From Megawatts to Kilotons: A Survey of Accelerator-Based Oscillation Experiments

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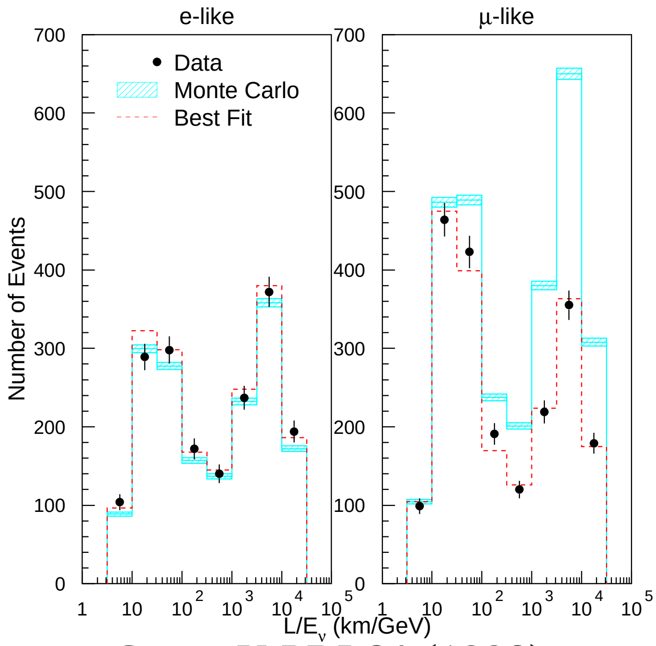
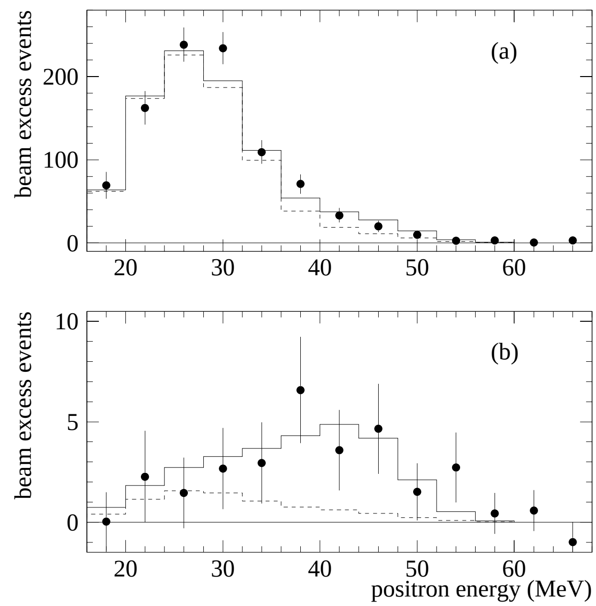
- Running or Soon to run Experiments
  - → K2K
  - → MiniBooNE
  - → MINOS
  - → OPERA
  - → ICARUS
- What comes Next?
  - → J-PARC to Super-Kamiokande
  - → NuMI Off-Axis
- And then what?...

Present Experiments: Motivation



Super-K,PRL**81** (1998)

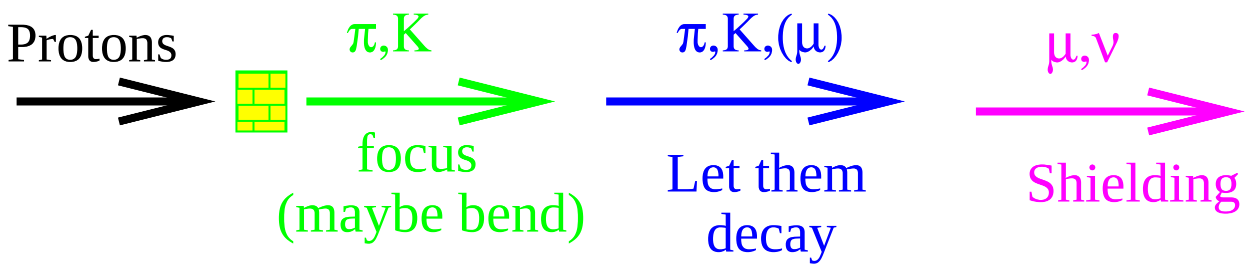


LSND, PR**C58** (1998)

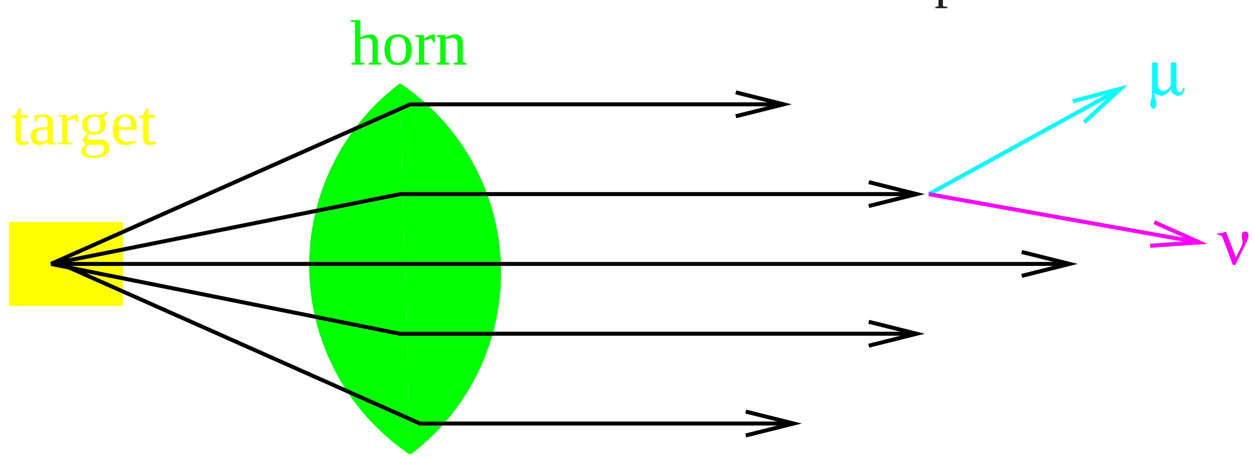
Experiment Name	Baseline (km)	Peak ν Energy (GeV)	Primary Goal
MiniBooNE	0.500	1	Confirm or refute LSND anomaly
K2K	250	1.3	Verify with beam ν_μ disappearance
MINOS	735	3.5	Measure Δm^2_{32} to 10%
OPERA	732	17	$\nu_\mu \to \nu_\tau$
ICARUS	732	17	$\nu_\mu \to \nu_\tau$

$$P(\nu_\alpha \to \nu_\beta)|_{\alpha\neq\beta} = sin^2 2\theta \sin^2 \frac{\Delta m^2_{\alpha\beta} L}{4E_\nu}$$

Current Experiments: Beamlines



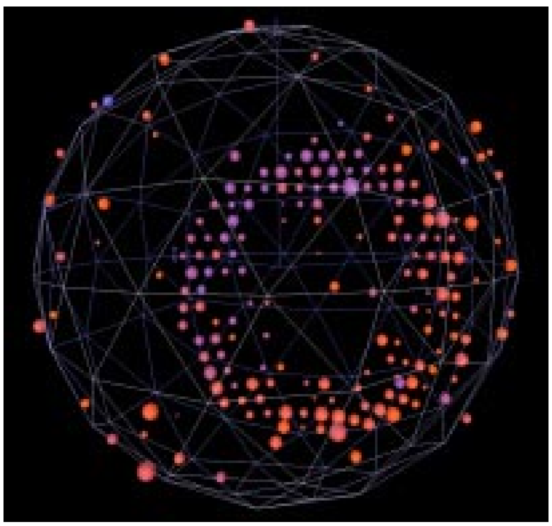
Experiment	E_ν (GeV)	E_p (GeV)	POT (/year)	Target Material	Decay Length
K2K	1.3	12	1e20	Al	200m
MiniBooNE	1	8	1e21	Be	50m
MINOS	3.5	120	2.5e20	Graphite	725m
OPERA	17	400	4.5e19	Graphite	1000m
ICARUS	17	400	4.5e19	Graphite	1000m

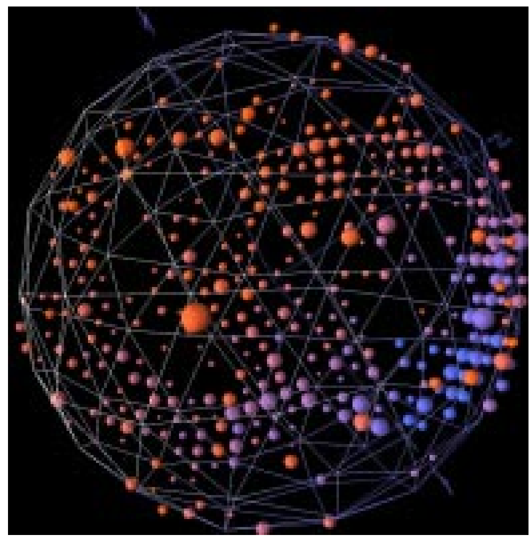


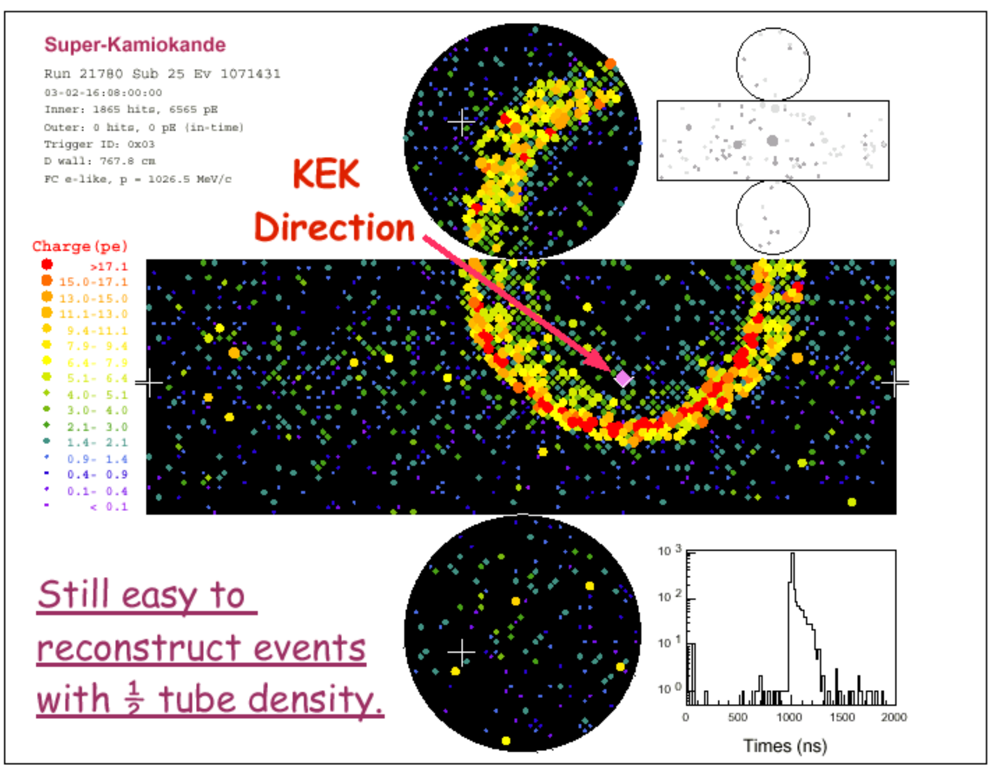
(Current) Events

- MiniBooNE–50K events on tape!

$\nu_\mu + N \rightarrow \mu^- + X$ $\qquad$ $\nu + N \rightarrow \pi^o + X$



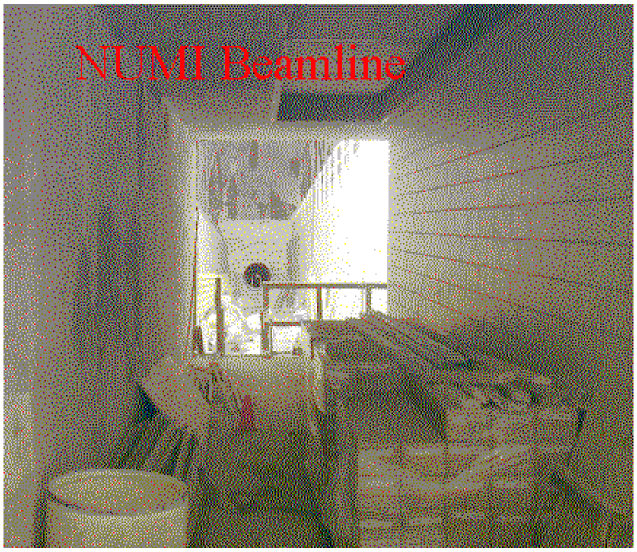




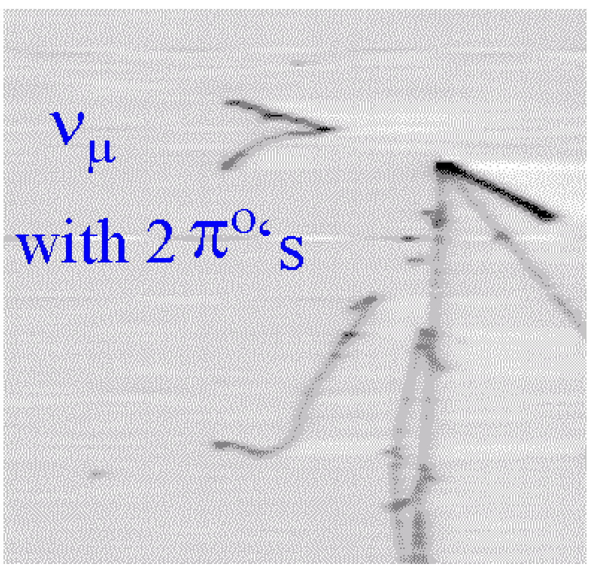
- K2K

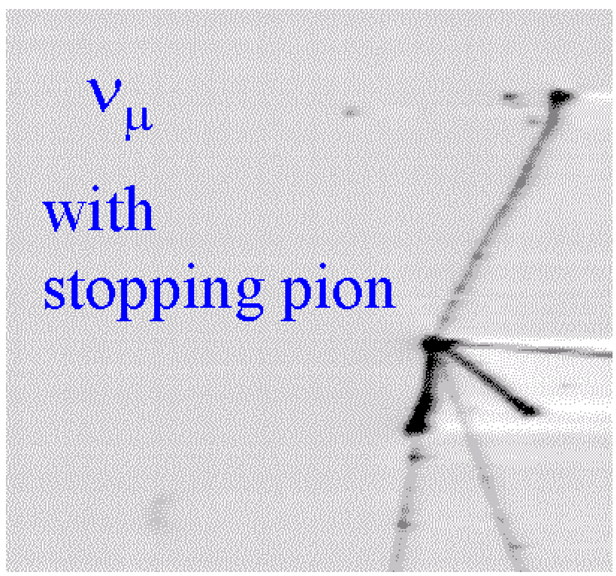
On the way to taking data...

- MINOS



- ICARUS

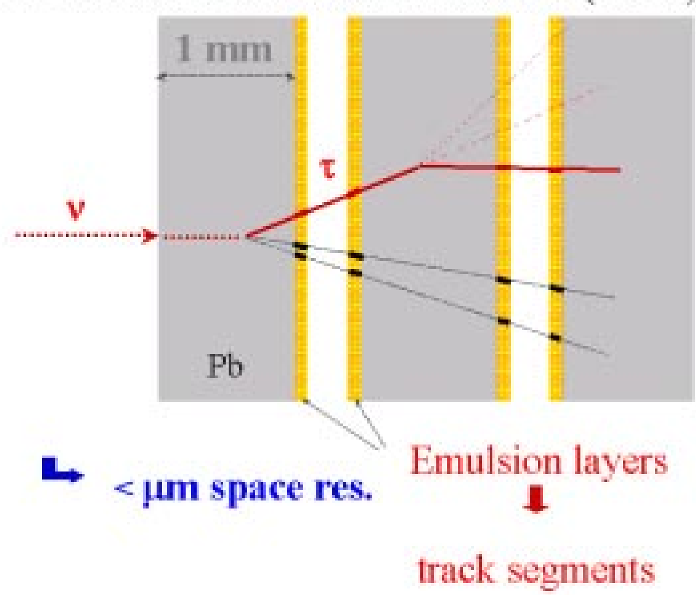




On the way to taking data...

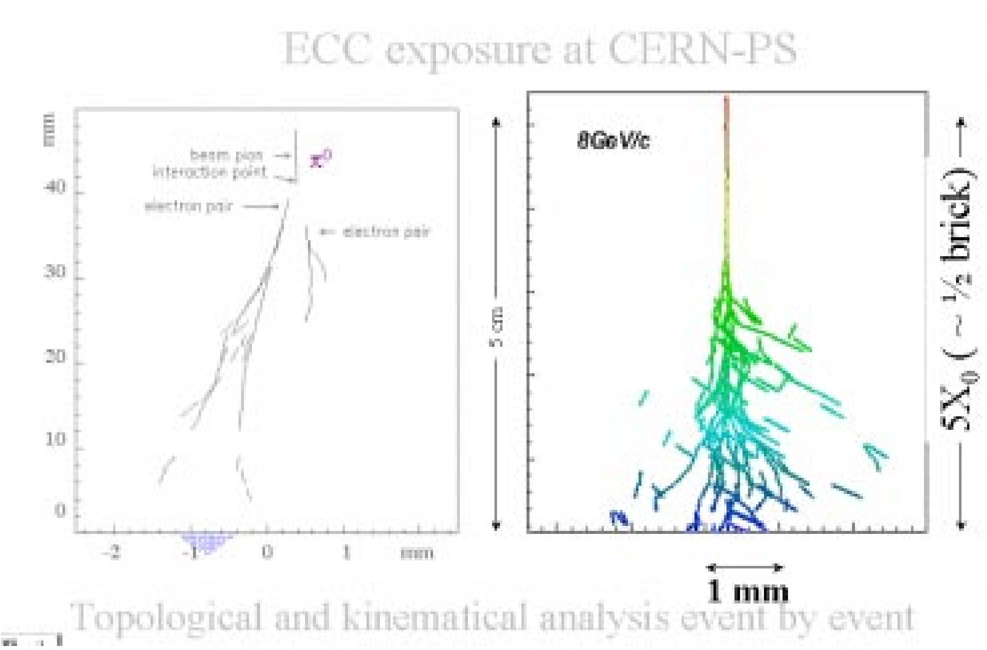
- OPERA

The Emulsion Cloud Chamber (ECC)



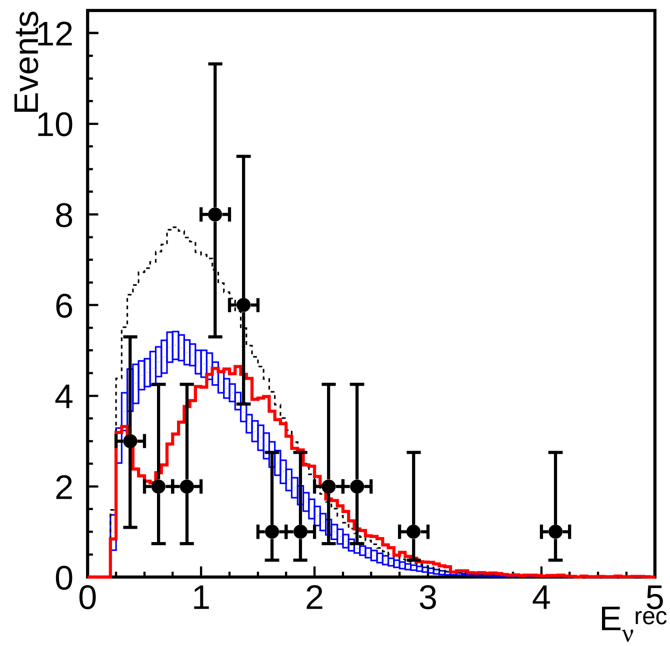
Performance measured in test beams at CERN

Event reconstruction with an ECC



Signatures–Disappearance

- K2K

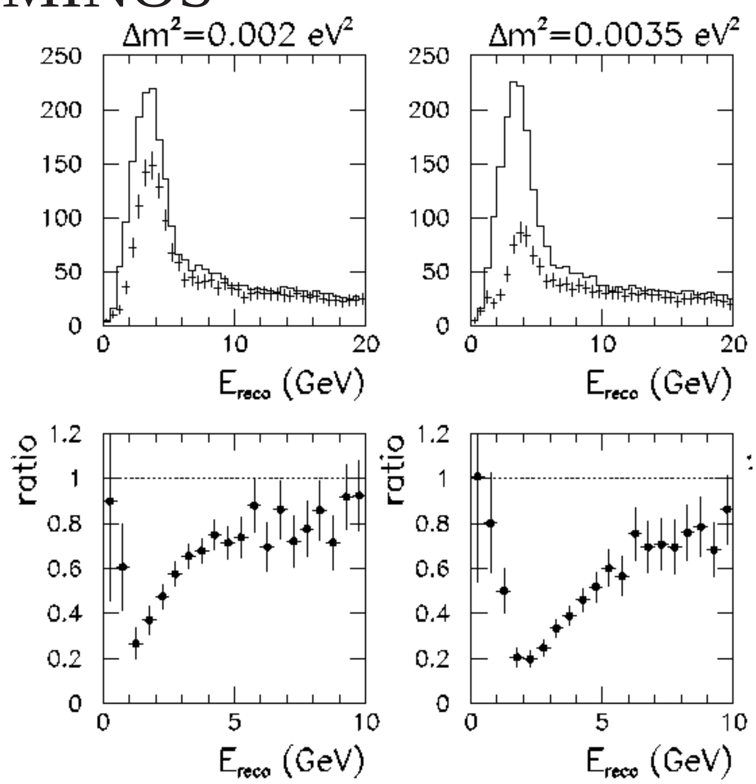


So far, 56 events seen, $80.1^{+6.2}_{-5.4}$ expected w/o oscillations

Ahn *et al*, PRL **90, 2003**

Statistics to double in next 2 years

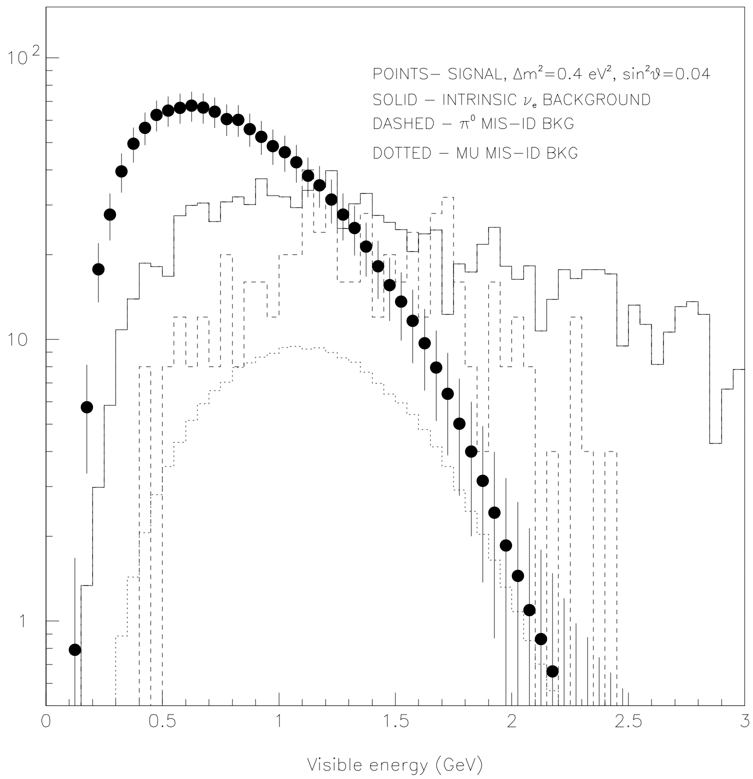
- MINOS



$> 10^3$ events with $E_\nu < 5 GeV$ w/o oscillations 10^{21} p^+ on target (3 years)

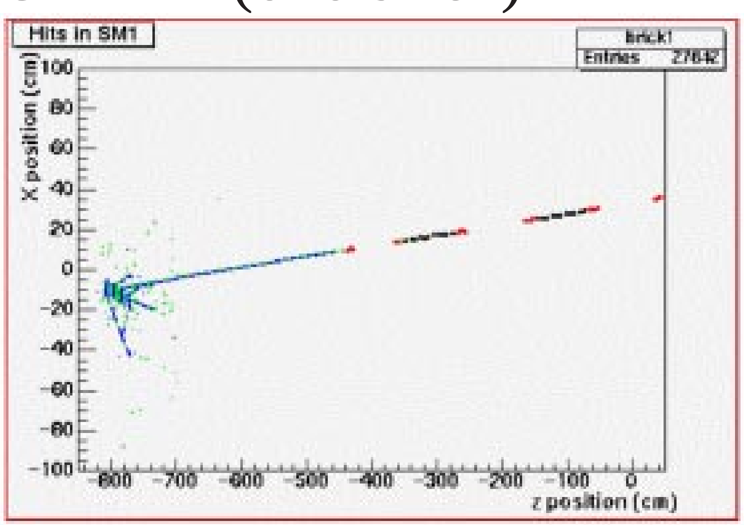
Signatures–Appearance

- MiniBooNE



500-1000
Signal if
LSND = osc
1000 beam ν_e
1000 π^0 or μ
MIS-ID

- OPERA (one brick)



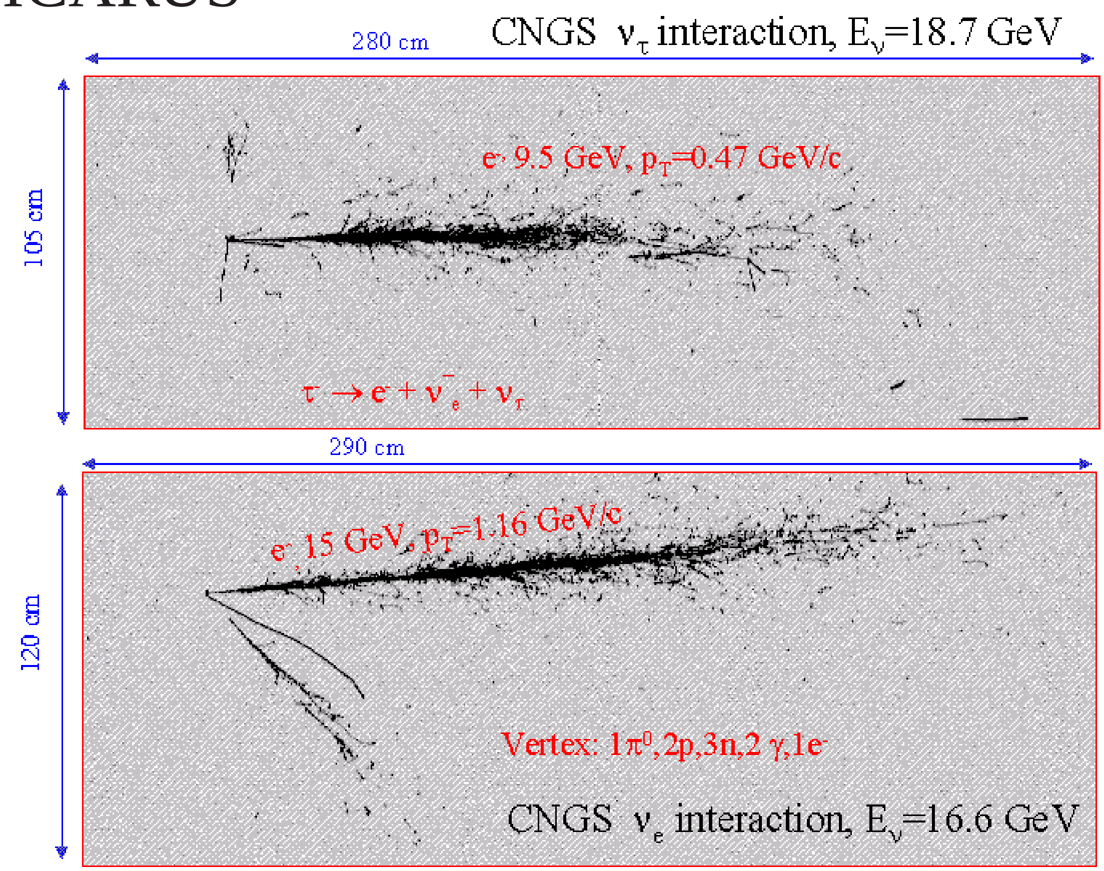
Events in 5 years at $6.8 \times 10^{19} p/yr$

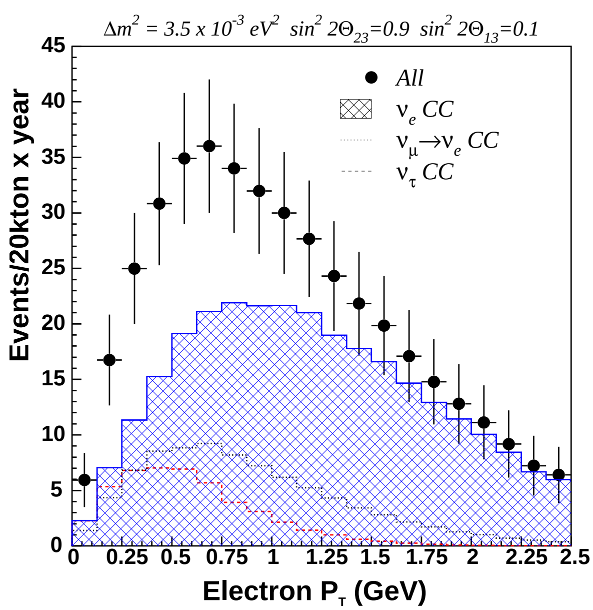
Δm^2 $\times 10^{-3}$	Design	Impr'd	Bkgd
1.8	9.0	10.3	.9
2.5	17.2	19.8	.9
4.0	43.8	50.4	.9

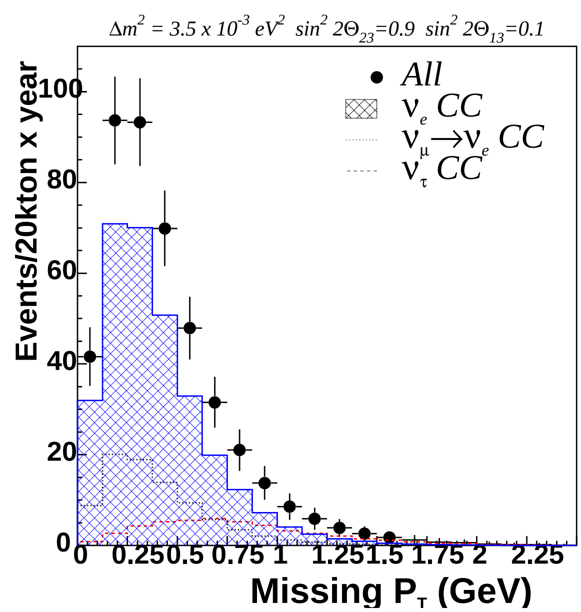
Ref: P.Migliozzi

Signatures–Appearance

- ICARUS







Status of Current Generation

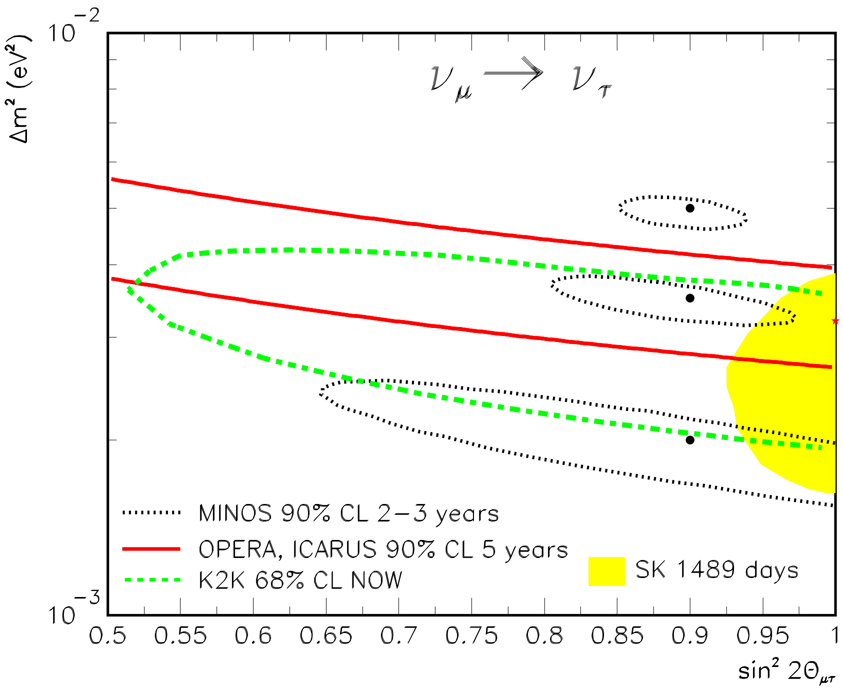
Milestone	MiniBooNE	K2K	MINOS	OPERA	ICARUS
Beamline Excavated	$\surd$	$\surd$	$\surd$	$.95\surd$	
Electricity water, air	$\surd$	$\surd$	now	2004-5	
Decay Pipe Installed	$\surd$	$\surd$	$\surd$	2003-4	
Beamline Installed	$\surd$	$\surd$	2004	2005	
p on Target	$\surd$	$\surd$	1/2005	mid 2006	
total POT	0.05	0.4			
Far Det.	1.00	1.00	> 0.92	0.2	
Near Det.	n/a	1.0	1.0	n/a	n/a
Test Beams		$\surd$	$\surd$	$\surd$	$\surd$
Cosmic μ	$\surd$	$\surd$	$\surd$	n/a	$\surd$
Atm. ν Seen	$\surd$	$\surd$	$\surd$		

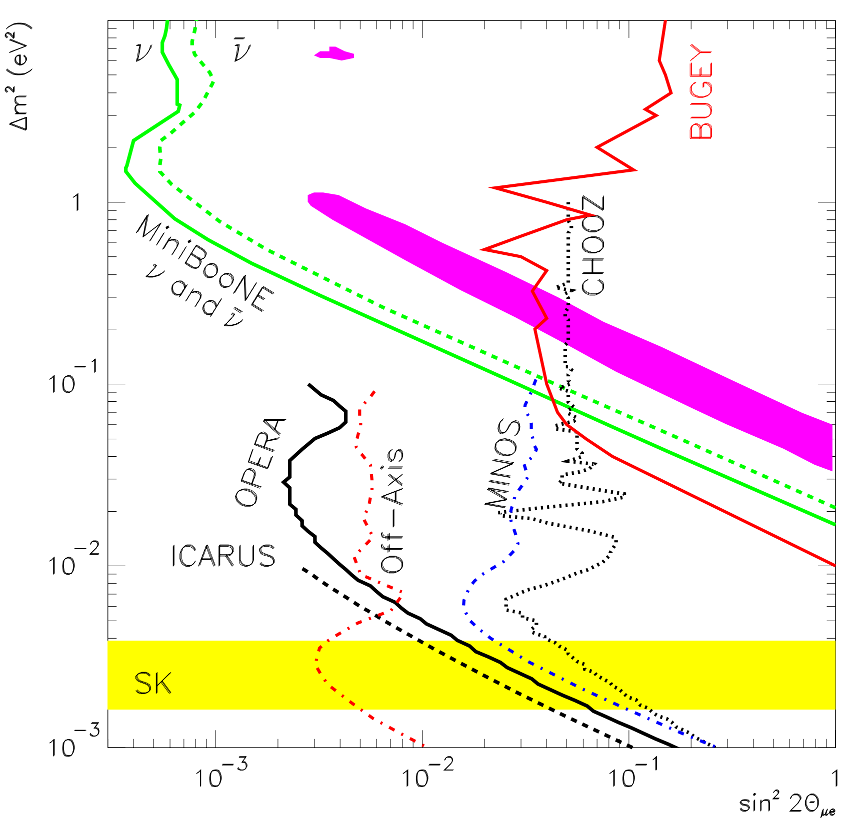
Caveats:

MINOS has assembled near detector on surface

ICARUS has run 0.6kton module in Pavia, approved for 0.6kton so far in Gran Sasso

2-Generation Mixing Sensitivities



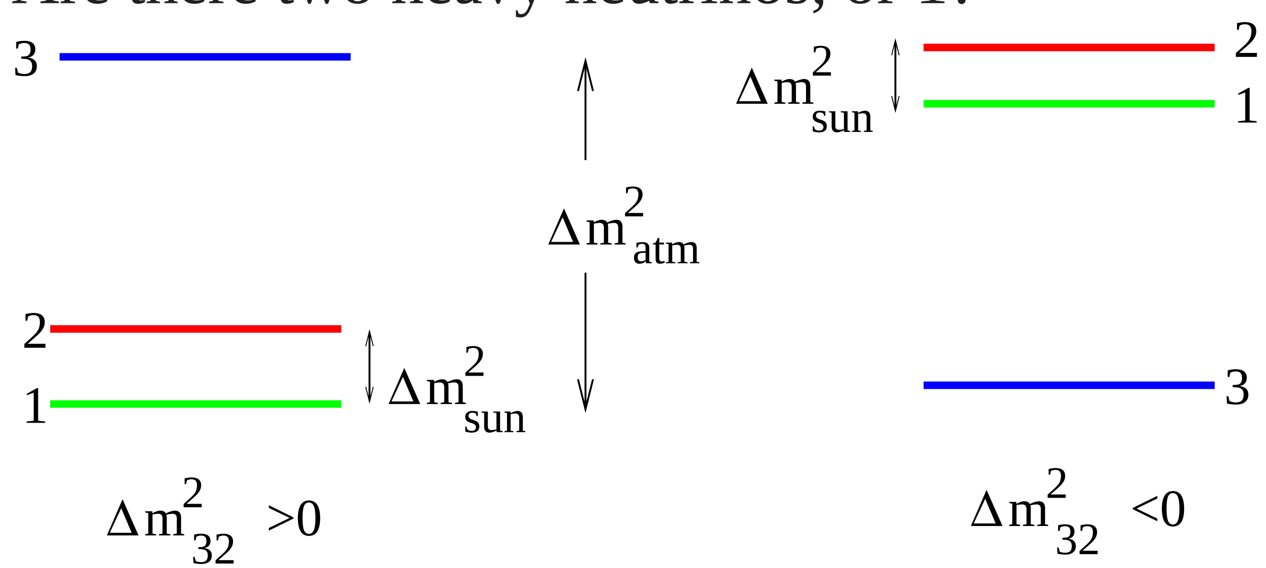


What will we know from these?

- Atmospheric ν anomaly due to oscillations
- LSND due/not due to oscillations (MiniBooNE) maybe $\sin^2 2\theta_{LSND}, \Delta m^2_{LSND}$ to about 10%
- $\sin^2 2\theta_{atm}, \Delta m^2_{atm}$ to about 10%
- Δm^2_{sol} (from KAMLAND)

What will we still want to know?

- Are any angles 0 or $\pi/4$ in the ν matrix?
- Is there CP violation in the Lepton Sector?
- Are there two heavy neutrinos, or 1?

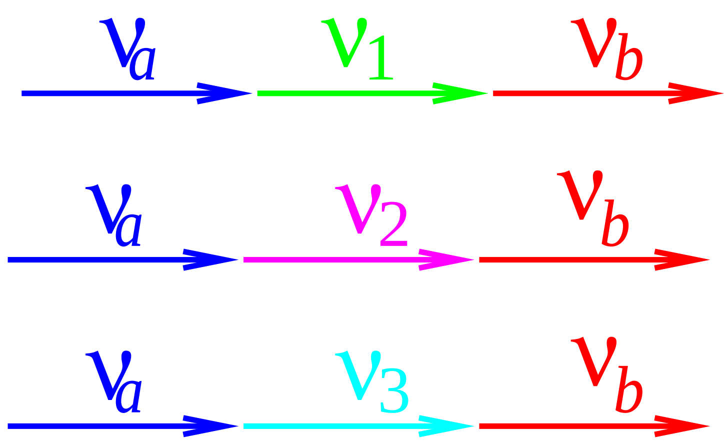


3 Generation ν Oscillations in 25 words or less

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

Produce Weak Eigenstate...
Detect Weak Eigenstate...
Propage Mass Eigenstate

To get the probability of $\nu_a \to \nu_b$:



Add all 3 amplitudes and square...

$$P(\nu_a \to \nu_b) = \Sigma_{i=1}^{3}\Sigma_{j=1}^{3} U_{ai}U_{aj}^{*}U_{bi}^{*}U_{bj}e^{-i\delta m_{ij}L/2E}$$

Every transition "oscillates" at every $\Delta m^2 L/E$

- $P(\nu_\mu \to \nu_\tau)$ at Δm^2_{atm} constrains U_{23}
- $P(\nu_e \to \nu_\tau \nu_\mu)$ at Δm^2_{sol} constrains U_{12}
- $P(\nu_\mu \to \nu_e)$ at Δm^2_{atm} constrains U_{13}

Measuring U_{13} is not so simple...

$$P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$$

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

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

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

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

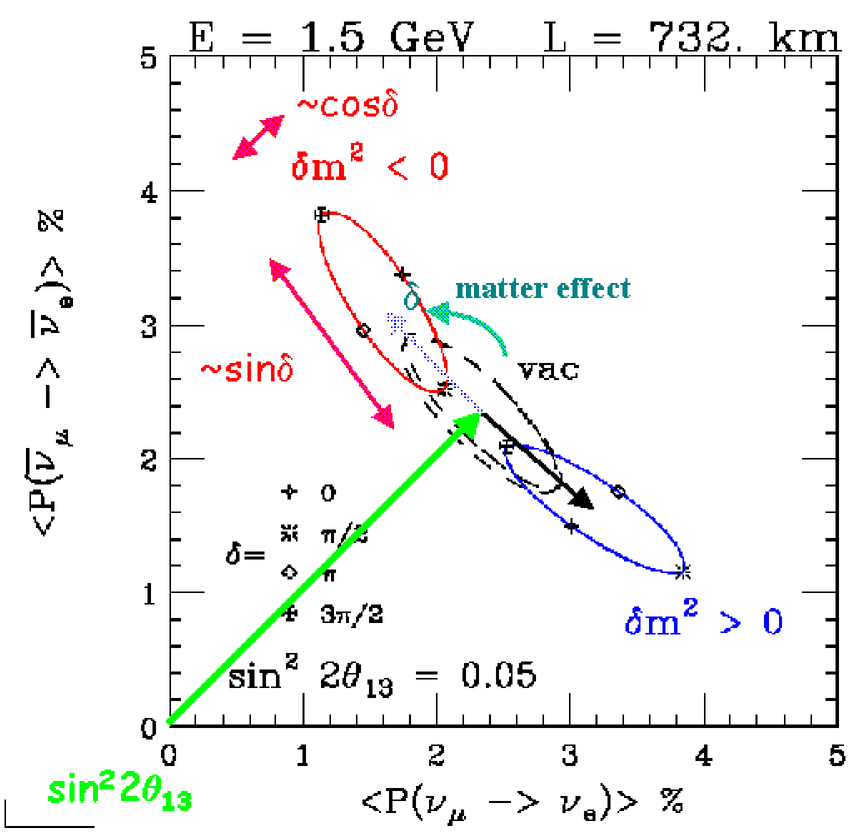
where the $\pm$ signifies ν or $\bar{\nu}$ and

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

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

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

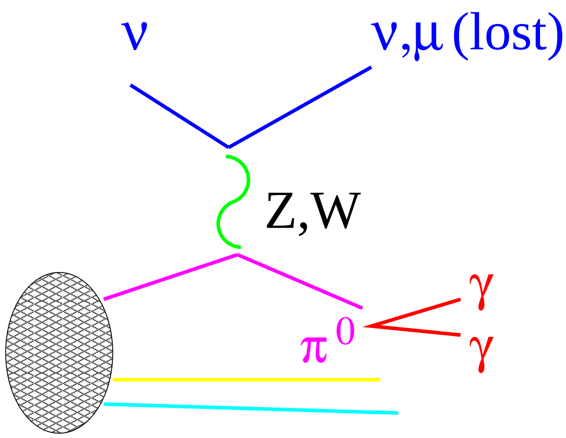
$$J = \cos\theta_{13} \times \sin 2\theta_{12} \times \sin 2\theta_{13} \times \sin 2\theta_{23}$$



Minakata and Nunokawa, `hep-ph/0108085`

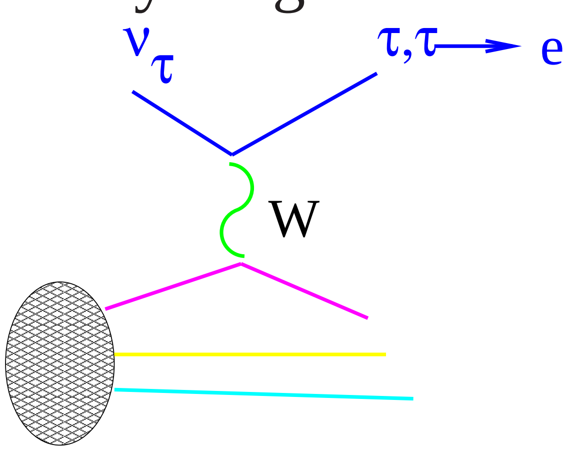
Why is $\nu_\mu \to \nu_e$ hard experimentally?

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



π^0 production in NC and CC events

- Today's signal is tomorrow's background



ν_τ Charged Current Events
Important for $E_\nu > 7GeV$

Ideas at Many Energies, and Baselines

Mode	E_ν	W/N	$\Delta m^2 L/2E$	Program	Detector
$\bar{\nu}_e \to \bar{\nu}_\mu$	0.2	W	$\sim \pi/2$	β-beam	$H_2 0$ Ч
$\nu_\mu \to \nu_e$	0.27	W	$\sim \pi/2$	CERN SPL	$H_2 0$ Ч
$\nu_\mu \to \nu_e$	0.8	N	$\pi/2$	J-PARC to SK	$H_2 0$ Ч
$\nu_\mu \to \nu_e$	.8	W	$(3-5)\pi/2$	CNGT	$H_2 0$ Ч
$\nu_e \to \nu_\mu$	0.9	W	$< \pi/2$	β-beam	$H_2 0$ Ч
$\nu_\mu \to \nu_e$	1-3	W	$(1-3)\pi/2$	BNL LOI	$H_2 0$ Ч
$\nu_\mu \to \nu_e$	2	N	$\pi/2$	NUMI-OA	$H_2 0$ Ч Fine Grain LAR TPC
$\nu_\mu \to \nu_e$	2	N	$\pi/2$	CNGS**	ICARUS
$\nu_e \to \nu_\mu$	10-20	W	$\leq \pi/2$	ν Factory	Steel Scintillator
$\nu_e \to \nu_\tau$	10-20	W	$<< \pi/2$	ν Factory	Emulsion-Lead

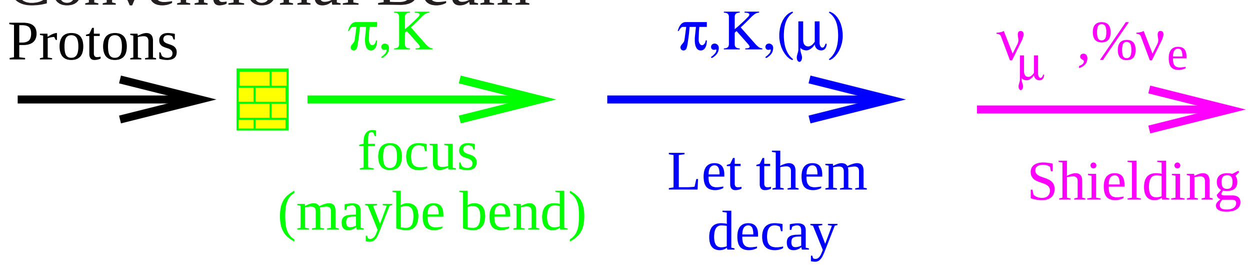
Red means matter effects are important

** modified from current optics,

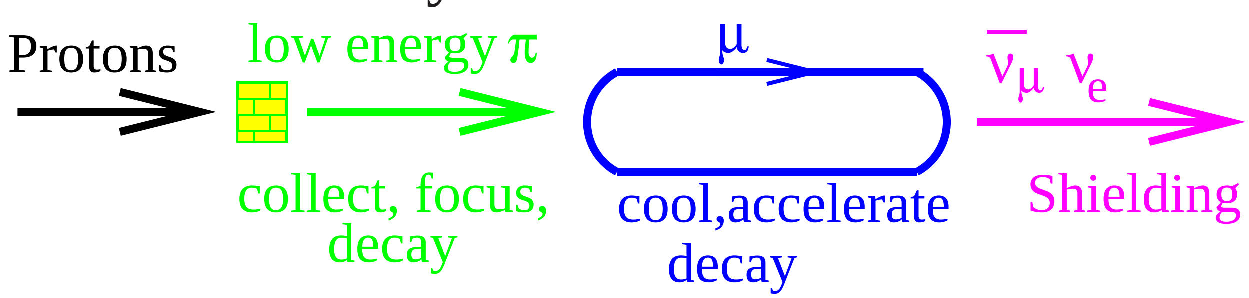
from A.Rubbia, P.Sala, `hep-ph/0207084`

Making Neutrino Beams

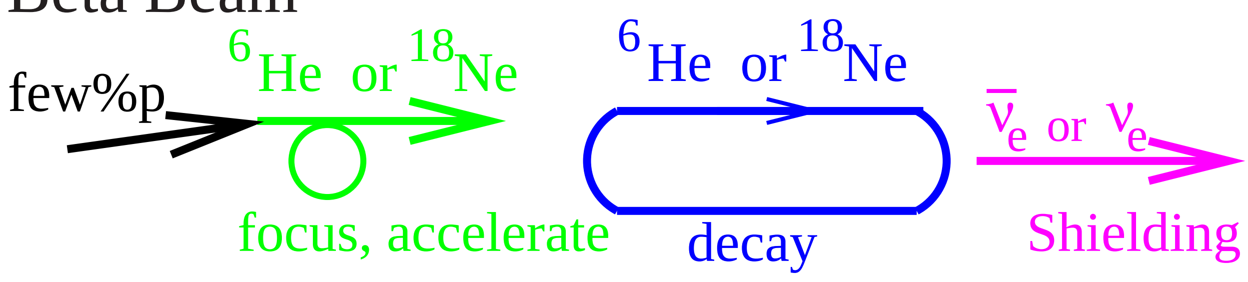
- Conventional Beam



- Neutrino Factory



- Beta Beam



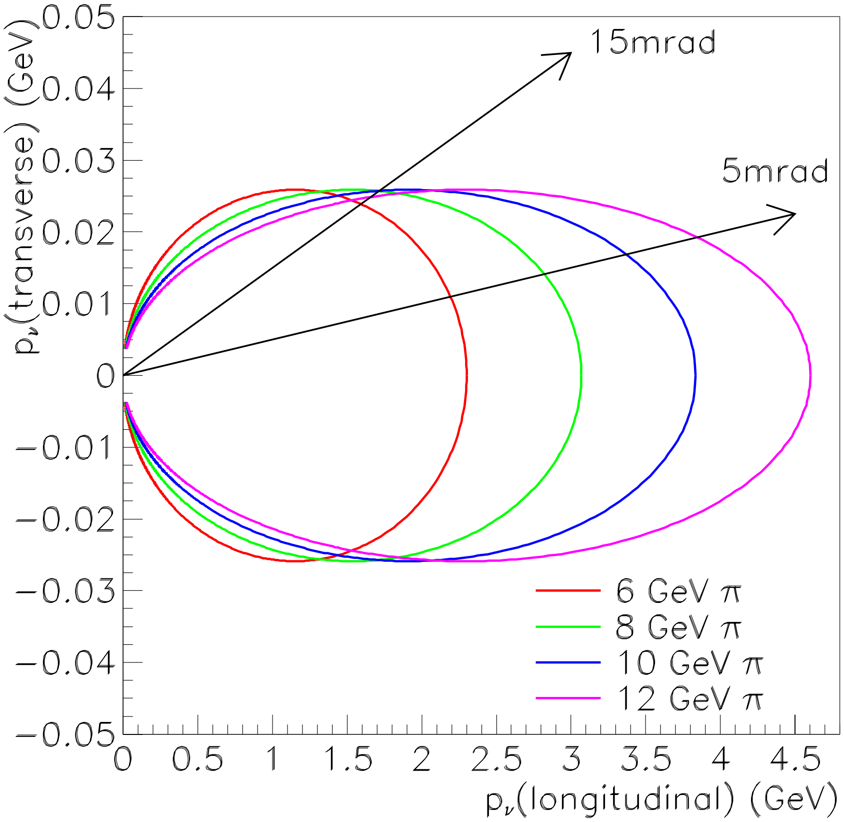
Events/parent at far detector:

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

Strategies for Beam Optimization, I

- Narrow Band Beams (J-PARC2K,NUMI-OA,CNGT)
  - → Good News: Backgrounds have broad energy spectrum
  - → Bad News: Beam width is much narrower than oscillation width

(D. Beavis et al., BNL No. 52459, April 1995)

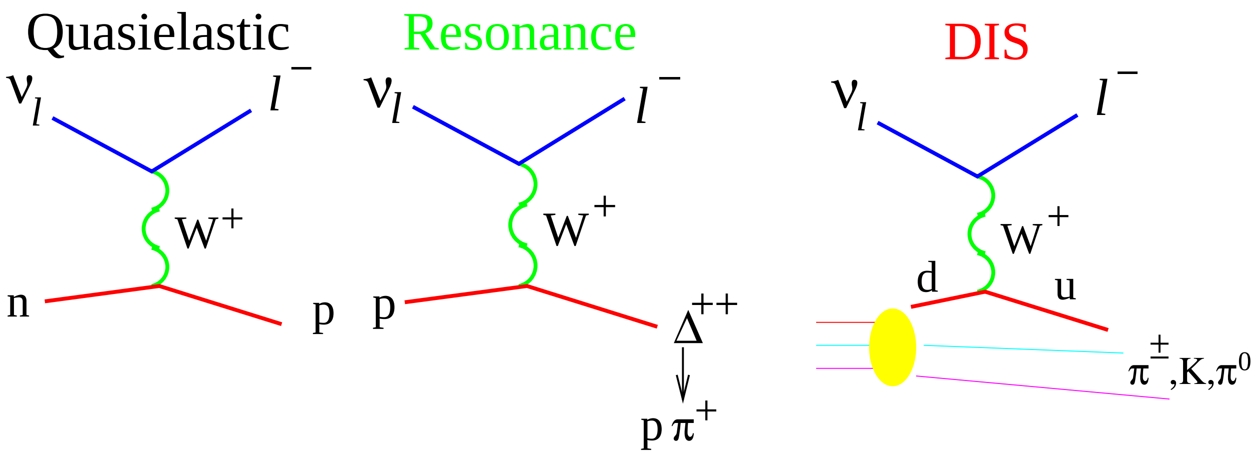


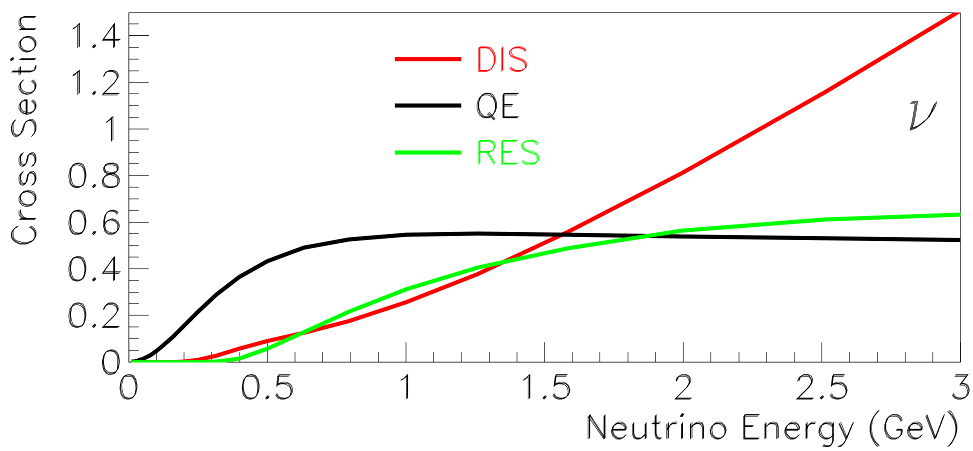
Strategies for Beam Optimization, II

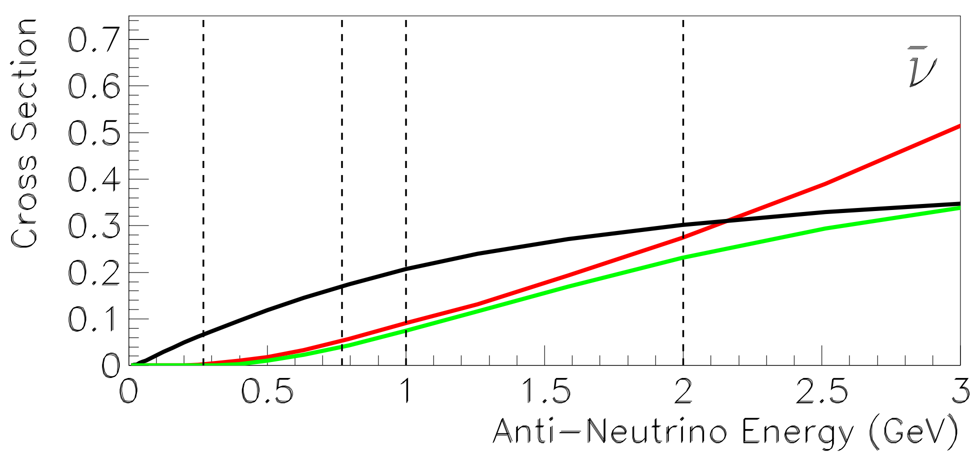
- Very Low Energy (CERN SPL, βBeams)
  - $\longrightarrow$ Good News: Good Signal Acceptance & bkgd rejection
  - $\longrightarrow$ Bad News: Cross Section is very small, esp. $\bar{\nu}$'s
- Very Long Distance (BNL2NUSL)
  - $\longrightarrow$ Good News: matter effects amplify signal
  - $\longrightarrow$ Good News: CP violating part increases with L
  - $\longrightarrow$ Bad News: have to **KNOW** ν_e background vs energy

Detector Optimization

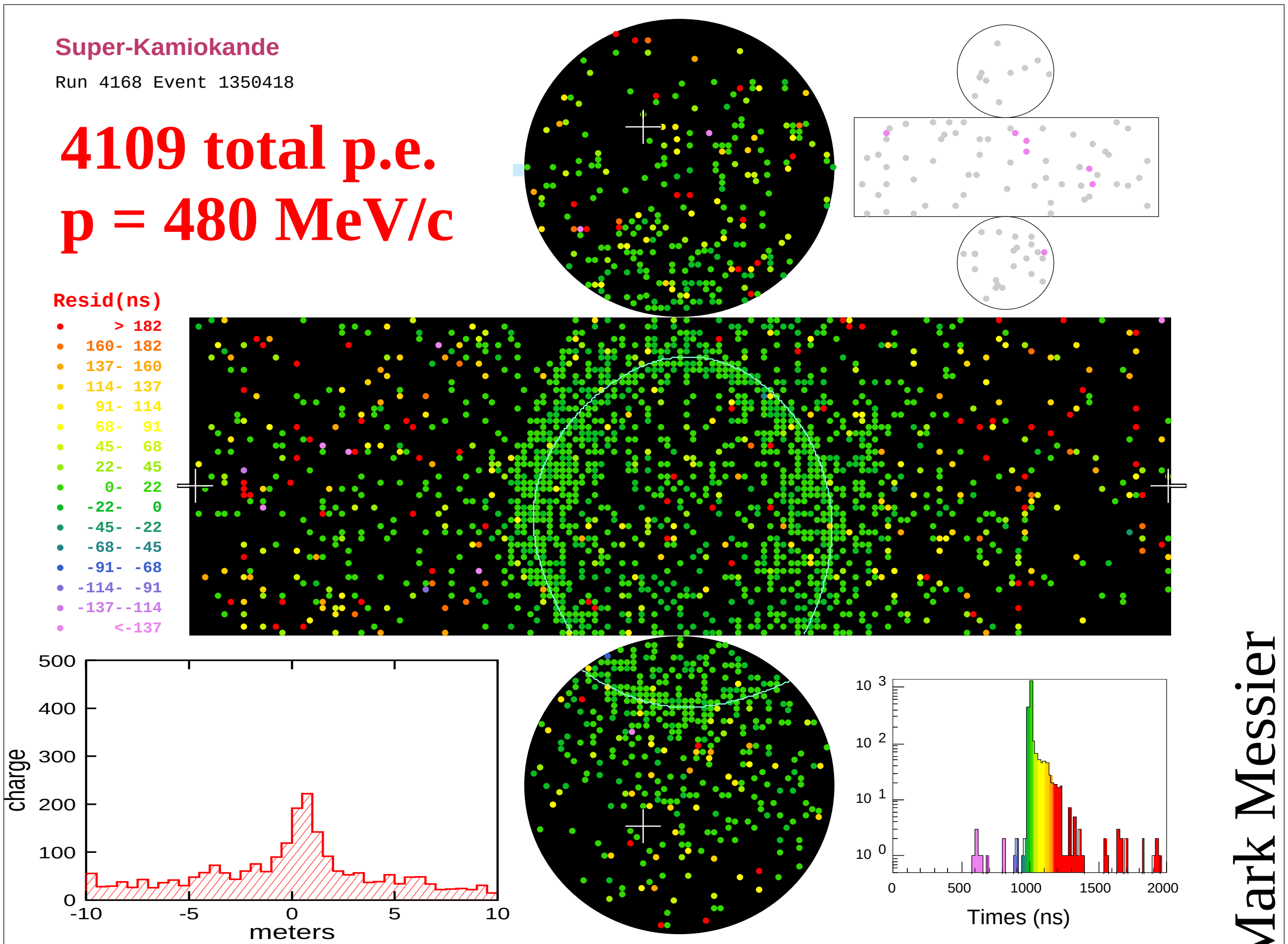
But first, a reminder about neutrino interactions



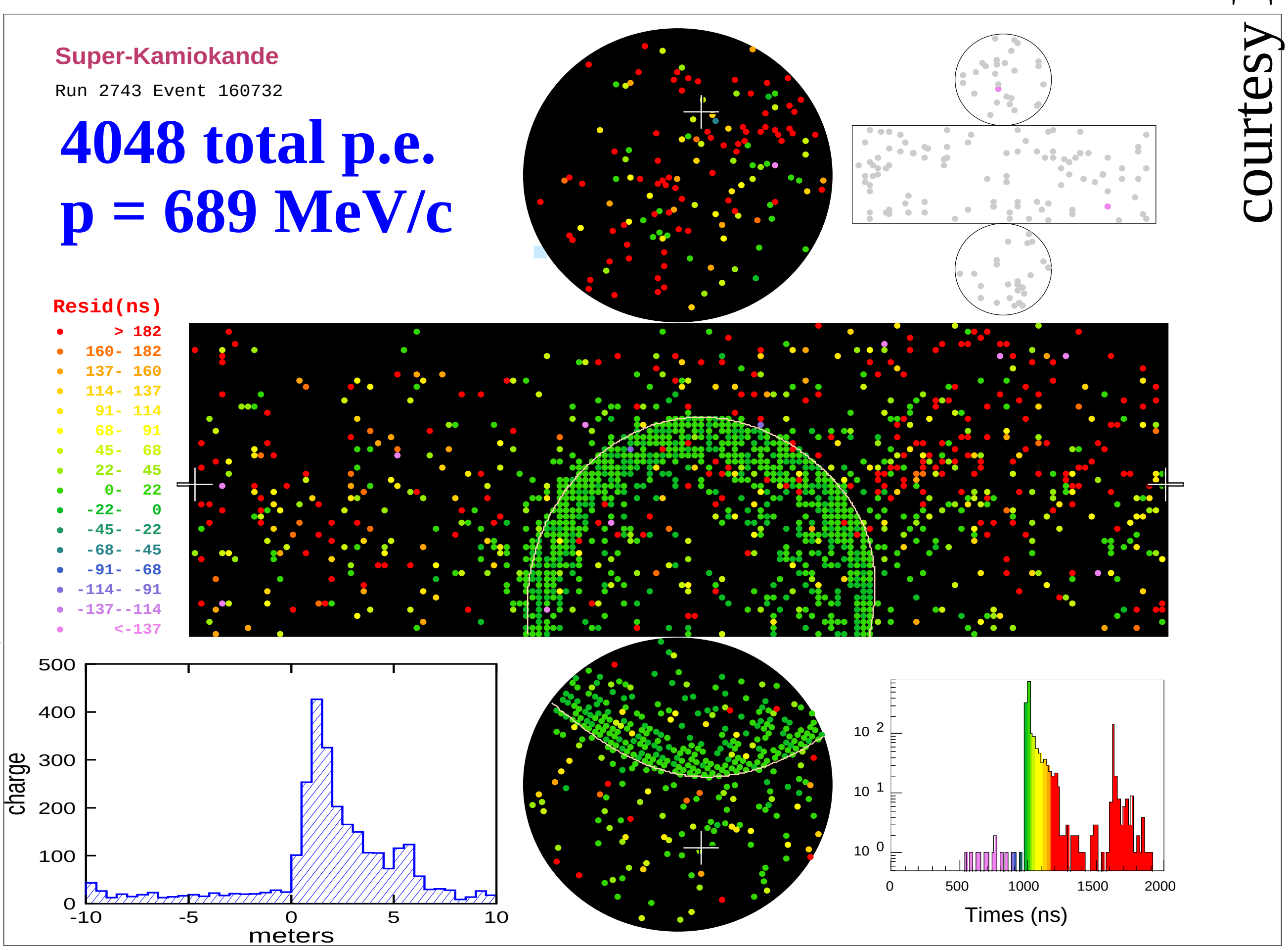




e−like



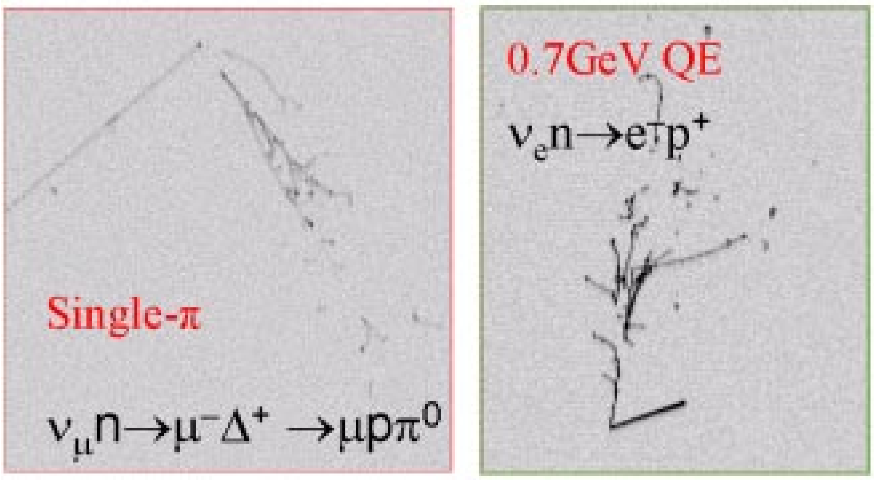
μ−like



courtesy Mark Messier

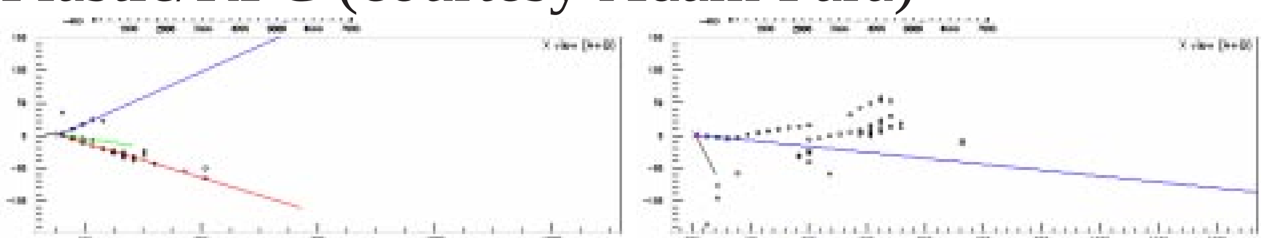
π^0/Electron Discrimination at 2GeV

- LAr TPC (courtesy Andre Rubbia)

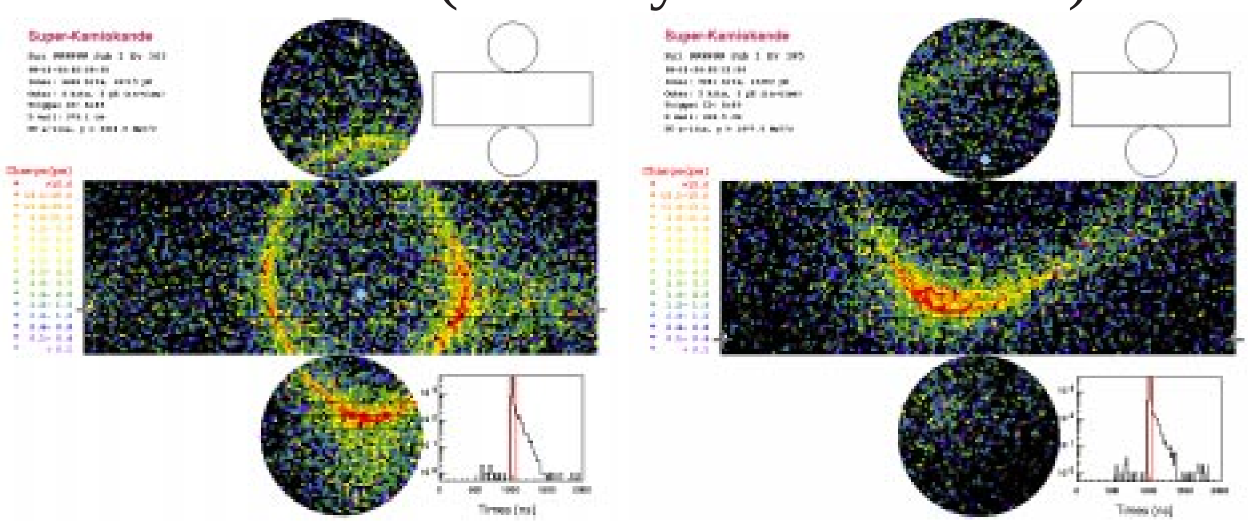


dE/dx in first few X_0 can discriminate

- Plastic/RPC (courtesy Adam Para)



- Water Cerenkov (courtesy Mark Messier)



In Praise of Near Detectors

For all the following experiments:
Even w/o oscillations they will see ν_e events!
Have to understand backgrounds well.

- Intrinsic ν_e – mostly $\mu^+ \to \nu_e \bar{\nu}_\mu e^+$ decays

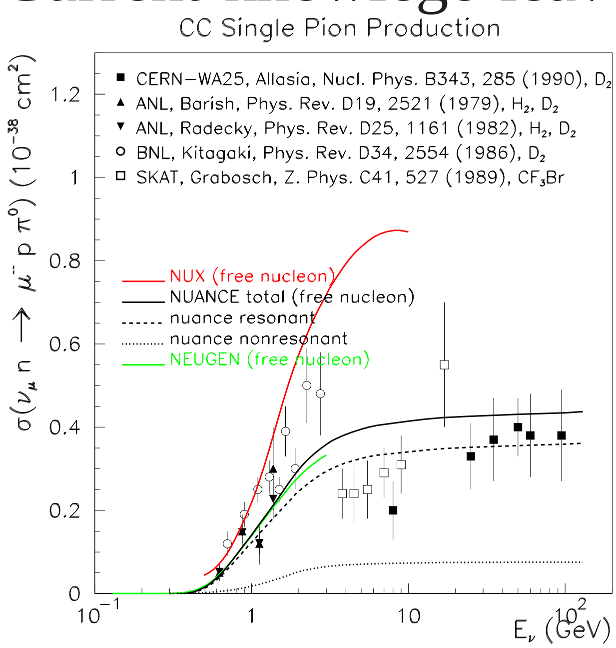
  $\to$ $\bar{\nu}_\mu CC$ events in near det. help

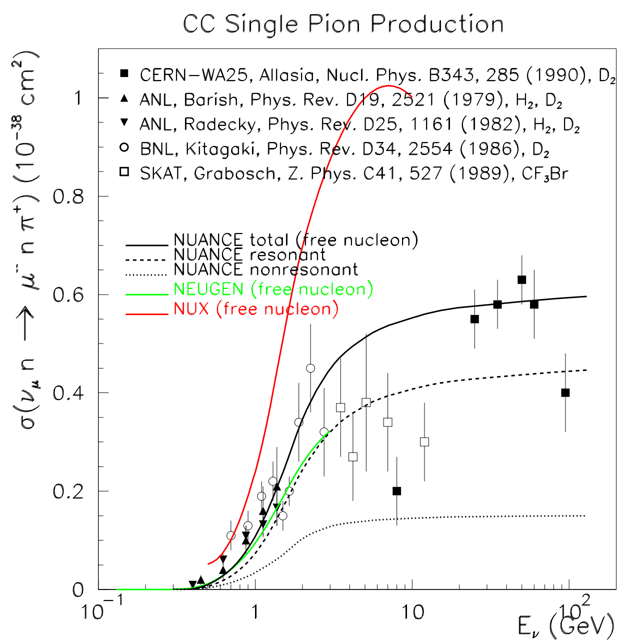
- Detector Mis-identification

  $\to$ Quasi-elastic/Resonance Contamination

  $\to$ neutral current π^0 production

Current knowlege leaves much to be desired...

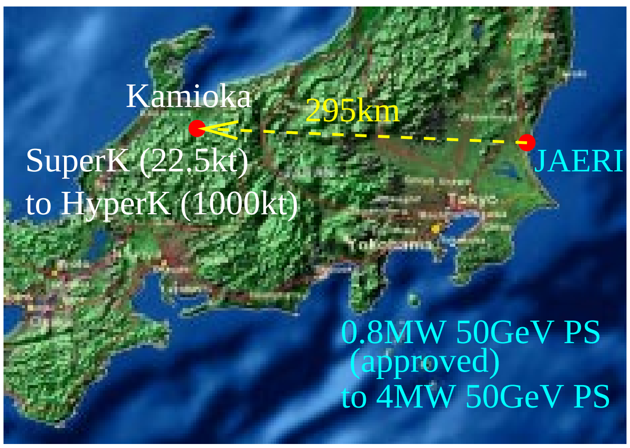


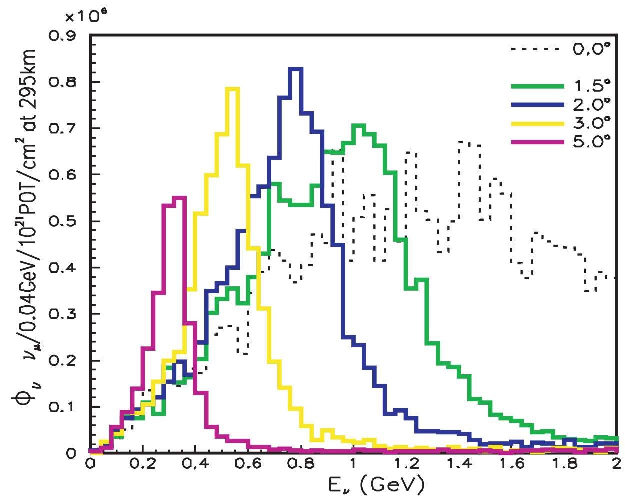


Ref: Sam Zeller, NuINT02, and here in $<$1 hour!

New ν Experiment Fluxes

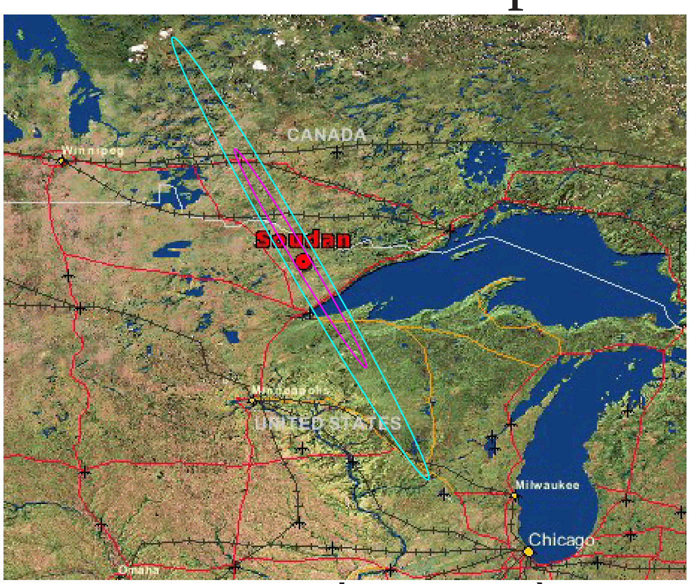
- J-PARC to Super-Kamiokande

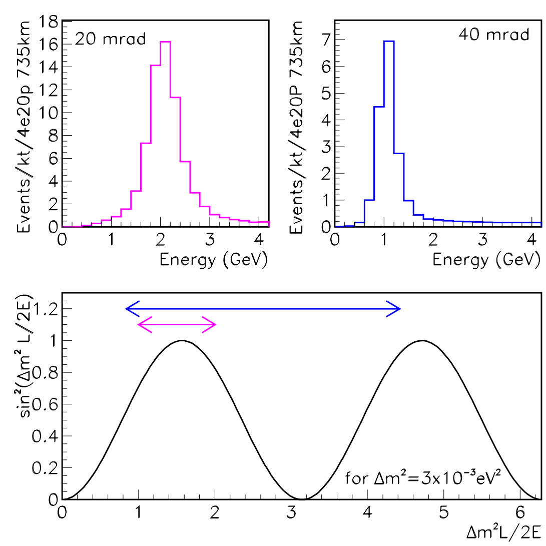




Itow *et al*, `hep-ex/0106019`

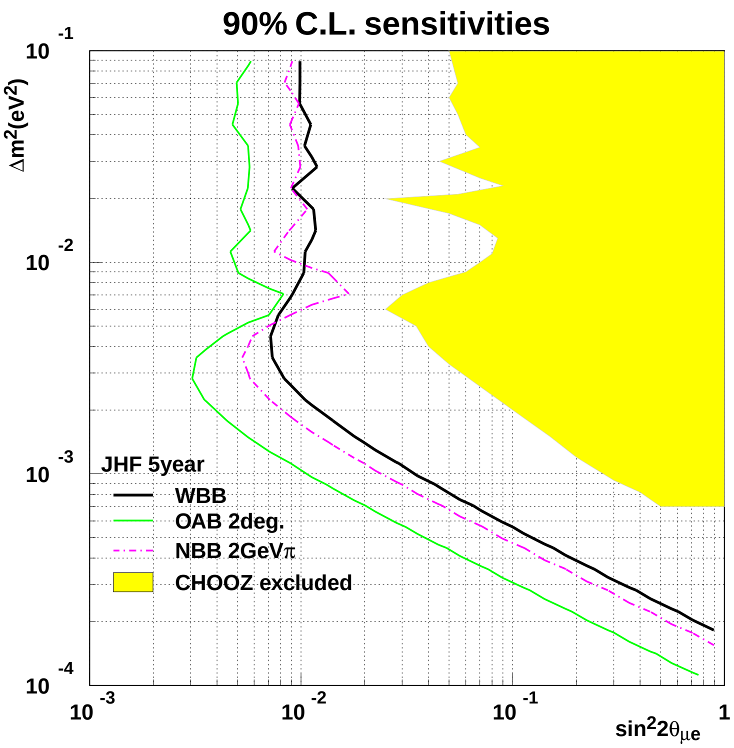
- NuMI-Off Axis Experiment





D. Ayres *et al*, `hep-ex\0210005`

Sensitivities

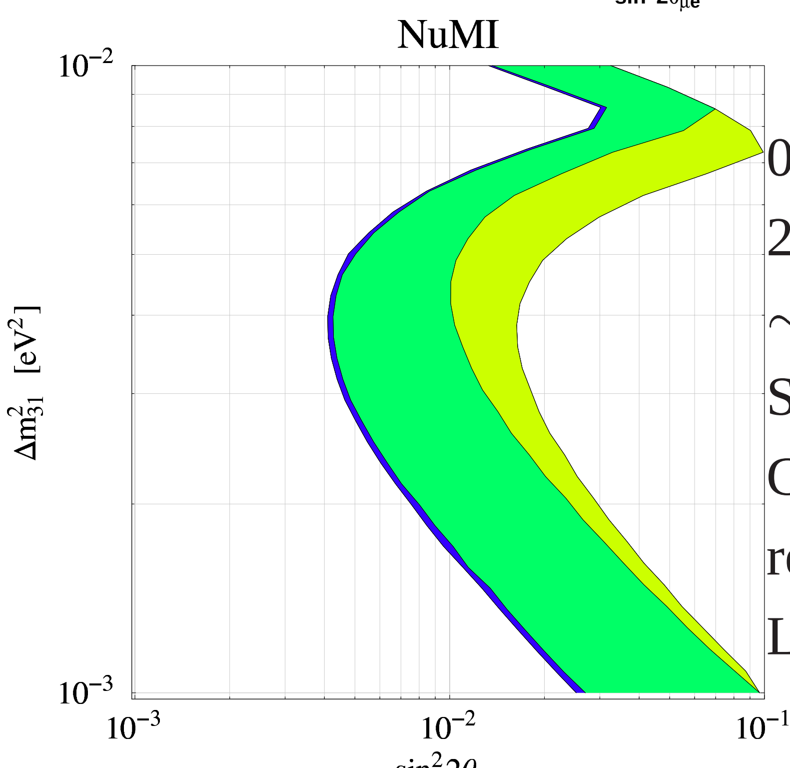


0.75MW p source

22.5kTon Super-K

$\sim 0.5\% \nu_e/\nu_\mu$

$\sin^2 2\theta_{\mu e} \approx \frac{1}{2}\sin^2 2\theta_{13}$



0.4MW source

20kton

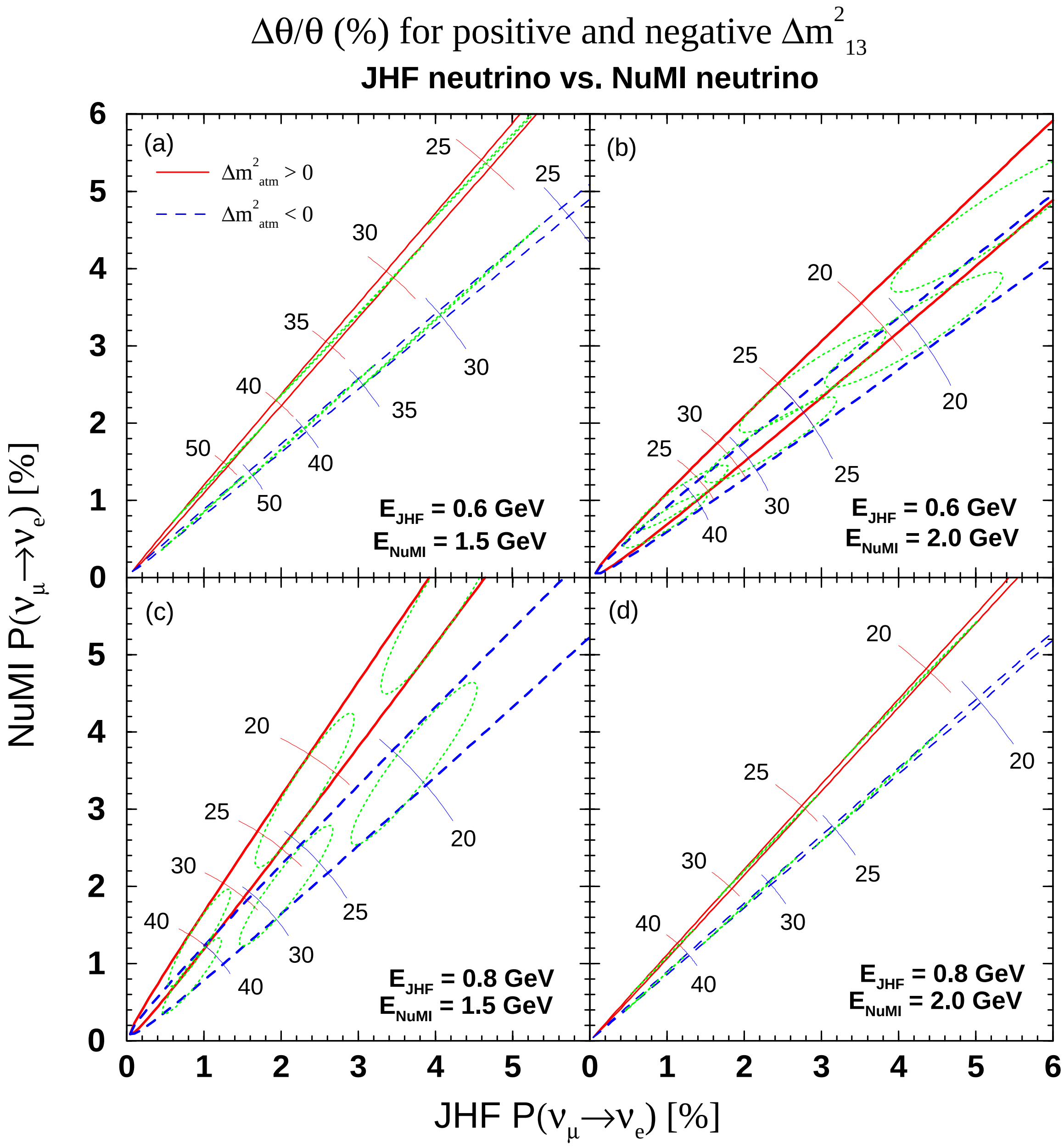
$\sim 0.5\% \nu_e/\nu_\mu$ Blue: Stat. only

Green: ambig. & correl.

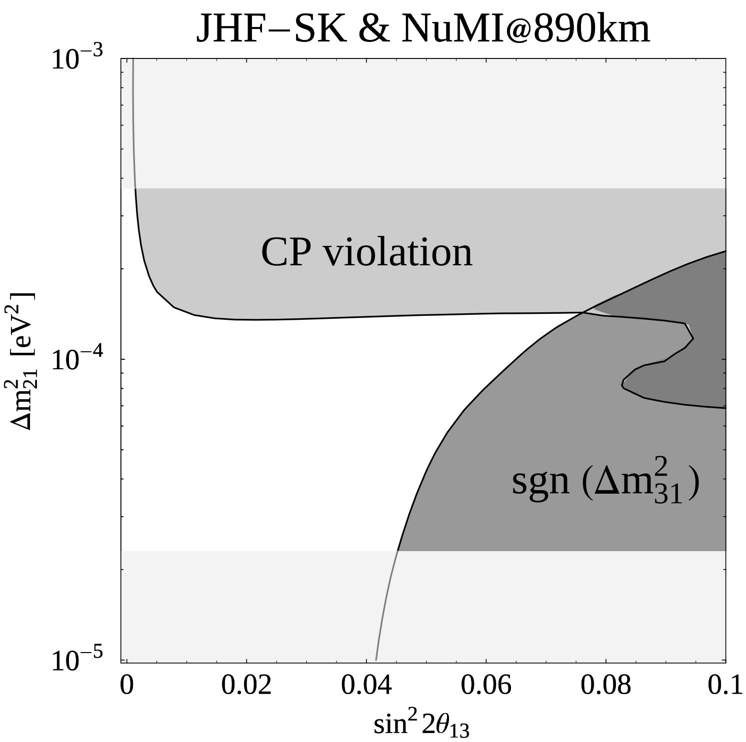
Lt. green: Syst.

What can you learn from J-PARC *and* NuMI-OA?

See mass hierarchy by comparing $P(\nu_e)$ with (NuMI) and without (J-PARC) matter effects Minakata, Nunokawa, Parke `hep-ph/0301210`



Where the whole is greater than the Sum of the Parts: NuMI and J-PARC



Huber, Lindner, Winter

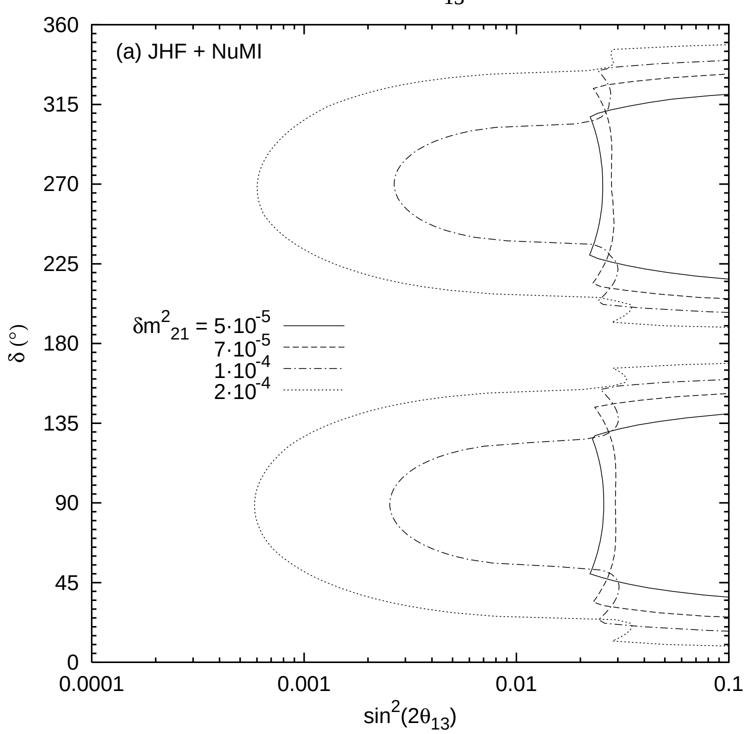
Nucl. Phys. **B654** 2003

J-PARC:.8MW, 22.5kT, 8yrs

NuMI:.4MW, 17kton*.4effic., 7yrs

$\Delta m^2_{23} = 3 \times 10^{-3} eV^2$,

$\theta_{23} = \pi/4$



Barger, Marfatia, Whisnant,

`hep-ph/0210428`

J-PARC:4MW, 22.5kT, 8Yrs

NuMI:1.6MW, 50kt, 7 yrs (assume .4 efficiency)

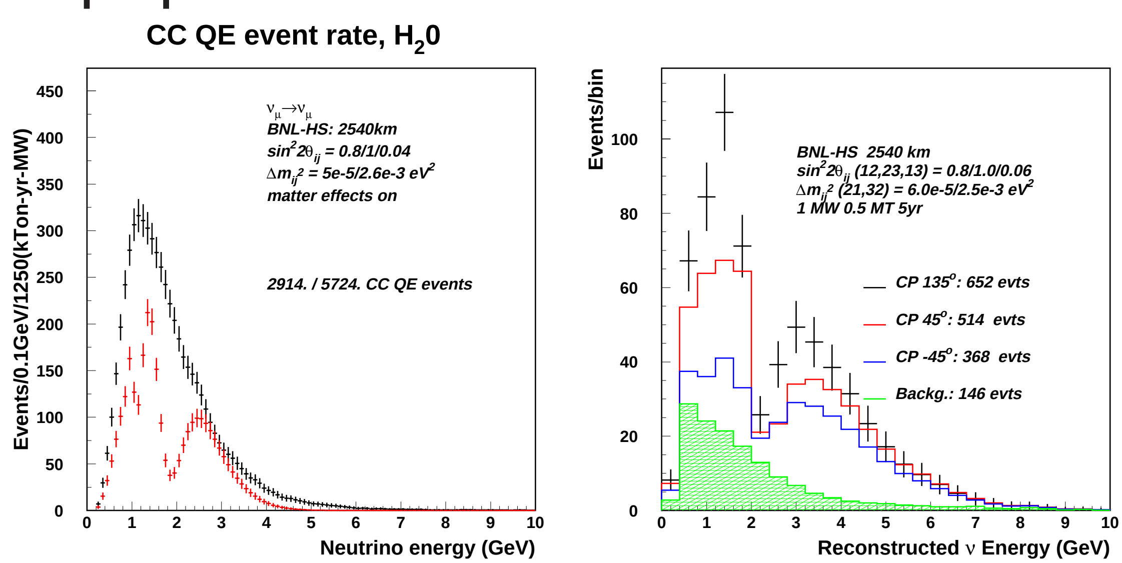
$\Delta m^2_{23} = 3 \times 10^{-3} eV^2$,

$\theta_{23} = \pi/4$

What happens next?

Megawatt Beamlines, $\mathcal{O}$(Megaton) detectors

- Upgrades to current program
  - $\rightarrow$ Upgraded J-PARC to Hyper-Kamiokande
  - $\rightarrow$ New Proton Driver at Fermilab+more mass
- Totally New Approaches (H_2O Черенков)
  - $\rightarrow$ Brookhaven LOI-$L > 2500km$!!! `hep-ph/0303081`



  - $\rightarrow$ CERN SPL–low energy ν beam, proton target like ν factory
  - $\rightarrow$ β beams–radioactive isotopes, all ν_e or $\bar{\nu}_e$
- μ storage ring $\nu_e \rightarrow \nu_\mu$, backgrounds at 10^{-4}

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
J-PARC2SK	22.5	0.8	0.006	-	-
NuMI-OA	50	0.4	0.004	-	$\geq$CP
SJ-PARC2HK	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] M. Komatsu, P. Migliozzi, F. Terranova `hep-ph/0210043`

[m] M.Diwan, M.Messier, B.Viren, L.Wai, NUMI-L-714

[s] Assume 5% systematic uncertainty!

[**]7 years, modified from current optics, from A.Rubbia, P.Sala, `hep-ph/0207084`

Conclusions

- Stay tuned for precision oscillation measurements!
  - $\rightarrow$ K2K
  - $\rightarrow$ MINOS
  - $\rightarrow$ MiniBooNE
  - $\rightarrow$ OPERA and ICARUS
- Two complementary near-term opportunties await us
  - $\rightarrow$ J-PARC to Super-K
  - $\rightarrow$ NuMI Off Axis
- Many more long-term ideas
  - $\rightarrow$ BNL LOI
  - $\rightarrow$ β-beams
  - $\rightarrow$ CERN SPL
  - $\rightarrow$ μ storage ring
  - $\rightarrow$ Upgrades to J-PARC and/or NuMI
- Need more than one Energy and Baseline...
  - $\rightarrow$ to get to CP violation and Mass Hierarchy
- 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?
- Not for the faint of heart, but
  the rewards will be enormous!

Thanks to: Chris Walter, Fancesco Pietropaolo, Pasquale Migliozzi, Sam Zeller, Dixon Bogert, Andre Rubbia

Web Pages and other References Used for This Talk

- MiniBooNE: `http://www-boone.fnal.gov`
- K2K: `http://neutrino.kek.jp/`
- MINOS: `http://www-minos.fnal.gov`
- OPERA: March 2003 presentation given to LNGS Scientific Committee
- ICARUS: `http://www.cern.ch/icarus` and CERN/SPSC talk
- J-PARC to Super-Kamiokande: `http://neutrino.kek.jp/jhfnu/`
- NuMI Off Axis: `http://www-off-axis.fnal.gov`
- Brookhaven LOI: `hep-ph/0303081` and `hep-ex/0205040`
- β Beams and CERN SPL: see Nufact02 Talks, M. Mezzetto and P. Zucchelli, verb+http://www.hep.ph.ic.ac.uk/NuFact02/+

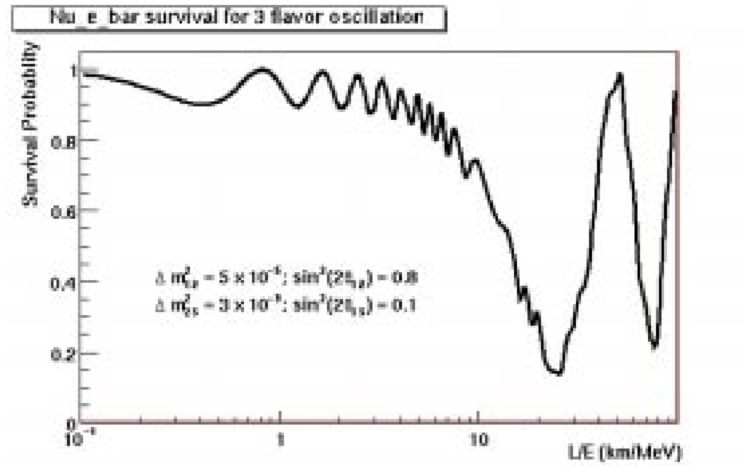
What about θ_{13} at Reactors?

Neutrino or Antineutrino Disappearance Probability:

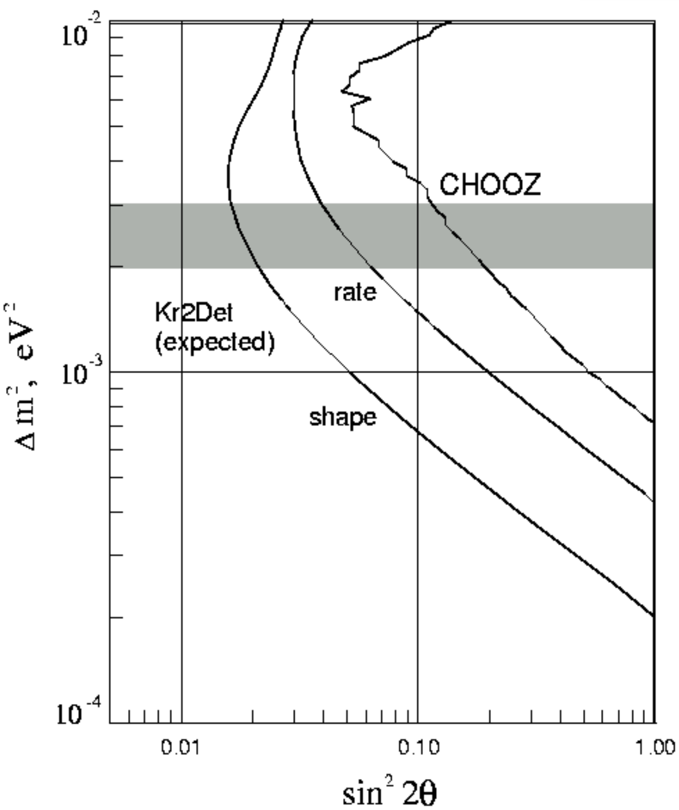
$$P(\nu_e \to \nu_e) = 1 - P_{sun}\sin^2(\Delta_{12}) - P_{atm}\sin^2(\Delta_{23})$$

$$P_{sun} = \cos^4\theta_{13}\sin^2 2\theta_{12}$$
$$P_{atm} = \sin^2 2\theta_{13}$$

(no $\cos\delta$
or matter effects)



Kr2DET



- 46 ton detectors at 115m, 1km
- Krasnoyarsk reactor
- 600MWE under-ground
- 4200(55) events/day near (far)
- $\sigma_{shape} = 0.5\%$
- $\sigma_{rate} = 0.8\%$

hep-ex/0211070

See also M.Goodman, Venice 2003, Shaevitz, NOON2002