Future experiments with
Neutrino Superbeams, Betabeams, and Factories

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So much to say, so little time...

- Goals for the Next Steps
- Why this is hard
- Beamline Strategies
- Detector Choices
- Whirlwind tour of prospects

Near-Term Prospects:

- J-PARC to SuperK
- NuMI Off Axis

Far-Term Prospects:

- Brookhaven LOI
- CERN SPL + β Beams
- Neutrino Factory

Thanks to:

M. Diwan	G. Feldman	S.Geer	A. Ichikawa
Y. Kuno	K. Long	K. McFarland	M. Mezzetto
K. Nishikawa	B.Palmer	B. Viren	W. Winter

and the hundreds of folks whose work is shown here...

What do we want to know, how do we get there?

What do we know about ν masses and mixing?

1. There are 2 large mixing angles ($\theta_{sol} \approx \theta_{12}, \theta_{atm} \approx \theta_{23}$), and maybe one small one (θ_{LSND})
2. There are 3 independent mass splittings, one of which is positive $\Delta m^2_{sol} \approx \Delta m^2_{12}, \Delta m^2_{atm} \approx \Delta m^2_{23}, \Delta m^2_{lsnd}$
3. Absolute ν mass limits from tritium β decay, cosmology

What do we want to know?

1. Absolute ν mass scale
2. How many ν's are there?
3. Are any of the mixing angles =0 or $\pi/4$?
4. Neutrino Mass Hierarchy–is it the same as the charged fermions?
5. Is there CP Violation in the lepton sector?

Accelerator-based ν experiments can address 4 out of these 5...

Designing a Neutrino Experiment

- current designs: pin down (or eliminating) Δm^2
- next designs: see if the last mixing angle θ_{13} is non-zero

$\rightarrow$ $P(\nu_\mu \rightarrow \nu_e) = A_\pm \sin^2 2\theta_{13} \pm B_\pm \sin\theta_{13} \sin\delta + \ldots$

$\rightarrow$ CP Violation without matter effects:

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

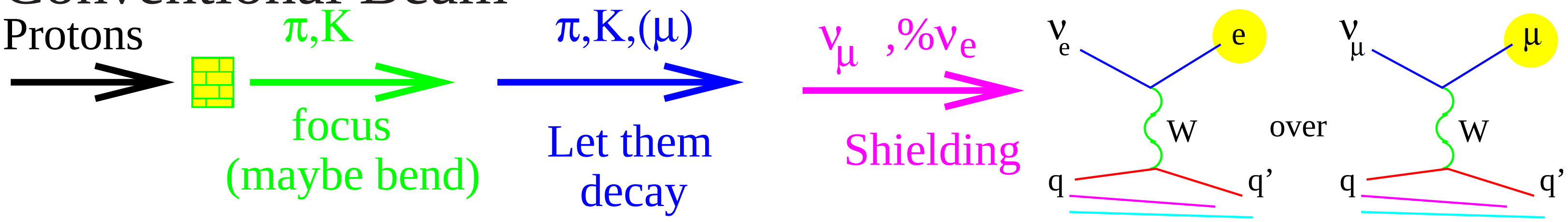
$\rightarrow$ Matter effects without CP violation:
Because earth is filled with electrons...

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

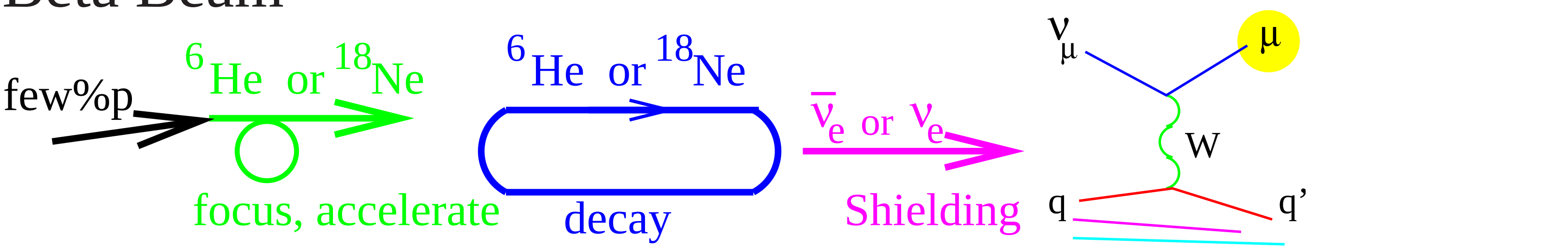
$$E_R = \frac{\Delta m^2_{atm}}{2\sqrt{2} G_F \rho_e} \approx 11 GeV$$

Making Neutrino Beams

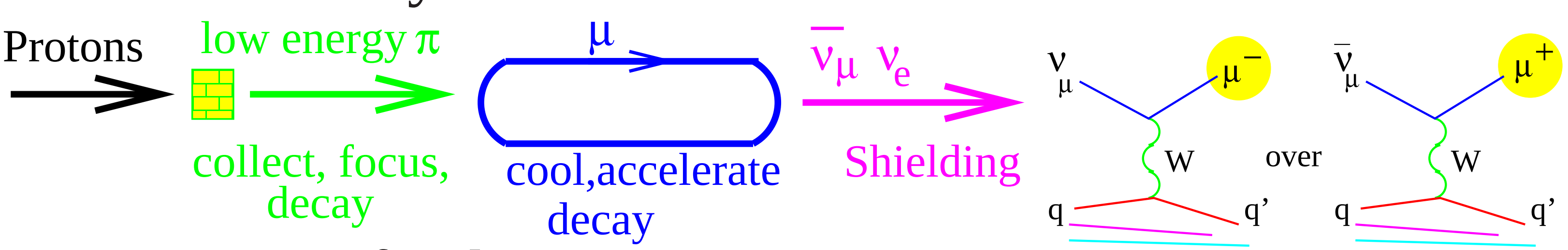
- Conventional Beam



- Beta Beam



- Neutrino Factory

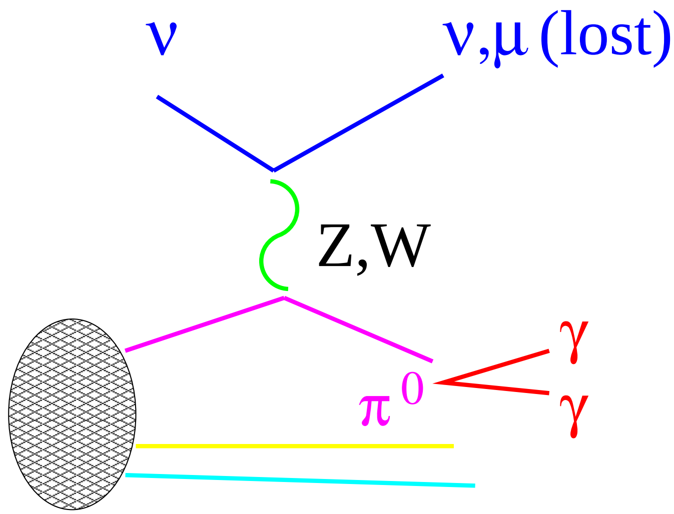


Events/parent at far detector:

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

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

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



π^0 production in NC and CC events

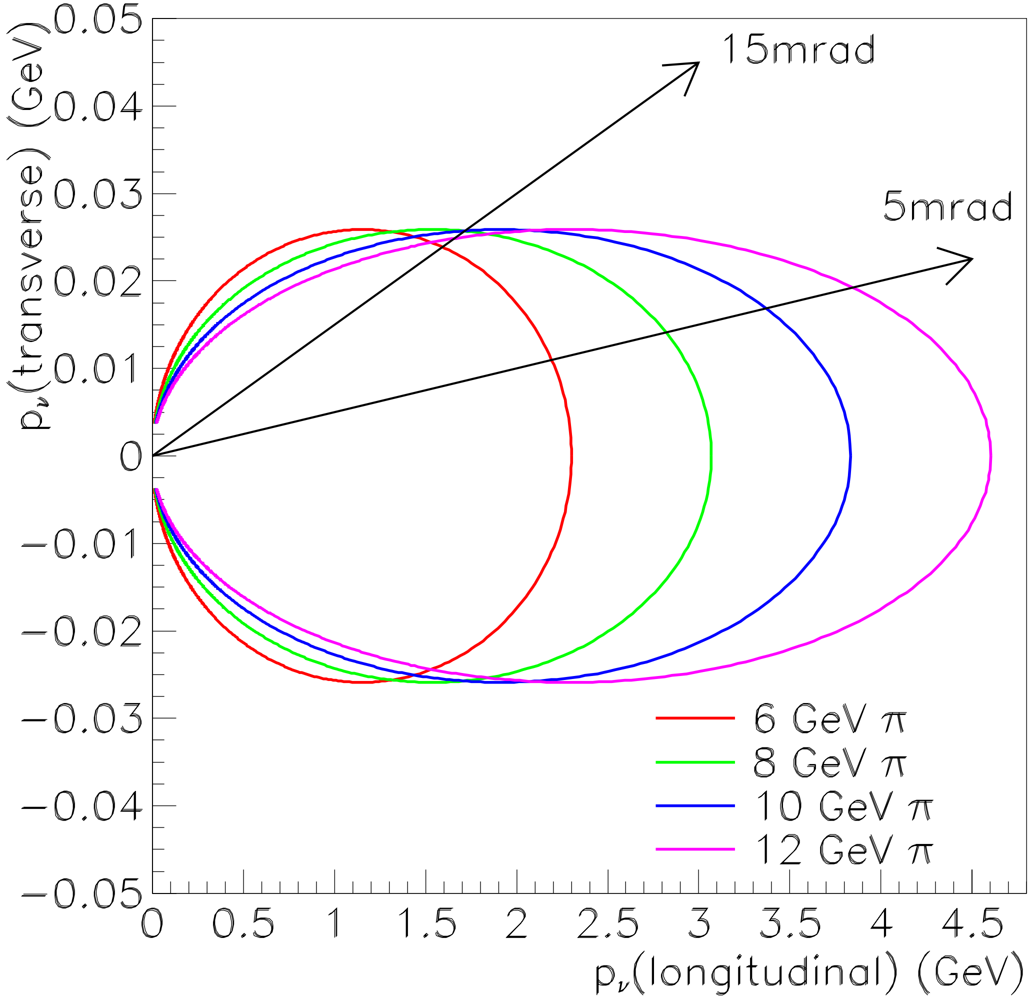
Why is $\nu_e \to \nu_\mu$ hard? It's the Beamline...

- Have to make a ν factory or β-beam

Strategies for Conventional Beam Optimization, I

- Narrow Band Beams (JHF2K,NUMI-OA,CNGT)
  - → Good News: Backgrounds have broad energy spectrum
  - → Bad News: Beam width is much narrower than oscillation width

Ref: D. Beavis et al., BNL No. 52459, April 1995



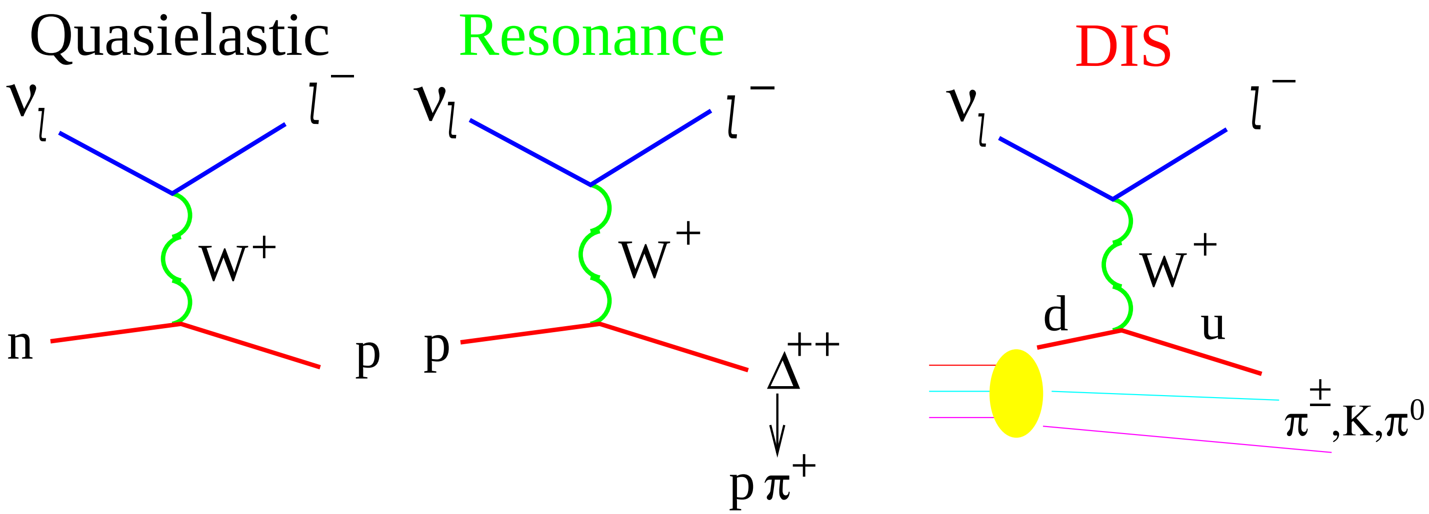
Strategies for Beam Optimization, II

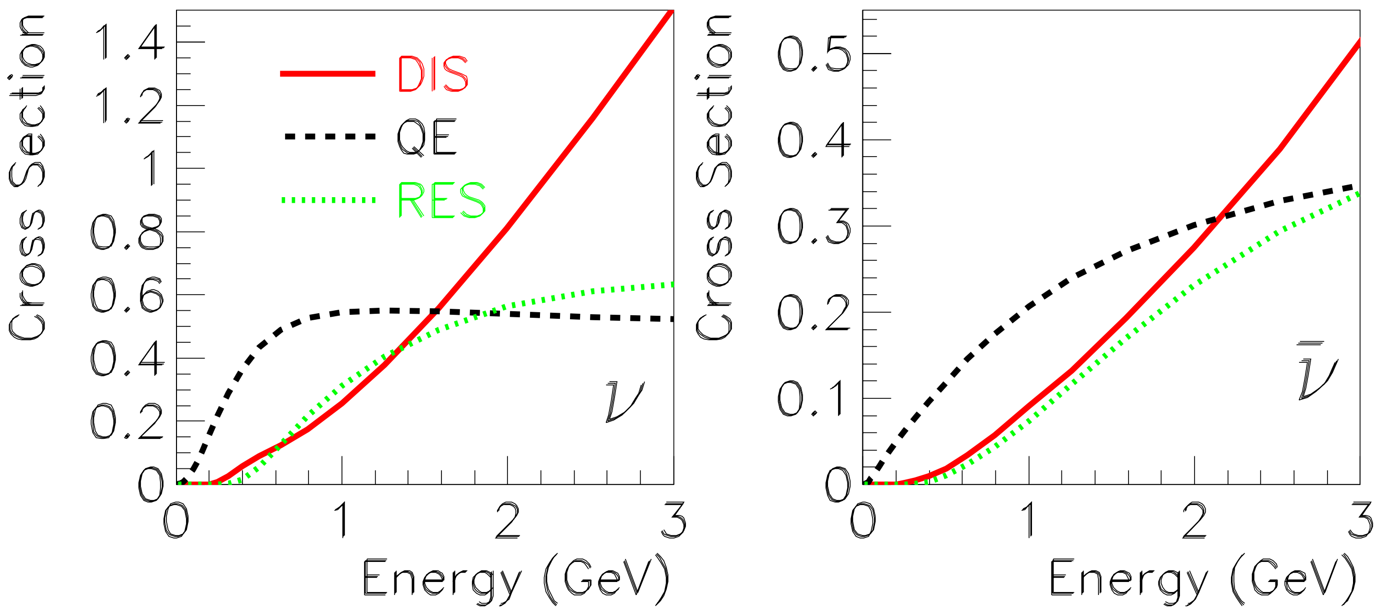
- Very Low Energy (CERN SPL, βBeams)
  - $\rightarrow$ Good News: Good Signal Acceptance & bkgd rejection
  - $\rightarrow$ Good News: barely have enough energy to make the backgrounds...
  - $\rightarrow$ Bad News: Cross Section is very small, esp. $\bar{\nu}$'s
  - $\rightarrow$ Bad News: Have to worry about atmospheric ν backgrounds!
- Very Long Distance (BNL2NUSL)
  - $\rightarrow$ Good News: matter effects amplify signal
  - $\rightarrow$ Good News: CP violating part increases with L

Bad News for Both: have to **KNOW** ν_e background vs energy

Detector Optimization

But first, a reminder about neutrino interactions

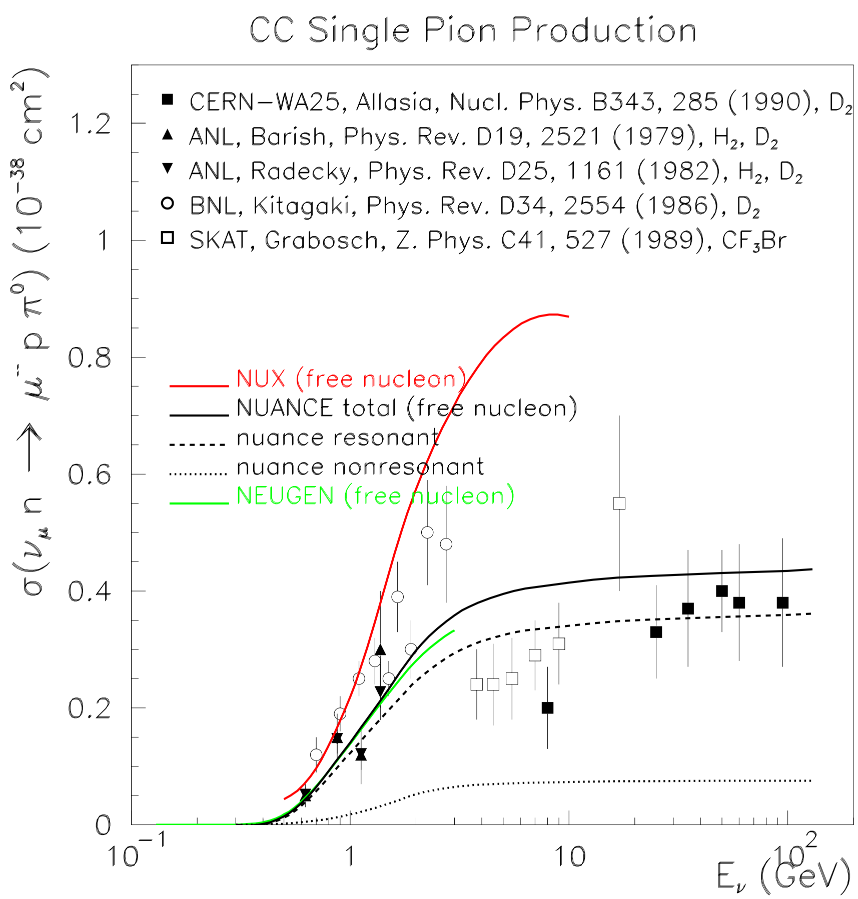




How well are these Cross Sections known?

Example Process: $\nu_\mu n \rightarrow \mu^- p \pi^0$

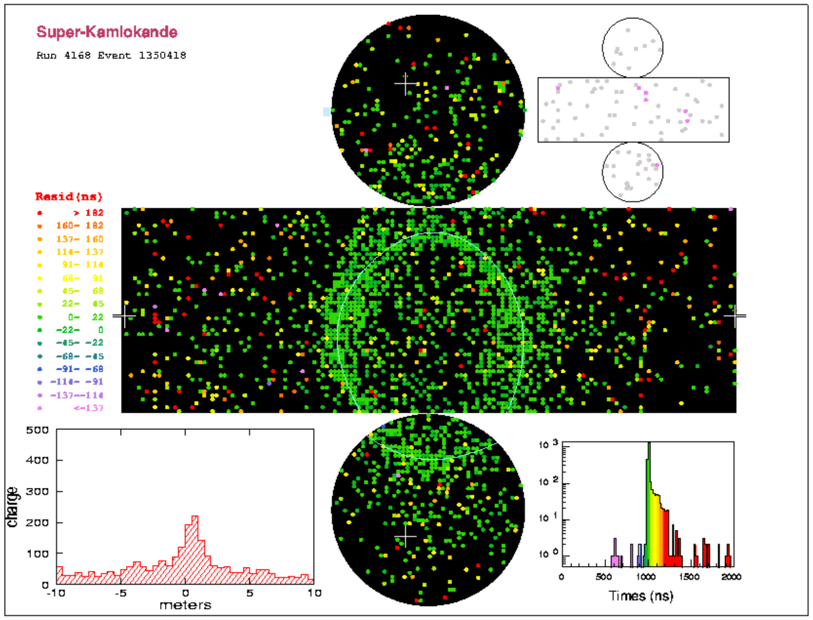
- one of most well-measured processes
- measurements differ by up to factor of 2
- nuclear effects important
- neutral current analog ($\nu_\mu n \rightarrow \nu_\mu n \pi^0$) much more poorly known!



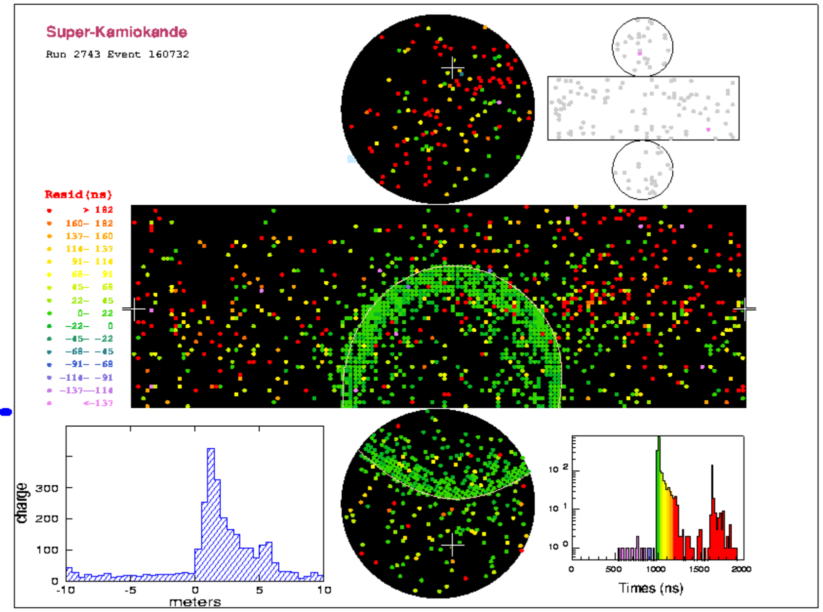
Ref: Sam Zeller, NuINT02,
`www.ps.uci.edu/~nuint/`

Particle ID in Water Cereknov-500MeV

e–like



μ–like



Courtesy Mark Messier

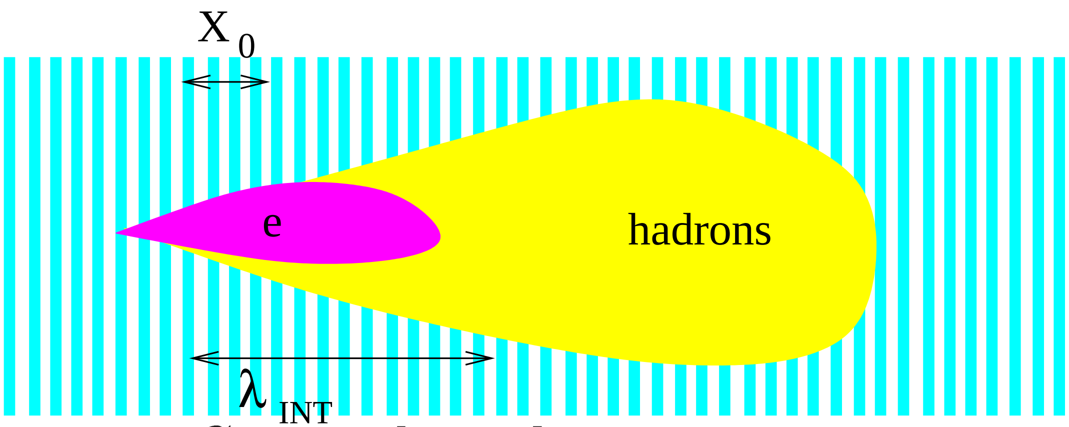
Extremely good separation for Single Particle Events

ν 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...

Fine-Grained Calorimetry



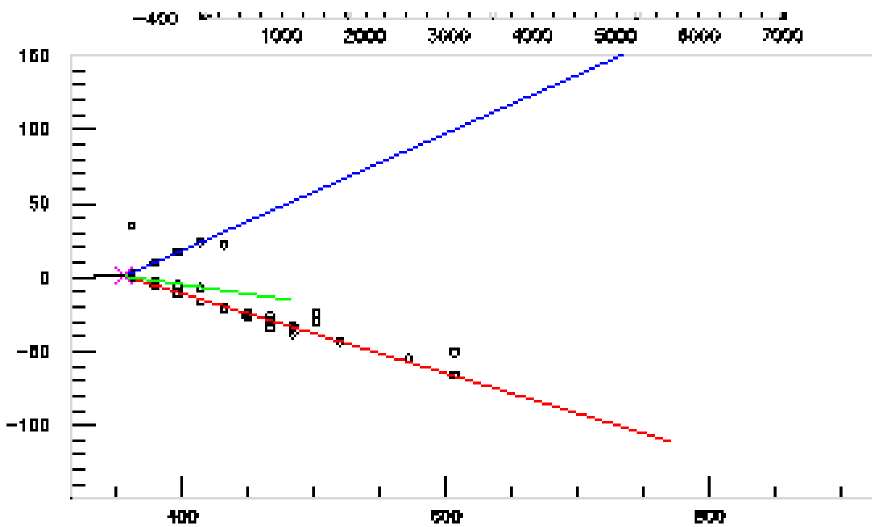
Tried and True Technology

1/3 X_O sampling calorimeter

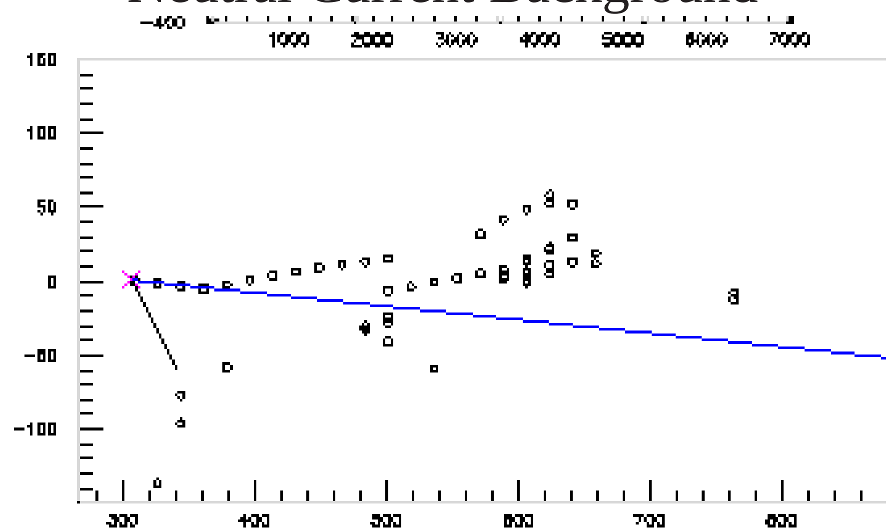
Hit counting:

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

$2GeV\,\nu_e$ Charged Current



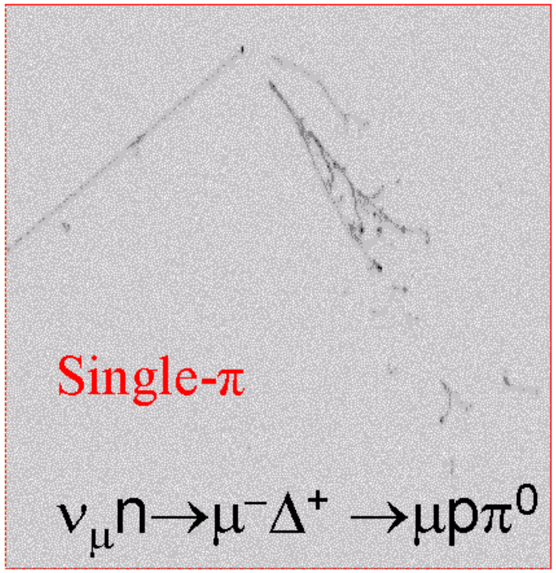
Neutral Current Background

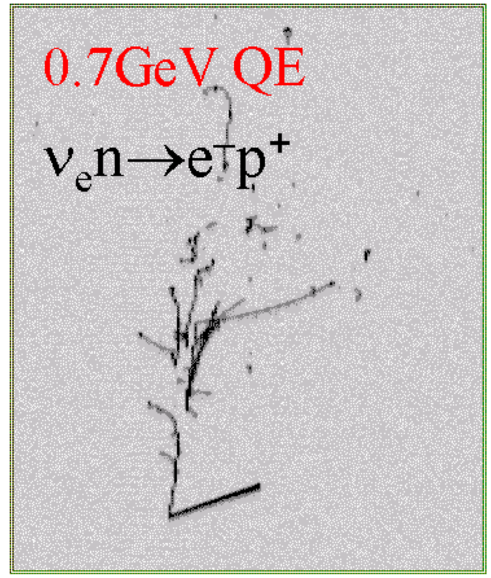


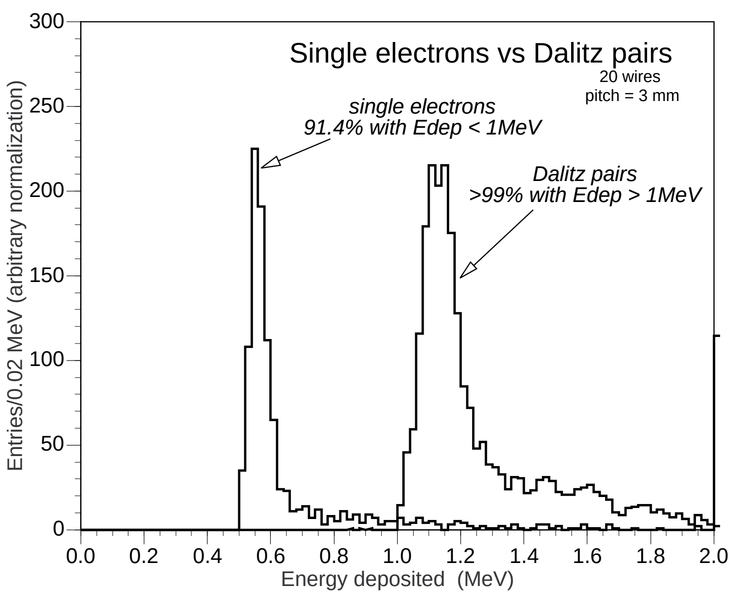
few $\times 10^{-}3$ NC rejection with 35-40% signal acceptance at 2GeV

Remaining backgrounds: CC and NC π^0 production

LAr TPC Strategy: Electronic Bubble Chamber







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

In Praise of Near Detectors

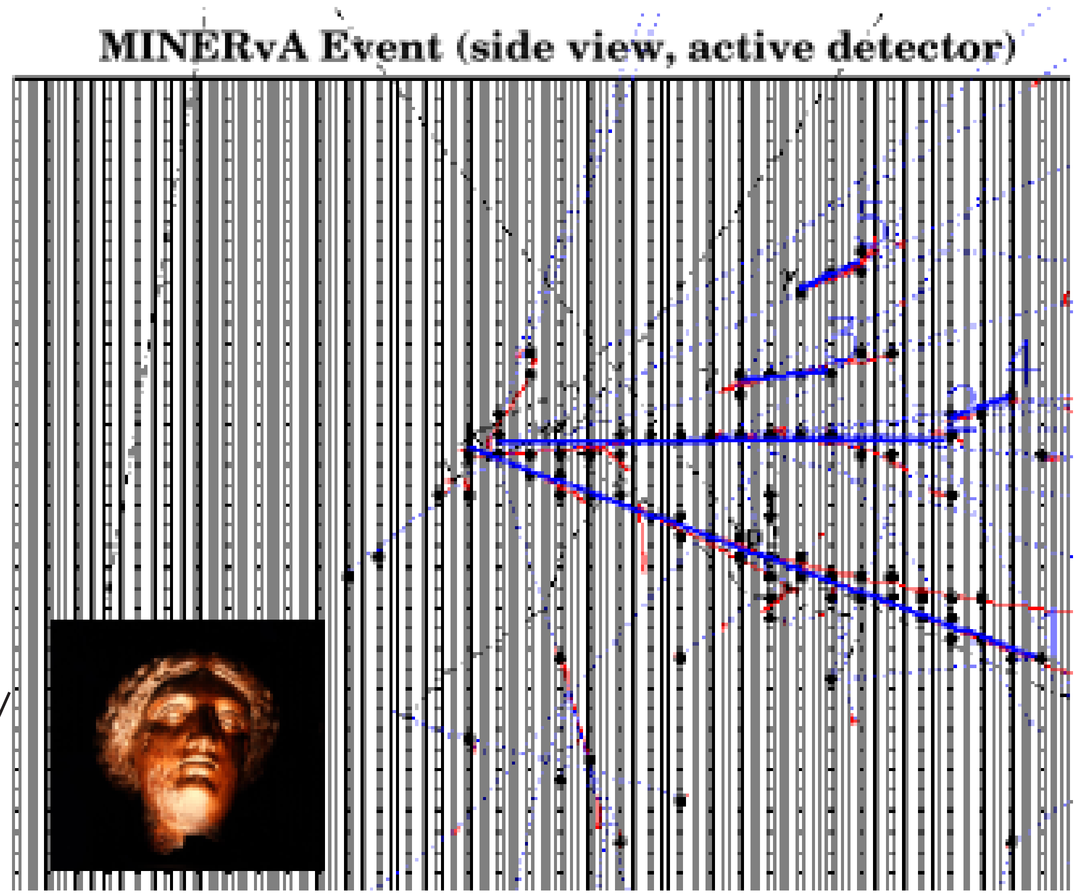
If you can't remove all the backgrounds...

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

One example:
MINERνA in NuMI/MINOS joint Nuclear/Particle project to

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

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



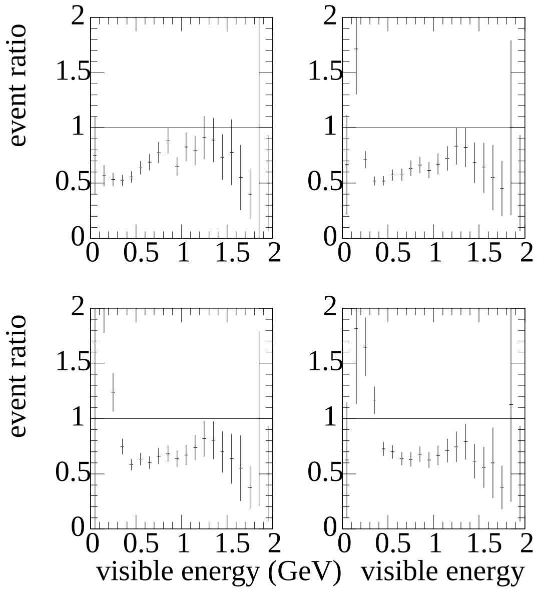
All of the experiments that come next have at LEAST 2 detectors in the beamline

First Order of Business: Are there more than 3 ν's

If MiniBooNE sees a signal, there is lots to measure:

- one or two mass scales?
- CP violation at high Δm^2?
- “direct” Sterile neutrino search

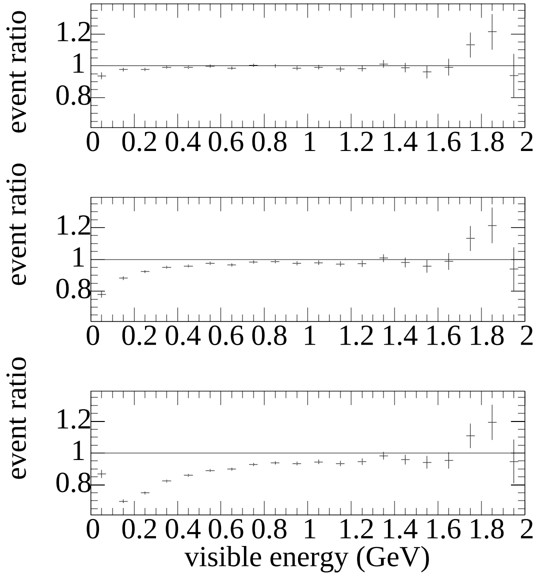
But for precsion, need second (identical) detector...



← ν_e appearance for different Δm^2

ν_μ disappearance for different Δm^2 →

Ref: MiniBooNE Proposal



Getting to θ_{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

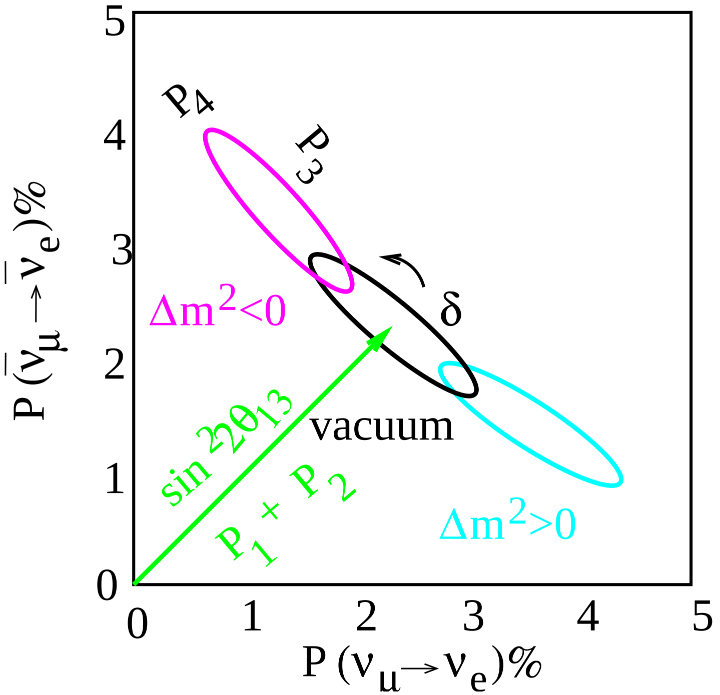
$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$

$$A = \sqrt{2}G_F n_e$$

$$B_\pm = |A \pm \Delta_{13}|$$

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

and the $\pm$ signifies neutrinos or antineutrinos

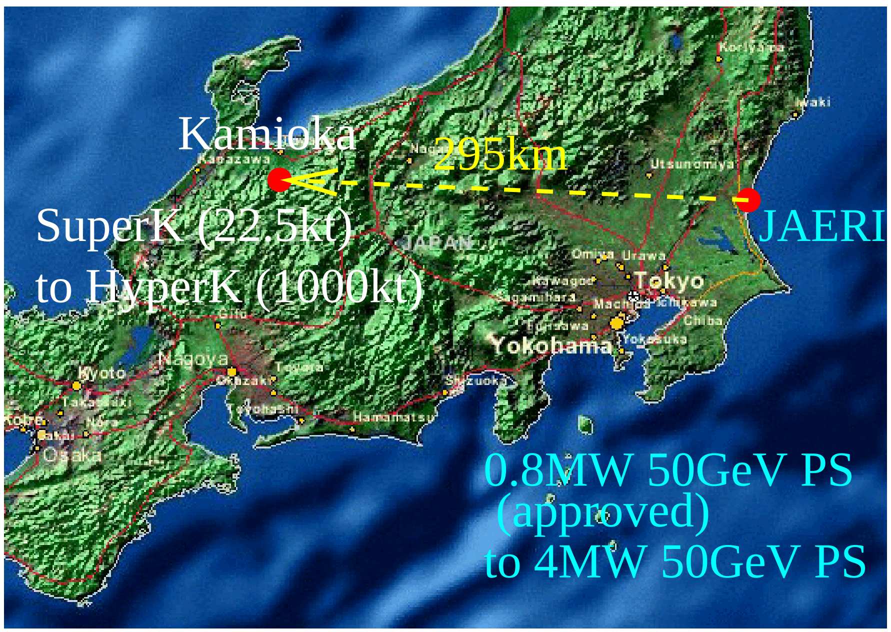


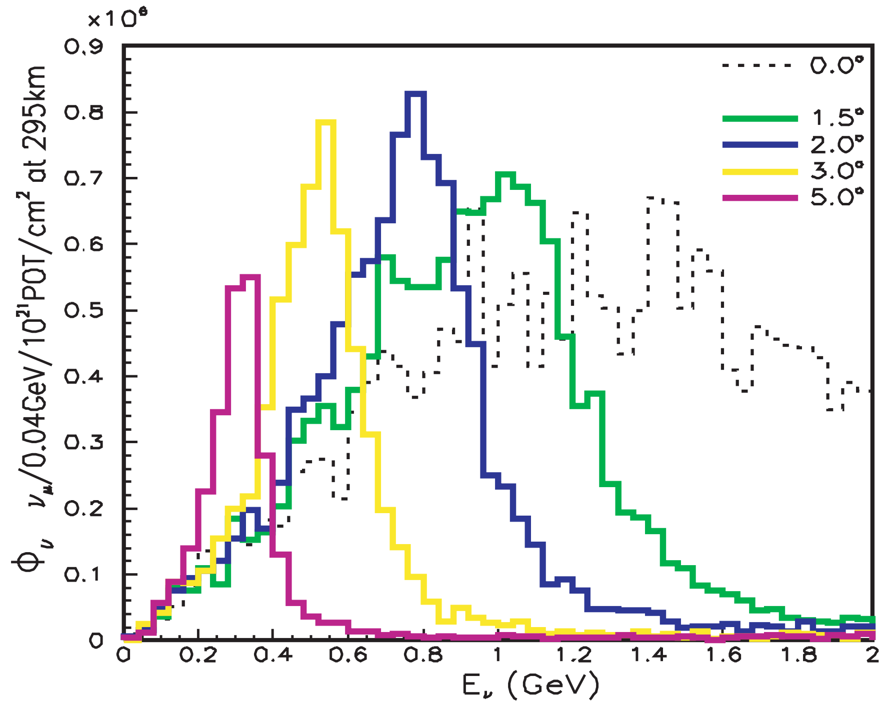
Scales of $\sin^2 2\theta_{13}$

10^{-1} $3\text{x}10^{-2}$ 10^{-2} 10^{-3} 10^{-4}

Finding $\theta_{13} \neq 0$	MINOS and CNGS	Conventional Superbeams Phase I		
Mass Hierarchy	Conventional Superbeams Phase I			
Evidence for $\not{CP}$	Conventional Superbeams Phase I			

J-PARC to SuperK





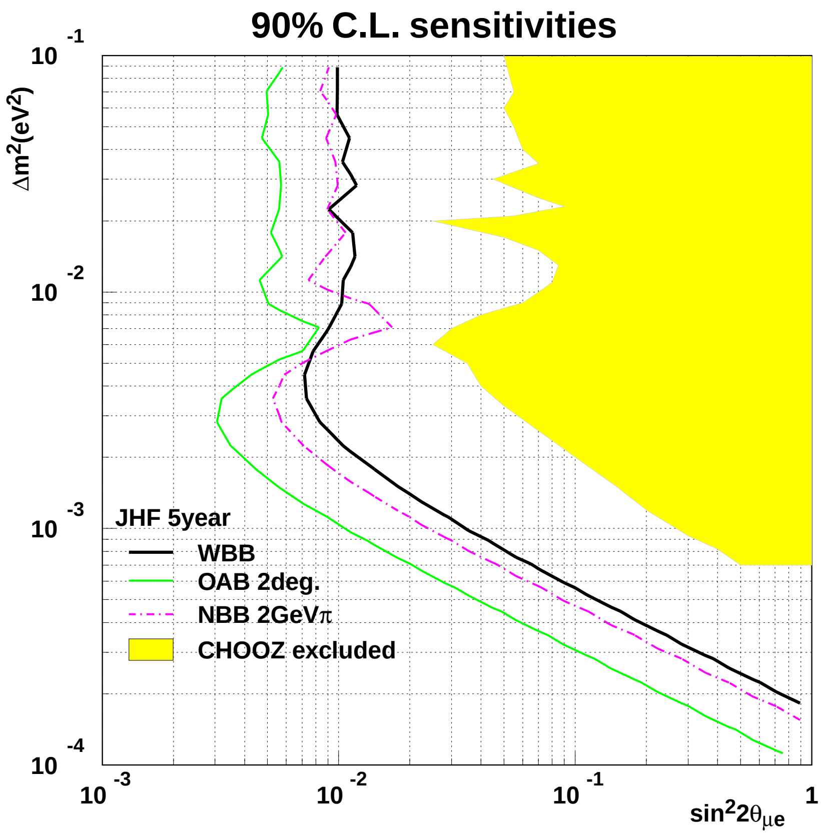
Ref: Itow *et al*, `hep-ex/0106019` and `neutrino.kek.jp/jhfnu/`

Status:

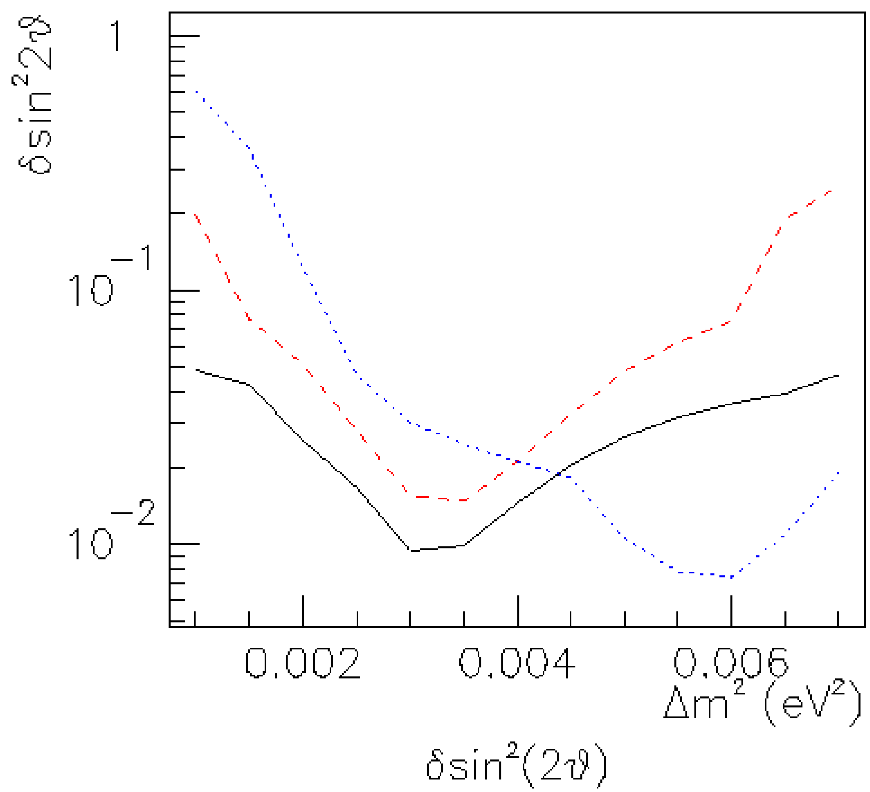
- J-PARC under construction
- budget request submitted to government in June 2003
- Part of decay pipe already installed!
- high intensity data: 2008

J-PARC to SuperK Sensitivity

ν_e Appearance θ_{13} Sensitivity



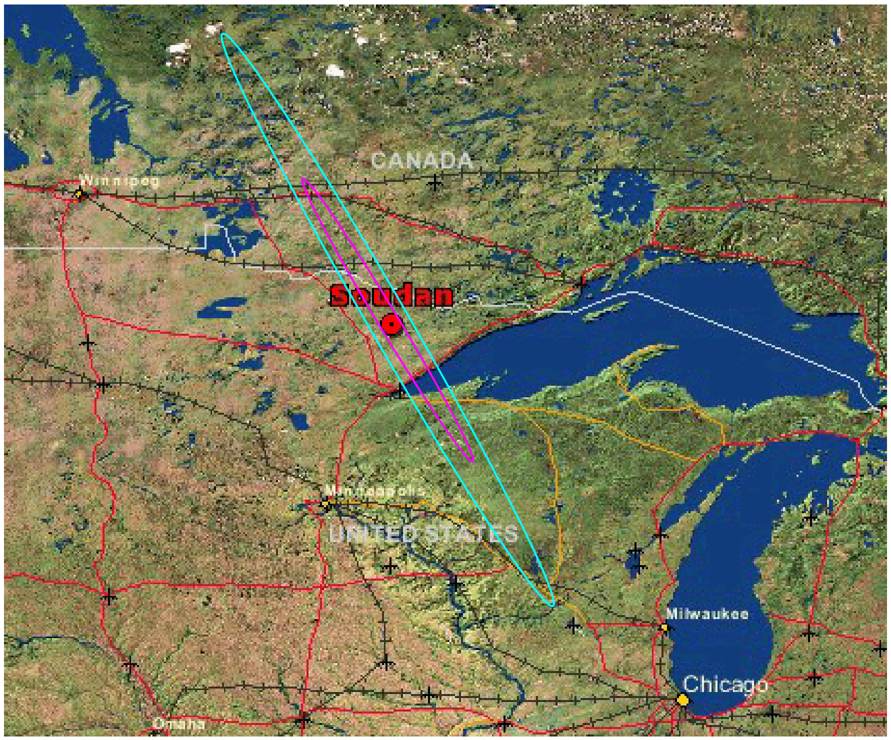
ν_μ Disappearance–θ_{23} sensitivity

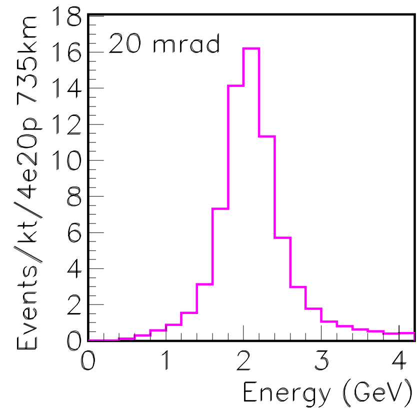


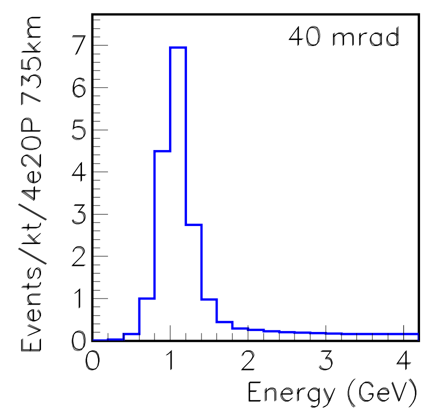
0.75MW p source, 22.5kTon SuperK, $\sim 0.5\% \nu_e/\nu_\mu$

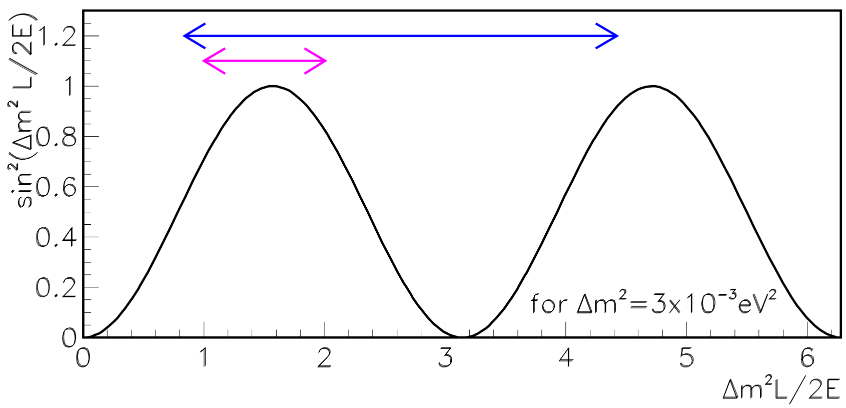
Different Off Axis angles shown

NuMI-Off Axis Experiment







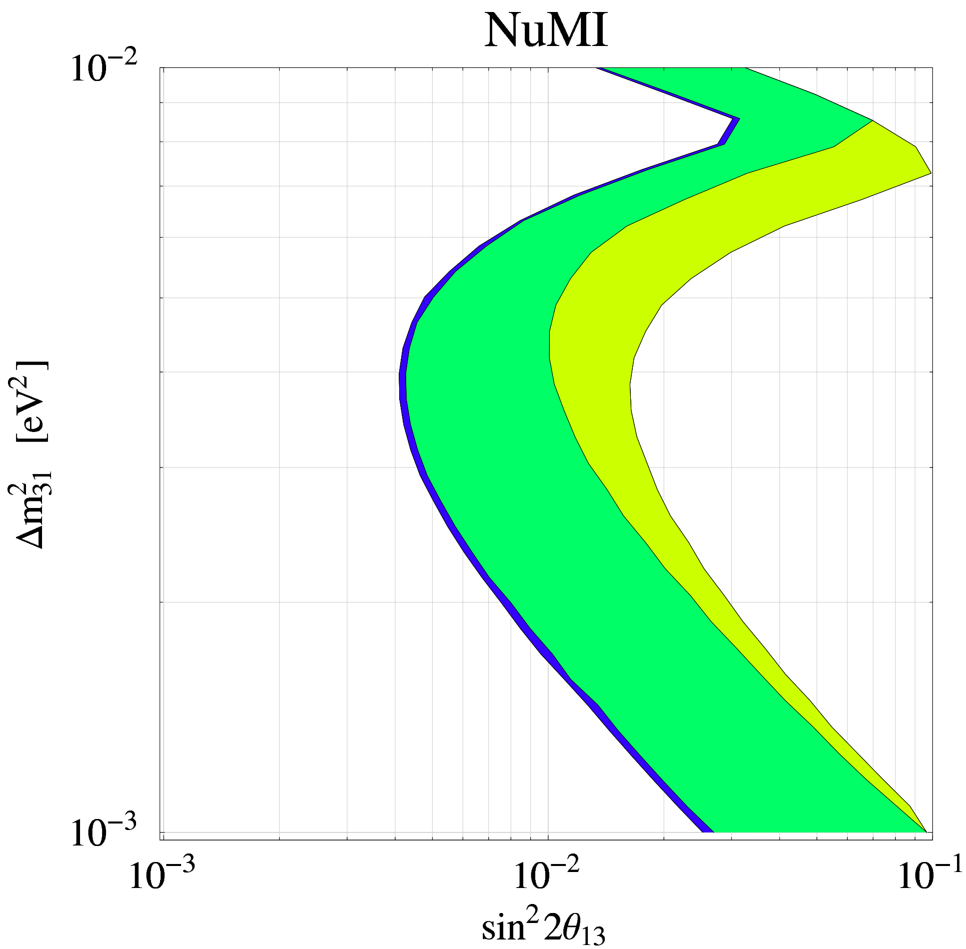


Narrow Beams from 1 to 2 GeV, distances from 400 to 1100 km!

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \propto$$

$$\frac{\Delta m^2_{sol} L}{E} \sin\theta_{13} \sin\delta$$

NUMI-OA Sensitivity



0.4MW source, 20kton, $\sim 0.5\% \nu_e/\nu_\mu$ Blue: Stat+syst. only Green: correlations Lt. green: ambiguities

Ref: Ayres *et al* `hep-ex/0210005`

Sensitivity for proposal: See $\sin^2 2\theta_{13}$ at 3σ a factor of 10 past CHOOZ

Current Status:

- Optimizing transverse segmentation
- Refining readout technology options
- writing proposal

Near Term Conclusions: Two Great Opportunities!

	JHF	NuMI-OA
Nominal Design	0.8GeV 295km	2GeV 730km or 980km
Range of Motion	0.5 to 1GeV	0.5 to 3GeV 500 to 1100 km
Natural Resource	Super-K (200M$ *)	NuMI Beamline (100M$)
Main Obstacles	Final Beam Design Build Beamline Proton Driver 0 to 0.8MW	Prove FG is cheap Prove surface operations ok Proton Driver 0.2 to 0.4MW

* means US accounting scheme

But what do you get if you build both instead of just one?

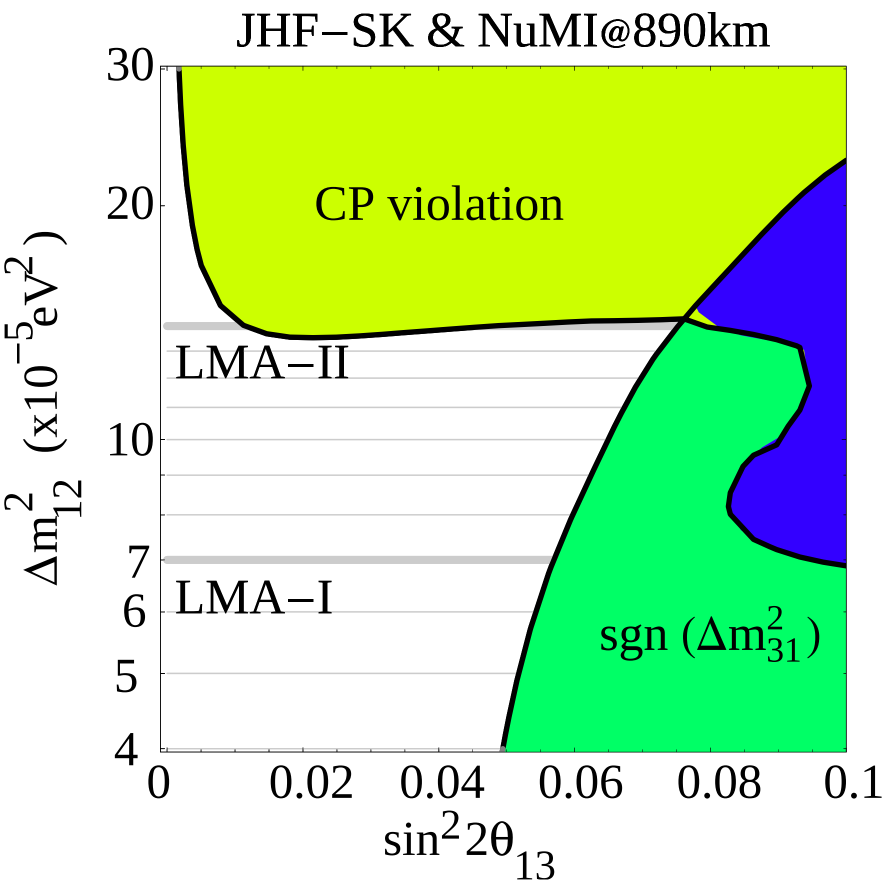
Scales of $\sin^2 2\theta_{13}$, continued

10^{-1} $3\text{x}10^{-2}$ 10^{-2} 10^{-3} 10^{-4}

Finding $\theta_{13} \neq 0$	MINOS & CNGS	Conventional Superbeams Phase I		
Mass Hierarchy	Combinations of Phase I Superbeams			
Evidence for $\not{CP}$	Combinations of Phase I Superbeams			

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

What can you learn from JHF *and* NuMI-OA?



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

With some regions of parameter space

we might even see hint of CP-violation

First Step–MORE MORE MORE

All the proposals discussed will see ν_e candidate events even w/o oscillations!
$\rightarrow$ Gains in Sensitivity come in square roots

$$N_{events} = \sigma\Phi(MW)M(kTon)\epsilon$$

- More Detector Mass than ever Before
  - $\rightarrow$ "Industrialization" of Detector Construction a must
  - $\rightarrow$ typical estimates: factors of 4 to 20 above current largest detector of any given technology
- More Beam Power
  - $\rightarrow$ New Proton Drivers
  - $\rightarrow$ New Super Rad-hard beamlines

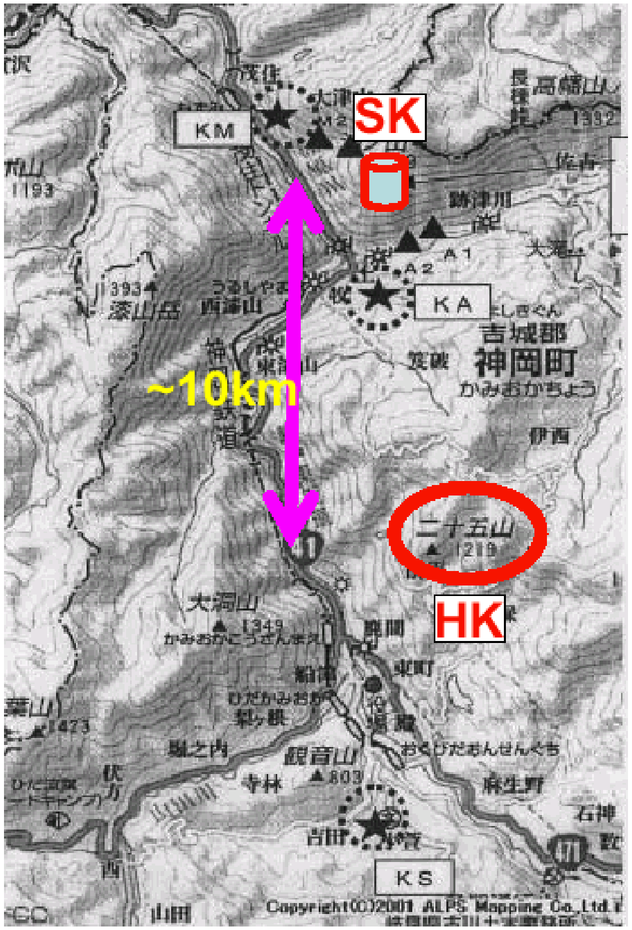
Scales of $\sin^2 2\theta_{13}$, continued

10^{-1} $3\text{x}10^{-2}$ 10^{-2} 10^{-3} 10^{-4}

Finding $\theta_{13}\neq 0$	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		

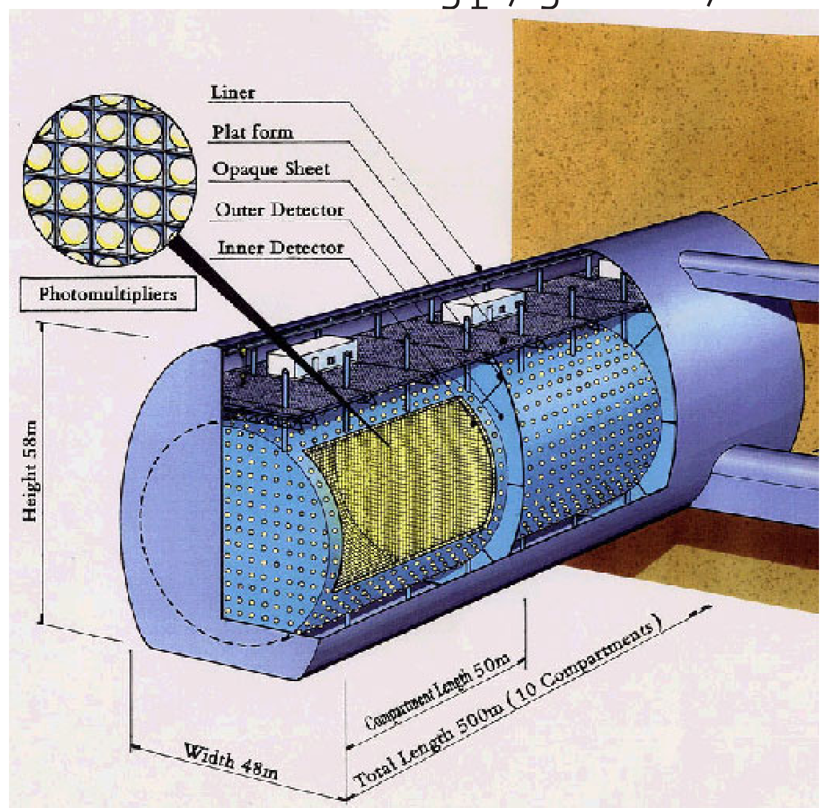
Phase II combinations: Barger, Marfatia, Whisnant 2002

Upgrades to J-PARC and Super-K



- New 1MTon water Ч Detector,
- 4MW proton source

neutrino.kek.jp/jhfnu/

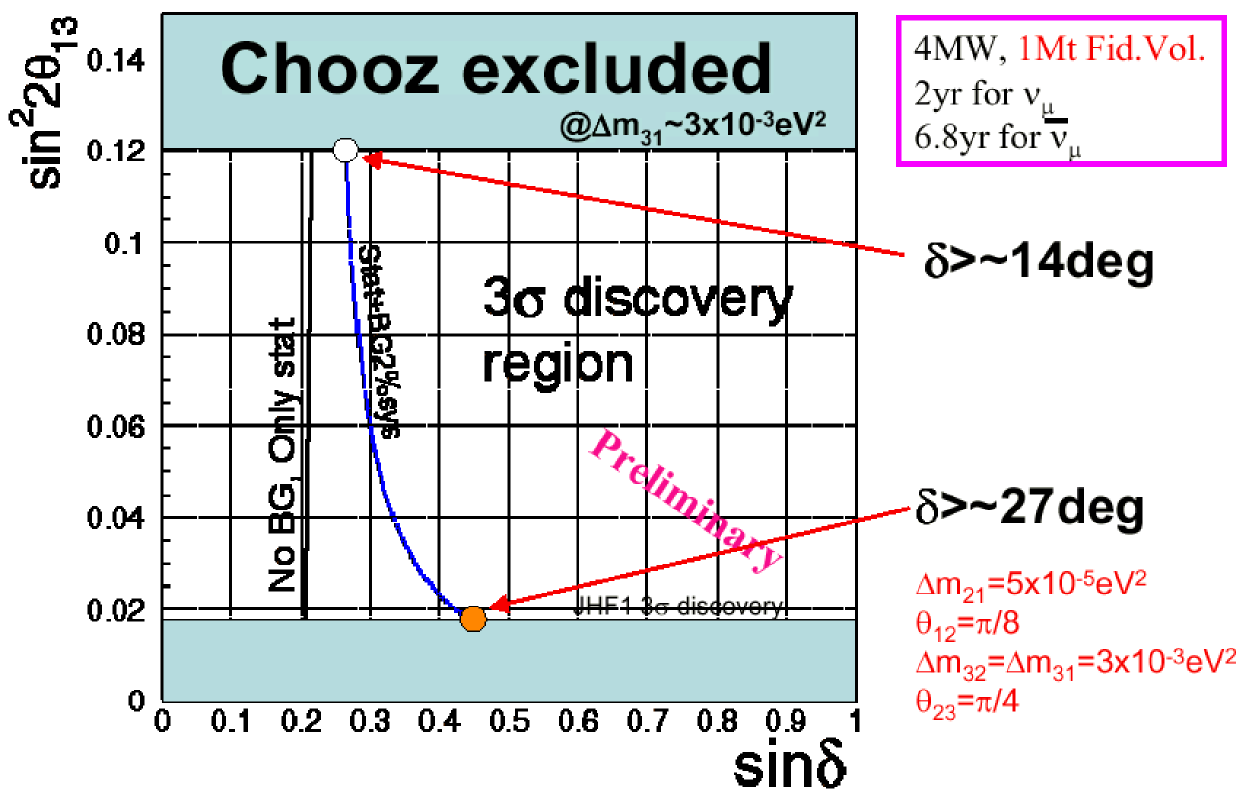


T. Kobayashi, NP02, Kyoto, 9/2002

J-PARC-HyperK Sensitivity

First glimpse: 5× proton power, 20× detector mass:
sensitivity to $\theta_{\mu e}$ improves by 10×...
Caveat: have to keep systematic errors to few % for this.
But if θ_{13} was discovered at Phase I, then...

2 yrs ν , 6.8yrs $\bar{\nu}$,4MW, 1MTon



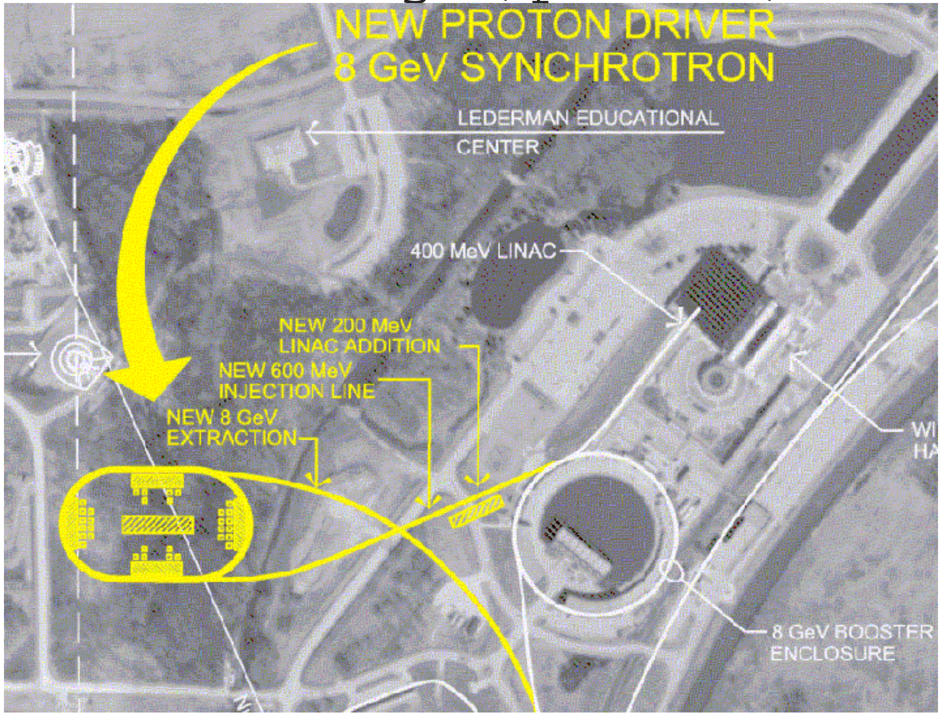
NB: These plots assume mass hiearchy determined elsewhere

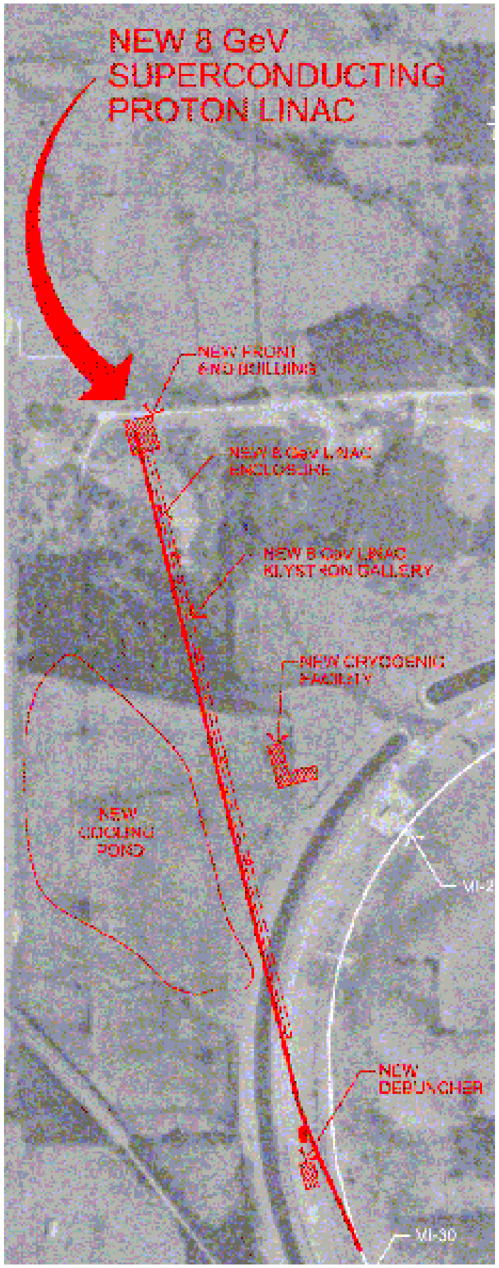
Upgrades to NuMI-OA

Goal is 5× power (2MW?), 5× detector mass

- Proton Driver Upgrade
- New Detector
- L, E Depend on what first detector sees

Two p driver designs:
www-bd.fnal.gov/pdriver/8GEV





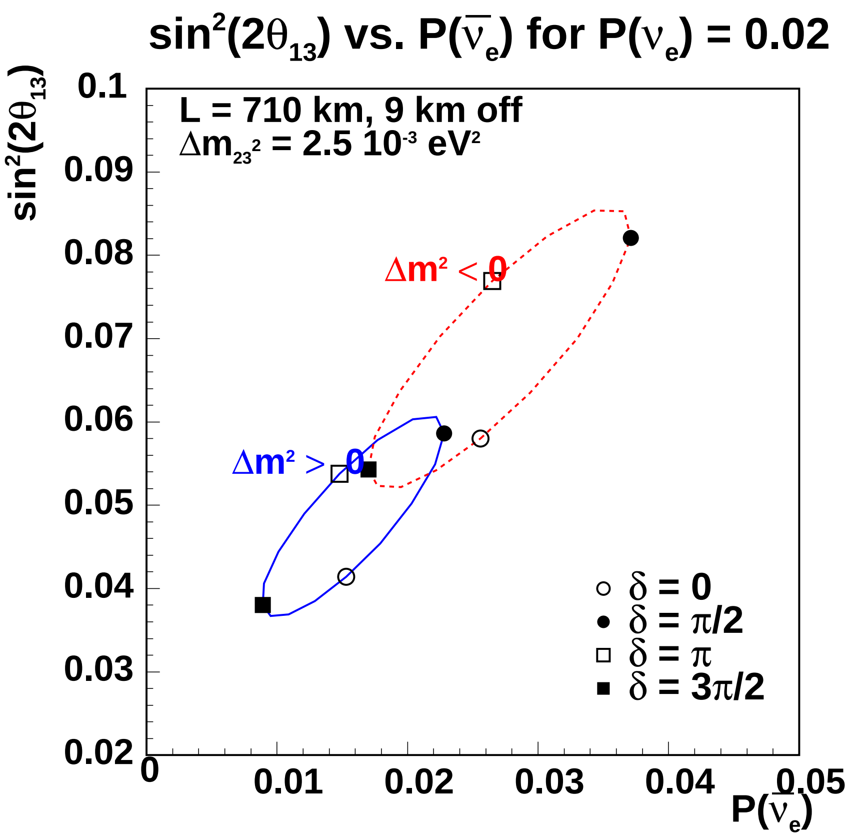
NUMI Off-Axis–Phase II

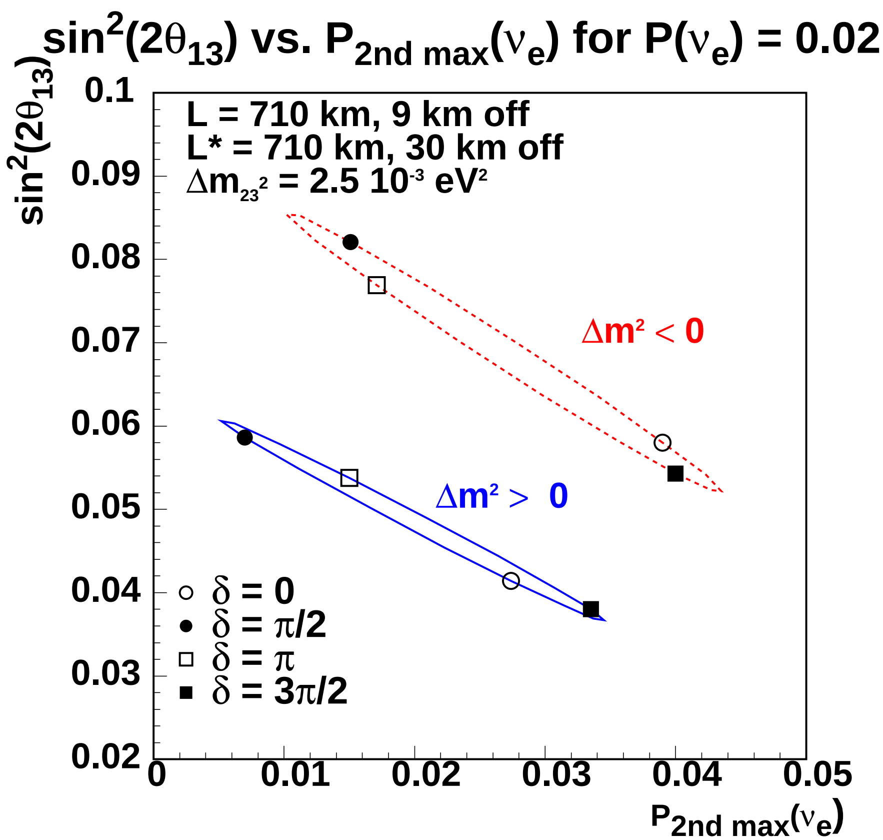
Imagine NuMI Off Axis and/or J-PARC measures $P(\nu_\mu \to \nu_e) = 0.02$...

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

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

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

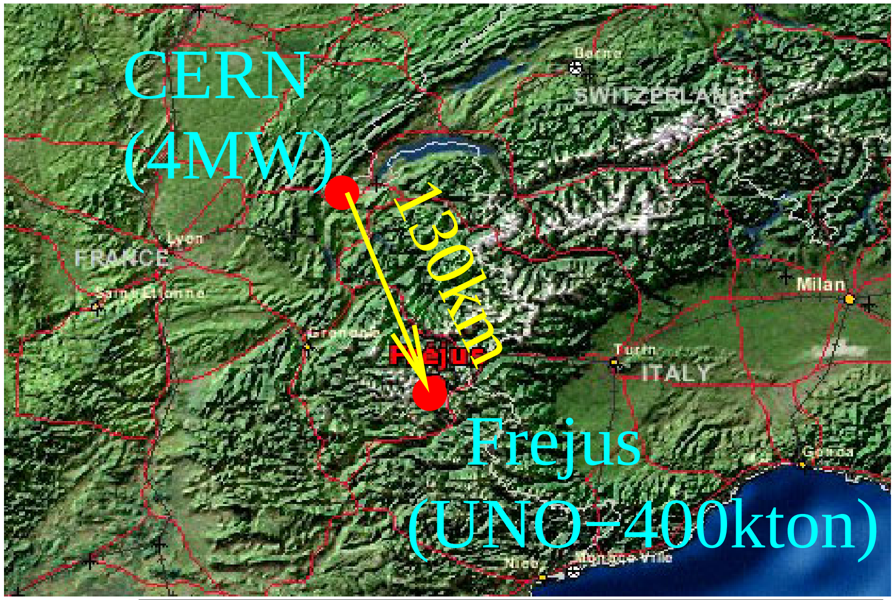




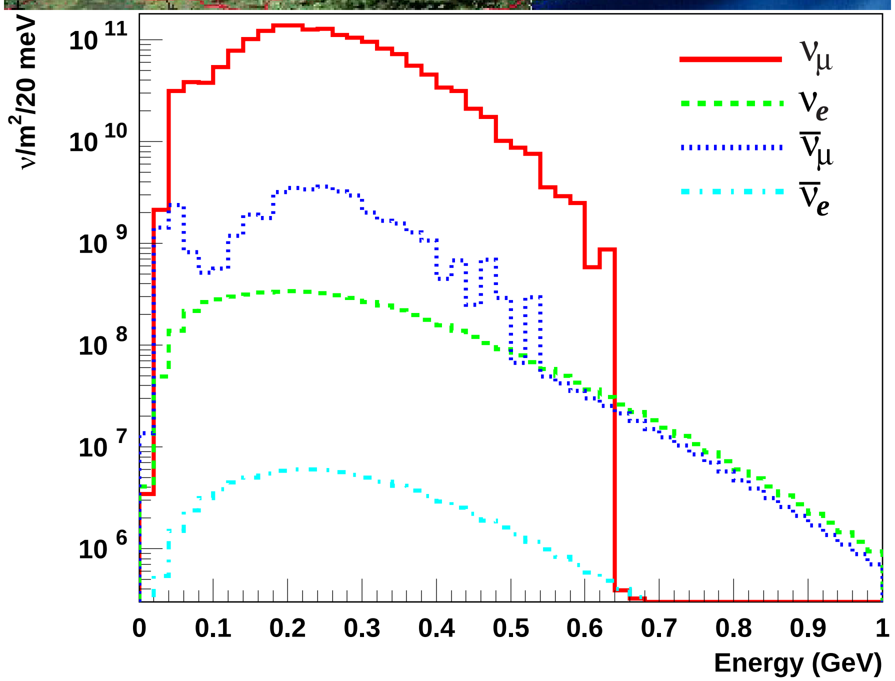
Maybe mass hierarchy can be determined, maybe not...
Now imagine it can't...

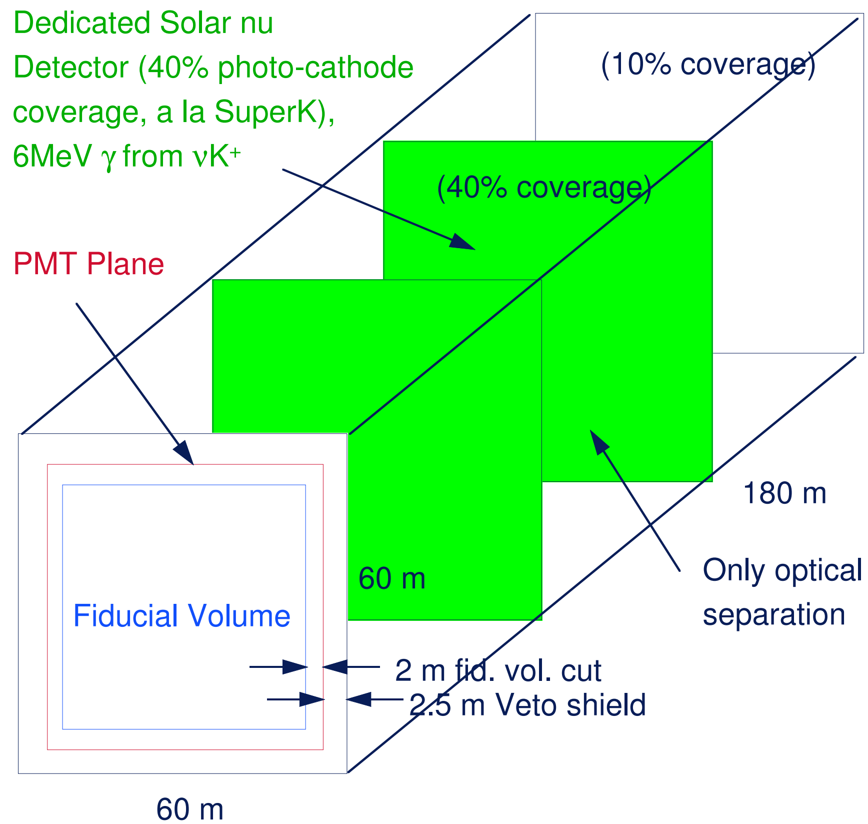
G.Feldman, HEPAP meeting

How Low Can you Go? CERN SPL



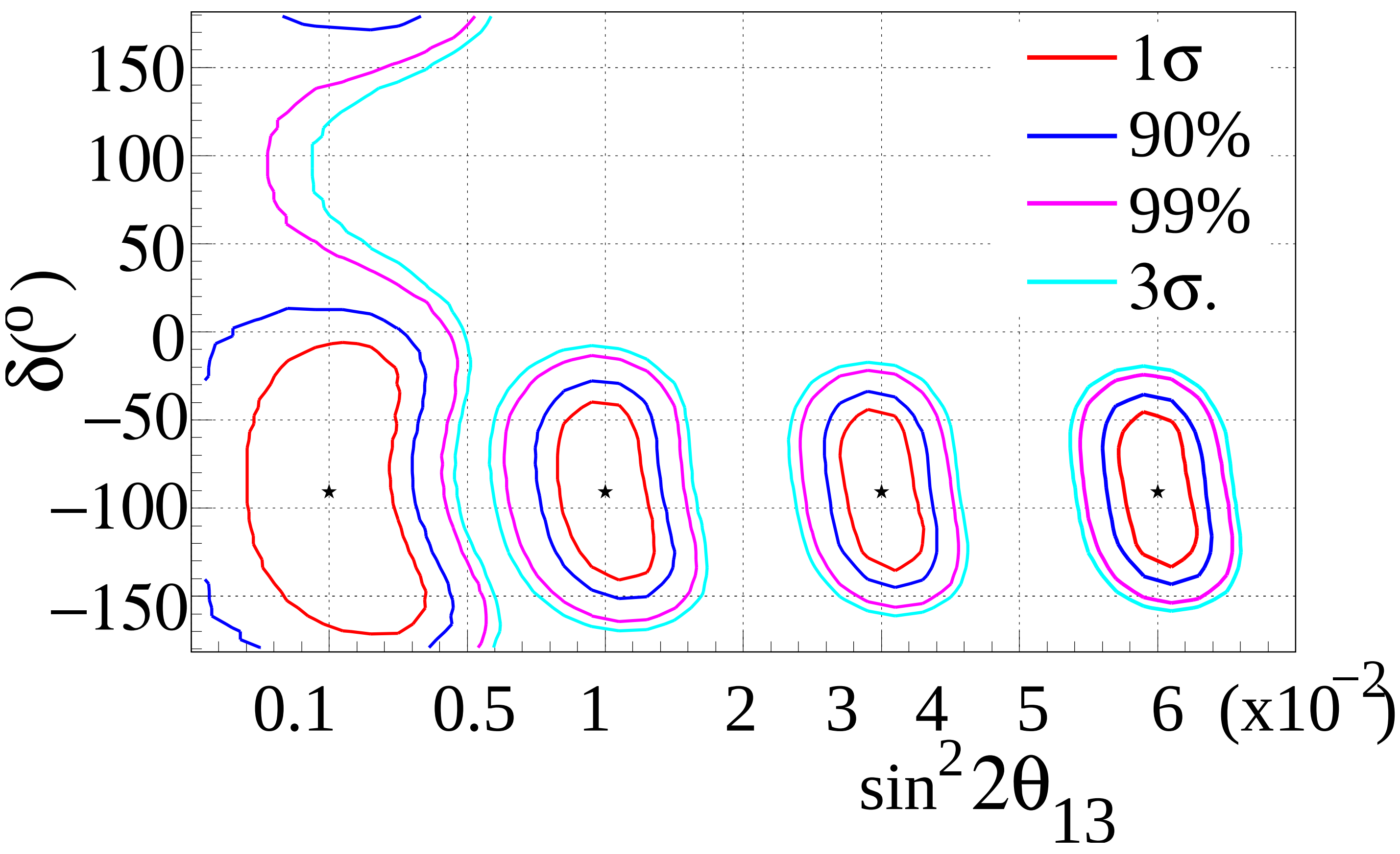
Use 2.2GeV protons,
and UNO detector (400kton Water Ч)





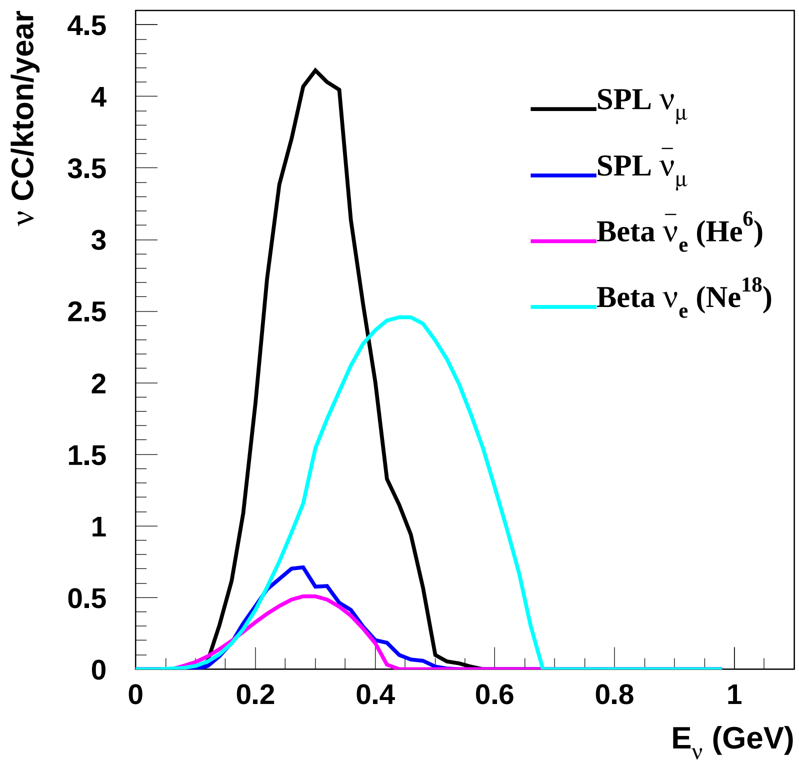
CERN SPL: ν_e Appearance

5 years, 4MW source (!), get to Factors of 10-50 past CHOOZ
front end for ν Factory 3σ evidence for CP Violation
2 yrs ν 10 yrs $\bar{\nu}$ 400kton

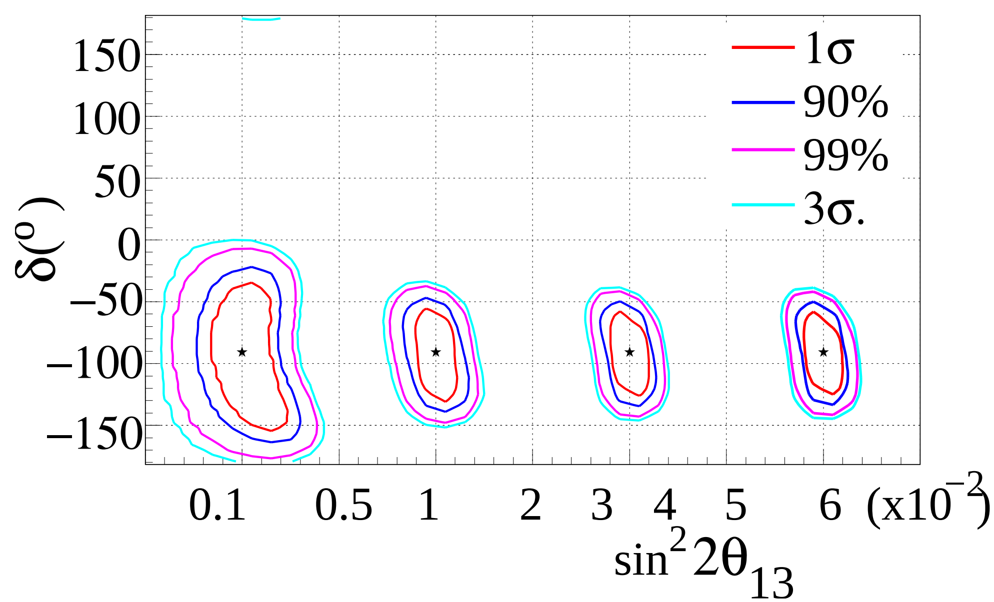


M. Mezzetto, NuFact03

How Pure can you be? β-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



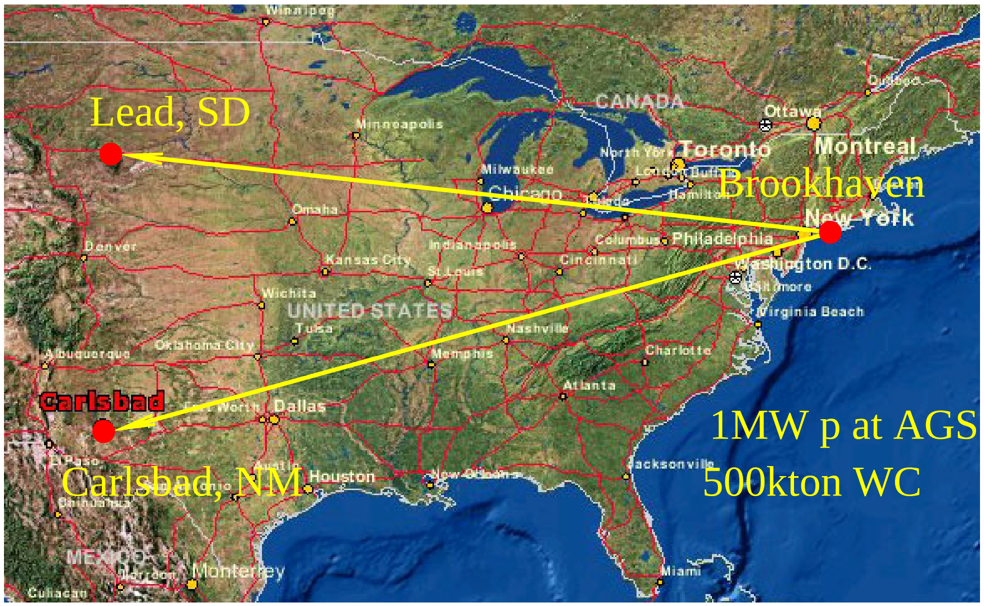
Conventional Ion production & acceleration, use same H_2O Ч detector in Frejus

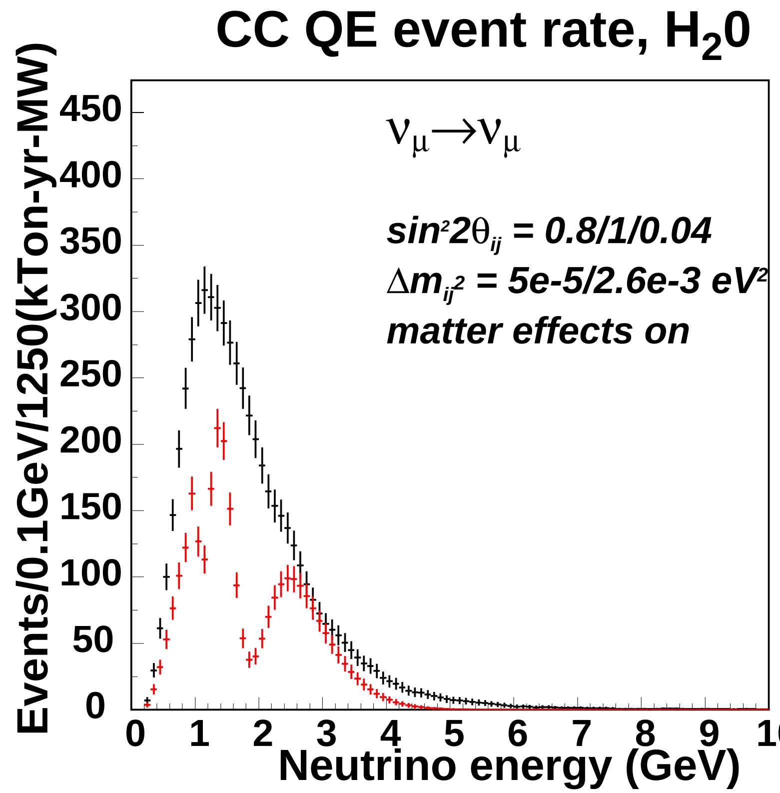
Run $\nu_e(Ne^{18})$ and $\bar{\nu}_e(He^6)$ in separate bunches, using timing to distinguish beams

1° means $\sin^2 2\theta_{13} = 1.2 \times 10^{-3}$

Ref: M. Mezzetto, NuFact03

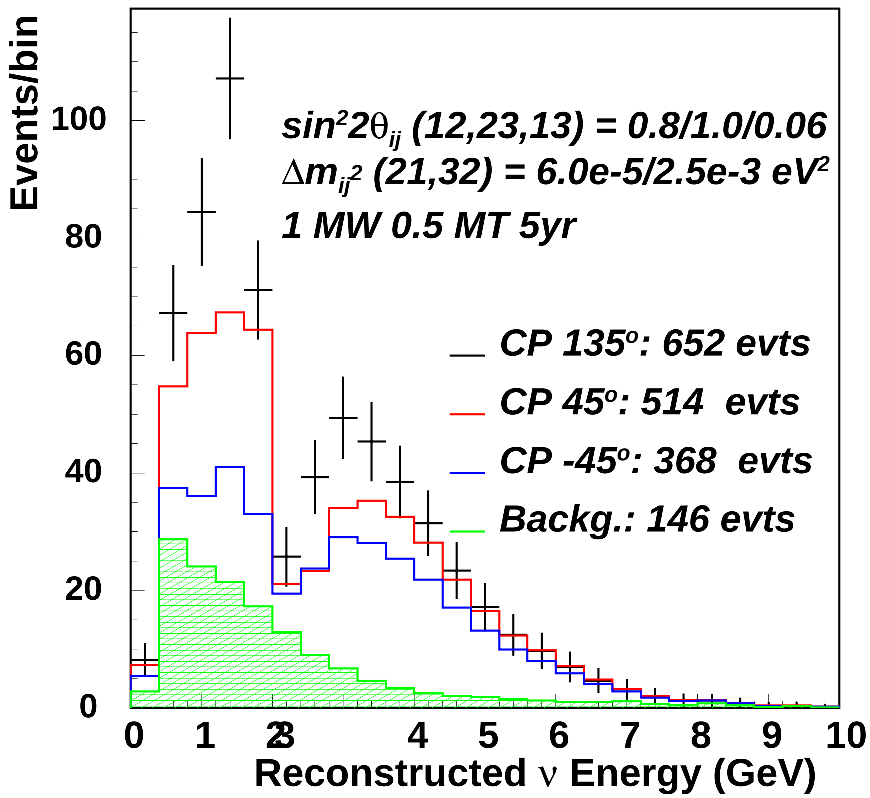
How Far Can you Go? BNL LOI

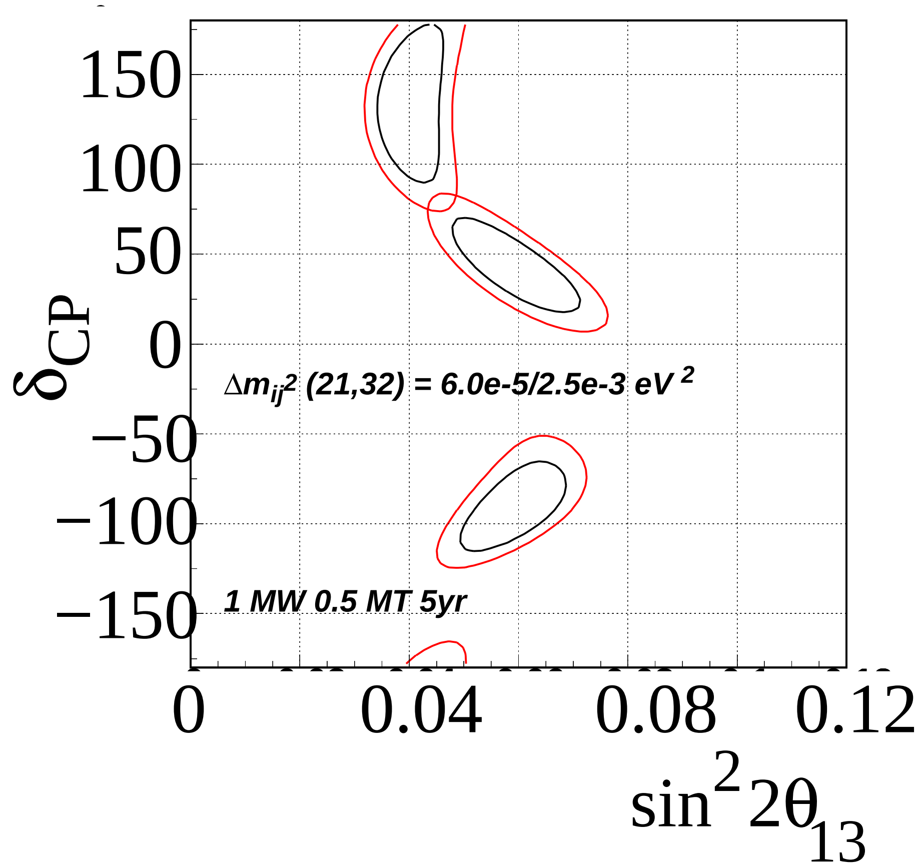




Brookhaven LOI `hep-ex/0211001`
Goal is two oscill. maxima, see δ with ν only
Use ONLY single-ring events in detector,
agressive background rejection plan

BNL LOI ν_e Appearance



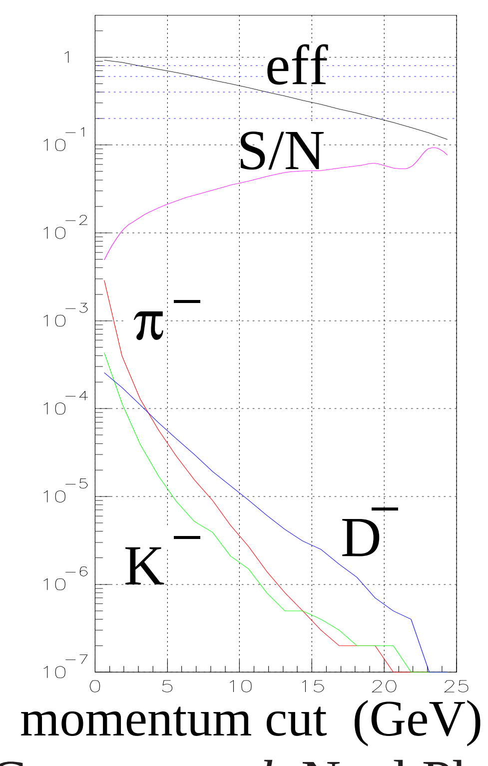


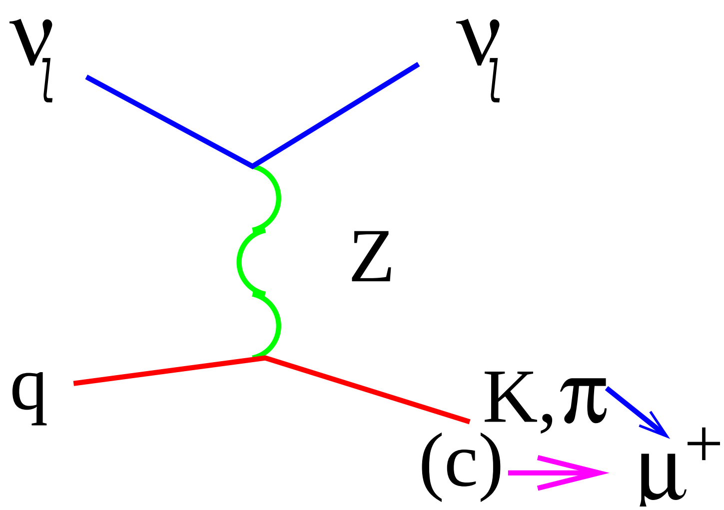
again, ONLY 1-ring events in detector, include π^0 backgrounds

90% CL limits, different test points 5 years ν running only! (assume normal hierarchy)

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

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





Momentum cut on muon easily removes backgrounds

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

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

10^{-1} $3\text{x}10^{-2}$ 10^{-2} 10^{-3} 10^{-4}

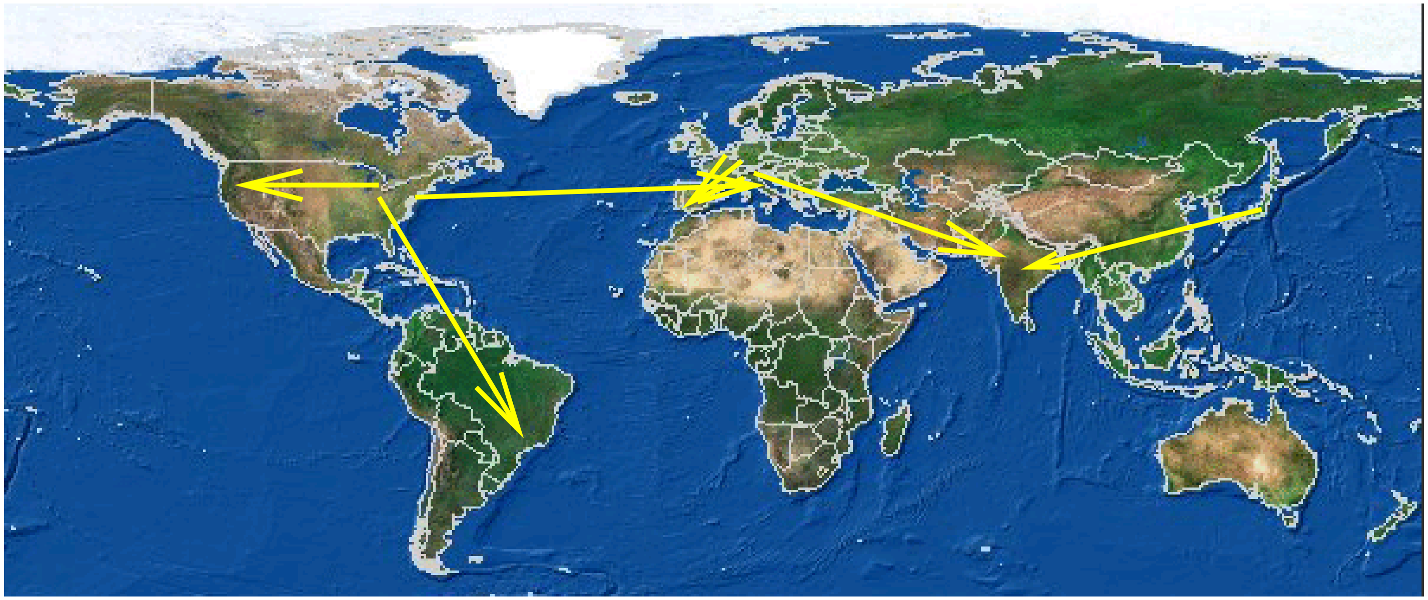
Finding $\theta_{13}\neq 0$	MINOS & CNGS	Conventional Superbeams Phase I	Conventional Superbeams Phase II	Combinations of ν Factories
Mass Hierarchy	Combinations of Phase I Superbeams	Combinations of Phase II Superbeams	Combinations of νFactory+SB	Combinations of ν Factories
Evidence for ~~CP~~	Combinations of Phase I Superbeams	Combinations of Phase II Superbeams	Combinations of ν Factories	

Superbeam νFact combo: Burguet-Castell *et al*, 2002

νFactory with τ ID: Donini, Meloni, Migliozzi,2002; Autiero *et al*, 2003

ν Factory "magic baseline": Lipari, 2000; Burguet-Castell, 2001; Barger, Marfatia, Whisnant, 2002; Huber, Lindner, 2002; Huber and Winter, 2003, Asratyan *et al*, 2003

ν 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

Asymmetry is close to 1 in this case: seeing $\nu_\mu \to \nu_e$ in either sign is tantamount to seeing θ_{13} and mass hierarchy!

Getting to a ν Factory–Making an affordable Design

Lots of progress for design of three Cost Drivers (B.Palmer, DOE review talk)

- Phase Rotation

  Induction Linac $\rightarrow$ Warm RF

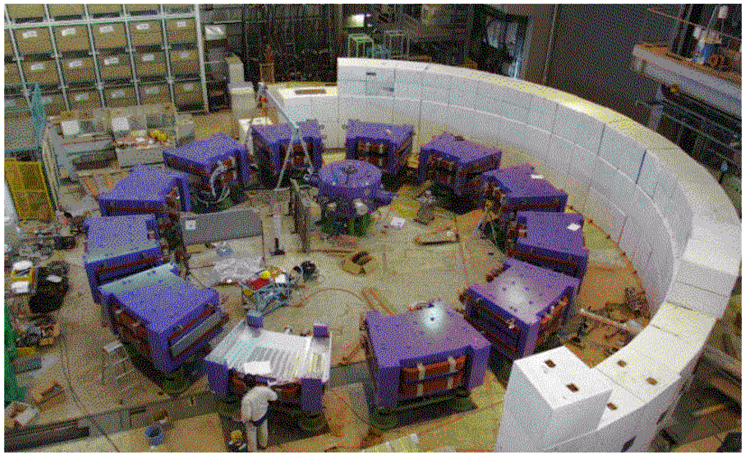
	Study 2	Now	Factor
Tot Length (m)	328	166	51 %
Acc Length (m)	269	35	13 %
Acc Type	Induction	Warm RF	

- Cooling

  Long Cooling channel to RFOFO (ring)

	Study 2	Now	Factor
6D Cooling	15	160	10 $\times$
Tot Length (m)	108	33	30 %
Acc Length (m)	54	16	30 %
Acc Grad	16 MV/m	12 MV/m	66 %

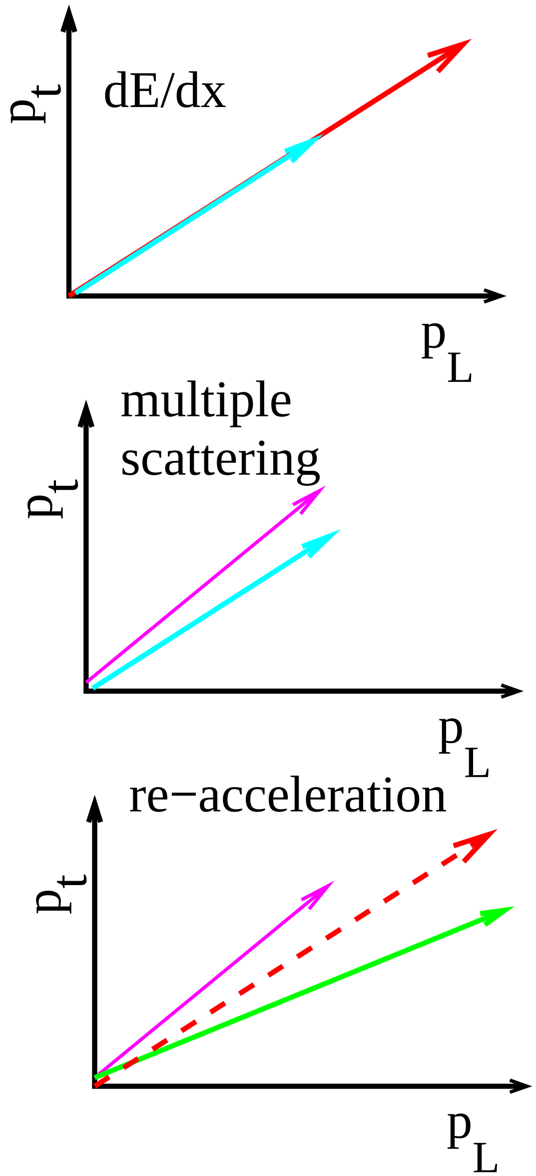
- Acceleration–new Fixed Field Alternating Gradient scheme



150MeV FFAG in Japan
First beam: April 2003
20-50% reduction in lengths *cf* recirculating linacs

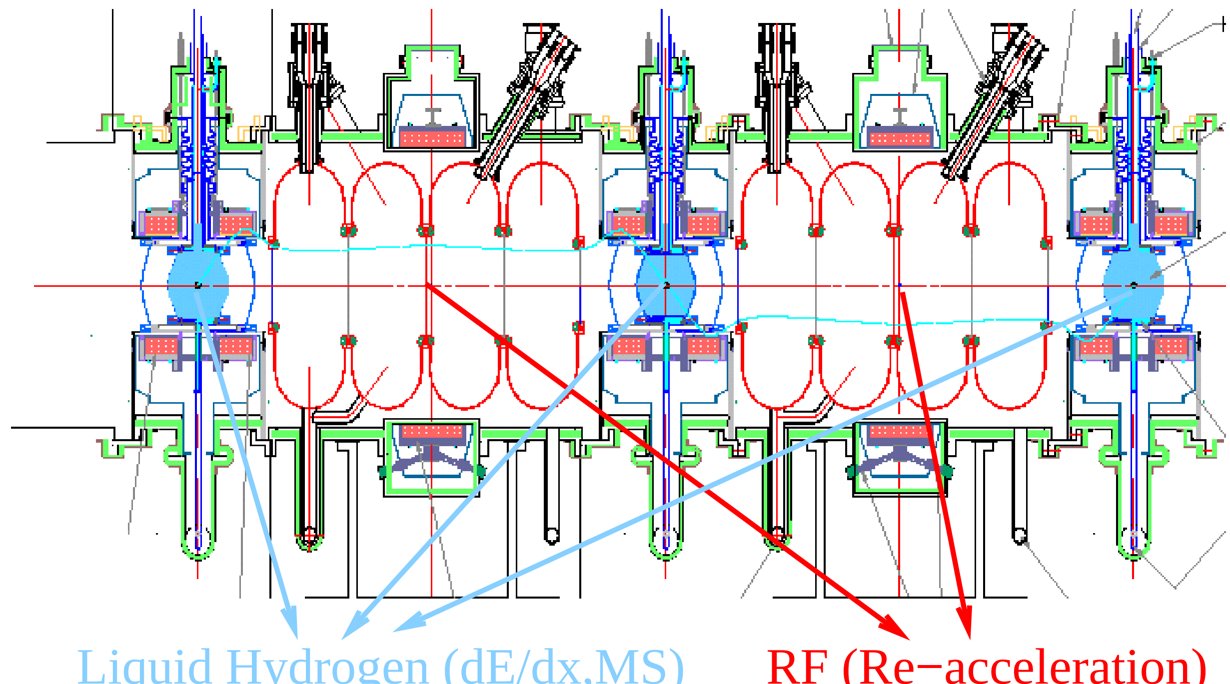
Getting to a ν Factory–Proving it can be done

Ionization Cooling:



Critical Proof of Principle: Prove Ion. cooling works!

- MuCOOL at Fermilab
  - → Build LH_2 absorber and RF cavities
  - → Make sure they can live together
  - → send them to Muon Int'l Cooling Experiment (MICE)
- MICE at RAL
  - → measure cooling with muon beam



Summary of Sensitivities

Beam Name	Mass (kton)	Power (MW)	$\sin^2 2\theta_{13}$ sens.[a]	δ[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
JHF2SK	22.5	0.8	0.006	-	-
NuMI-OA	50	0.4	0.004	-	$\geq$CP
SJHF2HK	450	4	$\sim 0.001^s$	$\lvert\delta\rvert > 20°$	$<$CP
SNUMI-OA	100	2	$\sim 0.001^s$	135 ± 20	$\geq$CP
BNL2NUSL	500	1	0.004	45 ± 20	$>$ & $<$ CP
CERN SPL	400	4	0.0016	90 ± 30	$\ll$CP
β Beam	400	.04		T viol.	$\ll$CP
ν Factory	50	4	$< 10^{-4}$	90 ± 20	**huge!**

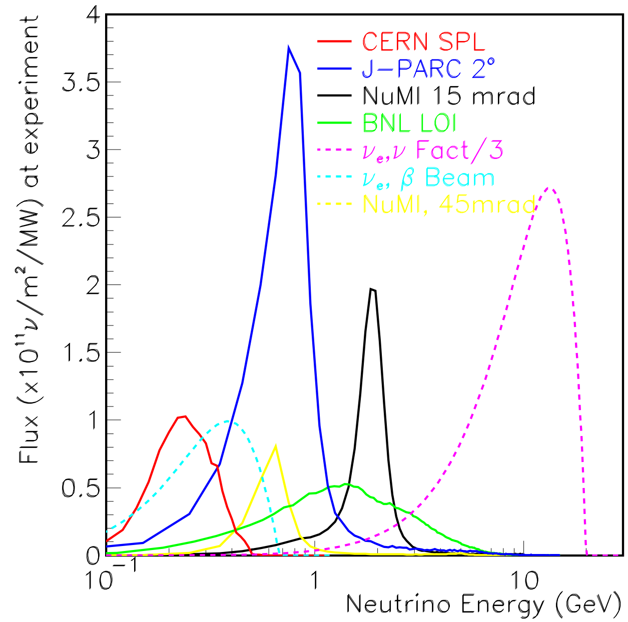
[a] at $\Delta m^2_{32} = 3 \times 10^{-3} eV^2$,at $90\% CL$

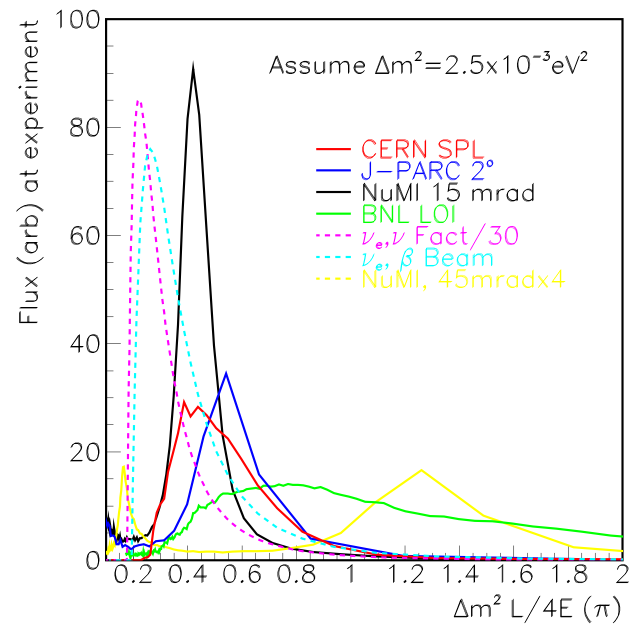
[b] all evaluated at different regions of parameter space!

[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`

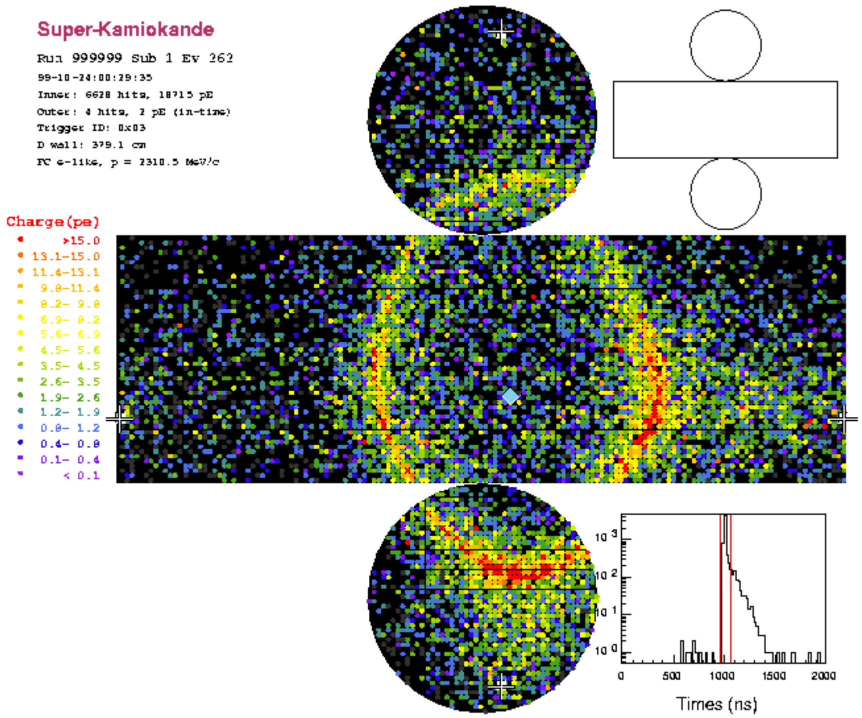


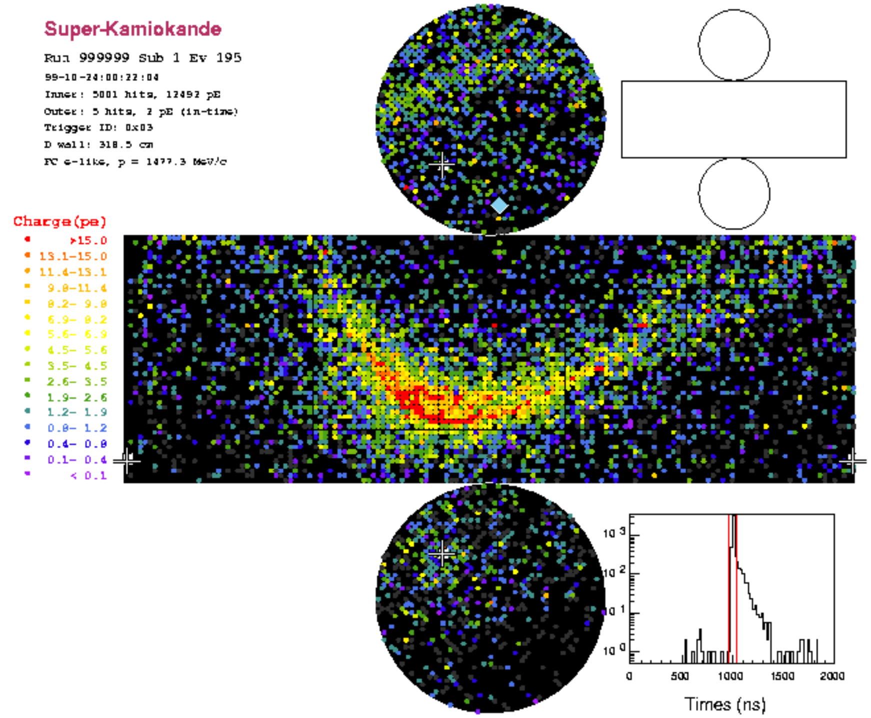


Conclusions

- Two complementary near-term opportunties await us
  - $\rightarrow$ J-PARC to Super-Kamiokande
  - $\rightarrow$ NuMI Off Axis
- Many more long-term ideas
  - $\rightarrow$ BNL LOI
  - $\rightarrow$ CERN SPL
  - $\rightarrow$ β-beams
  - $\rightarrow$ Upgrades to J-PARC and/or NuMI
  - $\rightarrow$ CNGT
- We need more than one measurement
  - $\rightarrow$ one with and one without matter effects
- Long-term Step depends on what Near-Term finds!
  - $\rightarrow$ LSND?
  - $\rightarrow$ Atmospheric Δm^2 1.5 or 3.5 $\times 10^{-3} eV^2$?
  - $\rightarrow$ Solar Δm^2 big or huge?
  - $\rightarrow$ θ_{13} just around the corner?
- Enough detector and beamline challenges to keep experimentalists busy
- Not for the faint of heart, but the rewards will be enormous!

Backup: Particle ID in Water Cereknov-2GeV





Courtesy Mark Messier

At higher energies, Quasielastic fraction is low,
multiparticle final states become important.
Exercise for the audience:
which of these is a ν_e charged current event,
which is a NC π^0 event?