# Neutrino Factory Physics Update

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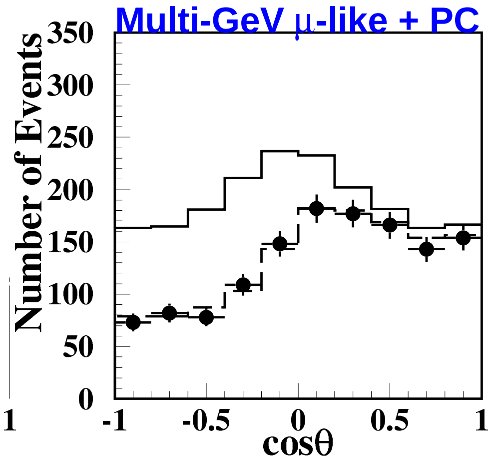
Brookhaven National Laboratory

# Outline

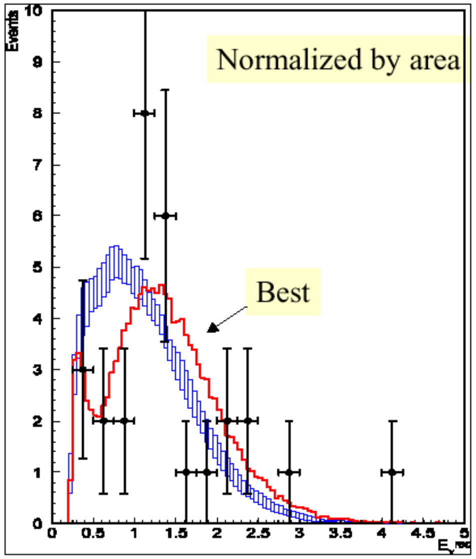
- Intro–what do we know, what do we want to know?
- $\nu$ beam choices
- Detector Choices
- From Probabilities to Mixing Angles
- Conventional $\nu$ Beam Proposals
  - → Broad band, narrow band
  - → First Maximum, Second Maximum
  - → Combining Conventional Experiments
- $\nu$ Factory
  - → Ultimate reach in $\sin^2 2\theta_{13}$
  - → Combining $\nu$ factory measurements

# From Discovery to Confirmation:

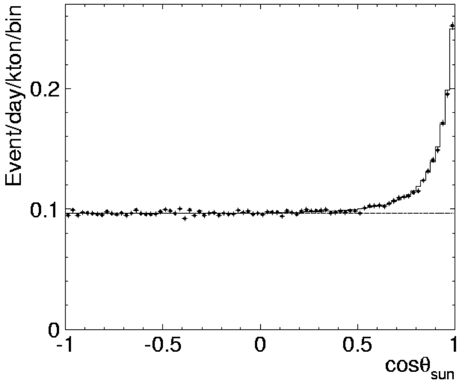
## SuperK:



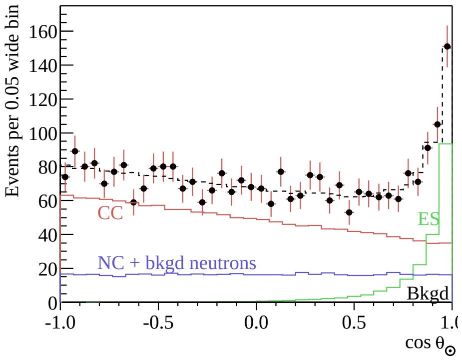
## K2K:



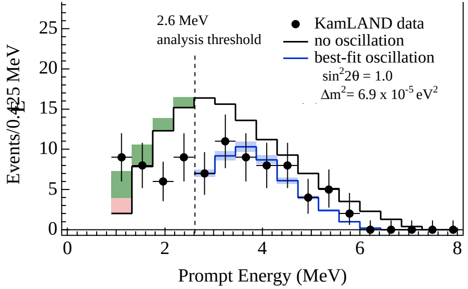
## SuperK:



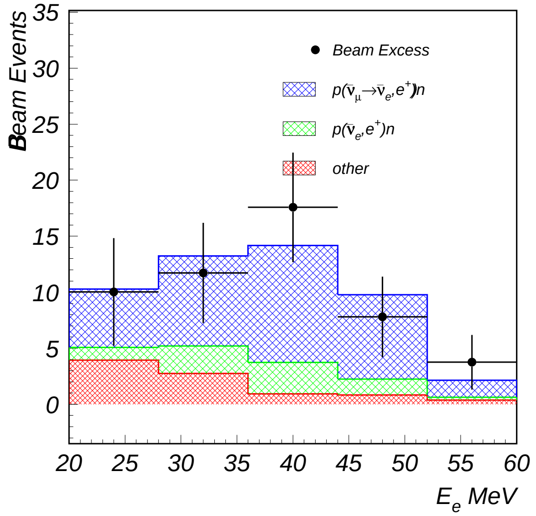
## SNO:



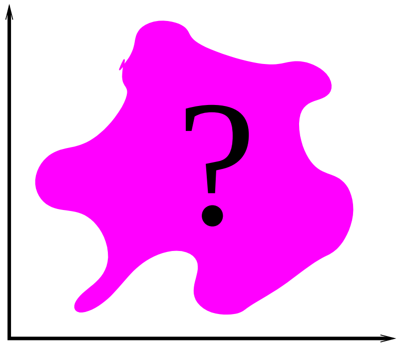
## KamLAND:



## LSND:



## MiniBooNE:



# From Confirmation to a Framework...

While MINOS and more KamLAND and SNO data take us from cofirmation to precision, framework is being developed...

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} & \boldsymbol{U} & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Produce Weak Eigenstate...

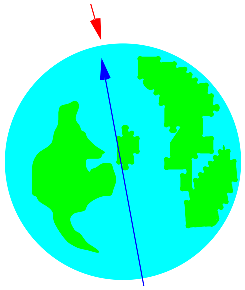
Detect Weak Eigenstate...

Propage Mass Eigenstate

if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

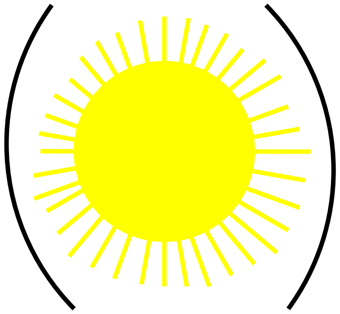
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

U=



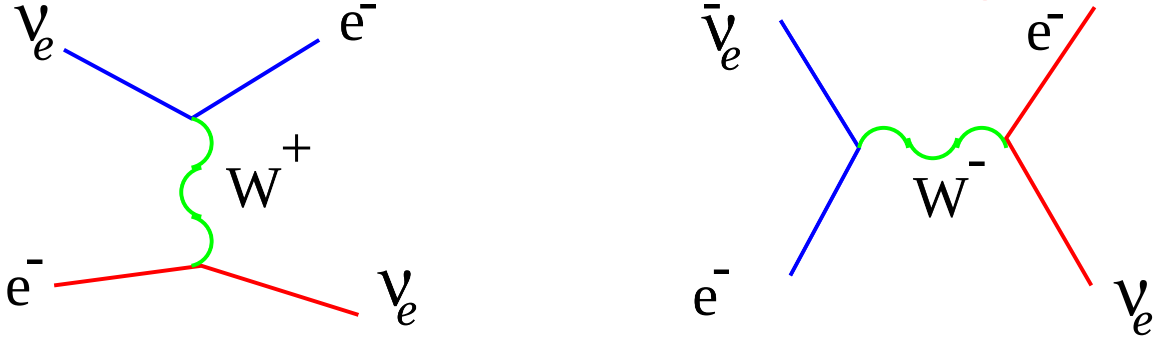
$\nu_e \longleftrightarrow \nu_\mu$

at atmospheric $\Delta m^2$



# $\theta_{13}$ and $\delta$: More than just an angle and phase...

- **Are Neutrino Masses in the "wrong" order?**



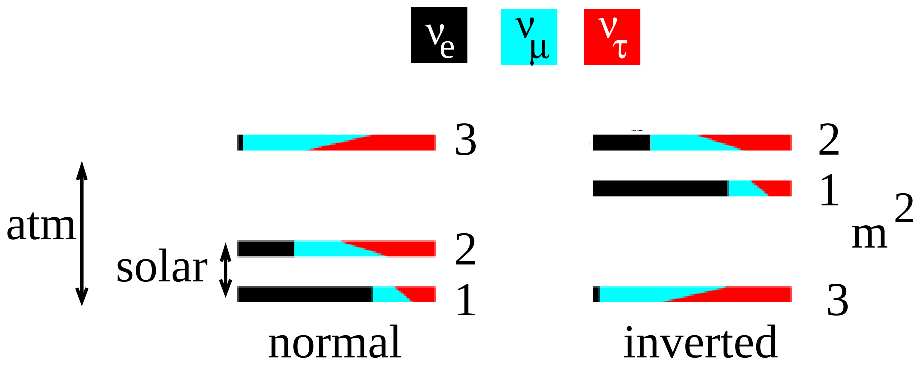
Coherent Elastic Scattering: $\nu_e$ $\bar\nu_e$ only!

Changes $\nu_e$ oscillation probability

Wolfenstein, Phys. Rev. **D17** (1978)

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar\nu_\mu \to \bar\nu_e)}{P(\nu_\mu \to \nu_e) + P(\bar\nu_\mu \to \bar\nu_e)} = \frac{2E_\nu}{E_R} \quad \text{for low } E_\nu$$

$$E_R = \frac{\Delta m^2_{atm}}{2\sqrt{2}G_F\rho_e} \approx 11 GeV$$



from Mena and Parke, `hep-ph/0312131`

- **CP violation → This could be what brings us all here...**

# Designing a Neutrino Experiment

- current designs: pin down (or eliminating) $\Delta m^2$
- next generation: Discovery of a non-zero $\theta_{13}$
- from discovery to confirmation to precision...
  - → $P(\nu_\mu \to \nu_e) = A_\pm \sin^2 2\theta_{13} \pm B_\pm \sin\theta_{13} \sin\delta + \ldots$
  - → CP Violation without matter effects:

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \propto \frac{\Delta m^2_{sol} L}{E} \frac{\sin\delta}{\sin\theta_{13}}$$

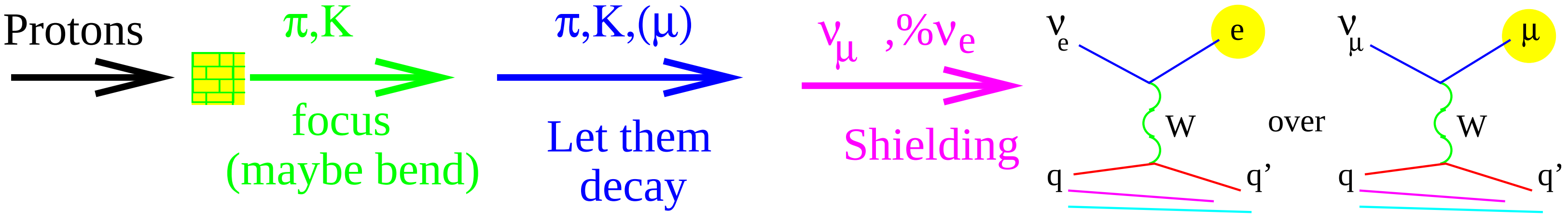
  - → Matter effects without CP violation:
    Because earth is filled with electrons...

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} = \frac{2E_\nu}{E_R} \quad \text{for low } E_\nu$$

$$E_R = \frac{\Delta m^2_{atm}}{2\sqrt{2} G_F \rho_e} \approx 11 GeV$$

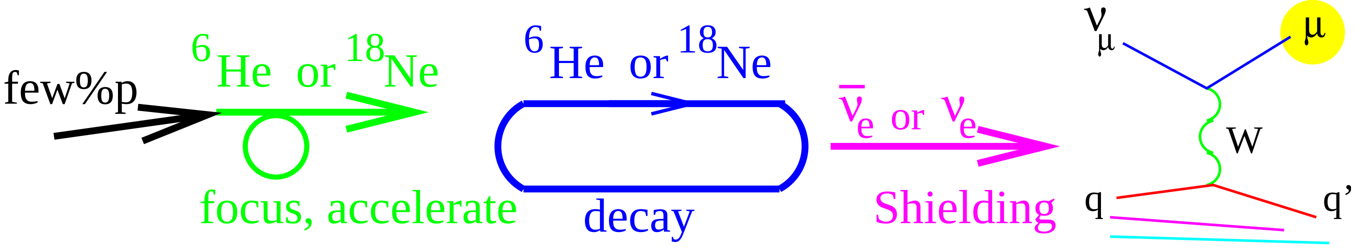
# Neutrino Beam Choices

- Conventional Beam



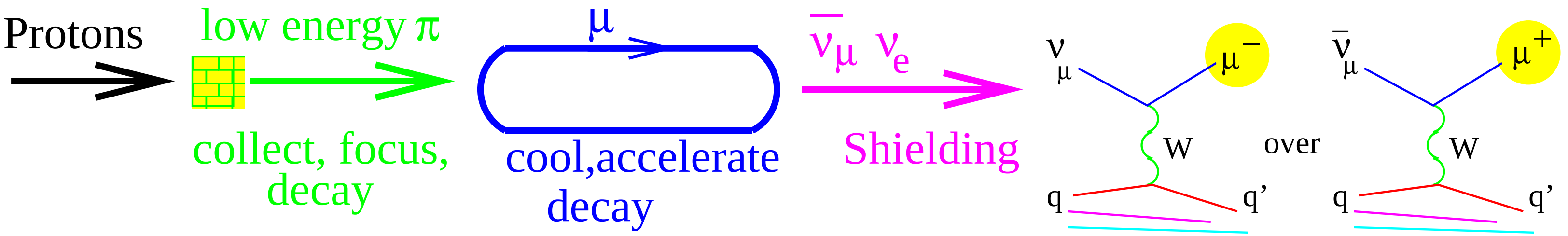
Protons → $\pi$,K focus (maybe bend) → $\pi$,K,($\mu$) Let them decay → $\nu_\mu$ ,%$\nu_e$ Shielding

- Beta Beam



few%p → $^6$He or $^{18}$Ne focus, accelerate → $^6$He or $^{18}$Ne decay → $\bar{\nu}_e$ or $\nu_e$ Shielding

- Neutrino Factory

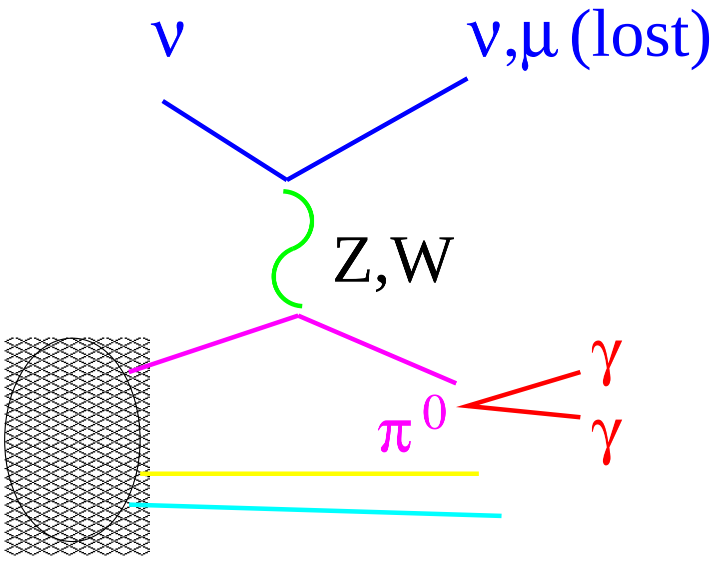


Protons → low energy $\pi$ collect, focus, decay → $\mu$ cool,accelerate decay → $\bar{\nu}_\mu$ $\nu_e$ Shielding

Events/parent at far detector:

$$N \propto \frac{\gamma m_{parent} K}{4\pi L_{det}^2} \frac{4\gamma^2}{\left(1+\gamma^2\theta^2_{\nu parent}\right)^3}$$

## Why is $\nu_\mu \rightarrow \nu_e$ hard? It's the Detector...



- We already know it's $< 5\%$ effect (CHOOZ)
- Unavoidable $\nu_e$ contamination of $\mathcal{O}(\%)$
- Can mistake $\pi^0, \mu, \pi^\pm$ for $e^-$

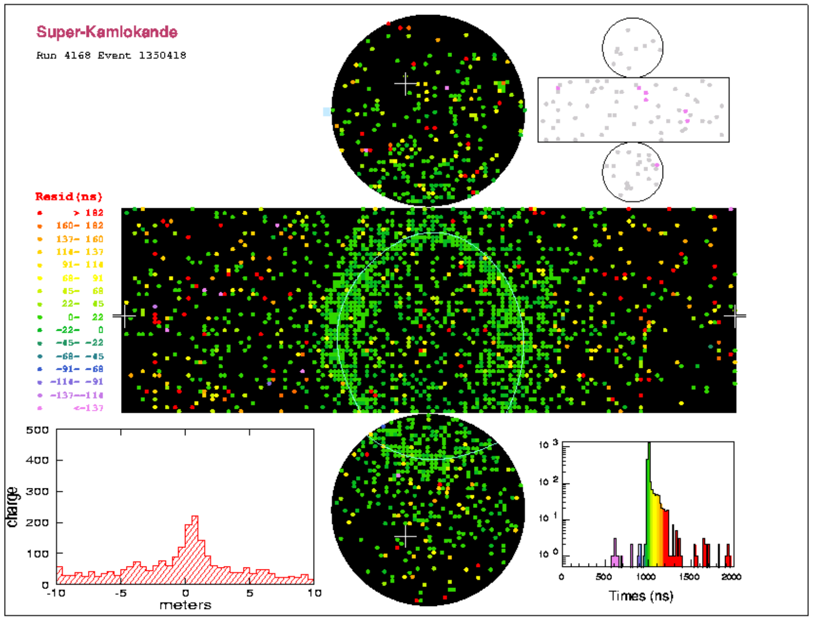
## Why is $\nu_e \rightarrow \nu_\mu$ hard? It's the Beamline...

- Have to make a $\nu$ factory or $\beta$-beam

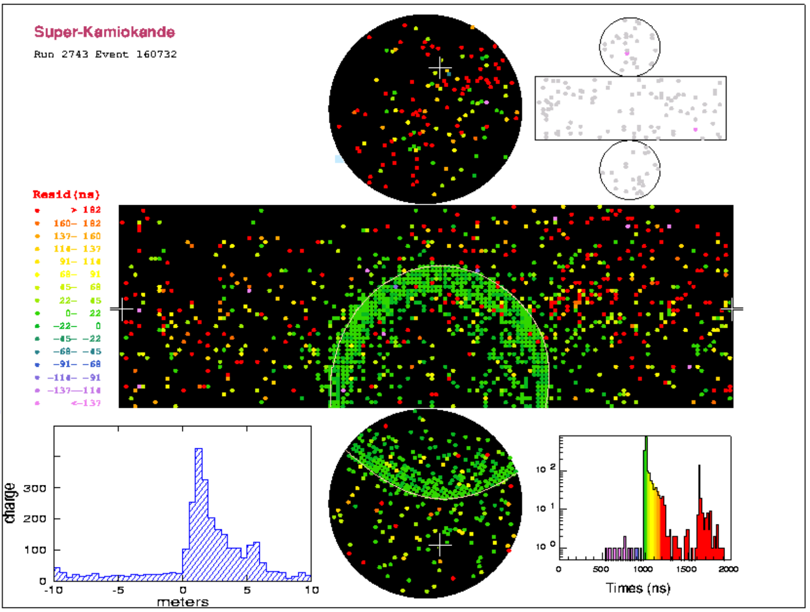
## Why is $\nu_e \rightarrow \nu_\tau$ hard? Beamline and Detector

# Detector Choices: Water Cereknov

**e–like**



**μ–like**



Courtesy Mark Messier

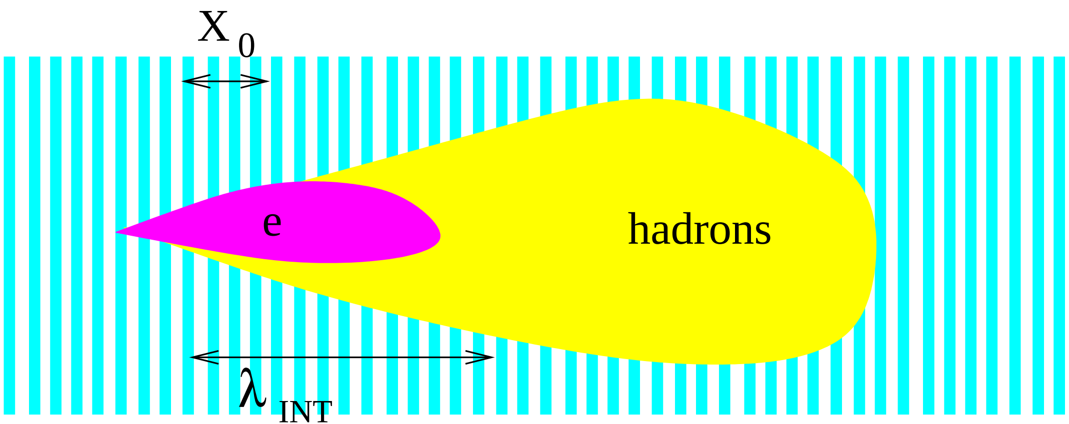
Extremely good separation for Single Particle Events

$\nu$ Quasielastic Energy Reconstruction works very well...

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

But this equation fails for inelastic processes: enter backgrounds...

# Detector Choices: Fine-Grained Calorimetry



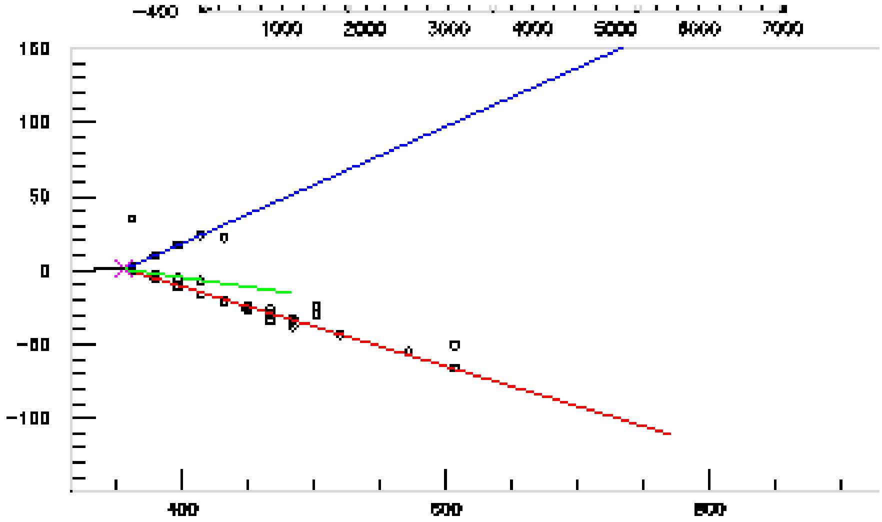
Tried and True Technology

1/3 $X_O$ sampling calorimeter

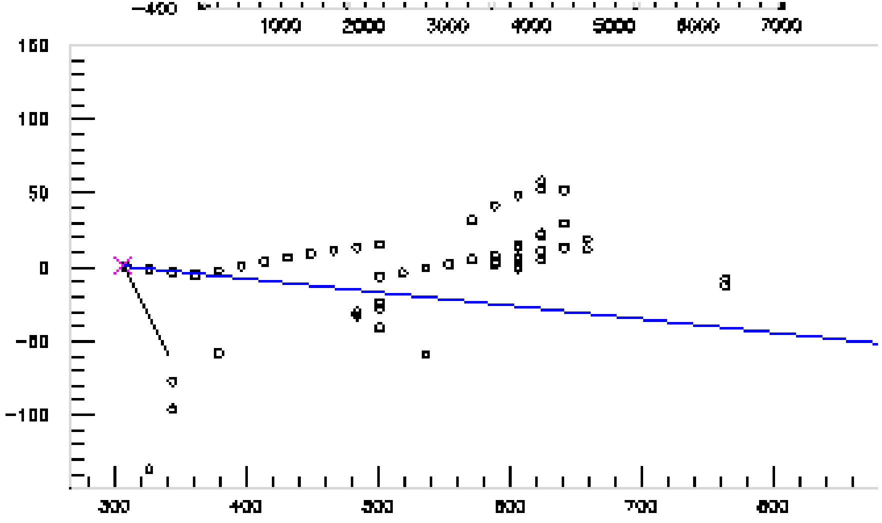
Hit counting:

$\sigma(E)/E = 12 - 15\%$ 2GeV

$2GeV\,\nu_e$ Charged Current



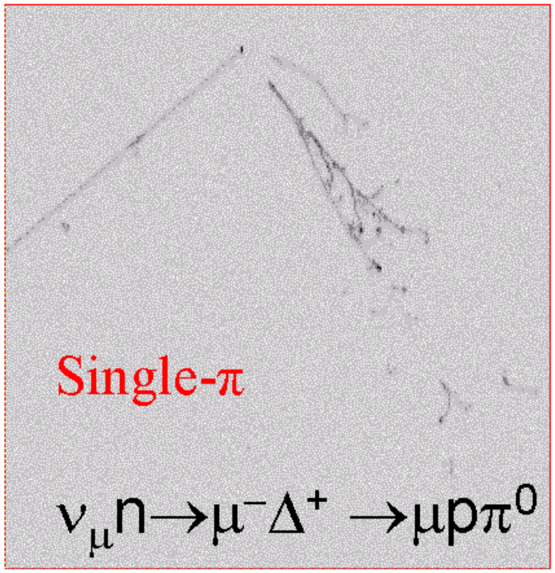
Neutral Current Background

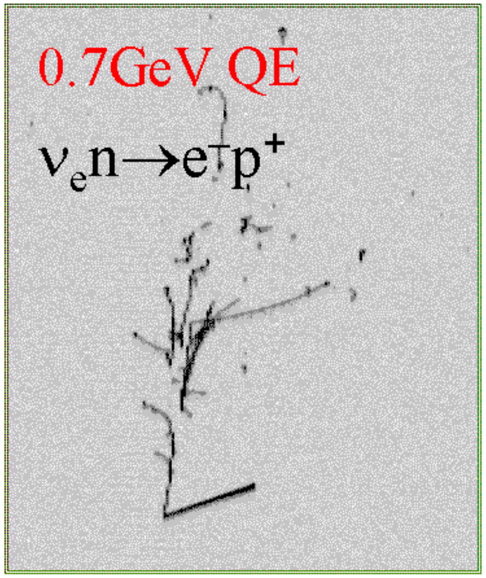


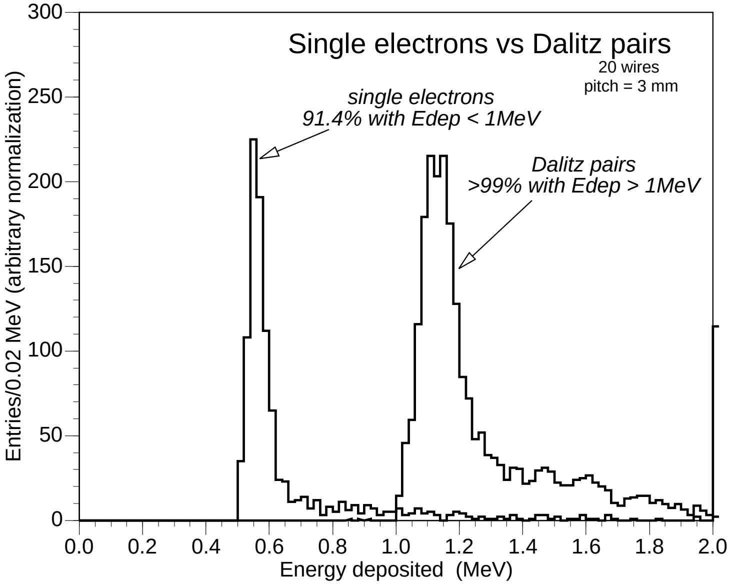
few $\times 10^{-}3$ NC rejection with 35-40% signal acceptance at 2GeV

Remaining backgrounds: CC and NC $\pi^0$ production

# Detector Choices: LAr TPC





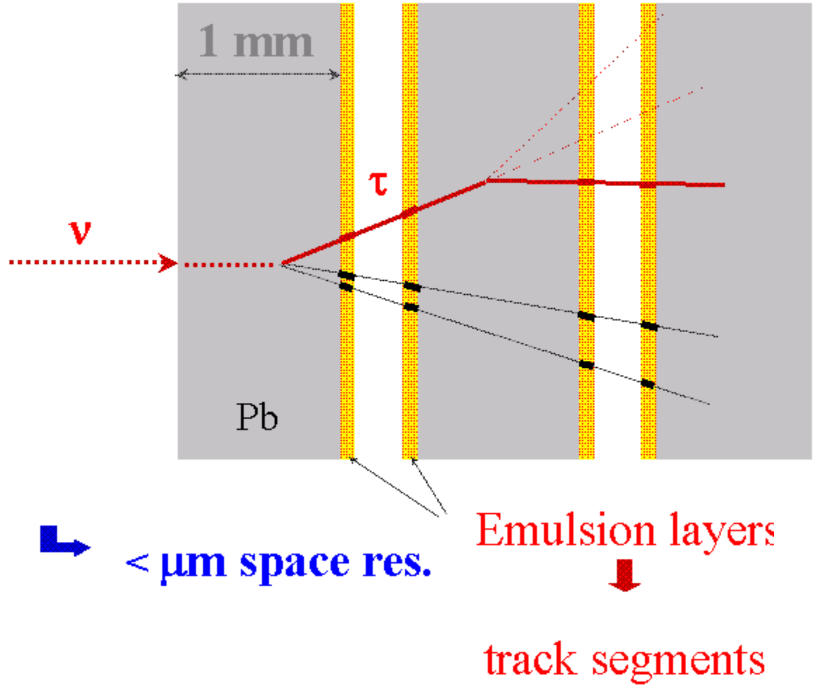


Excellent PID and energy reconstruction
Ref: ICANOE proposal LNGS P21/99 and
`www.aquila.infn.it/icarus/`
Events courtesy A. Rubbia

By far the smallest detector-related backgrounds here, but... by far the most technically challenging detector

# Emulsion Detectors for $\tau$ Appearance

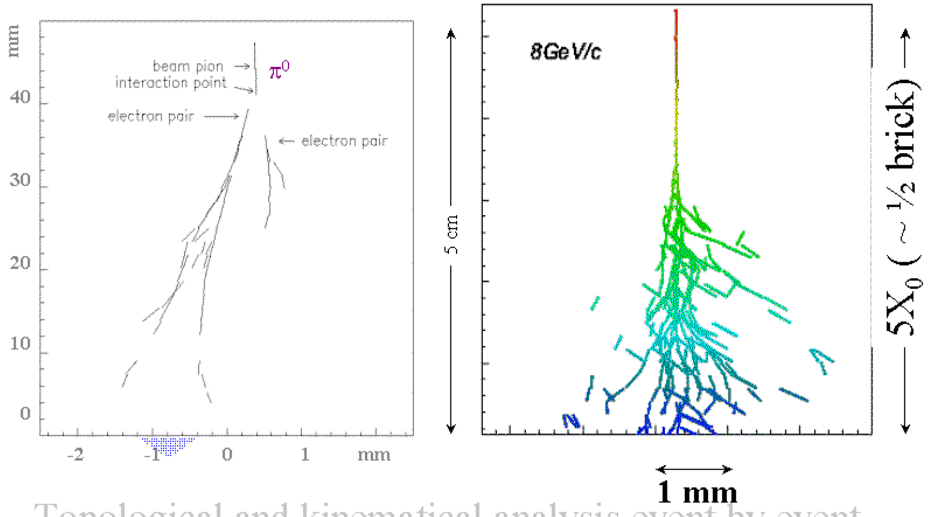
The Emulsion Cloud Chamber (ECC)



- What if MiniBooNE Confirms LSND??
- What about measuring $\nu_e \rightarrow \nu_\tau$?
- OPERA Design:
  Pb-Emulsion Sandwich

Event reconstruction with an ECC

ECC exposure at CERN-PS



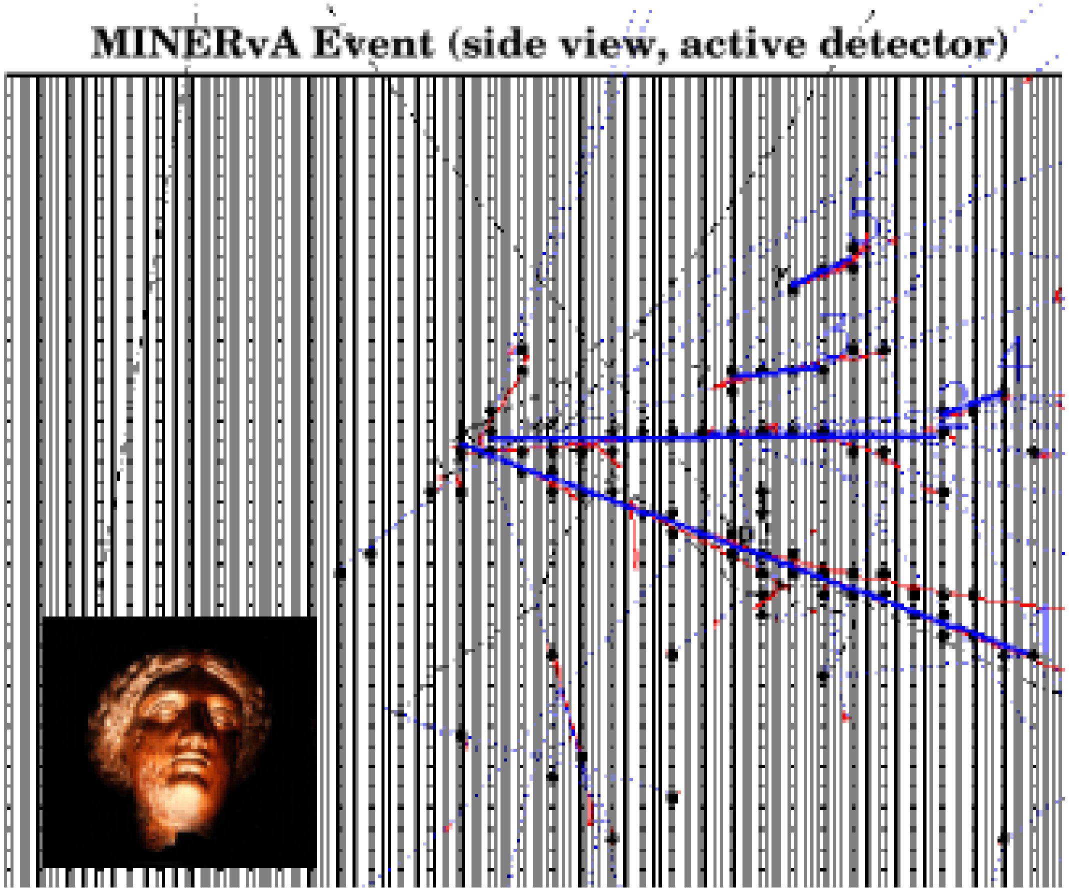
Topological and kinematical analysis event by event

- Performance measured in $e^-$ test beam at CERN
- Want to test this in known $\nu$ beam too!

# In Praise of Near Detectors

If you can't remove all the backgrounds...

- measure them precisely in a near detector
- understand processes well enough to make far detector prediction



One example:
MINER$\nu$A in NuMI/MINOS joint Nuclear/Particle project to

- measure cross sections
- validate models based on nuclear physics data
  (e.g. JLab CLAS, Hall C)

`http://www.pas.rochester.edu/minerva`

Conventional Beamlines will require better knowlege of cross sections...then again so does nuclear physics...

# Getting to $\theta_{13}$ in 3 generations... $P(\nu_\mu \to \nu_e) = \Sigma_{i=1,4} P_i$

$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2} \qquad \text{atmospheric part}$$

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2} \qquad \text{solar part}$$

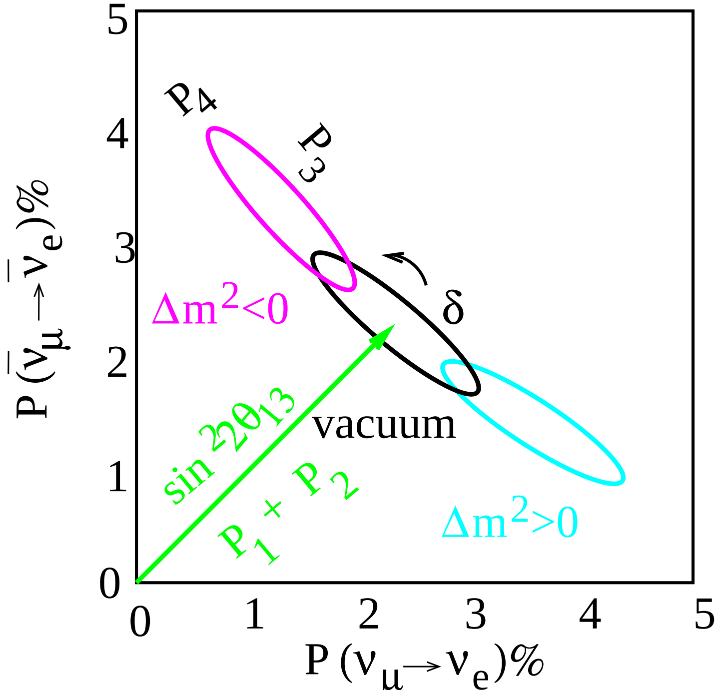
$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2} \qquad \text{interference}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2} \qquad \text{interference}$$

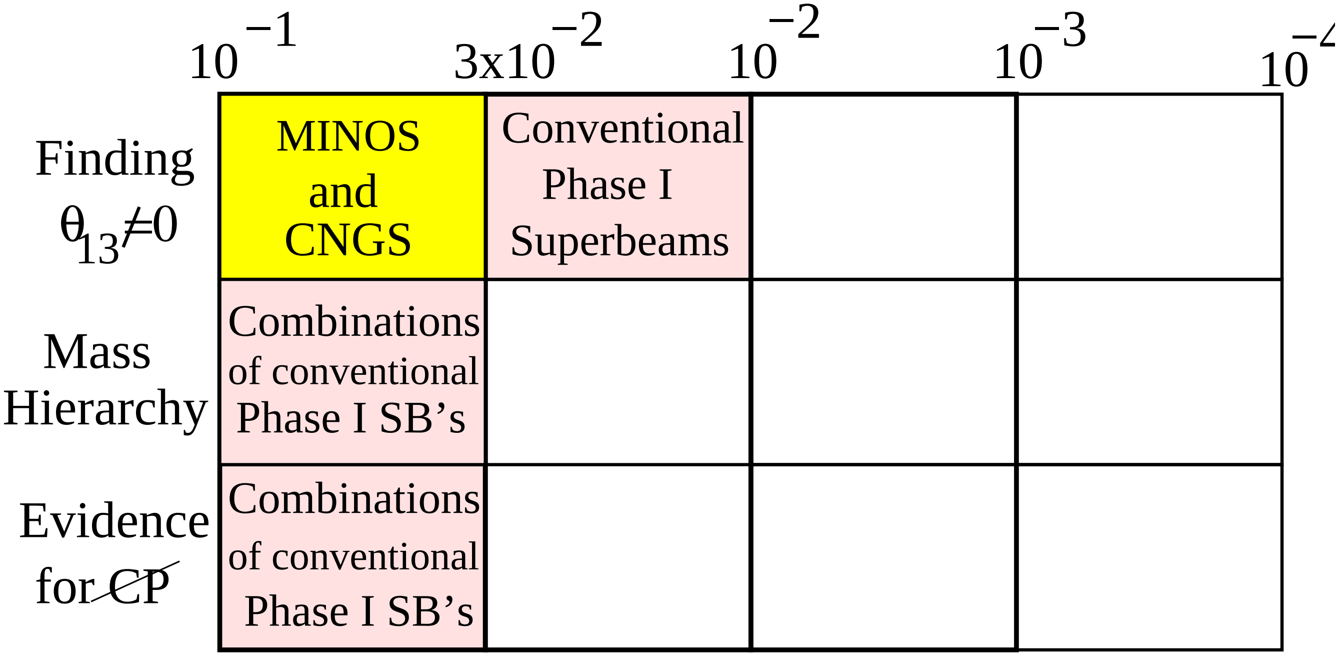
where

$$\begin{aligned} \Delta_{ij} &= \frac{\Delta m^2_{ij}}{2E_\nu} \\ A &= \sqrt{2}G_F n_e \\ B_\pm &= |A \pm \Delta_{13}| \\ J &= \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \end{aligned}$$

and the ± signifies neutrinos or antineutrinos



# Scales of $\sin^2 2\theta_{13}$

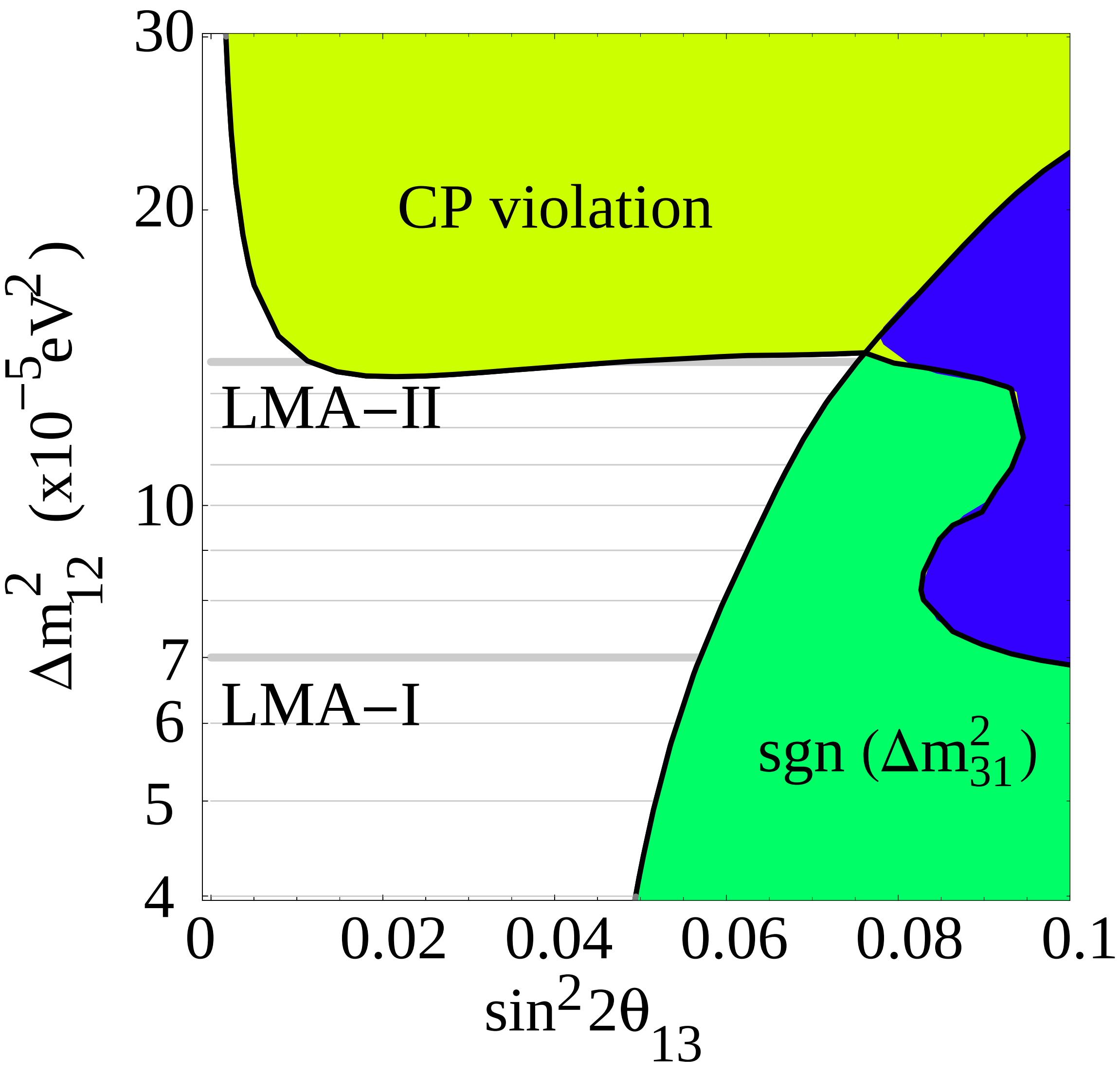


| | | | | |
|---|---|---|---|---|
| Finding $\theta_{13} \neq 0$ | MINOS and CNGS | Conventional Phase I Superbeams | | |
| Mass Hierarchy | Combinations of conventional Phase I SB's | | | |
| Evidence for ~~CP~~ | Combinations of conventional Phase I SB's | | | |

| Beam Name | Peak Energy (GeV) | Detector | Mass (kton) | Power (MW) | $\sin^2 2\theta_{13}$ sens.$^a$ | $\delta^b$ | Matter Effect |
|---|---|---|---|---|---|---|---|
| OPERA | 17 | Pb-Emulsion | 1.8 | 0.15 | 0.04 | - | |
| ICARUS | 17 | LAr TPC | 2.4 | 0.15 | 0.03 | - | |
| MINOS | 3.5 | Steel-Scint. | 5 | 0.4 | 0.05 | - | |
| T2K | .7 | $H_2O$ Ч | 22.5 | 0.8 | 0.006 | - | - |
| NO$\nu$A | 2 | Wood-Scint. | 50 | 0.4 | 0.004 | - | $\geq$CP |

Phase I Superbeam Combinations:
Minakata, Nunokawa, Parke, 2002; Huber, Lindner, Winter, 2002

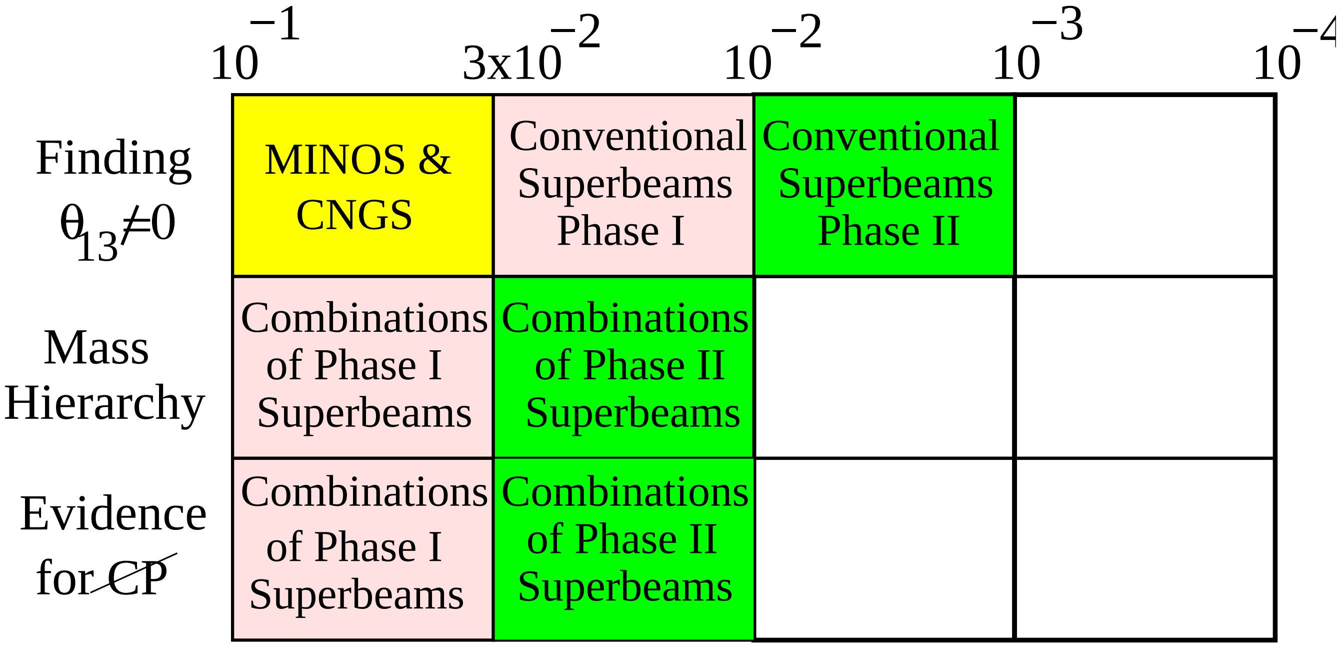
# What can you learn from T2K *and* NO$\nu$A?



Winter, Huber, Lindner Ref: Nucl. Phys. **F654**, 2003

With some regions
of parameter space
we might just see
hint of CP-violation

# Scales of $\sin^2 2\theta_{13}$, continued



| | | | | |
|---|---|---|---|---|
| Finding $\theta_{13}\neq0$ | 🟨 MINOS & CNGS | 🟥 Conventional Superbeams Phase I | 🟩 Conventional Superbeams Phase II | |
| Mass Hierarchy | 🟥 Combinations of Phase I Superbeams | 🟩 Combinations of Phase II Superbeams | | |
| Evidence for $\not{CP}$ | 🟥 Combinations of Phase I Superbeams | 🟩 Combinations of Phase II Superbeams | | |

| Beam Name | Peak Energy (GeV) | Detector | Mass (kton) | Power (MW) | $\sin^2 2\theta_{13}$ sens.[a] | $\delta$[b] | Matter Effect |
|---|---|---|---|---|---|---|---|
| T2HK | .7 | $H_2O$ Ч | 450 | 4 | 0.001 | $\|\delta\| > 20°$ | $<$CP |
| Super-NO$\nu$A | 2 | Wood-Scint. | 50+50 | 2 | 0.001 | $135 \pm 20$ | $\geq$CP |
| BNL2NUSL | 1 | $H_2O$ Ч | 500 | 1 | 0.004 | $45 \pm 20$ | $>$ & $<$ CP |
| CERN SPL +$\beta$ | .25 | $H_2O$ Ч | 400 | 4 | 0.0016 | $90 \pm 30$ | $\ll$CP |

Phase II combinations: Barger, Marfatia, Whisnant 2002

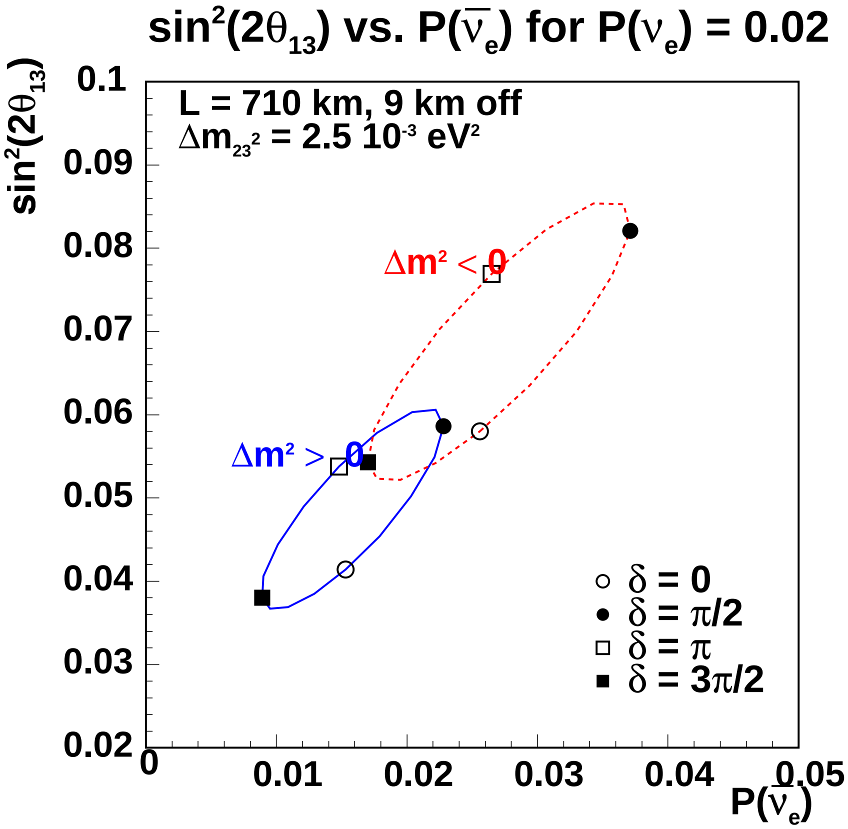
# Running at Second Oscillation Maximum

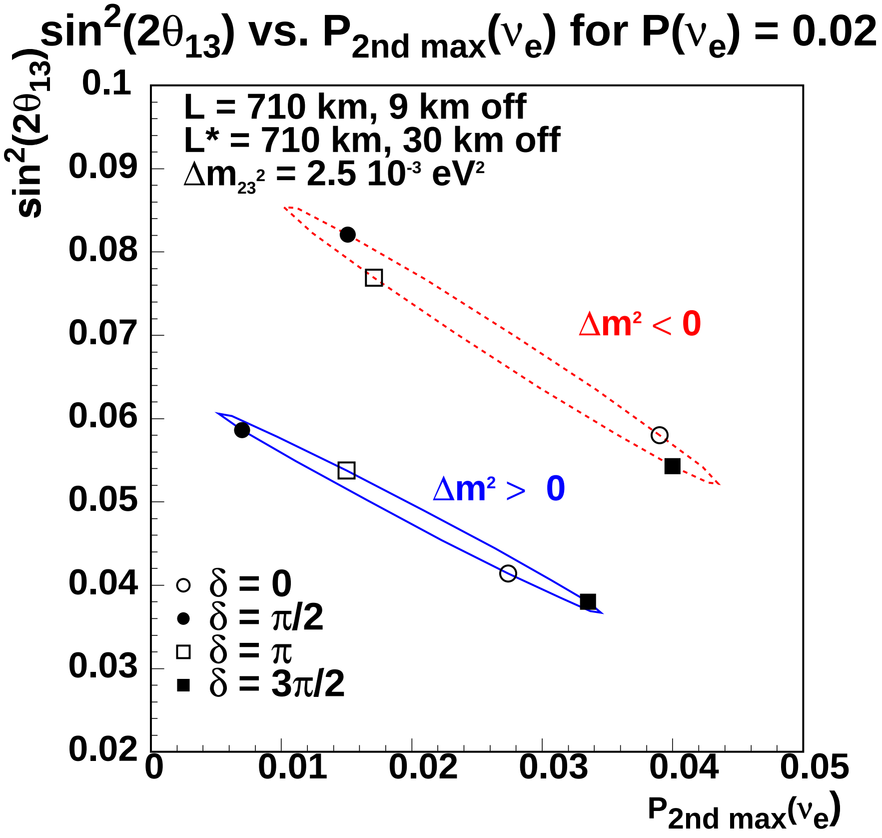
Imagine NO$\nu$A and/or T2K measures $P(\nu_\mu \to \nu_e) = 0.02$...

$1^{st}$ max: $CP \approx Matter$

$2^{nd}$ max: $CP \to 3 \times CP$

$Matter \to E_{2nd}/E_{1st}$

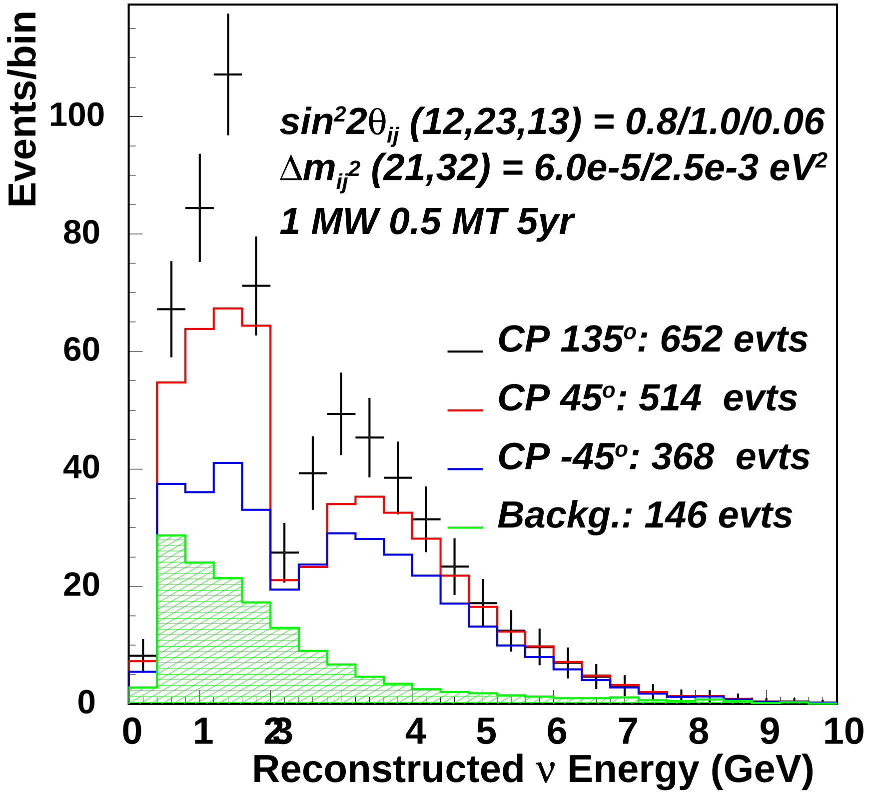


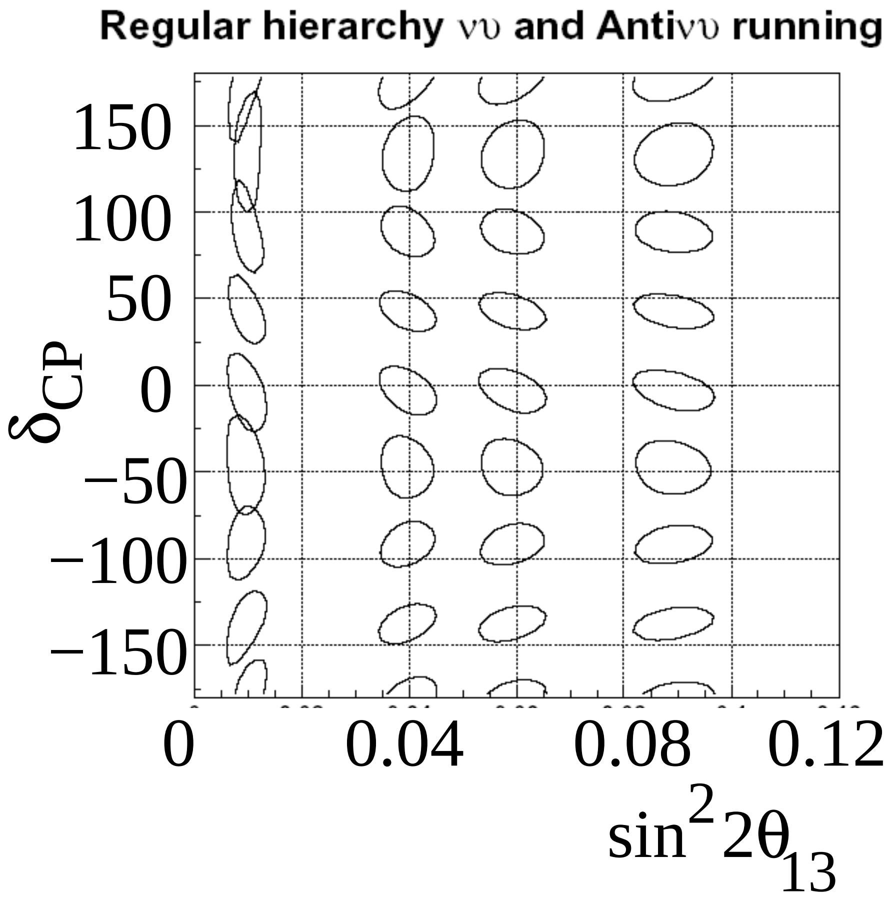


Maybe mass hierarchy can be determined, maybe not...
Now imagine it can't...

G.Feldman, HEPAP meeting

# BNL LOI $\nu_e$ Appearance





again, ONLY 1-ring events in detector, include $\pi^0$ backgrounds

**CP violation effects huge at second oscillation maximum...**

68% CL limits, different test points

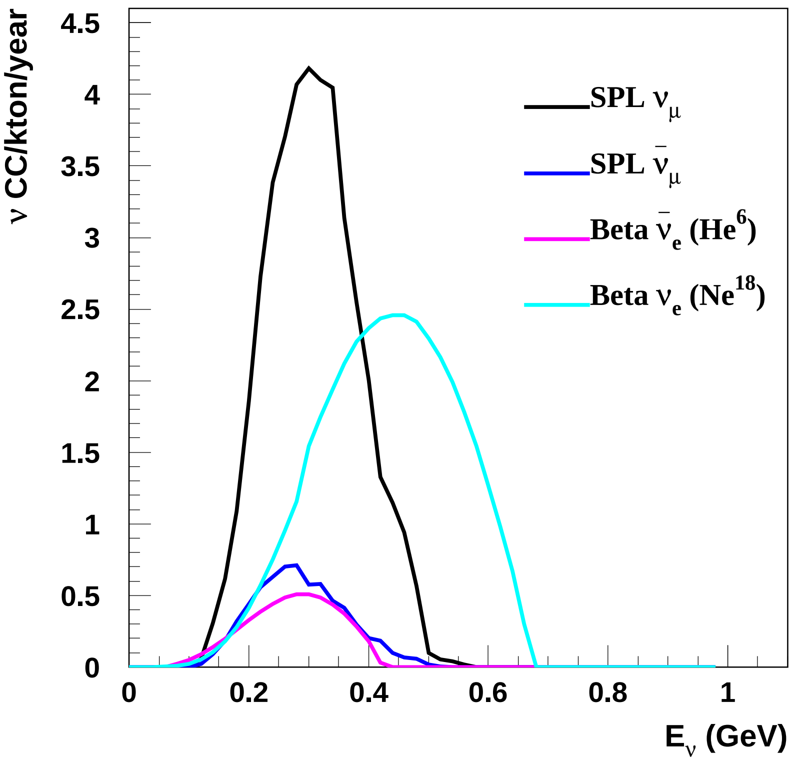
5 years $\nu$ running

5 years $\bar{\nu}$ running

similar for other hierarchy

Diwan, 1/30/04 APS Study meeting

# $\beta$ and Conventional Beams at CERN

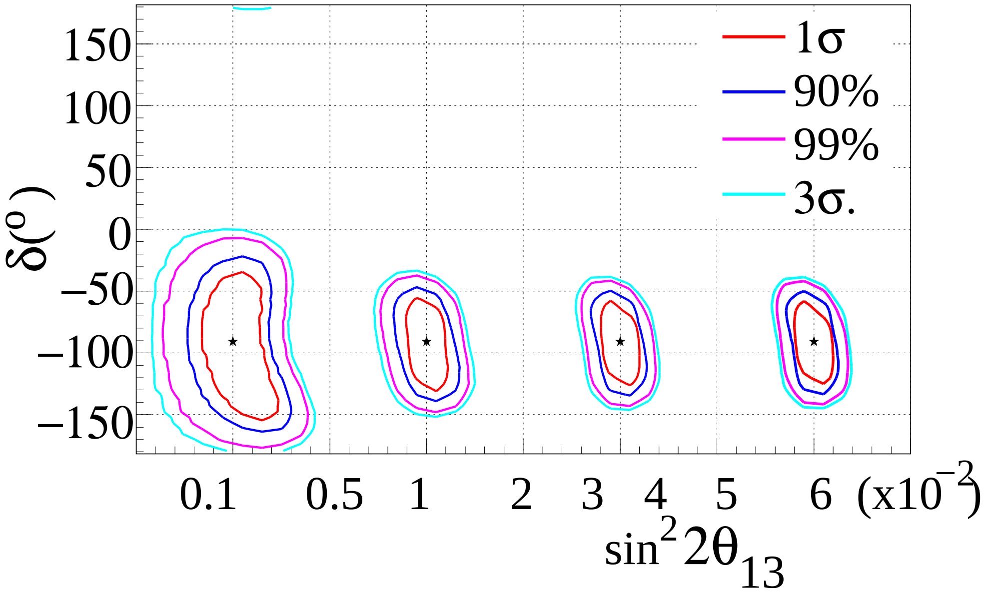


- Ability to see maximal CP violation:
- Cross-Check of Framework

$\rightarrow \nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$

$\rightarrow \nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- added precision...
  by including all measurements

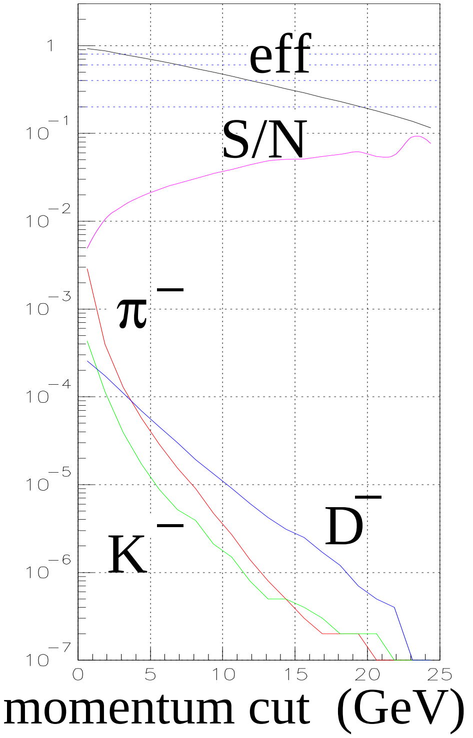


Conventional Ion production & acceleration, use same $H_2O$ Ч detector in Frejus
Run $\nu_e(Ne^{18})$ and $\bar{\nu}_e(He^6)$ in separate bunches, using timing to distinguish beams

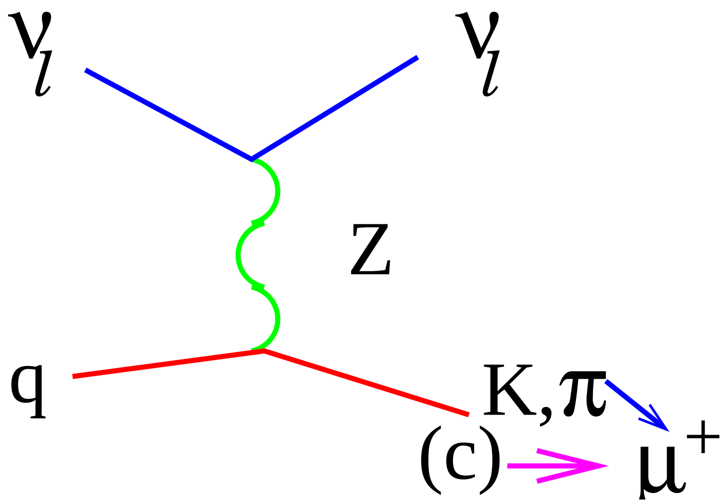
1° means $\sin^2 2\theta_{13} = 1.2 \times 10^{-3}$
Ref: M. Mezzetto, NuFact03

# Why is $\nu_e \to \nu_\mu$ at a $\nu$ Factory Easy?

- Neutrinos/MW proton power *cf* conventional beams $\propto (E_\mu/15)^3$
- No Intrinsic $\nu_\mu$ in the beam, only $\bar{\nu}_\mu$'s
- Charge of Muon easier to measure than $e/\pi^0$ separation
- Detector Technology straightforward (see MINOS)
- Backgrounds at $\leq 10^{-4}$ level, not few $\times 10^{-3}$

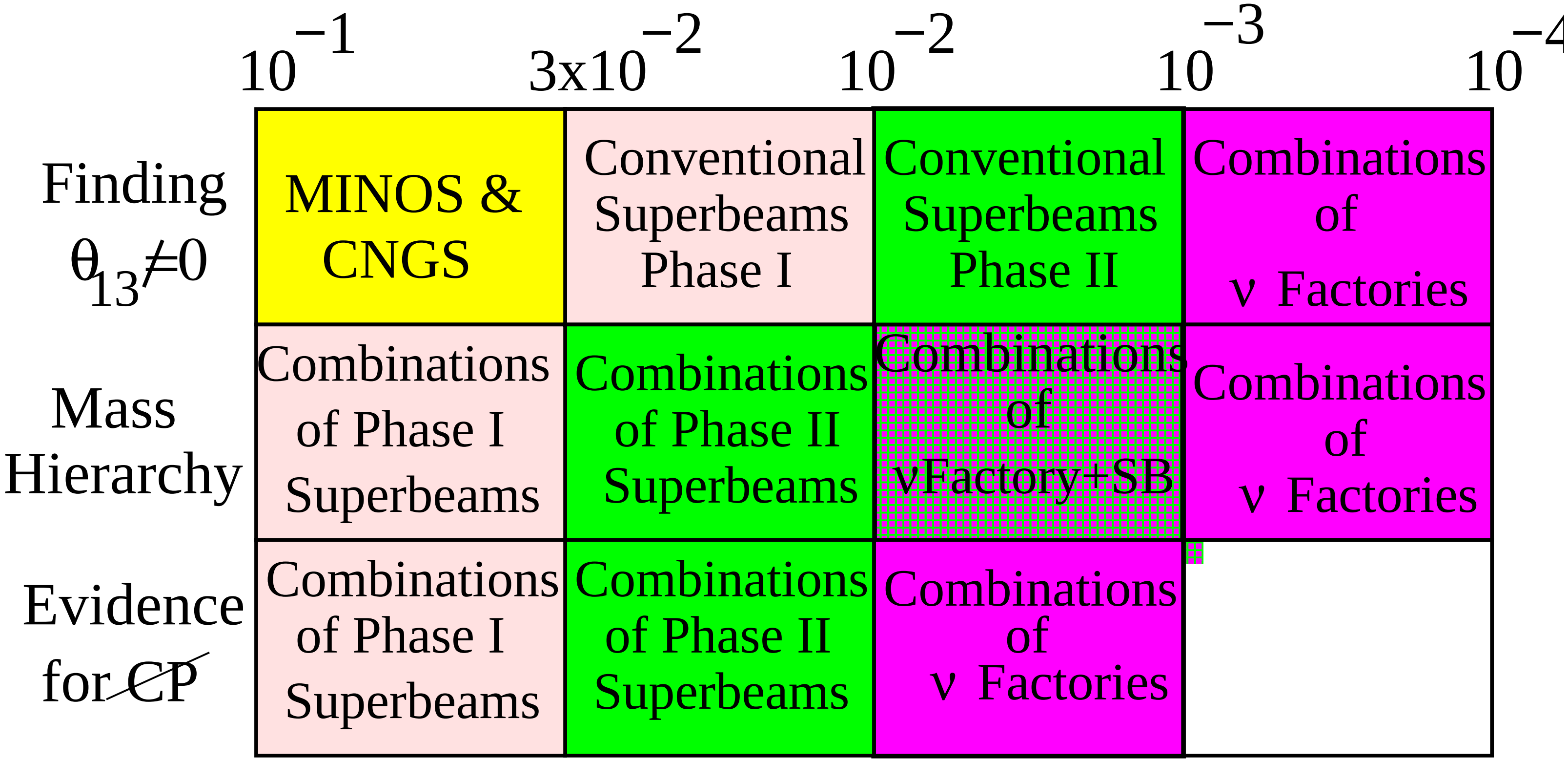


Cervera *et al*, Nucl.Phys.**B579** 17,2000



Momentum cut on muon easily removes backgrounds

# Scales of $\sin^2 2\theta_{13}$

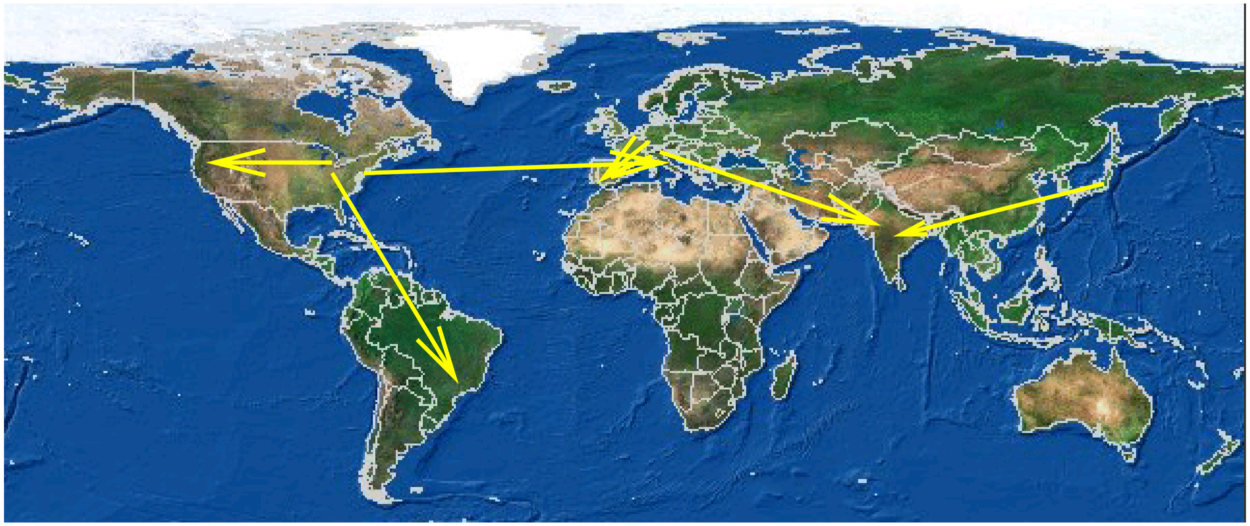


$10^{-1}$ $3x10^{-2}$ $10^{-2}$ $10^{-3}$ $10^{-4}$

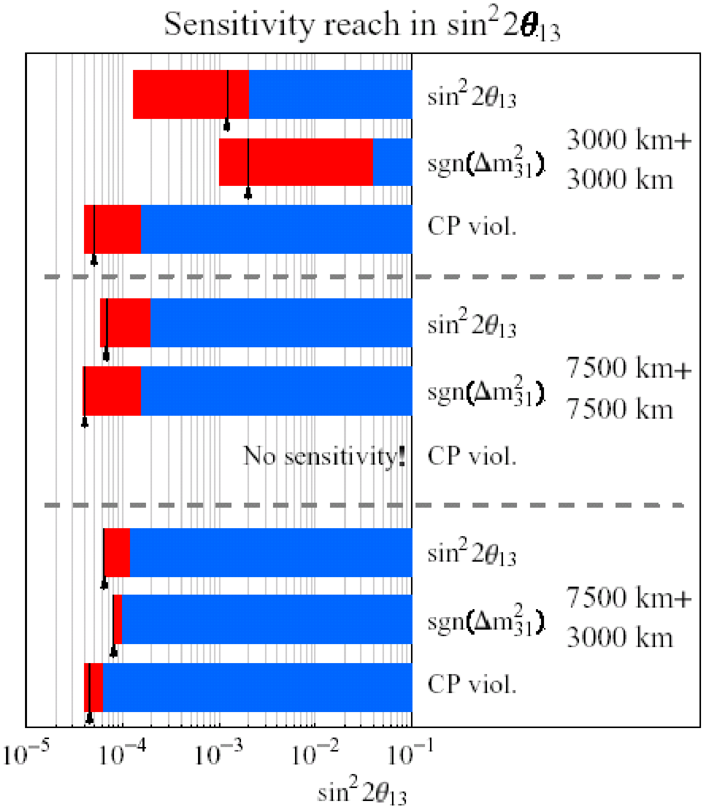
| | | | | |
|---|---|---|---|---|
| Finding $\theta_{13}\neq0$ | MINOS & CNGS | Conventional Superbeams Phase I | Conventional Superbeams Phase II | Combinations of ν Factories |
| Mass Hierarchy | Combinations of Phase I Superbeams | Combinations of Phase II Superbeams | Combinations of νFactory+SB | Combinations of ν Factories |
| Evidence for $\cancel{CP}$ | Combinations of Phase I Superbeams | Combinations of Phase II Superbeams | Combinations of ν Factories | |

Superbeam $\nu$Fact combo: Burguet-Castell *et al*, 2002
$\nu$Factory with $\tau$ ID: Donini, Meloni, Migliozzi,2002; Autiero *et al*, 2003
$\nu$ Factory “magic baseline”: Lipari, 2000; Burguet-Castell, 2001; Barger, Marfatia, Whisnant, 2002; Huber, Lindner, 2002; Huber and Winter, 2003, Asratyan *et al*, 2003

# Ultimate $\nu$ Factory Reach



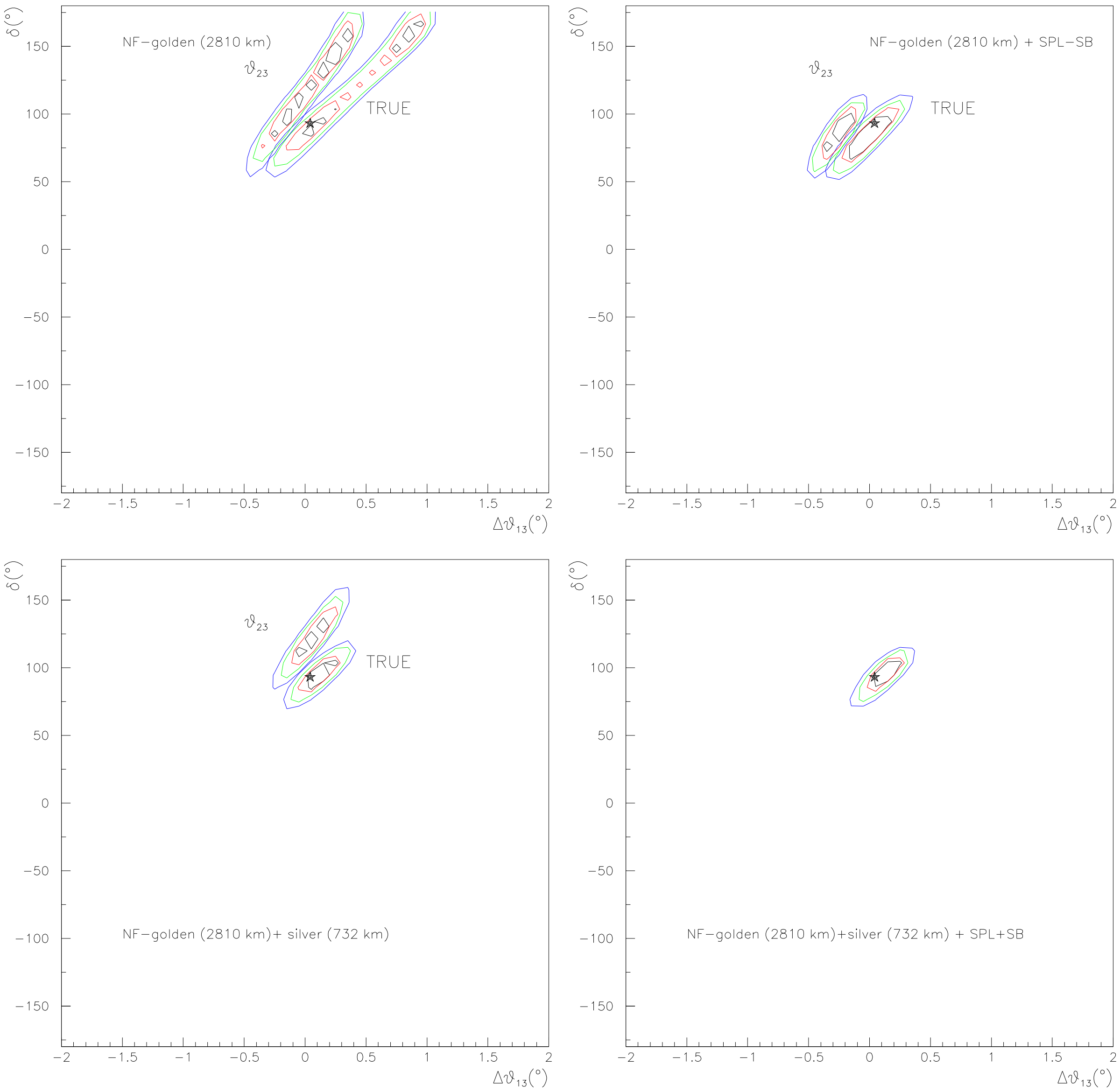
- Lots of work done in past
- apologies for not showing it
- New Studies: “magic baselines” $\sin\frac{\sqrt{2}G_F n_e L}{2} = 0$, for example $\frac{\sqrt{2}G_F n_e L}{2} = 2\pi$
  $L \sim 7250km$
  only $P_1$ remains of $P_1$ through $P_4$



Asymmetry is close to 1 in this case:
seeing $\nu_\mu \to \nu_e$ at this $L$ gives
$\theta_{13}$ and mass hierarchy!
Huber, Winter Phys.Rev.**D68** 2003

# Combining $\nu$ Factory and ...

From Donini, NuFact03: There were even ambiguities with the neutrino factory:



Getting to ultimate precision means combining data from several channels:

- Wrong-sign muons
- $\nu_e \rightarrow \nu_\tau$
- Conventional Beams

`hep-ph/0310014`

# Summary of Sensitivities

| Beam Name | Mass (kton) | Power (MW) | $\sin^2 2\theta_{13}$ sens.[a] | $\delta$[b] | Matter Effect |
|---|---|---|---|---|---|
| OPERA[o] | 1.8 | 0.15 | 0.04 | - | |
| ICARUS[o] | 2.4 | 0.15 | 0.03 | - | |
| MINOS[m] | 5 | 0.4 | 0.05 | - | |
| CNGS** | 2.35 | .15 | $\sim 0.02$** | | $\geq$CP |
| T2K | 22.5 | 0.8 | 0.006 | - | - |
| NO$\nu$A | 50 | 0.4 | 0.004 | - | $\geq$CP |
| T2HK | 450 | 4 | $\sim 0.001$[s] | $\lvert\delta\rvert > 20°$ | $<$CP |
| Super-NO$\nu$A | 100 | 2 | $\sim 0.001$[s] | $135 \pm 20$ | $\geq$CP |
| BNL2NUSL | 500 | 1 | 0.004 | $45 \pm 20$ | $>$ & $<$ CP |
| CERN SPL | 400 | 4 | 0.0016 | $90 \pm 30$ | $\ll$CP |
| $\beta$ Beam | 400 | .04 | | T viol. | $\ll$CP |
| $\nu$ Factory | 50 | 4 | $< 10^{-4}$ | $90 \pm 20$ | **huge!** |

[a] at $\Delta m^2_{32} = 3 \times 10^{-3} eV^2$,at $90\% CL$

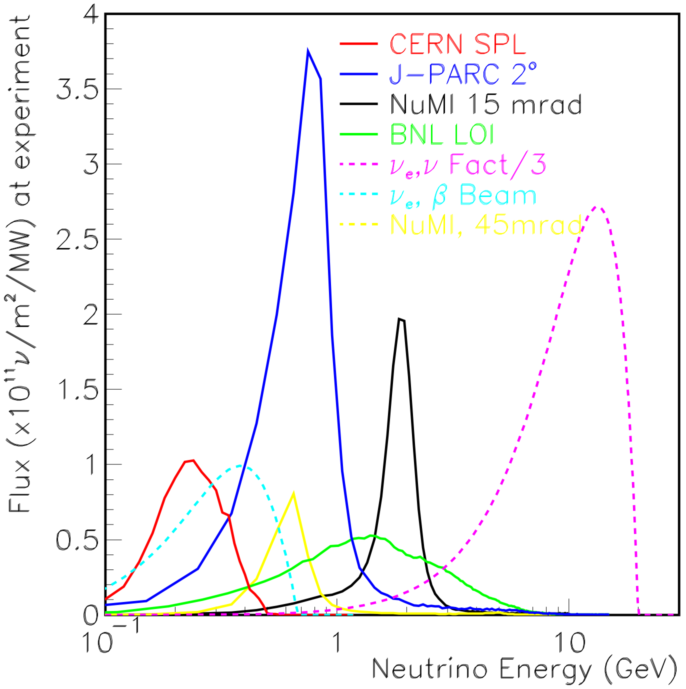
[b] all evaluated at different regions of parameter space!

[o] Komatsu, Migliozzi, Terranova J.Phys.**G29** 443, 2003 [m] Diwan, Messier, Viren, L.Wai, NUMI-L-714

[s] Assume 5% systematic uncertainty!

**modified, Rubbia, Sala, `hep-ph/0207084`

Comparison of Fluxes
per MegaWatt
at each experiment:



Note $\nu$ Factory flux
divided by 3
to fit on graph!

# Conclusions

**Our understanding of the reach of conventional $\nu$ beam has evolved...**

- Narrow band beams (“Off Axis”) mean lower backgrounds but...
- Going from Probabilities to Mixing angles not trivial
- Broad band beams (CERN,BNL) require MTon detectors for physics
  - → Making PMT’s takes time
  - → Even if water is cheap, MTon and MWatts are expensive units to work in
- if $\theta_{13}$ is right around the corner conventional beams may get us partly there

**But the Physics Case for a $\nu$ Factory is alive and well:**

- $\nu$ events/MW proton power still $\propto (E_\mu/10)^3$ *cf* conventional beams
- For precision measurements, want a precision machine!
  - → Detector Technology for wrong sign muon appearance well-understood
  - → Flux, cross section uncertainties still low
- Need to study many channels for real test of the framework...
- $\sin^2 2\theta_{13}$ **and mass hierarchy reach still** $100\times$**conventional beams...**