# Long-baseline neutrino experiment Status and Opportunities

**Milind Diwan**
**BNL**

**Neutrinos at KITP**
**Nov. 7, 2014**

# Outline

- Collaboration.
- Origin of the project and some milestones.
- Configuration of the experimental project.  Some technical details.  Cost/schedules.
- Beam/baseline optimization issues.
- Physics sensitivities.
- Conclusion regarding planning for reformation per P5.

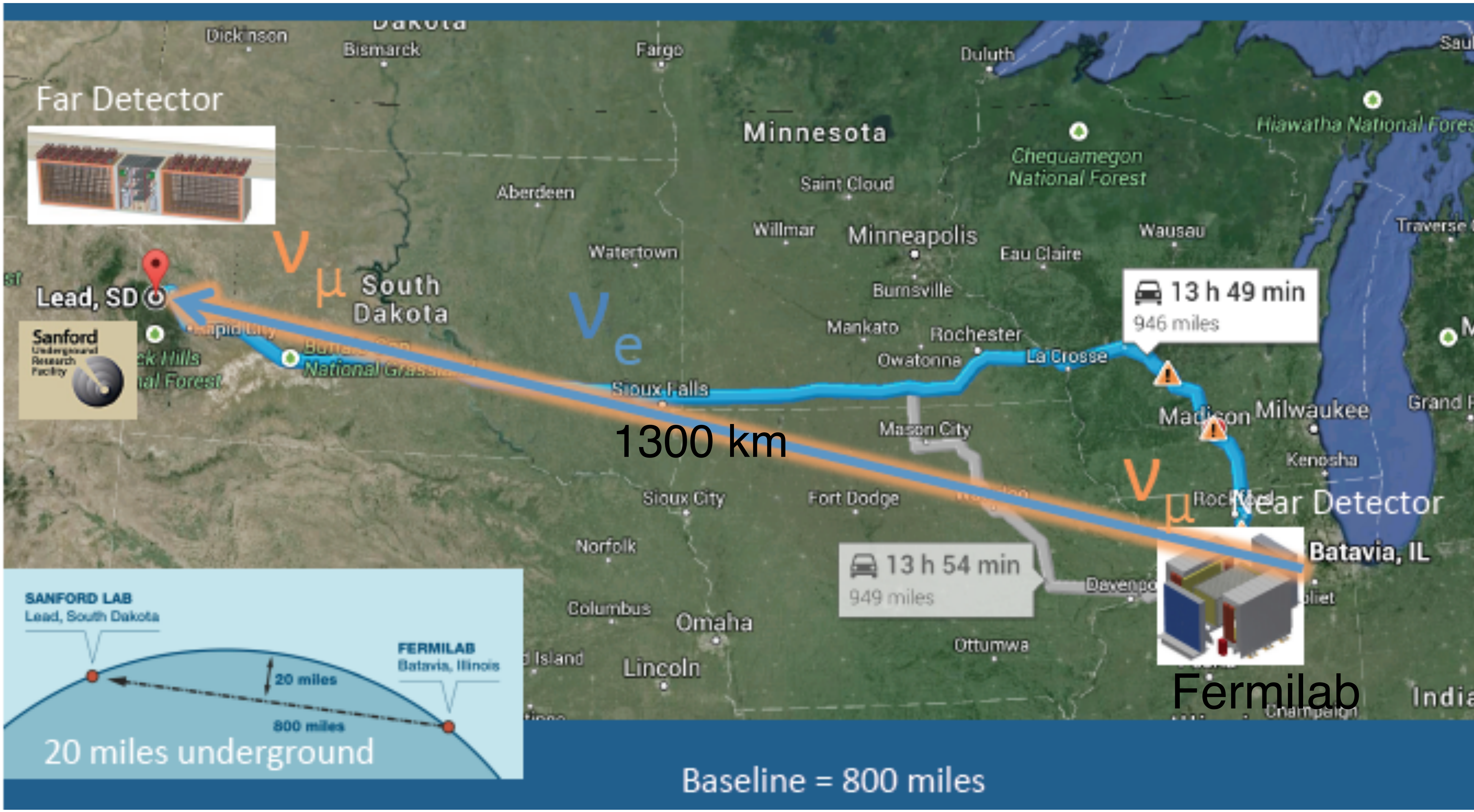
# Long-Baseline in the US

- 1998-99: New initiatives towards next generation underground detectors and beams ← NNN workshops, Nufact, and other workshops.
- 2001-2003: Realization of conventional approach towards neutrino CP violation with small dependence on $\theta_{13}$ and baseline. Al Mann: jumping from his chair ← 2003 US-HEP Facilities list: super neutrino beam. Evaluation at BNL or FNAL.
- 2004-2006: NSF Development of a plan for US underground laboratories and infrastructure. ← Scientific and engineering evaluation of 8 sites and establishment of Sanford facility with site donation from mining company.
- 2006-2008: US long-baseline study and evaluation by NUSAG, P5, and various PACs. ← Recommendation to proceed with a goal for a large underground detector and a super neutrino beam at FNAL.
- 2008-2011: Establishment of a collaboration and thorough engineering evaluation of beam and feasibility for Water and LAr detectors. ← Decision to proceed with liquid argon with full support from Fermilab, and the Department of Energy.
- 2012-2013: Detection of $\theta_{13}$, re-evaluation of the experimental configuration and strategy. ← Consensus to proceed with the FNAL to Sanford lab. configuration in phases. First phase ~$900M.
- 2013-2014: US community endorsement of the full scope configuration of LBNE and internationalization ← **Could start construction in 2018**

We expect the project to continue to change as new partners bring in important ideas.

Consistent focus on both science with breadth and frugality

# LBNE Configuration.




Far site is at the former Homestake mine (site of Davis experiment)

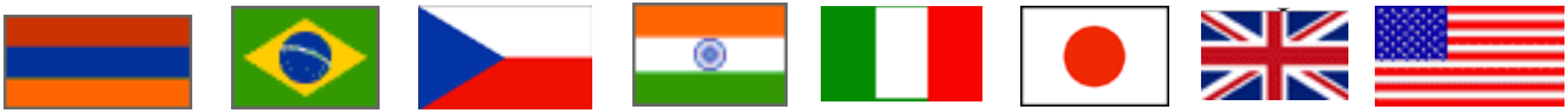
# LBNE Collaboration

Since DOE Critical Decision-1 (CD-1) approval (December 2012):

- Collaboration has increase by more than 40%
- Non-US fraction has more than doubled
- Working towards a full international collaboration

UFABC
Alabama
Argonne
Banaras
Boston
Brookhaven
Cambridge
Catania/INFN
CBPF
Charles U
Chicago
Cincinnati
Colorado
Colorado State
Columbia
Czech Technical U
Dakota State
Delhi
Davis
Drexel
Duke
Duluth
Fermilab
FZU
Goias
Gran Sasso
GSSI
HRI
Hawaii
Houston
IIT Guwahati
Indiana
Iowa State
Irvine
Kansas State
Kavli/IPMU-Tokyo
Lancaster
Lawrence Berkeley NL
Livermore NL
Liverpool
London UCL
Los Alamos NL
Louisiana State
Manchester
Maryland

Michigan State
Milano
Milano/Bicocca
Minnesota
MIT
Napoli
NGA
New Mexico
Northwestern
Notre Dame
Oxford
Padova
Panjab
Pavia
Pennsylvania
Pittsburgh
Princeton
Rensselaer
Rochester
Rutherfod Lab
Sanford Lab
Sheffield
SLAC
South Carolina
South Dakota
South Dakota State
SDSMT
Southern Methodist
Sussex
Syracuse
Tennessee
Texas, Arlington
Texas, Austin
Tufts
UCLA
UEFS
UNICAMP
UNIFAL
Virginia Tech
Warwick
Washington
William and Mary
Wisconsin
Yale
Yerevan



# LBNE Collaboration Demographics

- Collaboration growth
  - 341 Oct 2012 (pre-CD1): 53 pdoc, 44 eng, 27 stud., 212 Fac./Staff, 5 Other
  - 452 Sept. 2013 (post-Snowmass)
  - 488 April 2014 (pre-P5)
- **2014 Sep: 524 collaborators; 143 non-US, 381 US**
  - 87 postdoc, 72 engineer, 67 students, 285 faculty/staff, 7 other
  - 90 institutions: 36 non-US, 54 US; 9 countries
  - 1 pending application: 2 people, 1 new institutions, 1 new country
- LBNE project: June 2014 snapshot
  - 60 FTE -> 80 people @>10% on LBNE
  - Most in the collaboration; ~20 are not
  - 12 universities supported on project tasks
- Last Collaboration meeting was July 28-Aug 1 and included a near detector workshop. The meeting with >200 participants had the largest international participation.

# Experimental Strategy

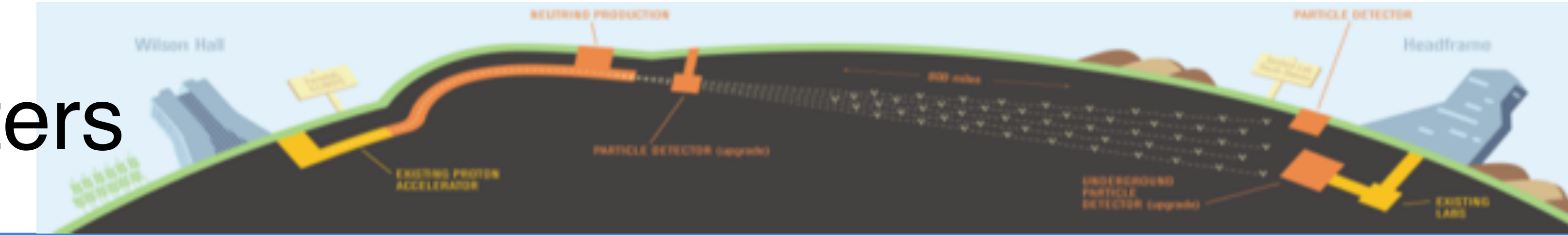
- **A comprehensive experiment with sensitivity to CP asymmetry, mass ordering and spectral shape.**
- **Our experimental focus is on $\nu_\mu \rightarrow \nu_e$ and anti-$\nu_\mu \rightarrow$anti-$\nu_e$ with superb particle identification and energy resolution, as this channel is most suitable for current neutrino beam and detector technologies.**
- **The measured neutrino mixing parameters in the 3-flavor framework suggest that the CP asymmetry will be <30% (first max) and higher at lower energies and therefore >1000 events are needed.**
- **World-wide studies have concluded that beams with 1-2 MW of power at high energies and unprecedented large far detector fiducial mass is needed regardless of baseline to achieve above statistics.**
- **A baseline of >1000 km and a broad-band beam are needed to satisfy these conditions.**
- **Detector must have sufficient overburden to allow sensitivity to nucleon decay and supernova.**

# Scientific Priorities

- LBNE design follows these priorities
  - ➡ CP violation in the neutrino sector
  - ➡ CP phase measurement regardless of its value.
  - ➡ Neutrino mass hierarchy determination.
  - ➡ Determination of $\theta_{23}$ octant and precision parameter measurements.
  - ➡ Precision tests of 3-flavor neutrino model.
  - ➡ Atmospheric neutrino measurements (confirmation of mass ordering with independent data)
  - ➡ Nucleon decay
  - ➡ Supernova burst neutrinos
  - ➡ As a very capable near detector will be needed, it is recognized that it could have a synergistic scientific program of precision neutrino and weak interaction physics.

(first five items: comprehensive program with beam neutrinos)

# Experimental Parameters

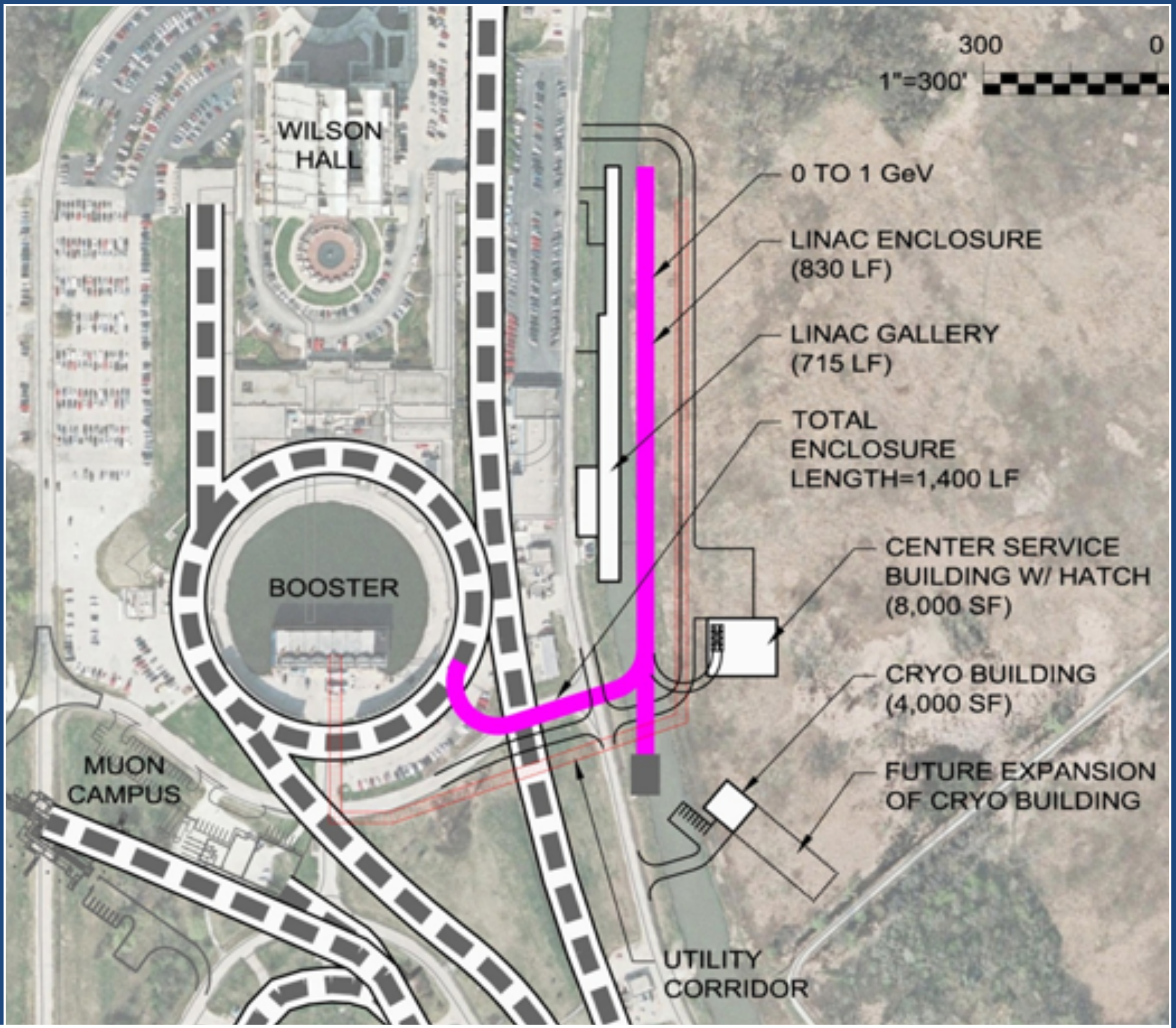



- Wide band neutrino beam from FNAL
  - protons: 60-120 GeV, 1.2 MW; upgradable to 2.3 MW
  - 10 $\mu$S pulses every 1.0 to 1.33 sec depending on P energy&power.
  - Neutrinos: sign selected, horn focused, 0.5 - 5 GeV
  - 1300 km thru the Earth to Sanford Underground Research Facility.
- Liquid argon TPC parameters
  - 34 kt fiducial (50kt tot) at 4850 ft level. cosmics ~0.1Hz, beam ~ 9k CC/yr
  - drift ~3.5 m, field: 500 V/cm, 2 mods = (14m(H)X 22m(W)X45m(L))
  - readout: x,u,v, pitch: 5 mm, wrapped wires, 2X108 APAs, 2X(275k ch)
  - Max Yield: ~9000 e/mm/MIP, 10000 ph/mm/MIP
- near detector parameters
  - distance ~450 m, ~3M events/ton/MW/yr
  - Magnetized Fine Grained Tracker (8 ton) with ECAL, and muon id.
  - Supplemented by a small LARTPC (few tons) or gas TPC.

**Scale of project is dictated by physics. Beam and ND and FD detectors require high technology. Project can be done in phases with international partners.**

# Proton-Improvement-Plan Phase II (PIP-II)

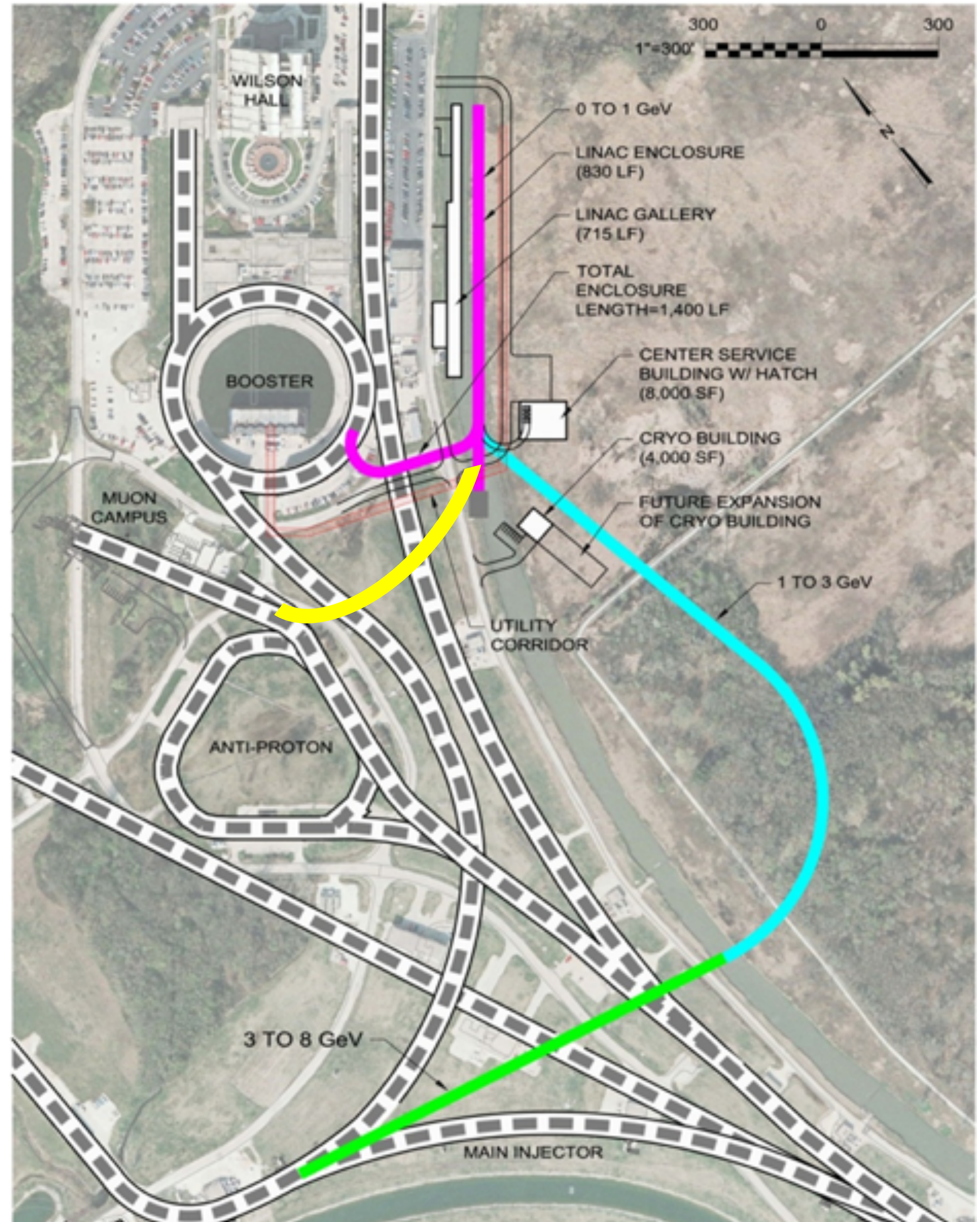
- Replace existing 400 MeV linac with a new 800 MeV superconducting Linac
- 1.2 MW beam power to LBNE at start-up of experiment.
- Plan is based on well-developed superconducting RF technology with international partnerships.
- Strong support from DOE and in the recent Prioritization Panel report.
- Flexible design - future upgrades could provide > 2MW to LBNE.




**Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.**

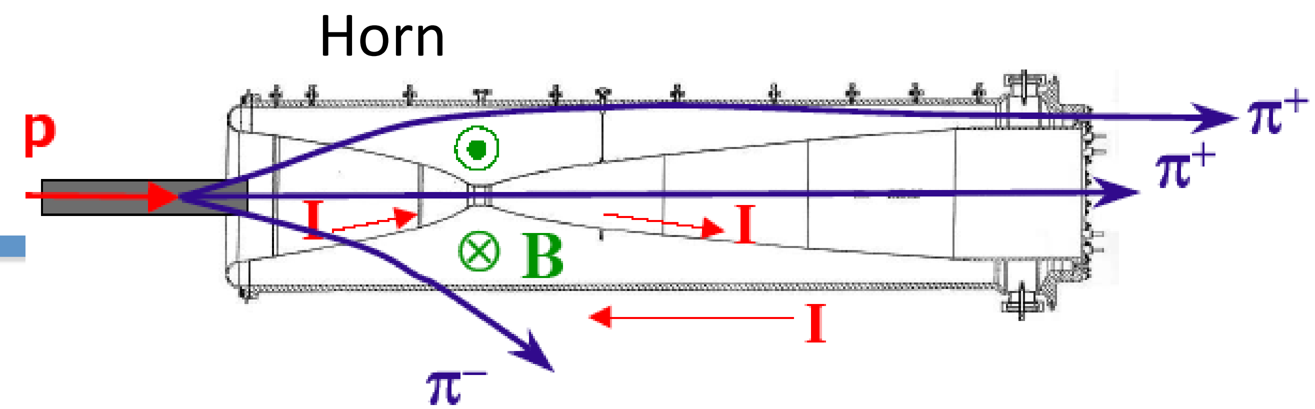
# Flexible Platform for the Future

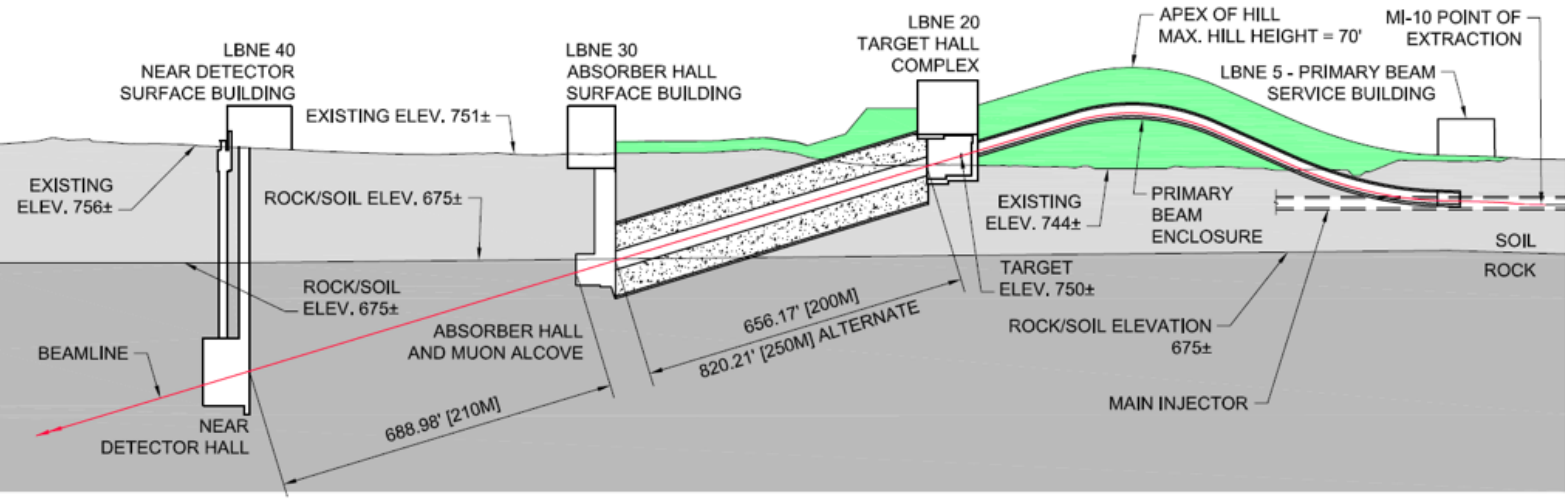
- PIP-II Inherent Capability
  - ~200 kW @ 800 MeV
- Future upgrade would provide > 2 MW to LBNE and flexibility for 800 MeV program.
- What are the technical issues for higher power ?
- Design is based on the loss limit of 1 W/m. This originates from dose rate limit of 0.1-1mSv/hr at ~30cm after 100 days of operation and 4 hr downtime.
- Target materials are second issue.




Fermilab

# LBNE Neutrino Beamline

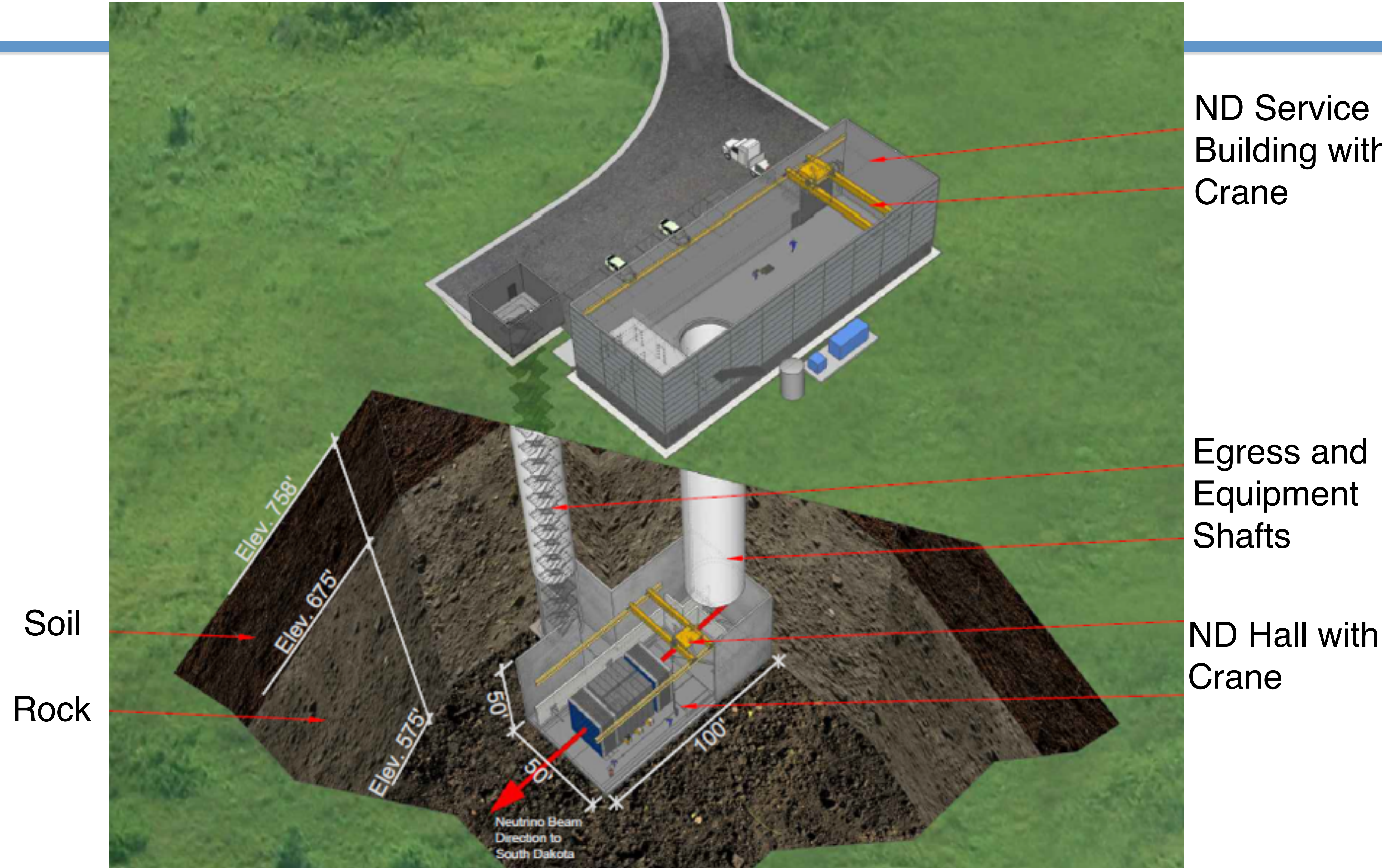



**Proton beam**

- $60 \leq E_{beam} \leq 120$ GeV. This flexibility may be quite important for precision.
- Beam power 700 kW, upgradeable to 2.3 MW
- Innovative design for safety and upgradeability.
- Many options still under development (hellium decay pipe, horns, targets,etc)

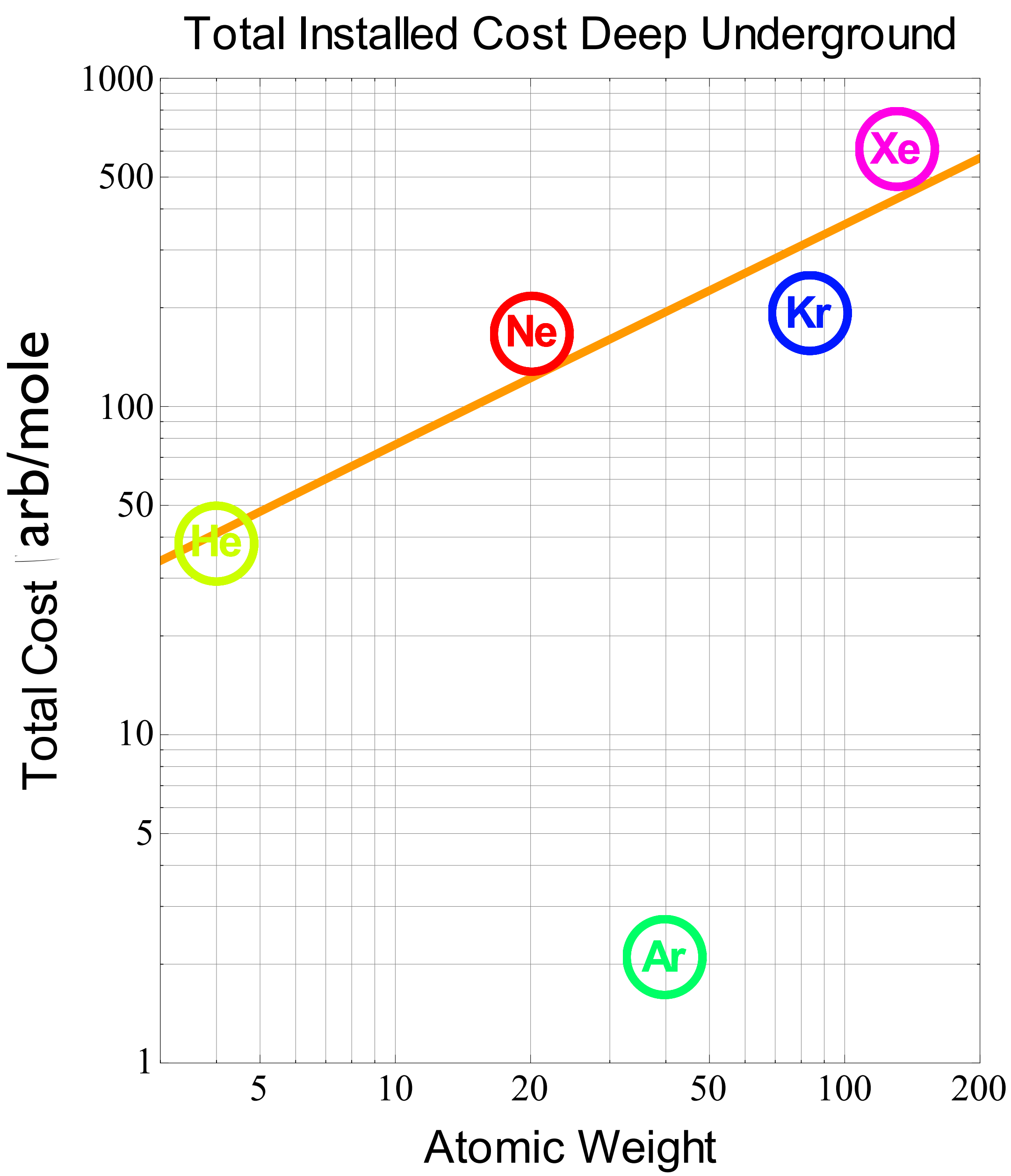
# Near Neutrino Detector Update




**Near conceptual design used for civil planning onsite**

# Why Liquid Argon ?

- One of the few pure, inexpensive substances with long electron lifetime
- Excellent tracking and calorimetric performance.

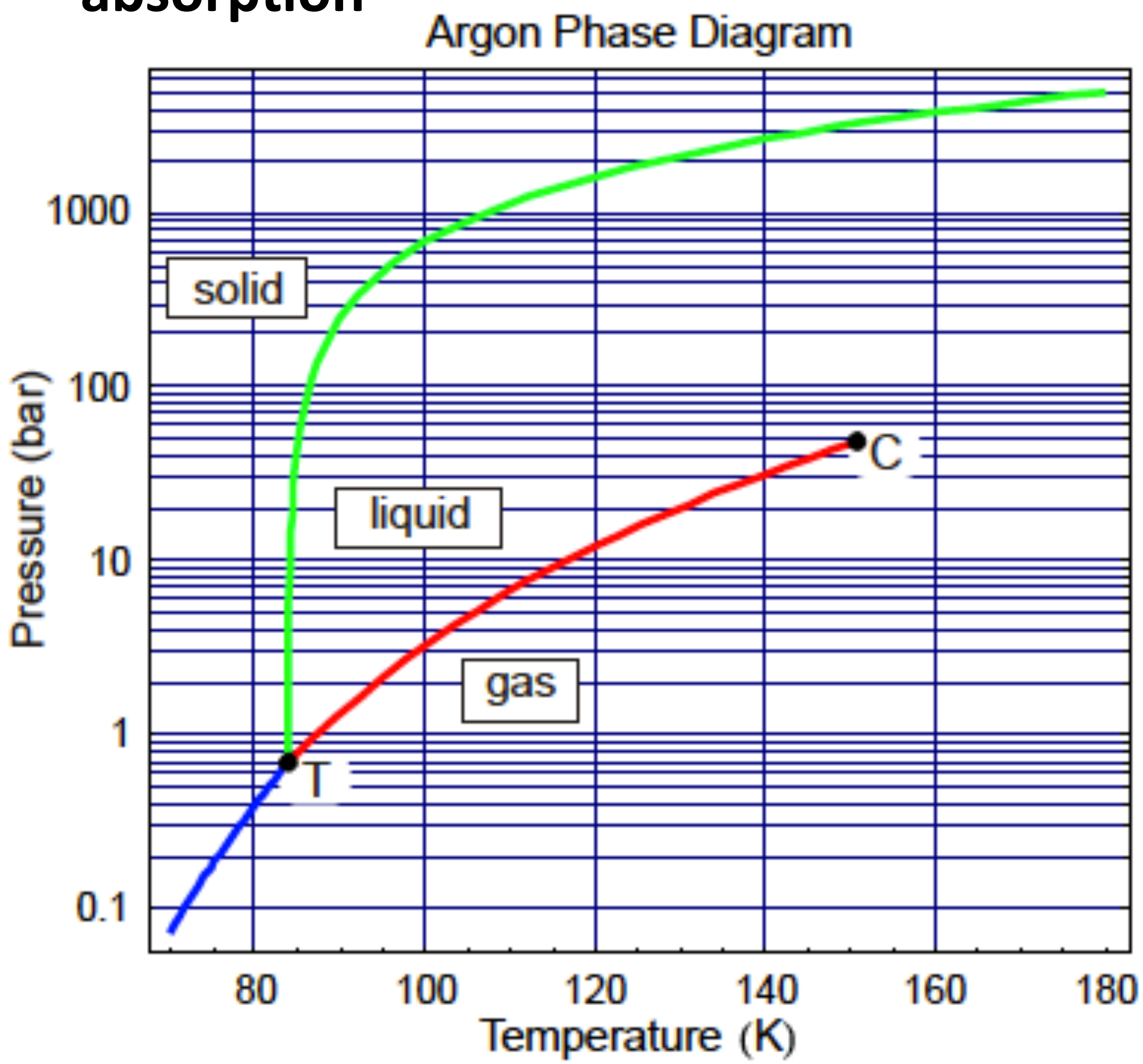


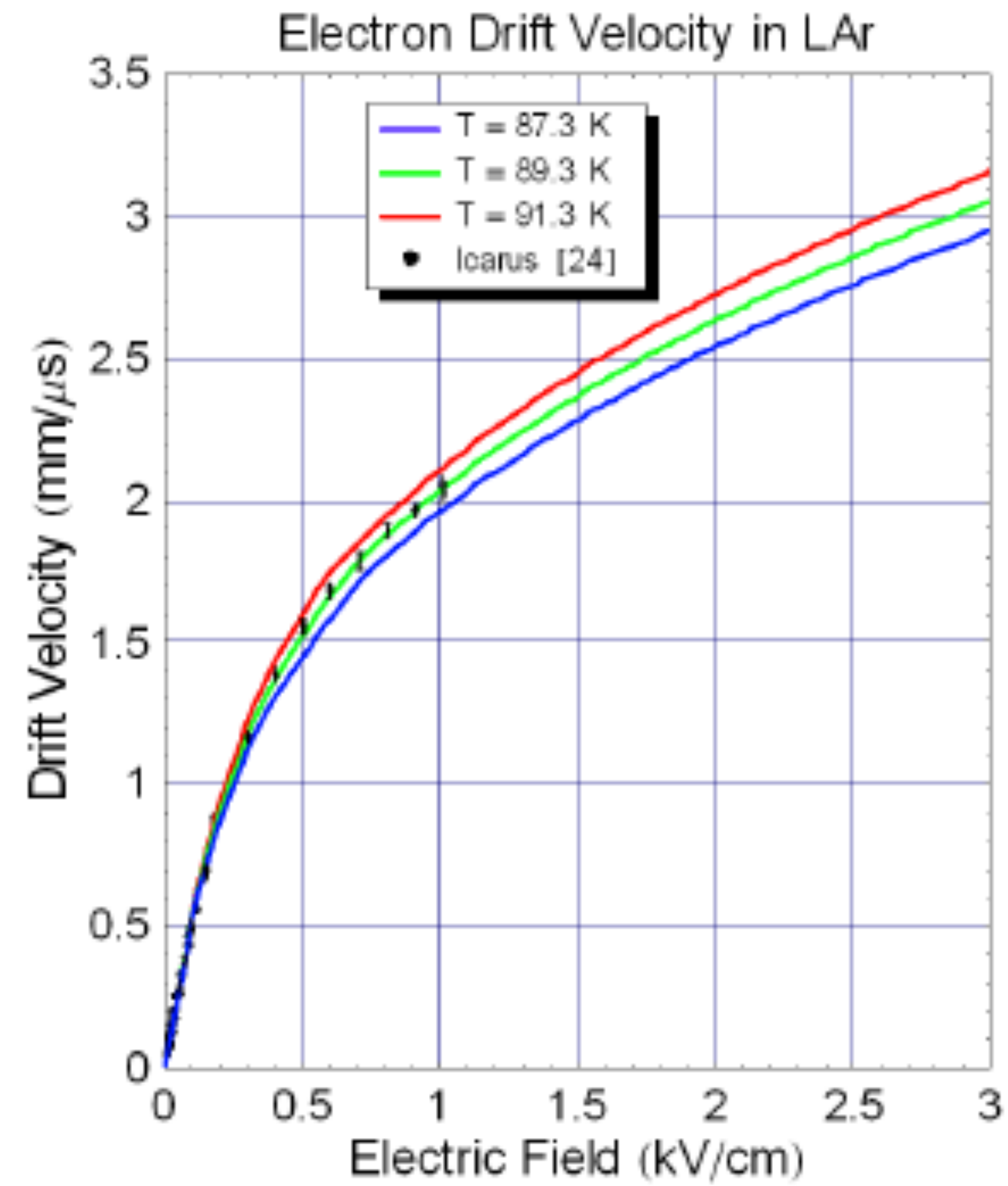

~$1 M per 1000 tons
Density at b.p. 1.3954 gm/cc
$X_0 \sim 14$ cm
$\lambda_{int} \sim 80$ cm
Backg. $^{39}Ar$ 1Bq/Kg Q = 0.565MeV

| | In Air (ppm) | In Crust (ppb) |
|---|---|---|
| **He** | **5.2** | **8** |
| **Ne** | **18** | **0.07** |
| **Ar** | **9300** | **1200** |
| **Kr** | **1.14** | **0.01** |
| **Xe** | **0.086** | **0.047** |

# Key Technical Issues for a Liquid Argon Detector

**liquid argon must be extremely pure: ~1 part in $10^{10}$ to allow long drift without absorption**

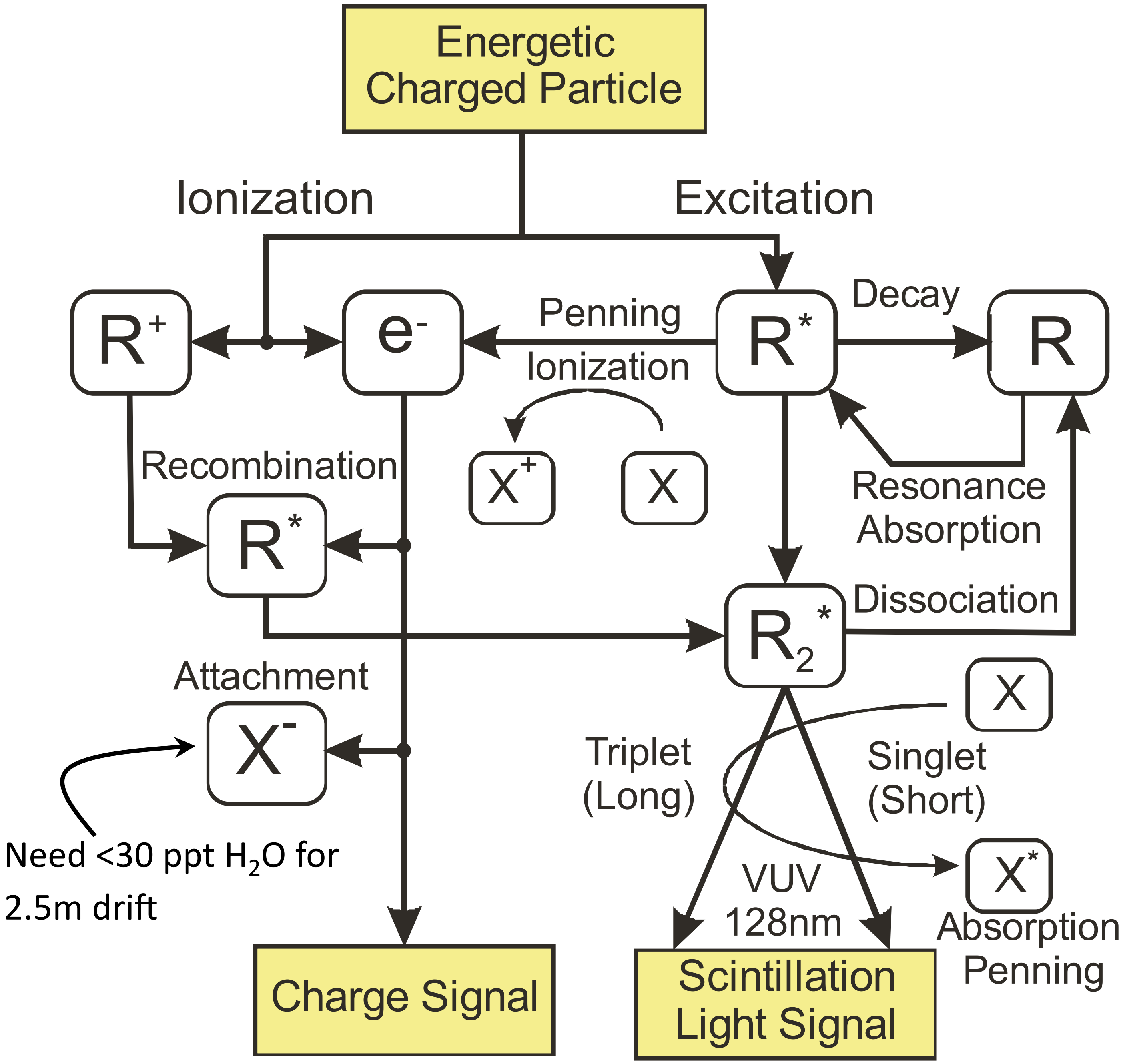


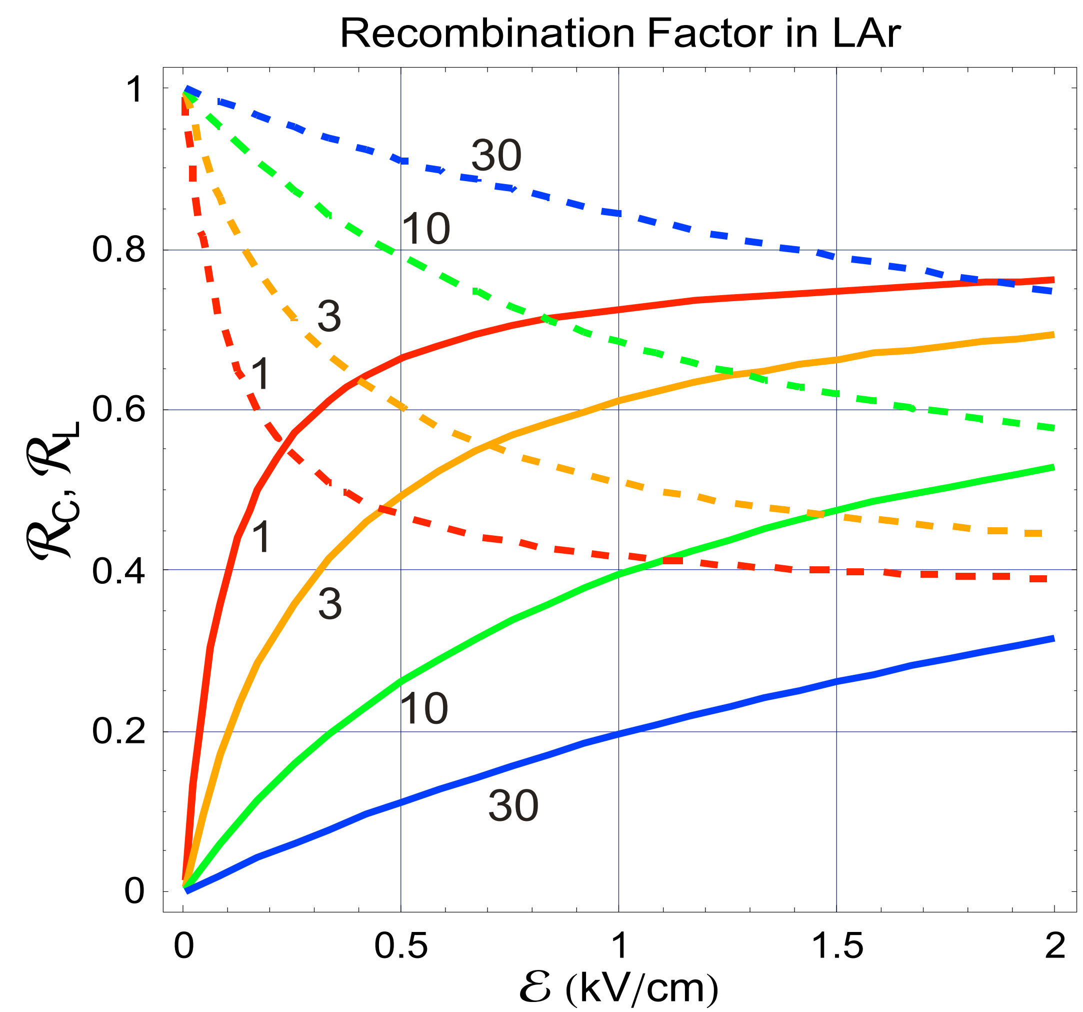

**It is cold ! And this makes it inaccessible and difficult to work with.**

**It is slow ! Electrons drift slowly. Drives many issues of design.**

# What happens to the energy as a charged particle traverses in LAr?




R={LNe, LAr, LKr, LXe}
X={$N_2$, $O_2$, $H_2O$, …}



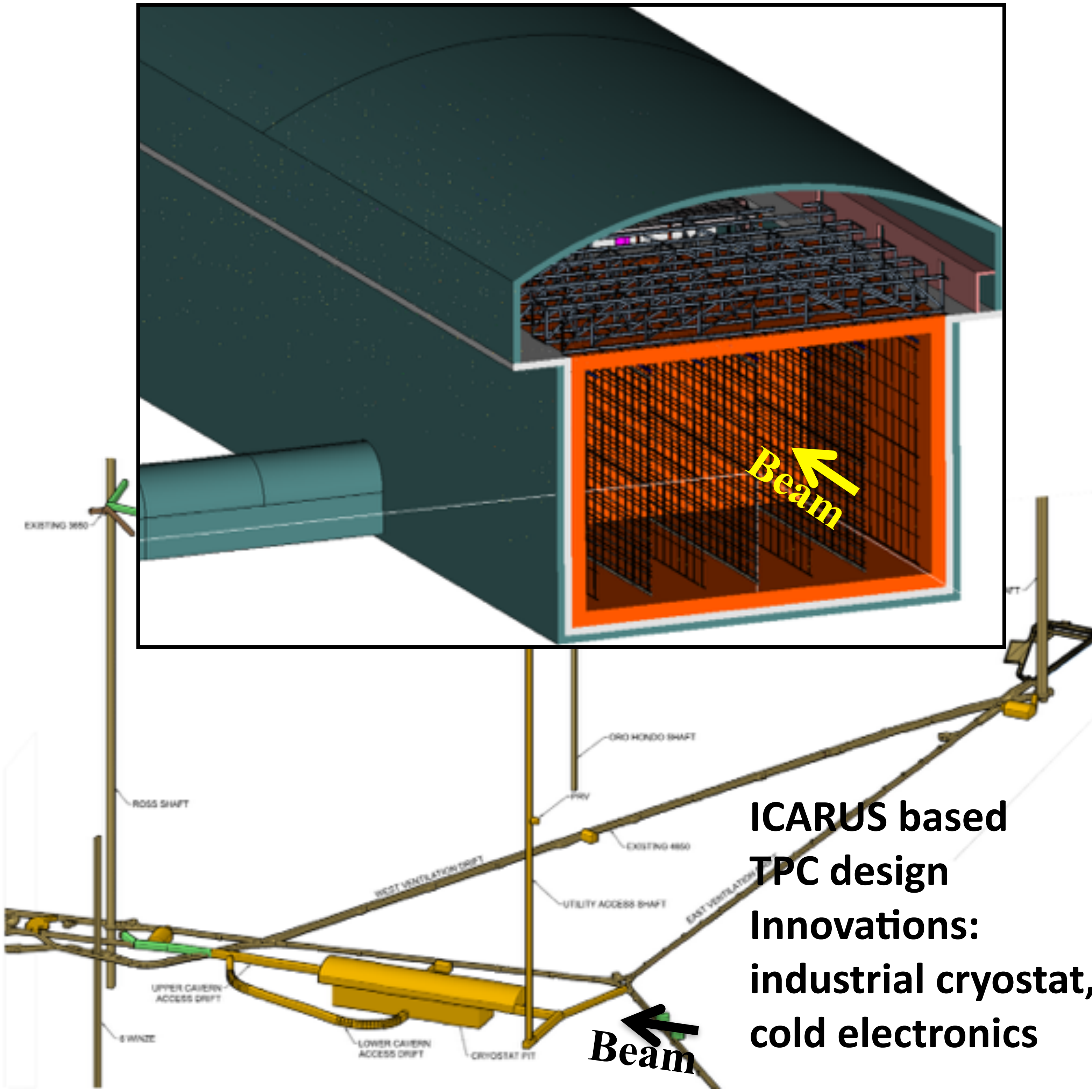

E→∞
42,000 e/MeV
8980 e/mm for MIP

E→0
51,300 ph/MeV
10,900 ph/mm for MIP

(40,000 for NaI(Tl))

Ratio w/r/t full yield
Solid: charge, Dashed: light
Numbers: Specific Eloss in MIPs

# Far Detector LArTPC Design at 4850 ft depth
## Conceptual design allows progress on civil construction, but not fixed

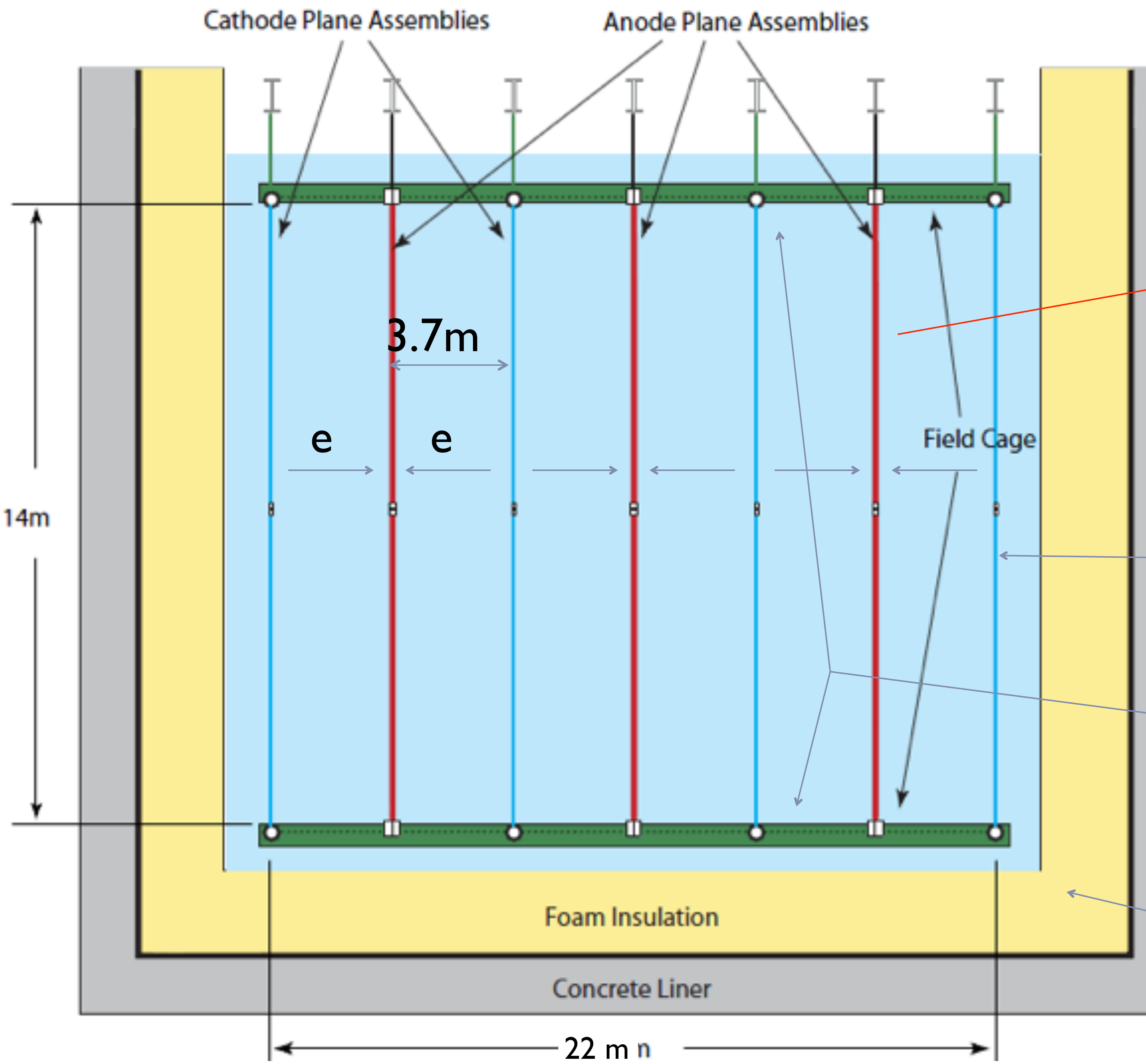


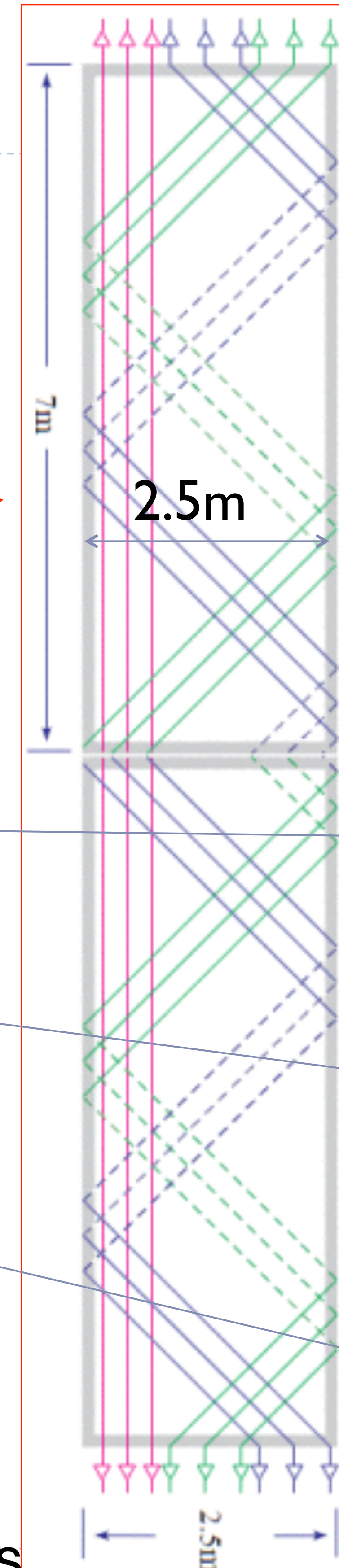

**ICARUS based TPC design**
**Innovations: industrial cryostat, cold electronics**

- Two detectors in a common cavern at 4850 ft. depth or two caverns.
- Active volume of each detector: 22.4 x 14 x 45.6 $m^3$
- 34 kt fiducial mass.
- 50kt tot/40kt active.
- TPC design:
  - ○3.7 m drift length 500v/cm
  - ○5 mm wire spacing
  - ○three stereo views
  - ○2X108 anode chambers

Challenges for scale up are under control : Purity, HV, installation, safety

# Detector Configuration




Anode Plane Ass'y (APA) - Standard wire chamber construction

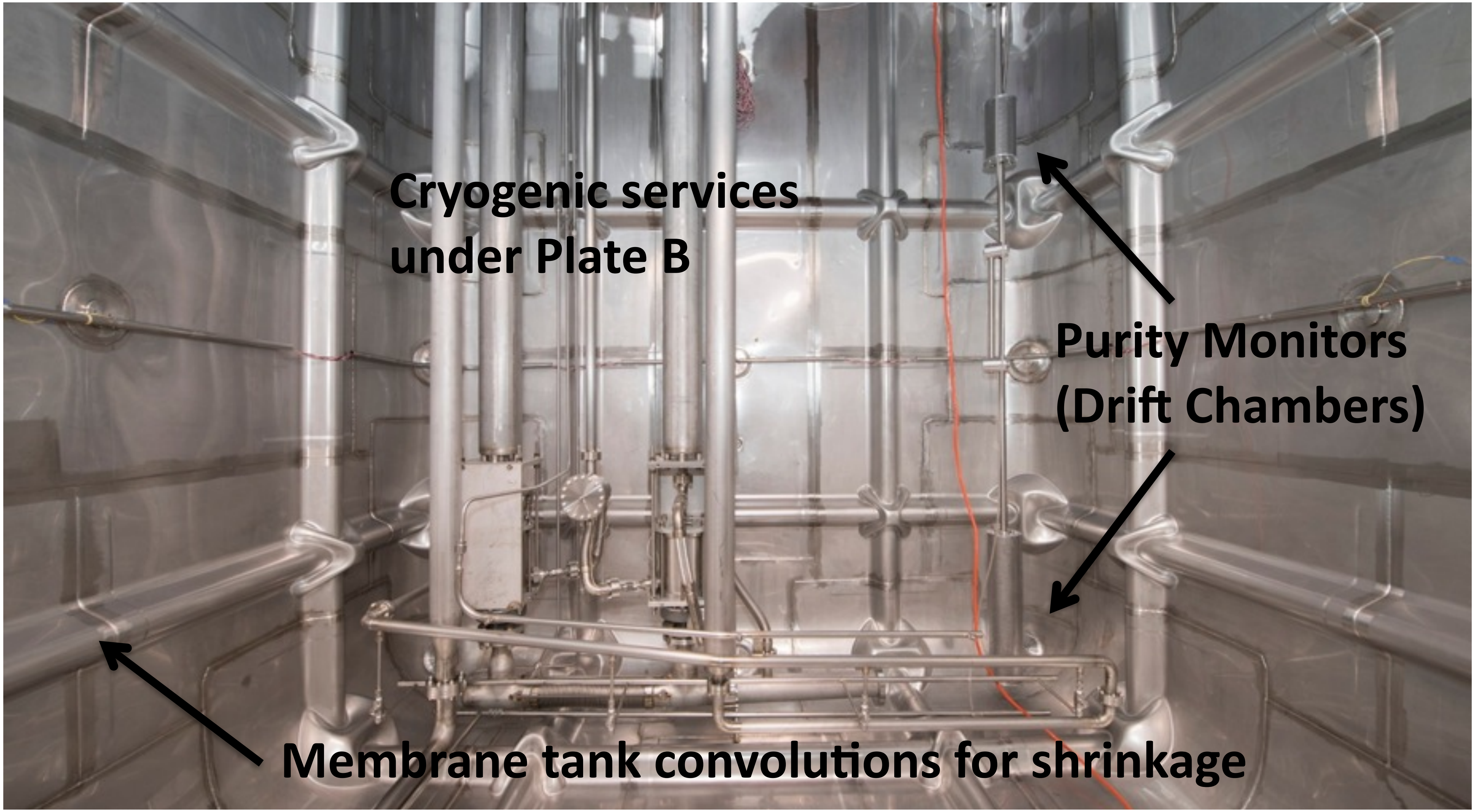
Cathode Plane Ass'y (CPA) - SS mesh

Field cage wraps detector

Membrane cryostat

Vertex Fiducial cut is 30 cm from planes, events will be stitched across planes. Drift ~2.5 ms

# View Inside of 35 Ton Tank

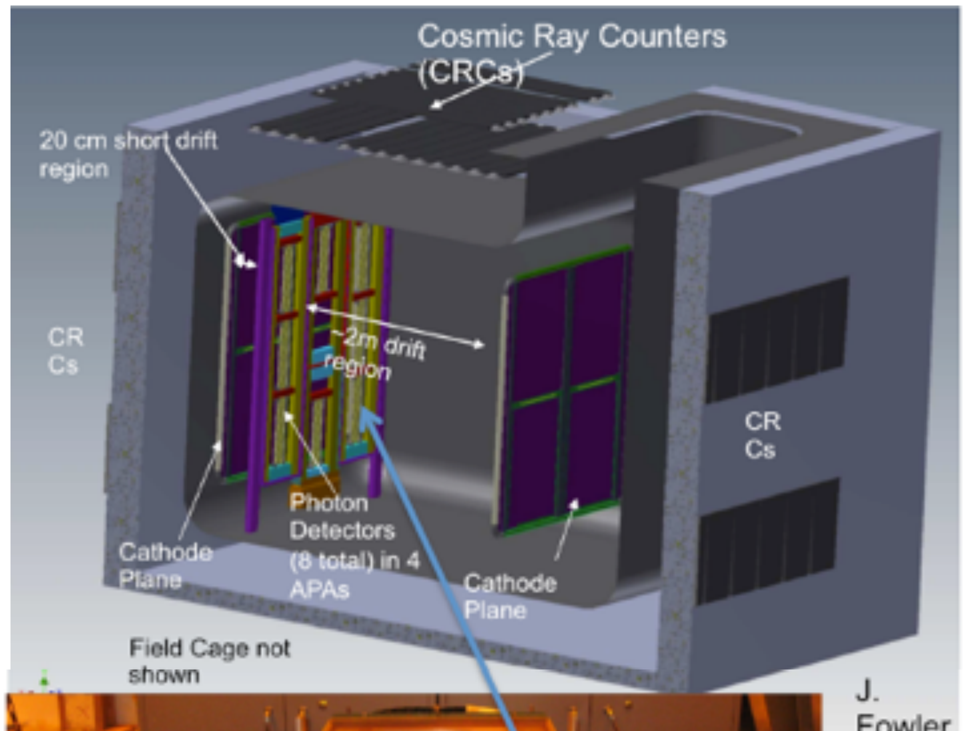


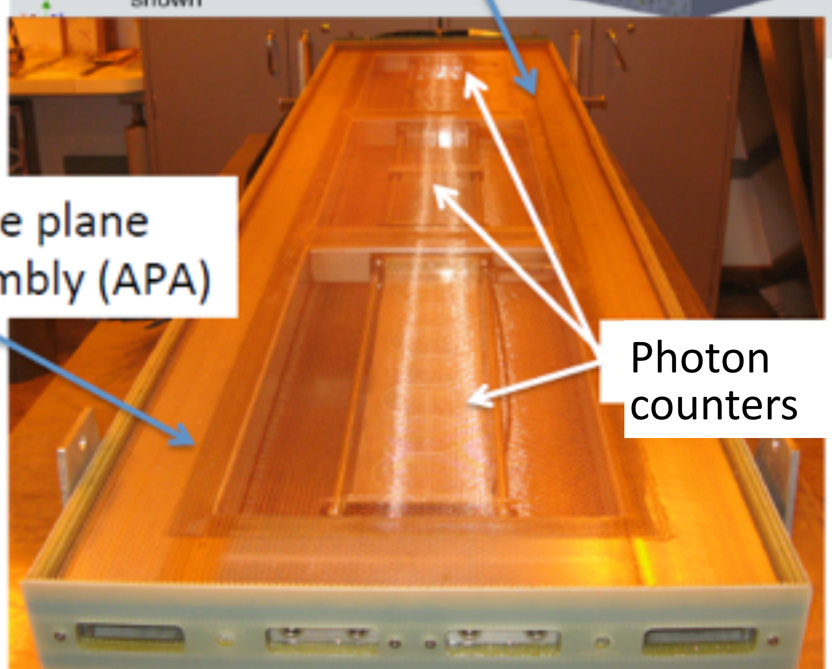
# View On Top of 35 Ton Tank

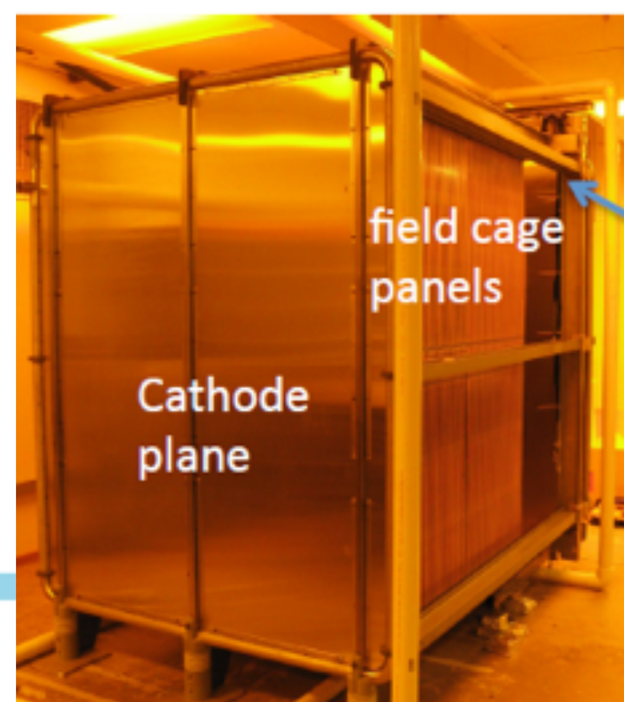
# Prototyping Work

Reduced-scale prototype in Fermilab 35 t cryostat

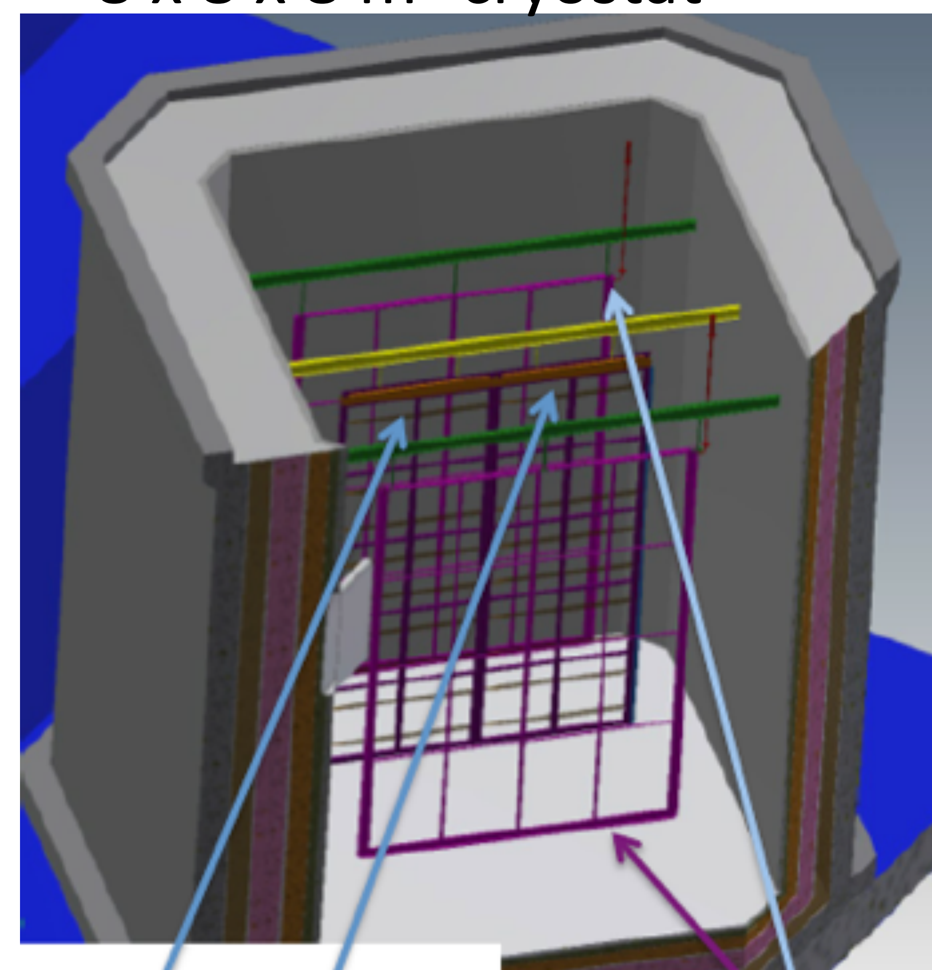
Proposed full-scale prototype and beam test in CERN Neutrino Platform



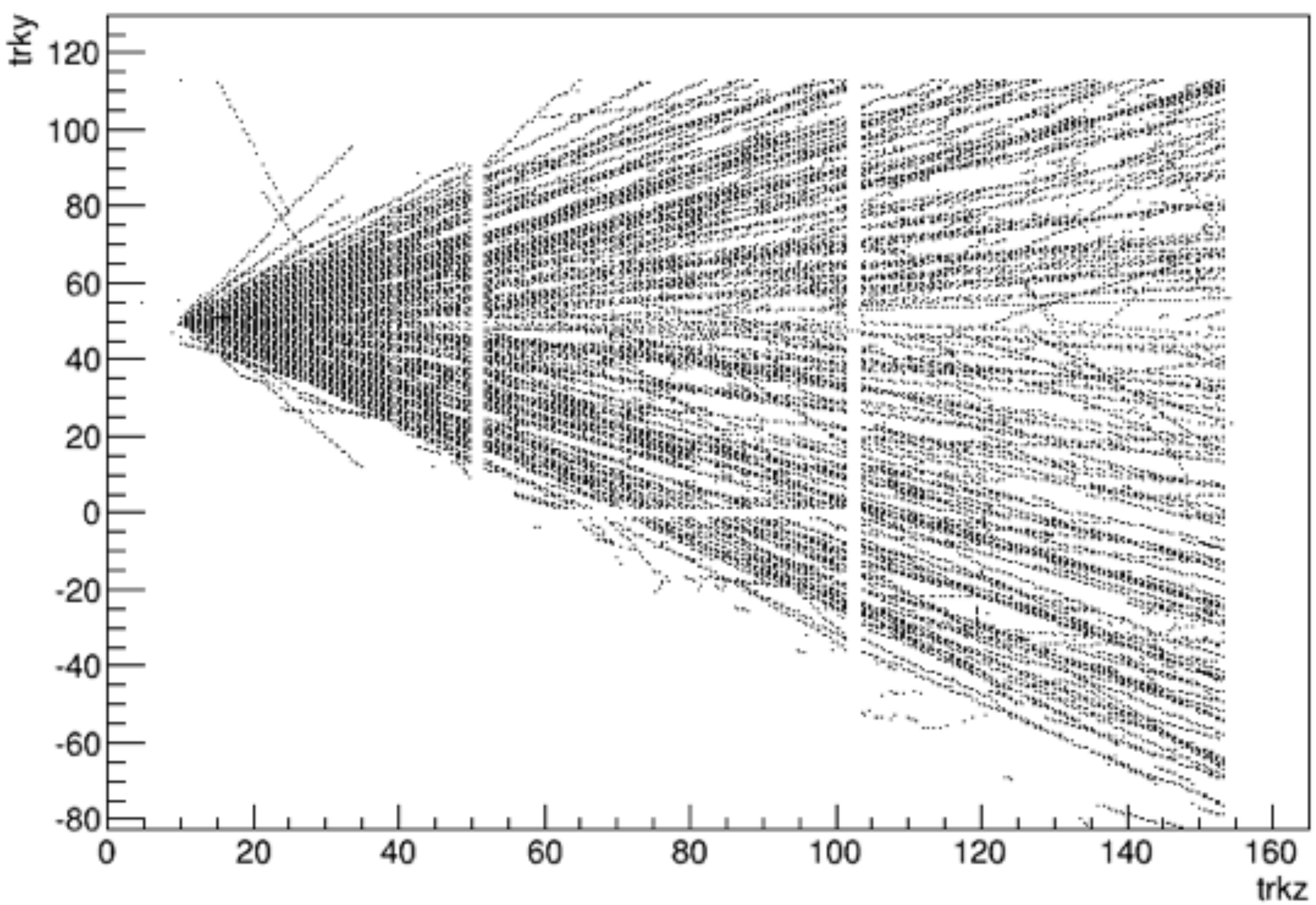




8 x 8 x 8 m$^3$ cryostat



# Physics Tools Progress I: Track Stitching

- Separate tracks are formed in each "TPC" (volume of LAr viewed by an APA)
- Must be "stitched" together to form tracks traversing the whole cryostat
- Stitching now working with CosmicTracker
- Photon system reconstruction also progressing.

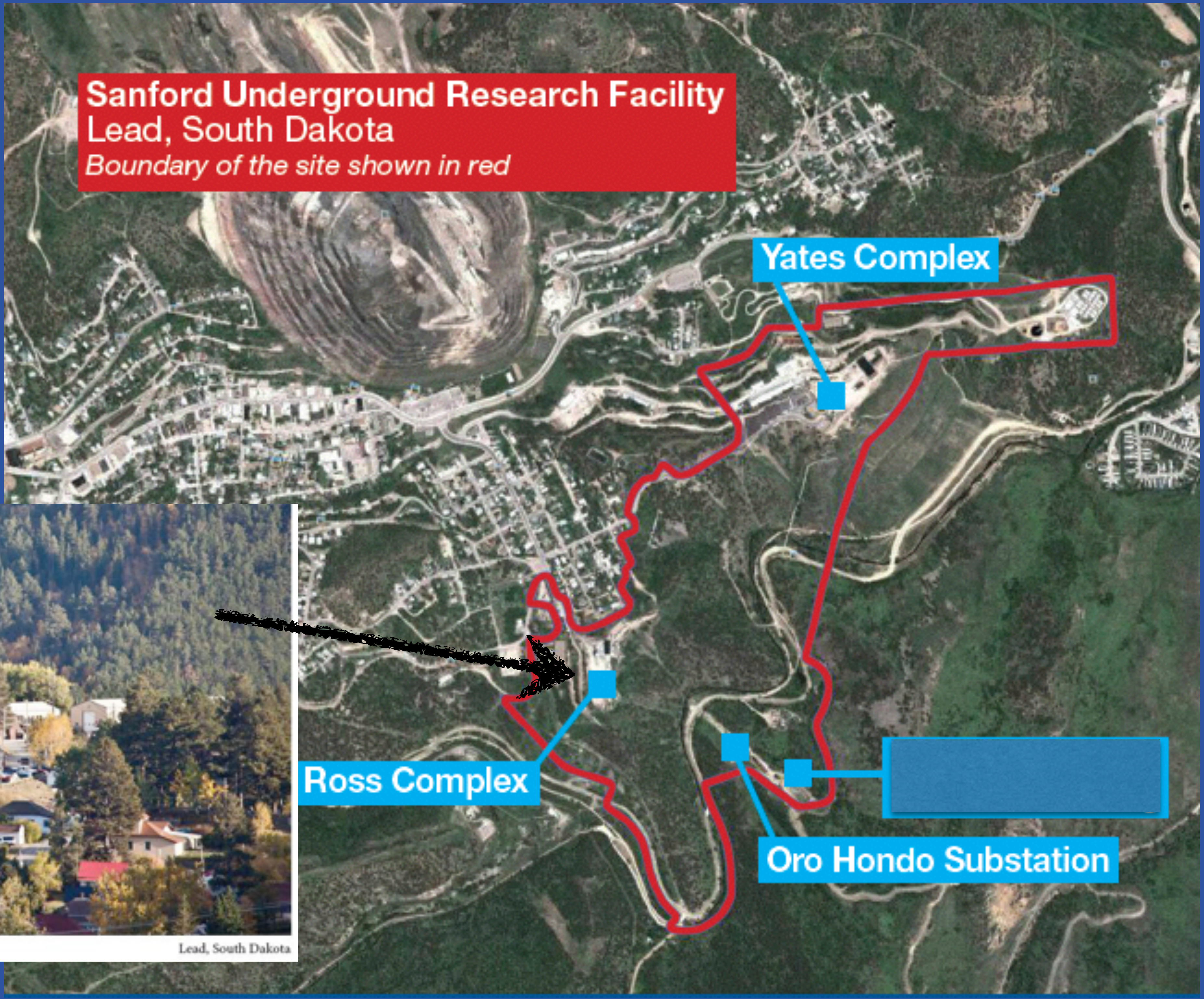



Muons generated starting at x=100cm, y=50cm, z=10cm
M.Elnimr

# Far Detector at Sanford Underground Research Facility in the Black Hills of South Dakota

SURF site is open for science with all legal issues in order

Donated to Science





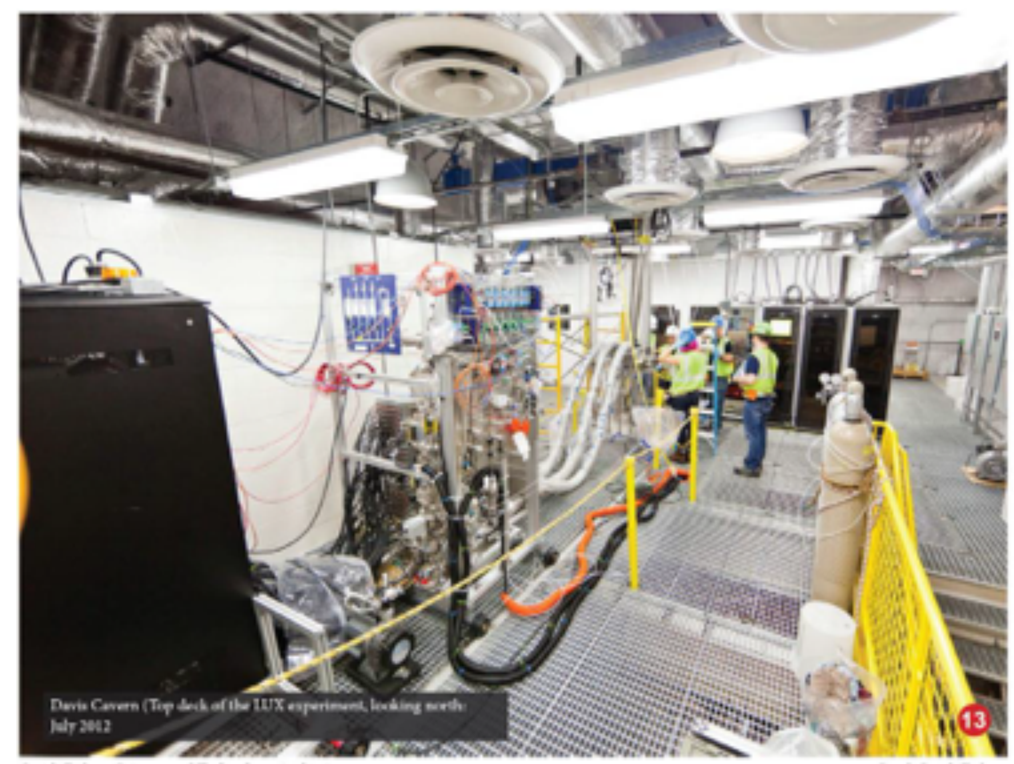
**The shafts go down to 4850 ft and are being upgraded. We have benefited greatly from early interactions with LNGS.**

# Sanford Underground Research Facility

**Majorana (0νββ)**



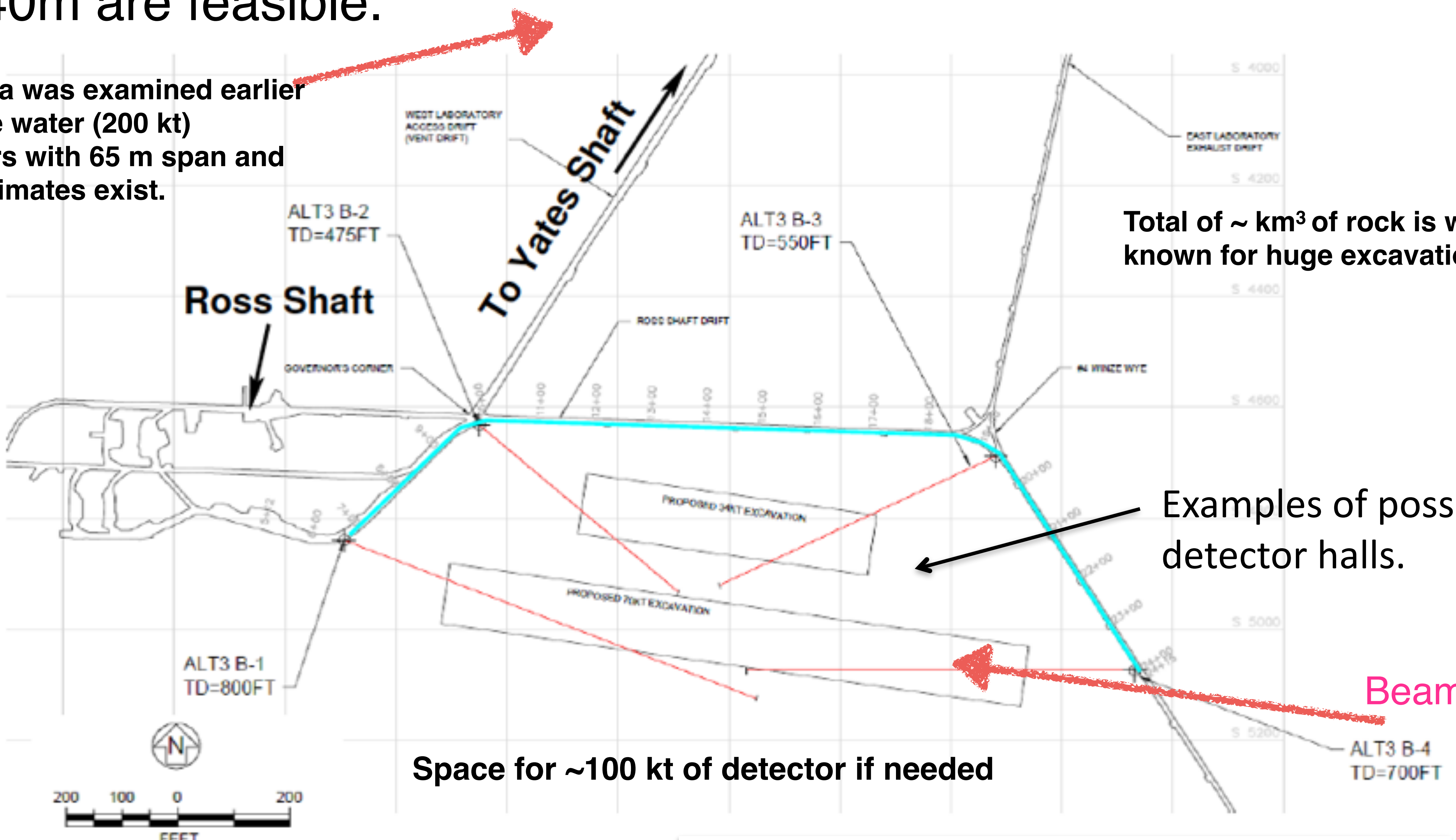
- Experimental Facility at 4300 MWE
- Two vertical access shafts for safety.
- Shaft refurbishment has been on-going and has reached 2000' level
- Total investment in underground infrastructure is >$100M.
- Facility donated to the State for science in perpetuity.




**LUX (dark matter)**

# CF Far Site Geotech Program

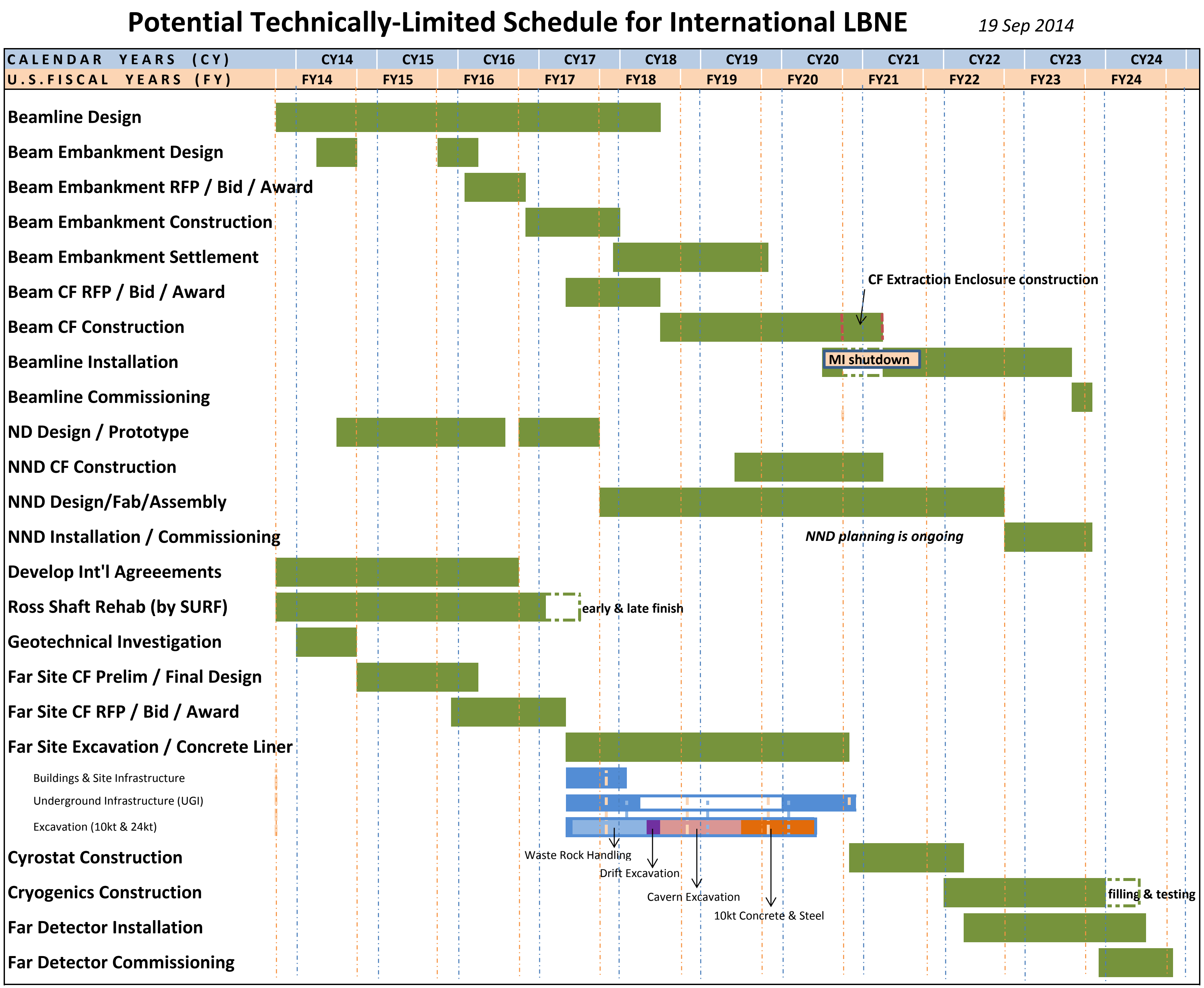
- General area where detector(s) could be placed is being explored.
- This drilling program was recently completed.  The rock is known to be quite capable of handling large excavations, but report states that spans of ~40m are feasible.



# Project Status and Schedule

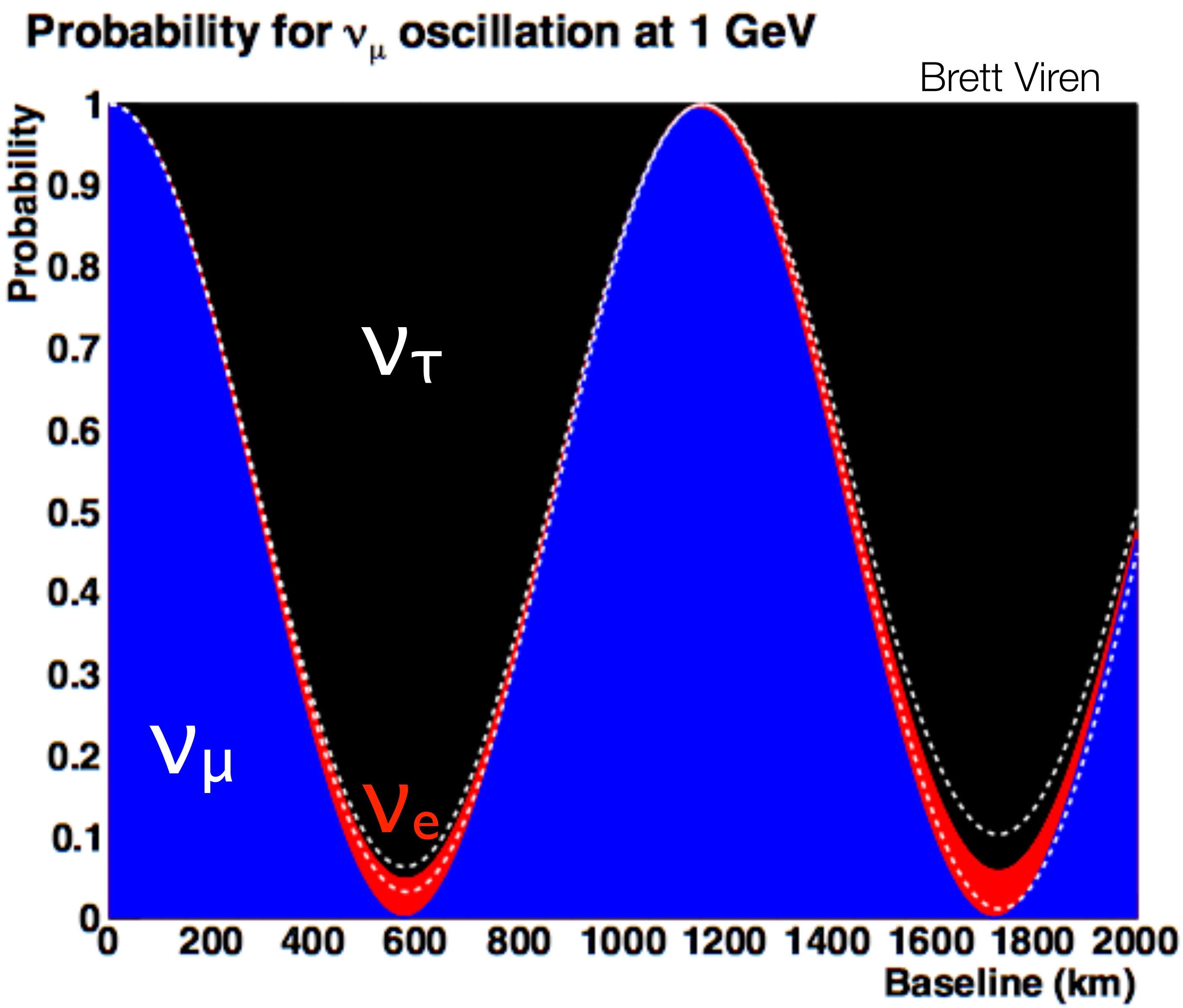
- P5 (2008) recommended moving ahead with investment into a long-baseline neutrino experiment.
- DOE has granted CD1 (critical decision on conceptual design with site decision) with $867M commitment with flexible scope in December of 2012.
- There is agreement that scope presented at CD1 (reduced surface FD, no ND) will be modified based on evolving partnerships.
- The total scope needed to satisfy P5 (2014) goals need ~$1.5B (this is a reviewed cost estimate which could change by ~0.1B).
- To obtain the full scope of LBNE (and money for operations), significant domestic and international partnerships and leadership are essential.
- The project schedule and funding profile from the DOE can be adjusted to produce the best global experiment.
- The new international collaboration will discuss collaborative and financial mechanisms with our respective funding agencies.
- The project will proceed according to the current DOE Critical Decision (CD) process modified to include multiple significant partnerships. We have many examples to guide us including CMS, ATLAS, LHC, Daya Bay, etc.

# Project Status and Schedule (cont.)




**Geotechnical examination at Sanford was completed recently.**

# The full picture of the oscillation effect starting with pure muon type neutrino.

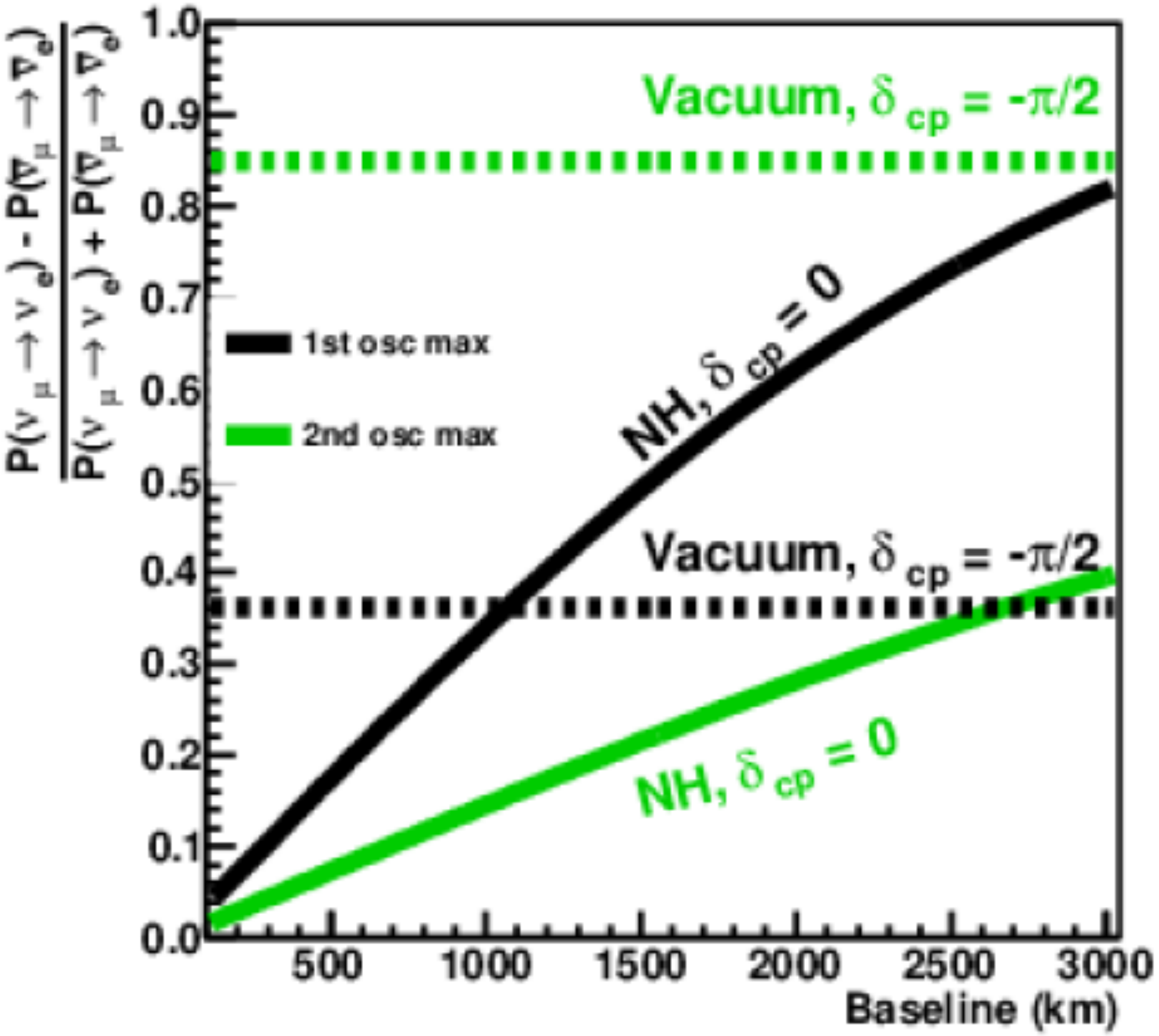


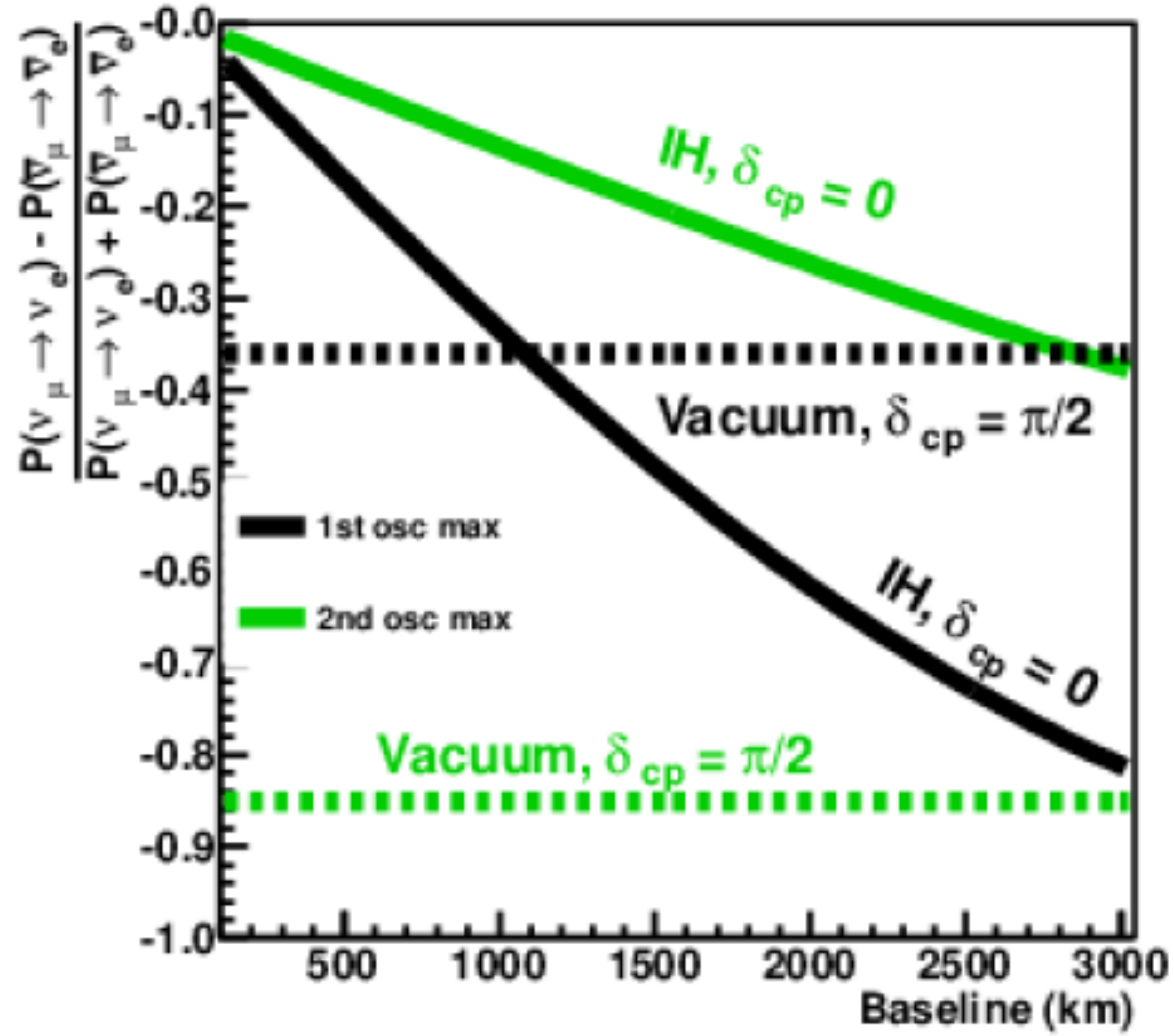

**Dashed white lines correspond to CP violation or the unknown phase.**

**Notice that for sizable effects one needs long distances and large energies.**

- **Above is a precise predictions based on best fit parameters:**
  - **Large Matter Effects (not yet seen in a laboratory experiment)**
  - **Potentially large CP violation (not yet seen)**
  - **We should measure this picture with a detailed spectrum with ~1000evts.**

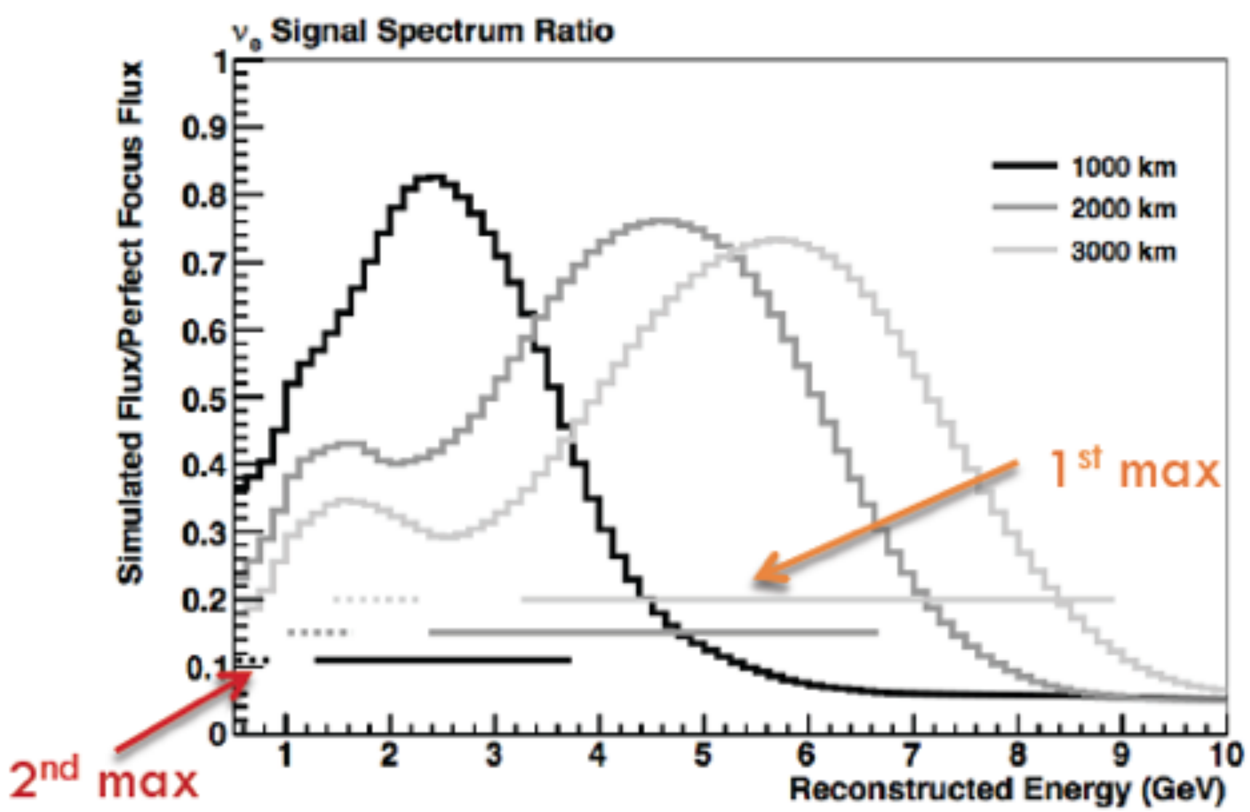
# Baseline optimization

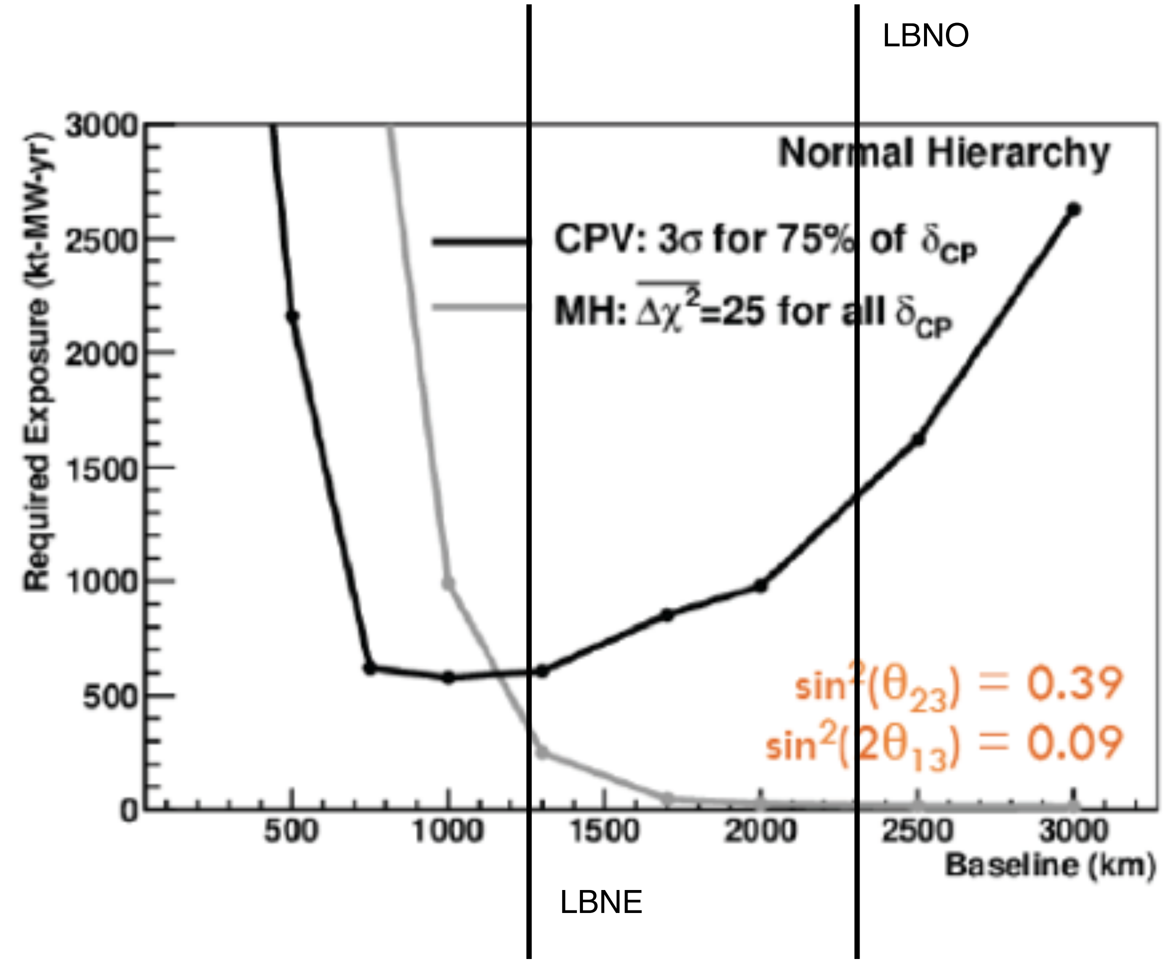



- **>1000 km is needed to break the degeneracy between CP and matter effects. Statistics (tot ~ 1000 evts) at both nodes improve sensitivity.**
- **At >2000 km suppression of events in one polarity is very high: nu/anu asymmetry measurement a challenge.**
- **On these general grounds we can state that 1000 - 2000 km is optimum.**

Exposure needed to reach a desired sensitivity.




- Uses NuMI-style beams individually optimized for each baseline
  - Cover **1st oscillation maximum,** as much of 2nd oscillation max. as possible
- Uses GLoBES-based sensitivity calculations
- Baseline of 1300 km near optimal
- arXiv:1311.0212

There are pros and cons to either choice 1300 km or 2300 km. Event rate is ~const vs baseline. 2300 will get mass hierarchy faster, but has very large event loss for one polarity.

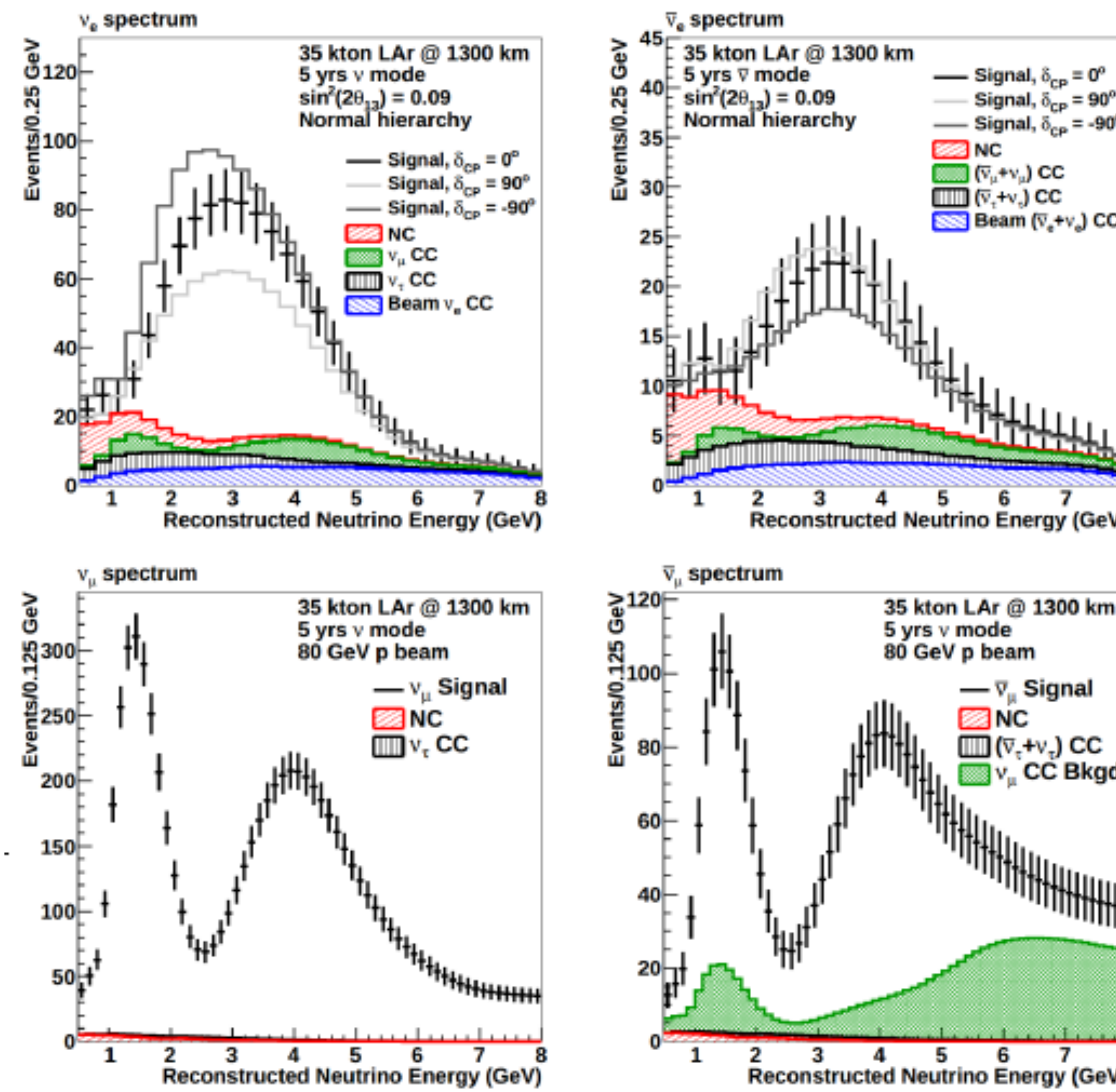


LBNO proposes more advanced beam design for higher sensitivity. This will benefit either 1300 or 2300.

# Event rate and spectra expectation.

**Assumptions:**
**35 kt LArTPC**
**1.2 MW operation at 80 GeV.**
**~3 yrs for each polarity.**
**Normal Hierarchy**
**$\delta_{CP}$= 0**
**Rest of the parameters are at best fit from 2012**

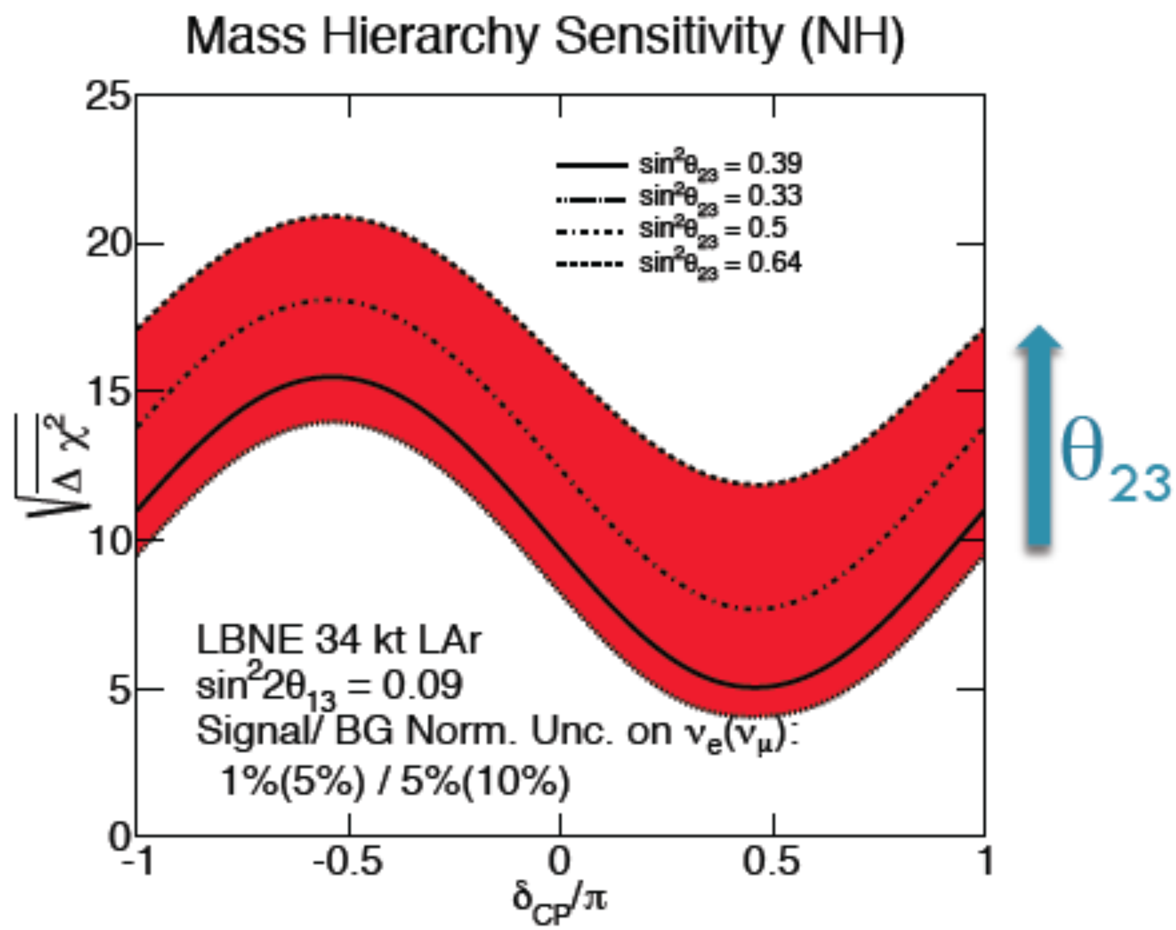
| 80 GeV Beam | $\nu$ mode | $\bar{\nu}$ mode |
|---|---|---|
| Signal: $\nu_e + \bar{\nu}_e$ | 777 | 189 |
| BG: NC | 67 | 39 |
| BG: $\nu_\mu + \bar{\nu}_\mu$ CC | 84 | 39 |
| BG: Beam $\nu_e + \bar{\nu}_e$ | 147 | 81 |
| BG: $\nu_\tau + \bar{\nu}_\tau$ CC | 49 | 32 |



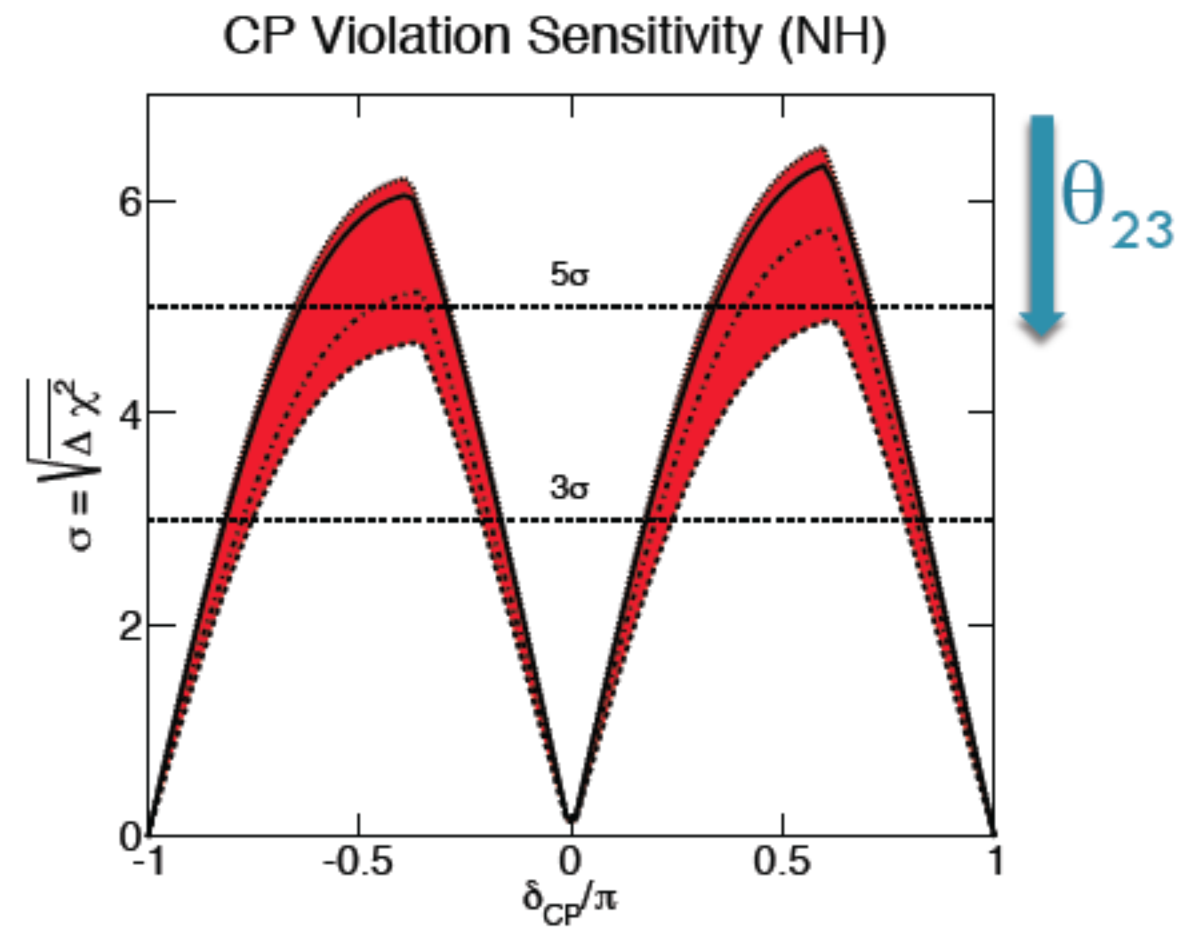

- **At 1300 km full oscillation structure is visible in the energy spectrum. A combined spectral fit provides unambiguous parameter sensitivity in a single experiment.**

# Sensitivity

## Mass Hierarchy



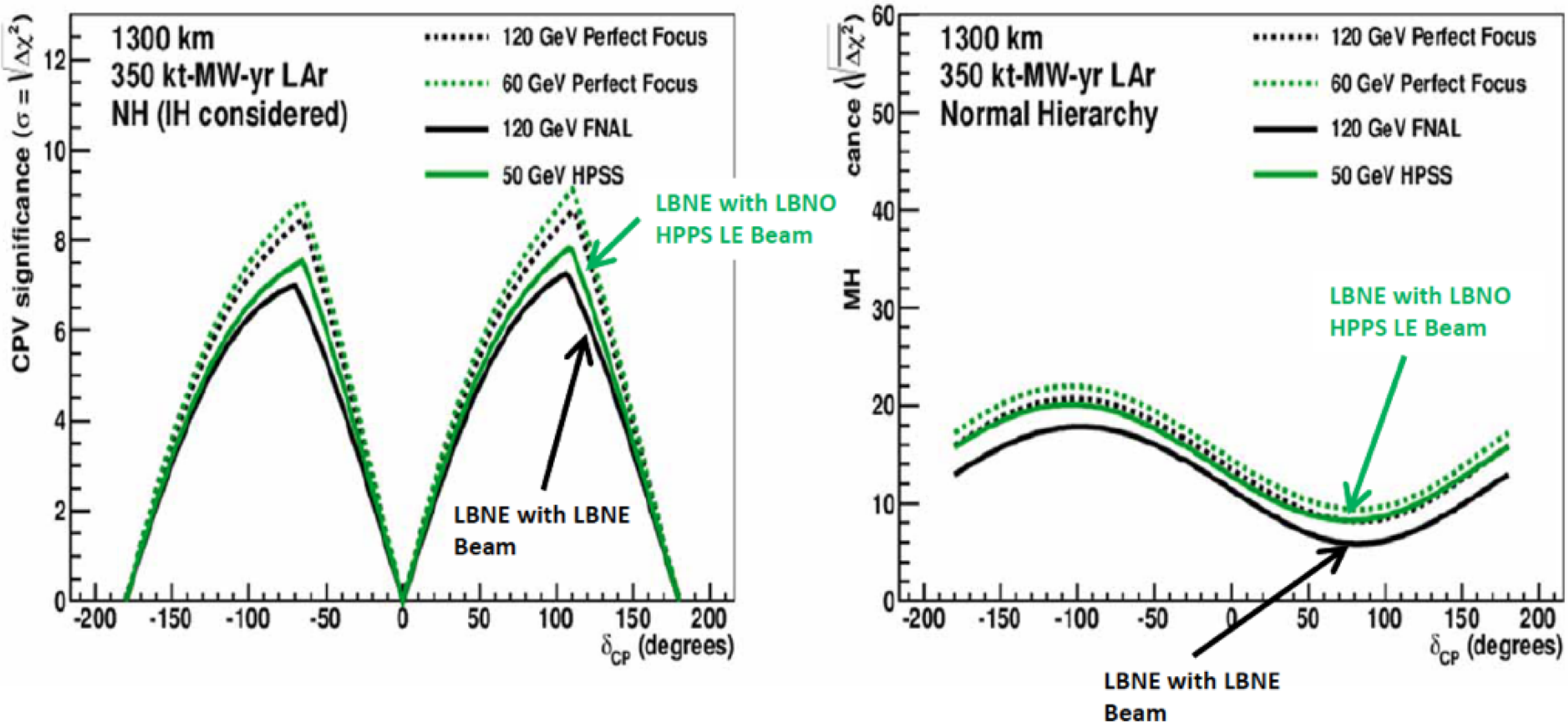

## CP Violation




Width of band indicates variation within the Capozzi 2013 allowed range for $\theta_{23}$.

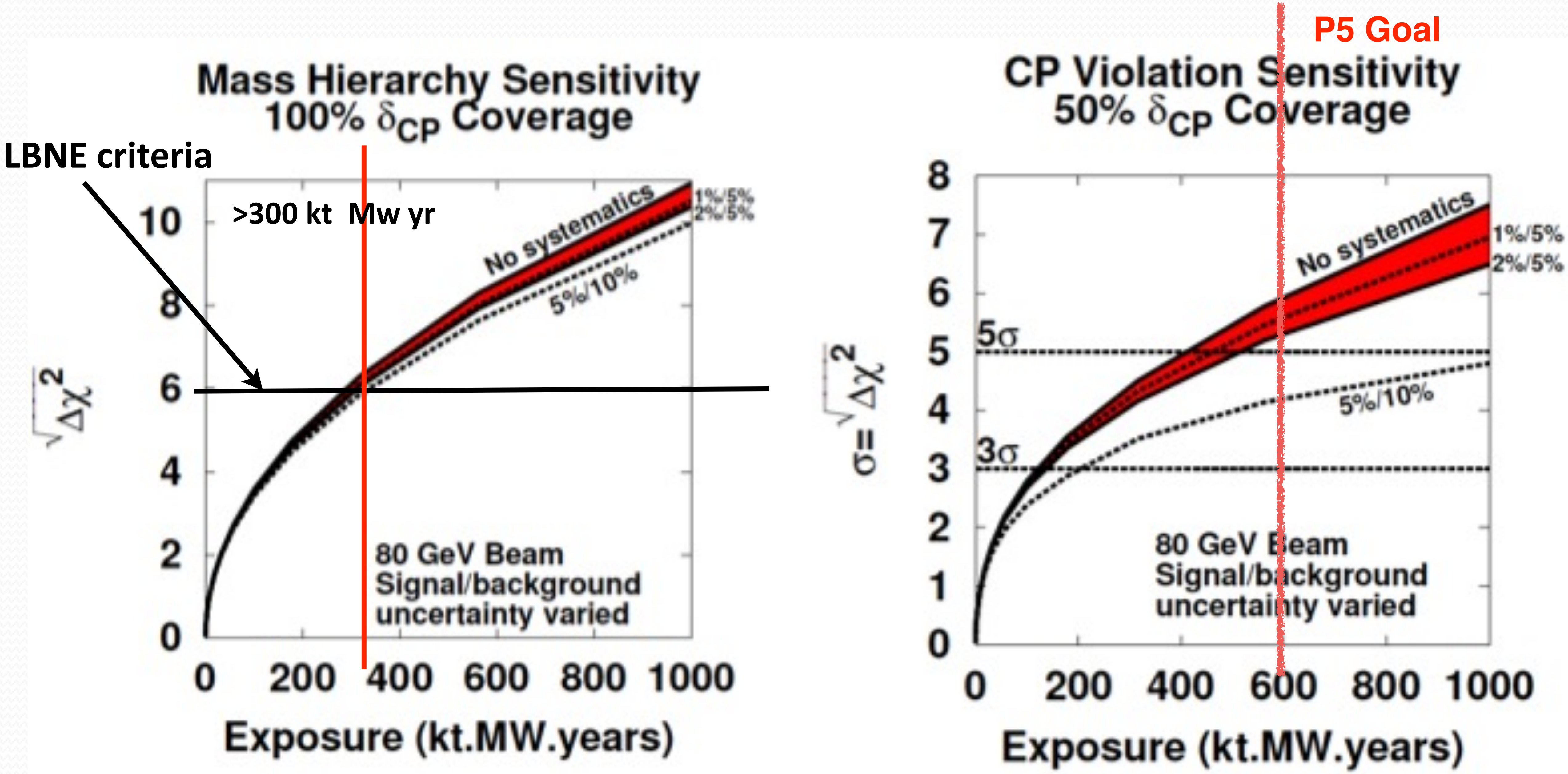
Exposure: 245 kt.MW.yr = 34 kt x 1.2 MW x ($3\nu+3\bar{\nu}$) years

# Apply LBNO-design low-energy beam (HPPS LE) to LBNE



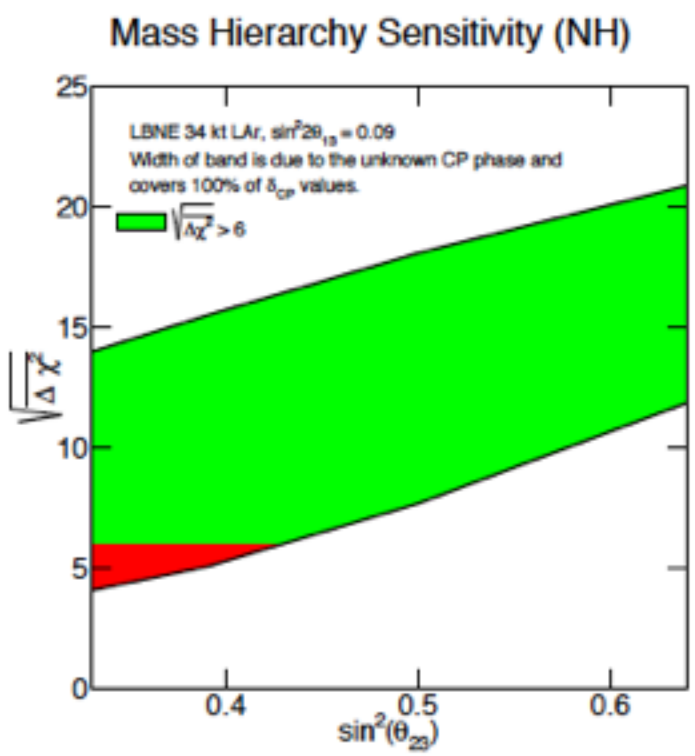

- Application of HPPS LE beam spectrum to LBNE baseline
  - modestly improves CP violation reach
  - improves minimum $\Delta\chi^2$ ~x2 for MH

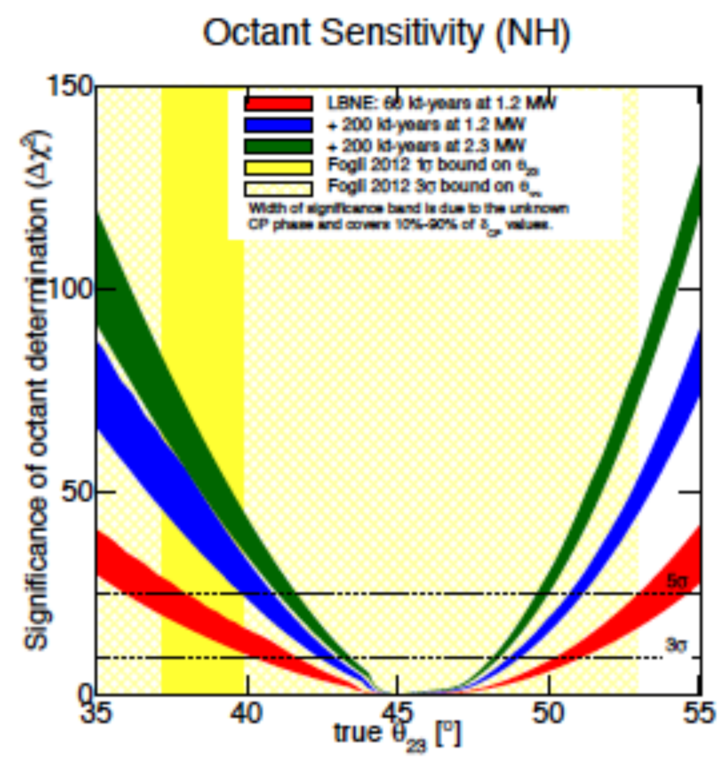
# Impact of Normalization Uncertainties

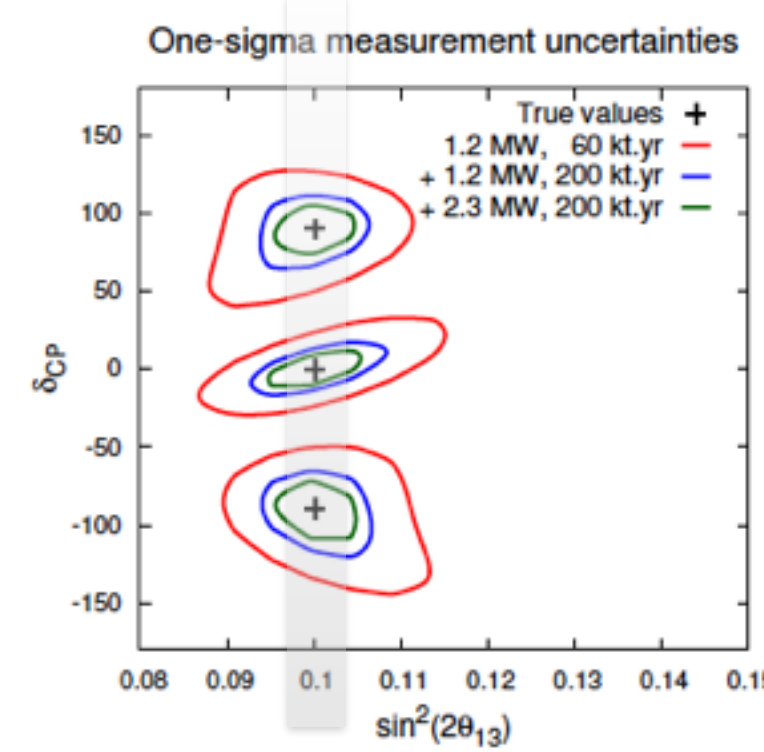



- <3% uncorrelated systematic errors appear realistic with recent progress.
- The systematic precision is required to be better than the expected statistics at each stage of the experiment. High precision is needed after 200kt*MW*yr.
- MH relatively insensitive to systematics; but further study needed.
- Large correlations and cancellations are expected in fitting the 4 far spectra and many near spectra. This work has reached the next level of sophistication.

# Other measurements for a comprehensive program.



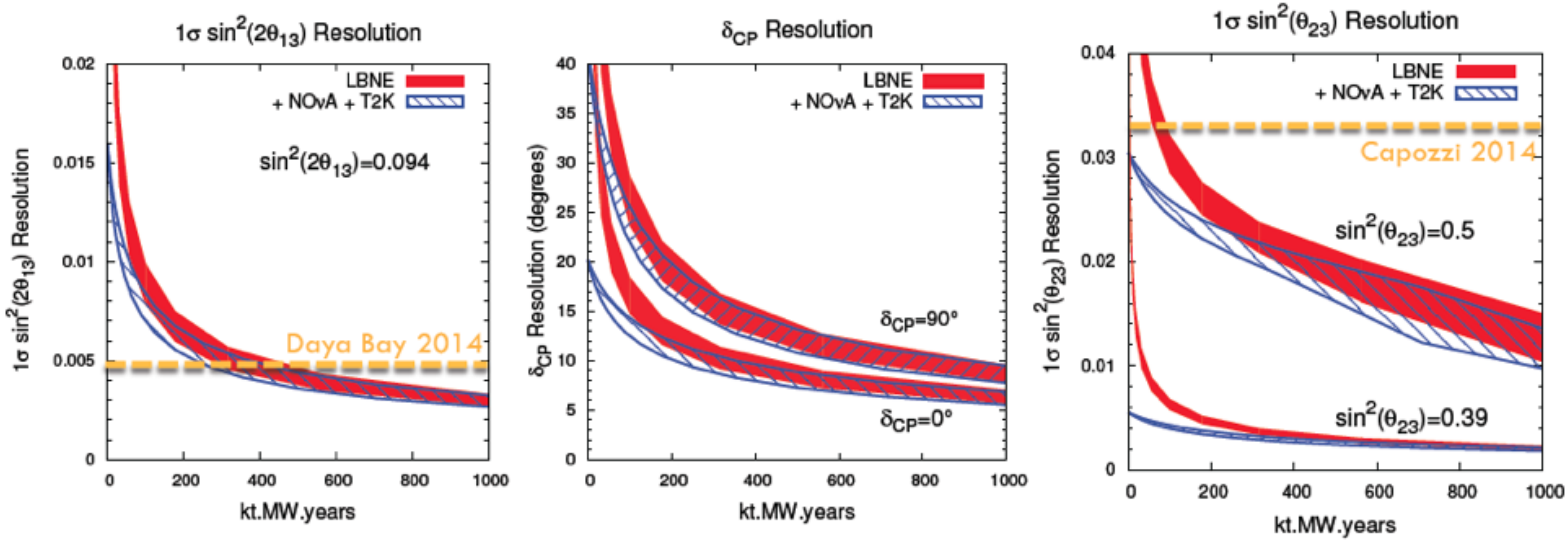




**Ultimate reactor sensitivity**

Because of the event rate the program will provide redundant and comprehensive parameter sensitivity for testing the 3-nu model.

Clearing some misunderstanding: For any exposure, we will get a measurement of the CP phase regardless of where it is. There are no ambiguities because of the broad-band beam. This sometimes gets confused with the significance regarding determination of CP violation.

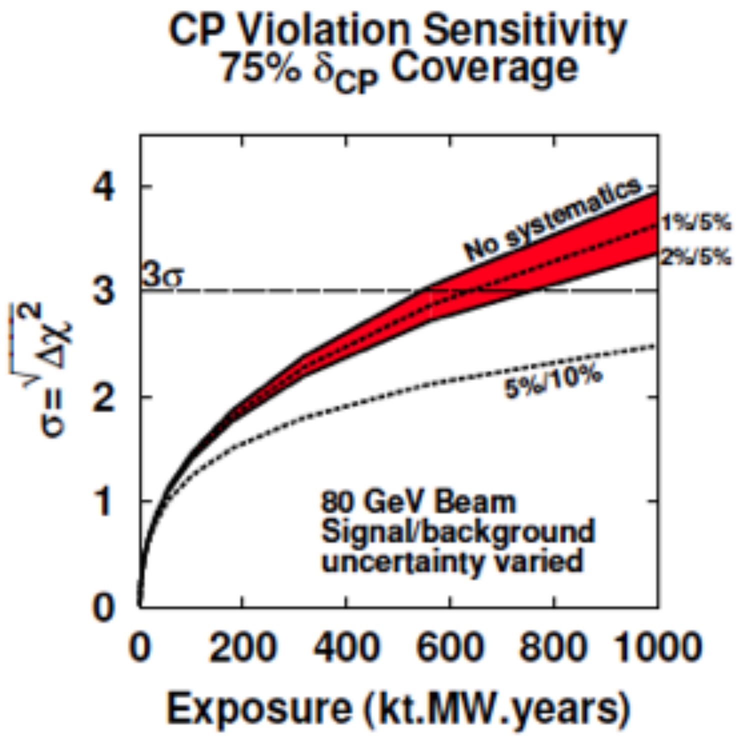
# Precision measurement of neutrino oscillation parameters in a single experiment:



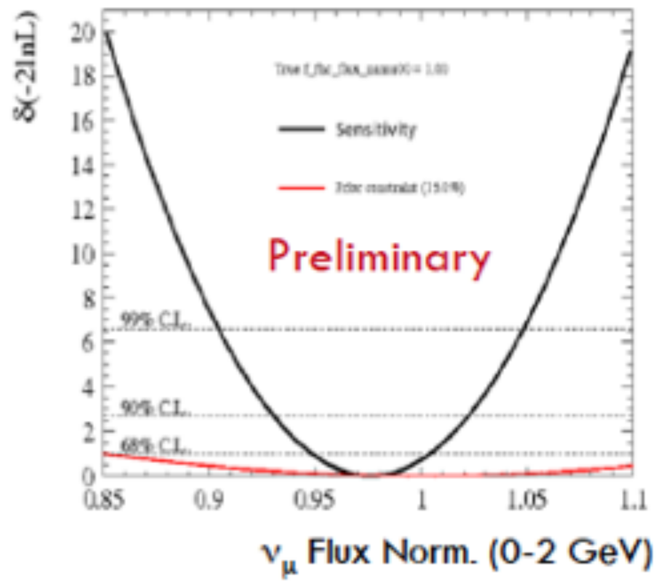

Elizabeth Worcester: Long-Baseline Neutrino Experiment NOW, 10 September 2014

**Parameter resolutions**

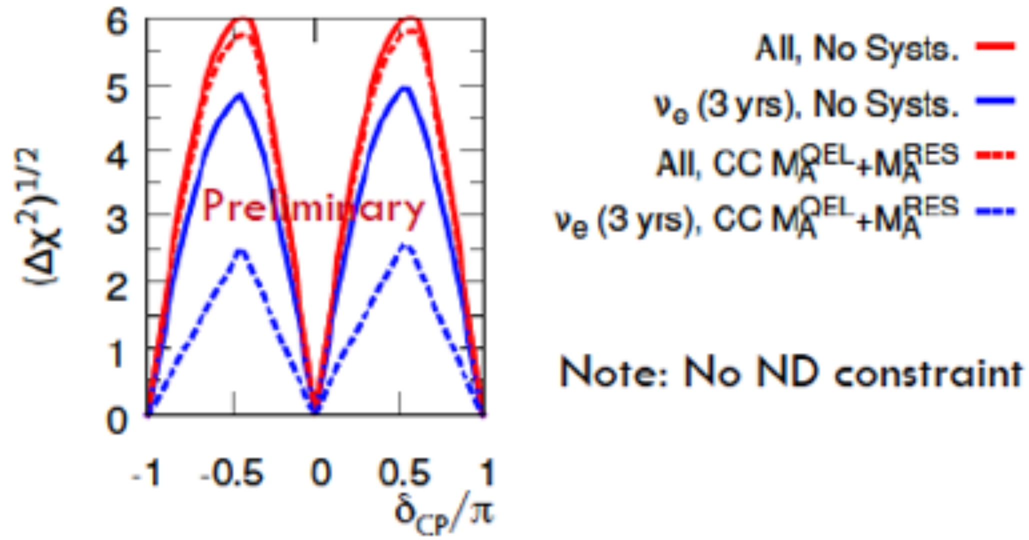
# Systematics




Example: Constraining flux with ND (VALOR)



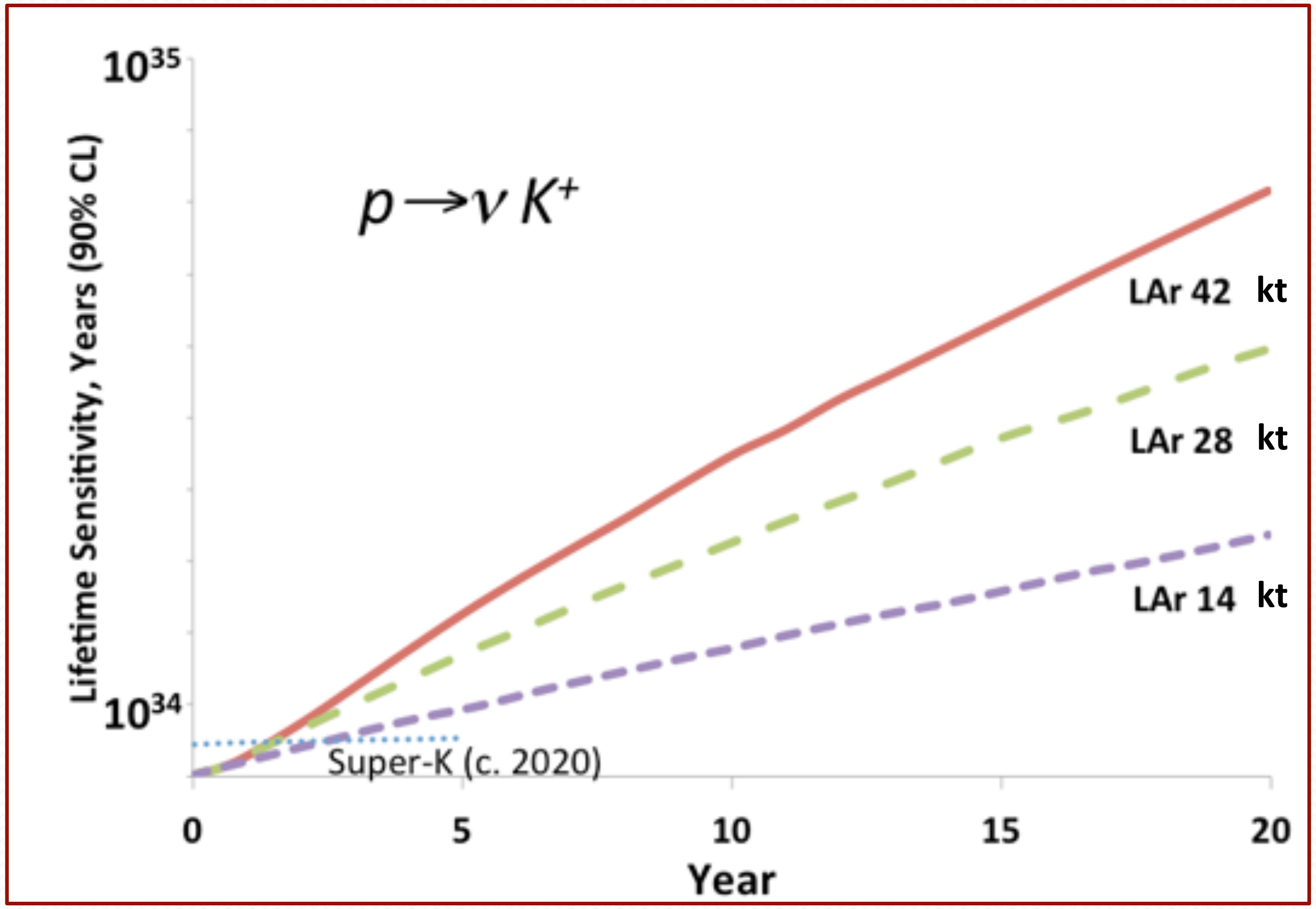

Example: Effect of cross-section uncertainty on CPV sensitivity using four FD samples (Fast MC)




- Signal and background normalization uncertainties used in GLoBES-based sensitivity studies are well-justified based on experience with previous experiments
- Evaluation of the extent to which more detailed treatment of systematic uncertainties affect sensitivity and the extent to which these uncertainties can be constrained by event samples in the near and far detectors are currently underway.
  - Preliminary studies show significant constraint on systematic uncertainty from both near and far detectors.
  - CETUP* 2014 workshop held July 2014 to develop plan for further study of systematic uncertainty.
- Design ongoing: **systematics-driven performance requirements will guide experiment design.**

# Proton Decay

In Liquid argon the Kaon will travel ~13 cm




**The key enabling issue is depth. The minimum depth required depends on active vetos if possible.**

**A depth at 4850 ft level would eliminate any risk.**

**What new justification can be made for this search, esp. regarding a LAr detector ?**

- LAr has high efficiency for SUSY-favored decay modes
- High spatial precision and energy resolution enable reconstruction of many potential decays modes

| Mode | Efficiency | Background Rate (evts/100 kton-y) |
|---|---|---|
| B-L | | |
| $p \rightarrow e^{+}\pi^{0}$ | 45% | 0.1 |
| $p \rightarrow \nu K^{+}$ | 97% | 0.1 |
| $p \rightarrow \mu^{+}K^{0}$ | 47% | $< 0.2$ |
| B+L | | |
| $p \rightarrow \mu^{-}\pi^{+}K^{+}$ | 97% | 0.1 |
| $p \rightarrow e^{+}K^{+}$ | 96% | $< 0.2$ |
| $\Delta B = 2$ | | |
| $N\bar{N} \rightarrow n(\pi)$ | TBD | TBD |

# $p \rightarrow K^+ \nu$ Signatures – I

- Two-body decay: for free protons, $K^+$ momentum 340 MeV,
  - But nuclear effects in Ar: (1) proton Fermi momentum (2) rescattering of K
  - Simulations in Geant4 show considerable smearing:

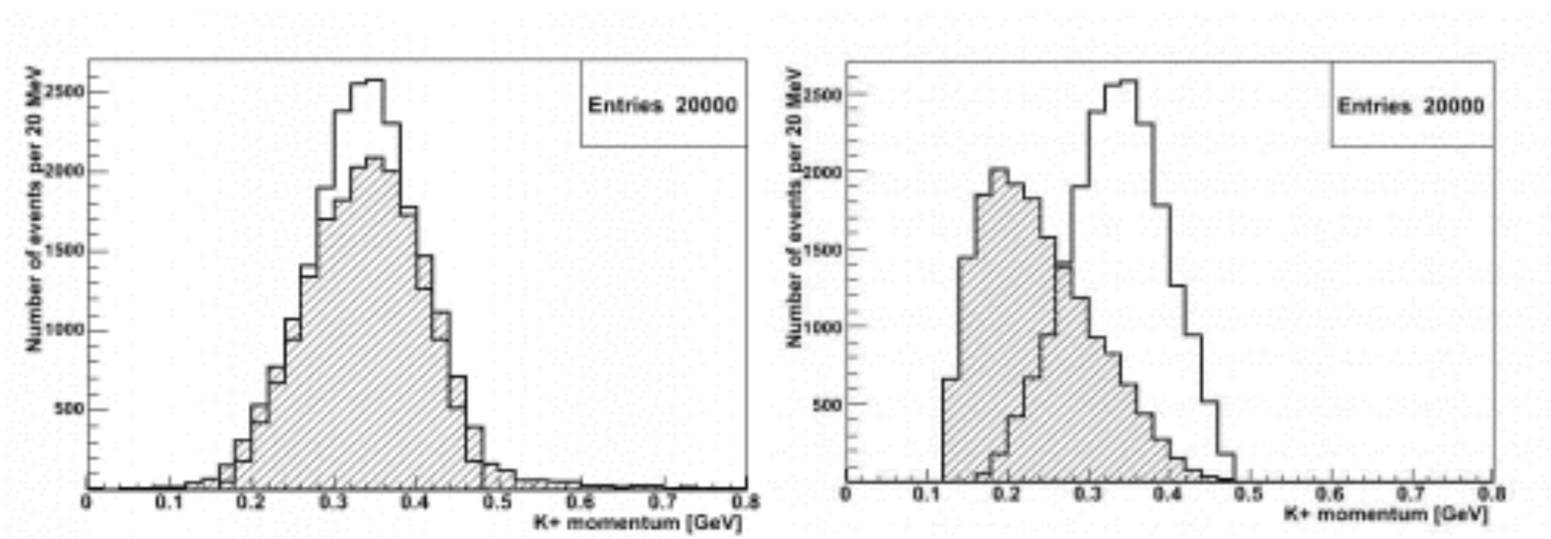
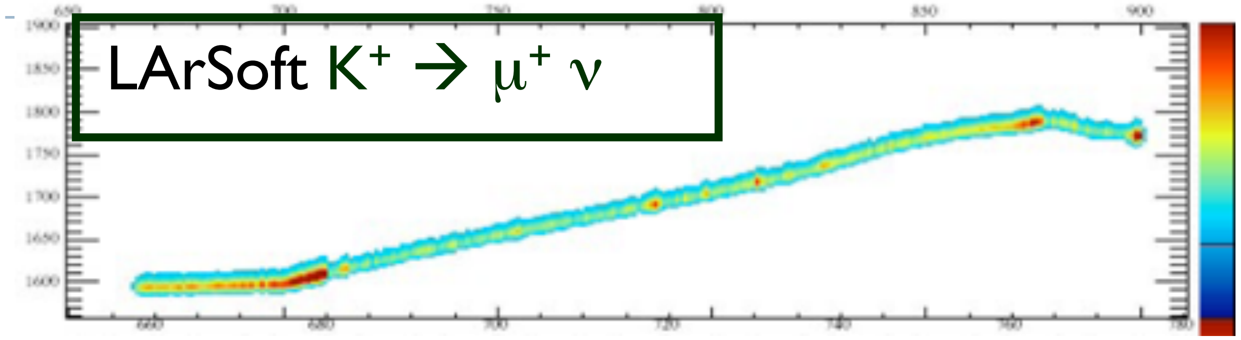



Fig. 1. Momentum distribution of kaons produced in the $p \to \bar{\nu} K^+$ decay inside the argon nucleus predicted by different approaches. Left: Calculations for the spectral function of argon (hatched) compared to the local Fermi gas model from GEANT4 without the intranuclear cascade (plain histogram). Right: GEANT4 with (hatched) and without (plain histogram) the cascade.

from Stefan & Ankowski, ArXiv:0811.1892 [nucl-th], 2009

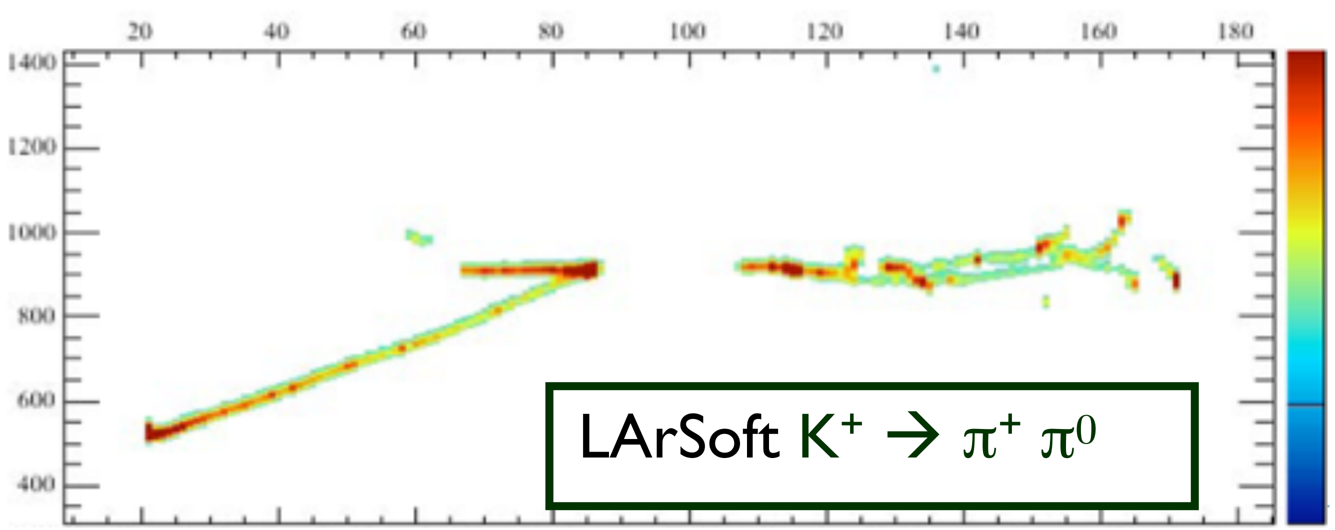
  - But note: below inelastic collision threshold → no absorption of $K^+$ within Argon nucleus → $K^+$ emerges intact in ~97% of $p \rightarrow K^+\nu$ decays.

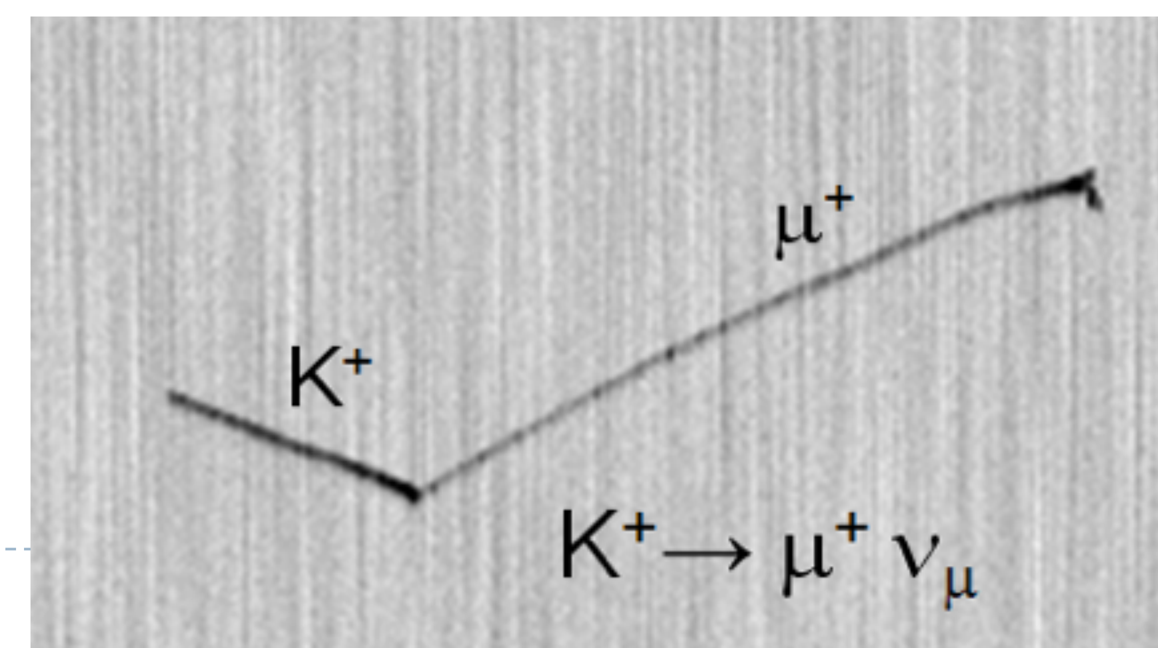
# $p \rightarrow K^+ \nu$ Signatures - III




- $K^+$ decay at rest: Simple topologies !
  - $\mu + \nu$ (63.6% BR): monochromatic $\mu$: $p_\mu = 236$ MeV
    - Minimum-ionizing track, momentum by range/multiple scattering/energy deposition
      - Note: muon from $\pi+$ decay-at-rest has $p_\mu = 30$ MeV
    - Followed by decay electron.
  - $\pi + \pi^0$ (20.7% BR): fully reconstructable final state
  - $3\pi$ ( 7.4% BR): fully reconstructable final states
  - $\pi^0 l^+ \nu$ ( 8.3% BR): kinematically constrained final states

ICARUS T300 data from 2001 surface run @ Pavia



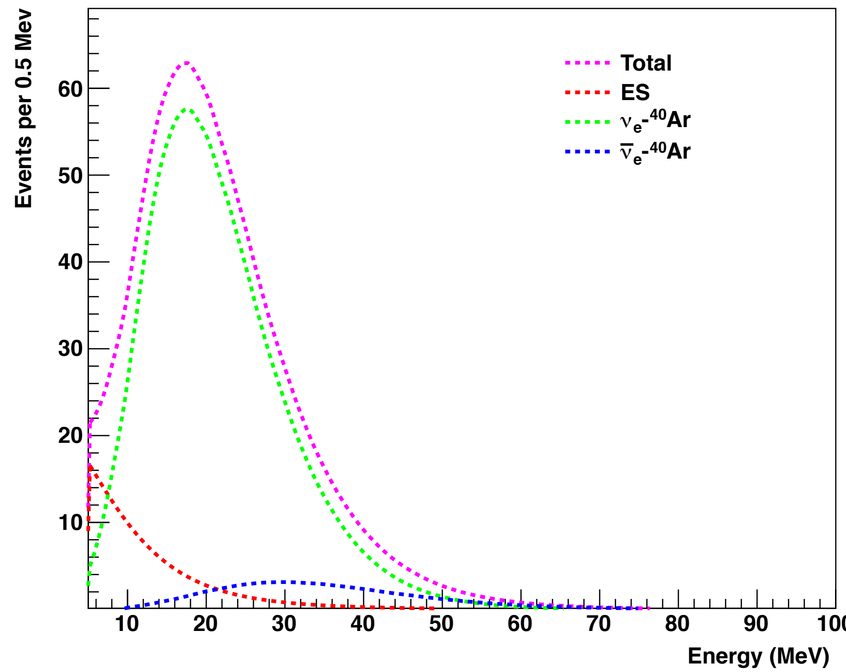
# p → $K^+$ ν: Background Issues

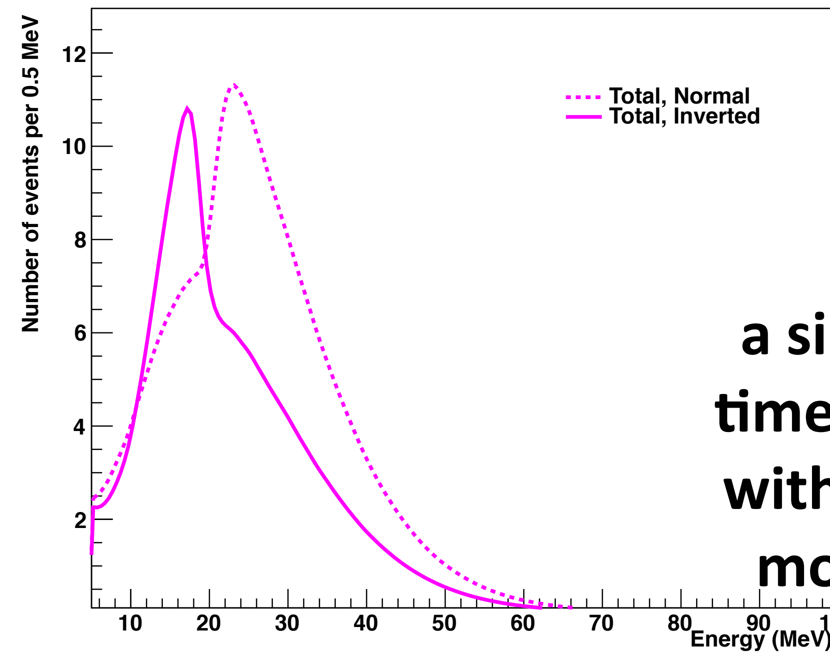
## Just Two Sources

- Cosmic ray muon induced backgrounds:
  - CR Rate at 4850L is ~0.1 Hz in 34-kt LBNE LArTPC
  - **10 yr run → ~3 x $10^7$ muons. Rejection needed is "only" at $10^{-7}$ level !!**
  - Easily met, since muons in detector volume are tracked with ~100% efficiency!

- Atmospheric Neutrinos:
  - Again consider: interaction rate in 34-kt detector only at level of few x $10^5$ per Mt-yr
  - **So rejection needed is 'only' at the$10^{-6}$ level !!**

# Supernova




**a single time slice with one model**

| Channel | Events, "Livermore" model | Events, "GKVM" model |
|---|---|---|
| $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*$ | 2308 | 2848 |
| $\bar{\nu}_e + ^{40}\text{Ar} \rightarrow e^+ + ^{40}\text{Cl}^*$ | 194 | 134 |
| $\nu_x + e^- \rightarrow \nu_x + e^-$ | 296 | 178 |
| Total | 2794 | 3160 |

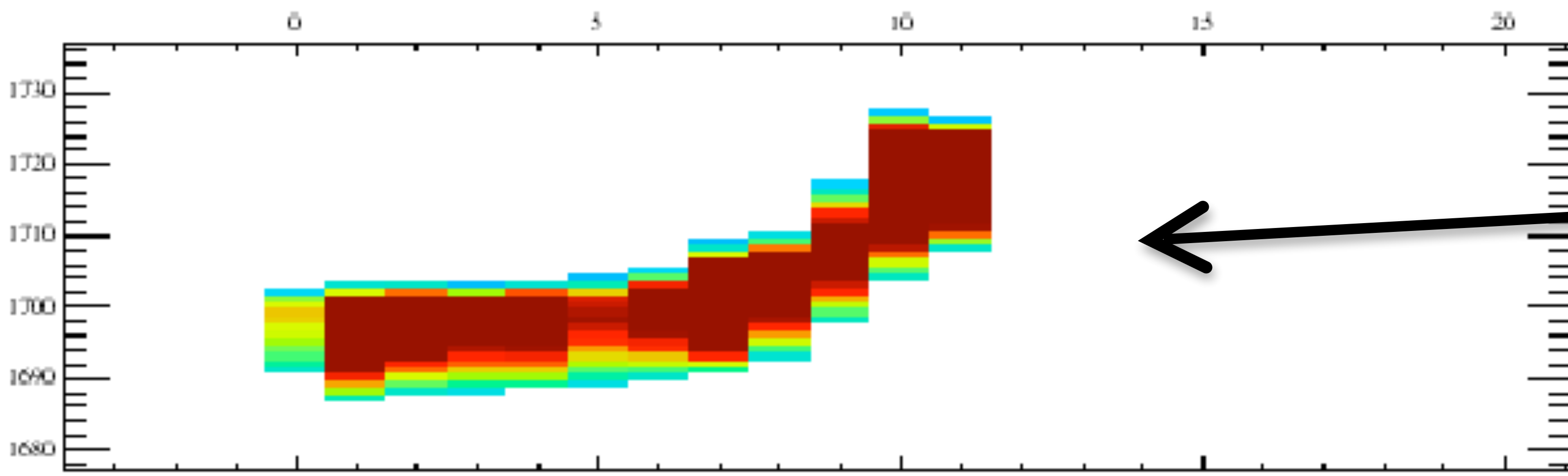
@10 kpc

**Table 6–7:** Supernova burst neutrino event rates for different models in 34 kton of LAr.

**Liquid Argon is sensitive to electron neutrinos. Water is sensitive to electron anti-neutrinos. Must have 10 MeV threshold for this physics. Need R&D on threshold and spallation backgrounds.**

**Fuller and Raffelt: Could extract a lot more physics and astrophysics from the supernova and other cosmic frontier data when we include the neutrino precision parameters in the fits.**

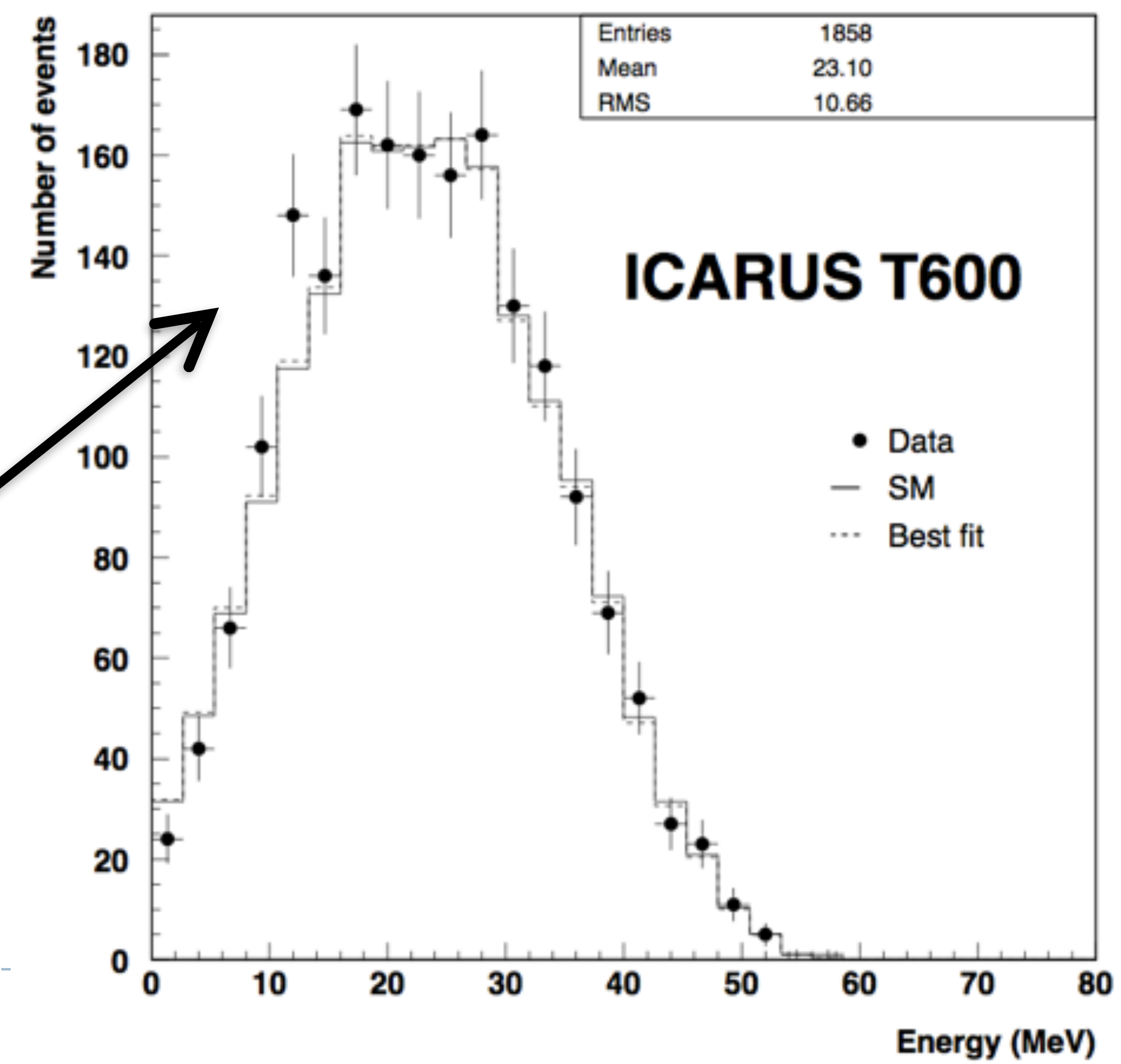
# Can SN $\nu_e$'s be Reconstructed?




20 MeV electron (LArSoft/LBNE geom)

- ICARUS 2003, Pavia CR Test
  - Michel electron energy spectrum
  - Note: sub-10 MeV threshold
  - Found resolution consistent with:

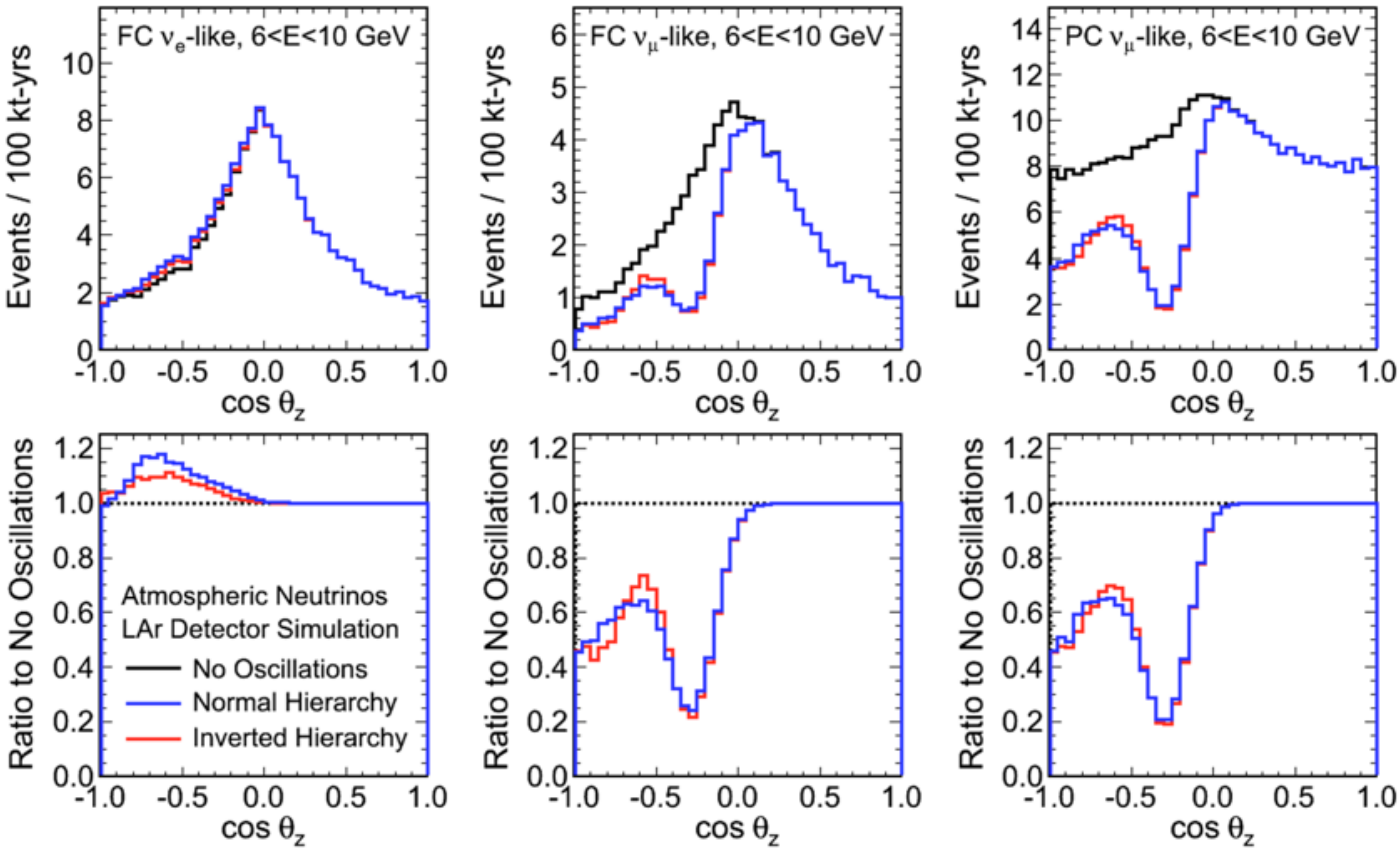
$$\frac{\sigma_E}{E} = \frac{11\%}{\sqrt{E[\mathrm{MeV}]}} + 2\%$$




Backgrounds from spallation could go up to 8 MeV, but for SN bursts a clever trigger could be devised.

# Atmospheric Neutrinos – MH sensitivity

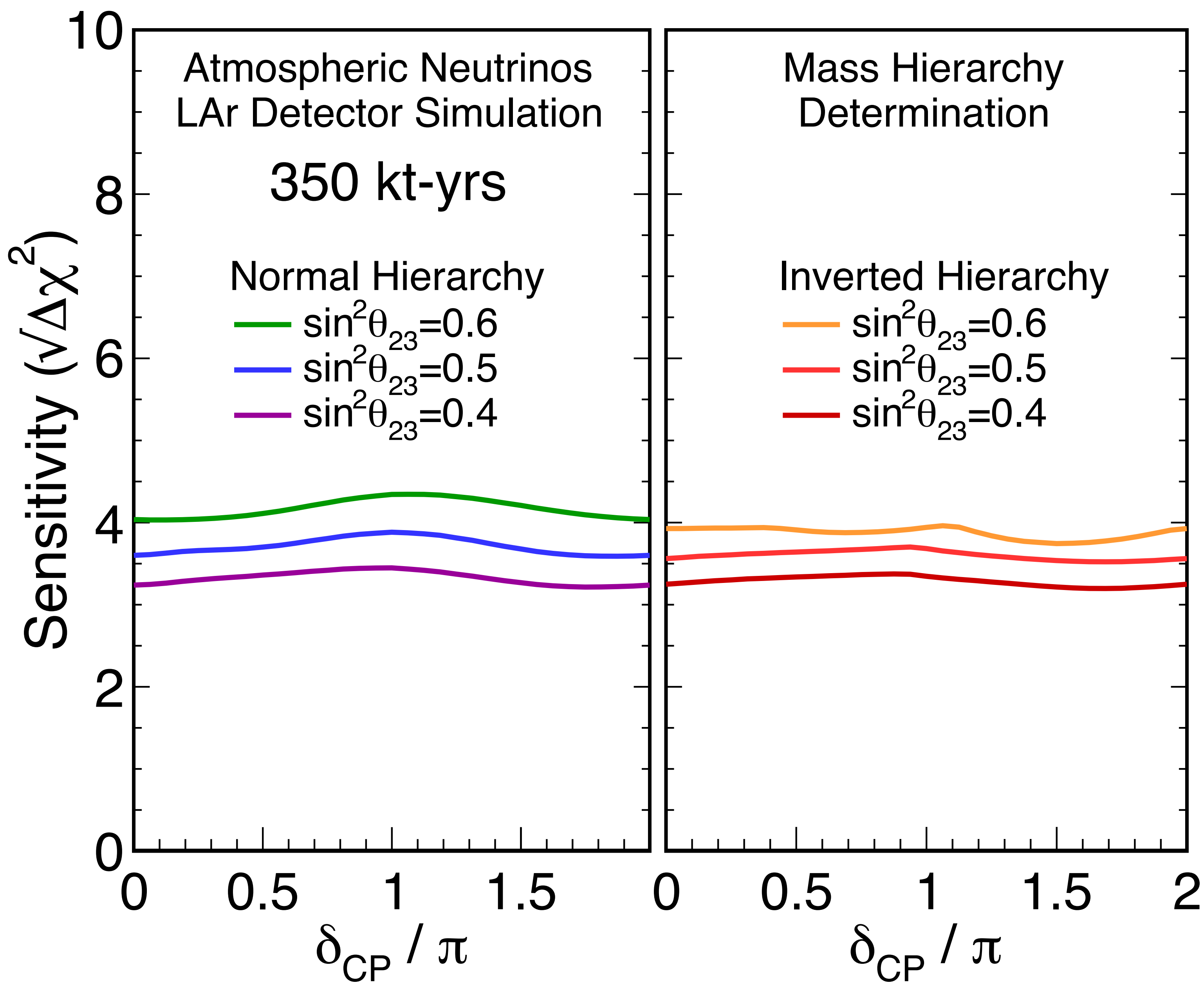
## Zenith angle distributions for events w/ E = 6-10 GeV
## Comparison of Normal vs Inverted MH





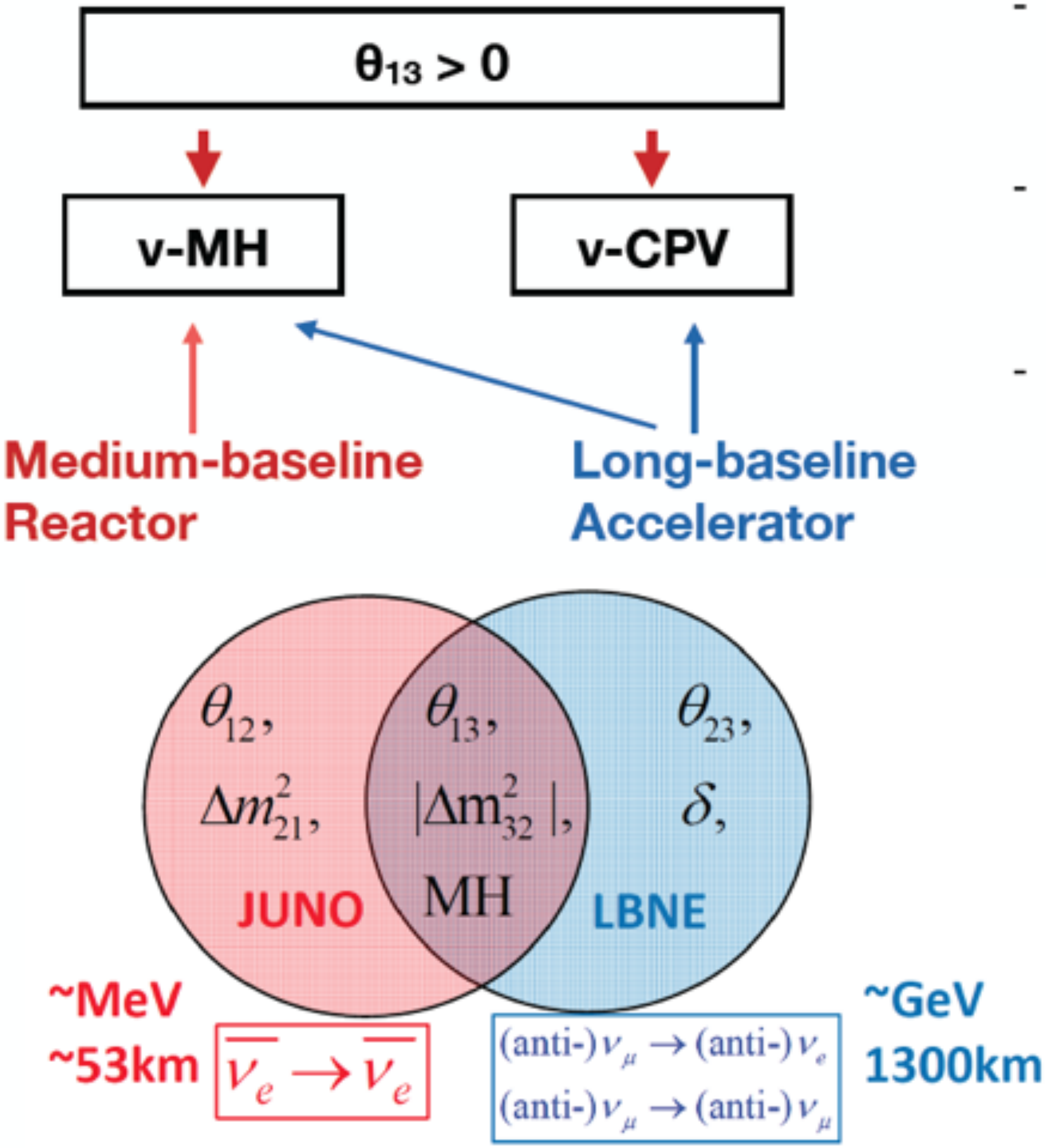

High resolution allows systematic checks within the data using upwards and downwards events.

# Atmospheric Neutrinos – MH results




Mass Hierarchy sensitivity is roughly independent of CP phase.

# Precision measurements of $U_{PMNS}$ with laboratory experiments.




**And, huge opportunities for underground science! proton decay, supernova… etc**

- Why is leptonic mixing angles large compared to quark mixing in CKM?
- Is there any pattern in $U_{PMNS}$ that guide us to the theory of flavor
- Is $U_{PMNS}$ unitary?

**The journey of PMNS unitarity test in the precision neutrino physics era just began!**

***X.Qian, C.Zhang, P.Vogel, M.Diwan arXiv: 1308.5700***

| | JUNO | LBNE |
|---|---|---|
| $\sin^2 2\theta_{12}$ | 0.7% | |
| $\Delta m^2_{21}$ | 0.6% | |
| $\|\Delta m^2_{32}\|$ | 0.5% | 0.3% |
| MH | 3-4σ* | >5σ |
| $\sin^2 2\theta_{13}$ | 14%** | 3% |
| $\sin^2\theta_{23}$ | | 3% |
| $\delta_{CP}$ | | 10° |

* 4σ requires 1% $|\Delta m^2_{uu}|$ ** Daya Bay reaches 3%

**LBNE is a comprehensive experiment. When combined with a reactor effort we characterize the whole matrix redundantly.**

**Table 2.1:** Best-fit values of the neutrino mixing parameters in the PMNS matrix (assumes normal hierarchy) from [54], their $1\sigma$ uncertainties and comparison to the analogous values in the CKM matrix [55]. $\Delta M^2$ is defined as $m_3^2 - (m_1^2 + m_2^2)/2$.

| Parameter | Value (neutrino PMNS matrix) | Value (quark CKM matrix) |
|---|---|---|
| $\theta_{12}$ | $34 \pm 1°$ | $13.04 \pm 0.05°$ |
| $\theta_{23}$ | $38 \pm 1°$ | $2.38 \pm 0.06°$ |
| $\theta_{13}$ | $8.9 \pm 0.5°$ | $0.201 \pm 0.011°$ |
| $\Delta m_{21}^2$ | $+(7.54 \pm 0.22) \times 10^{-5}$ eV$^2$ | |
| $\lvert\Delta M^2\rvert$ | $(2.43^{+0.10}_{-0.06}) \times 10^{-3}$ eV$^2$ | $m_3 >> m_2$ |
| $\delta_{CP}$ | $-170 \pm 54°$ | $67 \pm 5°$ |

$$J_{CP}^{\text{PMNS}} \approx 0.03 \sin \delta_{\text{CP}}. \qquad\qquad J_{CP}^{\text{CKM}} \approx 3 \times 10^{-5},$$

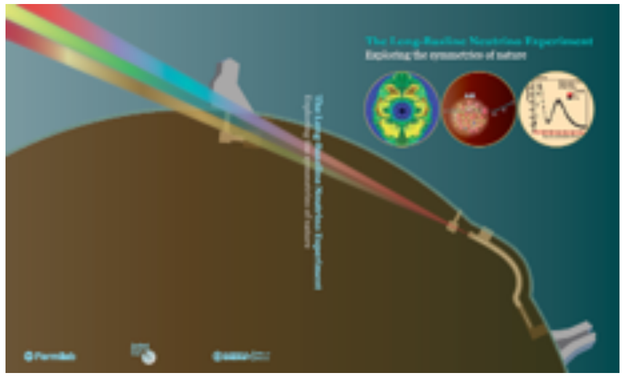
Whether or not this is due to deep underlying principles or has fundamental consequences (such as BAU), this sharp contrast requires imaginative solutions.

# LBNE →LBNF

- **An active process is taking place to create a new international collaboration that will completely reexamine the science and configuration choices for a very capable long-baseline experiment.**
- **Process started with an invited summit meeting at FNAL (July 21-22). First meeting of the formed interim International Exec Board took place Sep. 23-24. See https://indico.fnal.gov/conferenceDisplay.py?confId=8937**
- **Participation in iIEB is broad from Europe, Asia, Latin America.**
- **Interim International Exec board ended with broad agreement on**
  - **Scientific Goals.**
  - **Main configuration parameters and a process to reexamine them based on various scientific strategies.**
  - **Rapid process for assembling an LOI (Oct. 2014) and a CDR (FY2015)**

# Conclusion

- Scientific motivation and scale of the next generation long-baseline neutrino oscillation experiment is well-known. Discovery of $\theta_{13}$ has guaranteed that LBNE will measure the CP phase, and perform a comprehensive experiment.
- LBNE design in the US meets the requirements for a comprehensive experiment in the neutrino sector with community consensus.
- LBNE and LBNO (Europe) have independently designed regional solutions to this scientific opportunity. Transition to LBNF will create a global consensus.
- The US is in a unique position to execute this program given the availability of high intensity accelerator
  - 700 kW upgrade in commissioning
  - 1.2 MW by the time of LBNE start and 2.3 MW in the future.
- An operating world-class Sanford Underground Research Facility (Dark Matter and Double Beta Decay experiments have started at 4850L)
- Optimization of baseline and beam shows we have made correct choices.



- Science Document produced for Snowmass arXiv:1307.7335
- To be updated annually and printed.