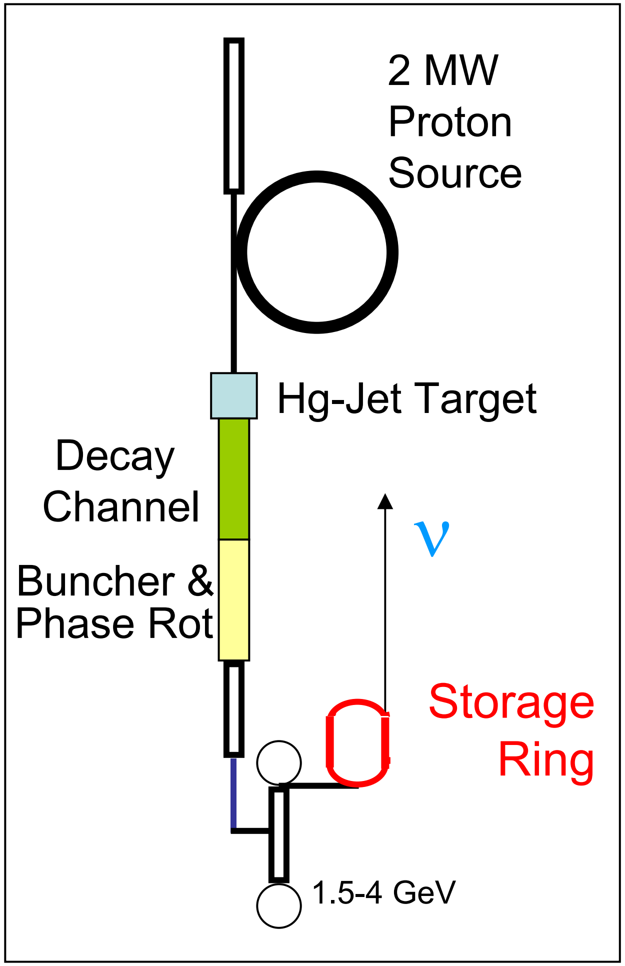
Fermilab



Low Energy Neutrino Factories

Steve Geer, Olga Mena, Silvia Pascoli

(Olga and Silvia did all the clever stuff)

IPPP/06/85; DCPT/06/170; Roma-TH-1443;
FERMILAB-PUB-07-021-E

Why Consider Low Energies Now ?

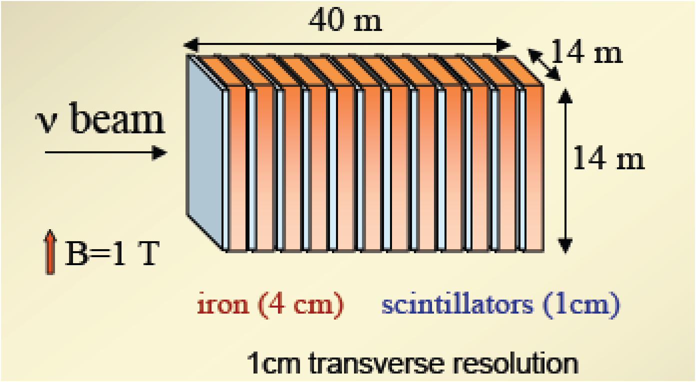
- Up to now, the NFMCC has focused on neutrino factories with energies of 20-50 GeV

- The collaboration has not studied lower energy neutrino factories because, until recently, the proposed NF detectors have had muon energy thresholds (for measuring wrong-sign muons with adequate background rejection) of a few GeV, which imposes a minimum threshold on the desirable neutrino energy, and hence a minimum NF energy $\rightarrow$ ~20 GeV.

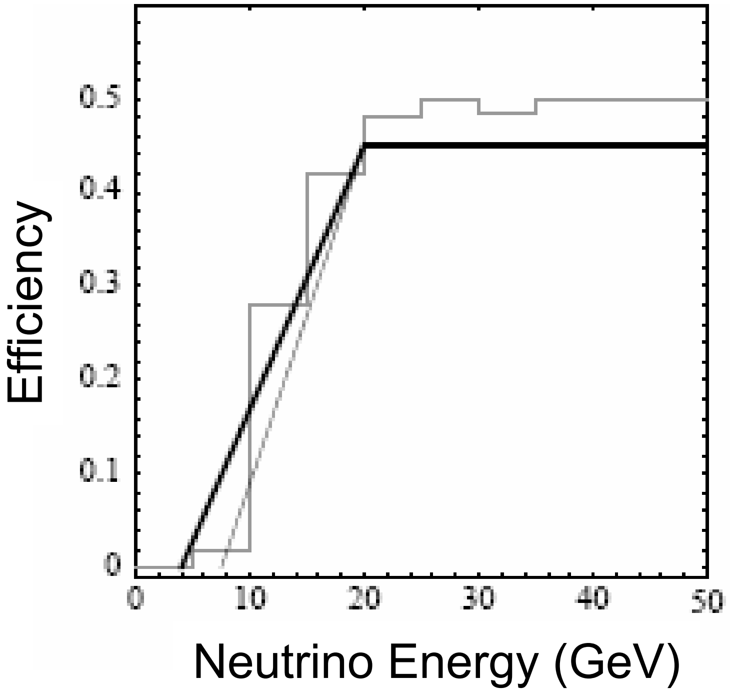
- In the ISS there was progress on understanding how to reduce the detector thresholds for measuring wrong-sign muons … so we can now consider lower energy neutrino factories.

NF DETECTOR PERFORMANCE

• We used to think that a large magnetized Fe-Scintillator NF detector was capable of measuring wrong-sign muons with good efficiency and adequate background rejection, only for neutrinos with energies greater than ~ 20 GeV:

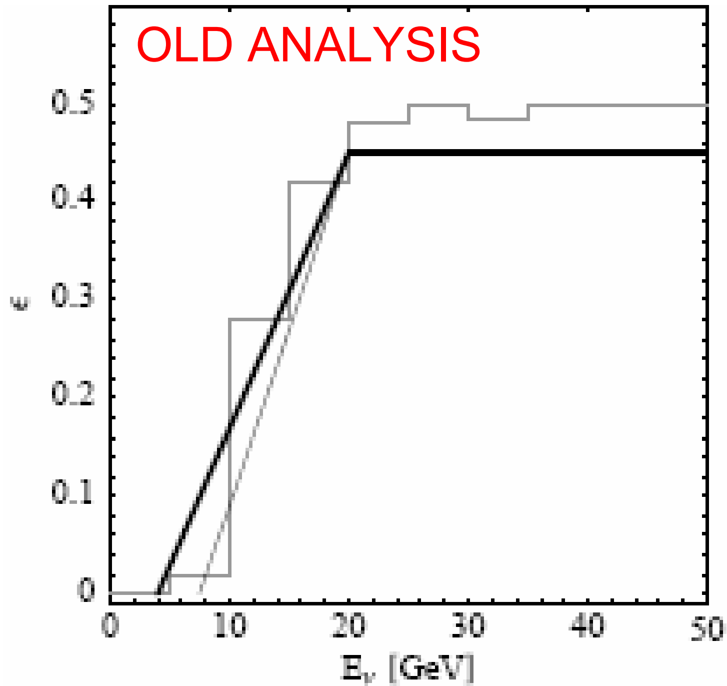


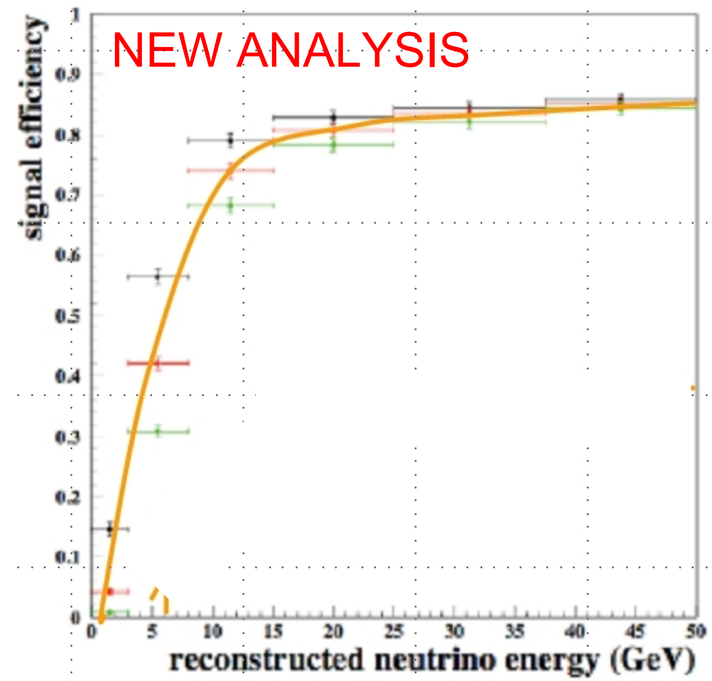
OLD ANALYSIS



UPDATED NF DETECTOR PERFORMANCE

- A new analysis (Cervera, ISS) , using better selection criteria, yields much greater sensitivity:





<u>ISS Results from M. Ellis talk (NUFACT06)</u>

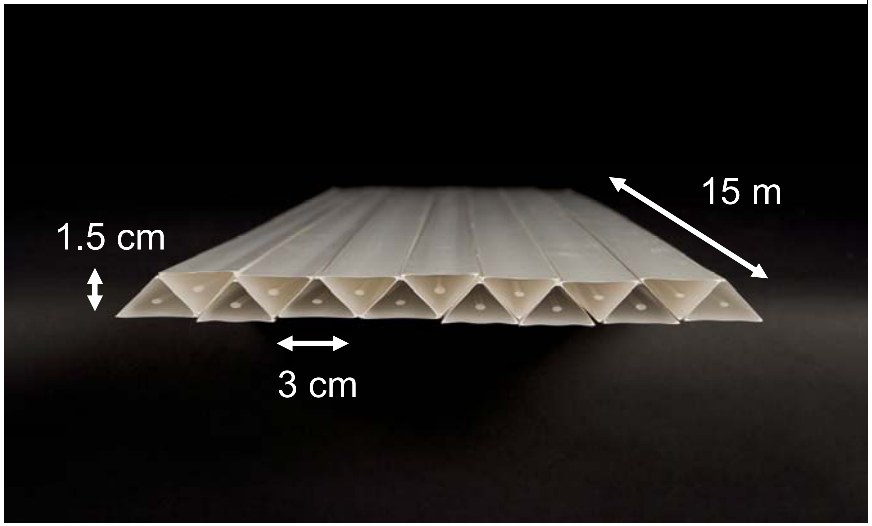
- A ~100 kton detector with a B-field of 1.4 T is feasible
- High efficiency above E_ν ~10 GeV (used to be 20 GeV)

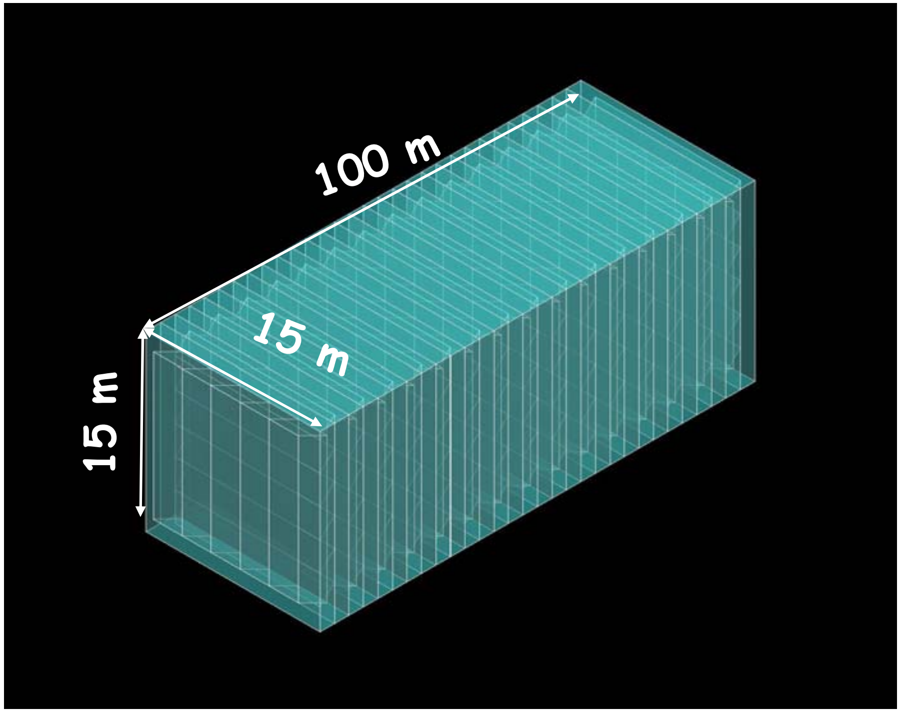
NEW DETECTOR CONCEPT

Simulation of a Totally Active Scintillating Detector (TASD) using Nova & Minerva concepts with Geant4 :

Ellis, Bross

- 3333 Modules (X and Y plane)
- Each plane contains 1000 slabs
- Total: 6.7M channels

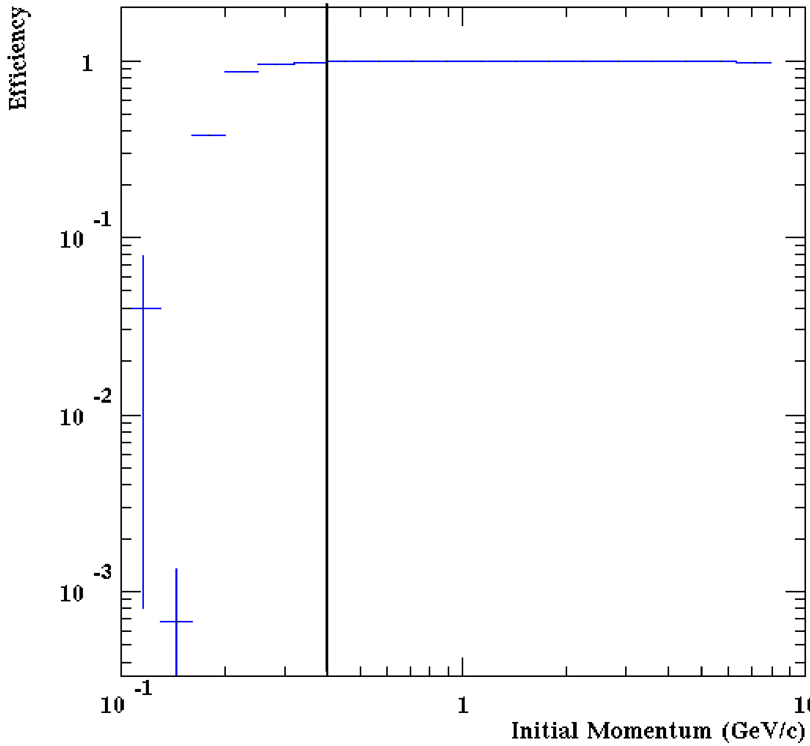




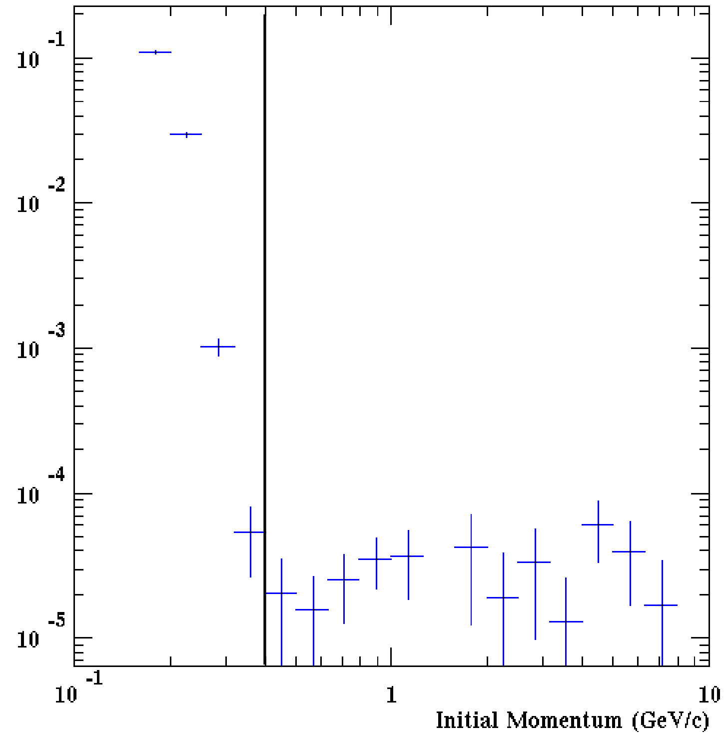
- Magnetic field considered: 0.5 T
- Reconstructed position resolution ~ 4.5 mm

NEW DETECTOR PERFORMANCE

Muon reconstructed efficiency

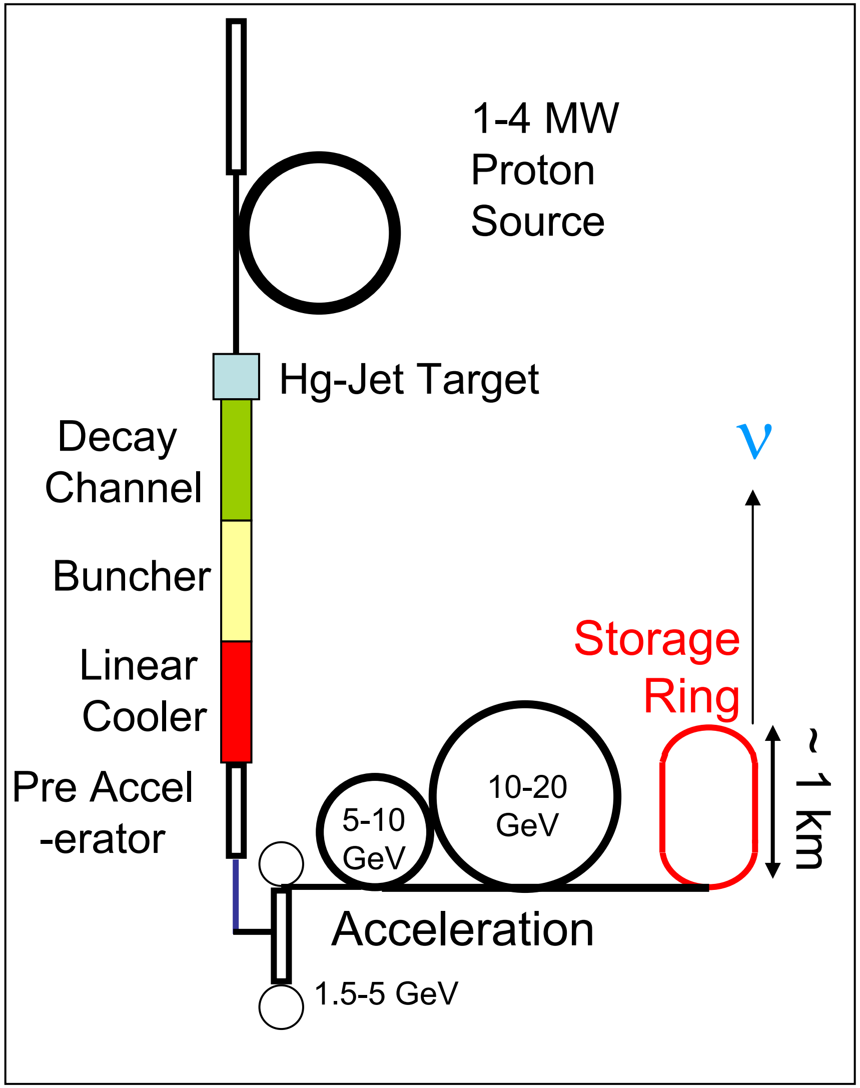


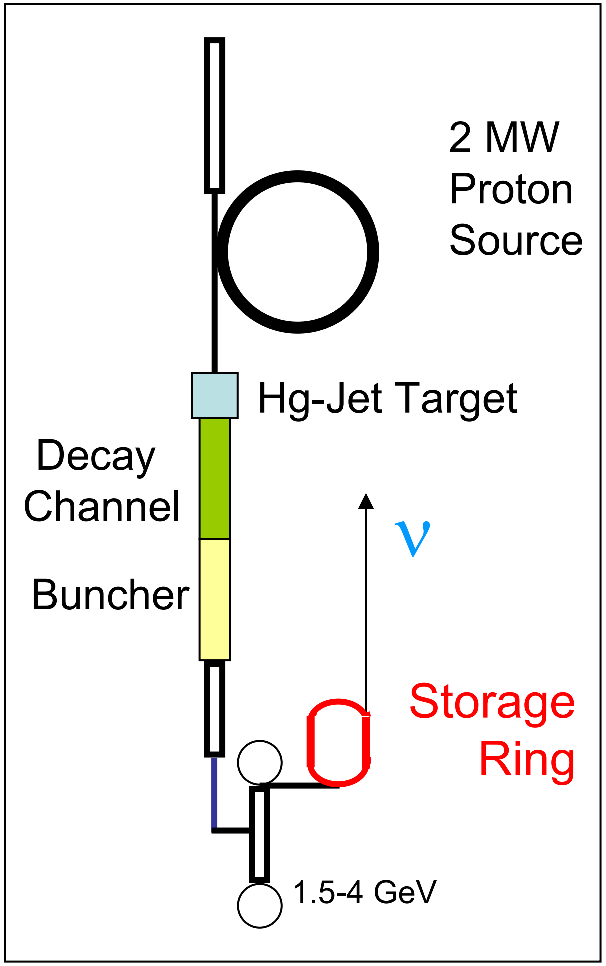
Muon charge mis-ID rate



- Good efficiency for muon momenta > 400 MeV/c !
- Suggests we can measure wrong-sign muons from neutrinos with energies down to O(1 GeV) !

IMPLICATION





PHYSICS STUDY

Steve Geer, Olga Mena, Silvia Pascoli

- We have looked at two baselines: 1280km (FNAL-Homestake) & 1480km (FNAL-Henderson). In the following, show only the L=1480km results. The L=1280km results are similar.

- Choose NF Energy ~ 4 GeV (Actually 4.12 GeV). This is motivated by the realization that for baselines O(1000km), if θ_{13} is not very small, the oscillation pattern is extremely rich below ~4 GeV.

- Will divide the simulated data into 3 energy bins, and fit the wrong-sign muon rates for each bin with positive- & negative-muons stored in the ring (6 rates to fit). Can also fit 6 right-sign muon rates.

- Energy bins: E_ν = [0.8,1.5], [1.5,3.5], [3.5,4.12] GeV.

- Bins chosen to optimize ability to resolve degenerate solutions.

PHYSICS STUDY PARAMETERS

- NF performance:

BASIC: (5 years) $\times$ (3 $\times$ 10^{20} useful decays/yr) $\times$ (2 signs) $\times$ (20Kt fid. Mass) = 3×10^{22} Kt-decays $\times$(2 signs)

BETTER: (10 years) $\times$ (5 $\times$ 10^{20} useful decays/yr) $\times$ (2 signs) $\times$ (20Kt fid. Mass) = 1×10^{23} Kt-decays $\times$(2 signs)

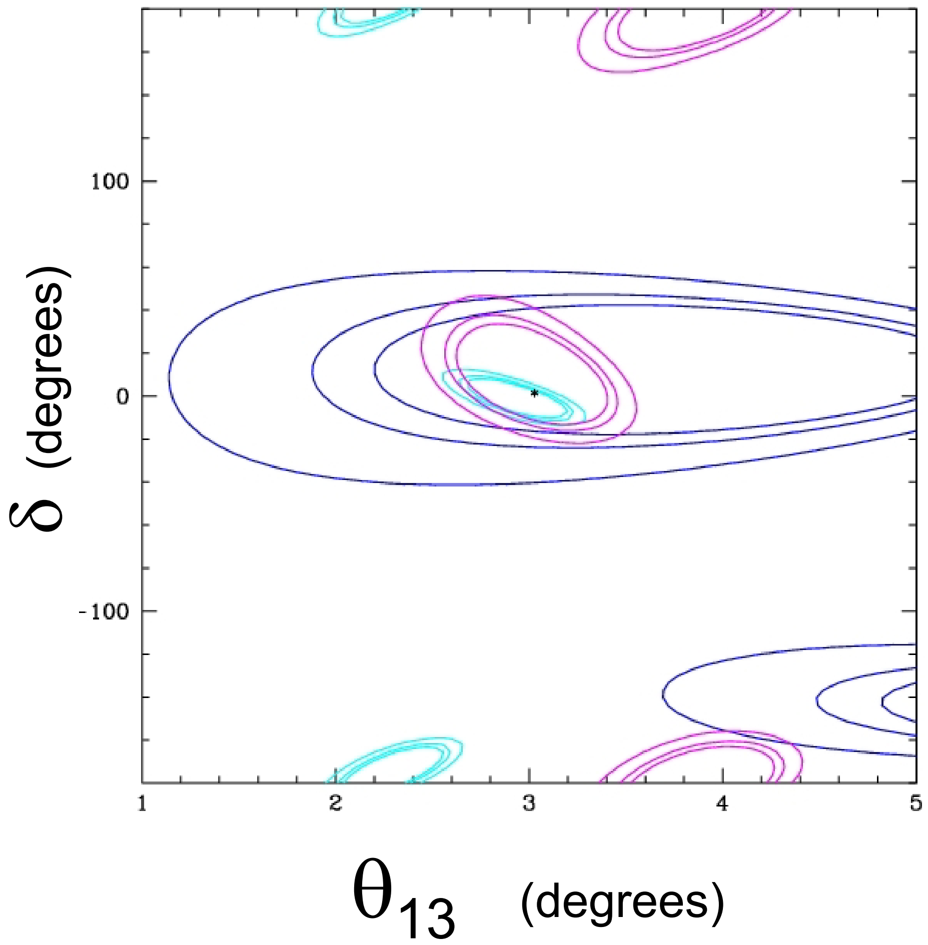
- Detector efficiency ε =0 for E_ν < 0.8 GeV; ε =1 for E_ν > 0.8 GeV

- Do not explicitly implement energy resolutions or cross-section uncertainties but include a 2% systematic uncertainty in the covariance matrix.

RESOLVING DEGENERACIES - 1

Solutions corresponding to correct sign Δm^2

90%, 95%, 99% CL Contours



<u>Illustration of how it works:</u>

- L=1480 Km
- Simulate θ_{13}=3°, δ=0, & fit $\nu_e \rightarrow \nu_\mu$ & $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ rates
- Fits for 3 neutrino energy bins:

  Dark: 0.8 – 1.5 GeV

  Cyan: 1.5 – 3.5 GeV

  Magenta: >3.5 GeV

- Each fit yields one correct & one false ("intrinsic degeneracy") solution … but the false solutions for the 3 bins do not overlap → unique solution !

RESOLVING DEGENERACIES - 2

Solutions corresponding to incorrect sign Δm^2

90%, 95%, 99% CL Contours

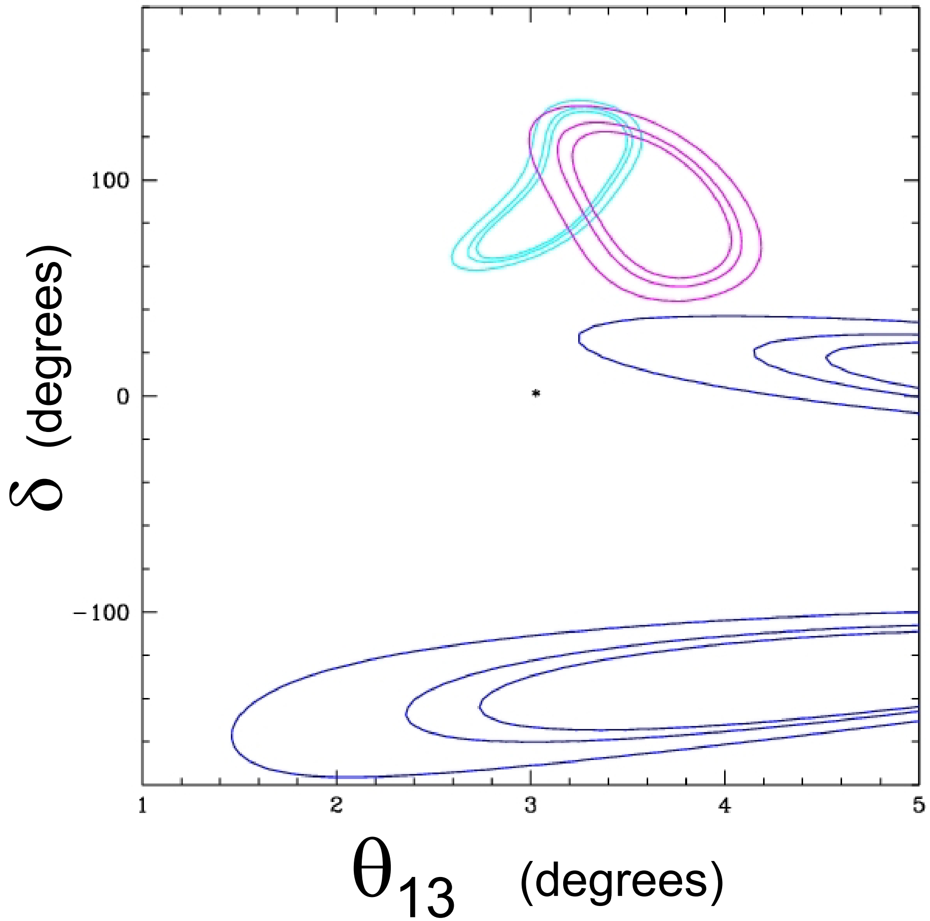


Illustration of how it works:

- Repeat, analysis, picking the wrong sign for Δm^2.
- The solutions for the 3 bins are no longer consistent

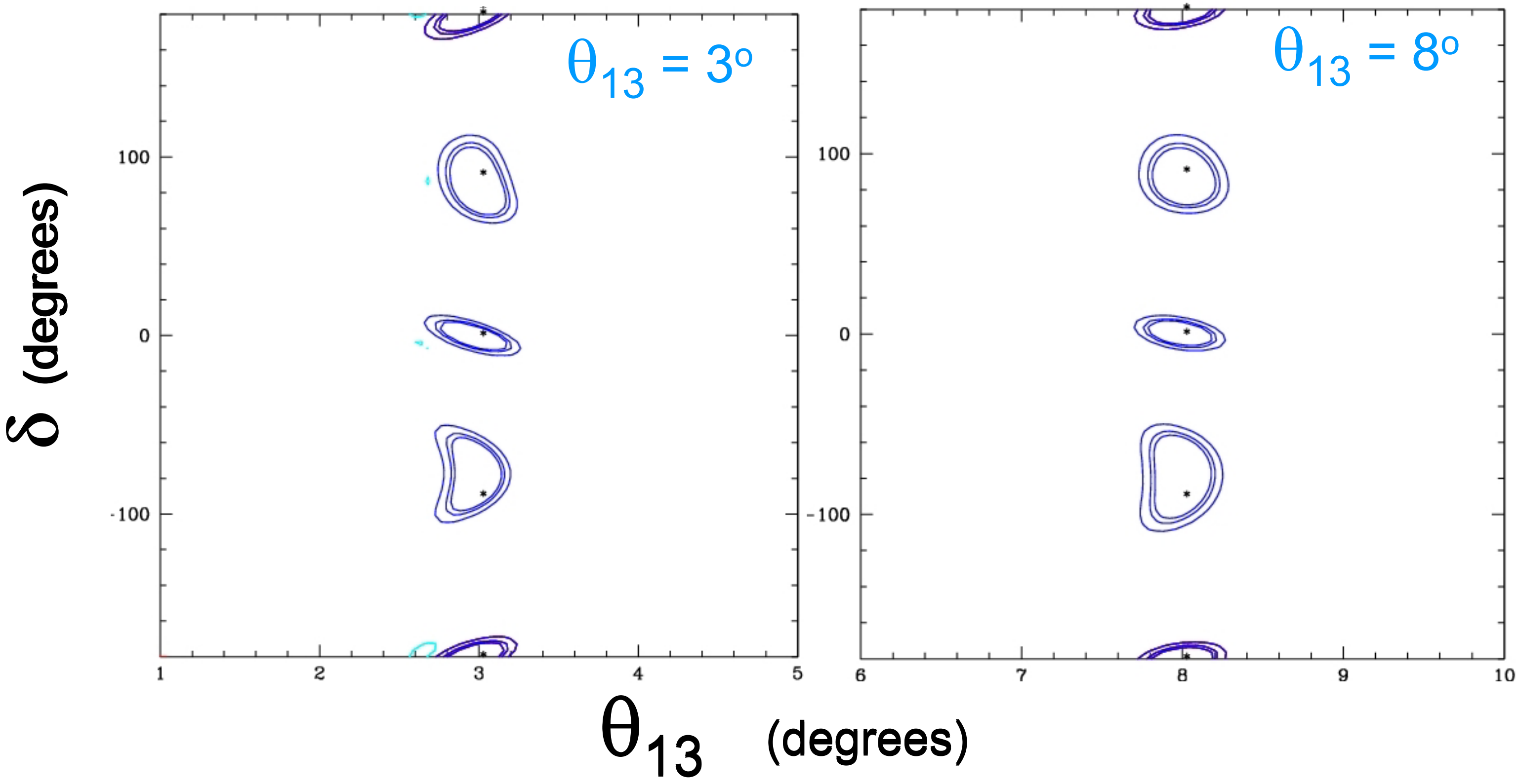
→ Can determine mass hierarchy.

- There is a 3rd degeneracy, arising from the same predicted rates for θ_{23} & $\pi/2$- θ_{23} … can show similar plots to illustrate how this degeneracy gets resolved.

RESULTS: $\nu_e \rightarrow \nu_\mu$ (3×10^{22} Kt-decays)

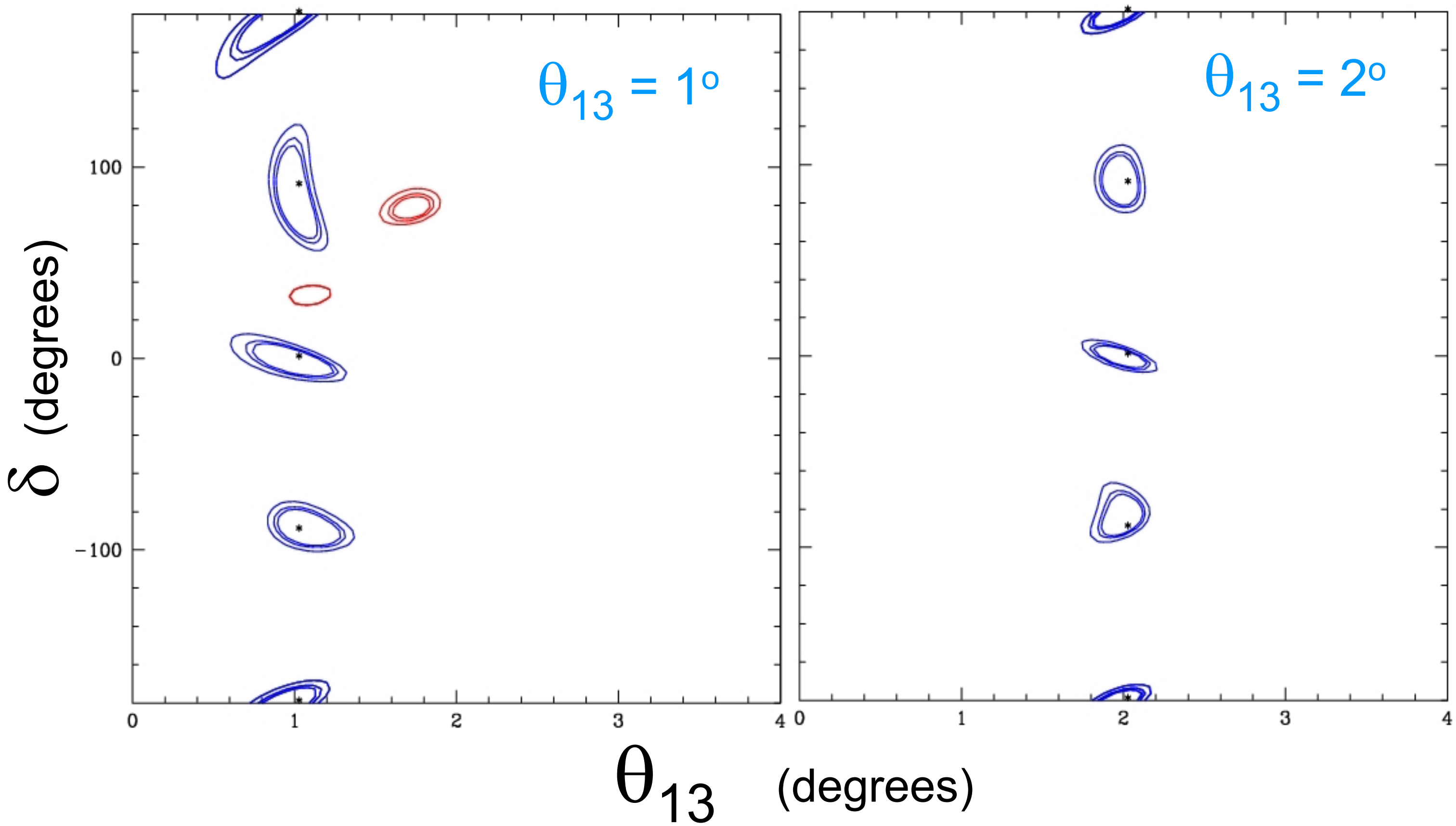
- Simulate 8 cases: $\theta_{13} = (3^o \;\&\; 8^o)$ & $\delta = (0, \pi/2, -\pi/2, \pi)$
  with $\sin^2\theta_{23} = 0.40$, $\Delta m^2_{13} = 2.5\times10^{-3}$ eV^2, and L=1480 Km

Fit $\nu_e \rightarrow \nu_\mu$ & $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ rates (90%, 95%, 99% CL Contours)



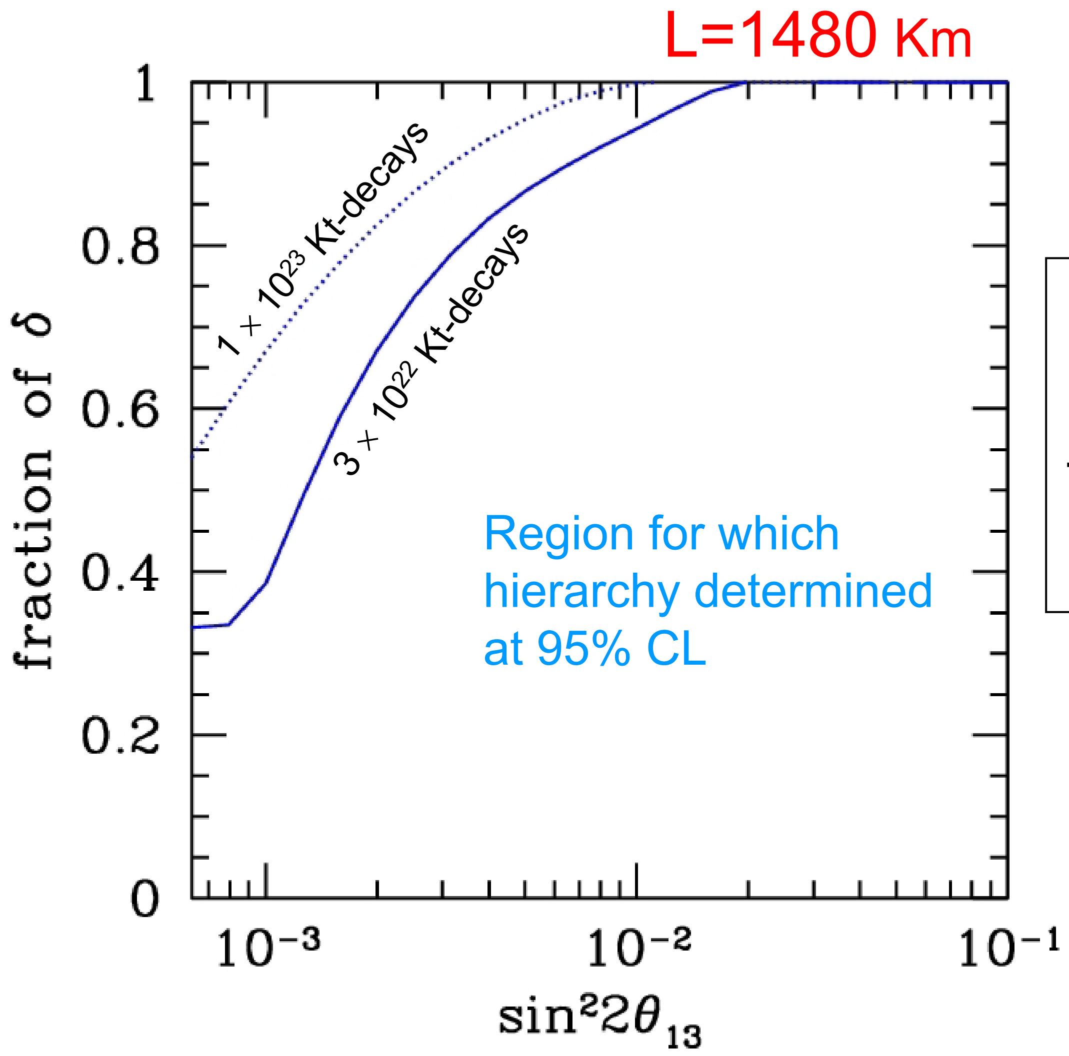
RESULTS: $\nu_e \rightarrow \nu_\mu$ (1×10^{23} Kt-decays)

Higher statistics: Repeat analysis for $\theta_{13} = (1^o \,\&\, 2^o)$



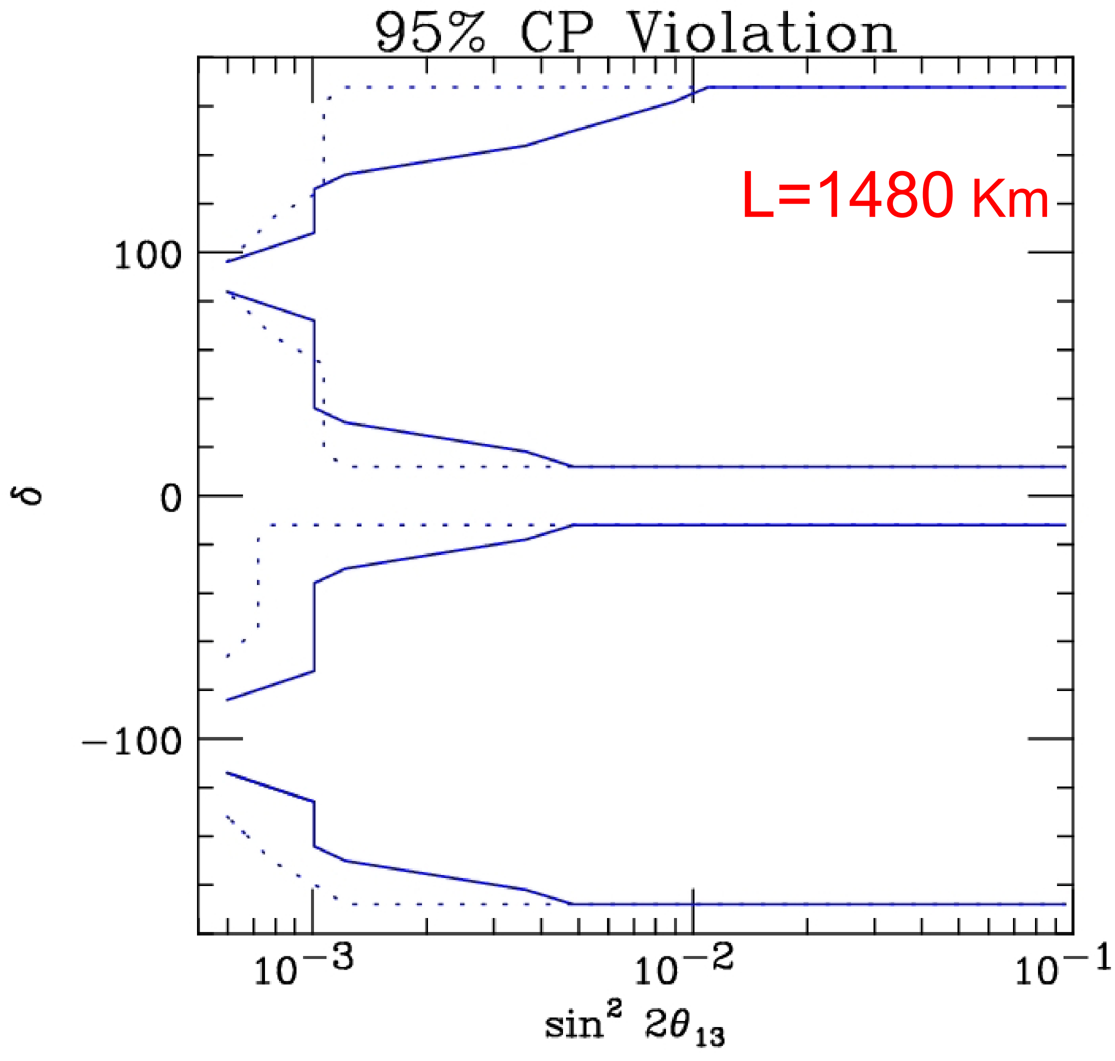
NOTE: For $\sin^2\theta_{23} = 0.40$ ($\theta_{23} = 40^o$), the θ_{23} octant is determined (99%CL), for all δ, if $\theta_{13} > 0.6^o$ ($\sin^2 2\theta_{13} > 4\times10^{-4}$) !

MASS HIERARCHY



Mass hierarchy can be determined for all δ, if $\theta_{13} > 3^o$ ($\sin^2 2\theta_{13} > 0.01$)

CP VIOLATION



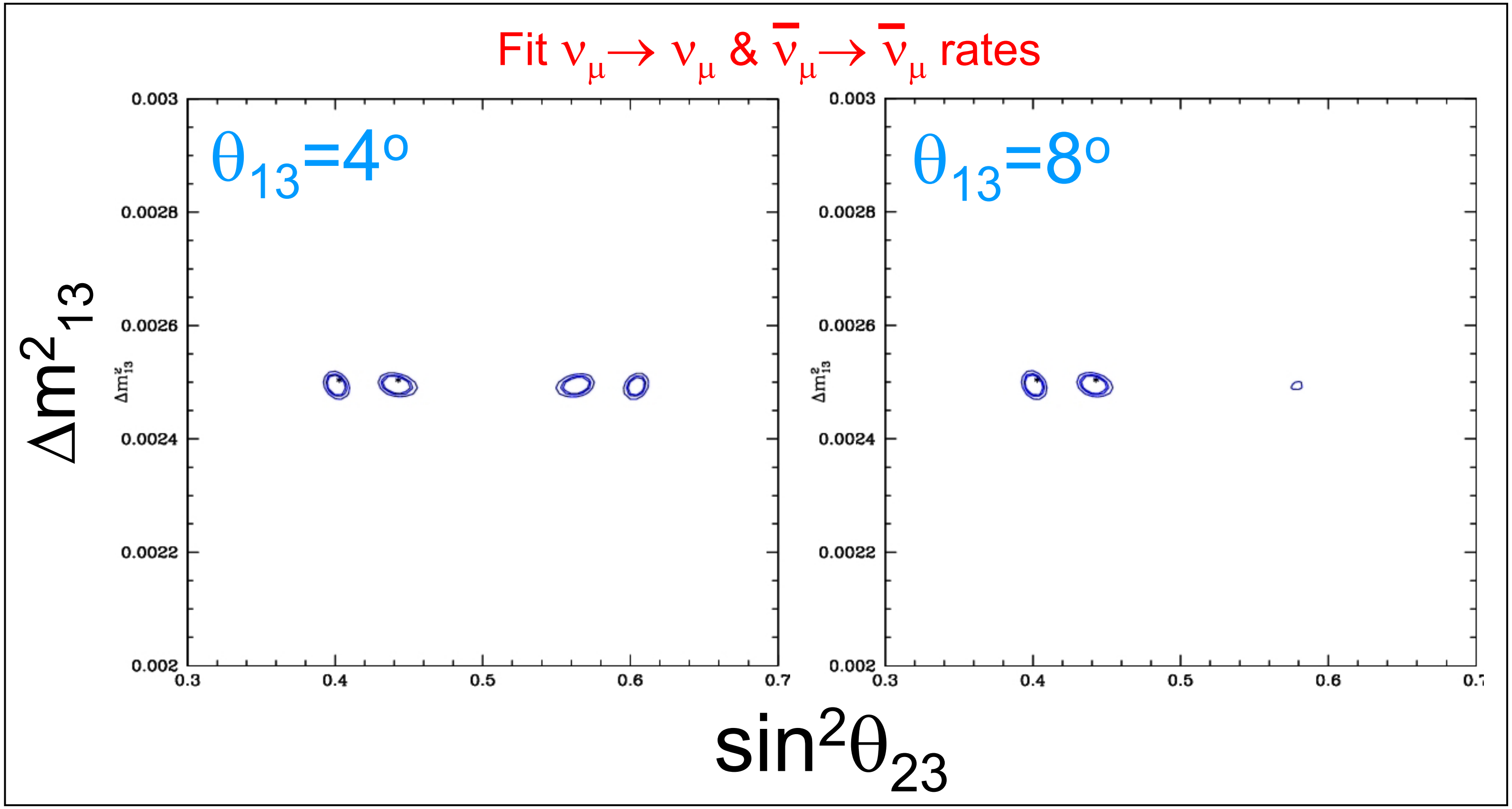
Solid: 3×10^{22} Kt-decays
Dotted: 1×10^{23} Kt-decays

CP Violation phase δ can be determined with 95% CL precision of 20^o, if $\sin^2 2\theta_{13} > 0.001$ ($\theta_{13} > 0.9^o$)

RESULTS: $\nu_\mu \rightarrow \nu_\mu$

- Simulate 4 cases: θ_{13} = (4° & 8°) & $\sin^2\theta_{23}$ = (0.40 & 0.44)

with $\Delta m^2_{13}=2.5\times10^{-3}$ eV^2, $\delta=0$, & L=1480 Km, 3×10^{22} KT-decays



- For all θ_{13}, maximal mixing can be excluded (99%CL) if $\sin^2\theta_{23} < 0.48$
- For θ_1 =8° the θ_{23} degeneracy resolved (99%CL) if $\sin^2\theta_{23} < 0.44$ using only disappearance channel

PHYSICS SUMMARY

Fitting $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ rates for 3 energy bins:

- CP Violation phase δ can be determined with 95% CL precision of 20^o, if $\sin^2 2\theta_{13} > 0.001$ ($\theta_{13} > 0.9^o$)

- Mass hierarchy determined for all δ, if $\sin^2 2\theta_{13} > 0.01$ ($\theta_{13} > 3^o$)

Fitting $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ rates for 3 energy bins:

- For all θ_{13} maximal mixing can be excluded (99%CL) if $\sin^2\theta_{23} < 0.48$ ($\theta_{23} < 43.8^o$)

- For large θ_{13} (=8^o) the θ_{23} degeneracy can be resolved (99%CL) if $\sin^2\theta_{23} < 0.44$ ($\theta_{23} < 41.5^o$)

FOOD FOR THOUGHT

•How much cheaper might a 4 GeV NF be ?

Bobs first guesstimate … dropping cooling and accelerating only to 4 GeV, the NF cost would be ~59% of the 20 GeV NF with cooling.

•How might we upgrade a basic low energy NF to later include cooling?

PROPOSAL:
In the upgrade build a new tunnel for the acceleration, and put the new cooling channel into the old accelerator tunnel.

•What about the ring for a 4 GeV NF ?

Scott says we want cooling anyway, because otherwise the low energy ring will be hard to design.

So if cooling, how much ?

SUMMARY & WISH-LIST

- This initial study suggests that if a 20KT magnetized detector that can measure wrong-sign muons down to a few hundred MeV/c is practical, a 4 GeV NF has a great physics capability for all $\sin^2 2\theta_{13} > 0.001$.

- This is only a first study. To better establish the physics reach of a 4 GeV NF we need to know more about the detector performance (resolutions, systematics …) and feasibility.

- On the NF side, the wish-list includes:

  Cost reduction – first estimate (Bobs guesstimate: 59% of 20GeV NF)
  4 GeV ring design … needs cooling ?
  Concept for upgrading first ring (add cooling & acceleration)

- Assuming MERIT succeeds, a 2 MW proton driver is built somewhere, & we succeed in understanding RF operation in magnetic fields, what remaining basic R&D issues are there …. Acceleration ?