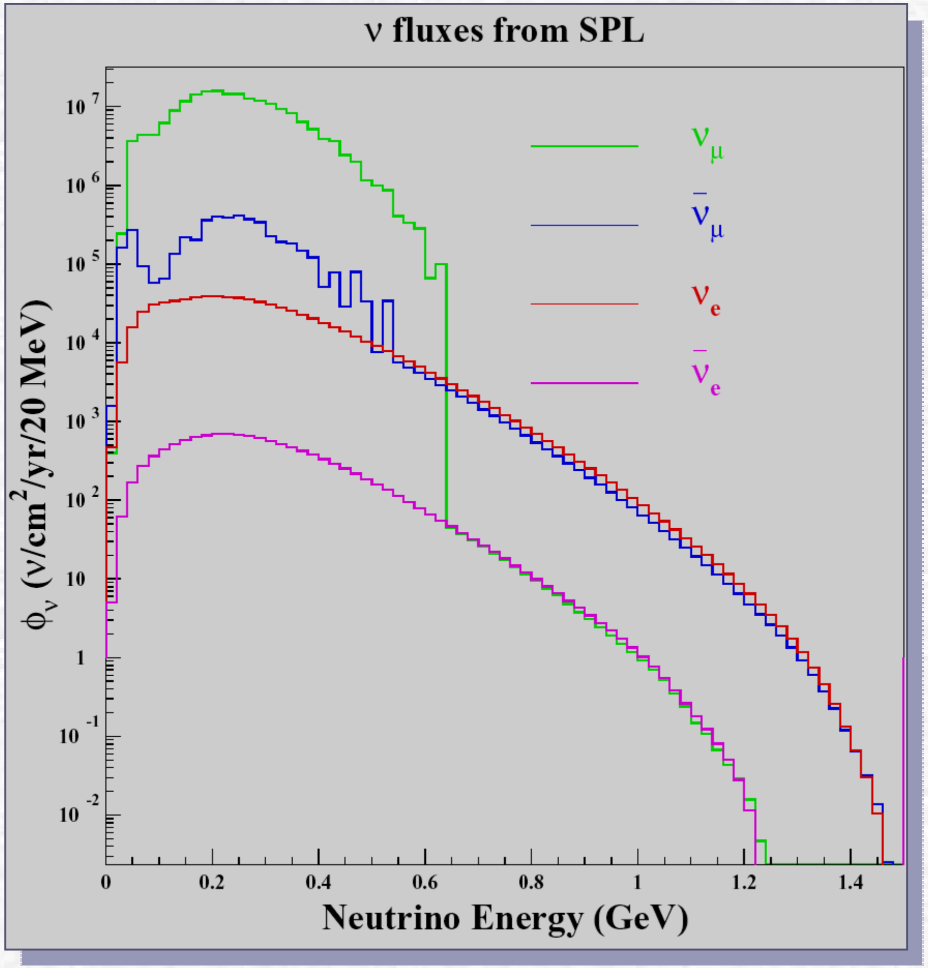




# SPL Neutrino Beam

- MARS Monte Carlo
- Liquid Hg jet target
- 20 m decay tunnel
- Kaon production negligible
- Few ‰ $\nu_e$ content
- $E_\nu$ ~ 250 MeV





# Beta Beam

- New idea proposed by P.Zucchelli
- The principle:
  - Accelerate $\beta^{\pm}$-unstable ions (in SPS) to $\gamma$~50-100, let them decay in storage ring pointed at far detector (poor-man's $\nu$-factory!)
  - Produce pure, high-energy electron-flavor beam
  - Spectrum perfectly known from lab measurements of ion decays
- Candidate ions:
  - $^{18}$Ne ($\beta^+$, neutrino emitter)
    - Projected luminosity: $3.6 \times 10^{17}$ "useful" decays per year
  - $^{6}$He ($\beta^-$, anti-neutrino emitter)
    - Projected luminosity: $2.9 \times 10^{18}$ "useful" decays per year
- Look for numu appearance:
  - Exploit low-energy to avoid pion production
  - Use muon mass and Cherenkov threshold to avoid e/mu confusion
- Possibility to run with neutrino and anti-neutrino sources

# Comparing Superbeams

- Upgraded NUMI
  - High energy (2-15 GeV)
    - Large event rates/kton, requires long baseline
    - Matter effects visible
    - Backgrounds probably worst at high-energy
- JHF
  - Intermediate energy (0.7-1 GeV)
    - Good compromise between backgrounds, baseline and rate
    - Matter effects small (20%)
    - 1% $\nu_e$ in off-axis beam (0.2% on peak)
- SPL, $\beta$ Beams
  - Low energy
    - Requires short baseline, large detector
    - No matter effects
    - Backgrounds smallest

# Oscillations with Superbeams

- Precision measurement of $\sin^2 2\theta_{23}$ and $\Delta m_{23}^2$ by high-statistics $\nu_\mu$ disappearance
- Search for $\theta_{13}$ by $\nu_e$ appearance
- Measure sign of $\Delta m_{13}^2$ using matter effects on neutrino/anti-neutrino beams
- Search for CP violation using $\nu_e$ appearance in neutrino/anti-neutrino beams

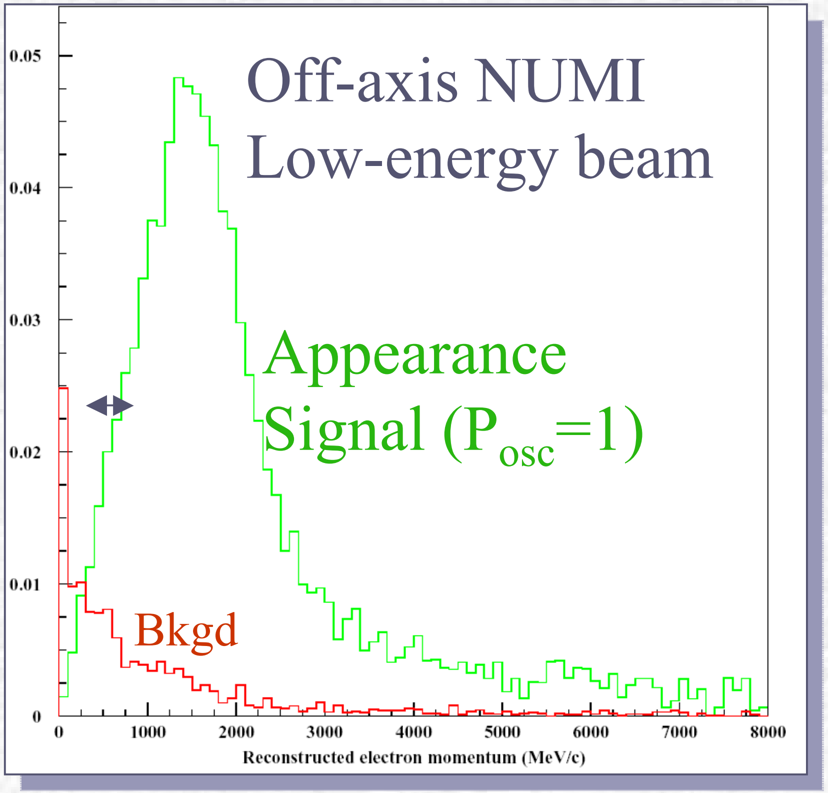
# Water Detectors

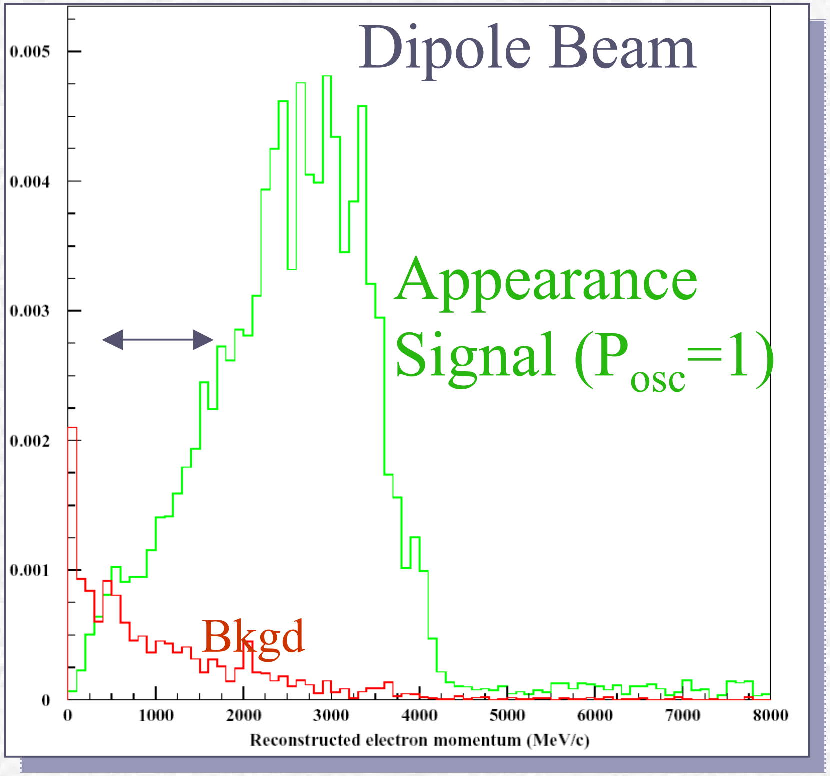
- Affordable large mass (UNO 440 kton fiducial)
- Broad physics capabilities (next talk)
  - Proton decay
  - Atmospheric neutrinos
  - Supernovae, solar neutrinos(?)
- Excellent performance on simple events
  - Lepton ID from pattern recognition
  - Good lepton momentum, direction resolution
  - Topological, kinematic rejection of some NC
- Difficult to identify neutrino flavor with perfect purity in complex events
  - Require single-ring topology → loss of efficiency for high-energy (E > 1 GeV) neutrinos
  - Efficiency less important than background rejection due to large size

# Upgraded NUMI Studies

- Exhaustive scans of parameter space for several detector scenarios, beams, and baselines performed by Barger, et al
    - Parameterize detector performance
- This study:
    - Use two different proposed beams
    - Full simulation of detector
    - Full reconstruction

# NUMI Beams in UNO





Mis-ID background: about 5% of single-ring CC rate

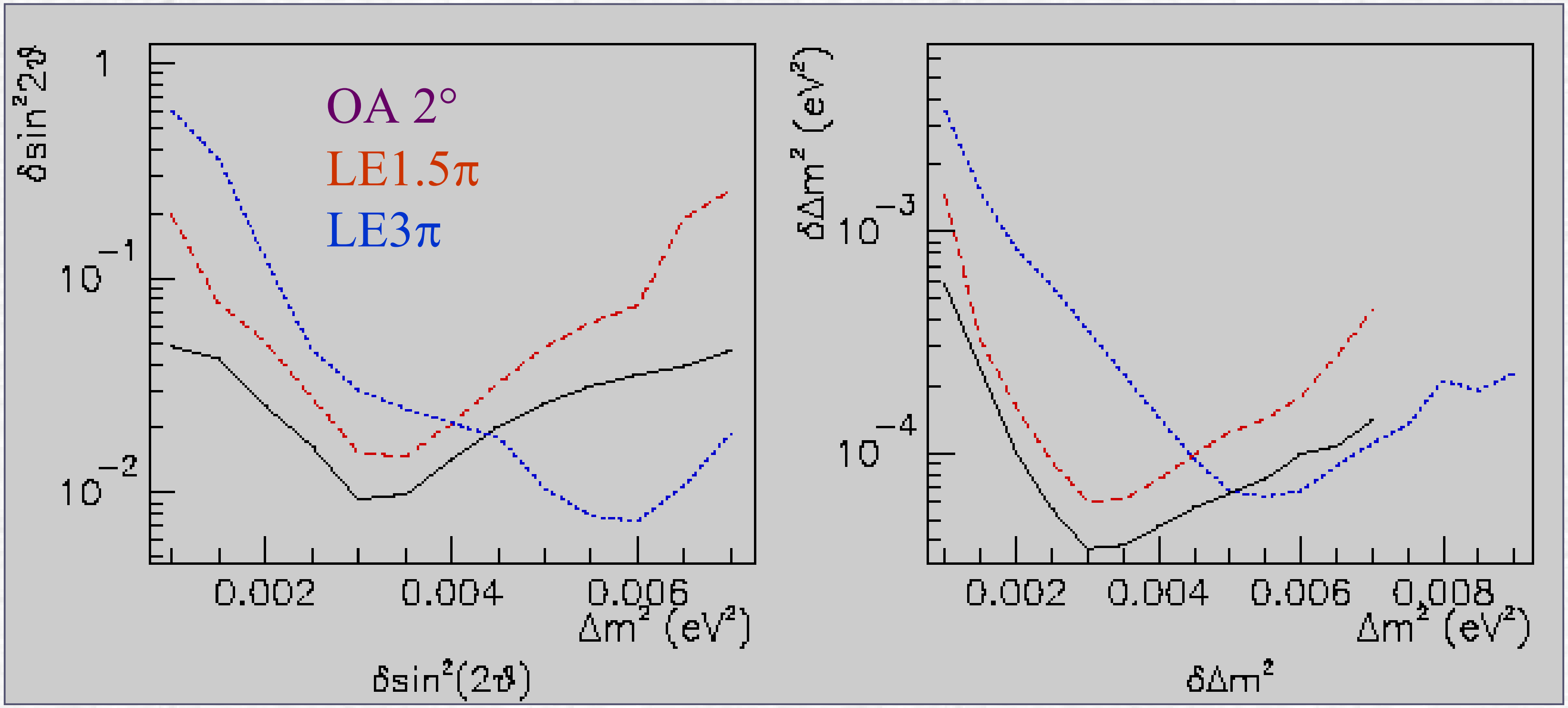
Efficiency for signal at 2 GeV ~ 25%(single ring cut)

Next talk will discuss NUMI beam physics reach

# JHF → Super-Kamiokande

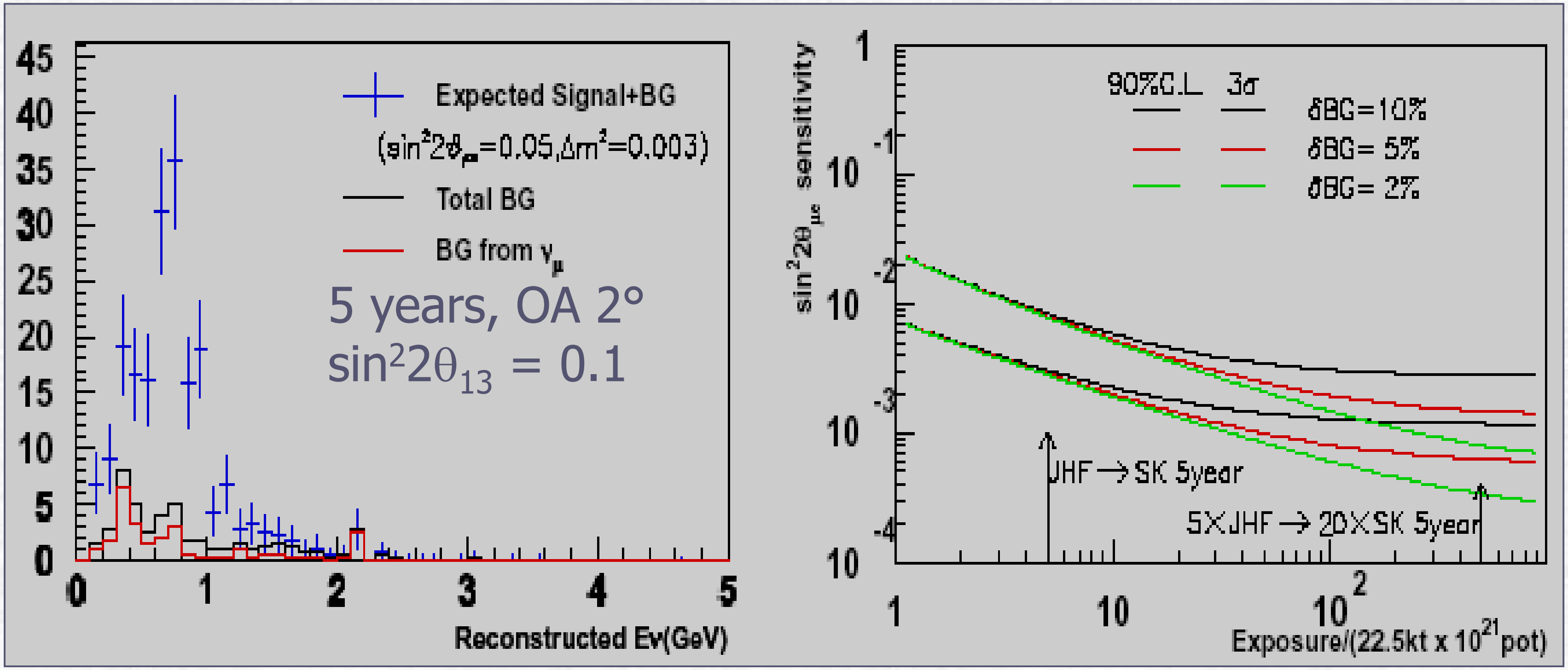
- 295 km baseline
- Super-Kamiokande:
  - 22.5 kton fiducial
  - Excellent e/$\mu$ ID
  - Additional $\pi^0$/e ID
- Hyper-Kamiokande
  - 20× fiducial mass of SuperK
- Matter effects small
- Study using fully simulated and reconstructed data

# JHF → SK: $\nu_\mu \rightarrow \nu_\tau$ Precision



5 years, JHF→SuperK

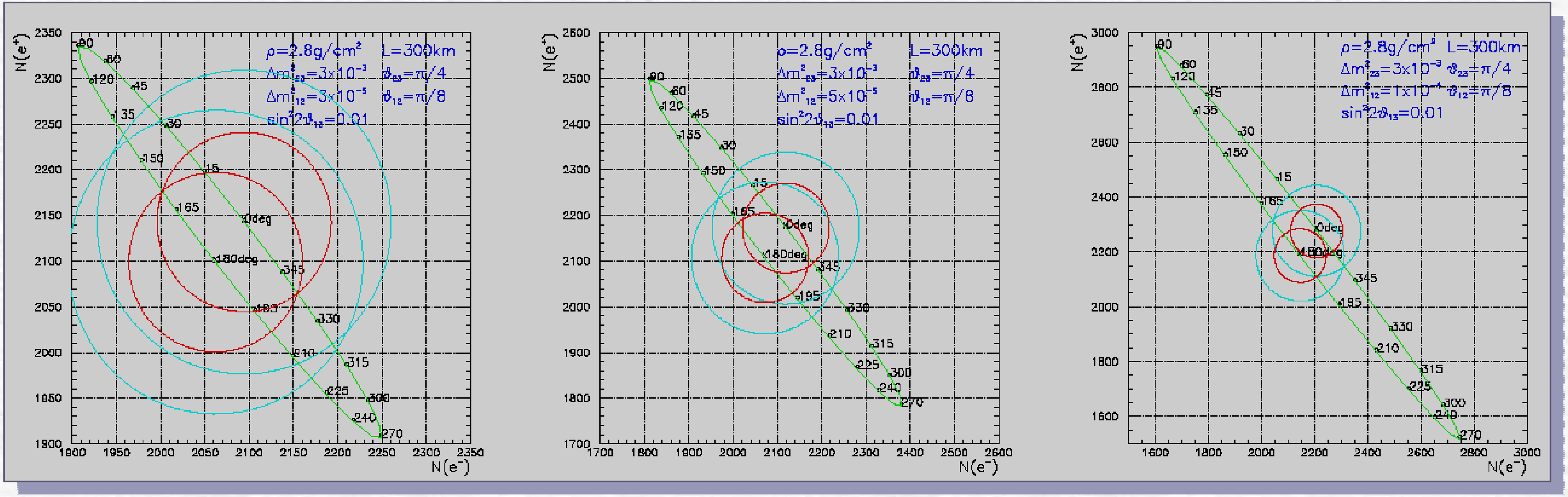
# JHF → SK: $\theta_{13}$ Sensitivity



5 years, OA 2°
$\sin^2 2\theta_{13} = 0.1$

- $\sin^2 2\theta_{13}$ 90% CL sensitivity ~ 0.01 for $1.6\times10^{-3} < \Delta m^2 < 4\times10^{-3}$ eV$^2$ (5 years)

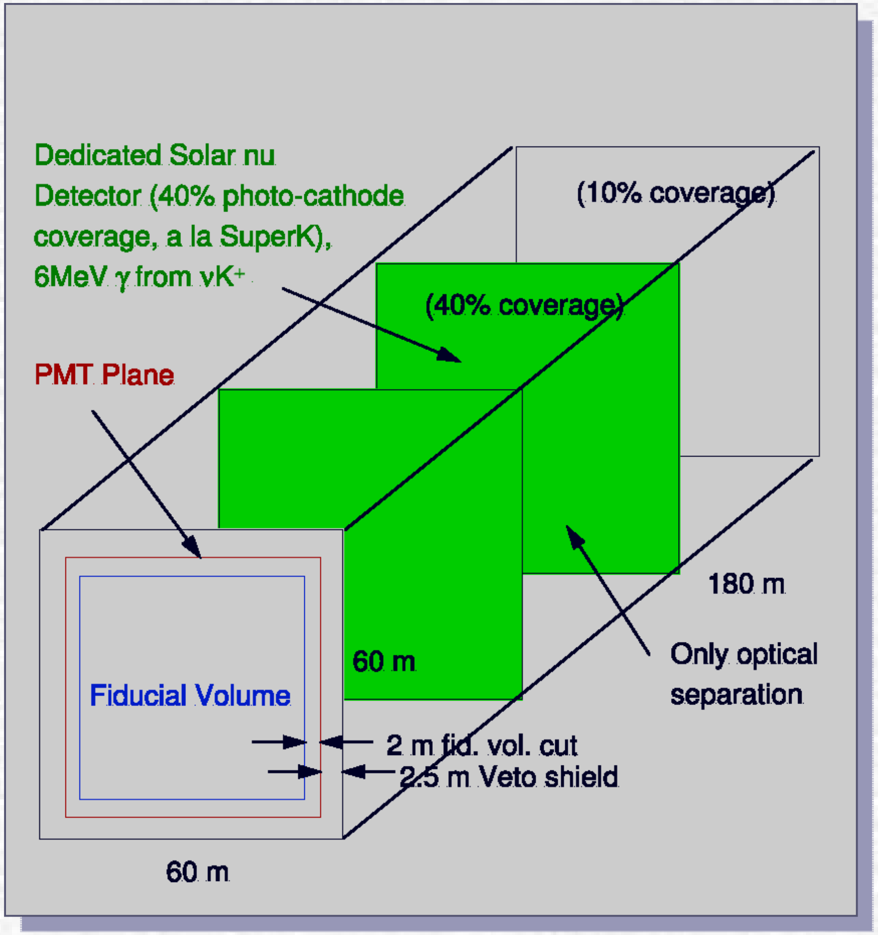
# SJHF → HyperK: $\delta_{CP}$ Sensitivity



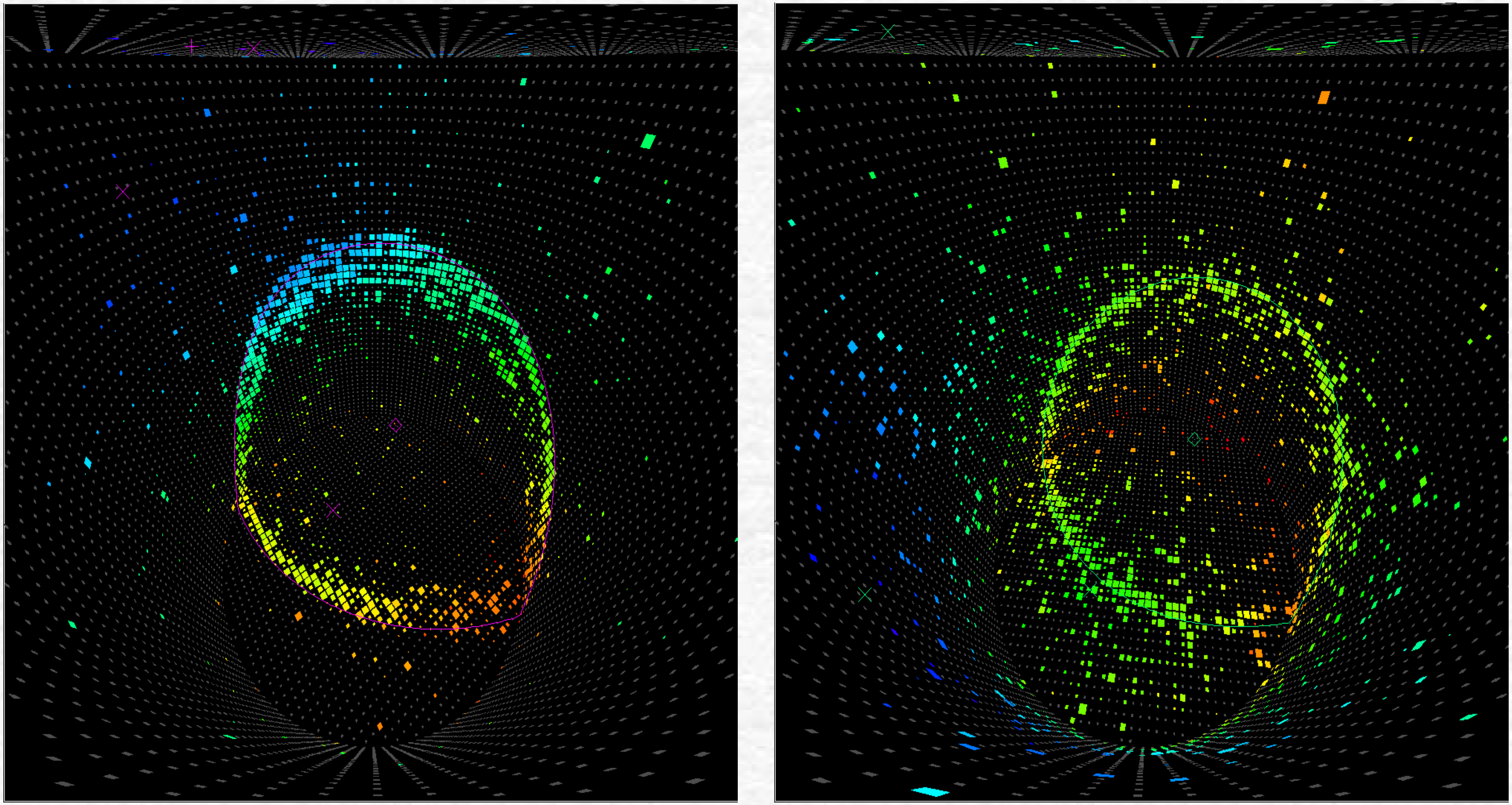
- 4 MW (upgraded) JHF→20×SuperK detector
- 2 years neutrinos, 6 years anti-neutrinos
- Sensitive to maximal $\delta_{CP}$ for LMA

# SPL → UNO

- SPL beam to Fréjus
  - 130 km baseline
- UNO:
  - Next-generation water Cerenkov nucleon decay and neutrino detector
  - 20× fiducial mass of SuperK (445 ktons)
- Study using fully-simulated and reconstructed data

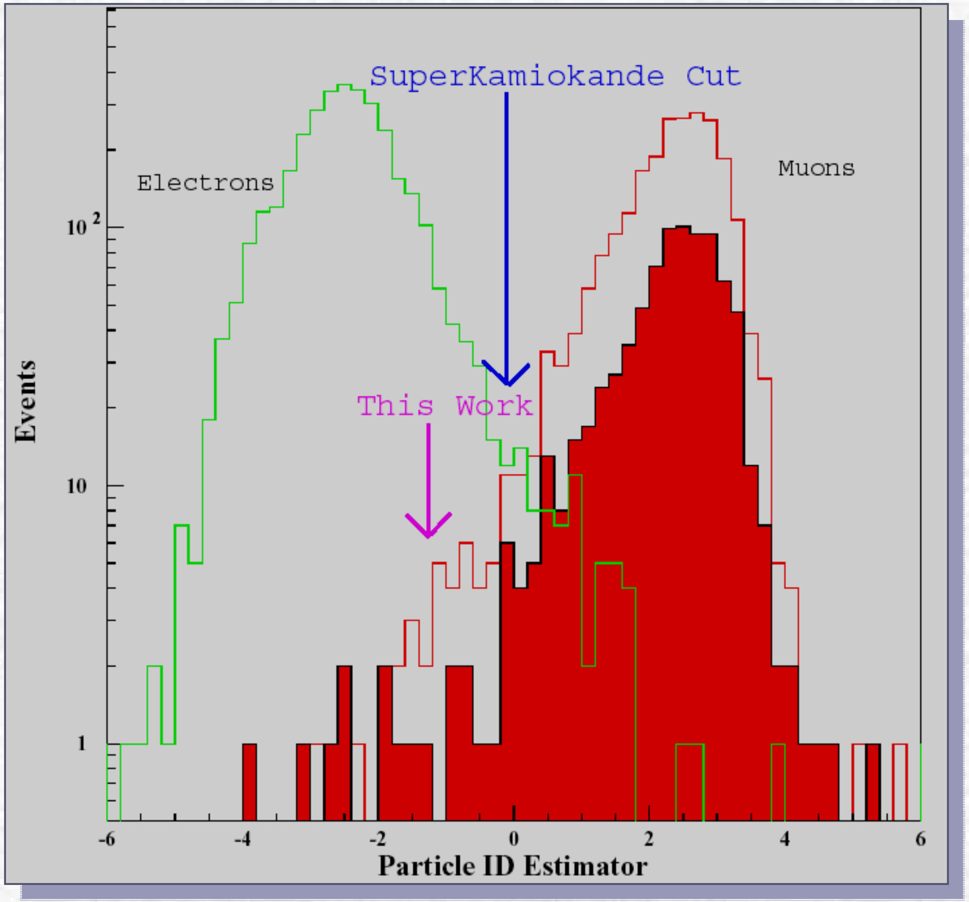


# $\mu$/e Background Rejection



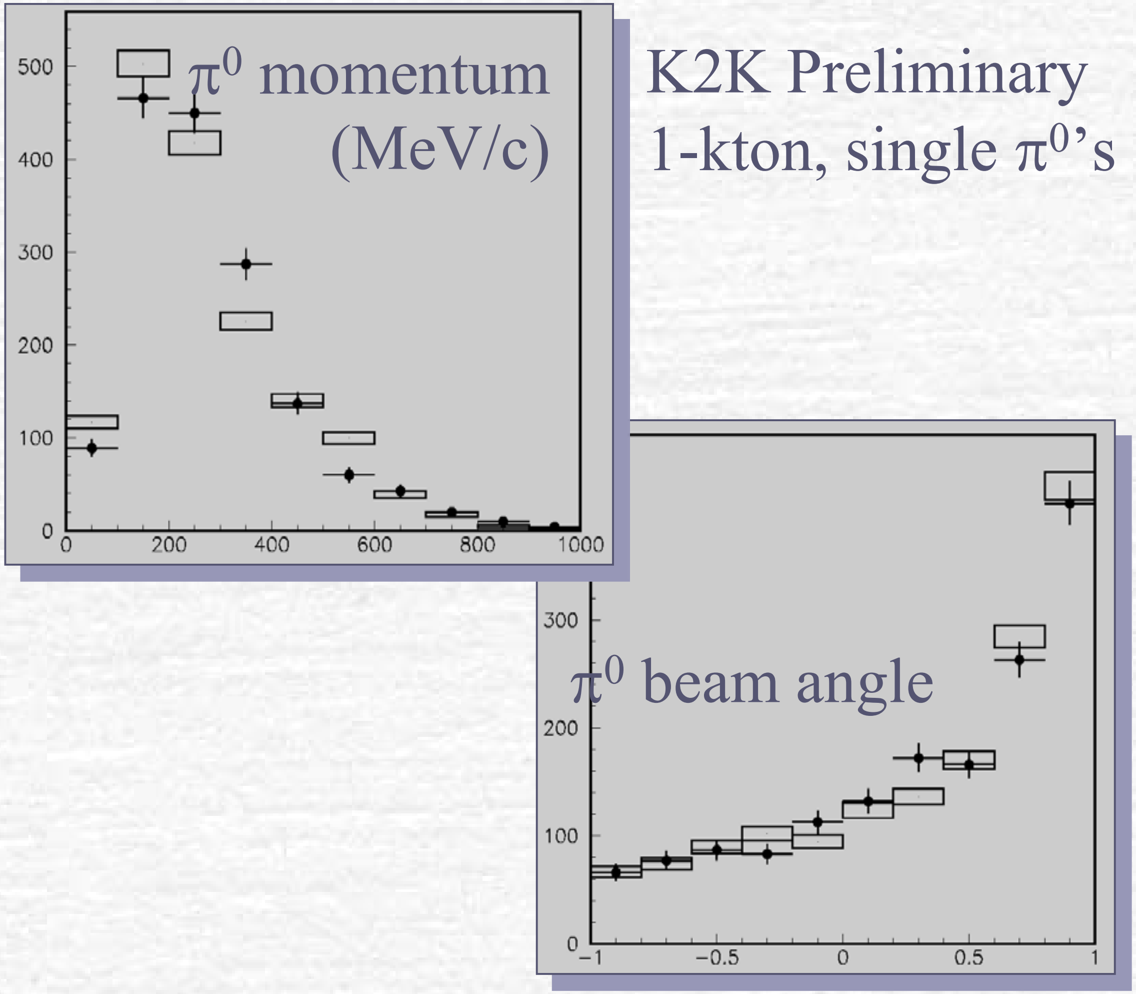
# Particle Identification Cut

- Use Cerenkov light pattern (including opening angle, if possible) as primary $\mu$ rejection
- Tighten cut to reduce mis-ID further
- $\nu_e$ CC Efficiency: 79%
- $\nu_\mu$ CC Contamination:~0.6%



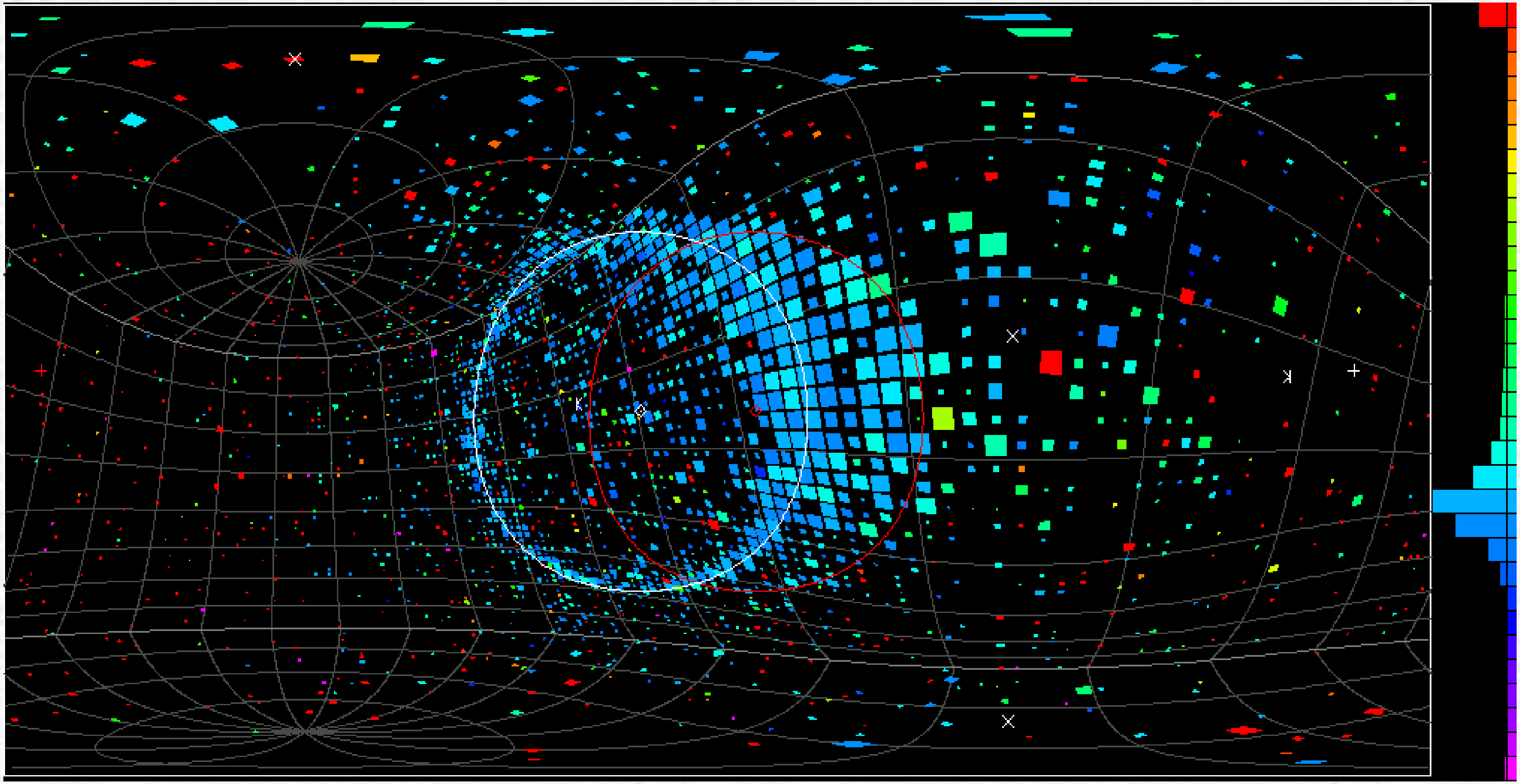
# Neutral Current $\pi^0$ Production

- Data very sketchy
  - ANL
    - $\nu\, p \rightarrow \nu\, n\, \pi^+$ (7 events)
    - $\nu\, n \rightarrow \nu\, n\, \pi^0$ (7 events)
  - Gargamelle
    - $\nu\, p \rightarrow \nu\, p\, \pi^0$ (178 events)
    - $\nu\, p \rightarrow \nu\, p\, \pi^0$ (139 events)
    - No cross-section
  - BNL
    - $\nu\, p \rightarrow \nu\, p\, \pi^- / \nu\, p \rightarrow \mu\, p\, \pi^+$
- Hope to measure with 1kton detector (K2K)



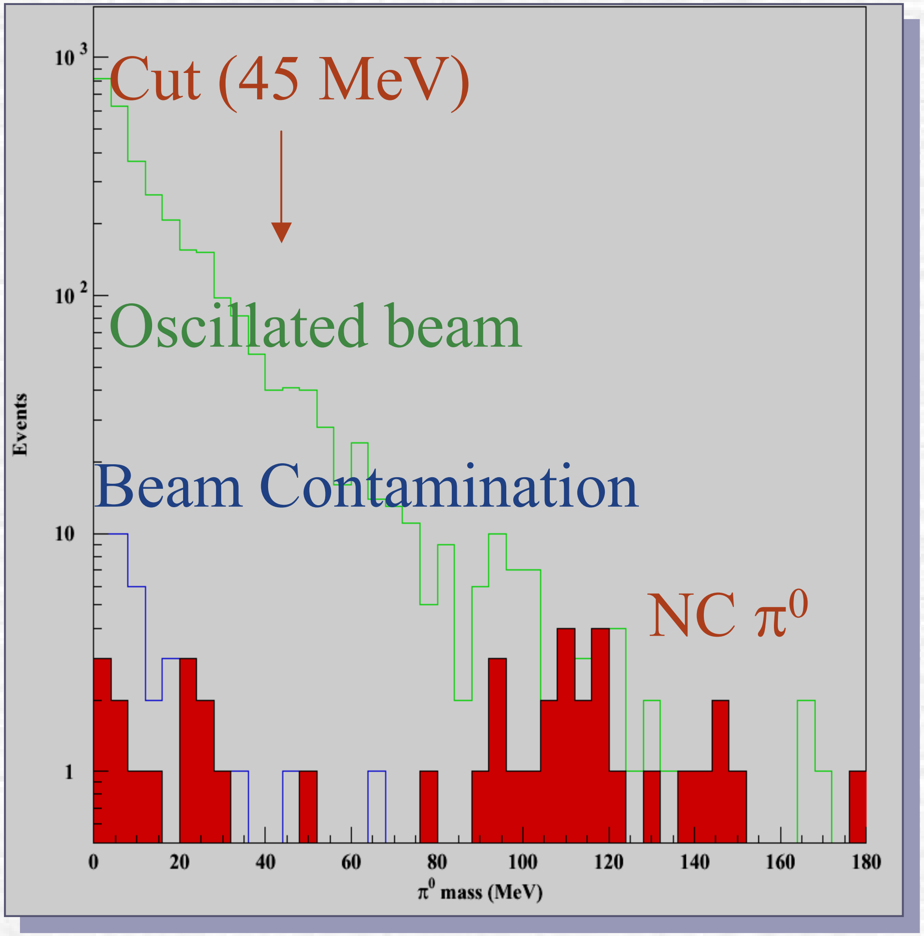
K2K Preliminary
1-kton, single $\pi^0$'s

# Energy Flow Fitter



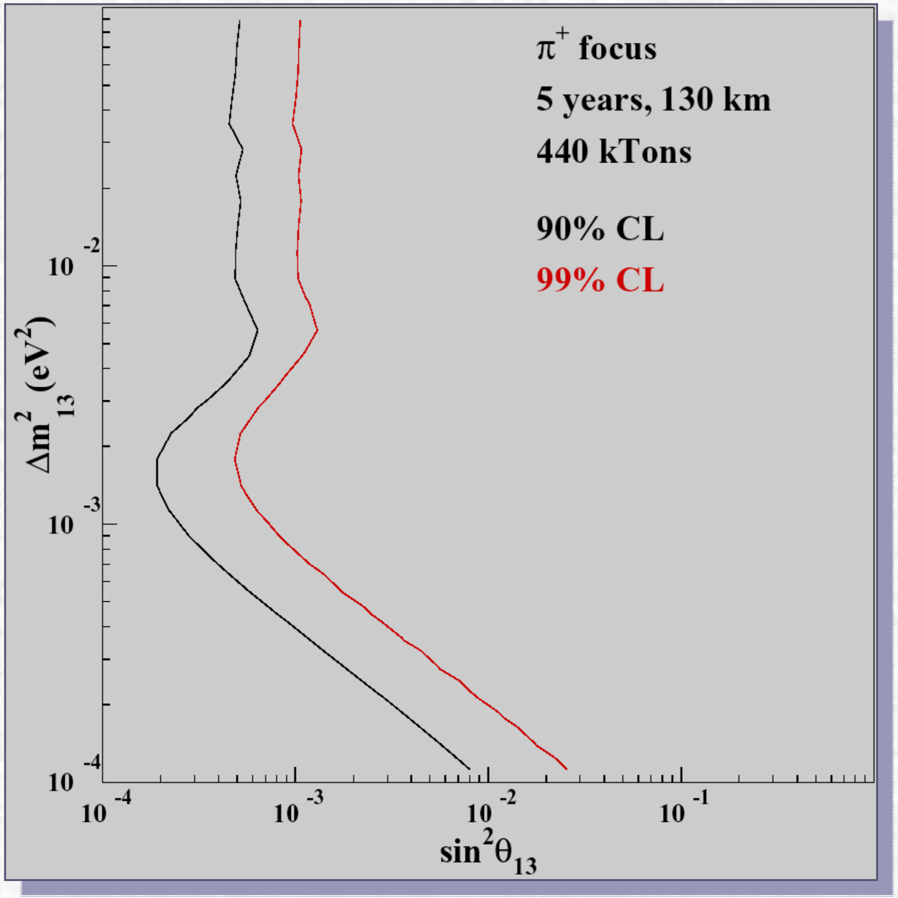
# $\pi^0$/e Background Results

- Apply energy-flow fitter to surviving events
- Cut:
  - $M_{\gamma\gamma} < 45$ MeV
- Most $\pi^0$ background eliminated



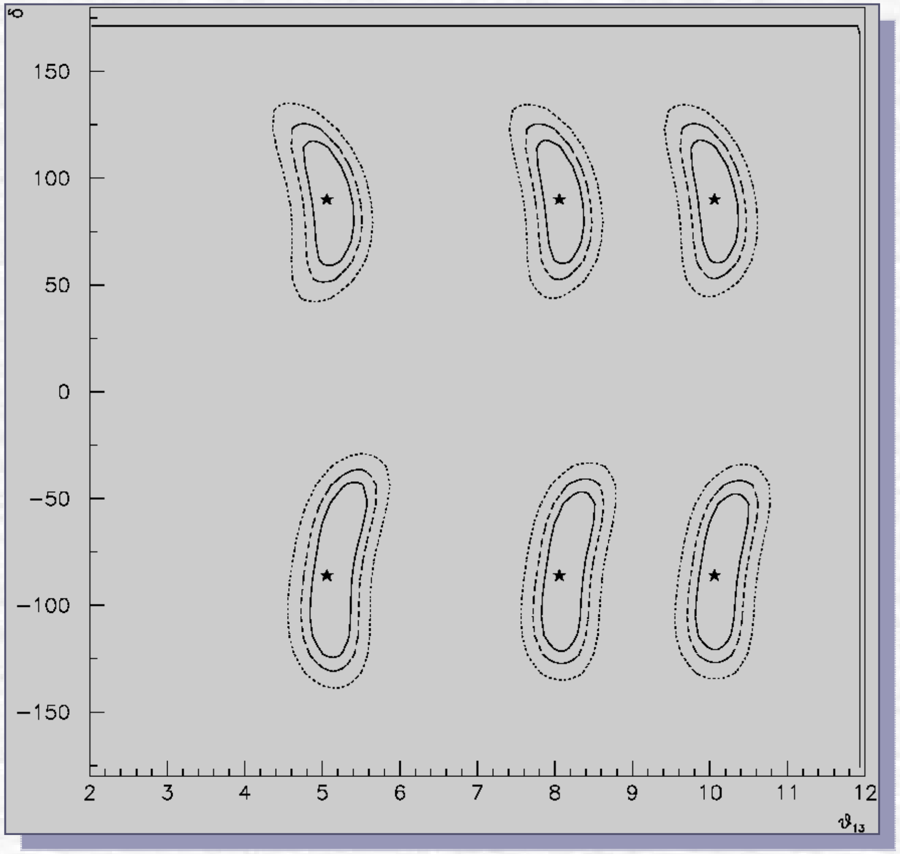
# CERN → UNO: $\theta_{13}$ Sensitivity

- Search for $\nu_e$ appearance
- 90% CL $\sin^2 2\theta_{13}$ sensitivity at ‰ level in favored $\Delta m^2$ region



# CERN → UNO: $\delta_{CP}$ Sensitivity

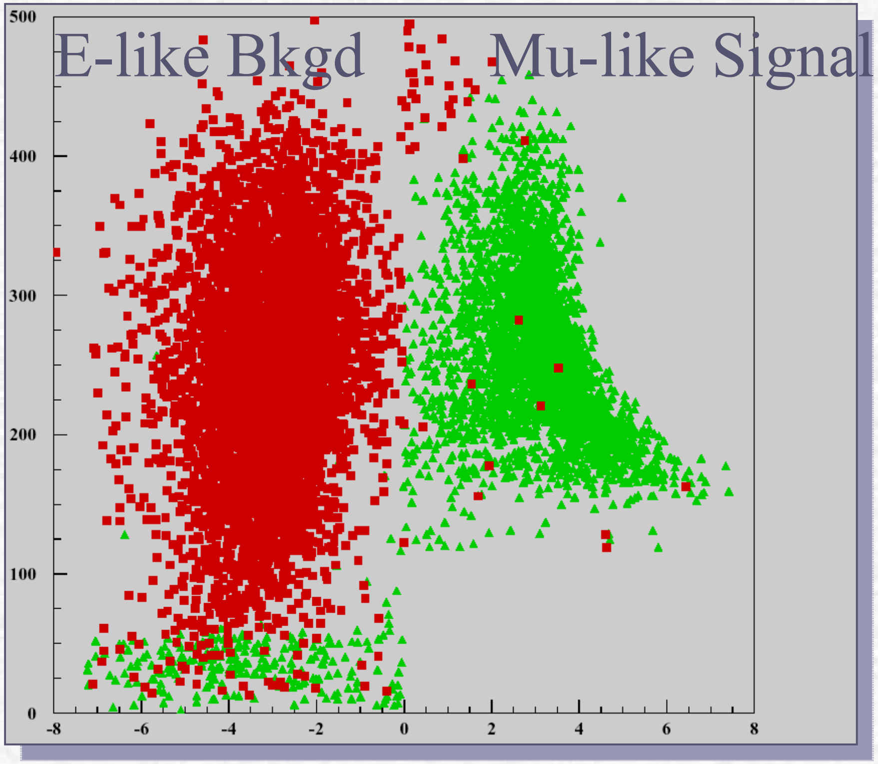
- Sensitivity to maximal $\delta_{CP}$ for LMA solution, $\sin^2 2\theta_{13}=0.03$ or less
- No confusion from matter effects



$\theta_{13}$

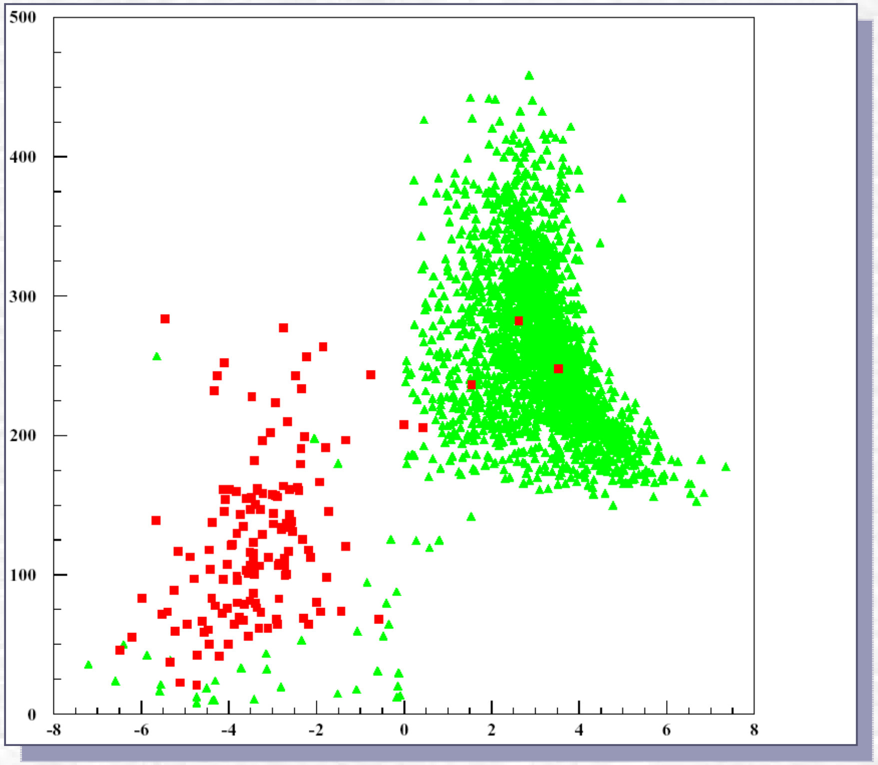
# Beta Beam (Ne18)

- Apply simple cuts
  - Fiducial volume
  - Single-ring
  - Particle ID
  - Directional cut possible in principle for $^{6}$He
- Assume atmospheric neutrinos are excluded by event time



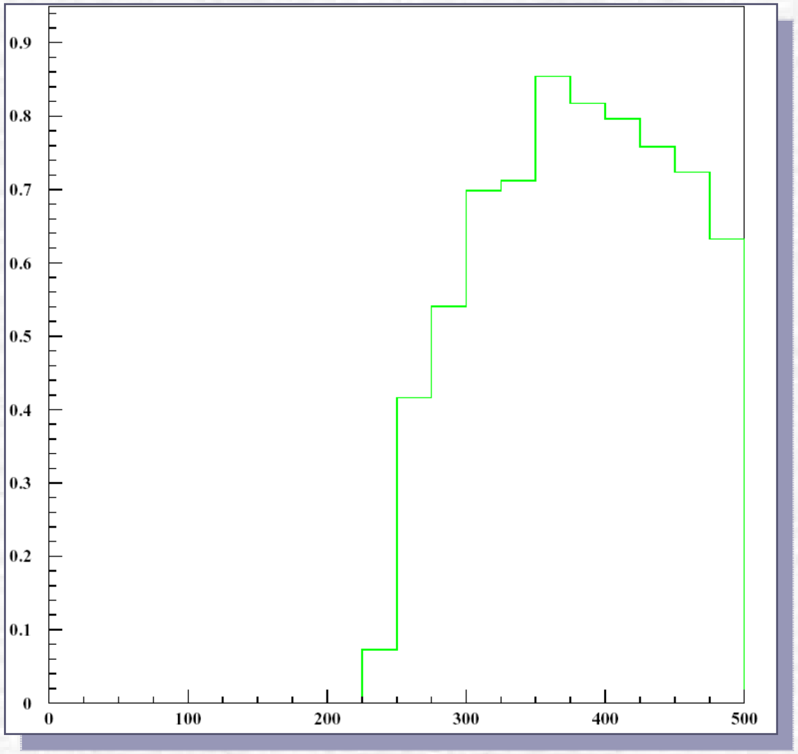
# Ne18 Beta Beam with Decay Cut

- Decay cut eliminates most mis-ID
  - Remaining events are NC charged pi
- About 3 events background in 5-year $^{18}$Ne run
- One event background in 10-year $^{6}$He run



# Efficiency for Beta Beam

- Inefficiency is essentially due to energy transfer leaving lepton below threshold
- Close to 100% for muon momentum > 200 MeV/c
- Need to tune beam energy with oscillation parameters and efficiency



# Summary

- Long-baseline experiments with superbeams offer:
  - 1% measurements of $\nu_\mu \rightarrow \nu_\tau$ oscillation
  - 1‰ sensitivity to $\sin^2 2\theta_{13}$
- Low or intermediate energy beams combined with large water detectors could also detect CP violation in favorable LMA scenarios
- Higher energy beams at very long baselines can measure sign of $\Delta m_{23}^2$
- Superbeams fall short of a neutrino factory, but could bring us a step closer to building one