High Energy Accelerator-Based Neutrinos

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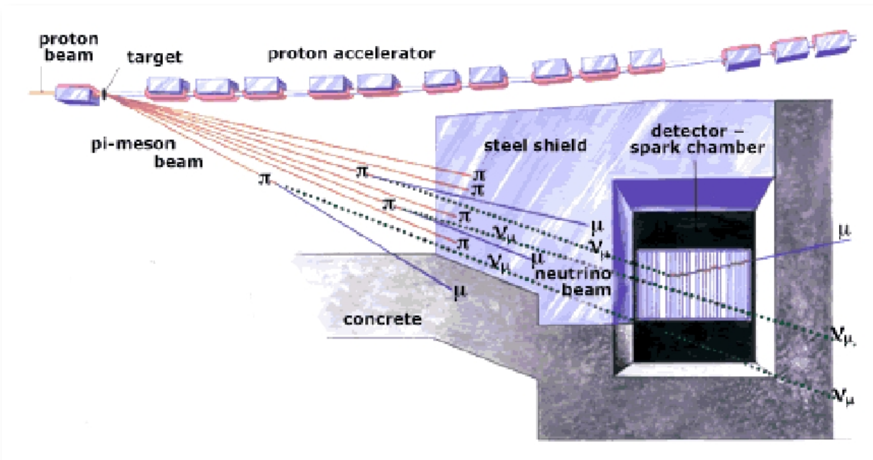
- will highlight the options for measuring neutrino oscillations using accelerator-based neutrinos
- survey the detectors currently being built and proposed for next decade's experiments

Accelerator Neutrinos

- we continue to produce neutrinos in essentially the same way we did in the first accelerator-based neutrino experiment

(Lederman, Schwartz, Steinberger, BNL 1962)

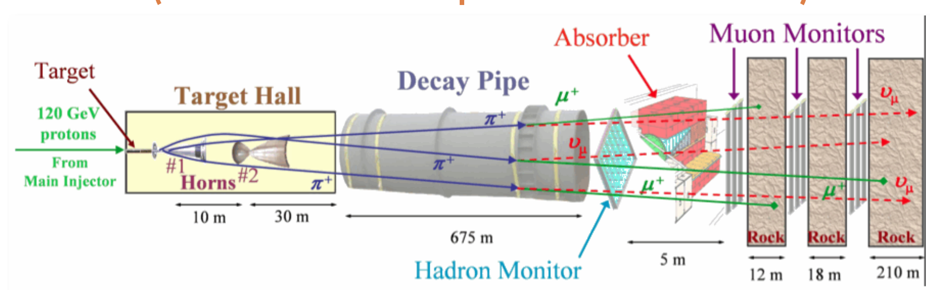


$\pi, K \xrightarrow{\sim 99\%} \nu_\mu$; $\nu_\mu \rightarrow \nu_\mu \xrightarrow{CC} \mu^-$; $\nu_\mu \rightarrow \nu_e \xrightarrow{CC} e^-$

$\pi, K \xrightarrow{\lesssim 1\%} \nu_e$

- primarily one ν flavor: ν_μ
- nuisance background of ν_e

(modern example: NuMI beam)



- now, horn-focused high powered ν beams (0.8 kW → 100's kW)

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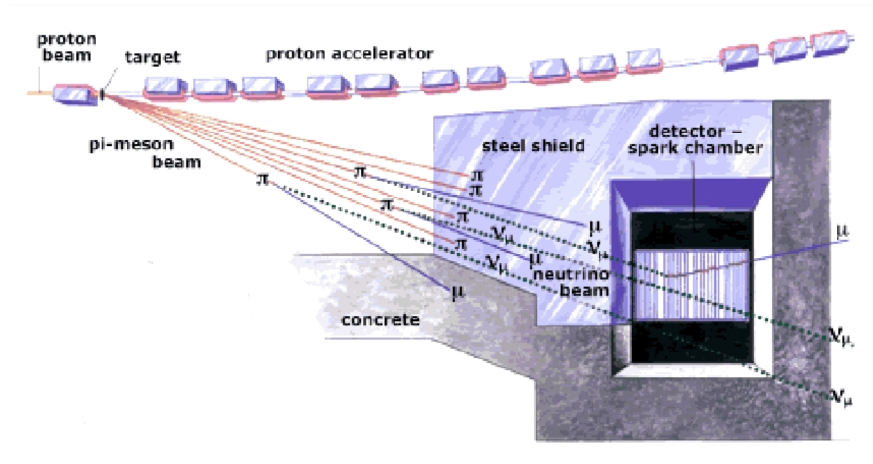
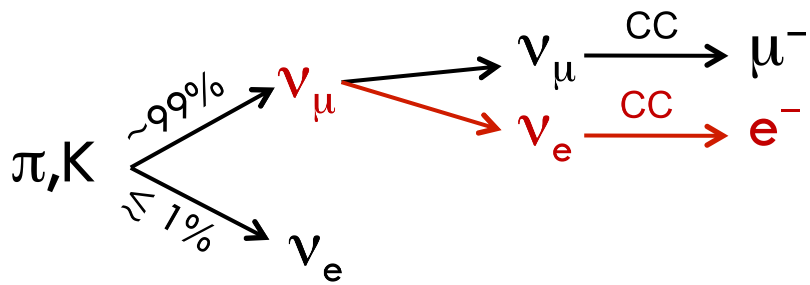
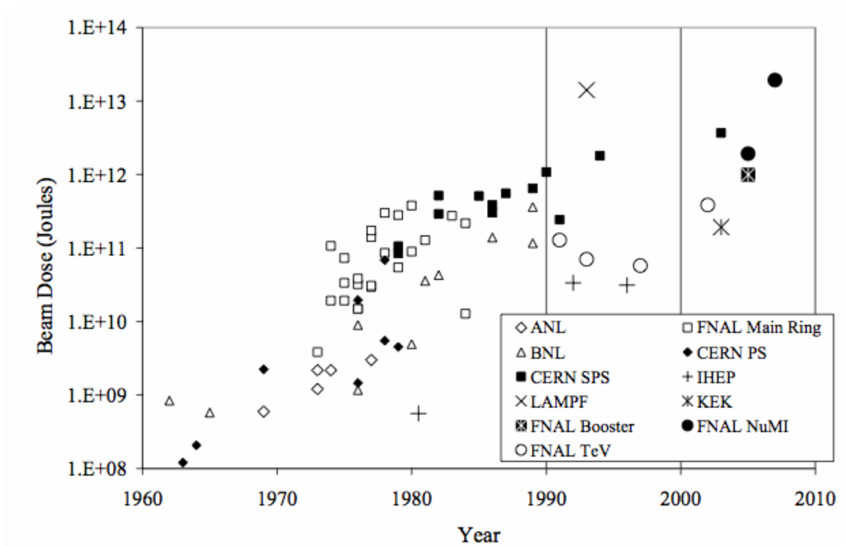




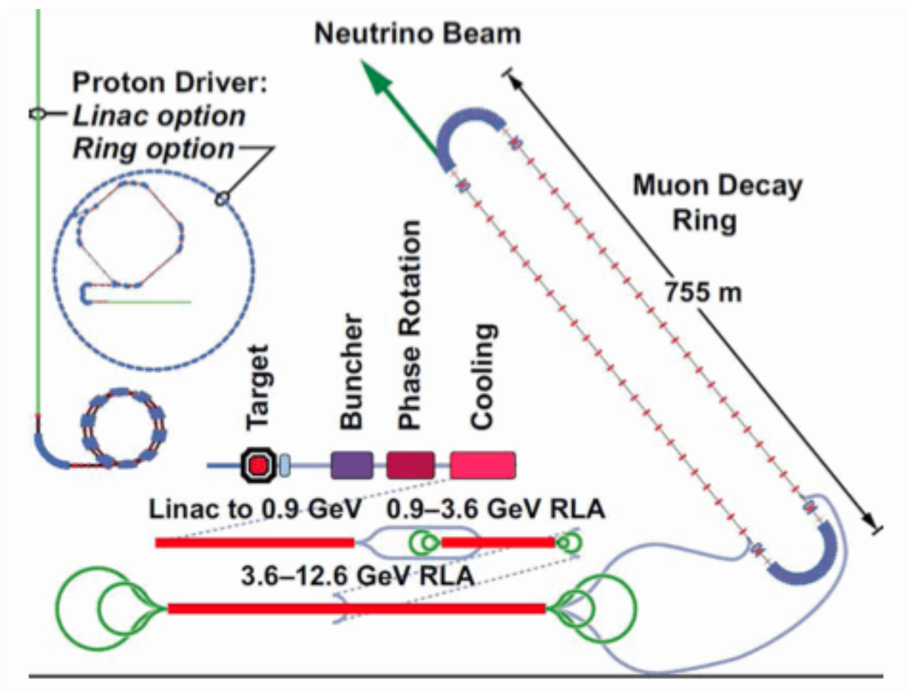
- not only are these superbeams, but are also more well-known



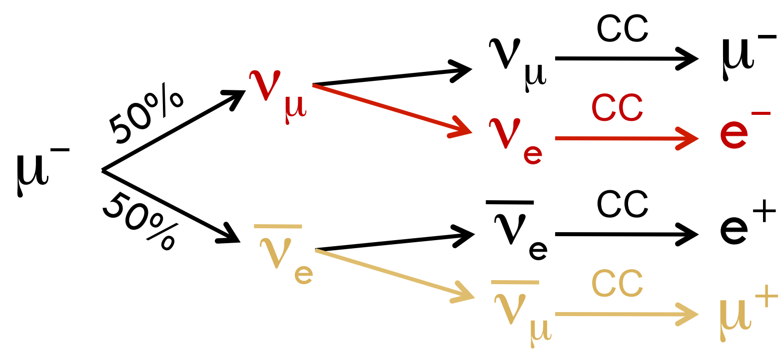
(S. Kopp)

Accelerator Neutrinos

- we have also been thinking about using muon storage rings as a source of neutrinos



(neutrino factory)



- 50/50 mix of both ν flavors

  $\mu^- \rightarrow \nu_\mu$ and $\bar{\nu}_e$

  $\mu^+ \rightarrow \bar{\nu}_\mu$ and ν_e

- uniquely well-known flux (flavor content and E spectra)

LBL Accelerator-Based ν Experiments

- existing experiments:
  - **- MINOS/MINOS+**
  - **- T2K**
  - **- NOvA**

- precision measurements of θ_{13}, θ_{23}
- MH for certain values of δ_{CP}
- maybe a hint at CP violation
- tests of 3ν mixing

- proposed experiments:
  - **- LBNE (U.S.)**
  - **- LBNO (Europe)**
  - **- Hyper-K (Japan)**
  - **- neutrino factory**

- MH for all values of δ_{CP}
- CP violation discovery
- measurement of δ_{CP}
- precision tests of 3ν mixing

LBL Accelerator-Based ν Experiments

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  - **T2K**
  - **NOvA**

conventional
π,K based ν beams

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  - **LBNE (U.S.)**
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  - **Hyper-K (Japan)**
  - **neutrino factory**

muon storage ring

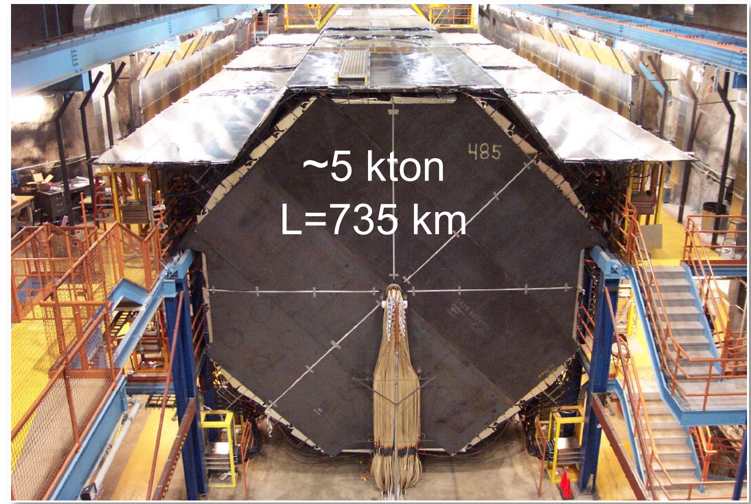
a variety of physics goals, a variety of L,E and hence a number of detector options

MINOS/MINOS+

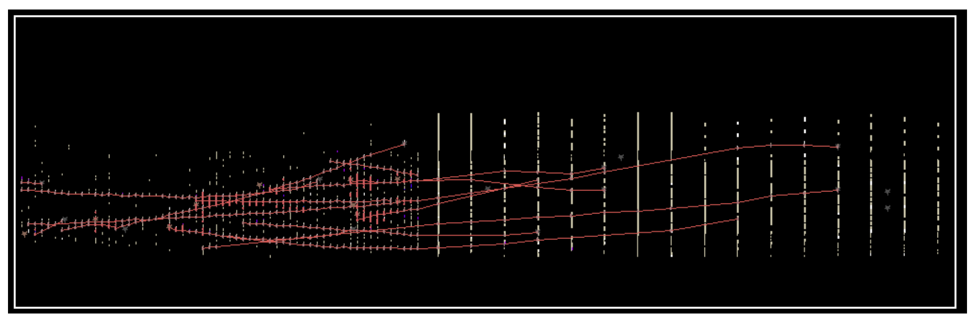
- L = 735km, NuMI LE beam, on-axis
  (MINOS+ to continue in NOvA-era ME beam)

- $\nu_\mu, \overline{\nu}_\mu$ disappearance (θ_{23}, Δm^2_{32})
  (plus θ_{13} from $\nu_e, \overline{\nu}_e$ appearance)

- magnetized steel/scintillator tracking calorimeters at near and far sites



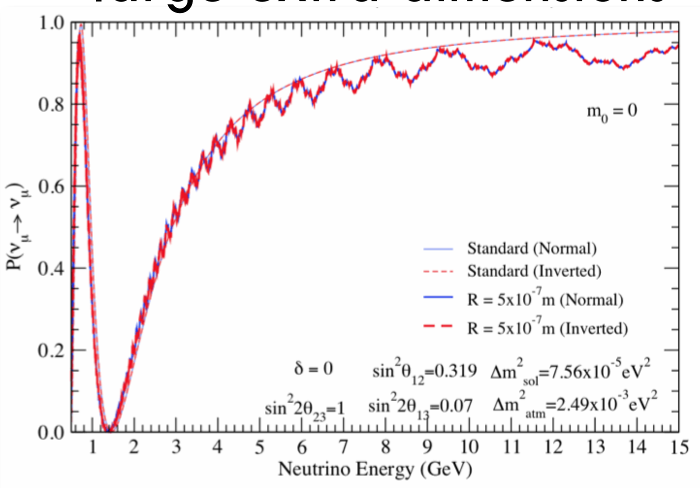
- *iron sampling calorimeters used in CDHS, CHARM, CCFR, NuTeV, etc.*
- *typically used in higher energy (> few GeV) beams*
- *excellent detectors for μ^-, μ^+ identification*
- *hadronic energy summed from active detector*



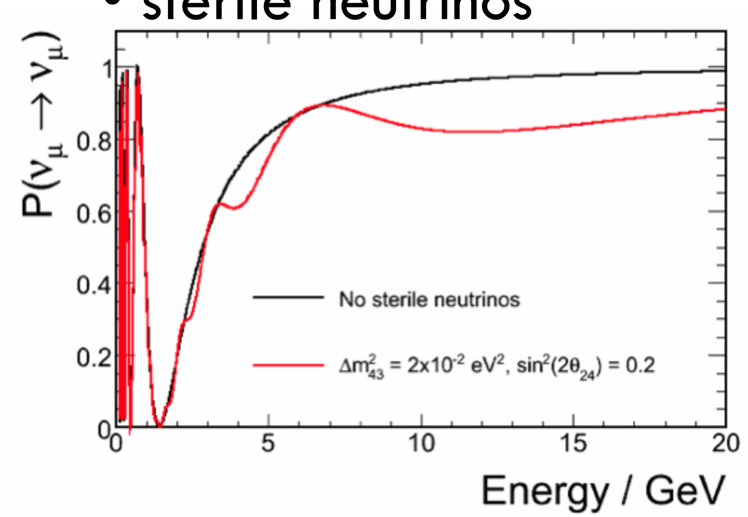
(ν_μ event in MINOS ND)

MINOS+

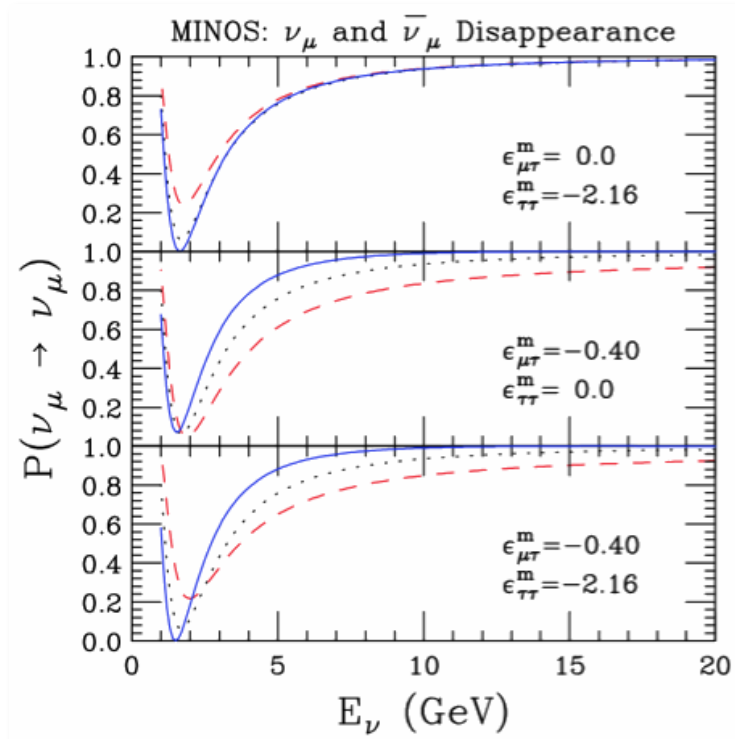
- large extra dimensions



- sterile neutrinos



- more precise measurements of atmospheric ν oscillation parameters

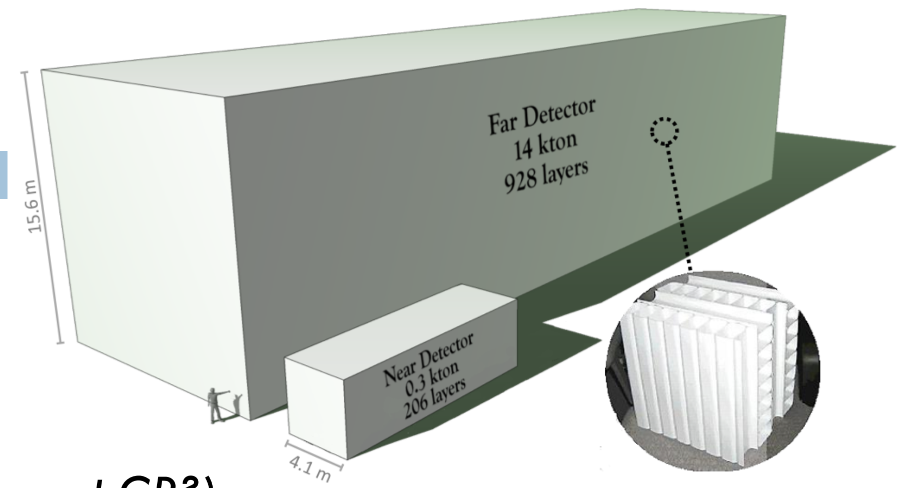


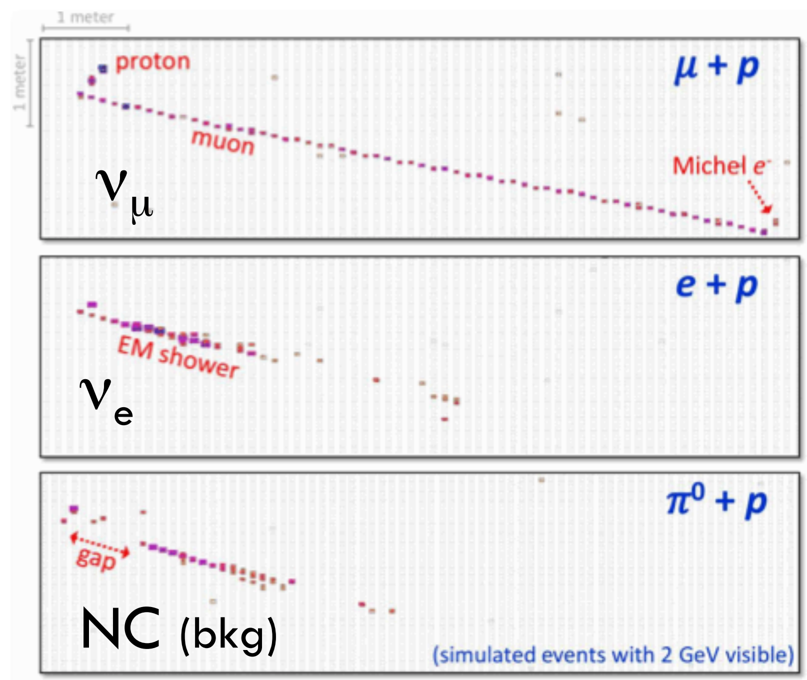
- non-standard interactions

NOvA

- L = 810km, NuMI ME beam, off-axis
- ν_e and $\bar{\nu}_e$ appearance
  (θ_{13}, θ_{23} octant, MH depending on δ_{CP}, glimpse at CP?)
- ν_μ and $\bar{\nu}_\mu$ disappearance
  (Δm^2_{32}, θ_{23} maximal?)
- totally active liquid scintillator tracking calorimeters at near and far sites

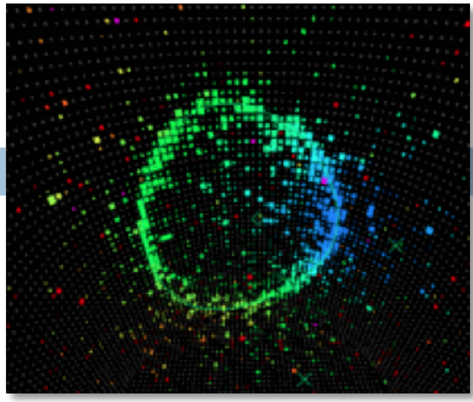
  - *improved resolution for electrons*
  - *scintillation light is isotropic (no directionality) and there is no threshold (ala WC)*
  - *challenge: achieve large detector mass while maintaining high granularity*

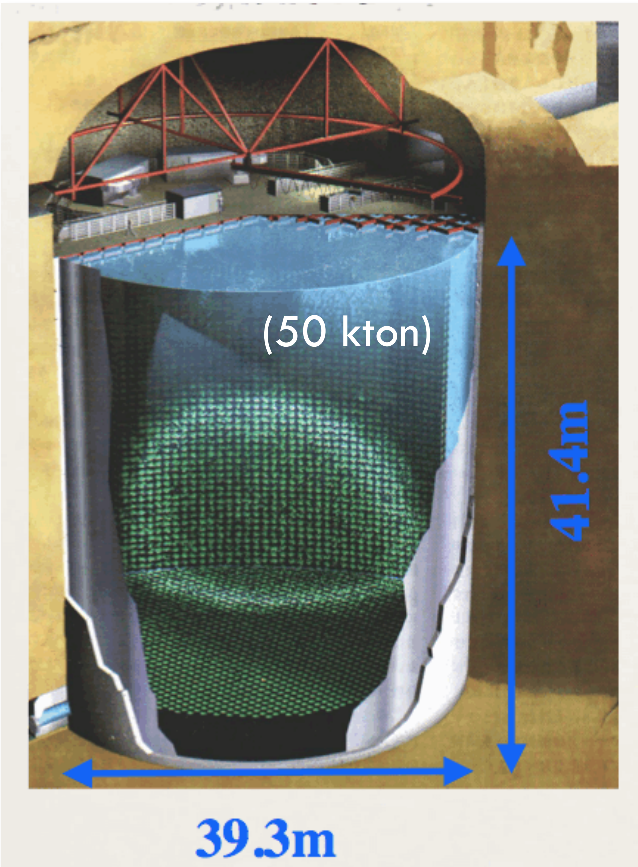




T2K

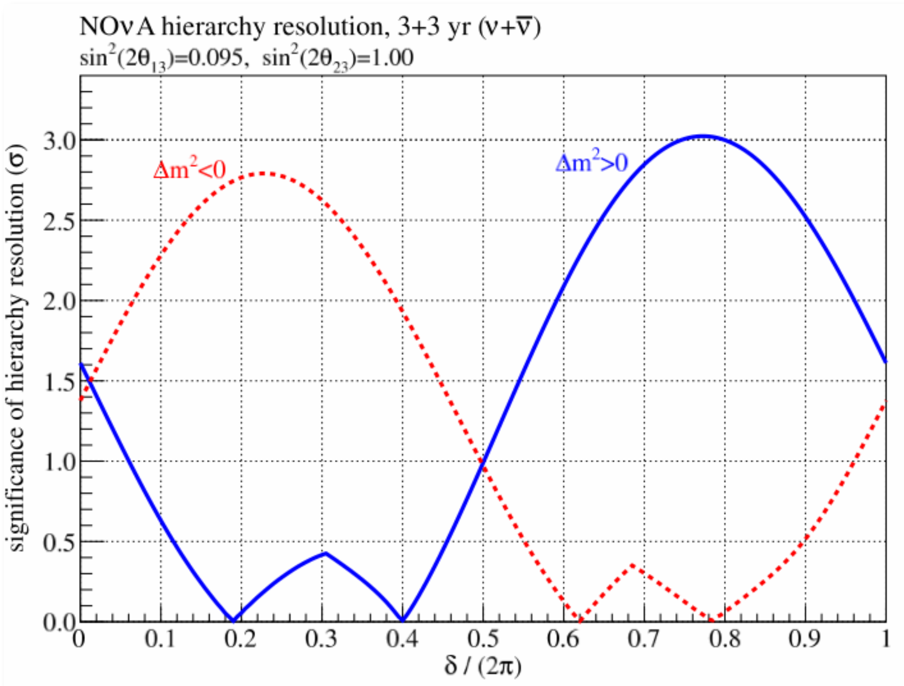
- L = 295km, JPARC beam, off-axis
- ν_e appearance
  (θ_{13}, θ_{23} octant, help with MH, glimpse at CP?)
- ν_μ disappearance
  (Δm^2_{32}, θ_{23} maximal?)
- water Cerenkov far detector paired with a suite of fine-grained near detectors
  - *a lot of experience with these detectors*
  - *excellent performance for sub-GeV neutrinos*
  - *can fill large volumes cheaply (water), large surface area of course needs to be instrumented*
  - *challenge to fully reconstruct higher energy, high multiplicity ν interactions*
    (E_ν recon typically based on QE; Cerenkov thresholds)



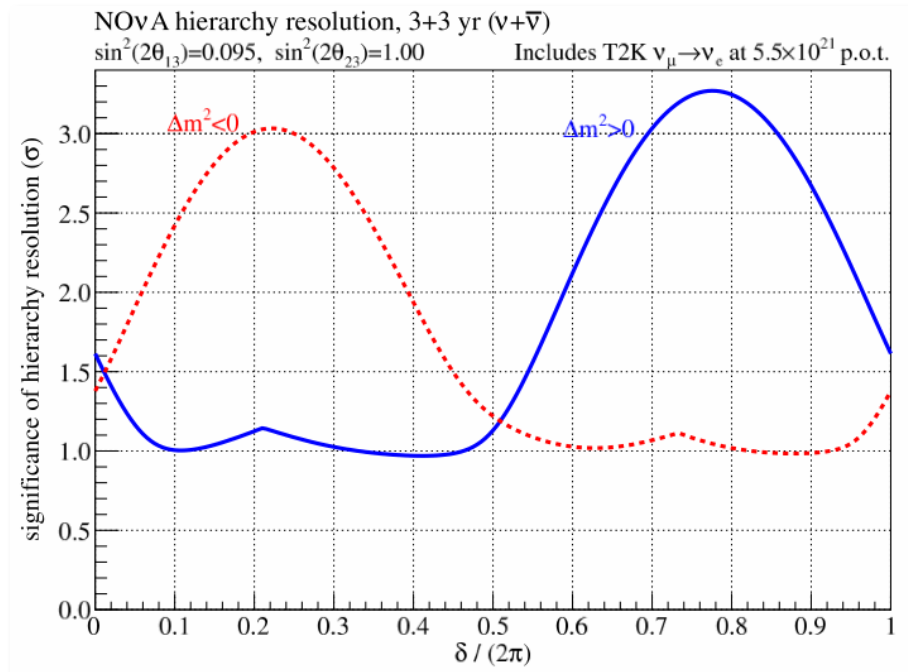


Mass Hierarchy & CP Violation

NOvA alone:



NOvA+T2K combination:



- no CP violation detection possible at $\geq 3\sigma$ with NOvA+T2K; but 90% CL possible for certain values of δ_{CP}

Next Generation

- One of the highest priority goals of the next generation accel-based LBL ν oscillation program is to go after CP violation in the ν sector and to measure the CP phase, δ_{CP}. These experiments also aim to fully test whether our ν-mixing picture is correct. Some can also measure the neutrino mass hierarchy (depends on L).

- proposed experiments:

  - **Hyper-K (Japan)**
  - **LBNE (U.S.)**
  - **LBNO (Europe)**

  conventional π,K based ν beams

  - **neutrino factory**

  muon storage ring

Key Issues for CP Measurements

- two strategies for $\not{CP}$ search using $\nu_\mu \rightarrow \nu_e$ oscillations
  - (1) measure spectrum of oscillated neutrinos
  - (2) observe differences in ν_e vs. $\overline{\nu}_e$ appearance

- CP asymmetry is small (θ_{13} is large)
- precision measurement of ν and $\overline{\nu}$ oscillation spectra requires:

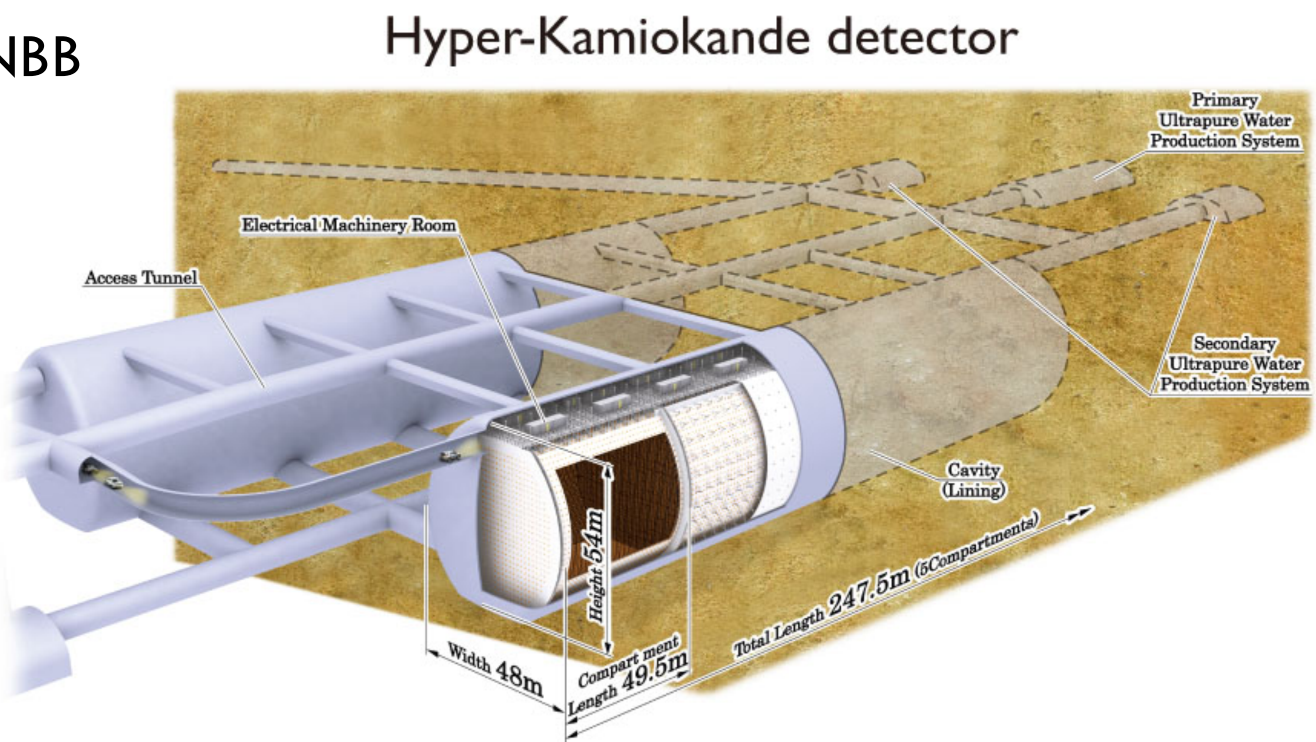
  - *high purity ν and $\overline{\nu}$ beams*
  - *high statistics*
    - *massive detectors*
    - *high power (eventually multi-MW) neutrino sources*
  - *detectors with high signal efficiency with low background contaminations and excellent neutrino energy resolution*
  - *careful control of systematics (especially ν vs. $\overline{\nu}$)*
  - *θ_{13} is a prerequisite* ✔

Hyper-K

- L=295km, off-axis, NBB
  (sub-GeV neutrinos)

- water Cerenkov
  detector
  (20x Super-K)

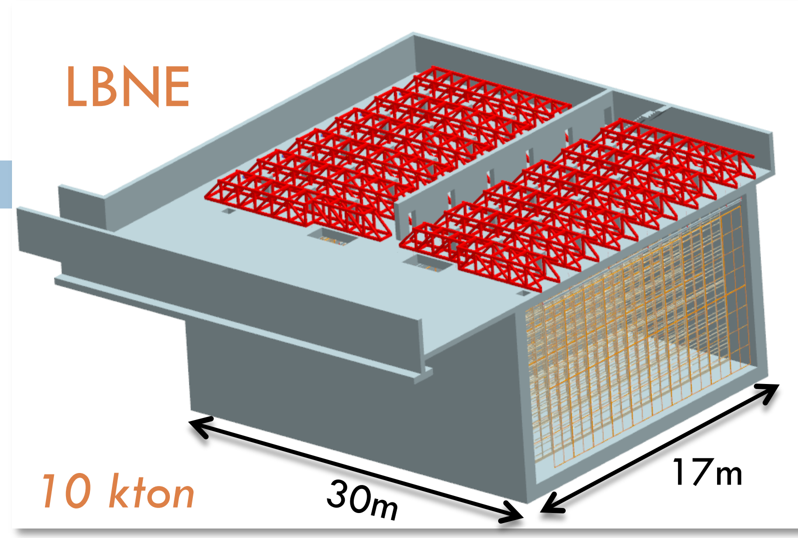
- excellent for
  LE off-axis beam
  (QE regime)
  and we have over 2 decades
  of experience operating this type of detector

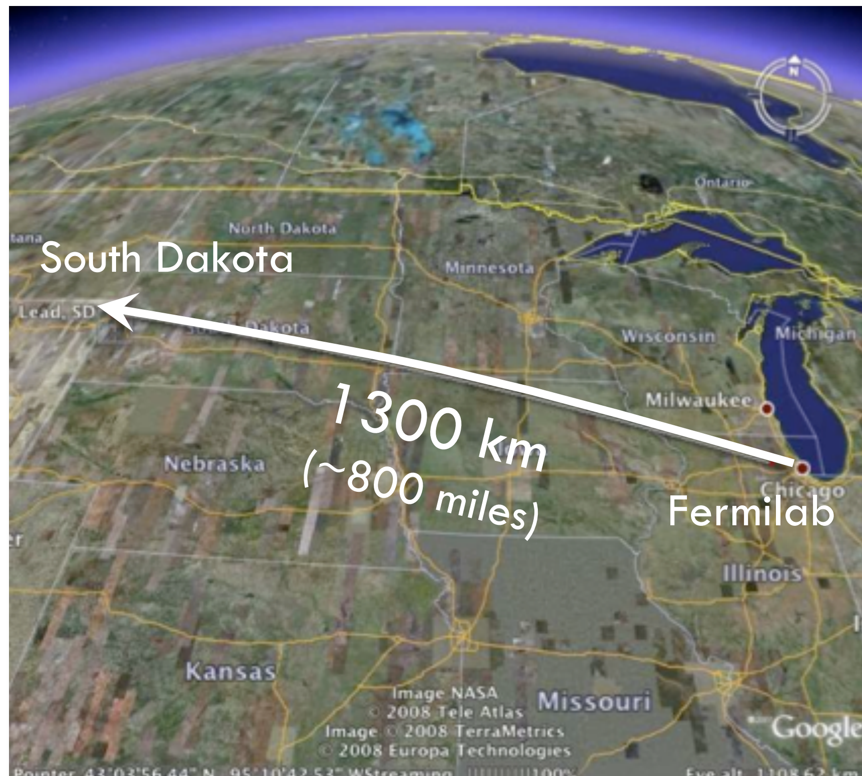


- $\not{C}\not{P}$ sensitivity, MH has to come from other sources (atm ν, other exps)

LBNE

- L=1300km, on-axis, WBB
  (see both 1st osc max=3 GeV & 2nd=0.8 GeV!)
- liquid argon TPC
  (10 kton in 1st phase)
  - *reconfiguration process in March 2012 also considered placing LAr TPCs at Soudan (735km) and Ash River (810km)*
- WBB and baseline optimized for simultaneous MH determination and $\not{CP}$ discovery; LAr TPC technology is ideal (high ε over broad E)





LBNE

- liquid argon TPC
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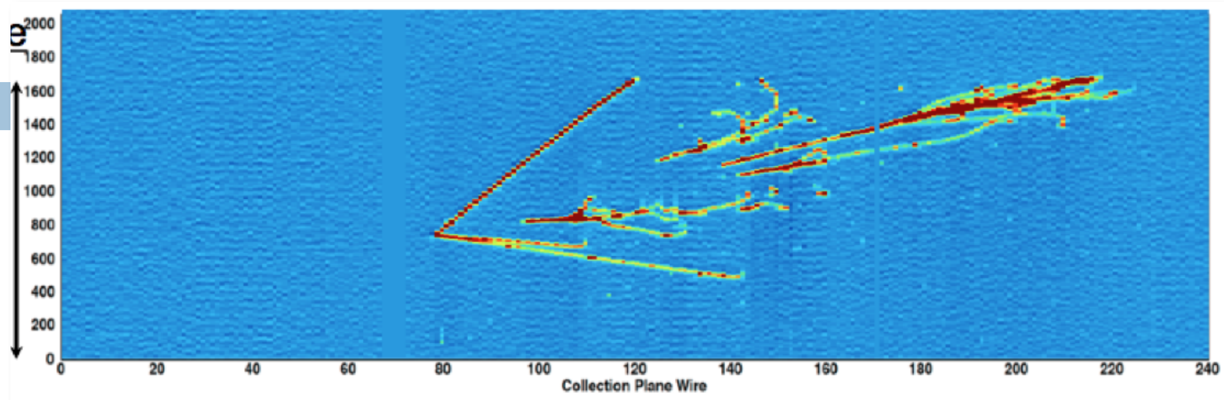
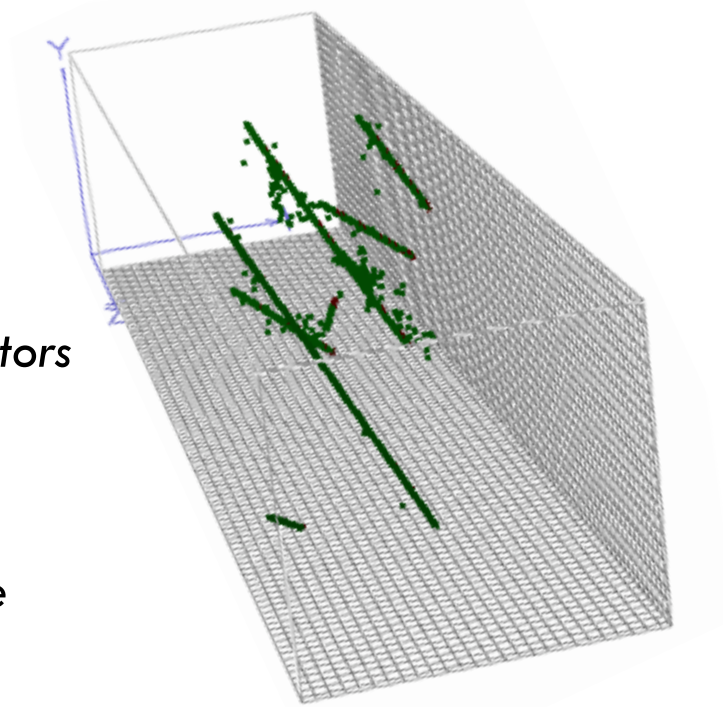


- *"electronic bubble chamber"*
- *can track every charged particle down to very low energies (E_ν based on total E)*
- *excellent PID/reconstruction capabilities and high detection ε's possible → "smaller" detectors*
- *issue: need to gain some more experience analyzing ν events in such detectors to fully demonstrate/quantify their performance (ArgoNeuT, ICARUS, LArIAT, MicroBooNE)*
- *need to scale up to 10+ kton size*

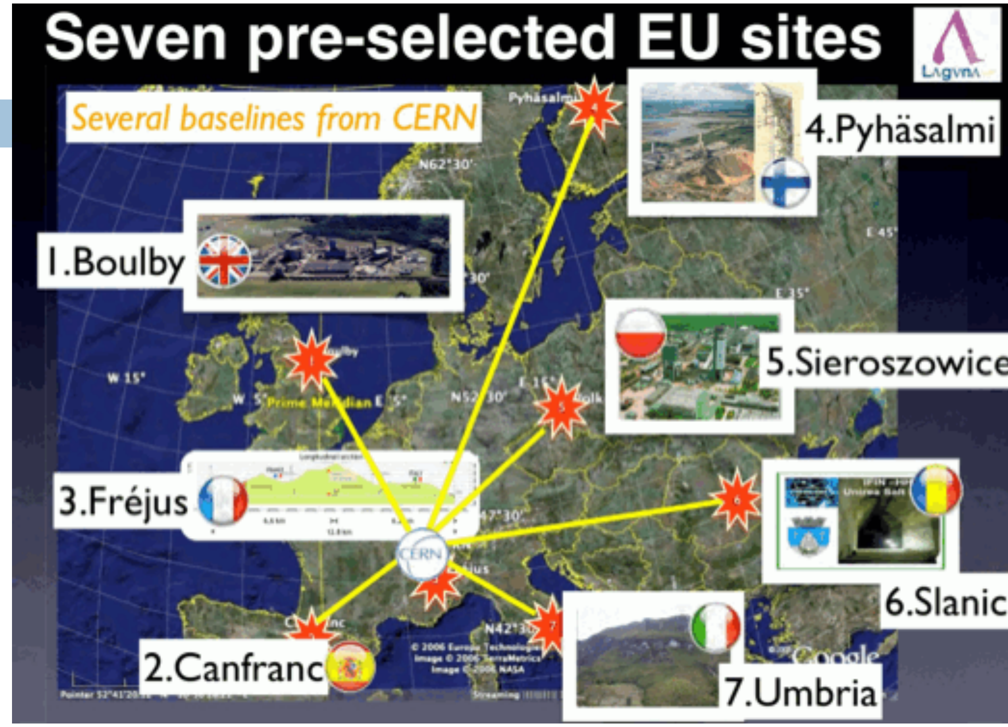


(3D reconstruction)

LBNO

- studied 7 possible sites (130 km → 2300 km) &

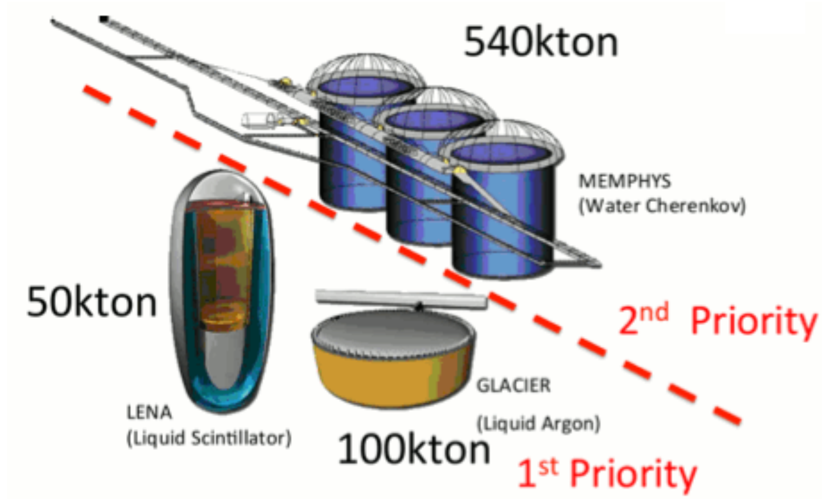
  3 detector technologies (WC, LAr TPC, LS)



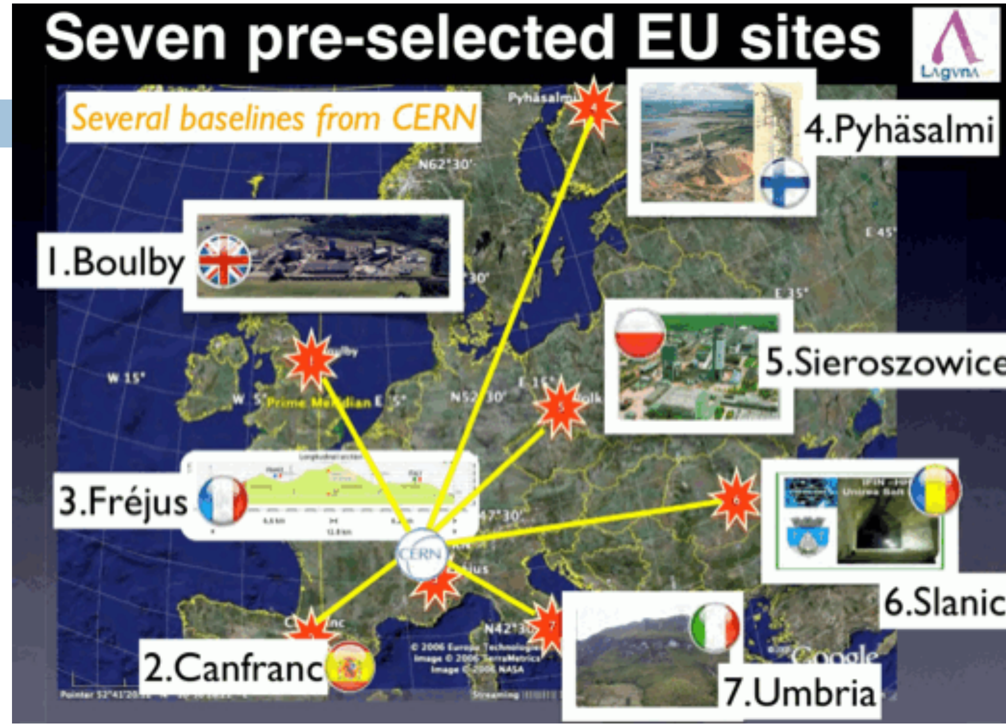
- two preferred options:

  (1) LAr TPC at 2300km Finland, ν's > 1 GeV

  (2) WC at 130km Frejus, ν's < 1 GeV



LBNO



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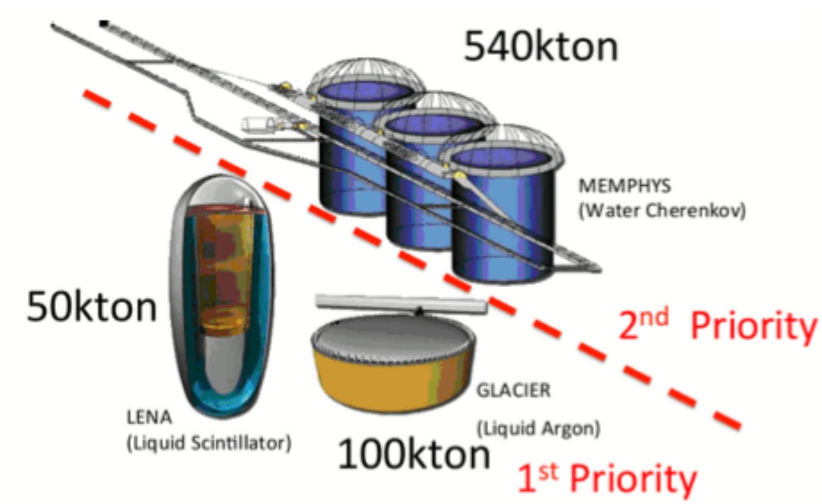
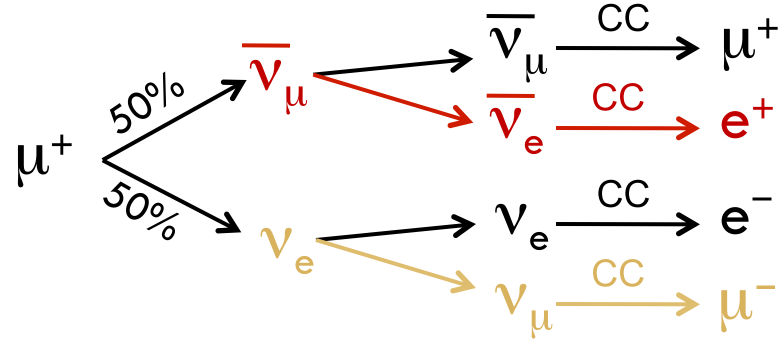


Neutrino Factory

TABLE I: *Oscillation channels contributing to flux from the decay of μ^+.*

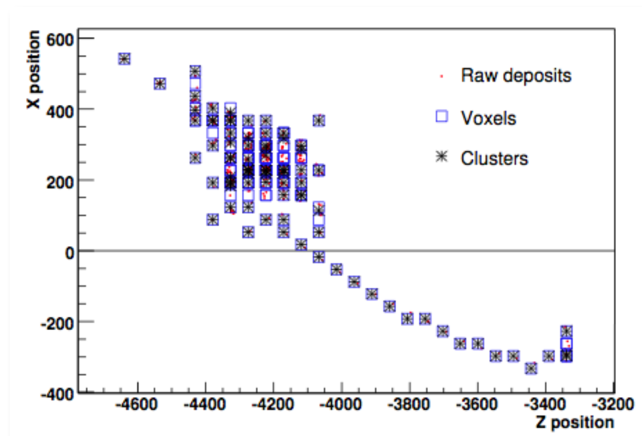
ν_e origin	$\overline{\nu}_\mu$ origin
$\nu_e \to \nu_e$ (ν_e disappearance channel)	$\overline{\nu}_\mu \to \overline{\nu}_\mu$ ($\overline{\nu}_\mu$ disappearance channel)
$\nu_e \to \nu_\mu$ (Golden channel)	$\overline{\nu}_\mu \to \overline{\nu}_\tau$ (Dominant oscillation)
$\nu_e \to \nu_\tau$ (Silver channel)	$\overline{\nu}_\mu \to \overline{\nu}_e$ (Platinum channel)



- 3 far detector candidates:
  - *magnetized iron neutrino detector (MIND)*
  - *LAr time projection chamber (LAr TPC)*
  - *totally active scintillator detector (TASD)*
- need magnetized detectors

although some work on what could do without it

(Huber and Schwetz, arXiv:0805.2019,
also MiniBooNE, PRD 84, 072005, 2011)



Conclusions

- exciting program of accel-based LBL ν osc exps will advance the field in the next decade *(MINOS+, NOvA, T2K)* + a clear idea of where we want to head next: $\cancel{CP}$ & tests of ν-mixing *(LBNE, LBNO, HK, ν factory)*
- to carry out our future goals, we need detectors that are:
  - massive *(large θ_{13} does not save us here)*
  - sited at near and far locations *(preferably with same target & technology)*
  - underground *(makes life easier + a lot of extra physics!)*
  - capable of detecting signals with high ε & good E_ν resolution while rejecting backgrounds
  - magnetized *(in the case of a neutrino factory)*
- we know the technologies *(MIND, WC, LAr TPC, TASD)* but we'd like the detectors to be larger, more efficient/capable, and deep

Questions

- What does phase 2 of LBNE look like?

- Does any of this strategy change if the MH is determined in the intervening years? What are the chances that we will likely know the MH within, say, the next 10 years?