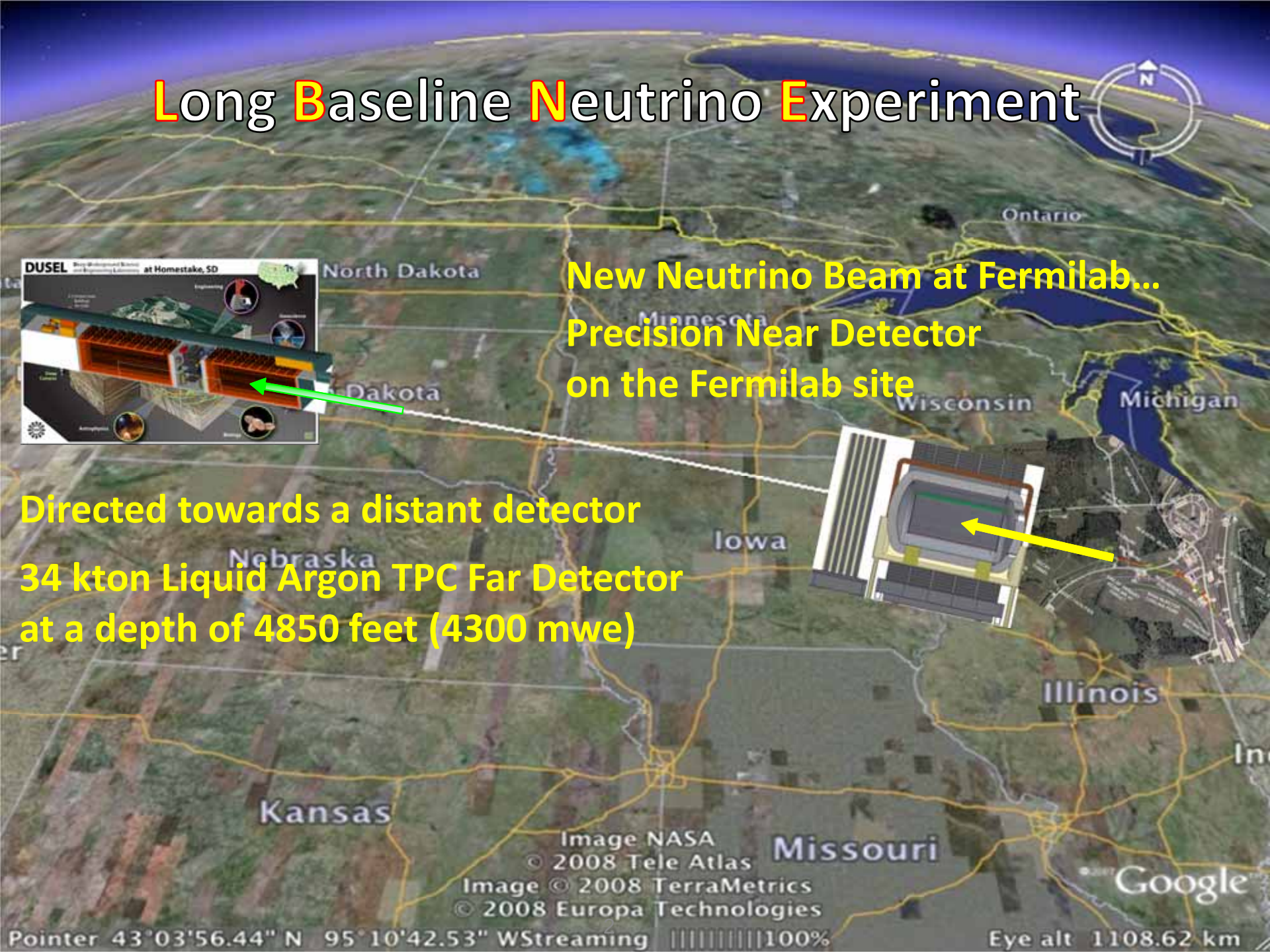
Long-Baseline Neutrino Experiment Plans

Jim Strait
Fermilab

Project X Physics Workshop
16 June 2012

Long Baseline Neutrino Experiment



New Neutrino Beam at Fermilab…

Precision Near Detector on the Fermilab site

Directed towards a distant detector

34 kton Liquid Argon TPC Far Detector at a depth of 4850 feet (4300 mwe)

Long-Baseline Neutrino Experiment Collaboration

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346 Members
62 Institutions
25 US States
5 Countries

1 June 2012 (346)

Physics Research Goals of LBNE

The primary science objectives of the LBNE Project are:

1. A search for, and precision measurements of, the parameters that govern $\nu_\mu \rightarrow \nu_e$ oscillations. This includes measurement of the third mixing angle θ_{13}, for whose value only an upper bound is currently known, and if θ_{13} is large enough, measurement of the CP-violating phase δ and determining of the mass ordering (sign of Δm^2_{32}).
2. Precision measurements of θ_{23} and $|\Delta m^2_{32}|$ in the ν_μ disappearance channel.
3. Search for proton decay, yielding a significant improvement in current limits on the partial lifetime of the proton (τ/BR) in one or more important candidate decay modes, e.g. $p \rightarrow e + \pi^0$ or $p \rightarrow K^+ \nu$.
4. Detection and measurement of the neutrino flux from a core collapse supernova within our galaxy, should one occur during the lifetime of LBNE.

Though outside of the primary objectives, the far detector placed at the proposed depth could enable studies of atmospheric ν physics, and with additional upgrades, studies of day/night ^{8}B solar ν physics and relic supernova neutrinos.

In addition to the physics goals of the Far Detector, the Near Detector Complex will enable precision measurements of neutrino cross sections which are needed for the long-baseline physics.

LBNE – Neutrino Oscillations

- LBNE plans a comprehensive program to measure neutrino oscillations
- With its 1300 km baseline, high-power beam, and precision detector, it will:
  - Measure full oscillation patterns in multiple channels, precisely constraining mixing angles and mass differences.
  - Cleanly separate matter effects from CP-violating effects.
  - Search for CP violation both by measuring the parameter δ_{CP} and by observing differences in ν and $\bar{\nu}$ oscillations.

LBNE – Project Design

- A robust conceptual design has been developed for all elements:
  - Beam optimized for this physics, upgradeable to >2 MW
  - Precision near detector: LAr TPC or straw-tube tracker.
  - Simple, scalable design for a large LAr TPC far detector.
  - All of the extensive civil engineering required to construct the beam and experiment.
- The engineering design and the project plan have been thoroughly reviewed and found to be sound.
- The project is ready to move forward to complete design and construction.

Staging LBNE

Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

A report outlining options and alternatives is needed as soon as practical to provide input to our strategic plan for the Intensity Frontier program. OHEP will provide additional details on realistic cost and schedule profiles and on the due date for the report.

We have considered both the science opportunities and the cost and schedule estimates for LBNE that you have presented to us. We have done so in the context of planning for the overall Office of Science program as well as current budget projections.

Based on our considerations, we cannot support the LBNE project as it is currently configured. This decision is not a negative judgment about the importance of the science, but rather it is a recognition that the peak cost of the project cannot be accommodated in the current budget climate or that projected for the next decade.

In order to advance this activity on a sustainable path, I would like Fermilab to lead the development of an affordable and phased approach that will enable important science results at each phase. Alternative configurations to LBNE should also be considered. Options that allow us to independently develop the Homestake Mine as a future facility for dark matter experiments should be included in your considerations.

A report outlining options and alternatives is needed as soon as practical to provide input to our strategic plan for the Intensity Frontier program. OHEP will provide additional details on realistic cost and schedule profiles and on the due date for the report.

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Criteria for a sustainable strategy

- Drives world-leading physics
- Is supported by the HEP community
- Continually produces scientific results
- Attracts international participation
- Is resilient relative to instability in the US system
- Is resilient relative to new discoveries
- Has the full support of the Office of Science
- Is affordable (the definition of affordability varies with time, up and down)

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Strategy: practical matters

- We have worked hard to design a strategy that:
  - Fits the likely budgetary constraints
  - Builds on getting the greatest returns from existing investments in our current accelerators and detectors
  - Sets the platform for future initiatives
  - Sets the trajectory for Fermilab and the US program to be leaders at the Intensity Frontier
- We enjoy DOE support to achieve these broad goals. DOE support includes: running the existing facilities, completing ongoing projects like DES and NOvA, building new projects like Mu2e and Muon g-2 and setting the path towards long term achievements with LBNE and Project X
- A key element of the strategy is LBNE

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The restructuring of LBNE

- Dr. Brinkman's letter: LBNE as currently designed is not affordable; requested phased approach and/or alternatives with physics at every stage
- We have carried out a major re-planning effort with the involvement of the community (many leaders); all major stakeholders; open process with all documentation on the web
- Held community workshop

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Organization of the effort

Steering Committee: Developed viable options, prepared the report

Physics Working Group: Analyzed physics reach with common assumptions

Engineering/cost Working Group: Developed cost with common methodology

Steering Committee Interim Report presented to DOE on June 6:
https://indico.fnal.gov/conferenceDisplay.py?confId=5622

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Issues for LBNE Phase 1

- Main issues:
  - What compromises to make in the physics for Phase 1 in order to make it affordable
  - What long-term physics limitations are imposed by the different options for Phase 1
- The fundamental practical choice:
  - Do we use the existing beamline to NuMI or do we develop a new beamline to Homestake?

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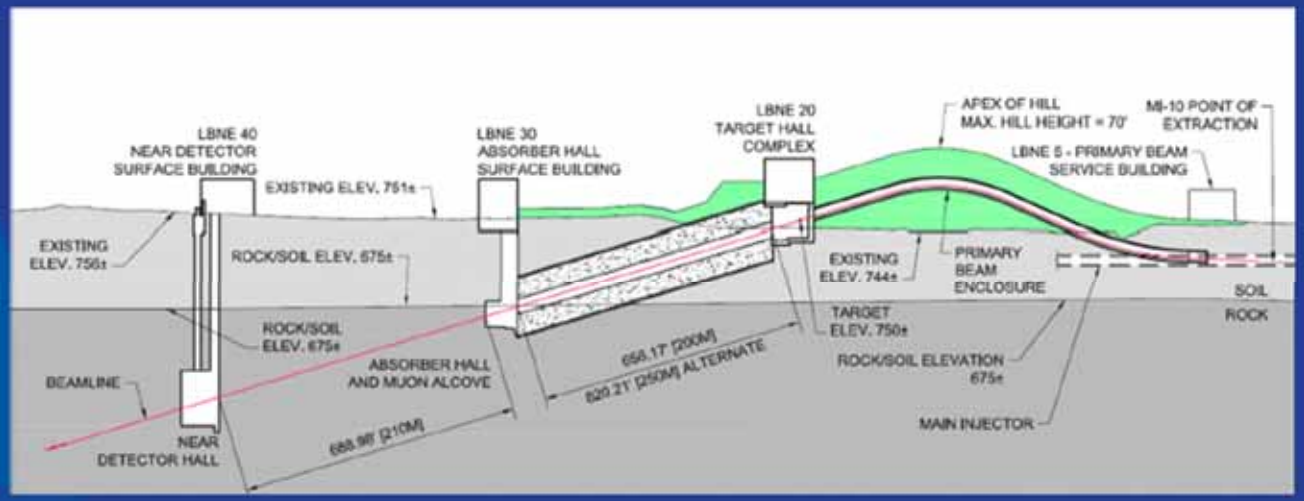
A beamline is a significant investment

- Extraction and transport from the Main Injector to target
- Target hall allows repairs in high-radiation environment
- Focusing horns for secondary particles
- Large underground decay pipe (675m for NuMI and 200m for Homestake), with aquifer protection to higher levels than NuMI beamline



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Issues for LBNE Phase 1

- Using the existing NuMI beamline saves the cost of a new beamline and allows funding a more ambitious detector in Phase 1 (allows either a very large detector on the surface or a smaller detector at depth) -- but permanently limits the future physics reach for neutrino physics. How significant is this?

- Developing a new beamline to Homestake requires the investment of substantial resources that, within limited budgets, reduces the scale of the Phase 1 detector -- but preserves the ability to develop the full physics potential in the long term. Is the Phase 1 physics reach "good enough" to justify the first phase and attract partners?

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Reconfiguration Process

- A large number of options were considered, with full study of the physics reach and corresponding engineering/cost studies
- We worked within a guideline of trying not to exceed about $700M to $800M for LBNE Phase 1 (including escalation and contingency), fully aware that it will be easier to get going with lower costs
- At the end, three options were considered viable, each with at least one strength greater than the others. One of the three options was strongly favored by the Steering Committee, but is also the most costly
- To understand how we arrived to a favored option we need to discuss some physics

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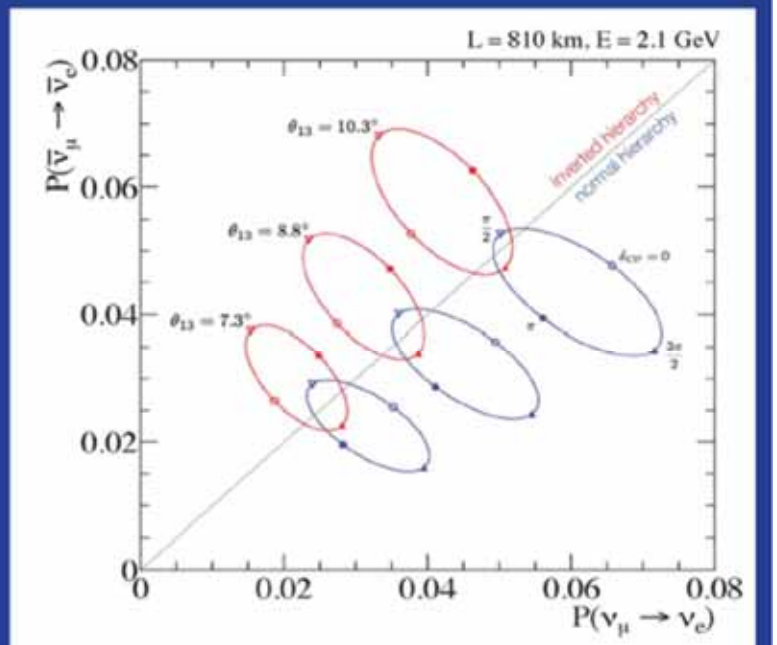
What does a large θ_{13} mean?

- For values of $\sin^2 2\theta_{13}$, >0.02 the measurement of δ_{CP} is largely independent of $\sin^2 2\theta_{13}$
- A large $\sin^2 2\theta_{13}$ helps the measurement of the mass hierarchy at baselines shorter than Homestake – but not over the full range of δ_{CP}
- A large $\sin^2 2\theta_{13}$ allows mass hierarchy measurement across the full range of δ_{CP} with a smaller detector at Homestake



Neutrino oscillations in NOVA

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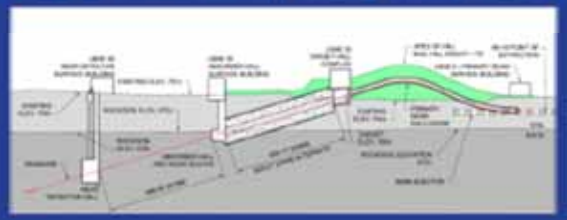
Three options with different strengths

- 1. The existing NuMI beamline in the "low-energy configuration" with a **30 kton** LAr-TPC **surface detector** 14 mrad off-axis at Ash River **(810 km)**
- 2. The existing NuMI beamline in the "low-energy configuration" with a **15 kton** LAr-TPC **underground (2300 ft) detector** on-axis at the Soudan mine **(735 km)**
- 3. The new LBNE beamline in the low-energy configuration on-axis with a **10 kton** LAr-TPC **surface detector** at Homestake in South Dakota (**1,300 km**)



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Three options with different strengths

	Ash River	Soudan	Homestake
Baseline	810 km	735 km	1300 km
Detector Mass	30 kt	15 kt	10 kt
Detector position	Surface	Underground 2300 ft	Surface
Beamline	Existing NuMI	Existing NuMI	New

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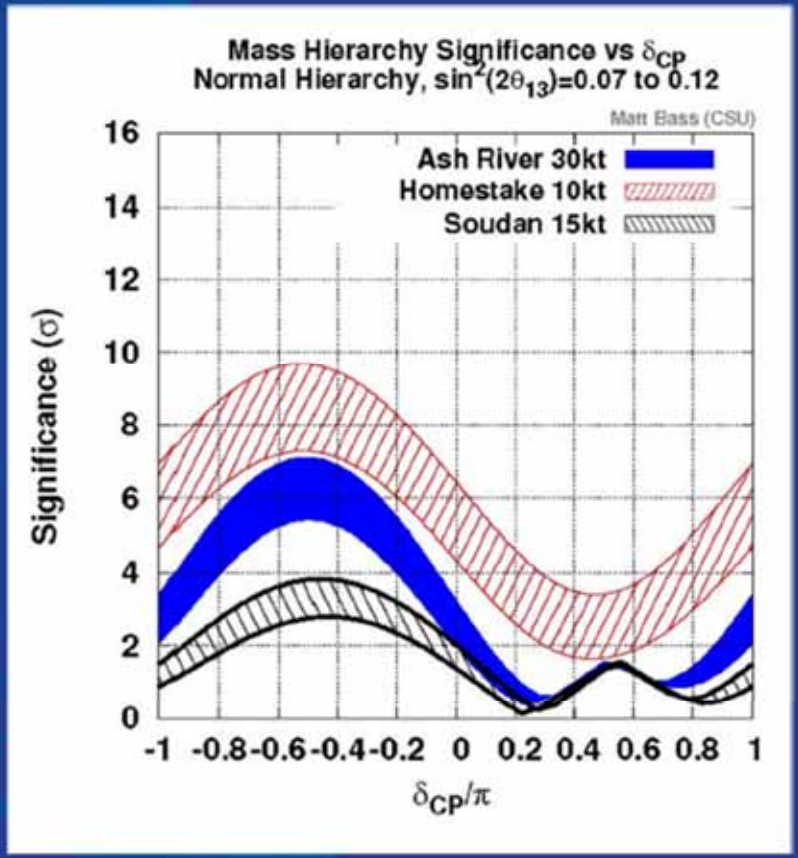
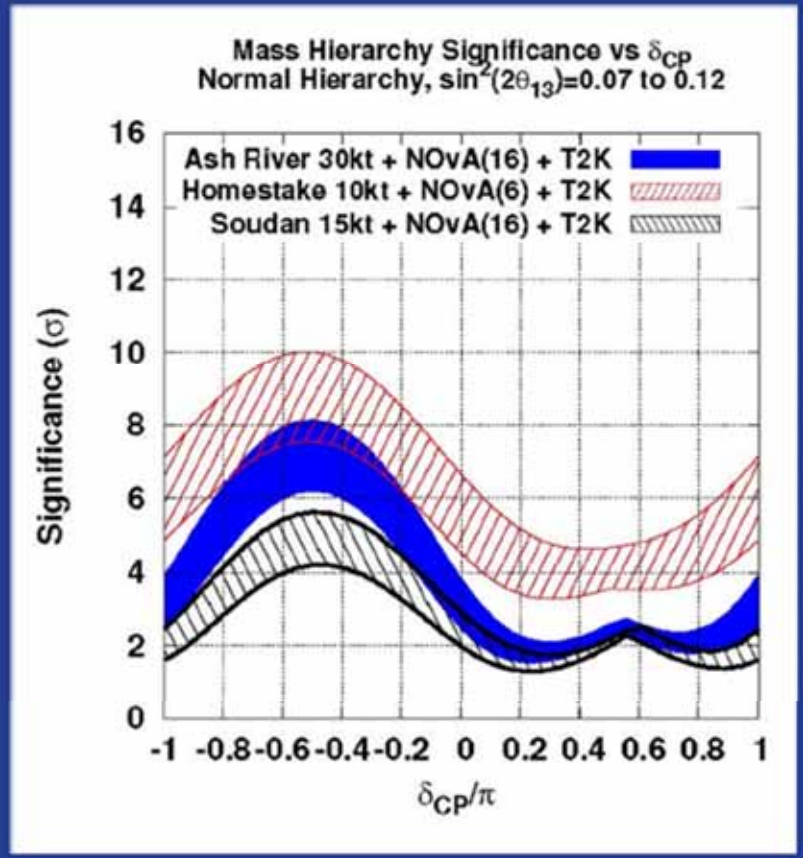
Mass hierarchy reach





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Mass hierarchy reach

- The oscillation effects due to δ_{CP} and the matter effect (mass hierarchy) can both go in the same direction in which case the mass hierarchy is easier to determine or in opposite directions in which case it is harder to determine
- Adding other baselines (e.g., T2K) to either Homestake or NuMI directions helps the weak part of the δ_{CP} range
- Distance makes a big difference. At a sufficiently long distance the effects of δ_{CP} and the matter effect do not overlap within the measurement precision
- A smaller detector towards Homestake does substantially better than larger detectors in the NuMI direction

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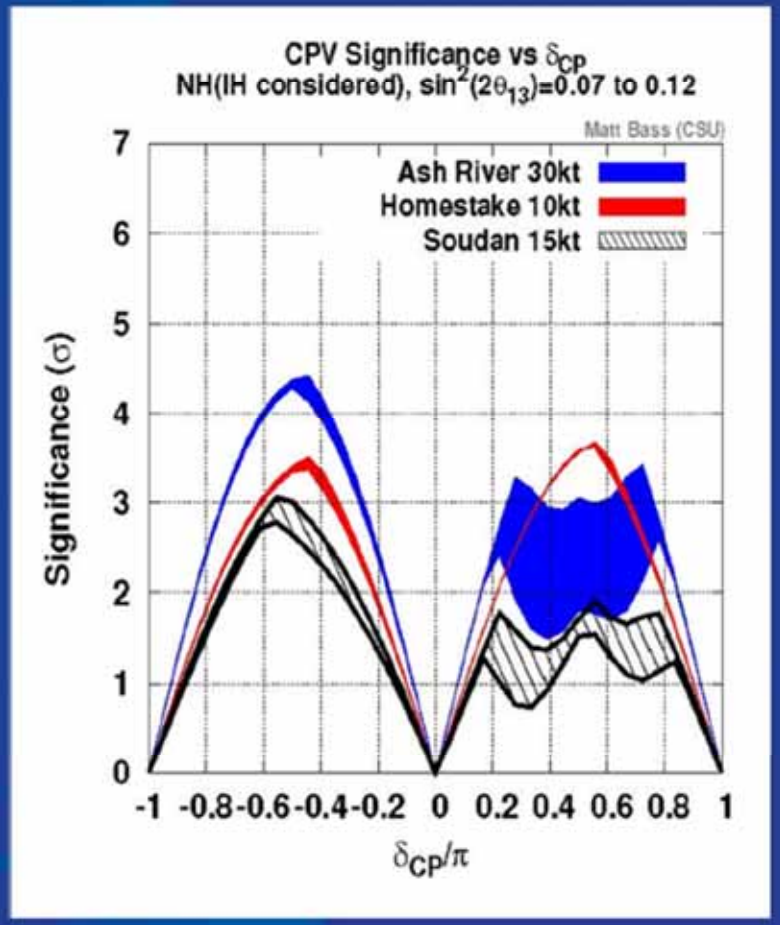
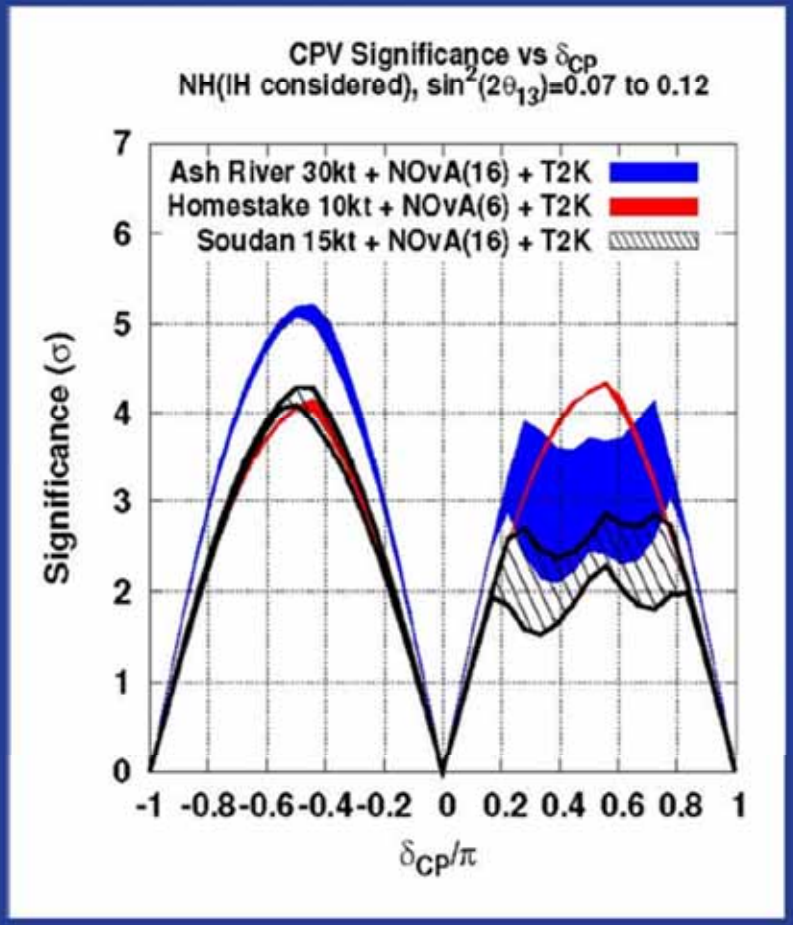
Reach in CP violation





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Reach in CP violation

- The larger tonnage at Ash River relative to Homestake and Soudan makes the Ash River option the best for CP violation in one half the delta space. If the mass hierarchy is resolved with the help of other experiments, then it is the Phase 1 option with the highest reach in δ_{CP}
- The Homestake option with the lowest mass of the three options does reasonably well for the full range of δ_{CP} for the Phase 1 experiment
- Soudan has a a more limited reach in δ_{CP} due to the shortest baseline and more limited tonnage than Ash River. It has the advantage of starting deep underground physics (proton decay, SN collapse) early.

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Beyond measuring parameters…

- Beyond the measurement of the missing parameters of the 3x3 mixing matrix, LBNE in the Homestake direction gives us the best sensitivity to new physics
- The beam energy spectrum and baseline are optimal for the exploration of the full oscillation phenomena, so it is a first stage of a long program
- LBNE in the Homestake direction is the one option capable of ultimately exploiting the full power of Project X due to fundamental limitations of the NuMI beam (total power and tritium mitigation)
- Reconfiguration studies confirm the validity of the initial choice of Homestake by previous studies (P5, NRC, Intensity Frontier Workshop)

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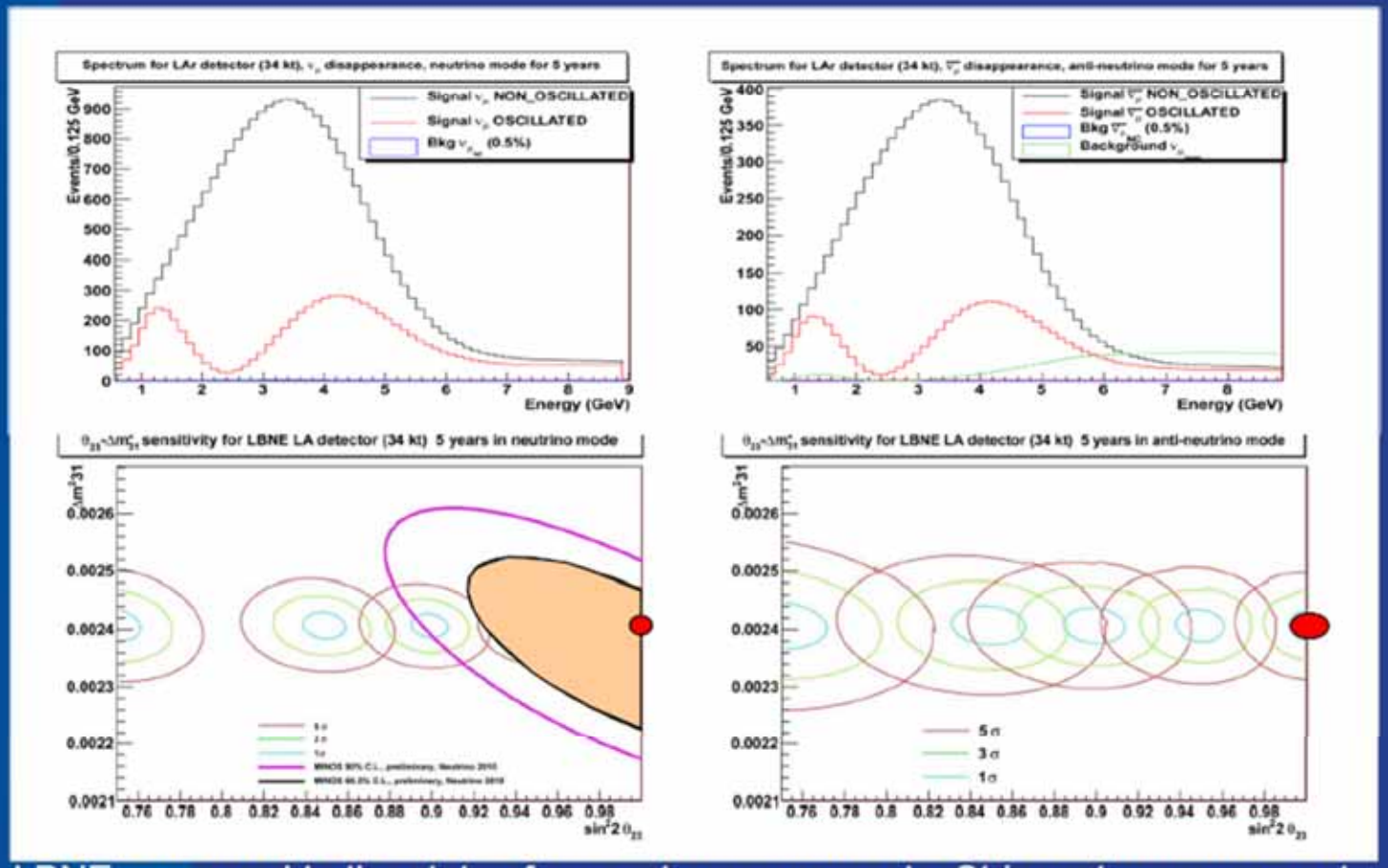
Example of long-term capabilities



LBNE compared to the state of present measurements. Stringent measurement of whether $\sin^2 2\theta_{23}$ is maximal possibly indicating new symmetry?

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Summary: 30 kton at Ash River

Pros	• Best Phase 1 CP-violation sensitivity in combination with NOvA and T2K results for the current value of θ_{13}. The sensitivity would be enhanced if the mass ordering were known from other experiments. • Excellent (3σ) mass ordering reach in nearly half of the δ_{CP} range.

Cons	• Narrow-band beam does not allow measurement of oscillatory signature.
	• Shorter baseline risks fundamental ambiguities in interpreting results.
	• Sensitivity decreases if θ_{13} is smaller than the current experimental value.
	• Cosmic ray backgrounds: impact and mitigation need to be determined.
	• Only accelerator-based physics.
	• Limited Phase 2 path:
	  ○ Beam limited to 1.1 MW (Project X Stage 1).
	  ○ Phase 2 could be a 15-20 kton underground (2,340 ft) detector at Soudan.

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Summary: 15 kton at Soudan (2300ft)

Pros	• Broadest Phase 1 physics program: ○ Accelerator-based physics including good (2σ) mass ordering and good CP-violation reach in half of the δ_{CP} range. CP-violation reach would be enhanced if the mass ordering were known from other experiments. ○ Non-accelerator physics including proton decay, atmospheric neutrinos, and supernovae neutrinos. • Cosmic ray background risks mitigated by underground location.
Cons	• Mismatch between beam spectrum and shorter baseline does not allow full measurement of oscillatory signature. • Shorter baseline risks fundamental ambiguities in interpreting results. This risk is greater than for the Ash River option. • Sensitivity decreases if θ_{13} is smaller than the current experimental value. • Limited Phase 2 path: ○ Beam limited to 1.1 MW (Project X Stage 1). ○ Phase 2 could be a 30 kton surface detector at Ash River or an additional 25-30 kton underground (2,340 ft) detector at Soudan.

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Summary: 10 kton at Homestake

- Excellent (3σ) mass ordering reach in the full δ_{CP} range.
- Good CP violation reach: not dependent on *a priori* knowledge of the mass ordering.
- Longer baseline and broad-band beam allow explicit reconstruction of oscillations in the energy spectrum: self-consistent standard neutrino measurements; best sensitivity to Standard Model tests and non-standard neutrino physics.
- Clear Phase 2 path: a 20 – 25 kton underground (4850 ft) detector at the Homestake mine. This covers the full capability of the original LBNE physics program.
- Takes full advantage of Project X beam power increases.

- Cosmic ray backgrounds: impact and mitigation need to be determined.
- Only accelerator-based physics. Proton decay, supernova neutrino and atmospheric neutrino research are delayed to Phase 2.
- ~10% more expensive than the other two options: cost evaluations and value engineering exercises in progress.

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Engineering/cost studies

- Scrubbed previous costs, did value engineering and reduced scope wherever possible consistent with the particular option. In the case of the Homestake direction, near detector would be built later or by collaborators
- Cost for previously estimated items maintained – overall cost reduced by eliminating requirements and/or items
- Significant cost savings achieved both for the beamline and for the conventional facilities at the detector site
- Comparative work at Homestake and Soudan was very helpful. There is experience with excavation and operations both at Homestake and at Soudan

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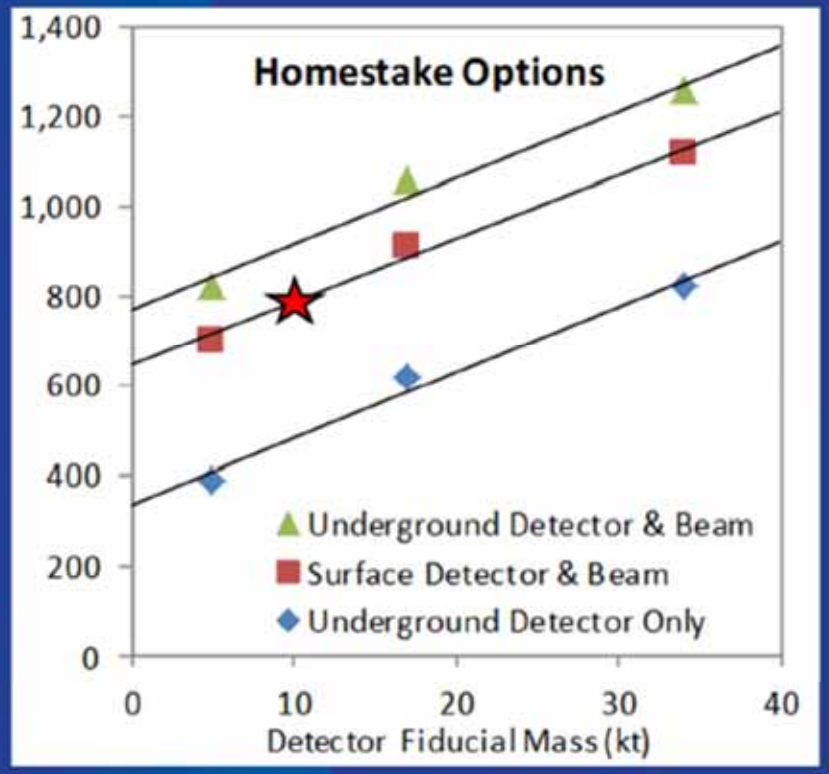
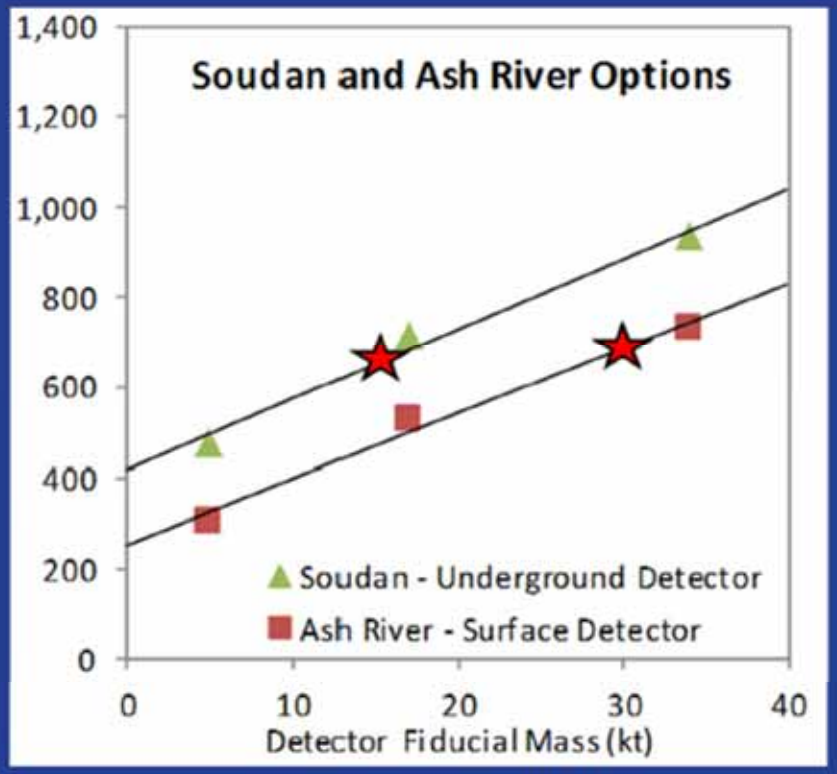
Cost curves for different choices





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Phased approach and alternatives

- Ideally we would like a detector that exploits both the long baseline of Homestake and operates underground. It requires a new beamline and development of the underground; it does not fit the cost guidelines (at Homestake +$135M to go underground for 10 kton detector)
- The option of Homestake on the surface offers strengths in the neutrino arena and has the best long-term prospects for a phased approach. Because the Phase 1 detector is small, international partners may be interested in adding additional mass.
- The Soudan option offers underground physics from the start; the mass is reduced relative to Ash River in order to fund the development of the underground

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Phased approach and alternatives

- Ash River would bring the largest detector early with the highest CP reach of any of the options in Phase 1, but in the long term it has neither the ideal baseline nor is it underground. Because we would be building only a detector, cost control can be achieved by scaling the mass back gracefully
- Of these viable options, the Steering Committee and the laboratory favor building 10 ktons on the surface at Homestake, provided the somewhat higher costs of this option could be handled (10%). The long-range physics potential may bring more partners than other options
- We are ready to discuss these issues and options in more detail with the Office of Science, select a path and integrate it into the ongoing project critical decisions

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Further phases of LBNE

- Further phases of LBNE can add mass to the detector, or go underground to extend the breadth of the program, depending on: a) the particular Phase 1 chosen, b) financial resources and physics results at the time when the choice needs to be made
- Importantly, we have broken up Project X in several phases as well so that phases in Project X can be intercalated with further phases of LBNE
- In particular, the first phase of Project X at approximately 1/3 the total cost would boost particles at 1 GeV by a factor of 100, and neutrino beams at high energies by 60-70%

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Phased approach to Project X

- Project X can be broken into three phases, each for about a third of the cost
  - Phase 1: Up to 1 GeV. Retires old linac, increases flux of neutrinos x1.7, enhances existing Mu2e by x10, starts EDM, nuclear-physics and nuclear-material studies
  - Phase 2: Up to 3 GeV. Starts powerful Intensity Frontier experiments with kaons and short baseline neutrino programs
  - Phase 3: Up to 8 GeV; Multiplies power to LBNE by factor of 3; power at 8 GeV by several fold for short-baseline neutrino experiments
- Decision on when these phases should start can wait to much later in the decade

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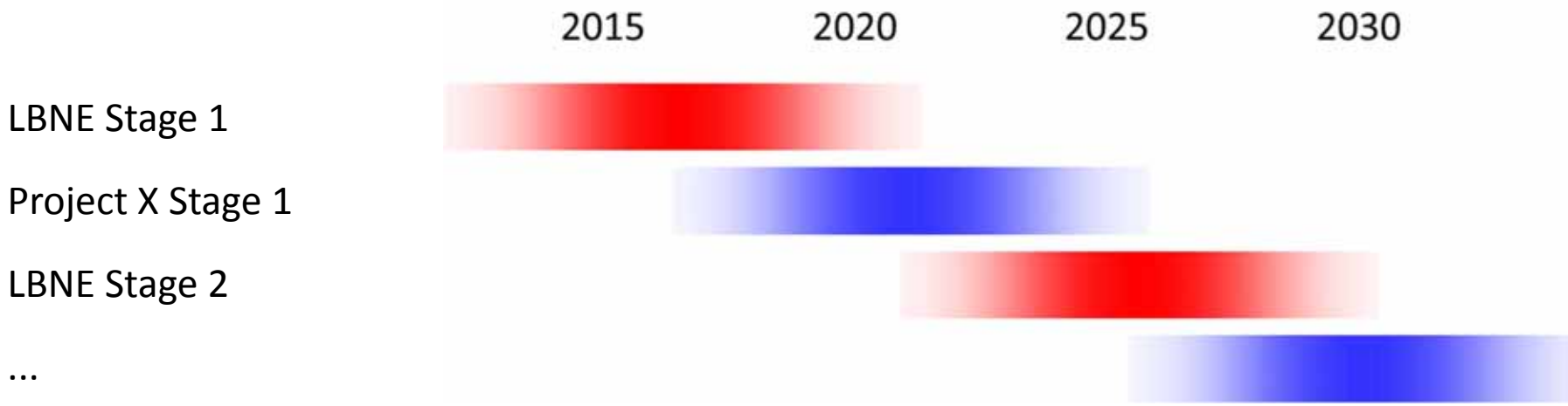
Interleaving LBNE and Project X Phases: An Example

1) LBNE Phase 1: 10 kt LAr detector on surface at Homestake + LBNE beamline (700 kW)
2) Project X Phase 1 → 1.2 MW LBNE beam
3) LBNE Phase 2: a) Near Detector,
   b) ~20 kt underground far detector



This program would come to fruition more rapidly with expanded collaboration.

LBNE Next Steps – The Path to CD-1

Complete Final Report of the Steering Committee	Jun 2012
Update conceptual designs and sub-project cost and schedule estimates	Jun-Sep 2012
Update integrated resource loaded schedule and other project documents	Oct-Nov 2012
Director's pre-CD-1 Review	Dec 2012
DOE (Lehman) CD-1 Review	Feb 2013
CD-1 Approval	Apr 2013

Summary

- A solid, nearly CD-1-ready conceptual design and project plan has been developed for LBNE.
- Budgetary constraints require LBNE to be implemented as a phased program.
- The LBNE Reconfiguration Steering Committee and Fermilab favor the phase 1 option of a new beamline to Homestake and a 10 kt far detector, which would be on the surface unless additional funding can be found.
- We are updating the design and project plan accordingly, with the goal of achieving CD-1 early next year.