Neutrino Factory Physics Case

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APS Neutrino Study
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Argonne National Laboratory

Outline

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

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

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

$\rightarrow$ CP Violation without matter effects:

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

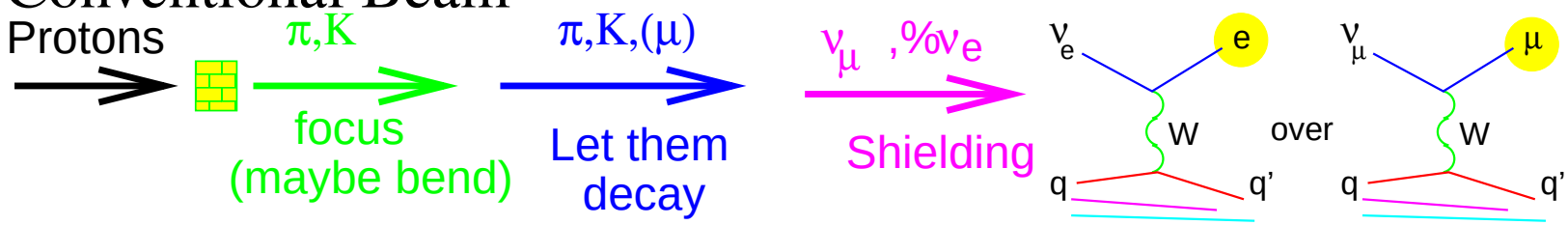
$\rightarrow$ Matter effects without CP violation:
Because earth is filled with electrons...

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

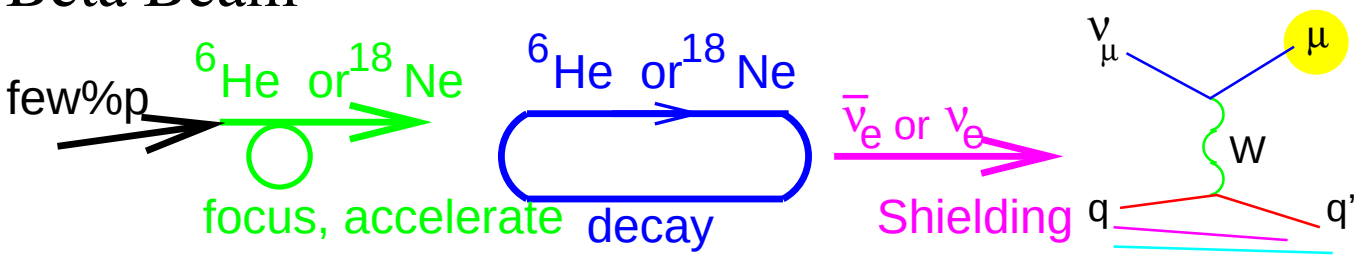
$$E_R = \frac{\Delta m^2_{atm}}{2\sqrt{2} G_F \rho_e} \approx 11 GeV$$

Neutrino Beam Choices

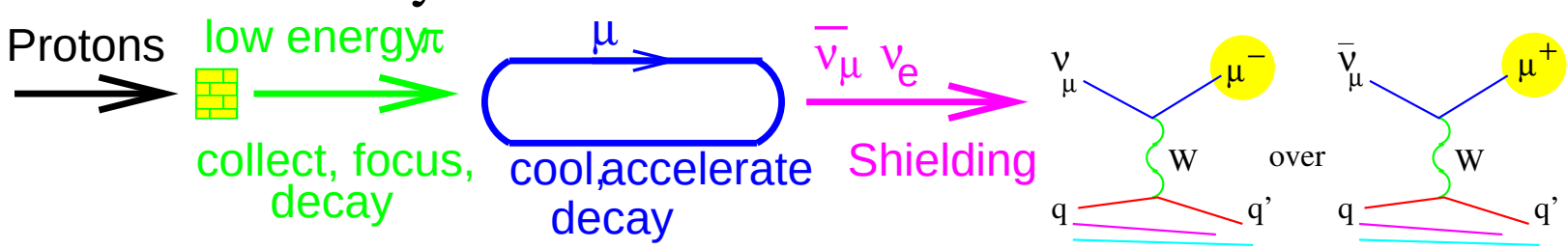
- Conventional Beam



- Beta Beam



- Neutrino Factory

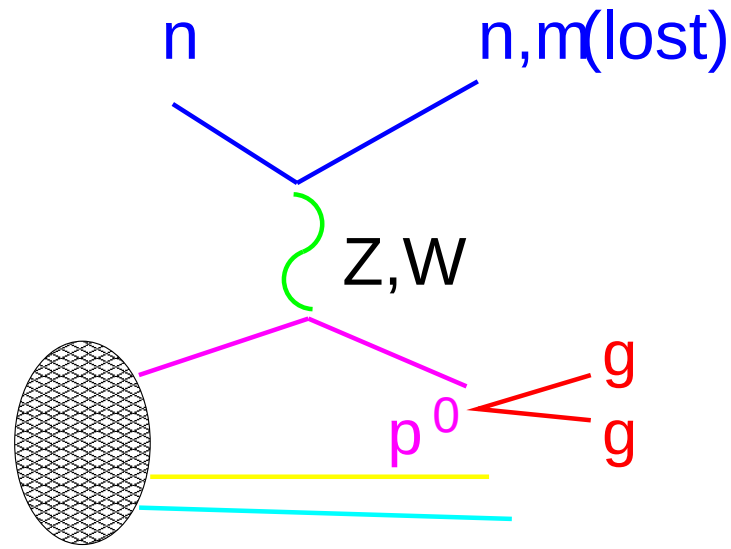


Events/parent at far detector:

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

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^-



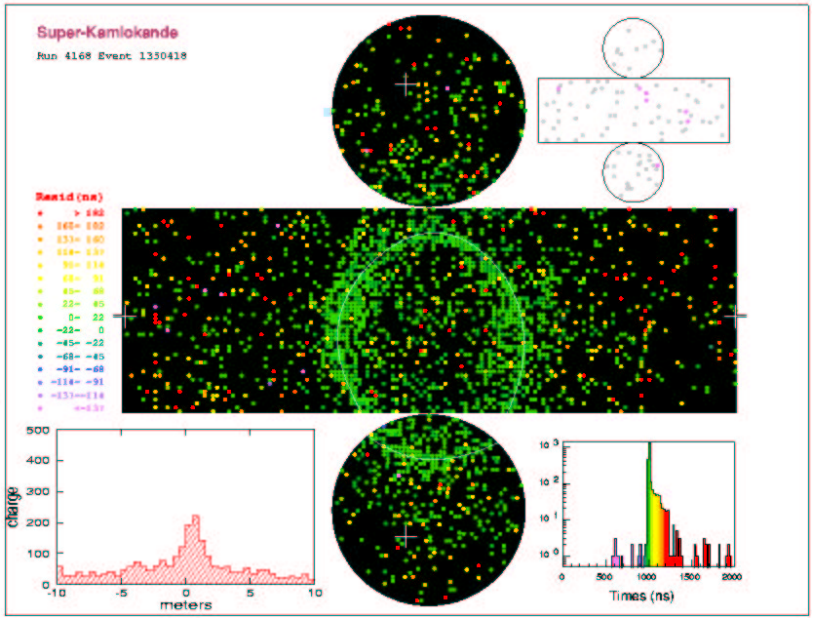
Why is $\nu_e \to \nu_\mu$ hard? It's the Beamline...

- Have to make a ν factory or β-beam

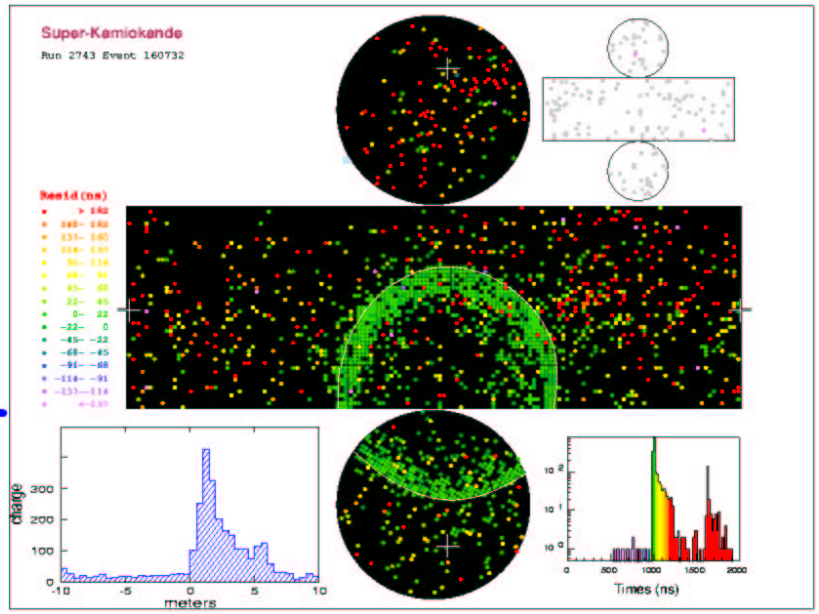
Why is $\nu_e \to \nu_\tau$ hard? Beamline and Detector

Detector Choices: Water Cereknov

e–like



μ–like



Courtesy Mark Messier

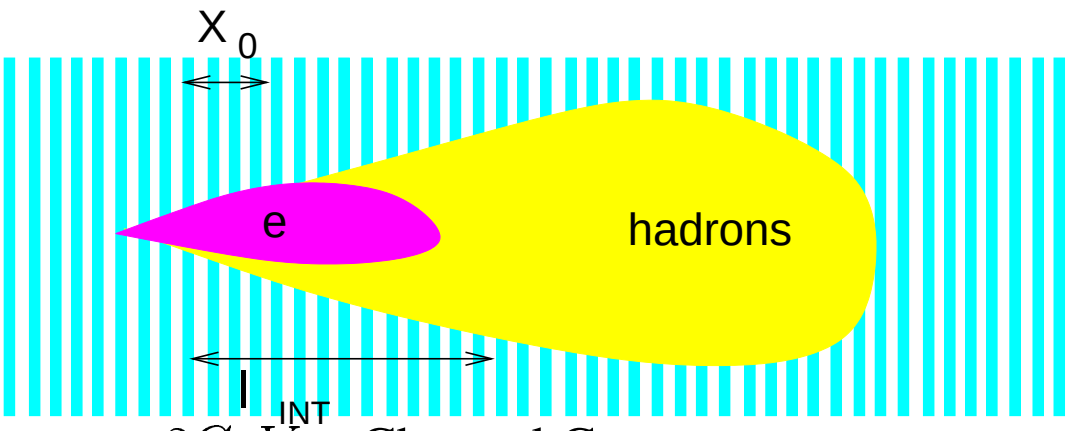
Extremely good separation for Single Particle Events

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...

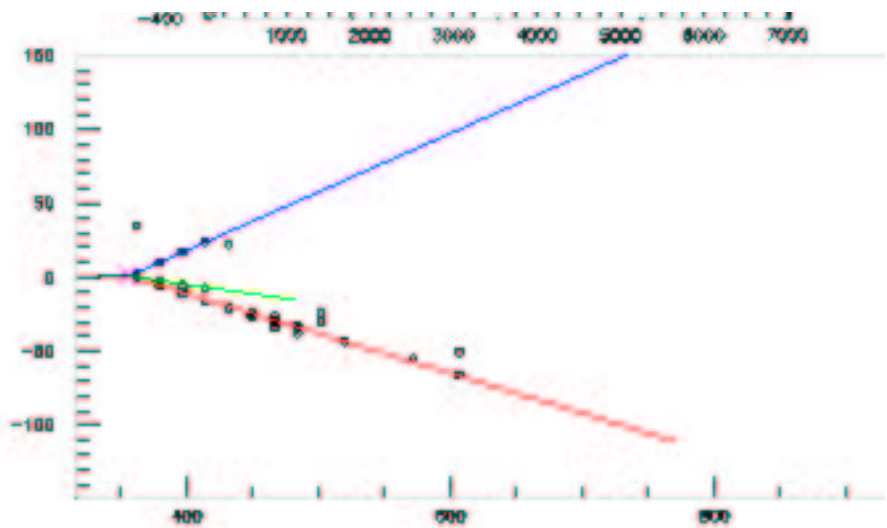
Detector Choices: Fine-Grained Calorimetry



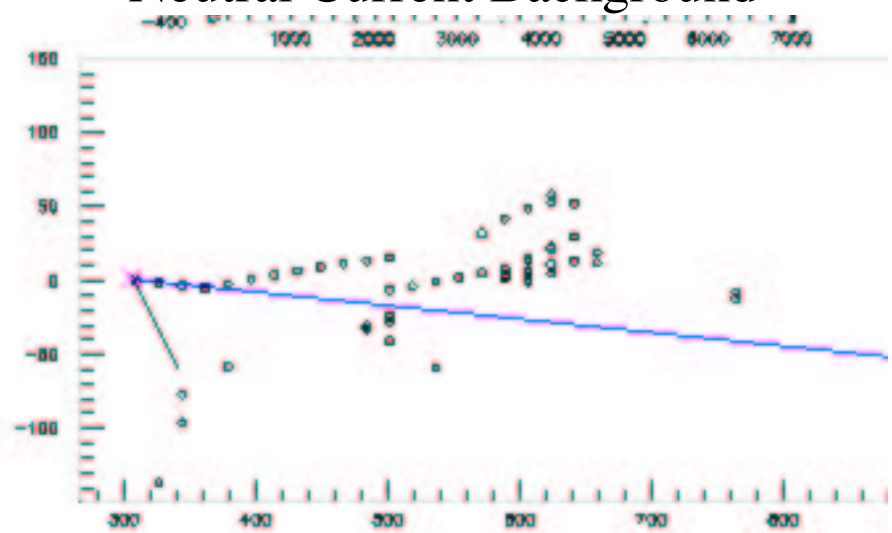
Tried and True Technology

1/3 X_O sampling calorimeter
Hit counting:
$\sigma(E)/E = 12 - 15\%$ 2GeV

$2GeV\nu_e$ Charged Current

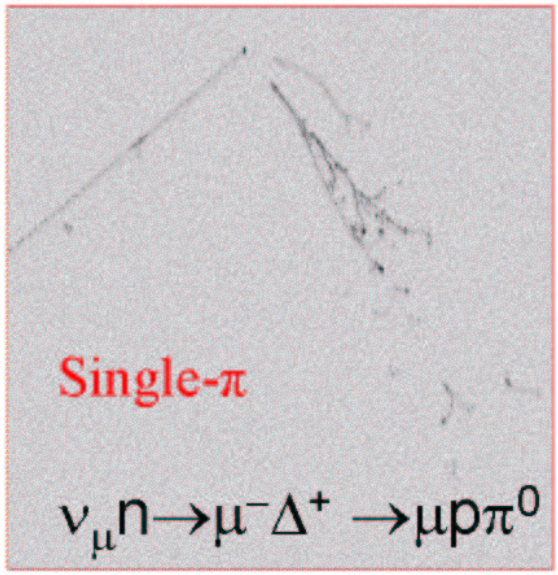


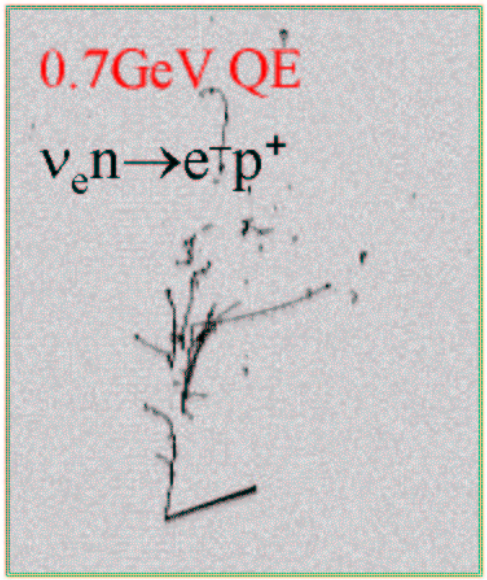
Neutral Current Background

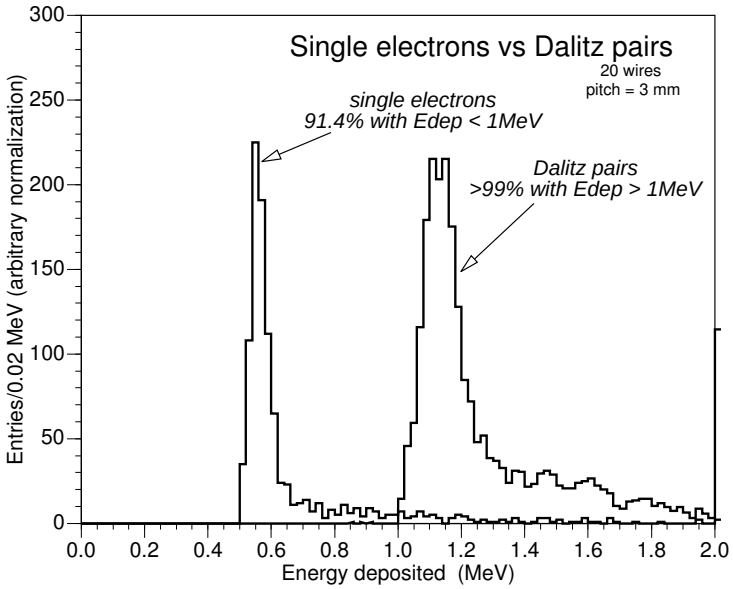


few $\times 10^{-}3$ NC rejection with 35-40% signal acceptance at 2GeV
Remaining backgrounds: CC and NC π^0 production

Detector Choices: LAr TPC





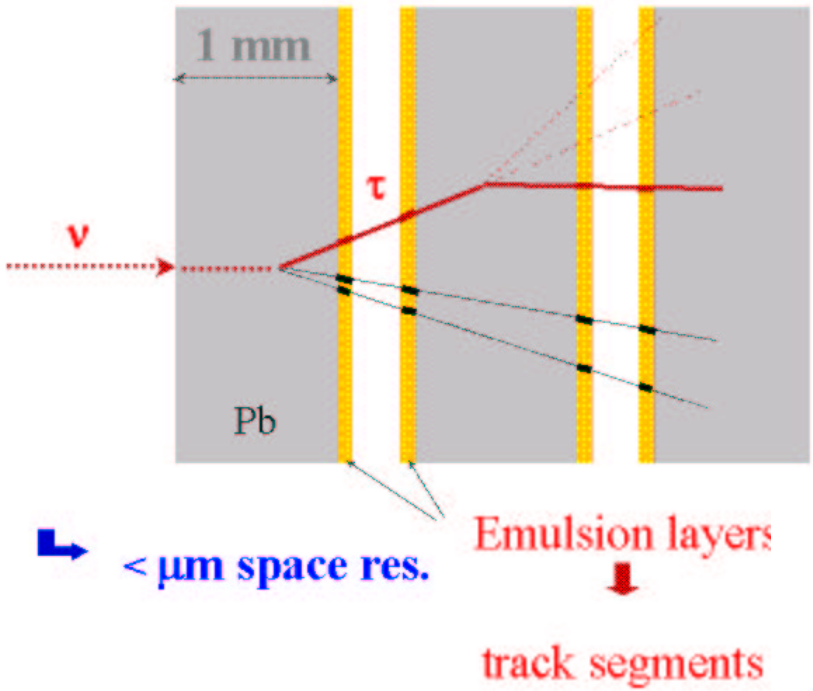


Excellent PID and energy reconstruction
Ref: ICANOE proposal LNGS P21/99 and
`www.aquila.infn.it/icarus/`
Events courtesy A. Rubbia

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

Emulsion Detectors for τ Appearance

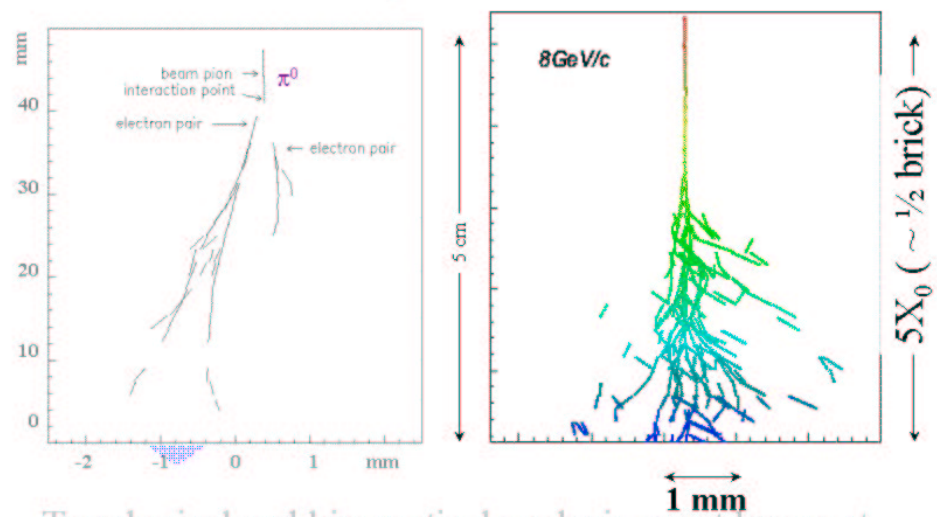
The Emulsion Cloud Chamber (ECC)



- What if MiniBooNE Confirms LSND??
- What about measuring $\nu_e \to \nu_\tau$?
- 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 ν beam too!

In Praise of Near Detectors

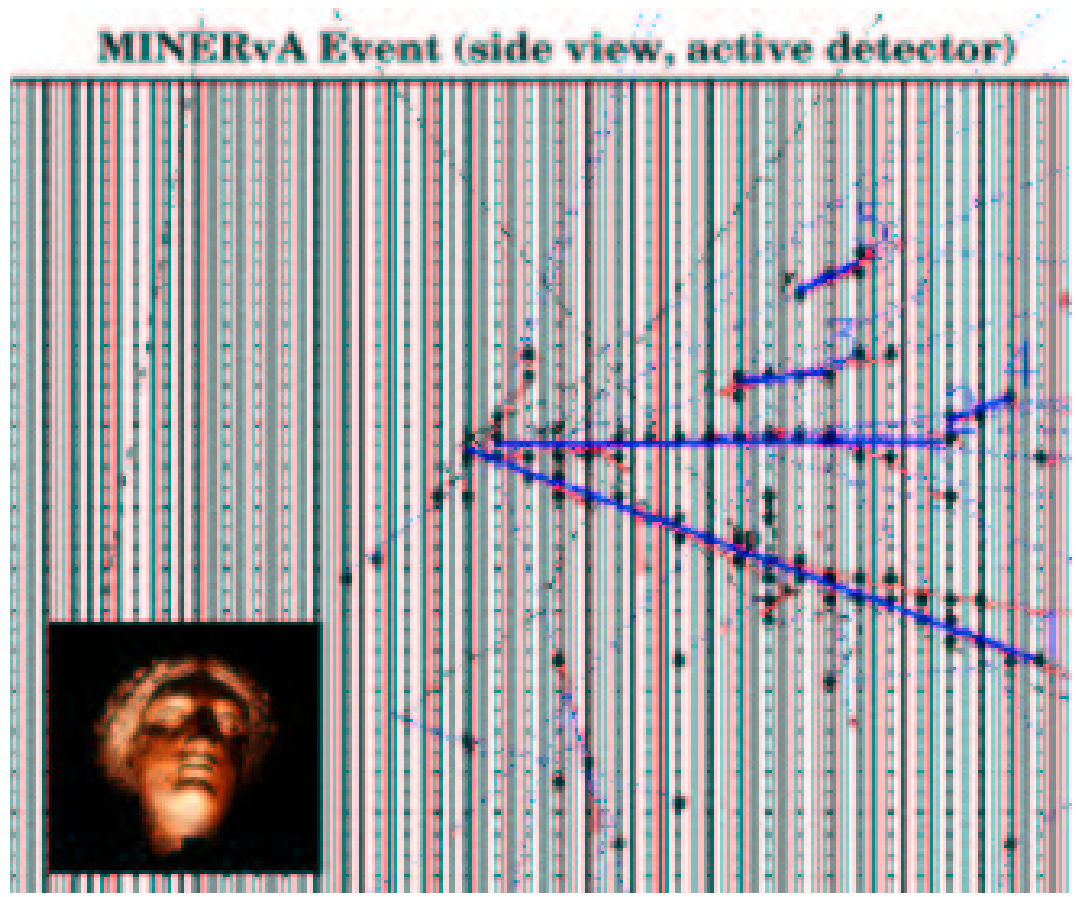
If you can't remove all the backgrounds...

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

One example:
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)

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



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

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

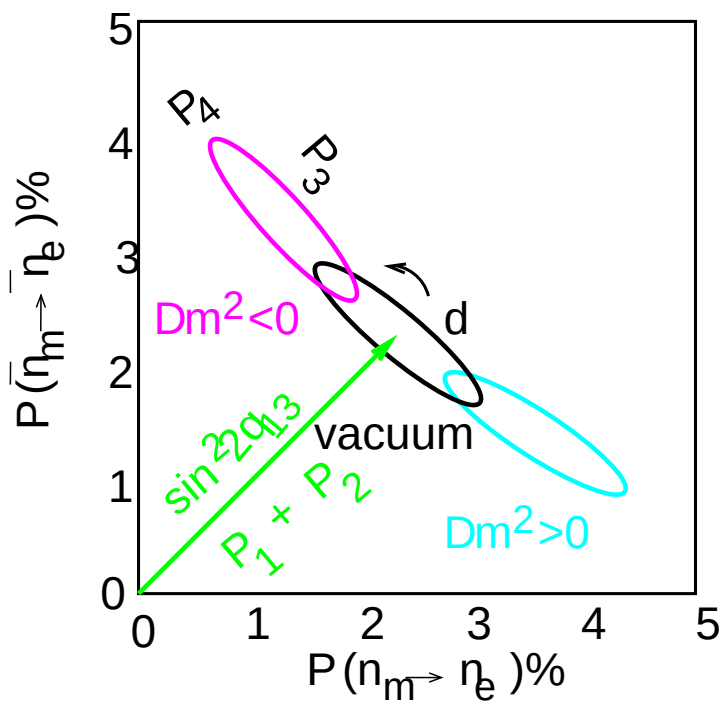
$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$

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

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

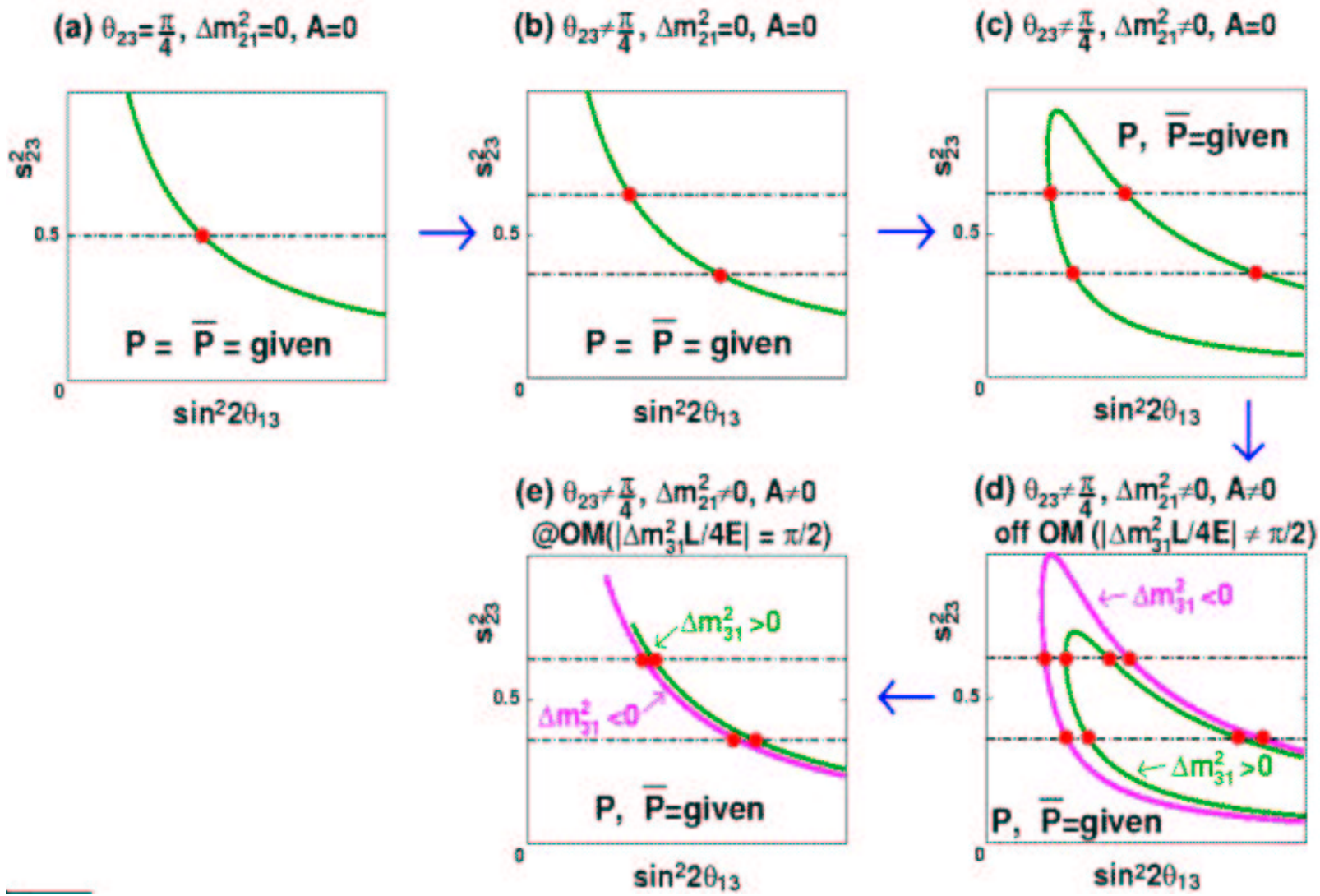
$$J = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

and the $\pm$ signifies neutrinos or antineutrinos



Degeneracies

Three Degeneracies: $(\theta_{13}, \delta), \Delta m^2_{31} \leftrightarrow -\Delta m^2_{31}$, and $\theta_{23} \leftrightarrow \pi/2 - \theta_{23}$
Minakata, Yasuda, NuFact03



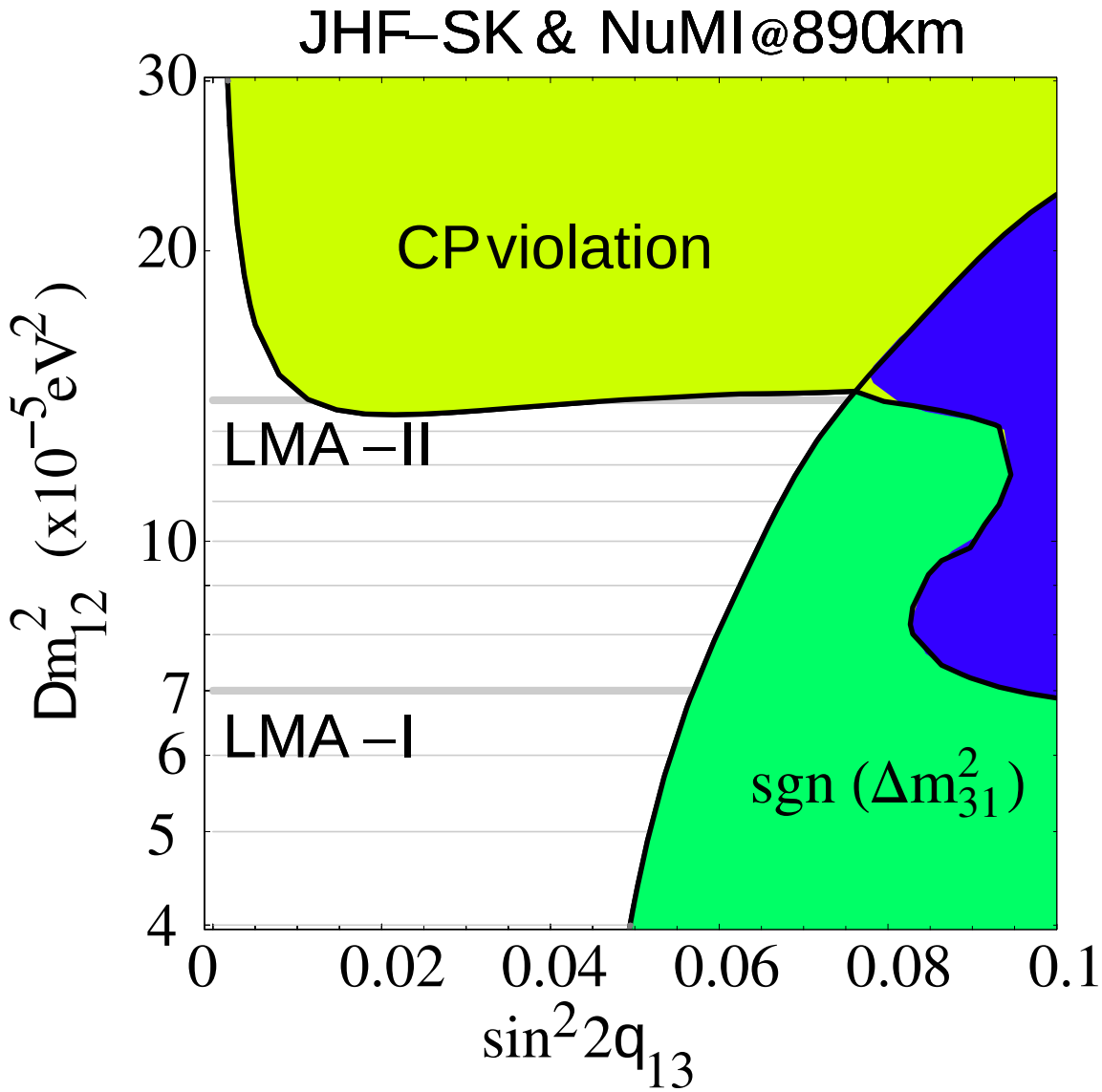
Scales of $\sin^2 2\theta_{13}$

	10^{-1}	3×10^{-2}	10^{-2}	10^{-3}	10^{-4}
Finding $\theta_{13}\neq0$	MINOS and CNGS	Conventional Superbeams Phase I			
Mass Hierarchy	Conventional Superbeams Phase I				
Evidence for $\not{CP}$	Conventional Superbeams Phase I				

Beam Name	Peak Energy (GeV)	Detector	Mass (kton)	Power (MW)	$\sin^2 2\theta_{13}$ sens.[a]	δ^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	-	-
NuMI-OA	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 JHF *and* NuMI-OA?



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

	10^{-1}	3×10^{-2}	10^{-2}	10^{-3}	10^{-4}
Finding $q_{13} \neq 0$	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			

Beam Name	Peak Energy (GeV)	Detector	Mass (kton)	Power (MW)	$\sin^2 2\theta_{13}$ sens.[a]	δ^b	Matter Effect
sT2K	.7	H_2O Ч	450	4	0.001	$\lvert\delta\rvert > 20°$	<CP
sNuMI-OA	2	Wood-Scint.	50+50	2	0.001	135 ± 20	≥CP
BNL2NUSL	1	H_2O Ч	500	1	0.004	45 ± 20	> & < CP
CERN SPL +β	.25	H_2O Ч	400	4	0.0016	90 ± 30	≪CP

Phase II combinations: Barger, Marfatia, Whisnant 2002

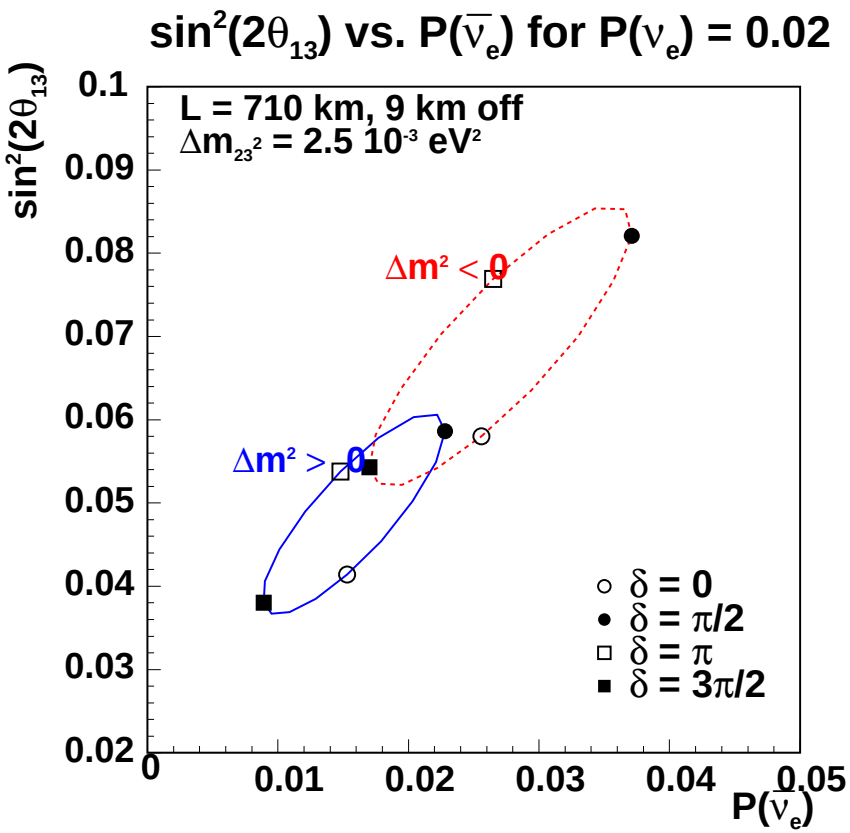
Running at Second Oscillation Maximum

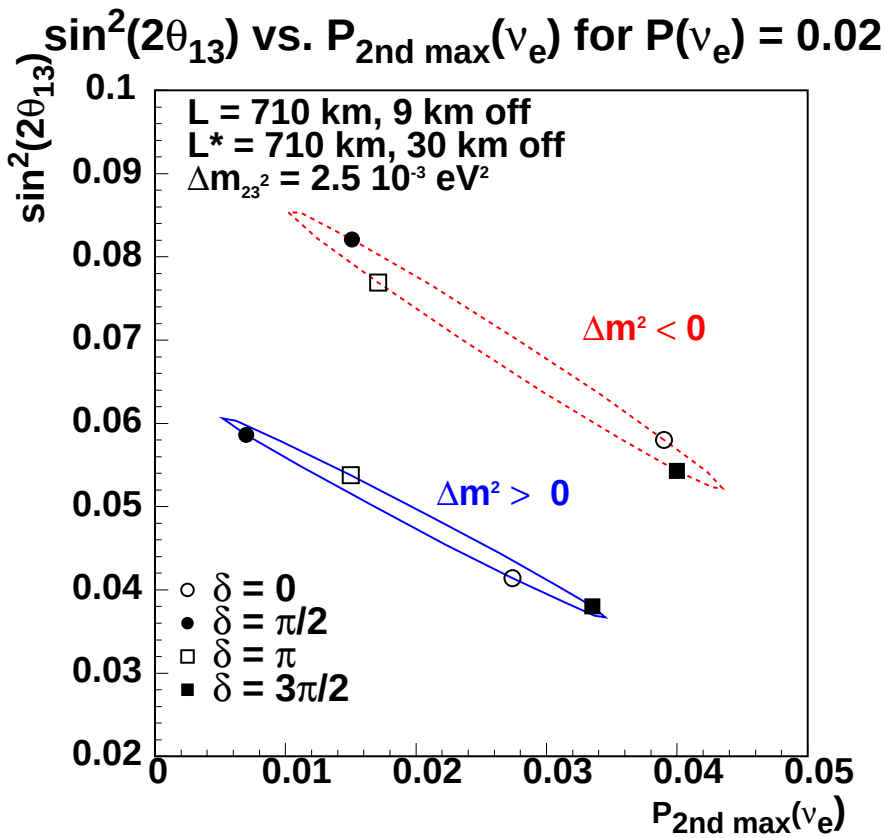
Imagine NuMI Off Axis and/or T2K measures $P(\nu_\mu \to \nu_e) = 0.02$...

1st max: $CP \approx Matter$

2nd max: $CP \to 3 \times CP$

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

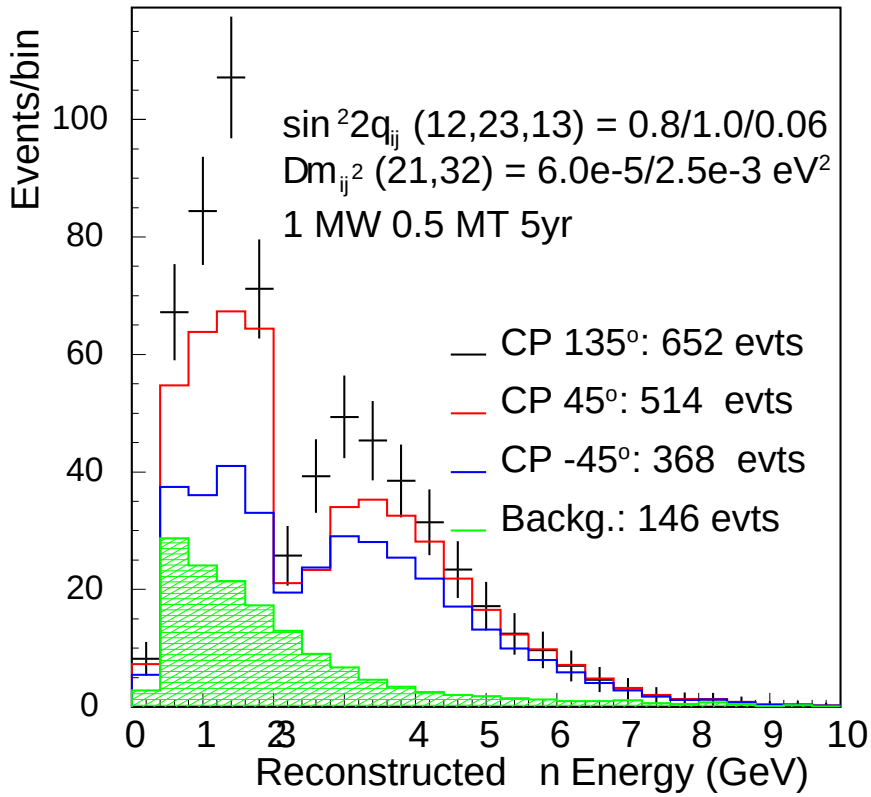


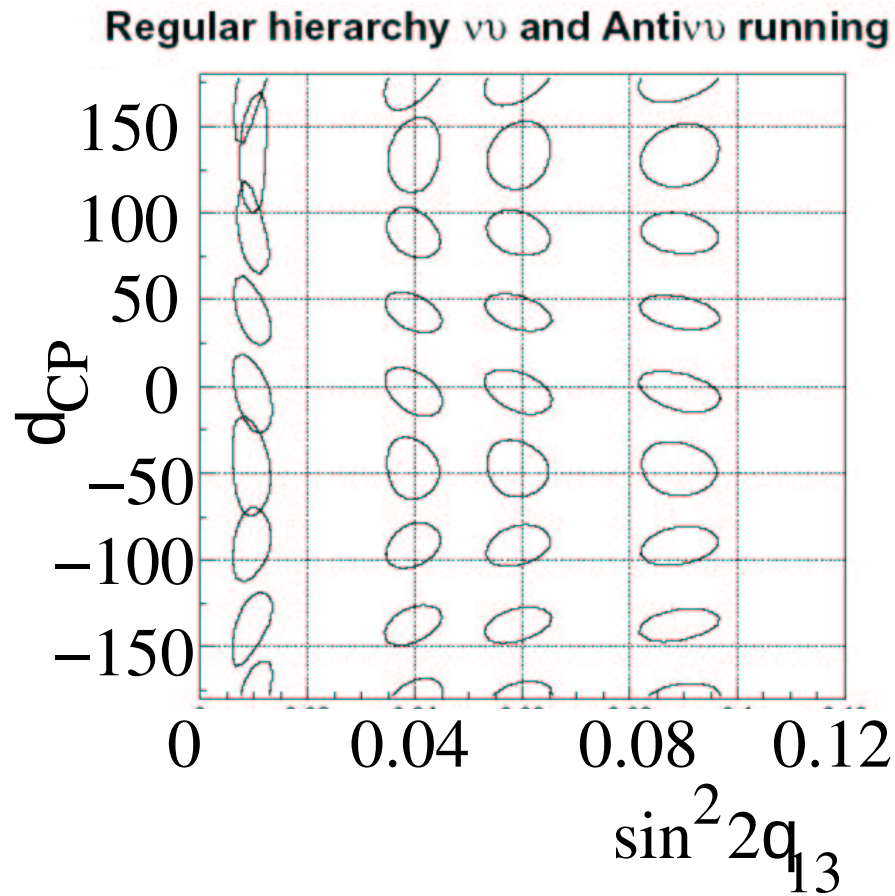


Maybe mass hierarchy can be determined, maybe not...
Now imagine it can't...

G.Feldman, HEPAP meeting

BNL LOI ν_e Appearance





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

CP violation effects huge at second oscillation maximum...

68% CL limits, different test points

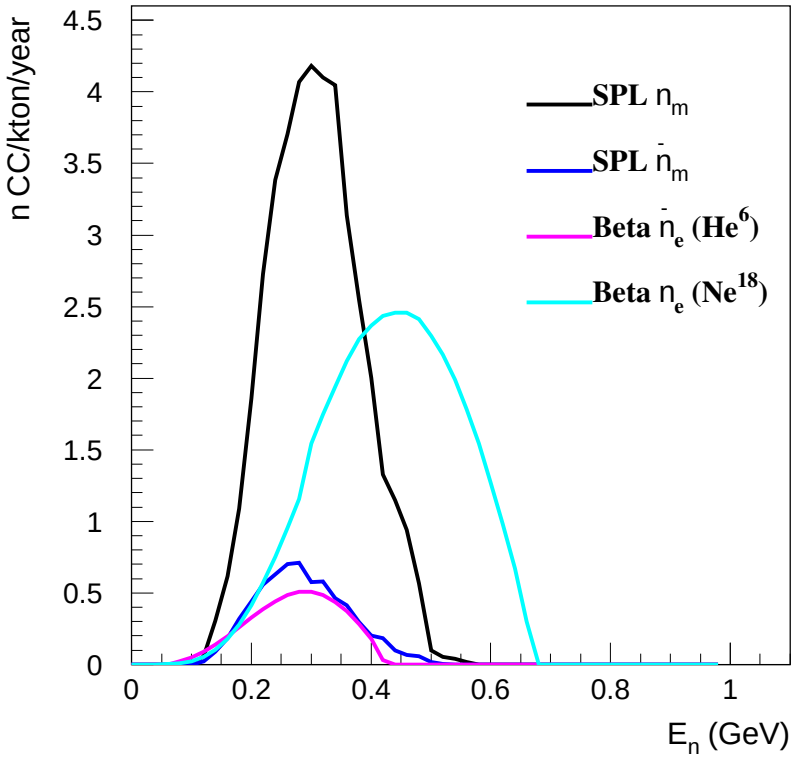
5 years ν running

5 years $\bar{\nu}$ running

similar for other hierarchy

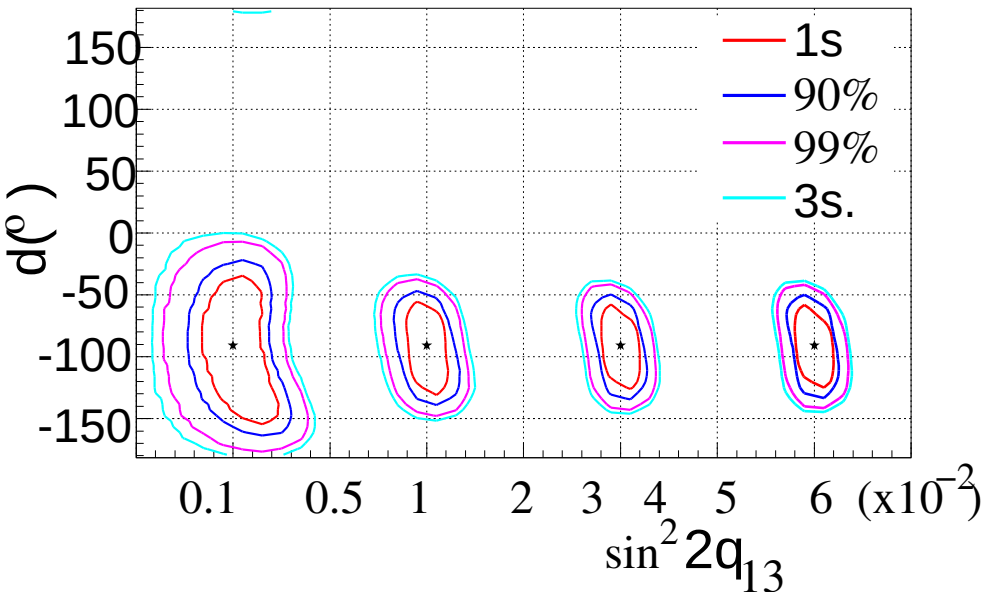
Diwan, 1/30/04 APS Study meeting

β and Conventional Beams at CERN



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

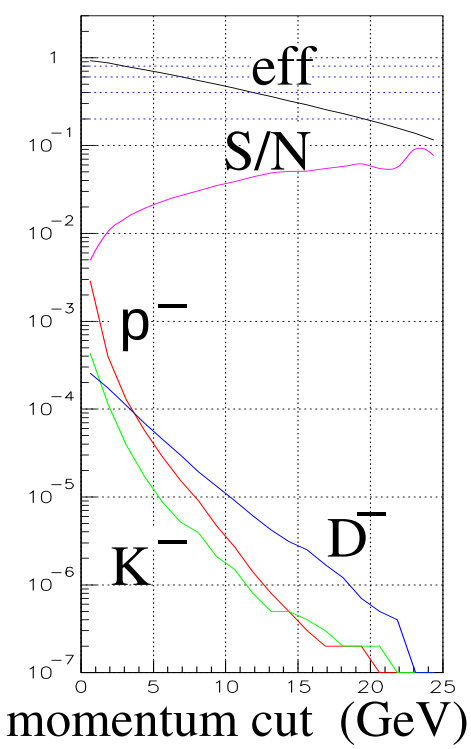
- Ability to see maximal CP violation:
- Cross-Check of Framework
  - $\rightarrow \nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$
  - $\rightarrow \nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- added precision...
  by including all measurements

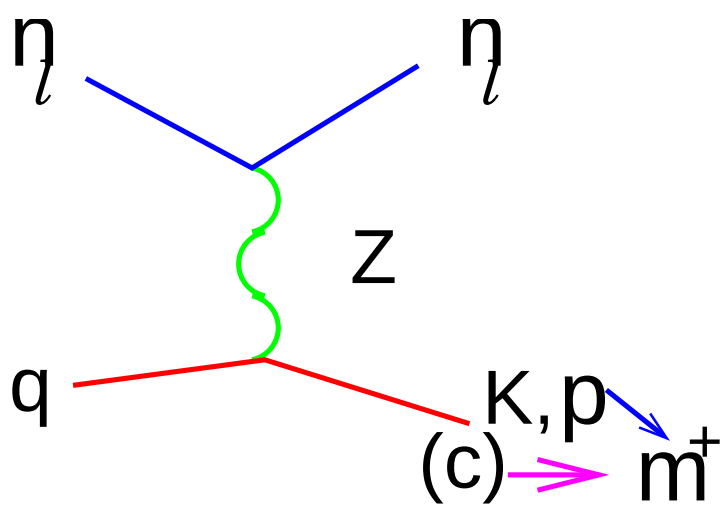


1° means $\sin^2 2\theta_{13} = 1.2 \times 10^{-3}$
Ref: M. Mezzetto, NuFact03

Why is $\nu_e \to \nu_\mu$ at a 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

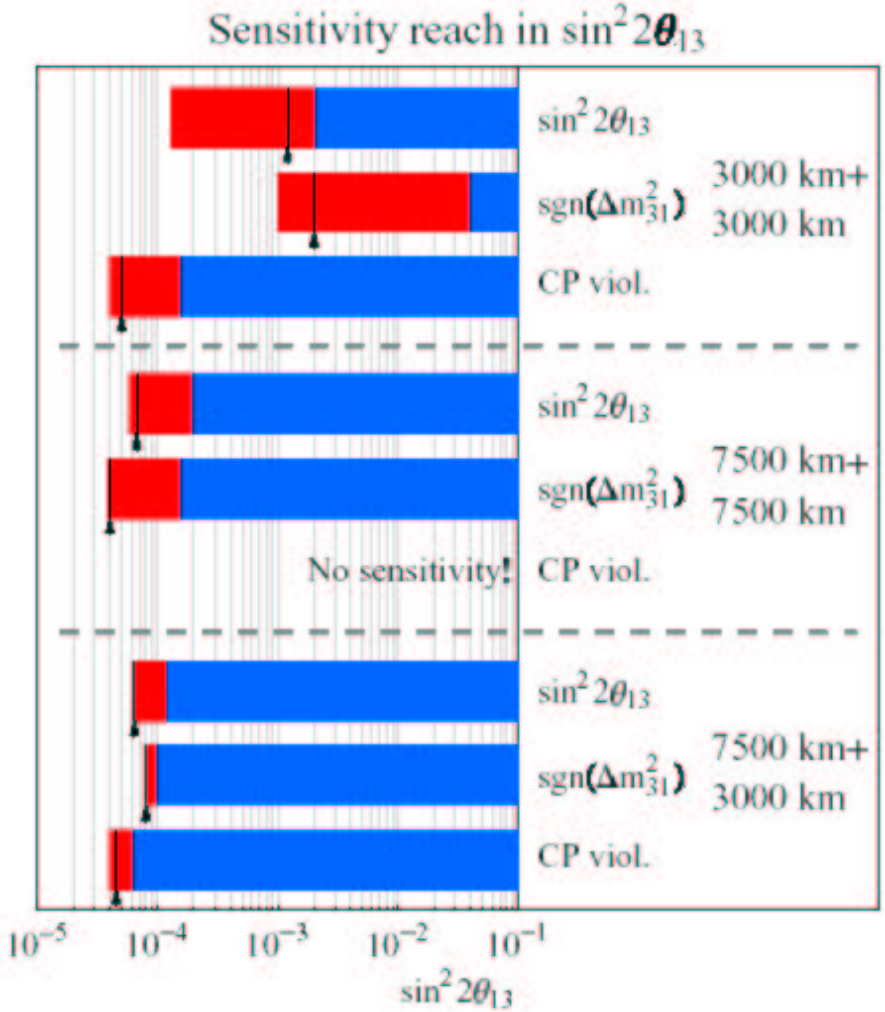
Cervera *et al*, Nucl.Phys.**B579** 17,2000

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

	10^{-1}	3×10^{-2}	10^{-2}	10^{-3}	10^{-4}
Finding $q_{13} \neq 0$	MINOS & CNGS	Conventional Superbeams Phase I	Conventional Superbeams Phase II	Combinations of n Factories	
Mass Hierarchy	Combinations of Phase I Superbeams	Combinations of Phase II Superbeams	Combinations of nFactory+SB	Combinations of n Factories	
Evidence for $\not{CP}$	Combinations of Phase I Superbeams	Combinations of Phase II Superbeams	Combinations of n 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

Ultimate ν Factory Reach



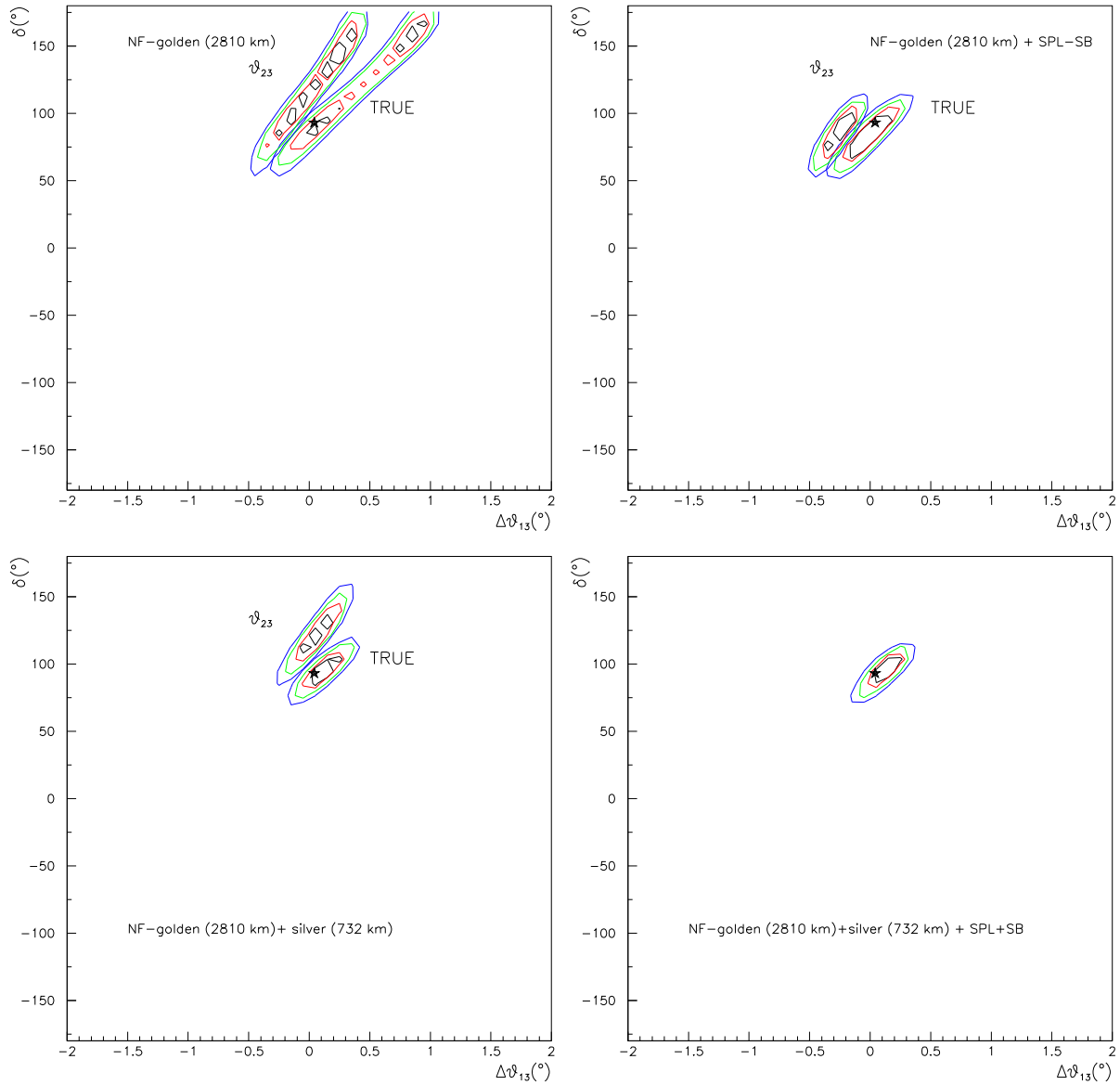
- New Studies: "magic baselines" $\sin\frac{\sqrt{2}G_F n_e L}{2} = 0$, for example $\frac{\sqrt{2}G_F n_e L}{2} = 2\pi\ L \sim 7250km$ only P_1 remains
  Huber, Winter Phys.Rev.**D68** 2003
- Indian Neutrino Observatory `hep-ph/0402246`

Tokai to Pushep	6595	31°
Tokai to Rammam	4880	22°
CERN to Pushep	7145	34°
CERN to Rammam	6890	33°
FNAL to Pushep	11300	62°
FNAL to Rammam	10500	55°

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

Combining ν 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
- $\nu_e \to \nu_\tau$
- Conventional Beams

`hep-ph/0310014`

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	~ 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!**

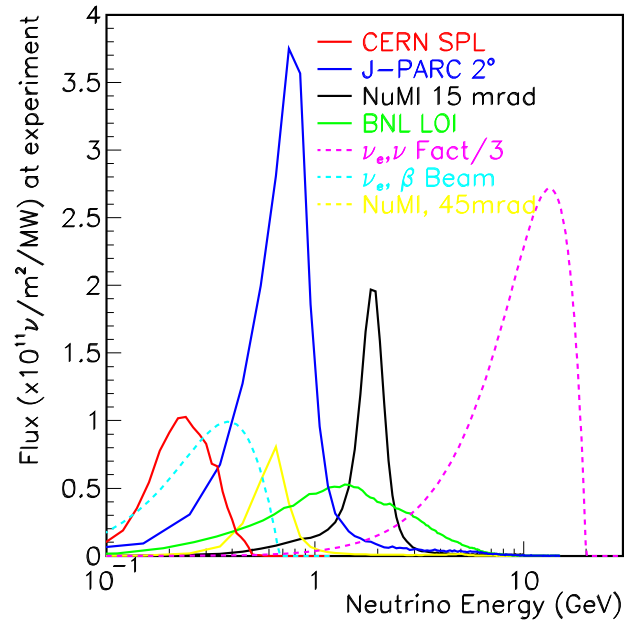
[a] at $\Delta m^2_{32} = 3 \times 10^{-3} eV^2$,at $90\% CL$

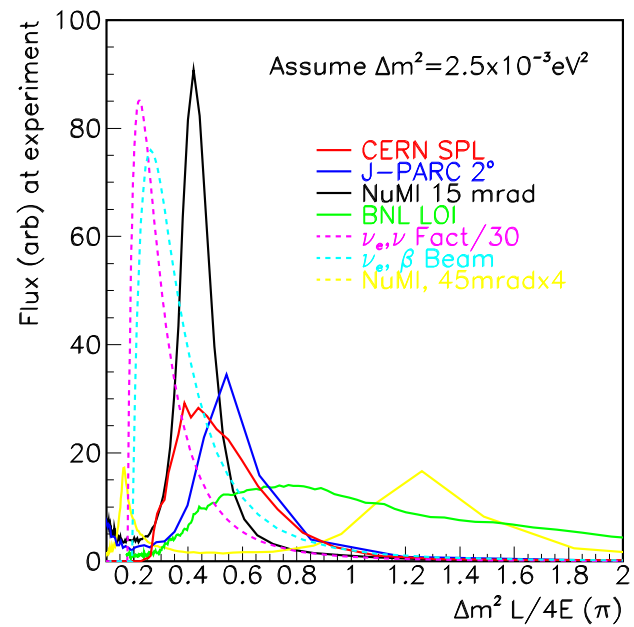
[b] all evaluated at different regions of parameter space!

[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

Our understanding of the reach of conventional ν 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
  - $\rightarrow$ Making PMT's takes time
  - $\rightarrow$ Even if water is cheap, MTon and MWatts are expensive units to work in
- if θ_{13} is right around the corner conventional beams may get us partly there

But the Physics Case for a ν Factory is alive and well:

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