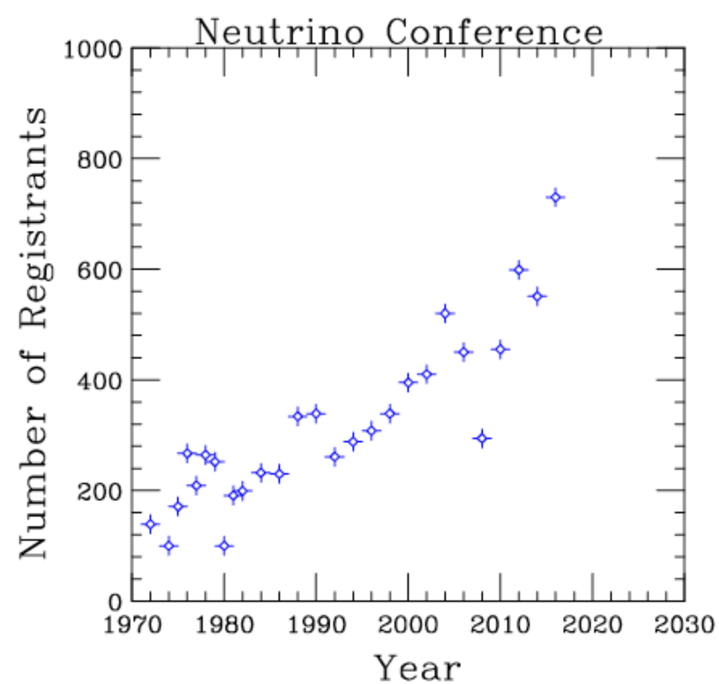
A forum for neutrino physics discussions at Nikhef

Why this meeting?

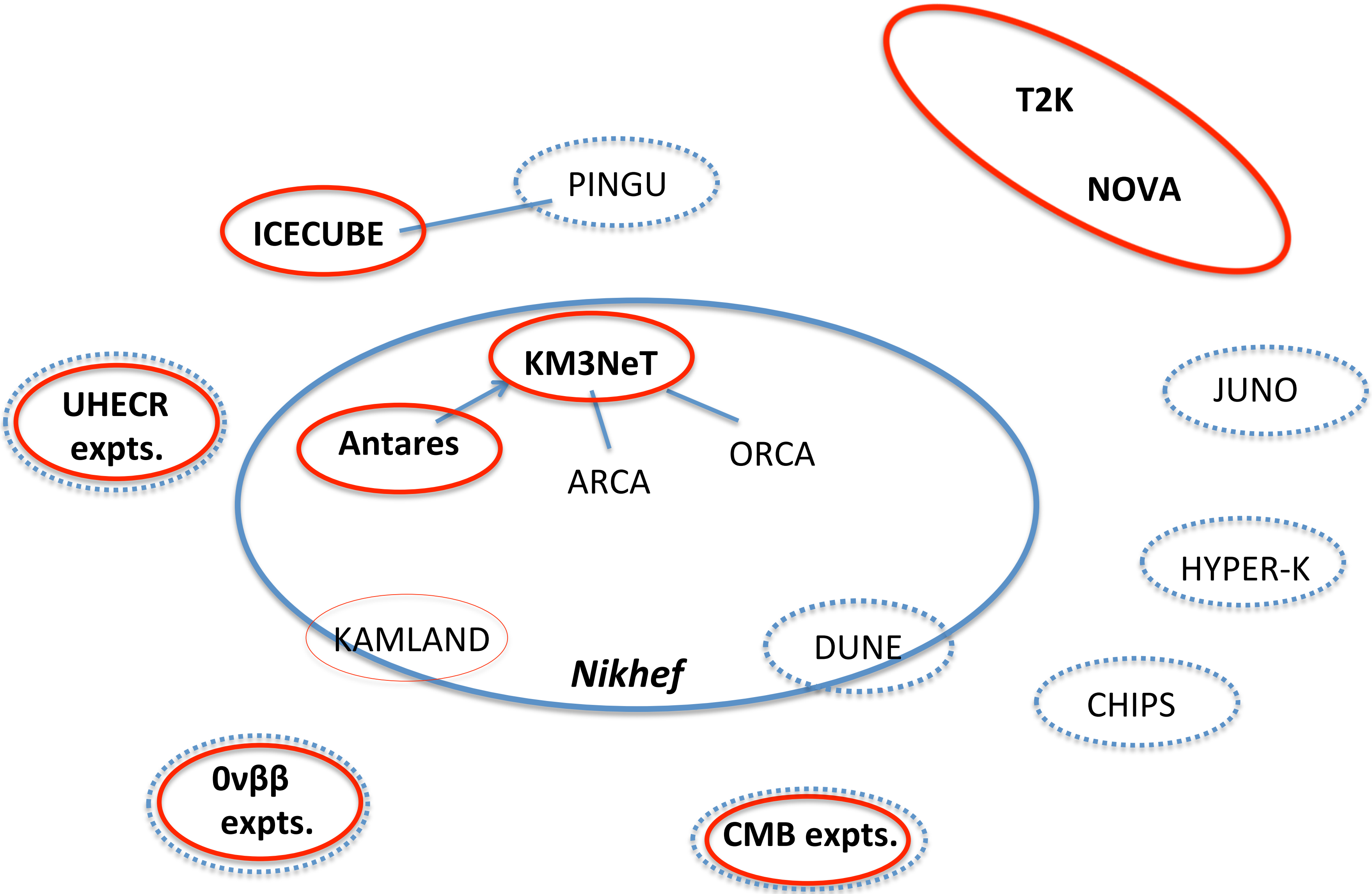
Neutrino physics is *superinteresting*.
Neutrino mass: solid evidence for beyond-the-original-SM physics
Window towards new physics: leptogenesis/flavour puzzle/sterile ν/DM…

Lots of activity in past years, but much more to come.
There is much more to explore (for discussion!)

The international field is very dynamic.
How should Nikhef stand in this?



Experimental landscape (personal impression…)



Goal: an informal forum to discuss:

- neutrino physics
- our ambitions
- detector technology
- simulation/reconstruction/analysis software
- new ideas

and benefit from each other → strengthen the neutrino community @ Nikhef

Informal: no need for slick presentations
no questions are taboo

Format: meetings < 2 hours, 1 or 2 presentations/meeting, once per 2 (?) months

Nikhef strategy discussion spring next year.
Would be nice if this forum could connect to the strategy discussion

I did not invite PhD students/postdocs today, but could join in the future

Today: introducing DUNE and protoDUNE

Future topics:

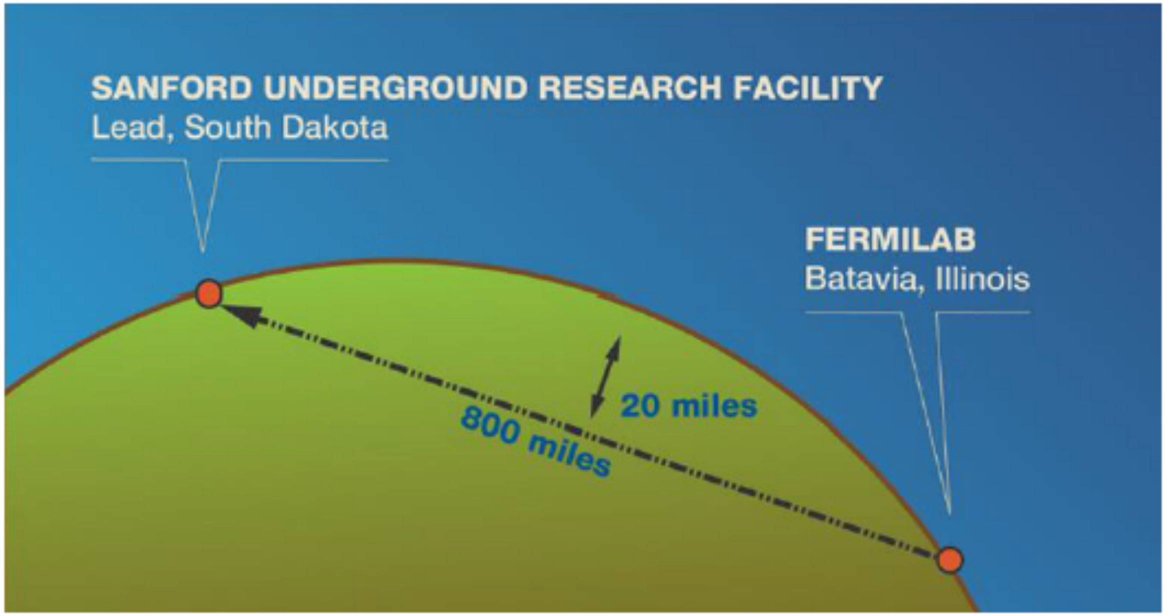
- status of the field after Neutrino 2016
- how does better knowledge of certain parameters influence the determination of other parameters?
- ORCA developments
- KM3NeT – DUNE – HyperK complementarity
- KM3NeT PMT technology transfer
- … (your input here) (CMB expts? UHE cosmic ν ?)

DUNE and protoDUNE

The Long Baseline Neutrino Facility (LBNF)

US Strategy Document

- P5 Recommendation:
  - Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text [of the report]. LBNF is the highest-priority large project in its timeframe.



In short, asks Fermilab to do for neutrinos what CERN did for the Higgs boson, involving the worldwide community

European Strategy Document

“Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. CERN should develop a neutrino program to ***pave the way*** *for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.”*

CERN interpretation

- ✓ *no ν beams at CERN !*
- ✓ *ν beams in the US and in Japan*
- ✓ *A structure at CERN to foster an active involvement of Europe and CERN in the US and Japanese new facilities*

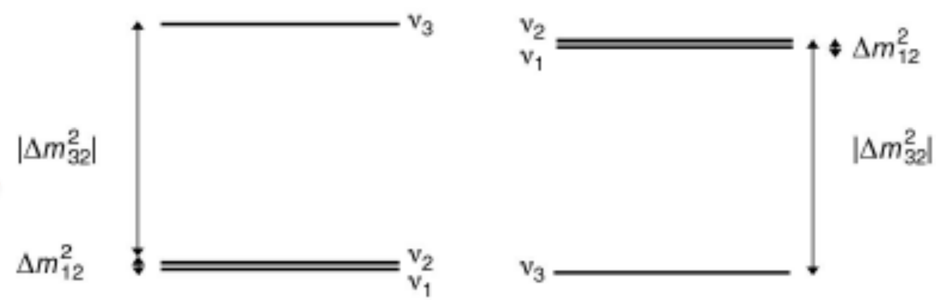
→ Neutrino Platform as a project at CERN

	LBNE (FNAL)	LBNO (CERN)	LBNF/DUNE
Baseline	1300 km	2300 km	**1300 km**
Protons power	1.2 MW	0.75 & 2 MW	**1.2 MW then upgrade to 2.4 MW**
Beam focusing	NUMI-style	CP-optimised	**NUMI-style or CP-optimised**
Far detector	10+30 kton	20+50 kton	**4x10 kton**
Far detector technologies	single phase LAr TPC	dual phase LAr TPC	**single and/or dual phase LAr TPC**
Near detector design	Magnetised fine grained tracker (FGT)	HP GAr TPC	**Magnetised FGT and/or LAr TPC and/or HP GAr TPC**

DUNE Primary Science Program

Focus on fundamental open questions in particle physics and astroparticle physics:

- **1) Neutrino Oscillation Physics**
  - **Discover CP Violation** in the leptonic sector
  - Mass Hierarchy



  - Precision Oscillation Physics:
    - e.g. parameter measurement, θ_{23} octant, **testing the 3-flavor paradigm**
- **2) Nucleon Decay**
  - e.g. targeting SUSY-favored modes, $p \rightarrow K^+\overline{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

The Standard 3-Flavour Paradigm

★ **Unitary PNMS matrix ⇒ mixing described by:**

- three "Euler angles": $(\theta_{12}, \theta_{13}, \theta_{23})$
- and one complex phase: δ

$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

with $s_{ij} = \sin\theta_{ij}$; $c_{ij} = \cos\theta_{ij}$

★ **If** $\delta \neq \{0, \pi\}$ then SM leptonic sector ⇒ CP violation (CPV)

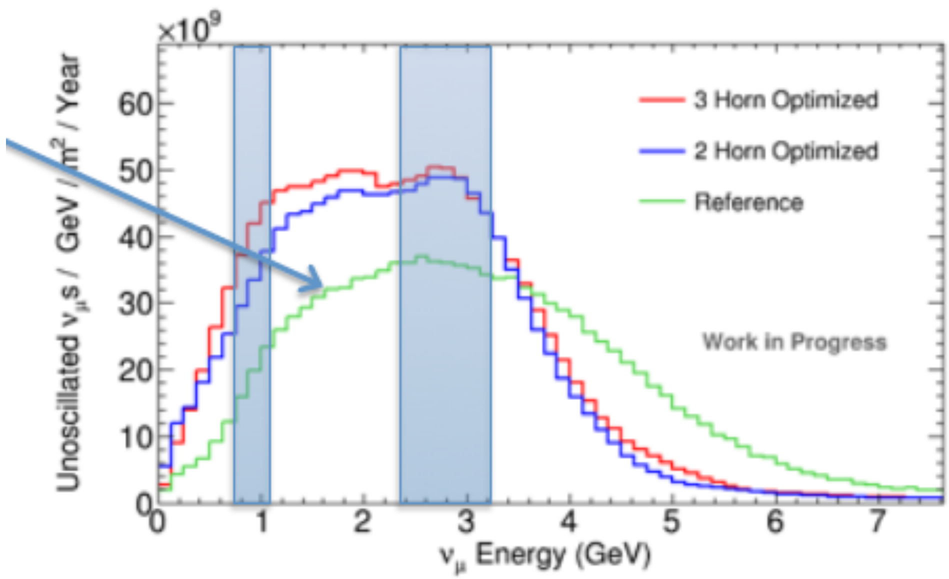
- CPV effects $\propto \sin\theta_{13}$
- **now know that θ_{13} is relatively large**

⇒ **CPV is observable with conventional ν beams**

⇒ **LBNF/DUNE**
Hyper-Kamiokande

DUNE: oscillation length 1300 km → large matter effects

Chosen solution: wide band beam, access to first and second oscillation maximum
muon-neutrino beam and muon-antineutrino beam
muon ν disappearance as well as electron ν appearance
disentangle mass hierarchy from δ by energy dependence



Improvement from optimization

(Compare Hyper-K: oscillation length 295 km, small matter effects
narrow band off-axis beam
lower energy, first oscillation maximum)

Matter effects

2-generation osc probabilty:

Vacuum: $$P = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

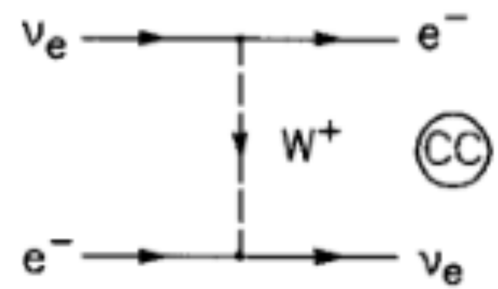
Matter: $$P = \sin^2 2\tilde{\theta} \sin^2 \frac{\Delta \tilde{m}^2 L}{4E}$$

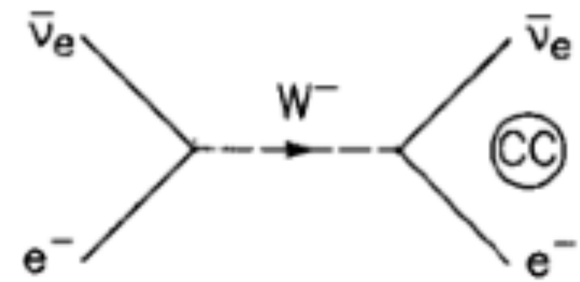
$$\sin 2\tilde{\theta} = \frac{\sin 2\theta}{\zeta}, \Delta \tilde{m}^2 = \zeta \cdot \Delta m^2$$

$$\zeta = \sqrt{\sin^2 2\theta + (\cos 2\theta - A)^2}$$

$$A = \frac{2EV}{\Delta m^2} \quad \begin{array}{l} V_\nu = +2\sqrt{2} G_F n_e \\ V_{\overline{\nu}} = -2\sqrt{2} G_F n_e \end{array}$$

Matter contains e, but no μ, τ





Resonance: $\cos 2\theta \rightarrow A$

	Normal Ord	Inverted Ord
ν	Resonance	Suppression
anti-ν	Suppression	Resonance

Three ν generations

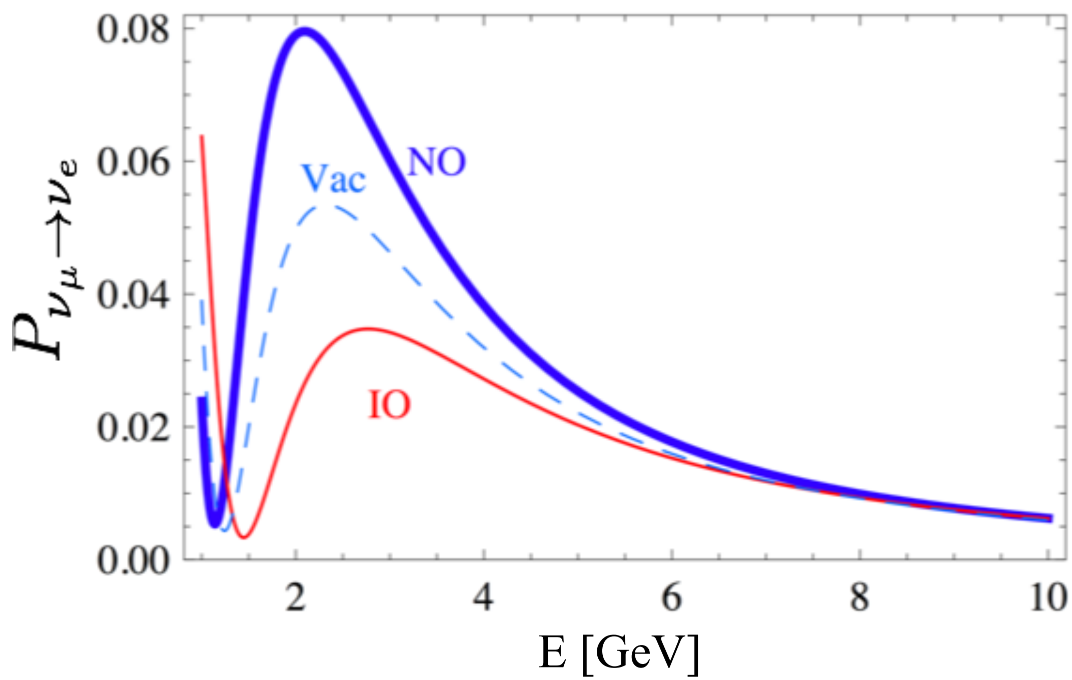
Octant: θ23 > 45° ?

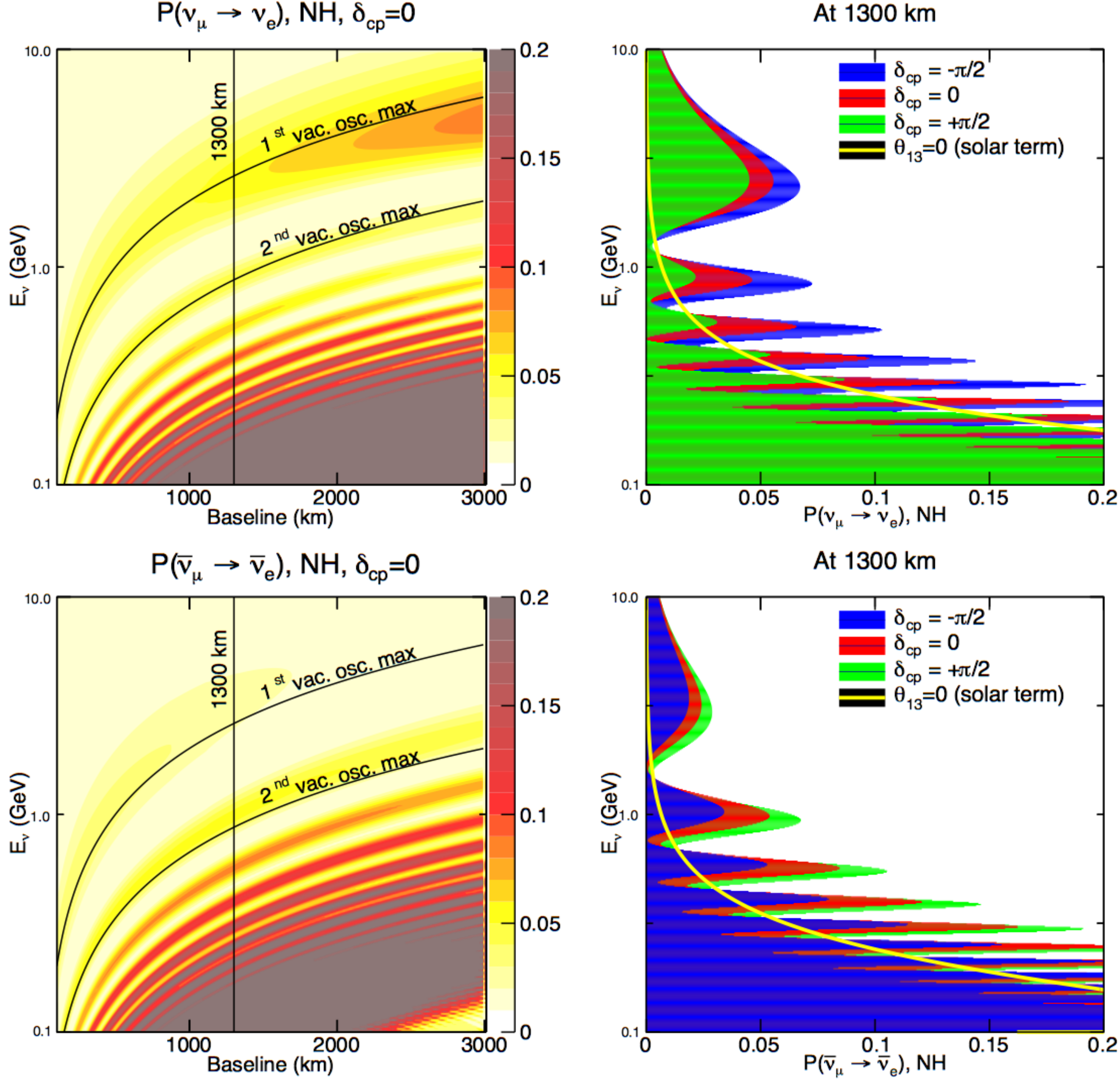
$$P_{\nu_\mu\to\nu_e} \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2\Delta_{31}(1-A)}{(1-A)^2}$$
$$+ \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(A\Delta_{31})}{A^2}$$
$$+ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(A\Delta_{31})}{A} \frac{\sin[\Delta_{31}(1-A)]}{1-A} \cos(\Delta_{31} \pm \delta_{CP})$$

$$\Delta_{31} \equiv \frac{\Delta m^2_{31} L}{4E}$$
$$A \equiv \frac{2EV}{\Delta m^2_{31}}$$
$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

Matter-induced enhancement

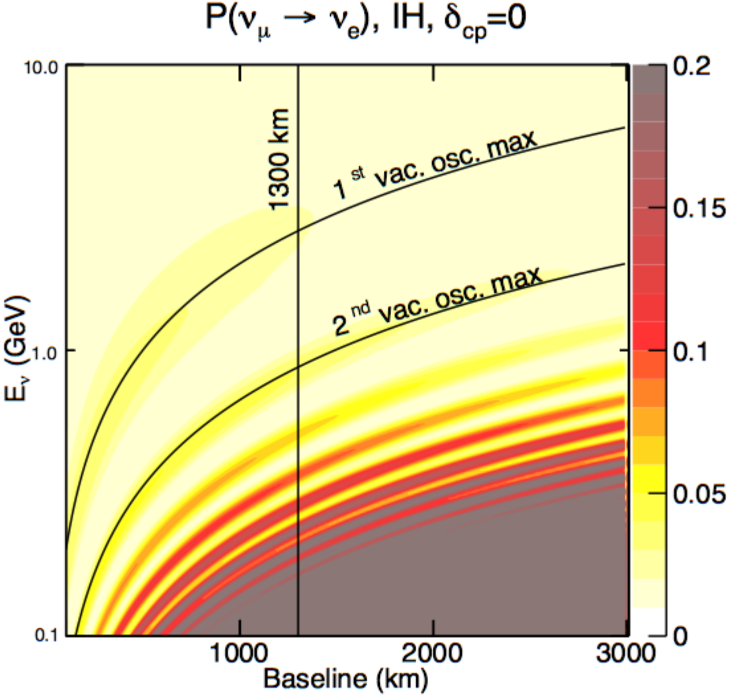
CP-term

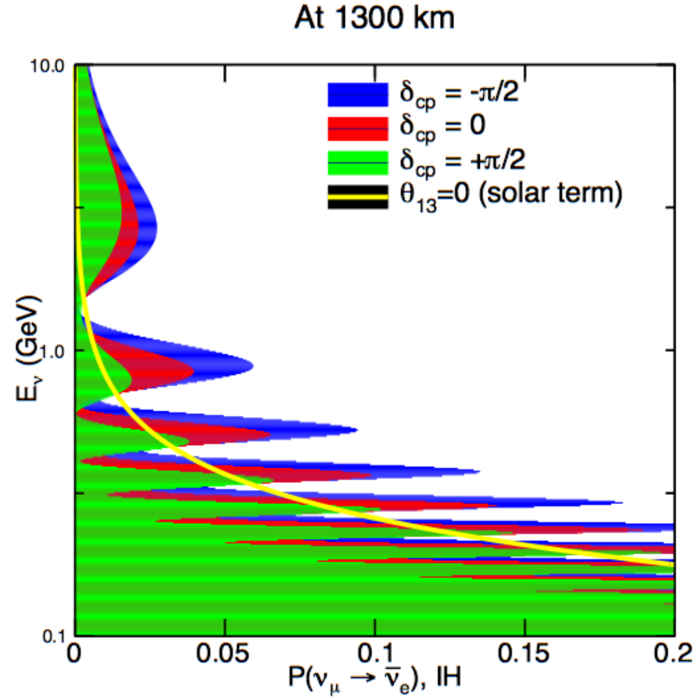



P(νμ → νe), NH, δcp=0
1300 km
1st vac. osc. max
2nd vac. osc. max
Eν (GeV)
Baseline (km)
0.1
1.0
10.0
1000
2000
3000
0
0.05
0.1
0.15
0.2
At 1300 km
δcp = -π/2
δcp = 0
δcp = +π/2
θ13=0 (solar term)
P(νμ → νe), NH
P(ν̄μ → ν̄e), NH, δcp=0
At 1300 km
P(ν̄μ → ν̄e), NH

NH

IH


P(νμ → νe), IH, δcp=0
1300 km
1 st vac. osc. max
2 nd vac. osc. max
Eν (GeV)
Baseline (km)
10.0
1.0
0.1
1000
2000
3000
0.2
0.15
0.1
0.05
0


At 1300 km
δcp = -π/2
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P(νμ → ν̄e), IH
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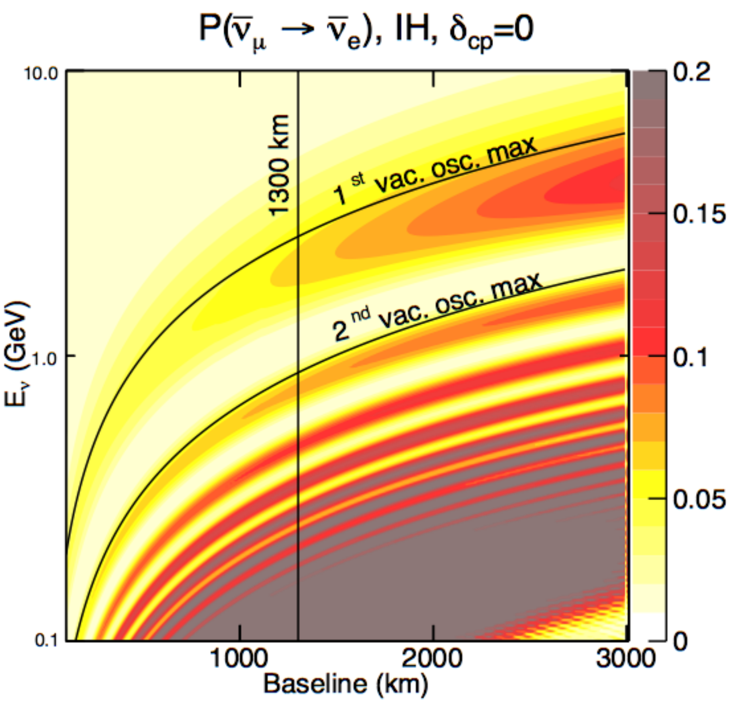
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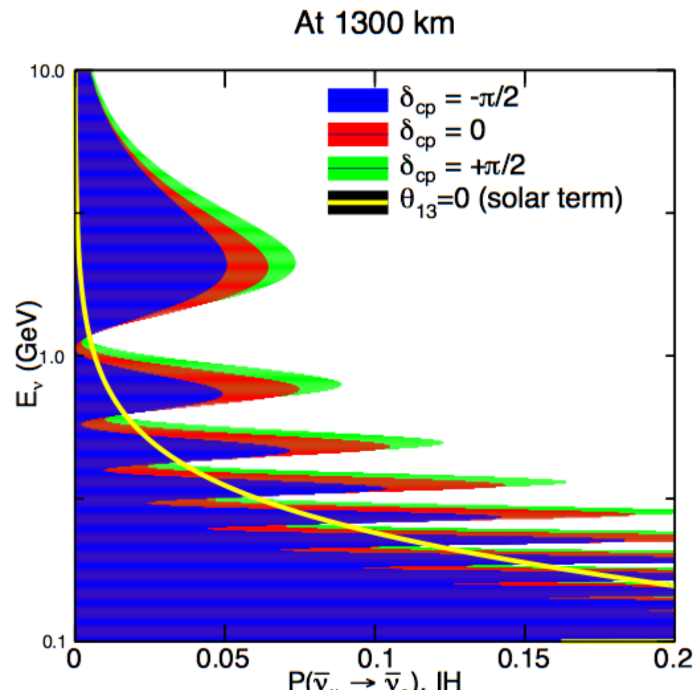

At 1300 km
δcp = -π/2
δcp = 0
δcp = +π/2
θ13=0 (solar term)
Eν (GeV)
P(ν̄μ → ν̄e), IH
10.0
1.0
0.1
0
0.05
0.1
0.15
0.2

DUNE Ancillary Science Program

Enabled by the intense LBNF beam and the DUNE near and far detectors

- **Other neutrino oscillation physics with BSM sensitivity**
  - Neutrino non-standard interactions (NSIs)
  - Sterile Neutrinos at the near and far sites
  - Measurements of tau neutrino appearance

  Benefit from wide band beam

- **Oscillation physics with atmospheric neutrinos**
- **Neutrino Physics in the near detector**
  - Neutrino cross section measurements
  - Studies of nuclear effects, FSI etc.
  - Measurements of the structure of nucleons
  - Neutrino-based measurements of $\sin^2\theta_W$

  > 100M neutrino interactions in a few years of operation

- **Search for signatures of Dark Matter**

Supernova νs

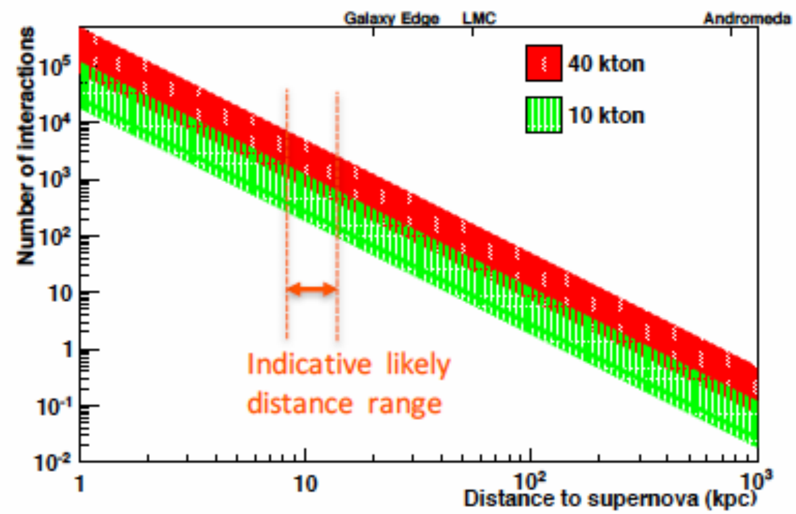
A core collapse supernova produces an incredibly intense burst of neutrinos

- Measure energies and times of neutrinos from galactic supernova bursts
  - In argon (uniquely) the largest sensitivity is to ν_e

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

~3000 interactions @ 10 kpc

Channel	Events "Livermore" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2720
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	230
$\nu_x + e^- \rightarrow \nu_x + e^-$	350
Total	3300



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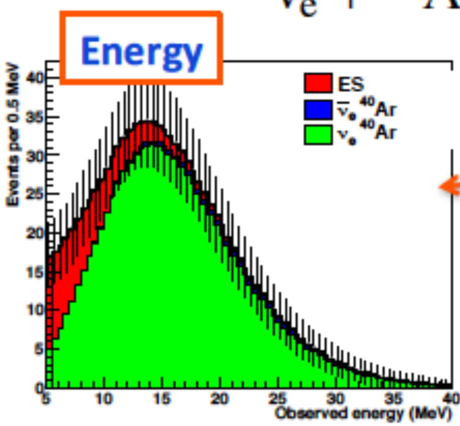
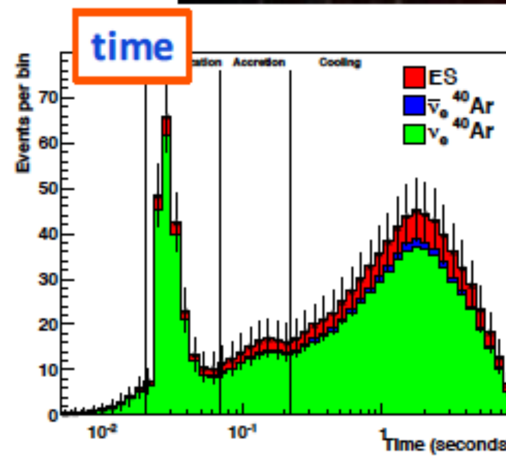


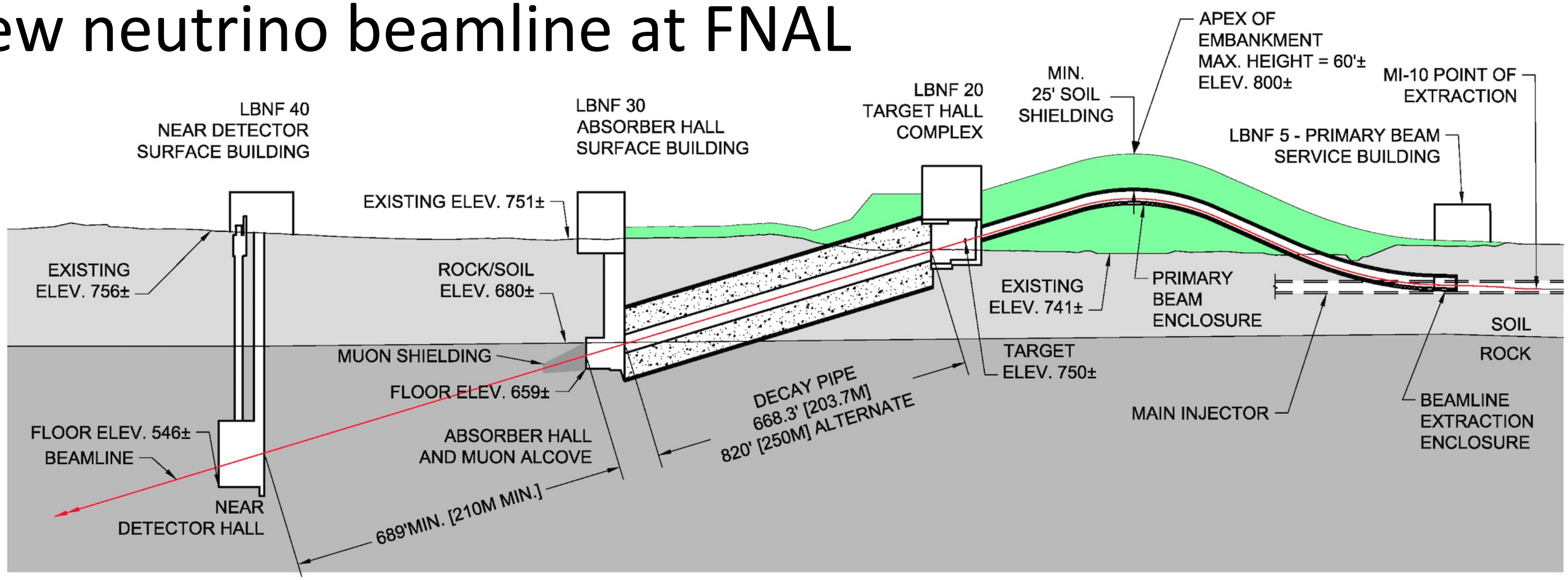
E ~ O(10 MeV)

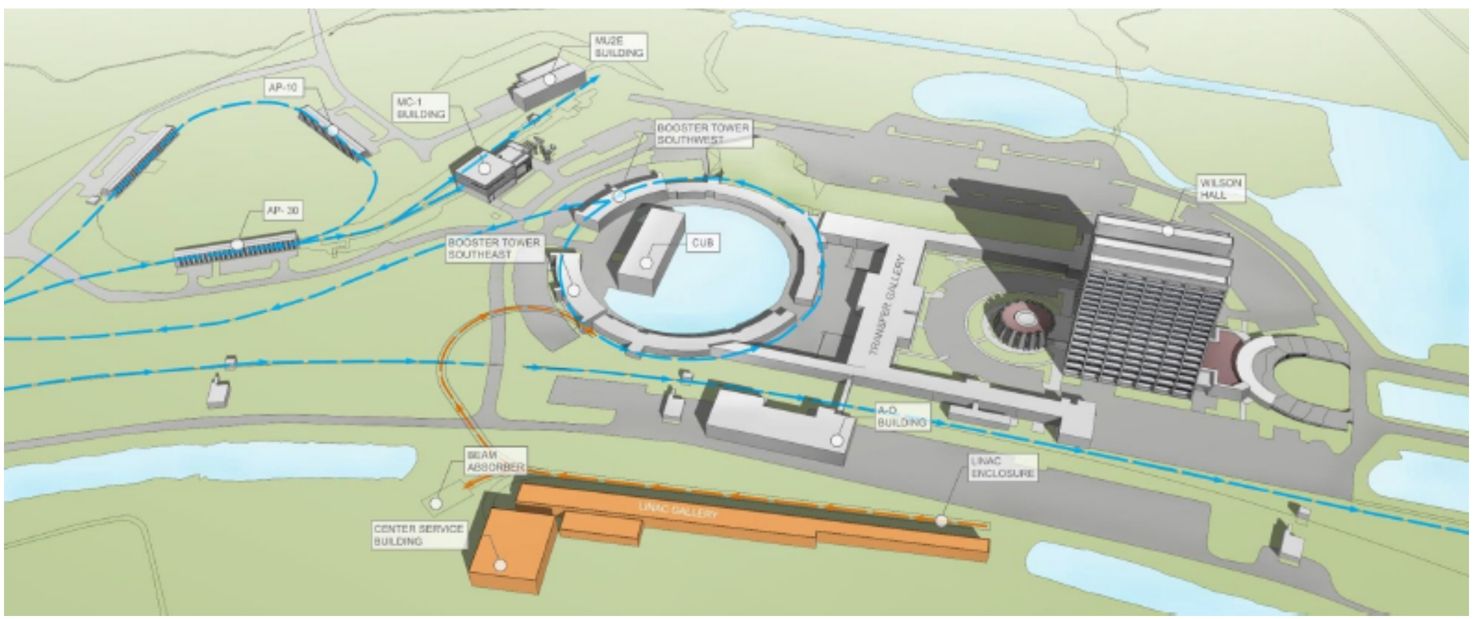


Physics Highlights include:

- Possibility to "see" neutron star formation stage
- Even the potential to see black hole formation !

New neutrino beamline at FNAL

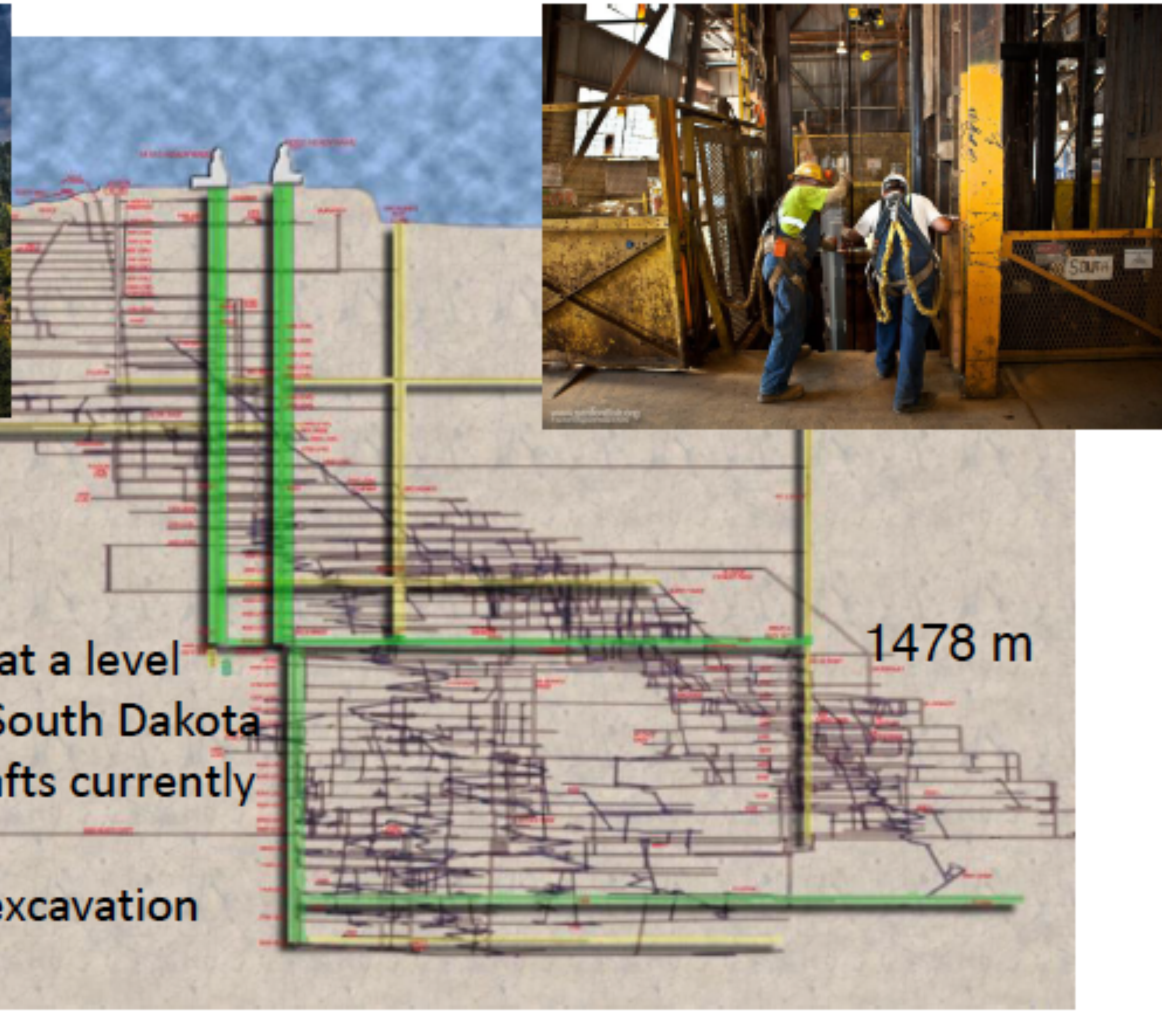




1.2 – 2.4 MW 60-120 GeV proton accelerator

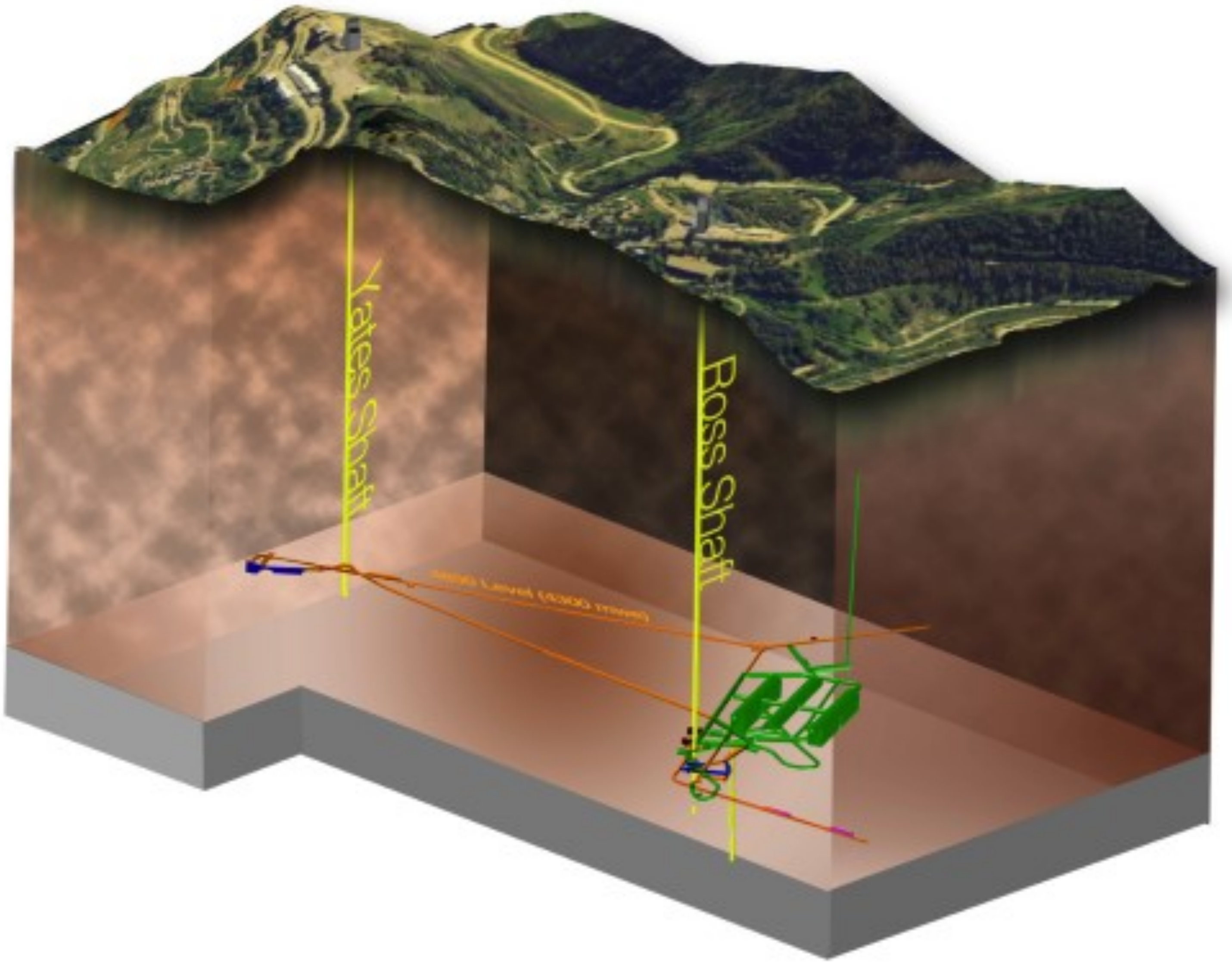

Kirk Road
N
Wilson Hall
LBNE Neutrino Beamline
Giese Road
Proposed embankment
Proposed LBNE Service Buildings
Protons from Main Injector
Main Injector Road

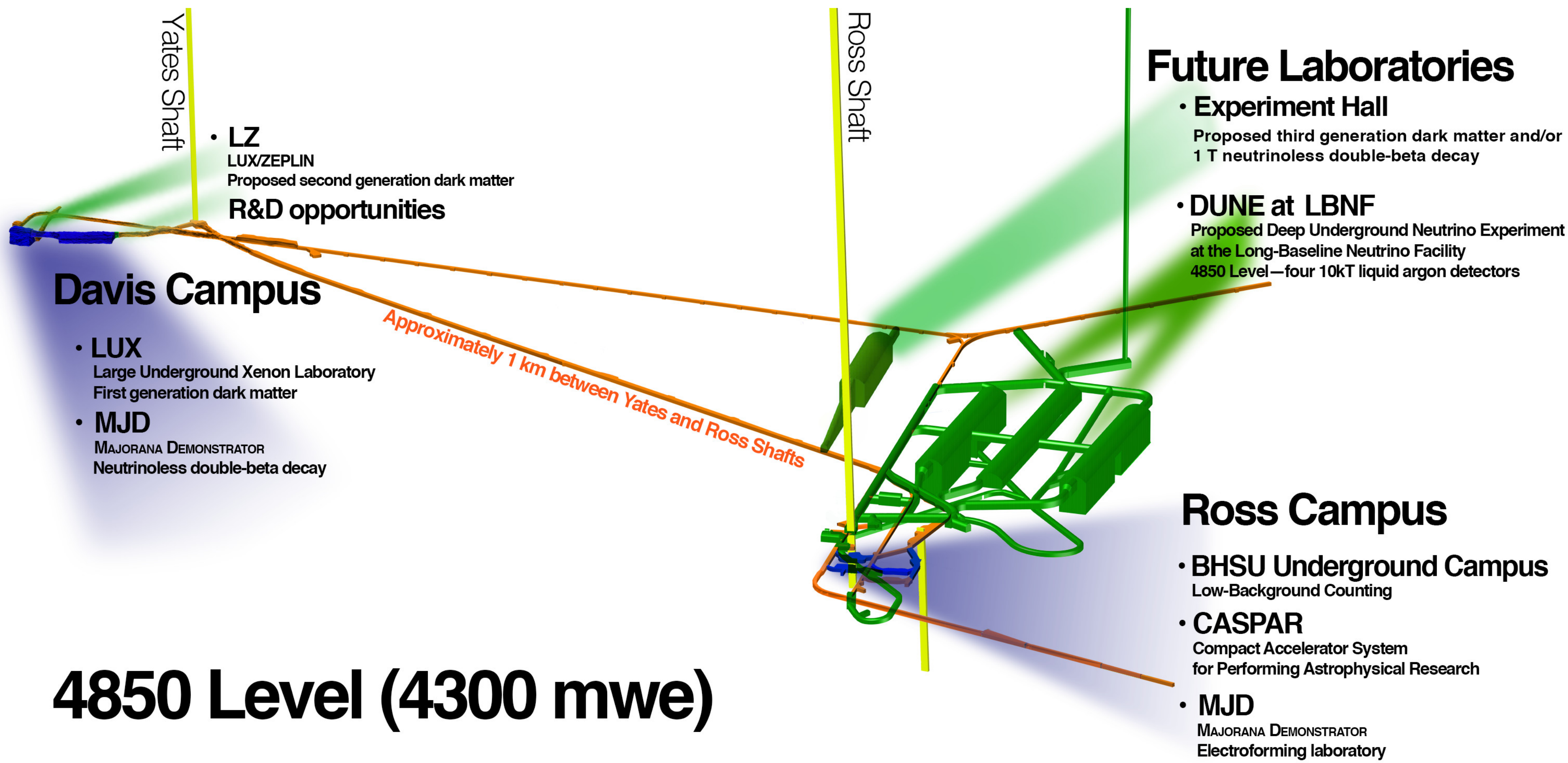
Sanford Underground Research Facility (SURF)



- Experimental facilities at a level of 1478 m, located in South Dakota
- Two vertical access shafts currently being refurbished
- Will allow allow large excavation at SURF in 2017

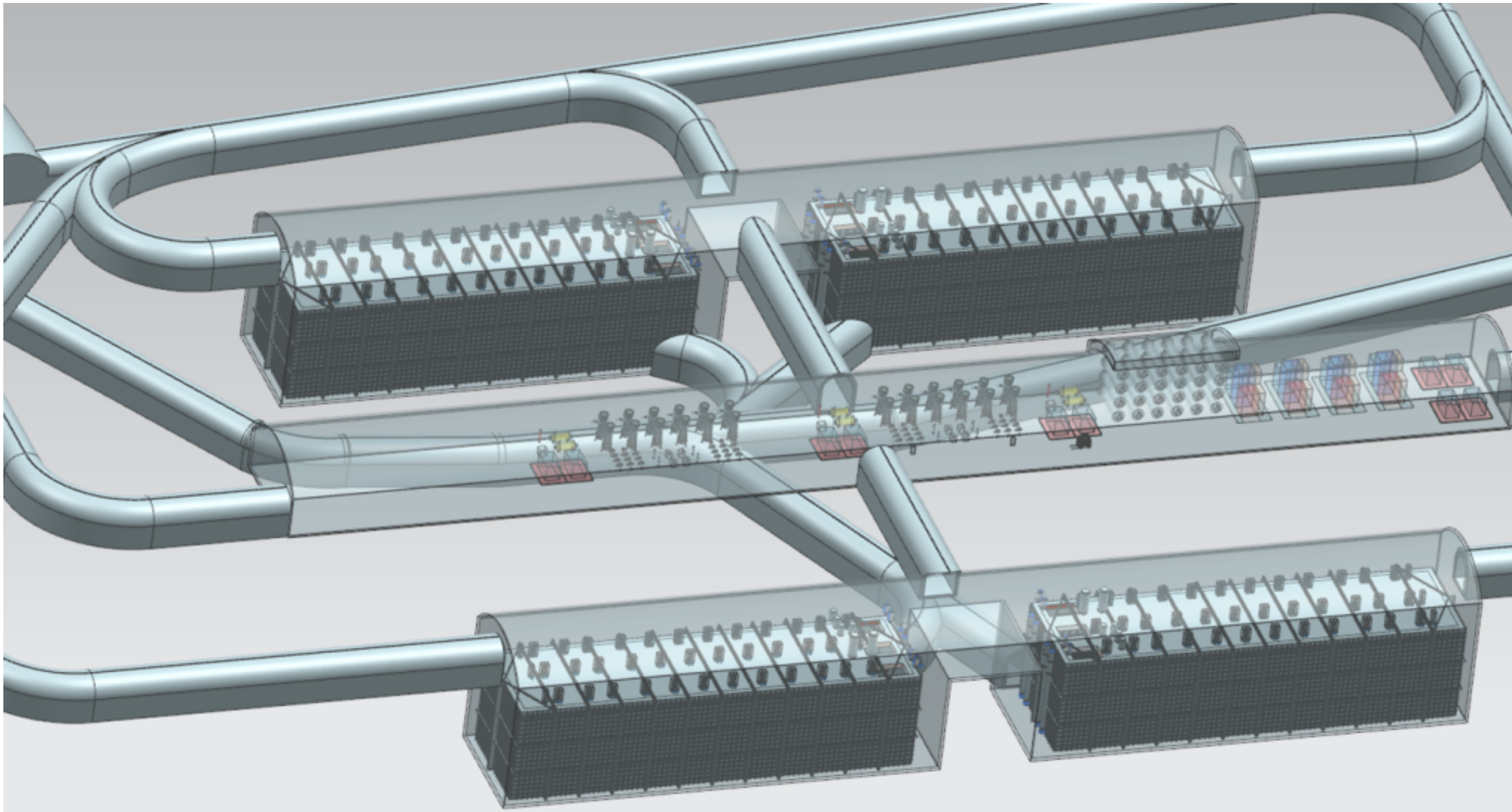
Former Homestake goldmine in Lead, South Dakota





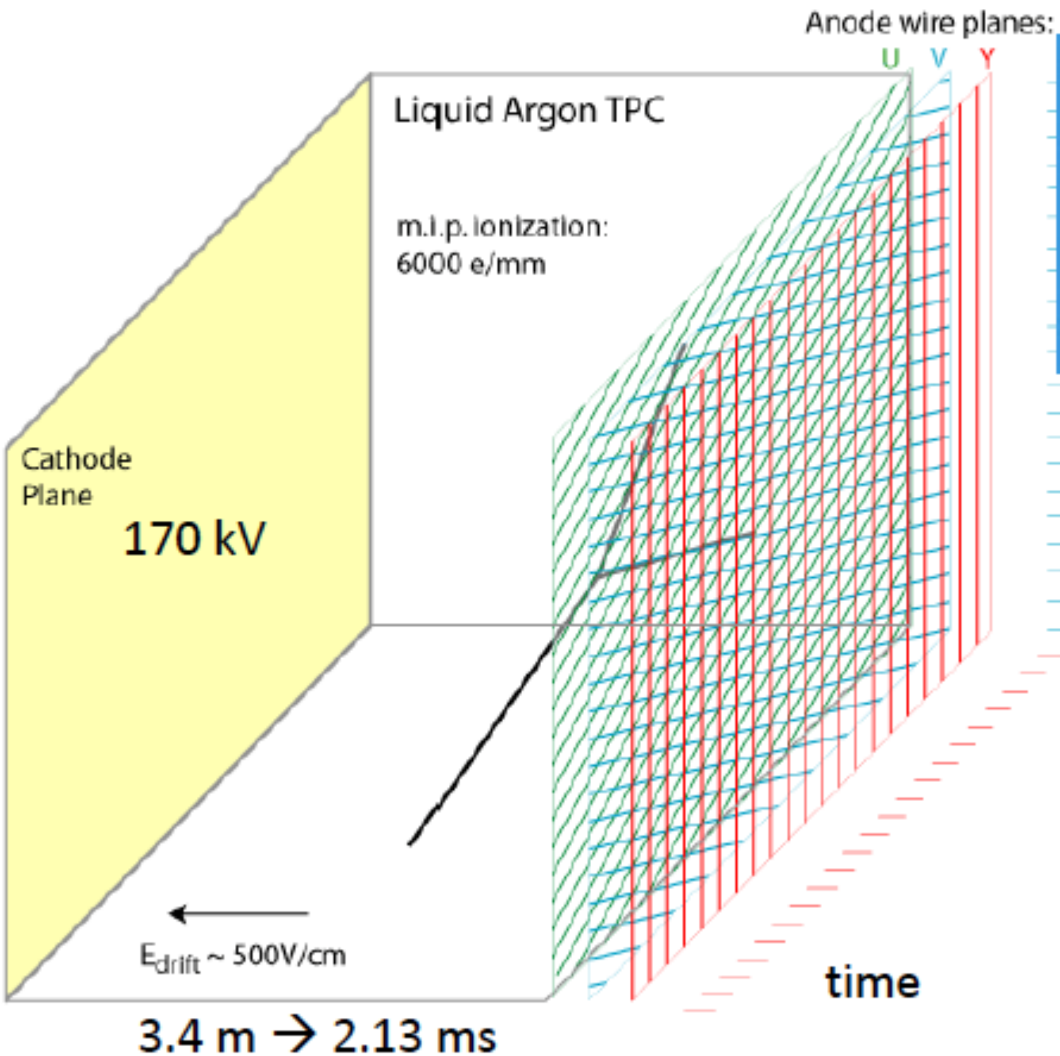
Yates Shaft
Ross Shaft
• LZ
LUX/ZEPLIN
Proposed second generation dark matter
R&D opportunities
Future Laboratories
• Experiment Hall
Proposed third generation dark matter and/or
1 T neutrinoless double-beta decay
• DUNE at LBNF
Proposed Deep Underground Neutrino Experiment
at the Long-Baseline Neutrino Facility
4850 Level—four 10kT liquid argon detectors
Davis Campus
• LUX
Large Underground Xenon Laboratory
First generation dark matter
• MJD
MAJORANA DEMONSTRATOR
Neutrinoless double-beta decay
Approximately 1 km between Yates and Ross Shafts
Ross Campus
• BHSU Underground Campus
Low-Background Counting
• CASPAR
Compact Accelerator System
for Performing Astrophysical Research
• MJD
MAJORANA DEMONSTRATOR
Electroforming laboratory
4850 Level (4300 mwe)

Caverns for 4 detectors (each 10 kton LAr TPC) + infrastructure

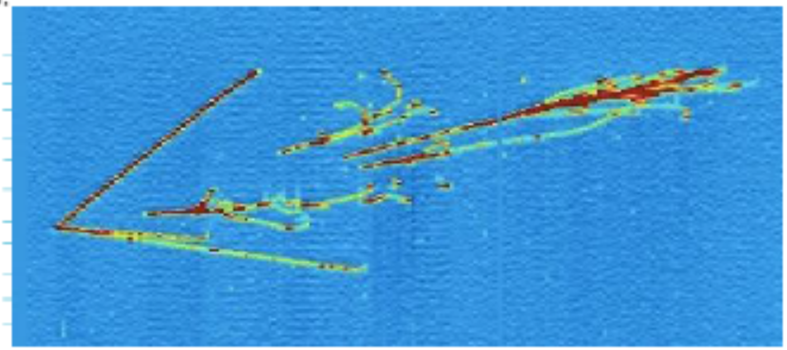


DOE approval of first 2 caverns, excavation to start in 2017/2018
DUNE far detectors (first two modules) ready 2025, beam 2026

Time Projection Chamber (TPC)



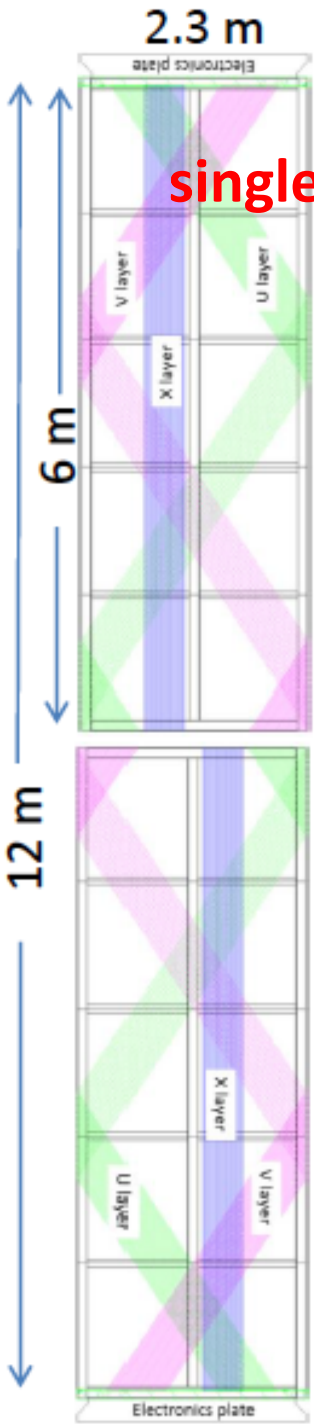
ArgoNeuT



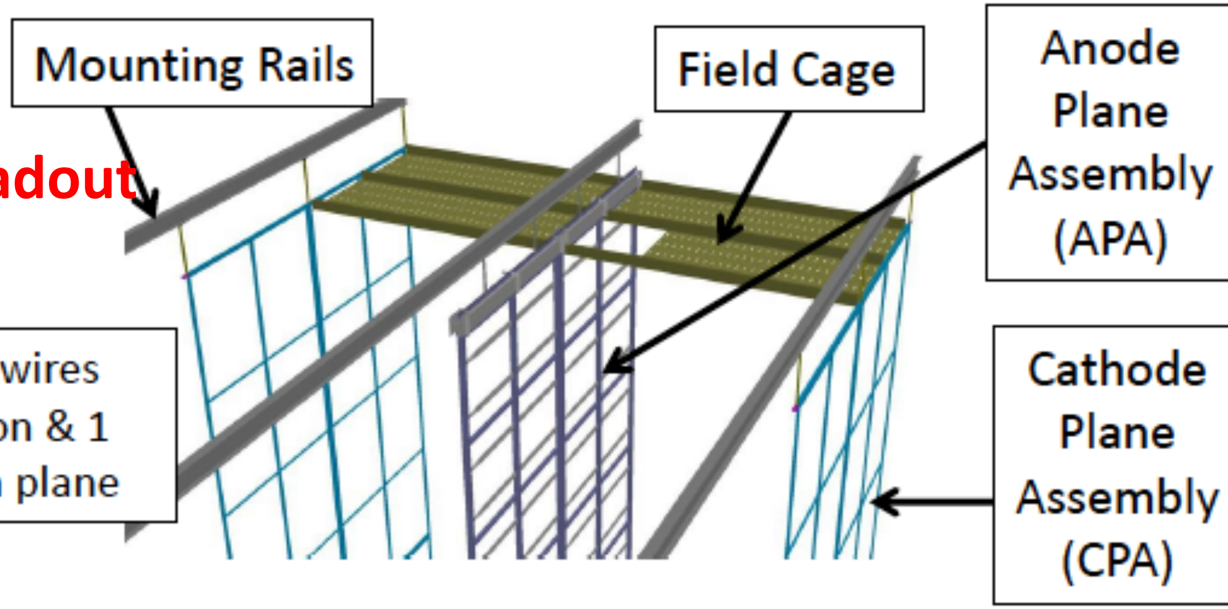
- "Bubble chamber" like imaging capabilities (few mm resolution).
- Excellent energy measurement.
- Excellent e-γ separation.
- Particle identification through dE/dx, range,..
- Timing through scintillation light

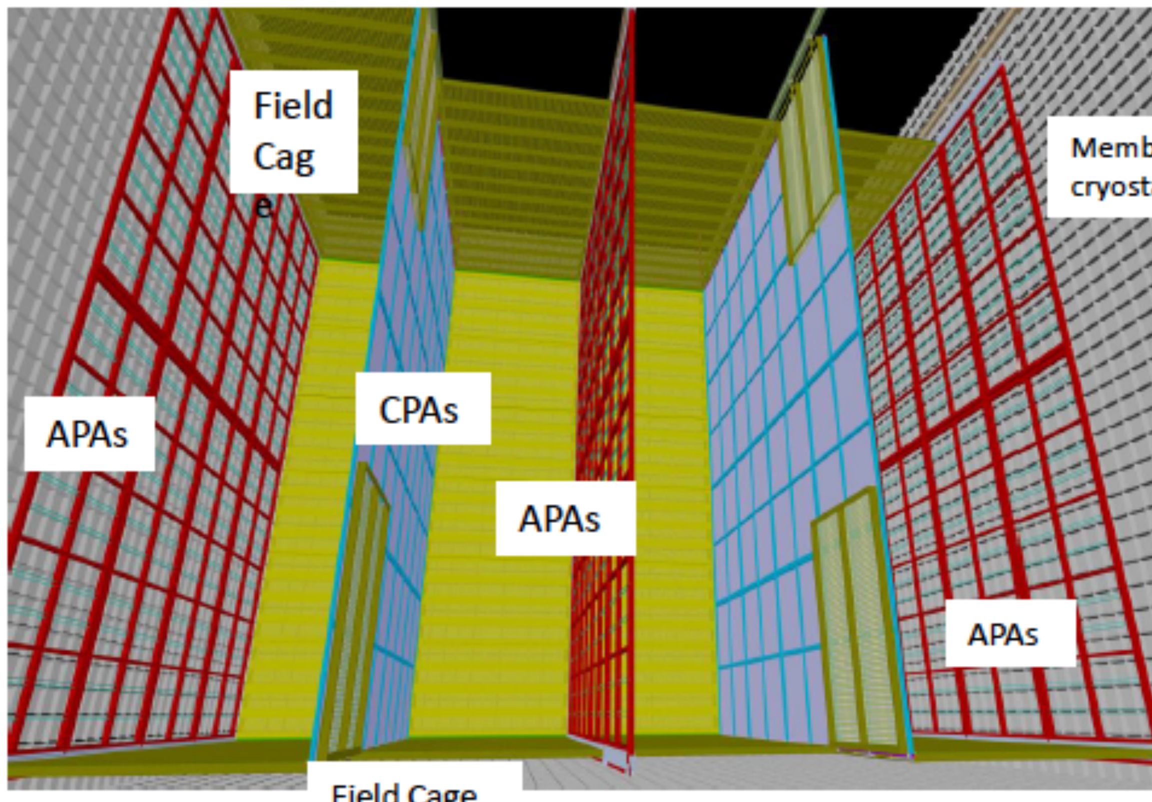
single-phase readout

single-phase readout



- wrapped wires
- 2 induction & 1 collection plane



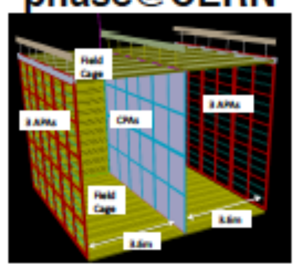


Far Detector Prototyping Program

- Basic technologies demonstrated by ICARUS, ArgoNEUT/LArIAT, MicroBooNE, WA105 but **DUNE scale is very different** (each module is 40x ICARUS) and different in many details → **need strong prototyping**
- DUNE has well-developed plans for a series of detector prototypes that will provide input to the process leading to the final design(s) for the DUNE far detector modules.
- **ProtoDUNE single- and dual-phase 300 tons prototypes to operate in 2018.**

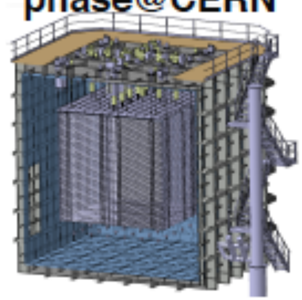
35T @ FNAL

protoDUNE single phase@CERN



WA105 3x1x1@CERN

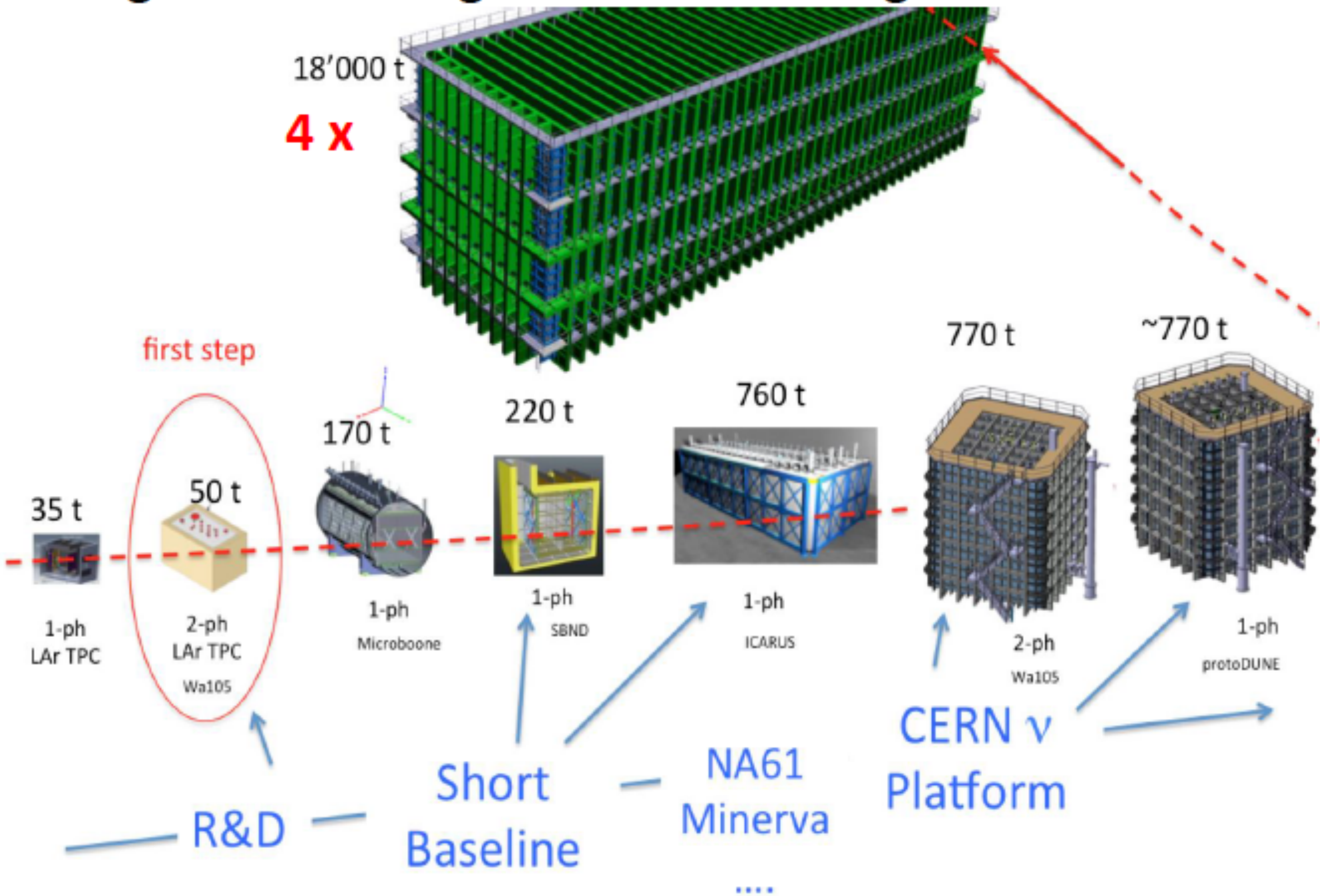
protoDUNE dual phase@CERN



- *Mitigation of risks associated with current detector designs*
- *Establishment of construction facilities required for full-scale production of detector components*
- *Early detection of potential issues with construction methods and detector performance*
- *Provide required calibration of detector response to particle interactions in charged particle test beams*

Step by step (LAr TPCs)

- .... the large scale is a big and new challenge

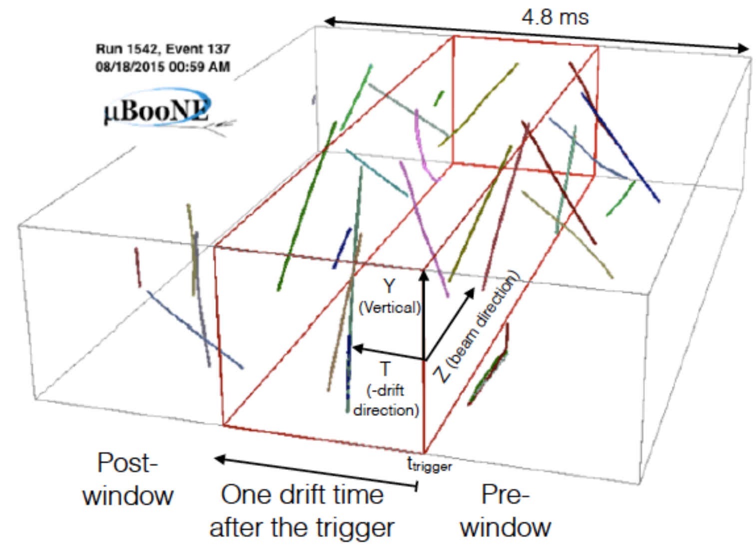


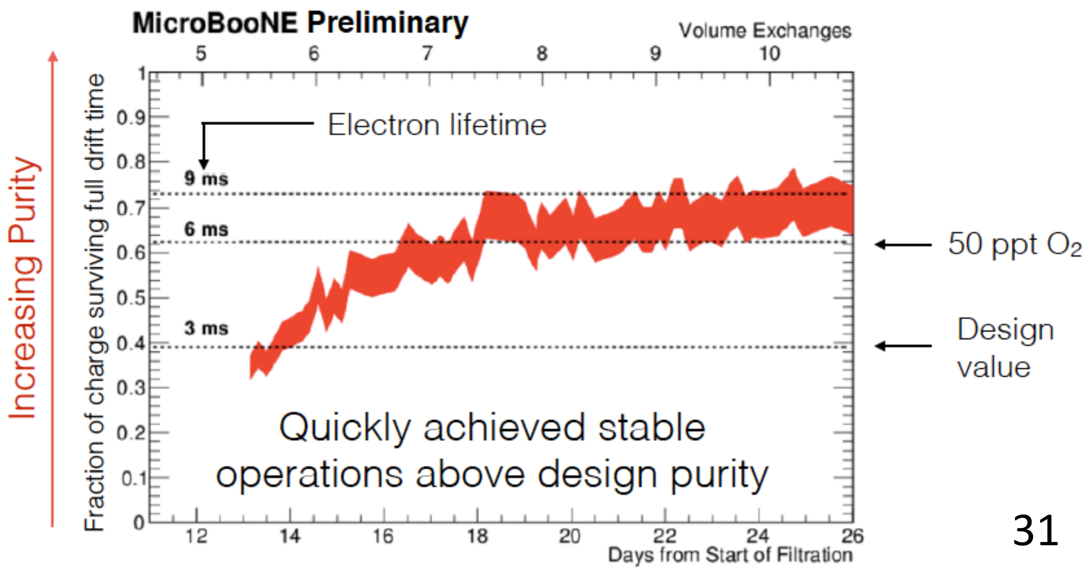
To succeed we need to proceed in steps (for cryostats, cryogenics and detectors)

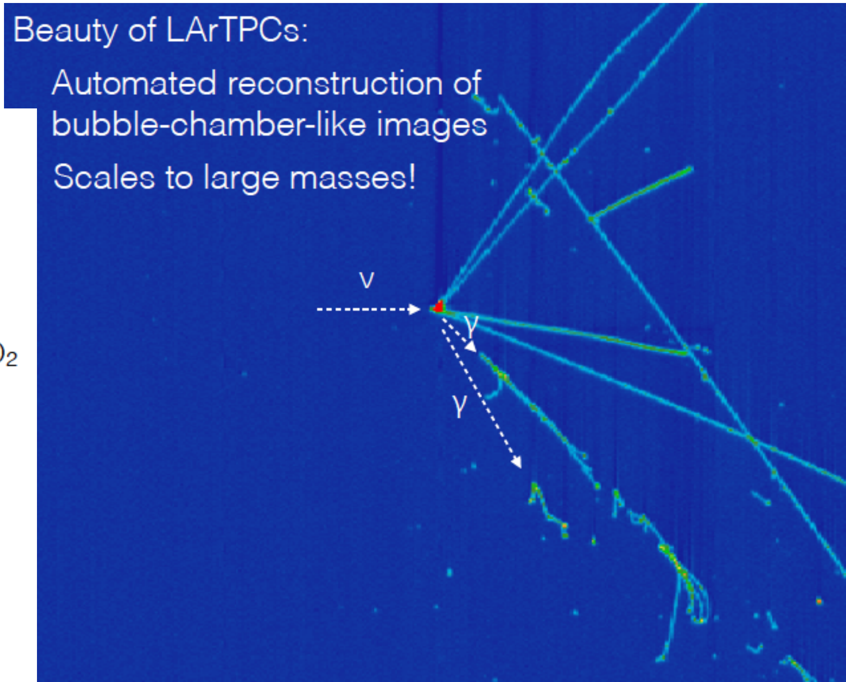
MicroBoone:

- 1. Can achieve high purity in fully-instrumented cryostats thanks to well-designed recirculating filtration system
- 2. Stable operations with high detector uptime possible with LArTPC experiments
- 3. Can achieve low noise levels in LArTPCs thanks to cold electronics
- 4. Robust signal calibration scheme important to correctly measure ionization charge with LArTPC technology
- 5. Space charge effects observable in LArTPC data when operating on surface
- 6. LArTPC experiments capable of producing high-level physics results with automated reconstruction

Reconstructed cosmic tracks in MicroBooNE data (assuming $t_0 = t_{trigger}$)







ν future landscape (oscillation physics)

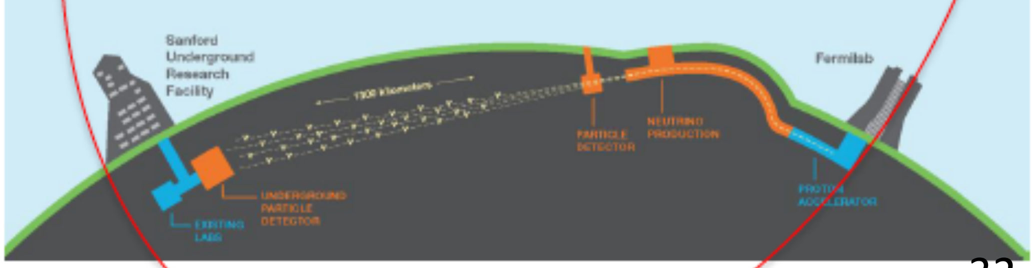
Neutrino Platform at CERN

LAr technology

T2K

SBN (short baseline)

LBNF/DUNE



CERN EHN1 test beam extension

NP04

Ready for Data taking in spring 2018

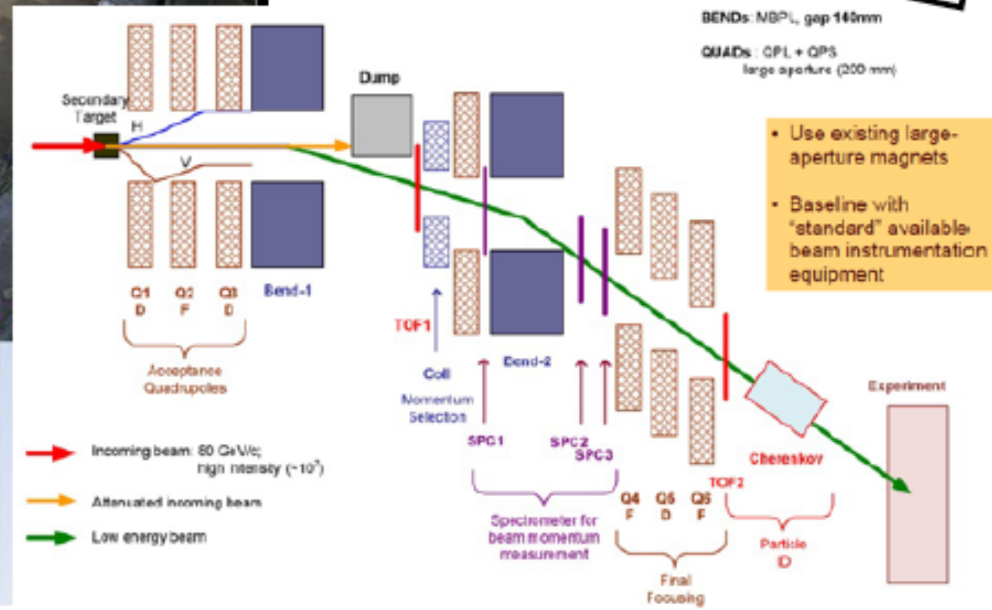


TABLE XIX: *Requirements for particles and their momenta. The particle rate here is the rate within a spill, regardless of the spill length, slow extraction is assumed.*

Type	Momentum [GeV/c]	Rate [kHz]	Total	Time est. [hrs]
Muon tracks				
$\mu^{+/-}$	0.8, 1.0, 1.5, 2.0, 5.0, 10.0, 20.0	0.1	$5\times10^{6}\times14$	200
Shower reconstruction				
$\pi^{+/-}$	0.5, 0.7, 1.0, 2.0, 5.0, 10.0, 20.0	0.1	$5\times10^{6}\times14$	200
e	0.5, 0.7, 1.0, 2.0, 5.0, 10., 20.0	0.1	$5\times10^{6}\times7$	100

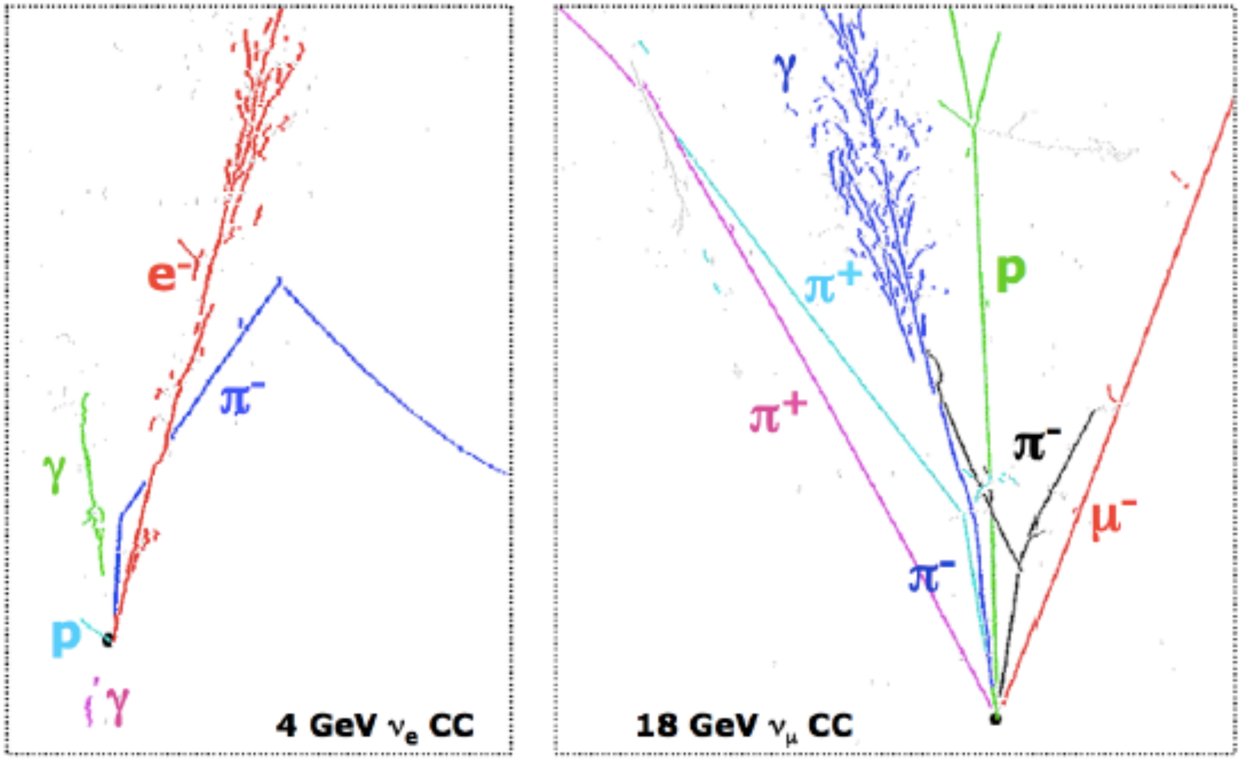
CERN North Area: 27/4/2016

single-phase proto-DUNE in the CERN SPS test beam in 2018

Particle	Momenta (GeV/c)	Sample Size	Purpose
π^+	0.2, 0.3, 0.4, 0.5, 0.7, 1, 2, 3, 5, 7	10k	hadronic cal, π^0 content
π^-	0.2, 0.3, 0.4, 0.5, 0.7, 1	10k	hadronic cal, π^0 content
π^+	2	600k	π^o/γ sample
proton	0.7, 1, 2, 3	10k	response, PID
proton	1	1M	mis-ID, PD, recombination
e^+ or e^-	0.2, 0.3, 0.4, 0.5, 1, 2, 3, 5, 7	10k	e-γ separation/EM shower
μ^-	(0.2), 0.5, 1, 2	10k	E_μ, charge sign
μ^+	(0.2), 0.5, 1, 2	10k	E_μ, Michel el.,charge sign
μ^- or μ^+	3, 5, 7	5k	E_μ MCS
anti-proton	low-energy tune	(100)	anti-proton stars
K^+	1	(13k)	response, PID, PD
K^+	0.5, 0.7	(5k)	response, PID, PD
μ, e, proton	1 (vary angle $\times 5$)	10k	reconstruction

Table 1: Requirements summary for particle types and momenta. The sample size column indicates the number of particles for each momentum point. Items in parenthesis indicate lower priority (see text).

Another Challenge: Event Reconstruction



Highly complex event topologies that require sophisticated reconstruction algorithms.

Need to reconstruct tracks and showers, measure their energy and perform particle identification. Automatisation a major challenge.

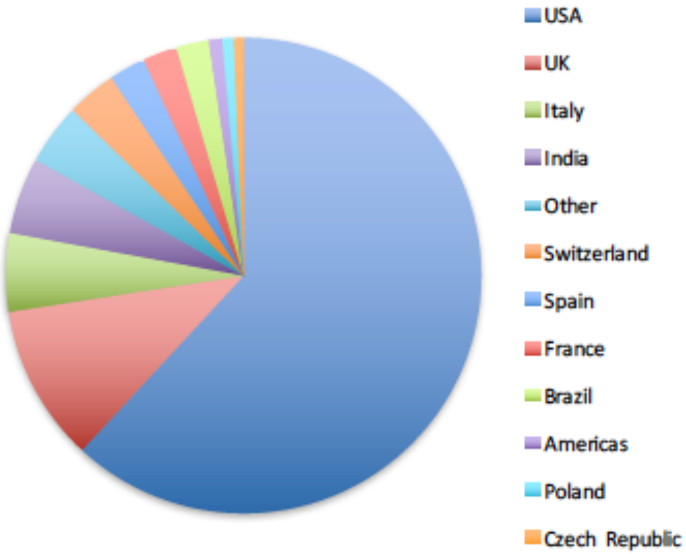
The DUNE Collaboration

162

As of today: **from 149 Institutions in**

856 Collaborators **29 Nations**

900



Armenia, Belgium, Brazil, Bulgaria, Canada, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, Spain, Sweden, Switzerland, Turkey, UK, USA, Ukraine

DUNE has broad international support and is growing
~70 new collaborators this calendar year

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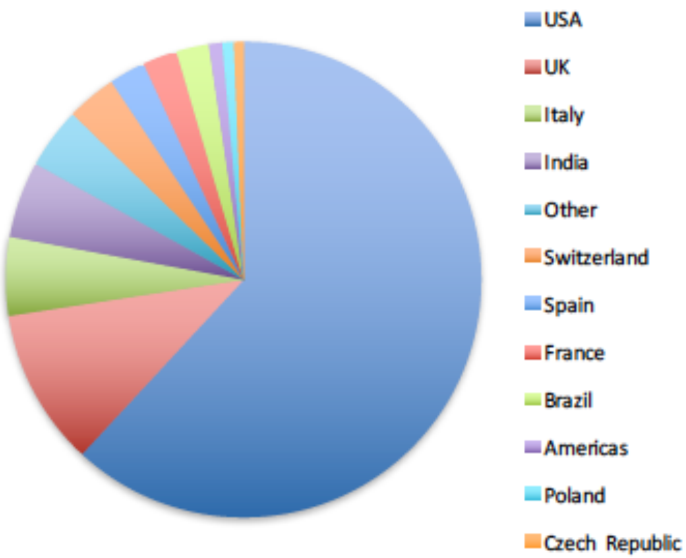

Armenia, Belgium, Brazil, Bulgaria, Canada, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, Spain, Sweden, Switzerland, Turkey, UK, USA, Ukraine

DUNE has broad international support and is growing
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DUNE Strategic Goals 2016 - 2019

Top-level goals for 2016 – 2019

- **Construction and operation of large-scale prototypes at CERN**
  - Critical for demonstrating the ability of the DUNE collaboration to implement a major construction activity
- **Preparation of DUNE TDR for CD-2**
  - Along with the protoDUNE programme, this is the major scientific and technical goal for the collaboration
- **Enlarging the Collaboration**
  - To meet the technical challenges ahead our goal is to enlarge the DUNE collaboration, with particular focus on further internationalization. CD-3a approval will present a major opportunity
- **Identification of the resources for construction of DUNE**
  - DUNE TDR will present institutional responsibilities for DUNE construction. Funding for TDR scope needs to be in place by 2019

Far Site Facilities Scope and Requirements

Scope Element	Funding Source
Excavation of 4850L detector and utility caverns and drifts	DOE
Surface buildings, utility infrastructure, cavern outfitting	DOE
LN2 cryogenic systems	DOE
Four 10kt fiducial cryostats	Non-DOE
LAr cryogenic systems	Non-DOE
LAr and LN2 cryogenic fluids procurement	DOE and Non-DOE

CD-3a Scope

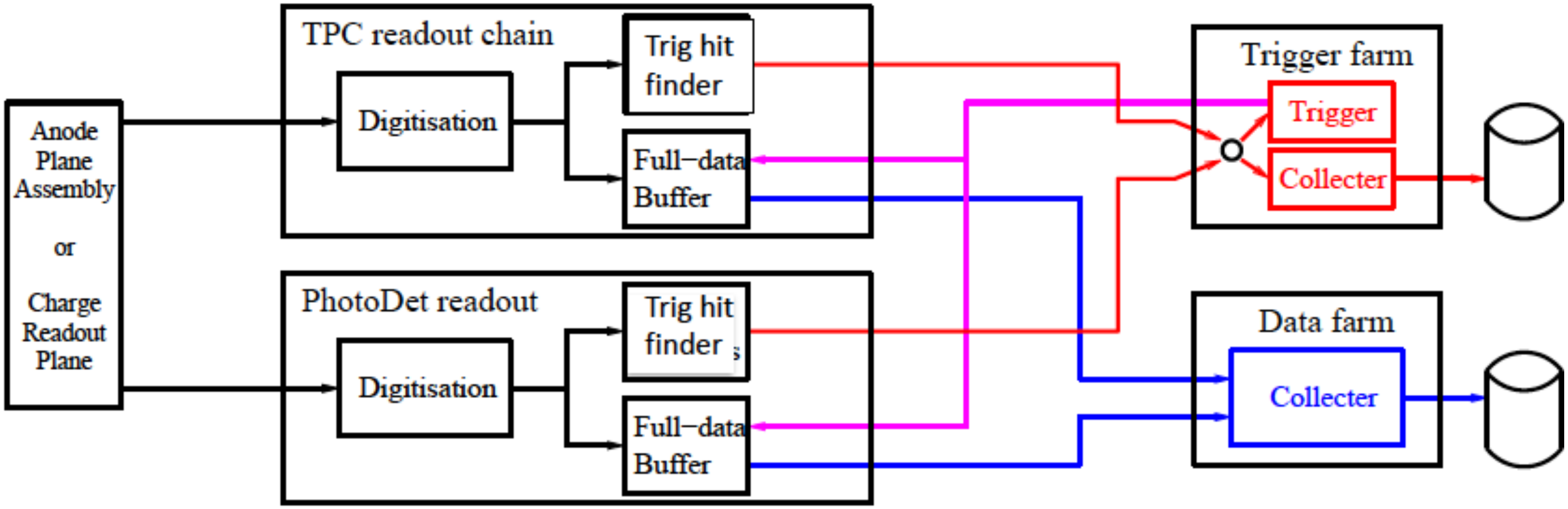
CERN taking lead in design of cryostats
CERN funds construction of one cryostat

DOE review now
If pass: start excavation

Opportunities for European (including Dutch) industry

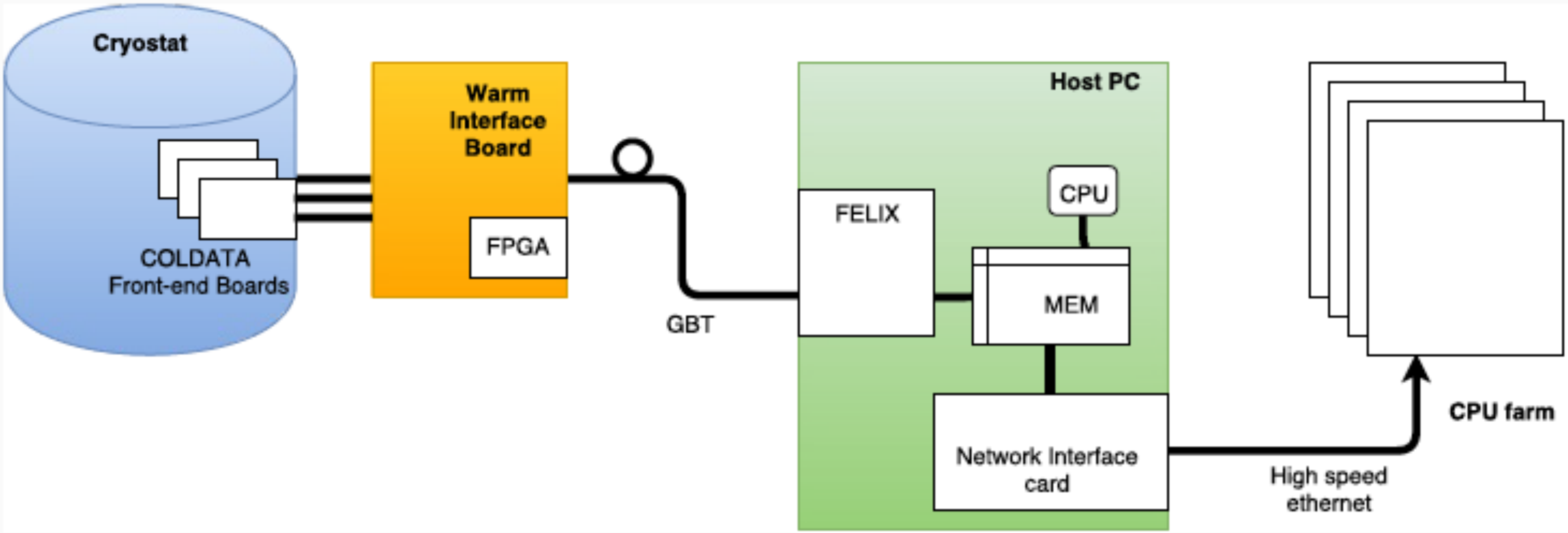
What could Nikhef contribute?

We want to focus on the single-phase readout TPC technology.



DAQ and trigger concepts still being developed

- Multiple streams
- Multiple types of trigger
- Multi-level triggering



FELIX is being developed in ATLAS for the phase 1 (LS-2) upgrade, and afterwards
Get data in computer memory, COTS networking equipment downstream
Essentially on a PCI-e card in a host PC, equipped with a FPGA
Nikhef is one of the major developers in ATLAS

protoDUNE plan: at least APA read out with FELIX. Test setup in ATLAS test room.
PhD student Milo Vermeulen, staff Frank Filthaut, Patrick Decowski, Paul de Jong

FELIX plans

Proposed hardware setup

1 FELIX PC (SuperMicro)

- single CPU (3.6 GHz E5-1650v4 or 3.5 GHz E5-1650v2), 6 cores, hyperthreading; 16 or 32 GB memory (2 hosts available; upgrade from 16 GB to 32 GB possible)
  - 8-lane PCIe Gen3 ➠ measured max. throughput > 6 GB/s
- HTG710 board, 6 input links ➠ input rate 57.6 Gb/s (payload: 45 Gb/s)
  - emulate 6 WIB links using VC709 (optical splitter to create 6 links from 4)
- dual port 40 Gb/s Ethernet (or 56 Gb/s Infiniband) NIC (Mellanox), 8-lane PCIe Gen3 (3 available)

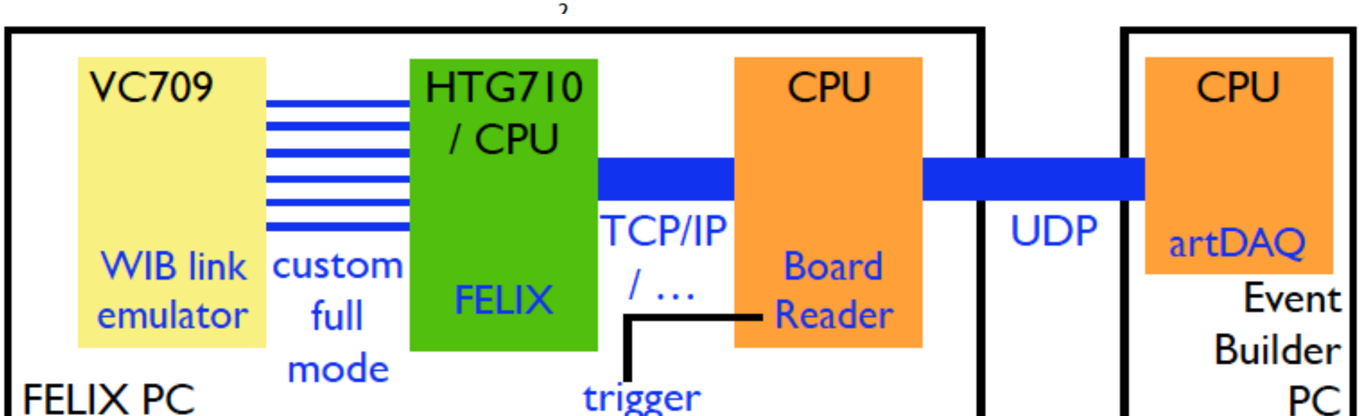
1 event builder PC

- data sink

BoardReader PC

- (if needed)

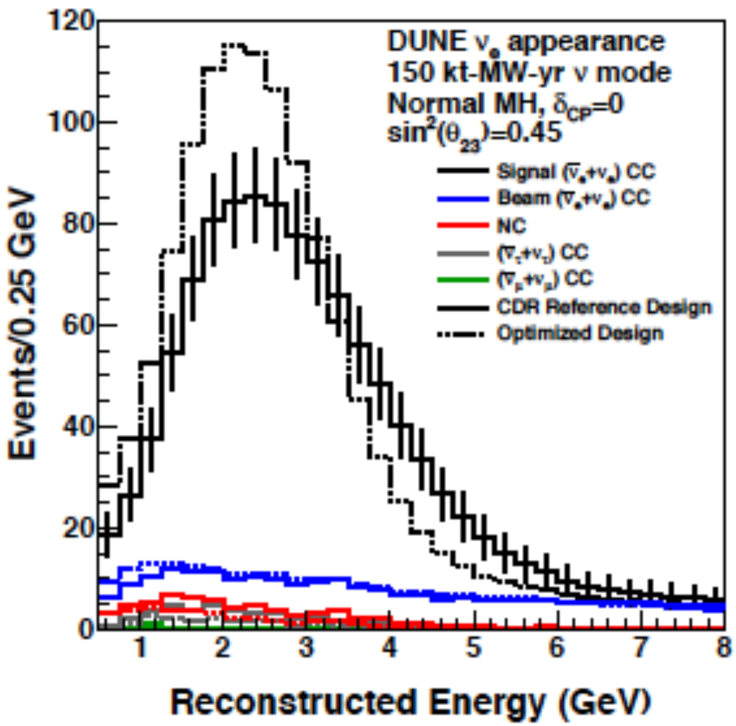
All hardware available (Nikhef DAQ test lab)

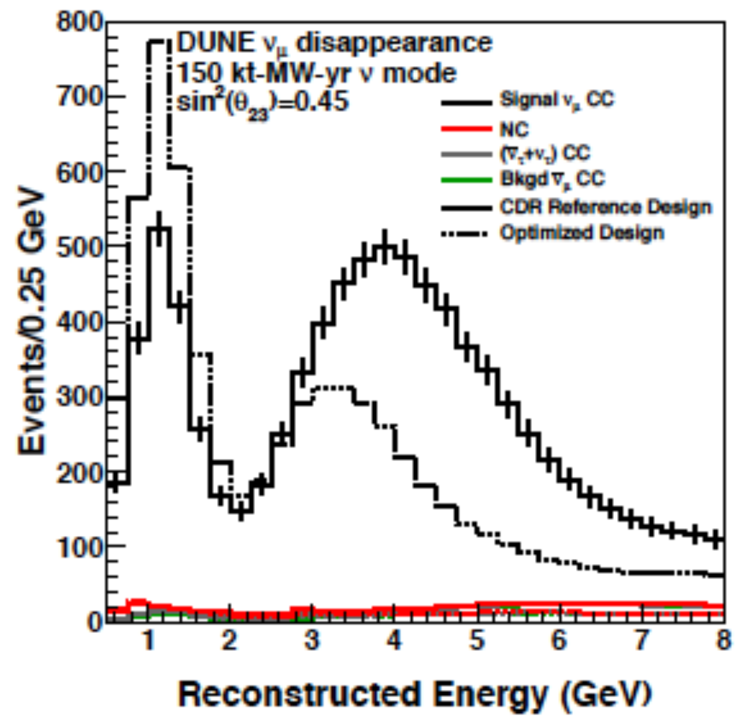


DUNE oscillation analysis:

Documented in CDR: arXiv:1512.06148, arXiv:1606.09550

- LBNF beamline simulator → fast MC using GENIE → GLOBES for fit (assumed syst.)



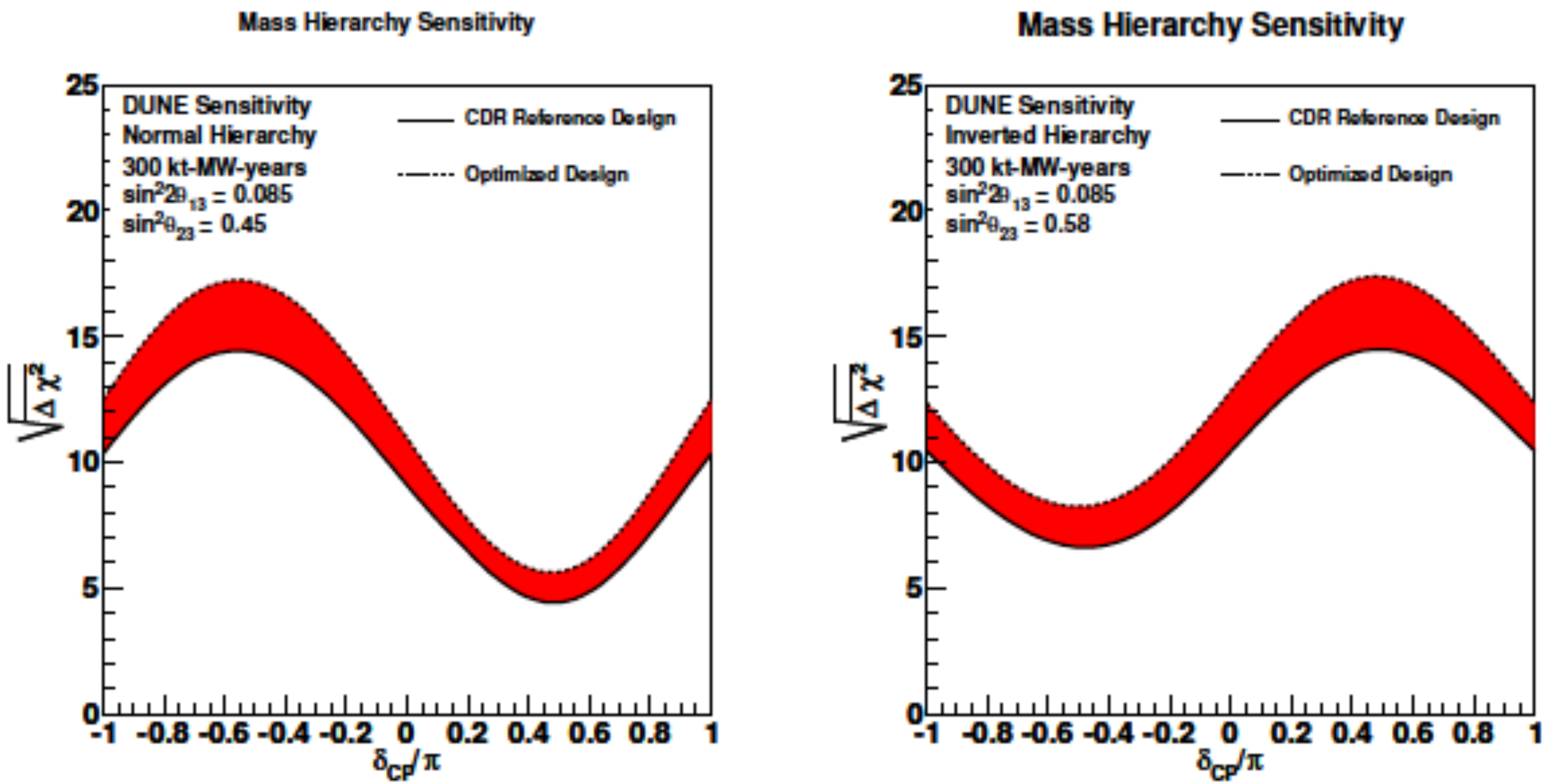


Next: more realistic simulation/reconstruction
Technical Design Report 2019

Assumptions in CDR

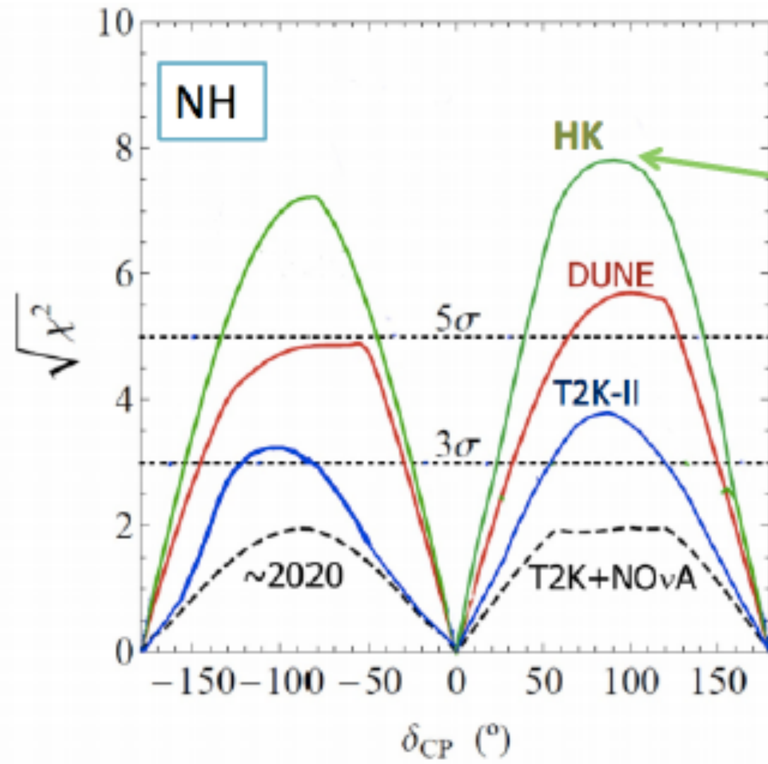
Particle type	Detection Threshold (KE)	Energy/Momentum Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained track: track length Exiting track: 30%	1°
$\pi^{\pm}$	100 MeV	μ-like contained track: track length π-like contained track: 5% Showering or exiting: 30%	1°
$e^{\pm}/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{E}$[GeV]	1°
p	50 MeV	p<400 MeV/c: 10% p>400 MeV/c: $5\% \oplus 30\%/\sqrt{E}$[GeV]	5°
n	50 MeV	$40\%/\sqrt{E}$[GeV]	5°
other	50 MeV	$5\% \oplus 30\%/\sqrt{E}$[GeV]	5°

Source of Uncertainty	MINOS ν_e	T2K ν_e	DUNE ν_e	Comments
Beam Flux after N/F extrapolation	0.3%	3.2%	2%	See "Flux Uncertainties" in Section 3.6.2
Interaction Model	2.7%	5.3%	$\sim 2\%$	See "Interaction Model Uncertainties" in Section 3.6.2
Energy scale (ν_μ)	3.5%	included above	(2%)	Included in 5% ν_μ sample normalization uncertainty in DUNE 3-flavor fit.
Energy scale (ν_e)	2.7%	2.5% includes all FD effects	2%	See "ν_e Energy-Scale Uncertainties" in Section3.6.2
Fiducial volume	2.4%	1%	1%	Larger detectors = smaller uncertainty.
Total	5.7%	6.8%	3.6 %	
Used in DUNE Sensitivity Calculations			$5\% \oplus 2\%$	Residual ν_e uncertainty: 2%

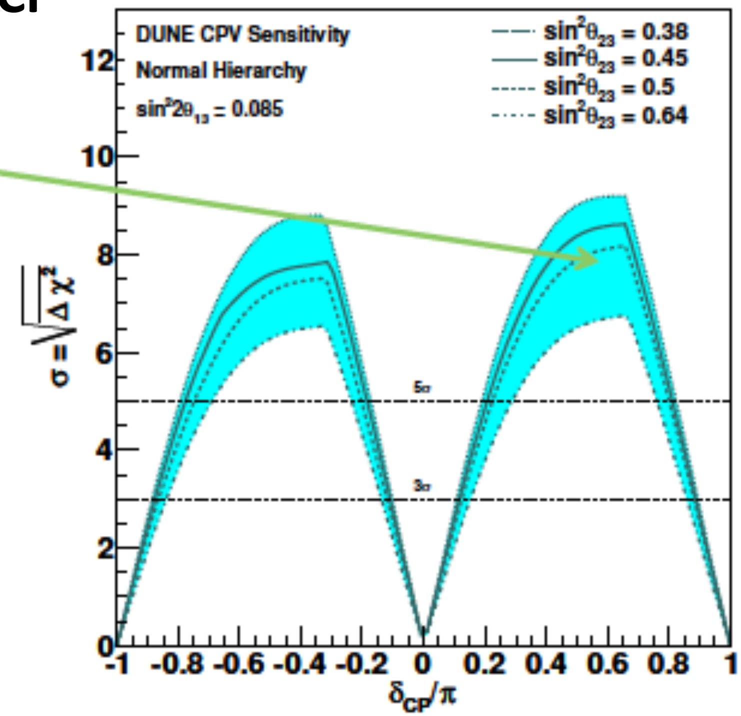

Mass Hierarchy Sensitivity
DUNE Sensitivity
Normal Hierarchy
300 kt-MW-years
$\sin^2 2\theta_{13} = 0.085$
$\sin^2\theta_{23} = 0.45$
CDR Reference Design
Optimized Design
$\sqrt{\Delta\chi^2}$
δ_{CP}/π
Mass Hierarchy Sensitivity
DUNE Sensitivity
Inverted Hierarchy
300 kt-MW-years
$\sin^2 2\theta_{13} = 0.085$
$\sin^2\theta_{23} = 0.58$
CDR Reference Design
Optimized Design
$\sqrt{\Delta\chi^2}$
δ_{CP}/π

M. Mezzetto, Neutrino 2016

δ_{CP}



DUNE 890 kt-MW-years

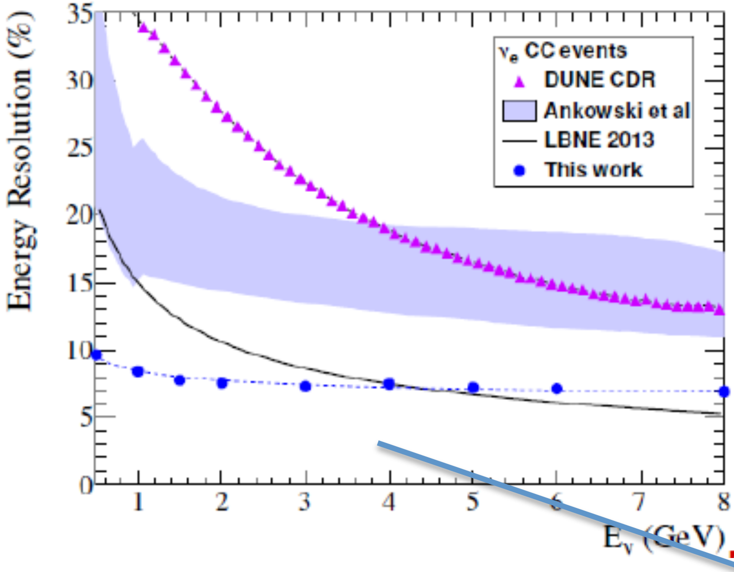


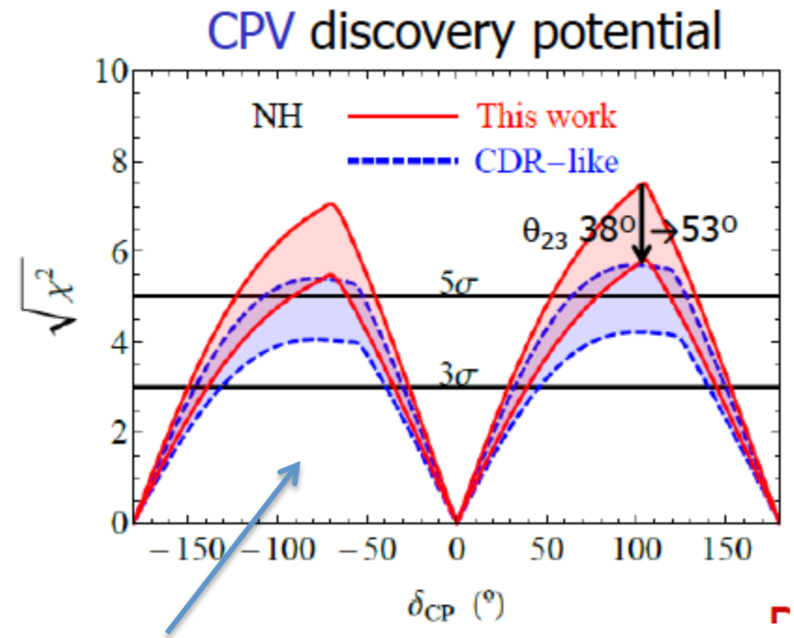
- DUNE curve is our 300 kt-MW-year exposure: ~1100 expected appearance events
- HK curve is a 10-year staged exposure -- 6 years with 1st tank (190 kt fiducial) + 4 years with both tanks (380 kt fiducial): ~4000 expected appearance events

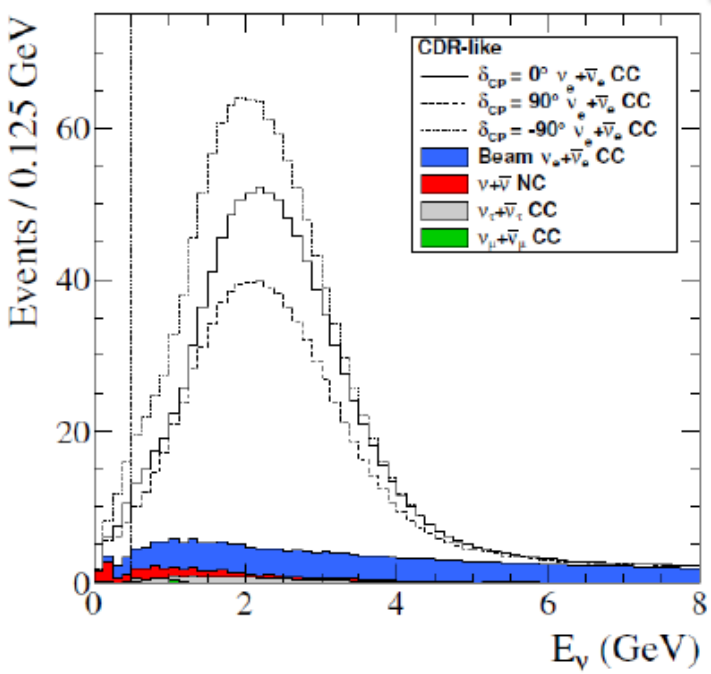
DUNE: 300 kt-MW-year = about 8 years of running, with current staging estimates
890 kt-MW-year = 11 years with full detector and upgraded proton beam

Role of energy resolution

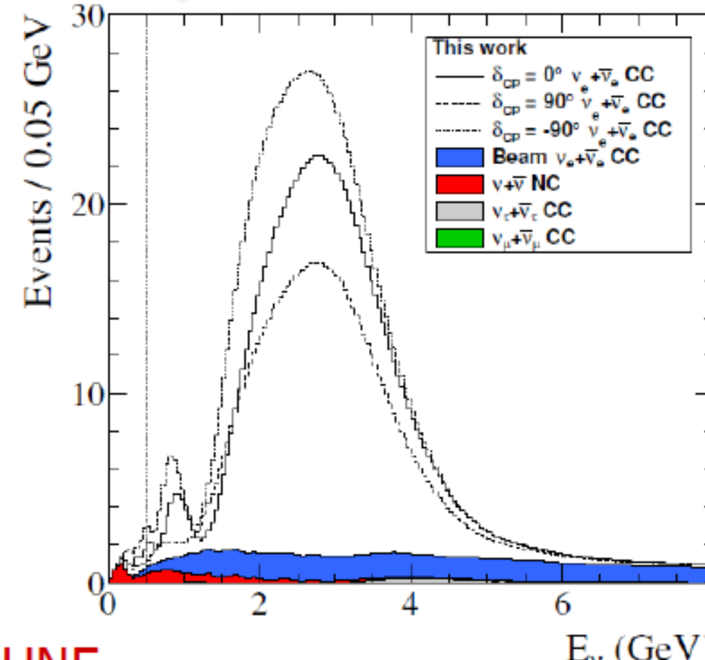
arXiv:1607.00293

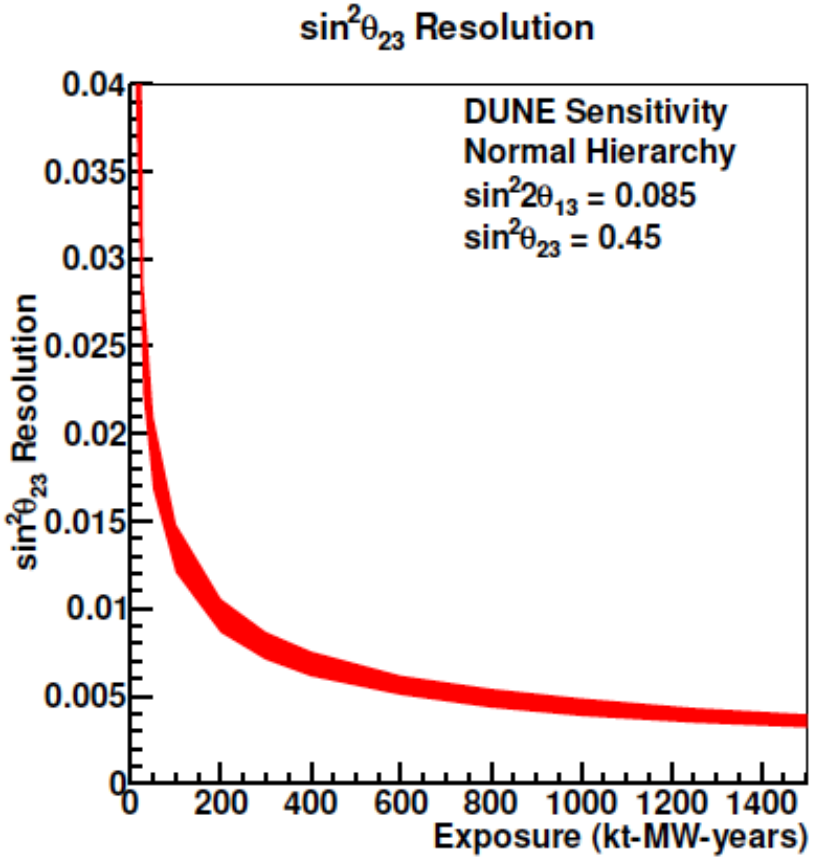


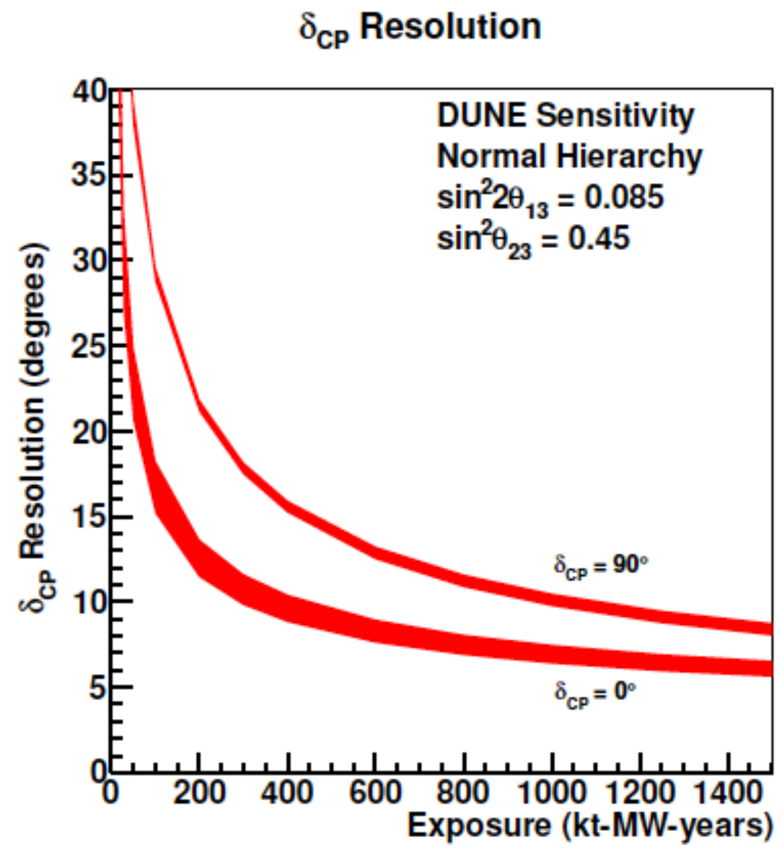




DUNE







DUNE is more than δ_{CP}:

Determination of mixing angles and Δm^2; consistency 3-generation picture,
BSM physics: non-standard neutrino interactions, proton decay,
Huge sample of neutrino interactions in near detector: SF, EW physics
Supernova neutrinos

Backup

FELIX development team

Argonne National Laboratory
- John Anderson
- Soo Ryu
- Jinlong Zhang

Brookhaven National Laboratory
- Hucheng Chen
- Kai Chen
- Weihao Wu
- Francesco Lanni

CERN
- Markus Joos
- Giovanna Lehmann
- Wainer Vandelli
- Benedetto Gorini

Nikhef
- Frans Schreuder
- Andrea Borga
- Henk Boterenbrood
- Jos Vermeulen

Universität Paderborn — Die Universität der Informationsgesellschaft
- Joern Schumacher

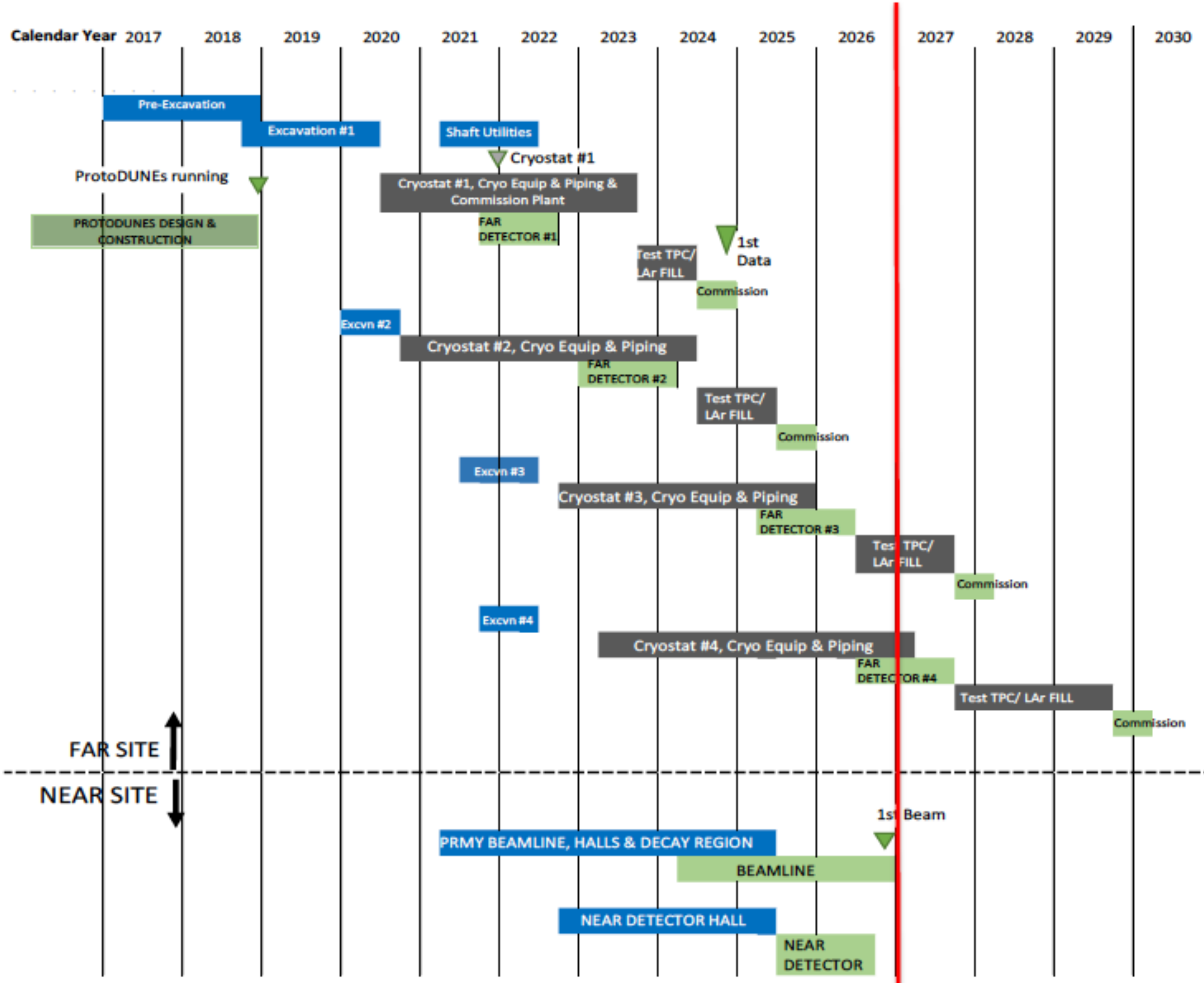
Radboud University
- Mark Donszelmann

UCI University of California, Irvine
- Daniel Guest
- Daniel Whiteson

Weizmann Institute of Science
- Julia Narevicius
- Alex Roich
- Lorne Levinson

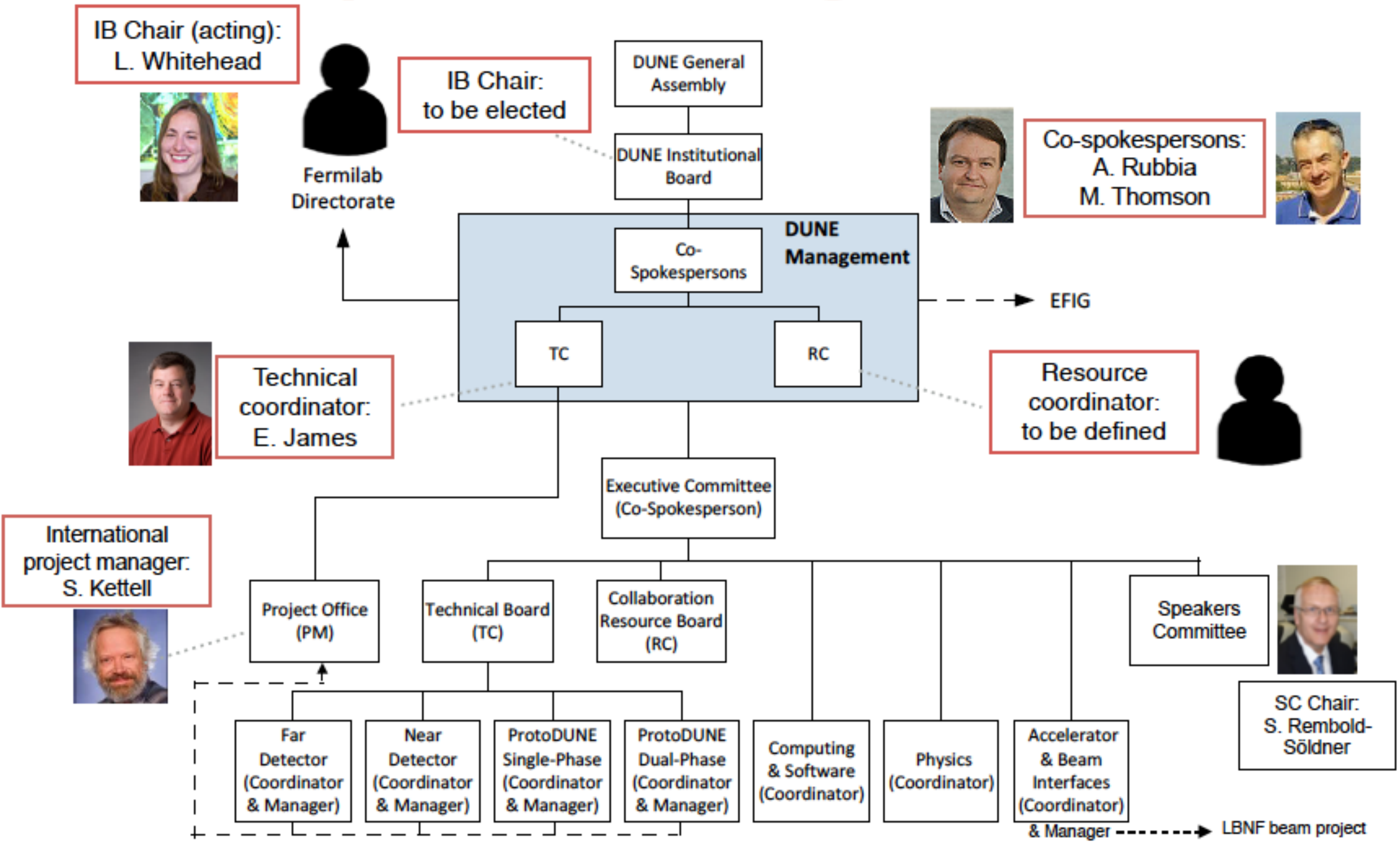
ROS/ROD effort on software framework:
- Gordon Crone (UCL)
- Will Panduro (RHUL)
- Joern Schumacher (CERN / Paderborn)
- Wainer Vandelli (CERN)

LBNF/DUNE – Construction Summary



LBNF

DUNE Top Level Management Team



Matter Effects

- ★ Even in the absence of CPV

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) \neq 0$$

Neutrinos travel through material that is not CP symmetric, i.e. matter not antimatter

- ★ Complicates the simple picture !!!!

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) =$$ ← What we measure

ME $$\frac{16A}{\Delta m^2_{31}} \sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$ ← Small

ME $$-\frac{2AL}{E} \sin\left(\frac{\Delta m^2_{31}L}{4E}\right) c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$ ← Proportional to L

CPV $$-8\frac{\Delta m^2_{21}L}{2E} \sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) \sin\delta \cdot s_{13}c^2_{13}c_{23}s_{23}c_{12}s_{12}$$ ← What we want

with $A = 2\sqrt{2}G_F n_e E = 7.6 \times 10^{-5}\mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$

Experimental Strategy

EITHER:

★ Keep L small (~200 km): so that matter effects are insignificant

- First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu < 1\,\mathrm{GeV}$$

- Since $\sigma \propto E_\nu$ need a high flux at oscillation maximum

⇨ Off-axis beam: narrow range of neutrino energies

OR:

★ Make L large (>1000 km): measure the matter effects (i.e. MH)

- First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu > 2\,\mathrm{GeV}$$

- **Unfold CPV from Matter Effects through E dependence**

⇨ On-axis beam: wide range of neutrino energies

Experimental Strategy

EITHER:

★ Keep L small (~200 km): so that matter eff re insignificant

- First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

- Since u high flux at oscillation maximum

⇨ Off- eam: narrow range of neutrino energies

Hyper-Kamiokande

OR:

★ Make L large (>1000 km): measure th atter effects (i.e. MH)

- First oscillation maxim

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

- **Unfold CPV from through E dependence**

⇨ On-axis beam de range of neutrino energies

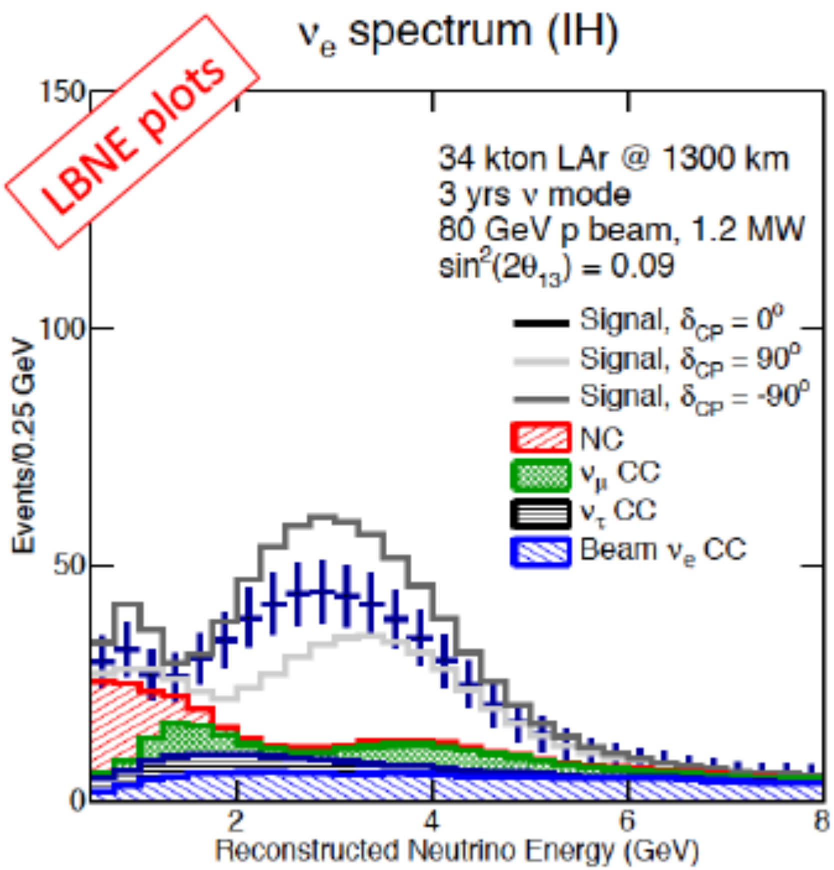
DUNE

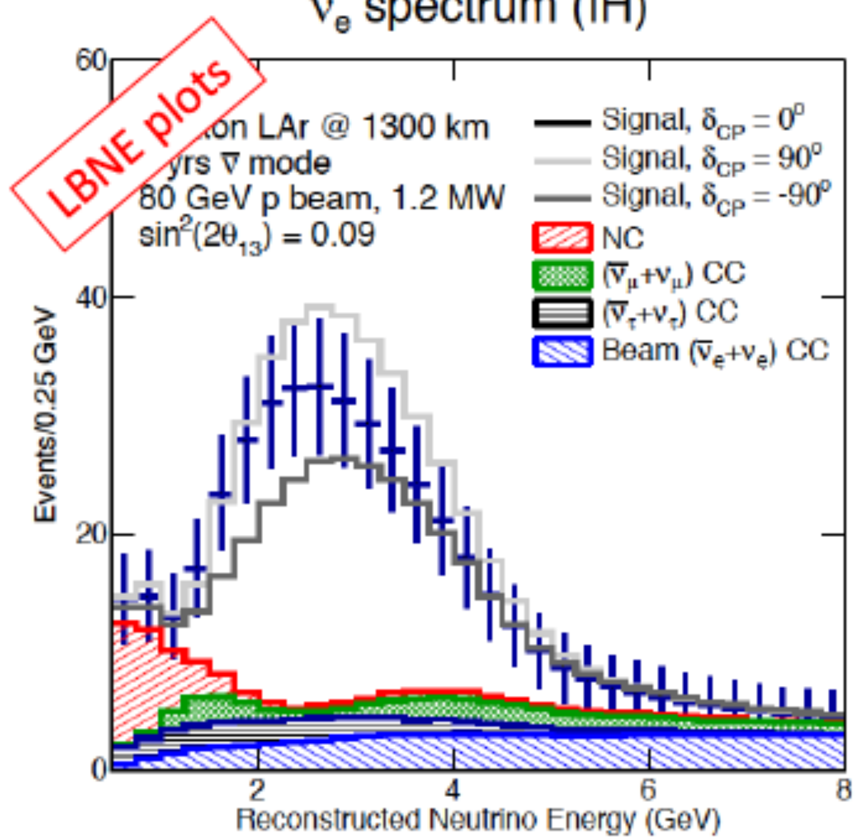
Separating MH & CPV

DUNE: **Determine MH and probe CPV in a single experiment**

Recall: $$\mathcal{A} = P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \mathcal{A}_{CP} + \mathcal{A}_{Matter}$$

with different energy dependence





Separating MH & CPV

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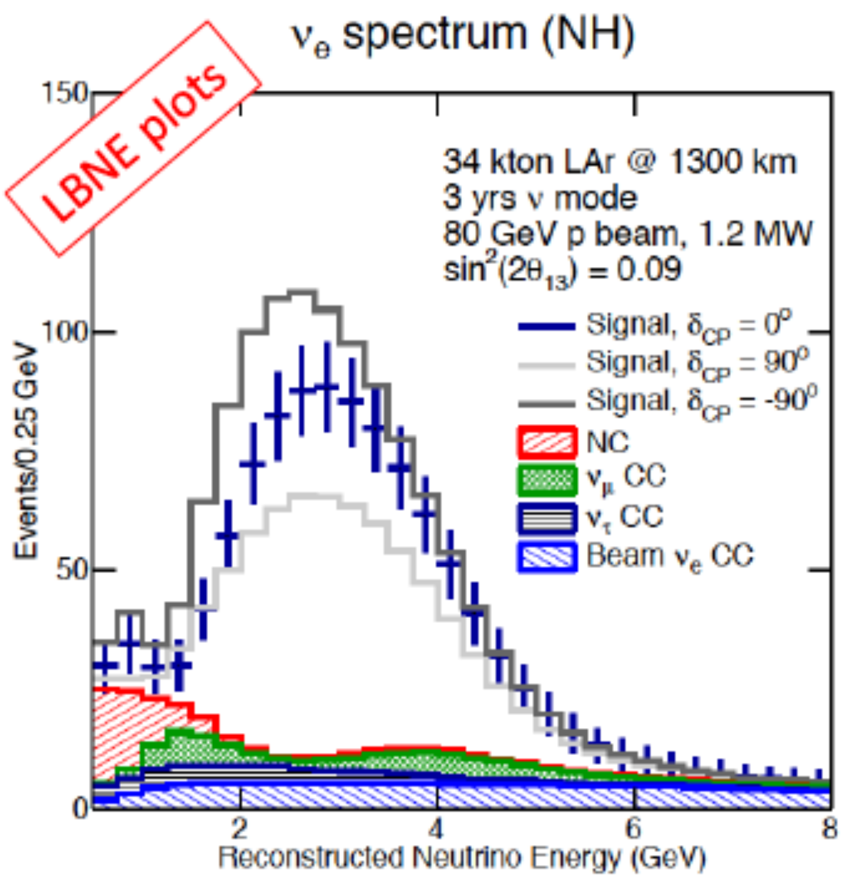
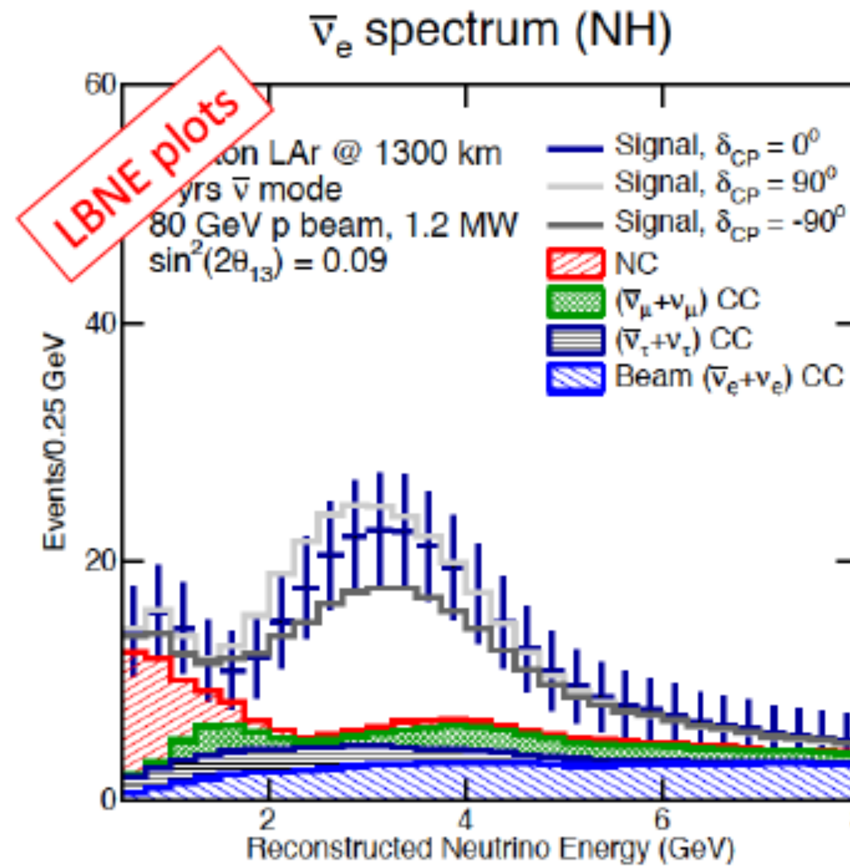
with different energy dependence





MH and CPV Sensitivities

★ Sensitivities depend on multiple factors:
- Other parameters, e.g. δ
- Details of beam spectrum, …