An Experimental Programme at the DUNE

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on behalf of the DUNE Collaboration

ICNFP2015

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Lancaster University

DUNE Primary Science Program

- **Neutrino Oscillation Physics**
  - CP symmetry violation in the leptonic sector
    - Is Leptogenesis the answer to matter dominance?
  - Mass Hierarchy
  - Precision Oscillation Physics & testing the 3-flavor paradigm
- **Nucleon Decay**
  - Predicted in beyond the Standard Model theories [but not yet seen]
    - e.g. the SUSY-favored mode, $p \rightarrow K^{+}\overline{\nu}$
- **Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e
    - Time information on neutron star or even black-hole formation
- **Precision neutrino interactions studies (Near Det.)**

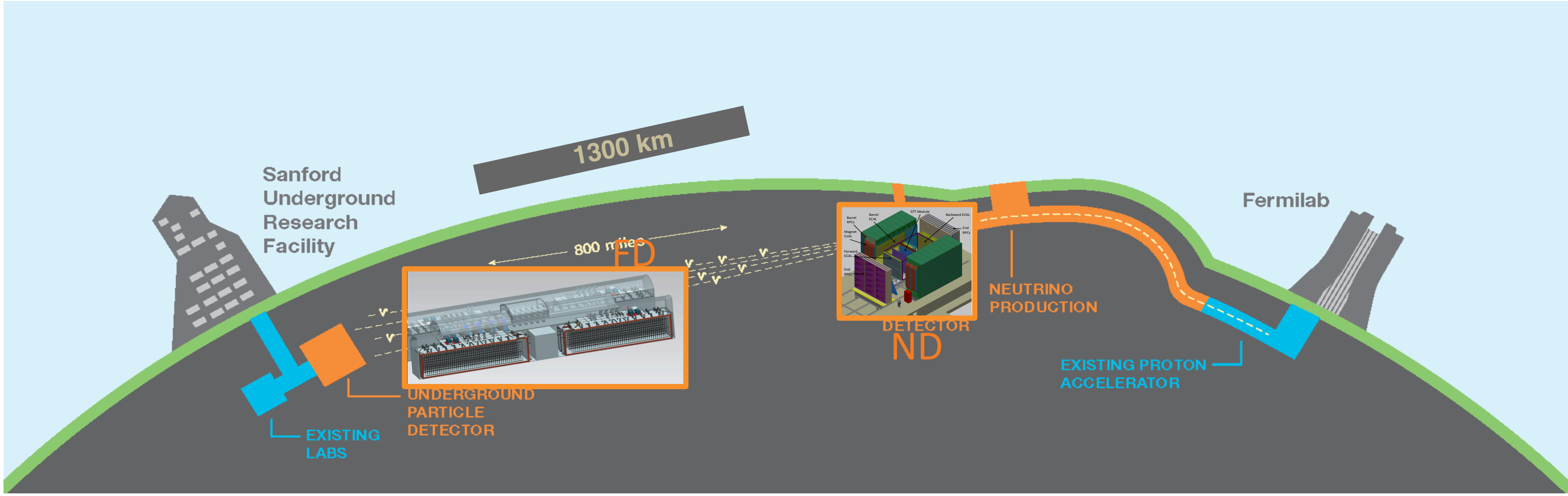
DUNE collaboration

782 Collaborators
144 institutions

from 26 Nations

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

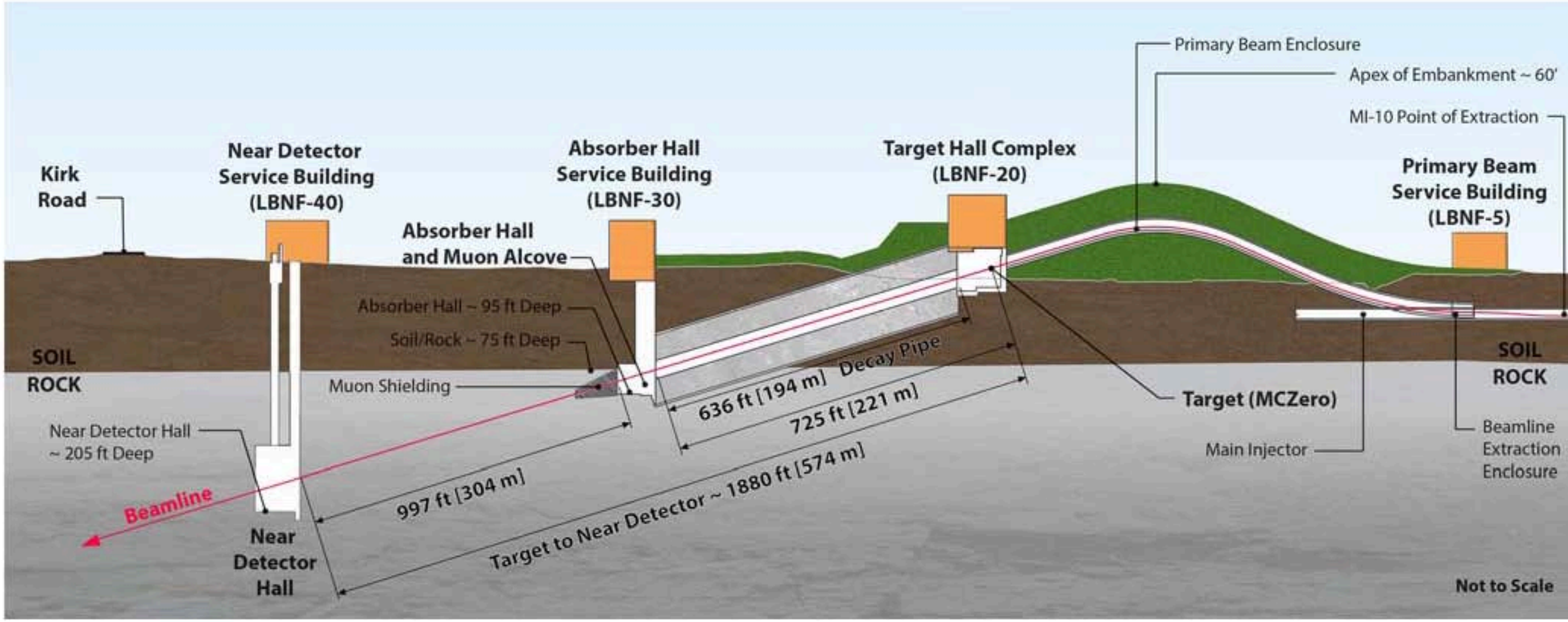
DUNE EXPERIMENT



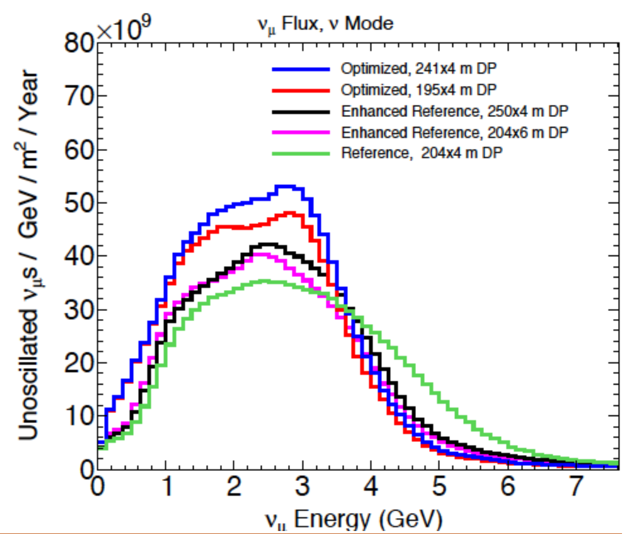
<u>Main features of the DUNE experiment are:</u>

- A high-intensity wide-band neutrino beam originating at FNAL
  - 1.2 MW proton beam upgradable to 2.4 MW
- Highly capable ND to constrain systematic errors in DUNE
- A ~40 kt fiducial mass liquid argon far detector
  - Located 1300 km baseline at SURF's 4850 ft level (2,300 mwe)
  - Staged construction of four ~10 kt detector modules. First module to be installed starting in 2021.

LBNF/DUNE Neutrino Beam



- 60 – 120 GeV Proton beam energy
- Initial power 1.2 MW upgradable to 2.4 MW
  - PIP II complete before start of data taking
- 10^{21} protons on target per year
- Good coverage 1 to 5 GeV



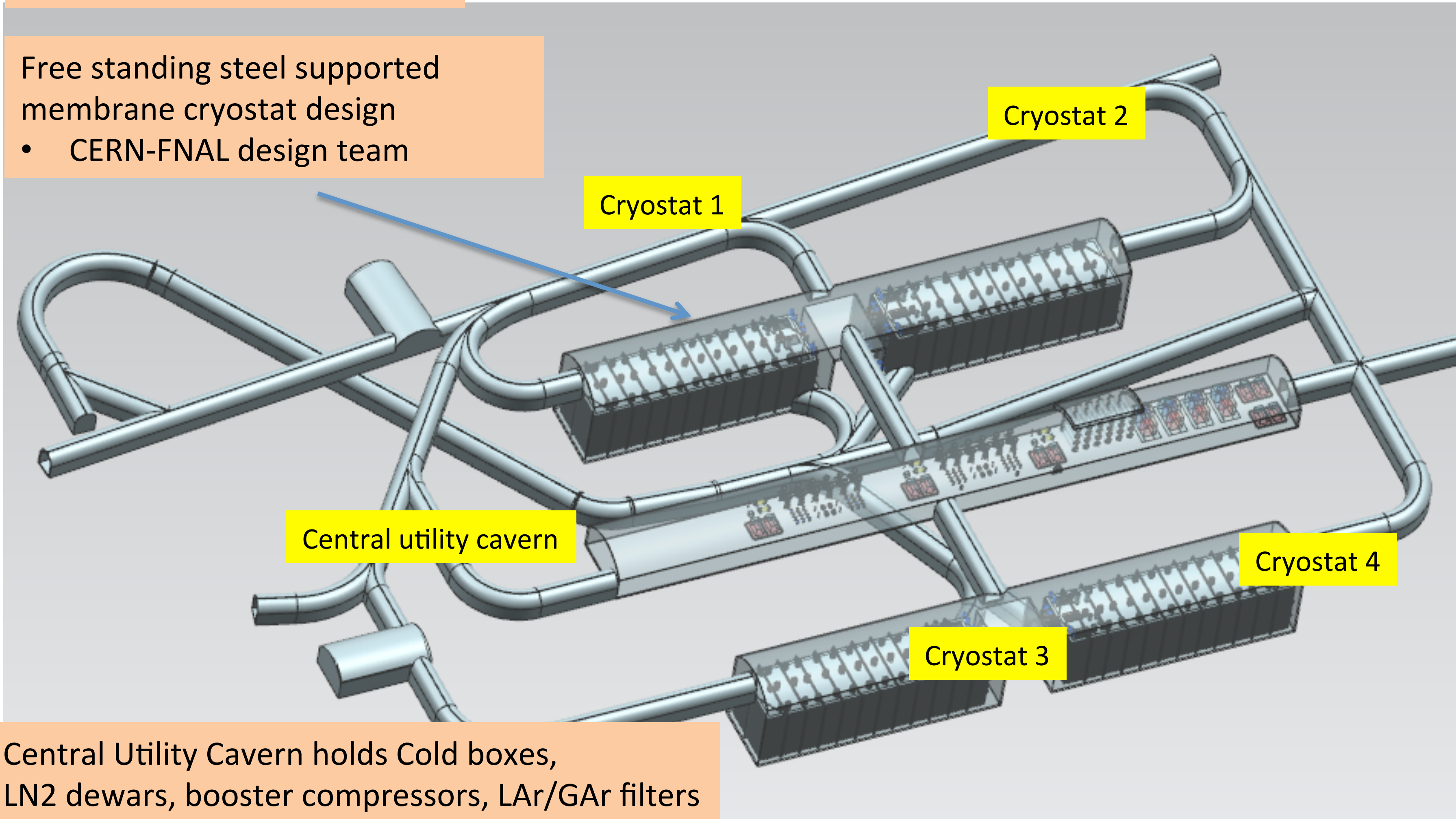
DUNE

Far Detector – Cryostat / Cryogenic Systems Layout

Each Cryostat holds 17.1kt Lar

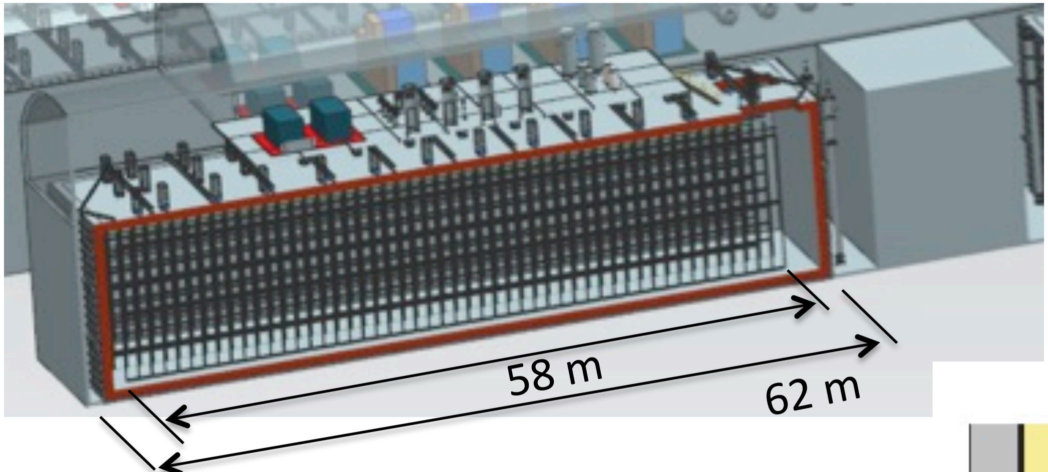
Free standing steel supported membrane cryostat design

- CERN-FNAL design team



Central Utility Cavern holds Cold boxes,
LN2 dewars, booster compressors, LAr/GAr filters

Nominal 10 kt Detector Configuration – Single phase readout

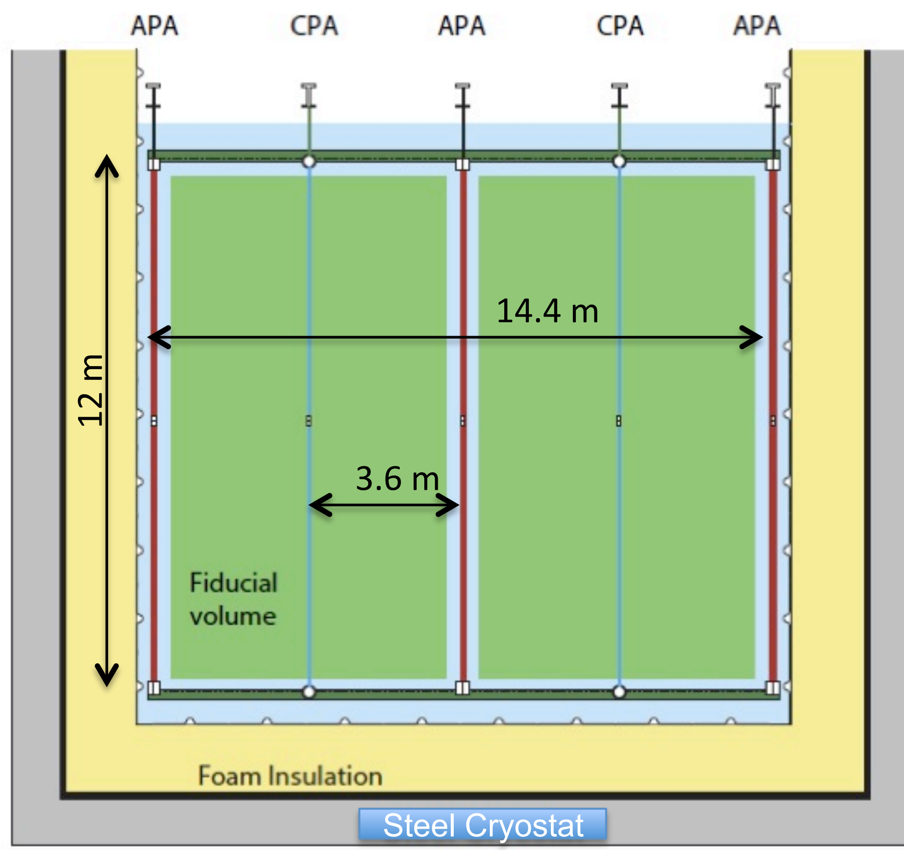


Liquid Argon Time projection chamber with both charge and scint. light readout.

First 10kt detector will be single phase

LAr Detector Module Characteristics

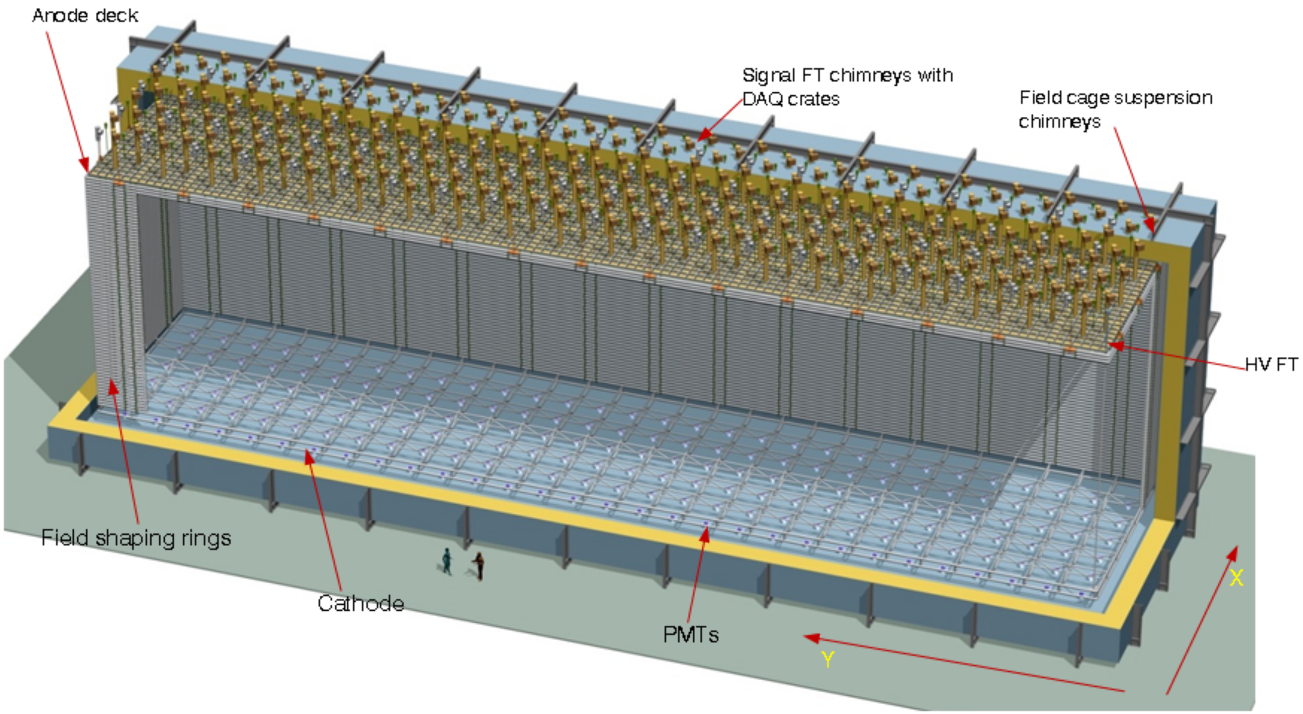
- 17.1/13.8/11.6 Total/Active/Fiducial mass
- 3 Anode Plane Assemblies (APA) wide (wire planes)
  - Cold electronics 384,000 channels
- Cathode planes (CPA) at 180kV
  - 3.6 m max drift length
- Photon detection for event interaction time determination for non-accelerator based physics



Alternative Far Detector Design

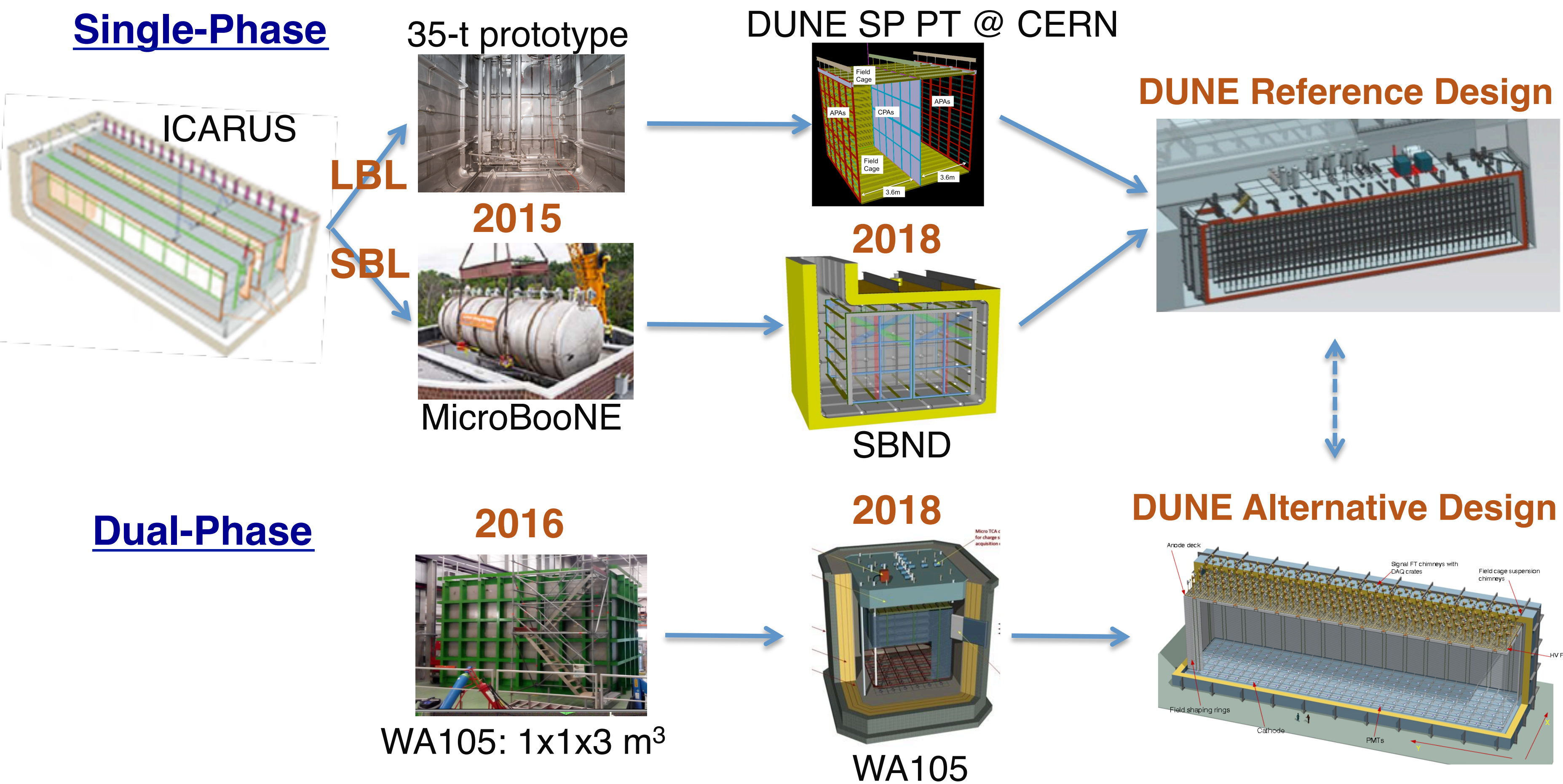
DUNE collaboration recognizes the potential of the dual-phase technology

- A dual-phase implementation of the DUNE far detector is presented as an **alternative design** in the CDR
- If demonstrated, could form basis of second or subsequent 10-kt far detector modules



LArTPC Development Path

Fermilab SBN and CERN neutrino platform provide a strong LArTPC development and prototyping program



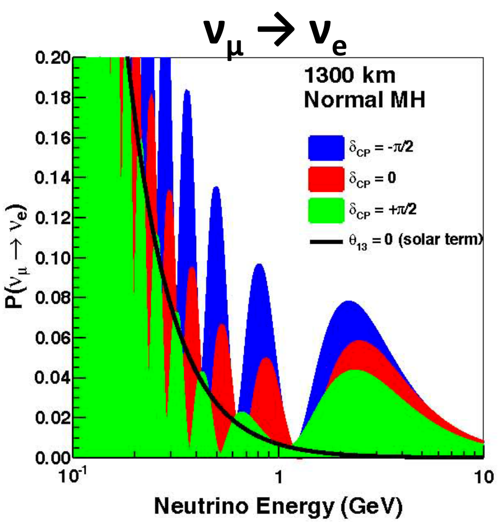
Oscillation Probability

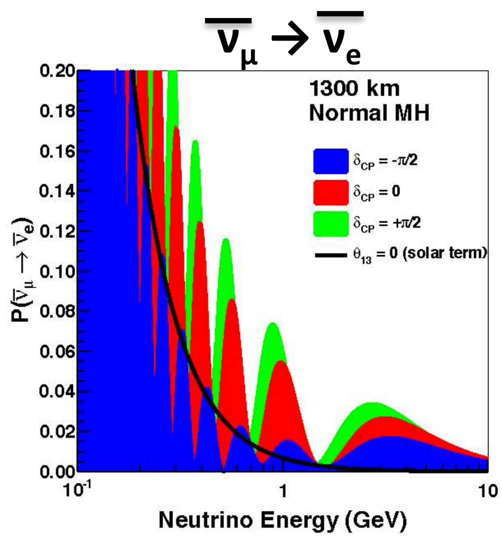
$$\Delta_{ij} = \Delta m^2_{ij} L / 4E_\nu$$

$$a = G_F N_e / \sqrt{2}$$

ν_μ oscillation probability

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$
$$+ \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)} \Delta_{21} \cos(\Delta_{31} + \delta_{CP})$$
$$+ \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2,$$





ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and mass hierarchy

Large value of $\sin^2(2\theta_{13})$ allows significant ν_e appearance sample.

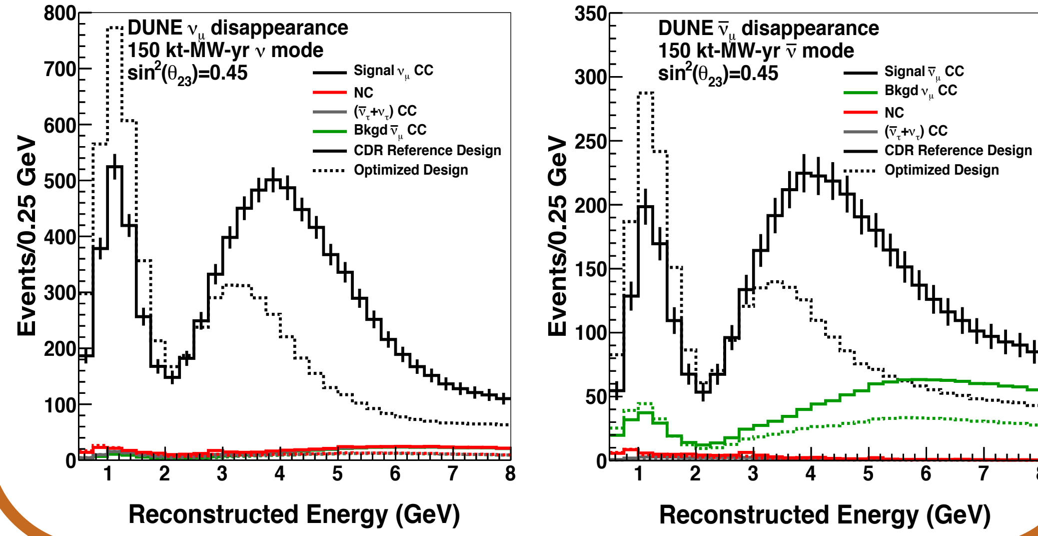
δ_{CP} and a switch signs in going from the $\nu_\mu \to \nu_e$ to the $\bar{\nu}_\mu \to \bar{\nu}_e$

DUNE

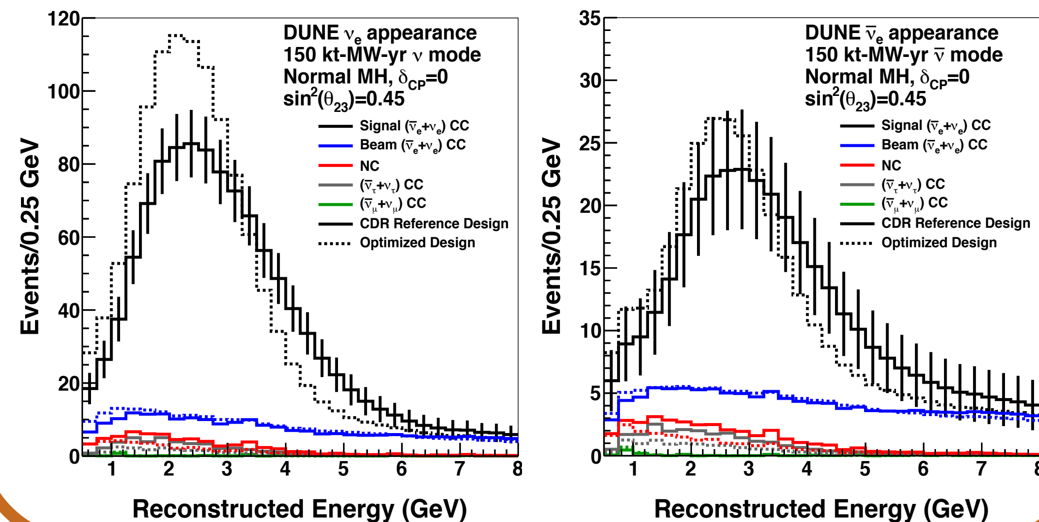
Event Spectra

The full power of the experiment comes from a simultaneous fit to these spectra

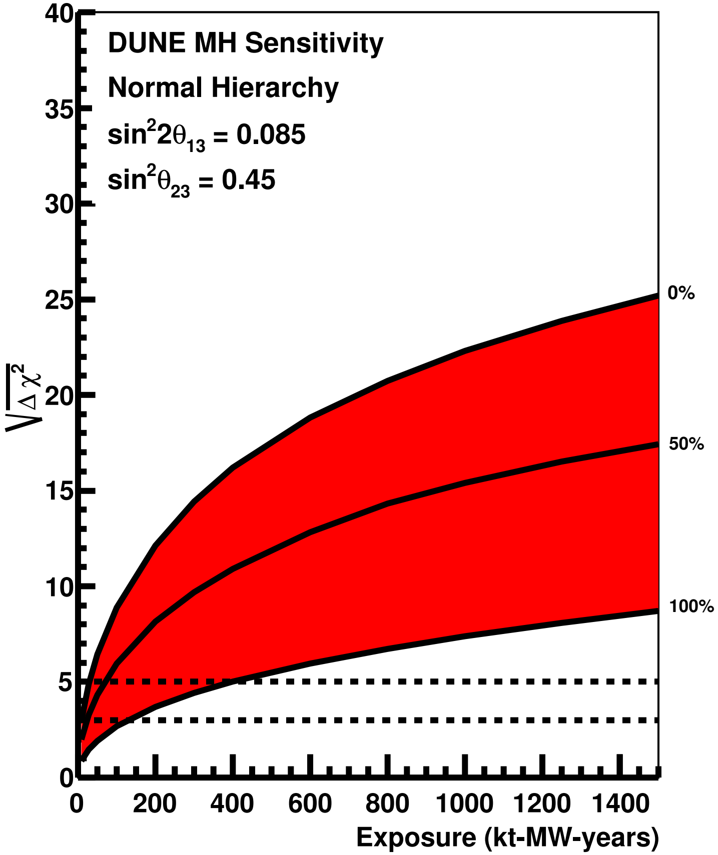
ν_μ / $\bar{\nu}_\mu$ disappearance

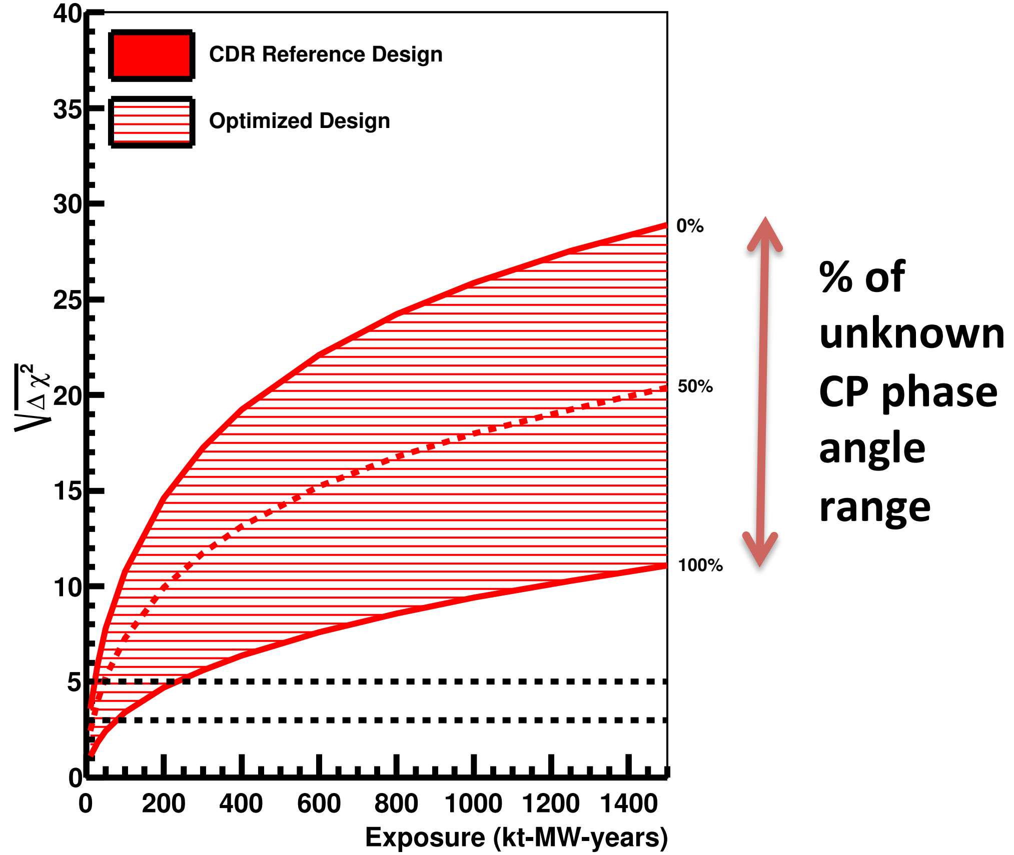


ν_e / $\bar{\nu}_e$ appearance



DUNE Mass Hierarchy Sensitivity



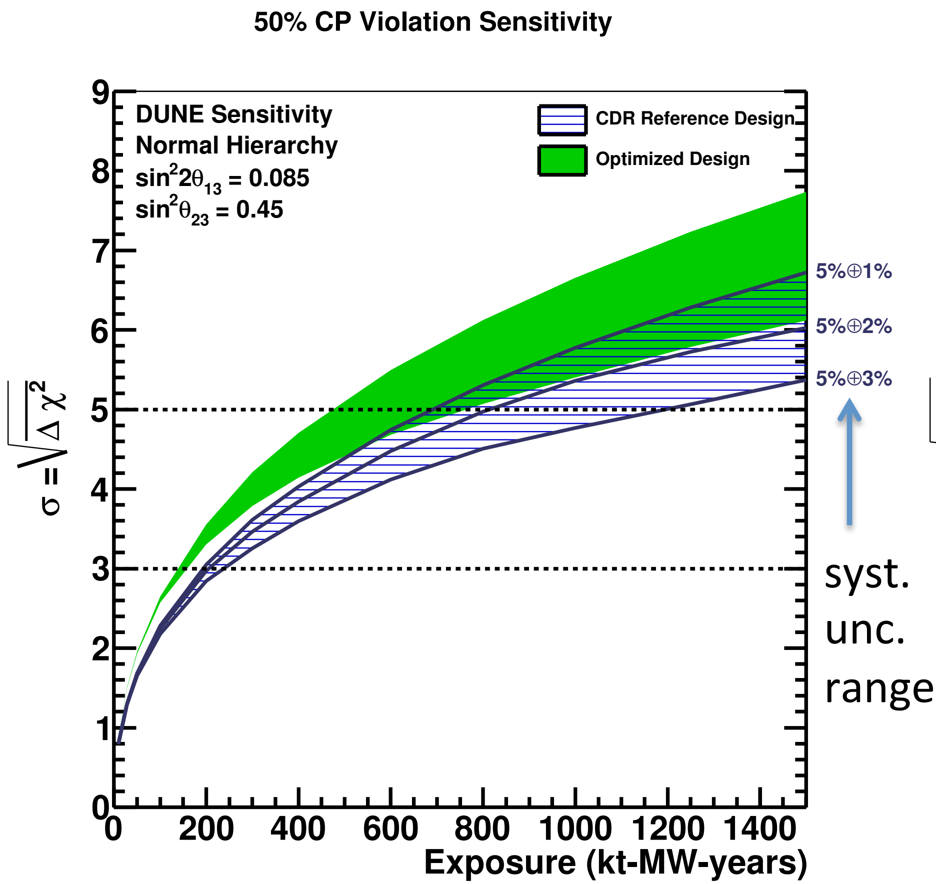


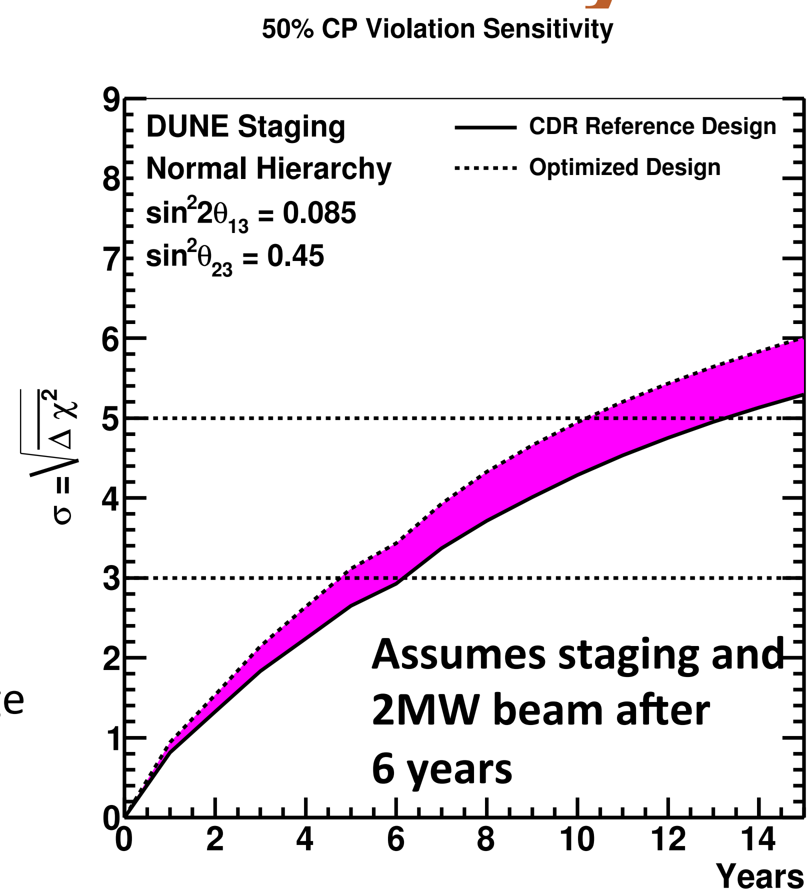
DUNE will definitively determine the neutrino mass hierarchy

For a favorable CP phase this could be achieved in a few years!

Optimization of the neutrino beam profile can greatly improve the sensitivity thus reducing the time needed for a definitive measurement

DUNE CP Violation Sensitivity





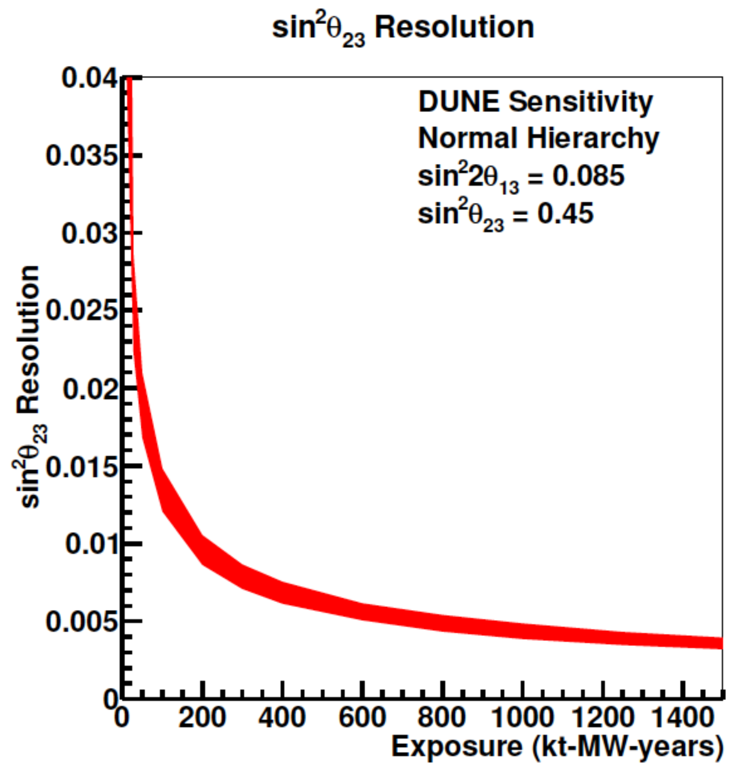
<3 % ν_e systematics important after ~200 kt.MW.yr

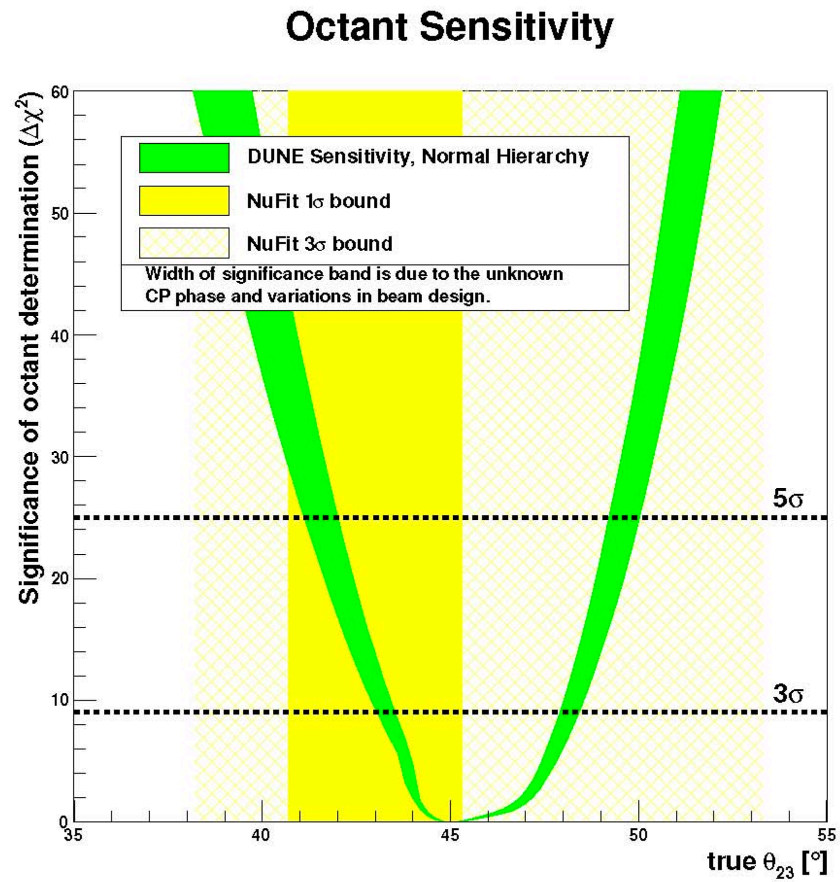
Optimization of the neutrino beam profile have significant impact

5 σ discovery of CP violation in half the possible phase space in ~10 years

Atmospheric neutrinos provide ~1σ increased sensitivity if combined with beam

θ_{23} Resolution and Octant Sensitivity





"Maximal mixing" (θ_{23} = 45º) would indicate equal contributions to ν_μ and ν_τ from ν_3 from unknown symmetry?

Current global neutrino fit prefers either IH & upper octant or NH & lower octant

Physics Milestones

Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - **with 60 – 70 kt.MW.year reach 3σ CPV sensitivity**
- e.g. in best-case scenario for MH :
  - **with 20 – 30 kt.MW.year reach 5σ MH sensitivity**

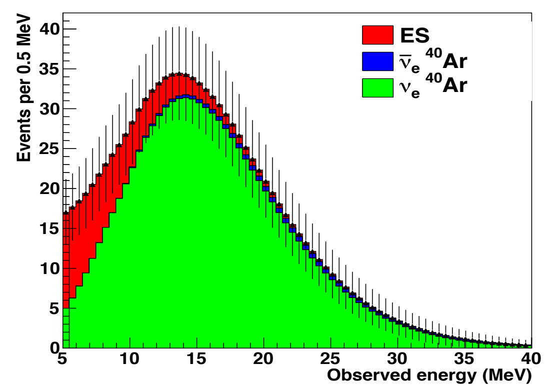
Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{CP} = 0$)	450	290
CPV at 5σ ($\delta_{CP} = -\pi/2$)	525	320
CPV at 5σ 50% of δ_{CP}	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of δ_{CP}	1320	850

← P5 Goal

Supernova νs

When a star's core collapses ~99% of the gravitational binding energy of the proto-neutron star goes into ν's

SN at galactic core (10 kpc) ⇒ several thousand interactions in 40kt LArTPC in tens of seconds – reconstructed with sub-millisec precision



- **Trigger on and measure energy of neutrinos from galactic SNB**
  - To date only observed $\bar{\nu}_e$ from single SN
  - In argon, the largest sensitivity is to ν_e
    - CC interaction: $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

E ~ O(10 MeV)

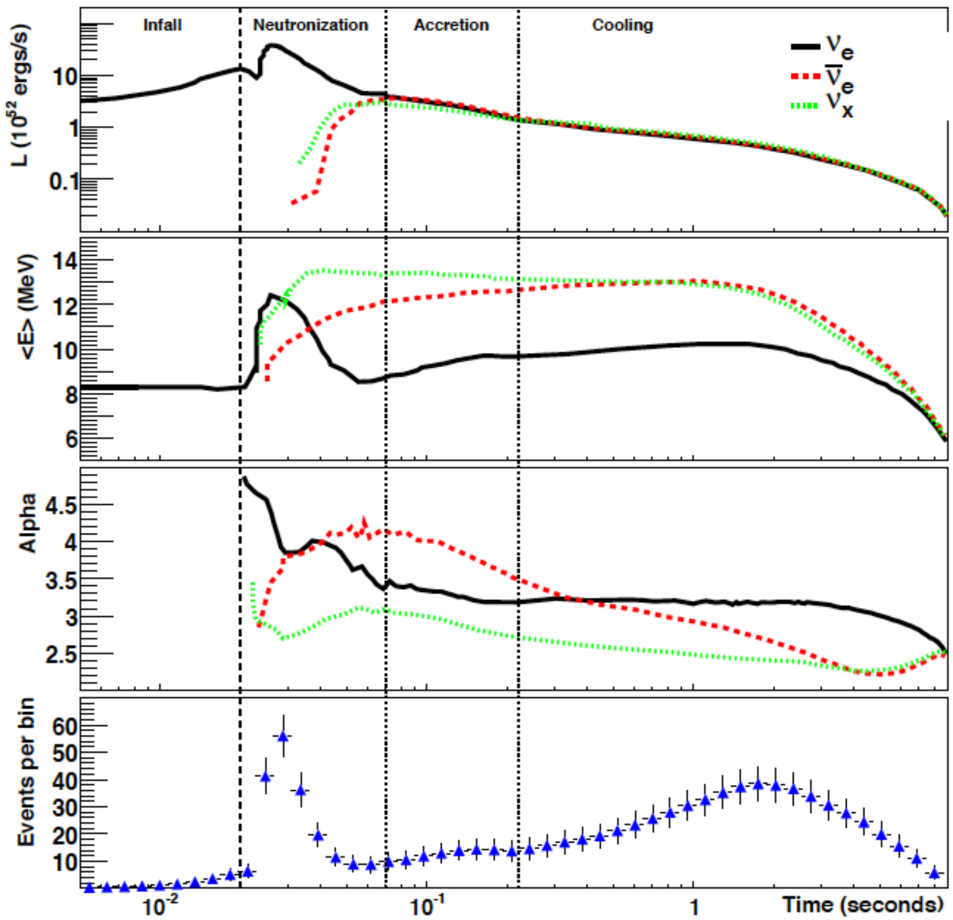
Signal for SN at 10 kpc

Neutronization peak

- uniquely among neutrino observatories,

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

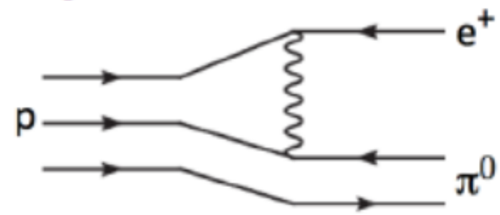
- large LAr detectors provide a direct probe of this stage of the supernova process



Nucleon Decay

- **Best limit from SK (1.3x10^{34} yr, 206kt-yr);**
- **Water has high-efficiency, clean signal;**
- **LAr should be even cleaner but can't compete easily with no. of free protons in water.**

$p \rightarrow e^{+} \pi^{0}$



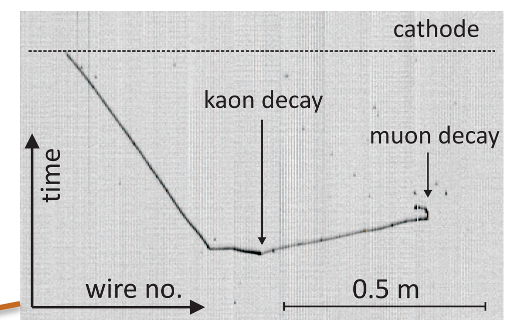
The strength of LAr

$p \rightarrow K^{+} \bar{\nu}$

- **Image particles from nucleon decay**
  - target sensitivity to kaons (from d*E*/d*x*) from SUSY-inspired GUT p-decay modes

E ~ O(200 MeV)

ICARUS kaon candidate



$K \rightarrow \mu\nu_{\mu} \quad \mu \rightarrow e\nu_{e}\nu_{\mu}$

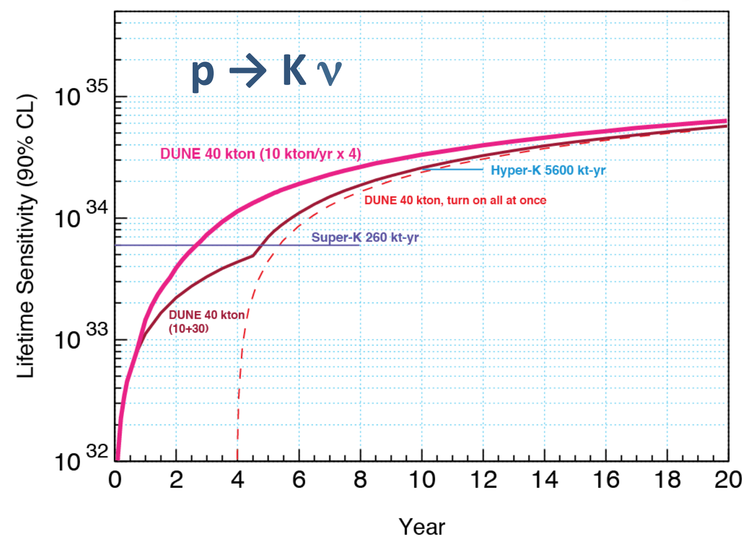
Baryon Number Violation

Efficiency and background in water and agron (events per Mton-yr)

Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to K^+\overline{\nu}$	19%	4	97%	1
$p \to K^0\mu^+$	10%	8	47%	< 2
$p \to K^+\mu^-\pi^+$			97%	1
$n \to K^+e^-$	10%	3	96%	< 2
$n \to e^+\pi^-$	19%	2	44%	0.8

*

High efficiency and low background in LAr for these modes



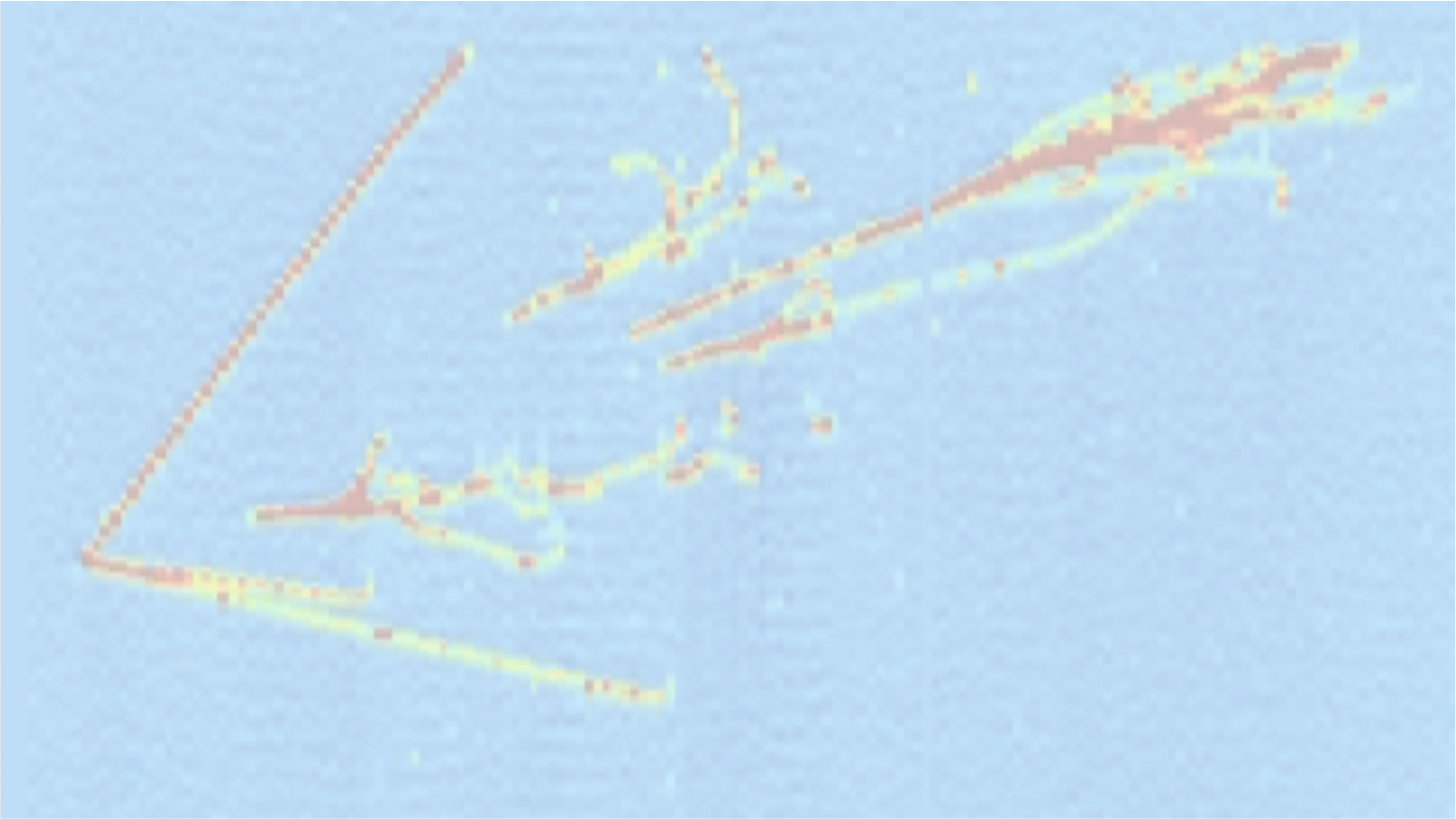
DUNE/LBNF Timeline

- July 2015 "CD-1 Refresh" review. Conceptual design review.
- Dec. 2015 CD-3a CF Far Site. Needed to authorize far site conventional facilities work including underground excavation and outfitting.
- 2017 Ongoing shaft renovation at SURF complete
- 2017 Start of far site conventional facilities.
- 2018 Testing of "full-scale" far detector elements at CERN
- 2019 Technical Design review
- 2021 Ready for start of installation of the first far detector module
- 2024 start of physics with one detector module
  - Additional far detector modules every ~2 years.
- 2026 Beam available
- 2026 Near detector available
- 2028 DUNE construction finished

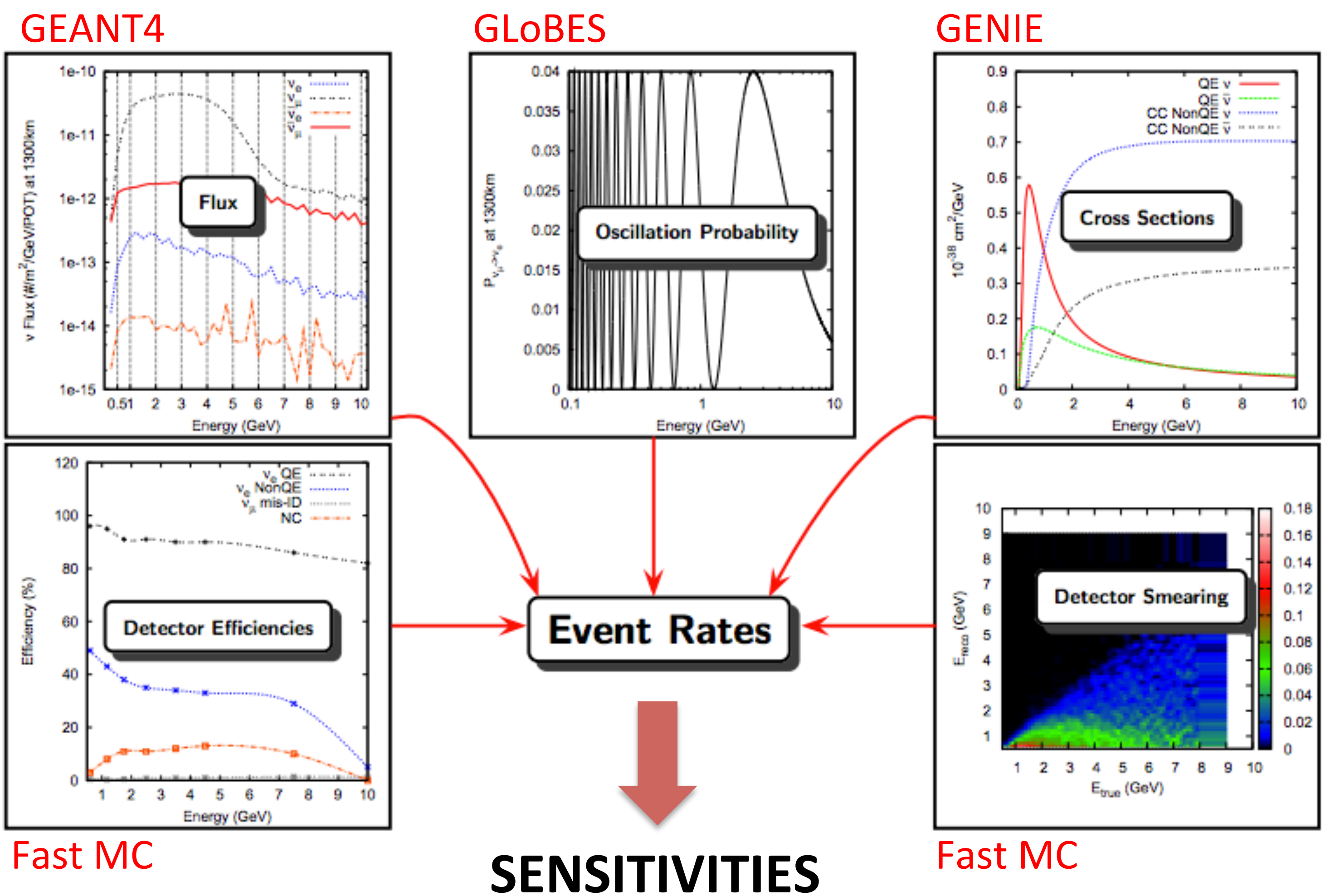
Summary

- The long-baseline DUNE experiment will perform measurements of CP violation, mass hierarchy, non-standard interaction, proton decay and supernova burst neutrino from intra-galactic distances.
- Start of physics in 2024 (beam avail. 2026)
- Many opportunities for early discoveries
- DUNE will be the definitive experiment for neutrino oscillations

Backup Slides



DUNE Sensitivity Calculations



Oscillation Probability

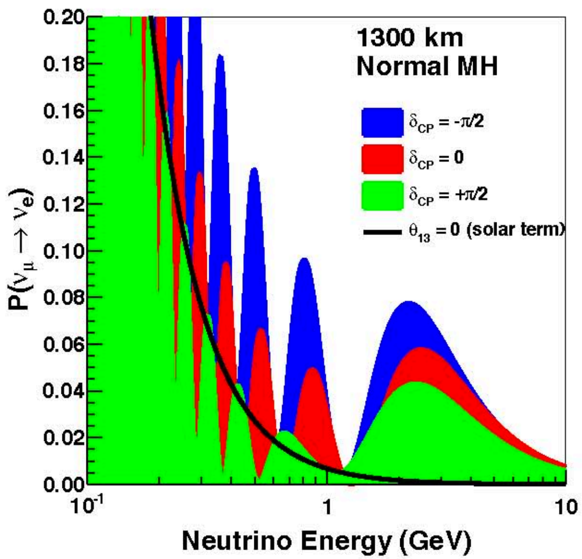
ν_μ oscillation probability

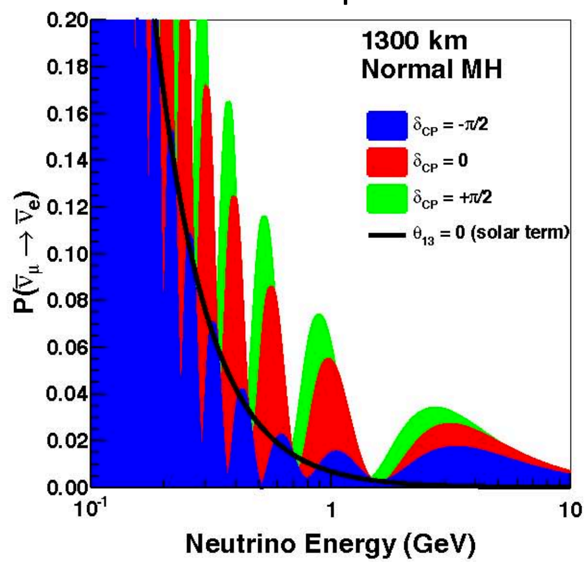
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 + \alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} - \alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin\Delta_{32}$$

$$\Delta_{ij} = \Delta m_{ij}^2 L / 4E_\upsilon$$

$$a = G_F N_e / \sqrt{2}$$

- ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects.
- Large value of $\sin^2(2\theta_{13})$ allows significant ν_e appearance sample.
- δ_{CP} and a switch signs in going from the $\nu_\mu \rightarrow \nu_e$ to the $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$





South Dakota Ross Shaft Rehabilitation

- Experimental Facilities at 4850 ft level
- Two vertical access shafts for safety
- Ross shaft refurbishment in process and is ~55% complete
- Over $100M invested from private and state funds
- Facility donated to the State of South Dakota for science in perpetuity
- Working two 12 hour shifts/day in order to be done by 2017
- Will allow large excavations at SURF in 2017!

Fermilab-CERN partnership

New DOE-CERN-NSF agreement signed May 7, 2015 at "White House"

"This agreement is also historic since it formalizes CERN's participation in U.S.-based programs such as prospective future neutrino facilities for the first time." Rolf Heuer DG CERN

"a model for the kinds of international scientific collaboration that can enable breakthrough insights and innovations."… John Holdren, President's Science Advisor

Our research programs…… are now deeply intertwined."…Jim Siegrist

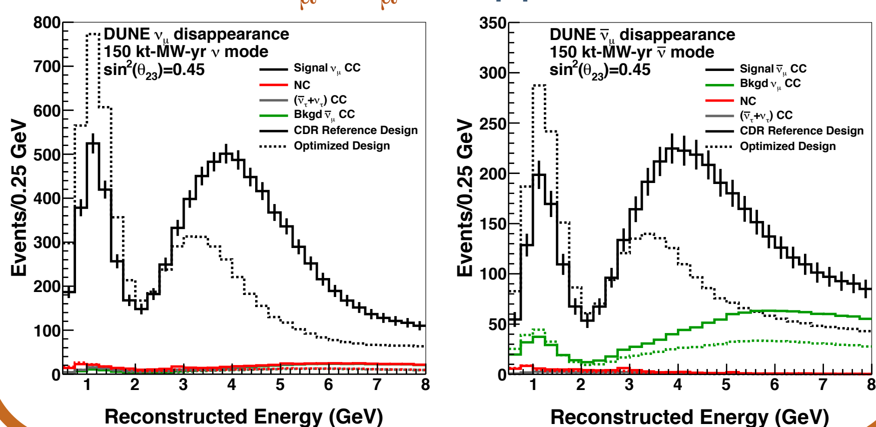
Neutrino Oscillation Strategy

Measure neutrino spectra at 1300 km in a wide-band beam

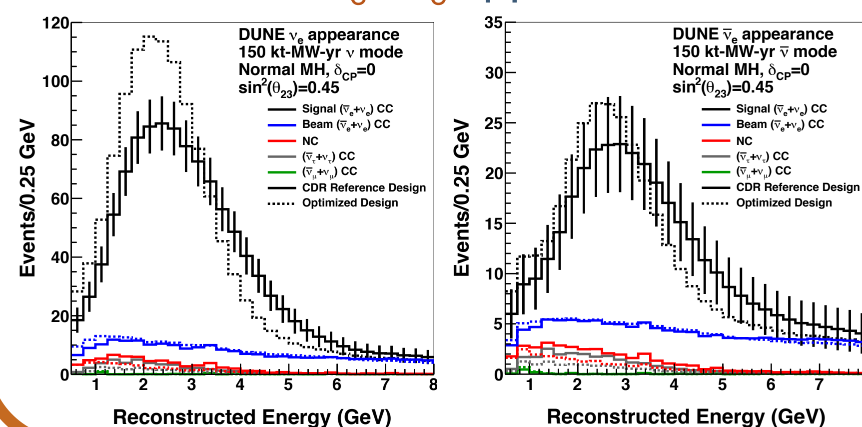
- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for ν NSI in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Measure ν_e appearance and ν_μ disappearance over range of energies
    - MH & CPV effects are separable

E ~ few GeV

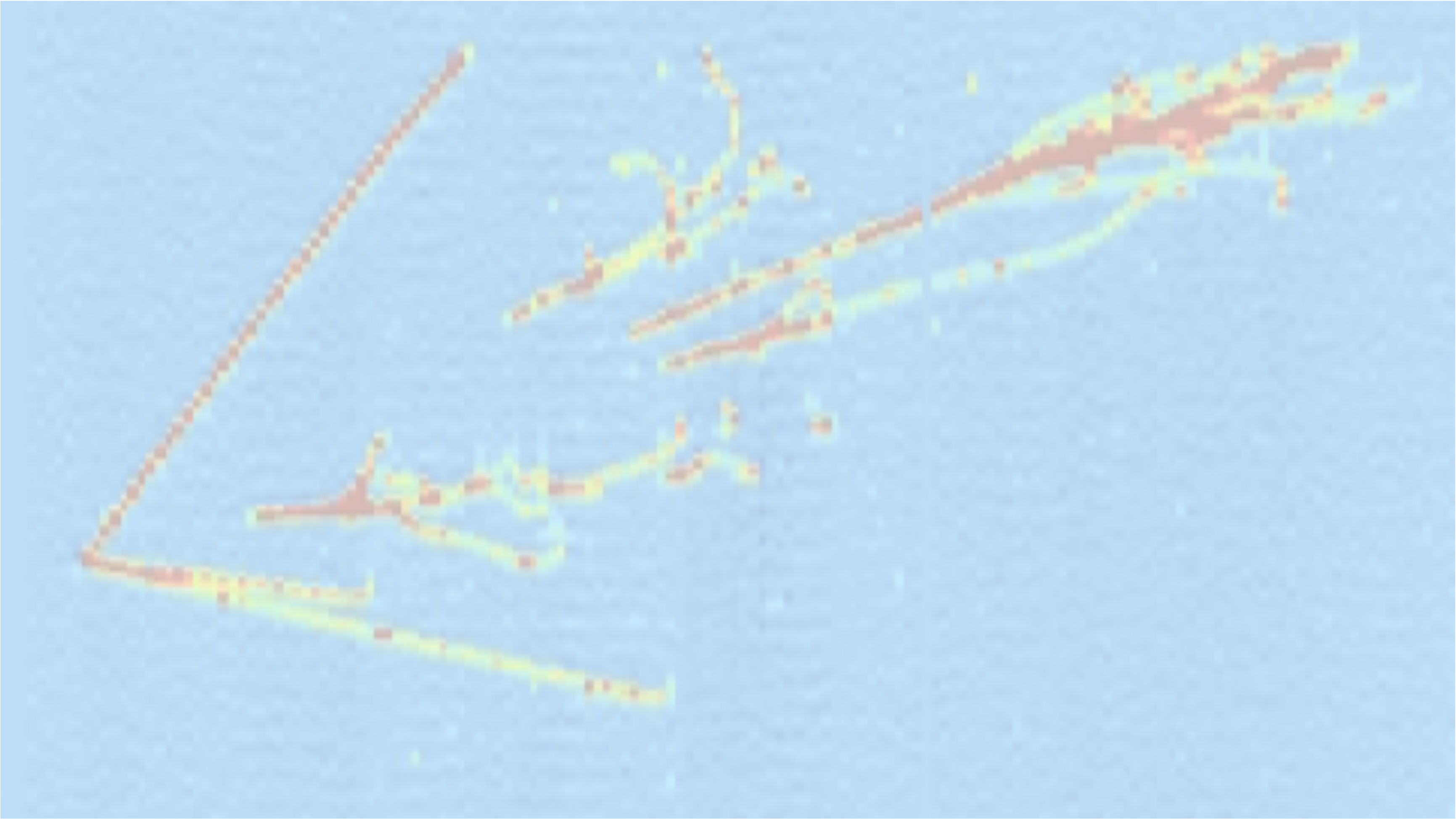
ν_μ / $\bar{\nu}_\mu$ disappearance



ν_e / $\bar{\nu}_e$ appearance



Cryostats

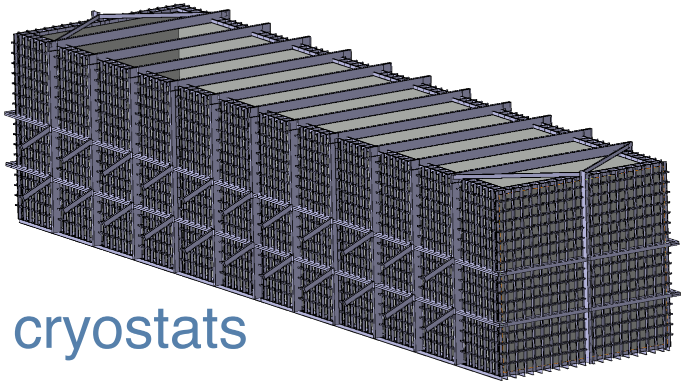


Cryostats

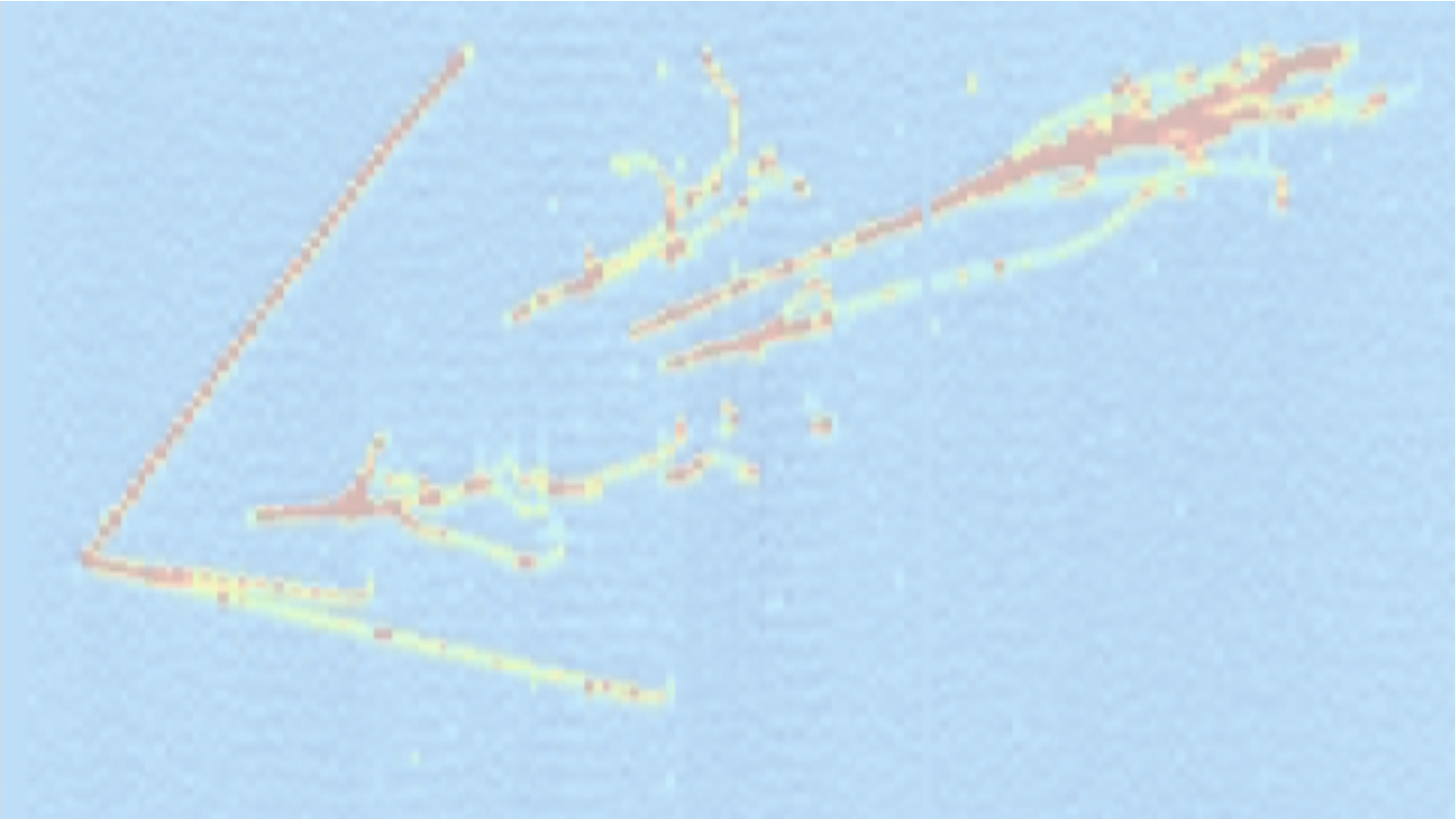
Steel-supported membrane cryostat

- **Today:**
  - WA105
  - 3 x 3 x 2 m^3 at CERN
- **Next steps ~2018**
  - SBND single-phase detector at Fermilab
  - WA105 & single-phase prototypes (8 x 8 x 8 m^3) at CERN
- **DUNE 10-kt Far Detector ~2021**
  - Inner dimensions:

    15.1 (W) x 14.0 (H) x 62 (L) m^3
  - Assume common design for all 4 FD cryostats



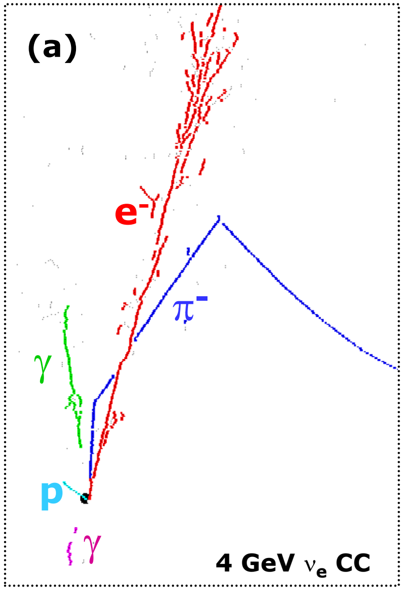
Reconstruction

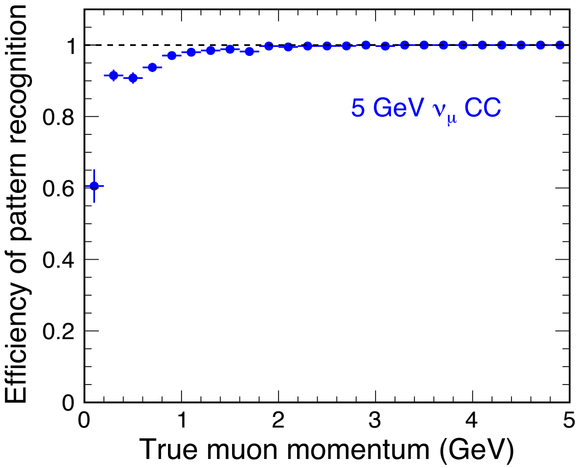


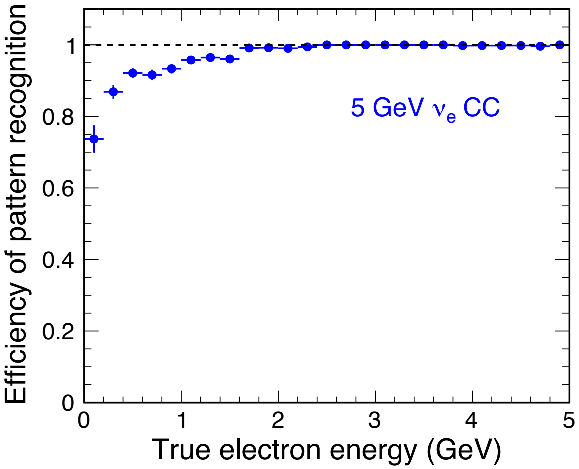
LAr-TPC Reconstruction

Real progress in last year – driven by 35-t & MicroBooNE

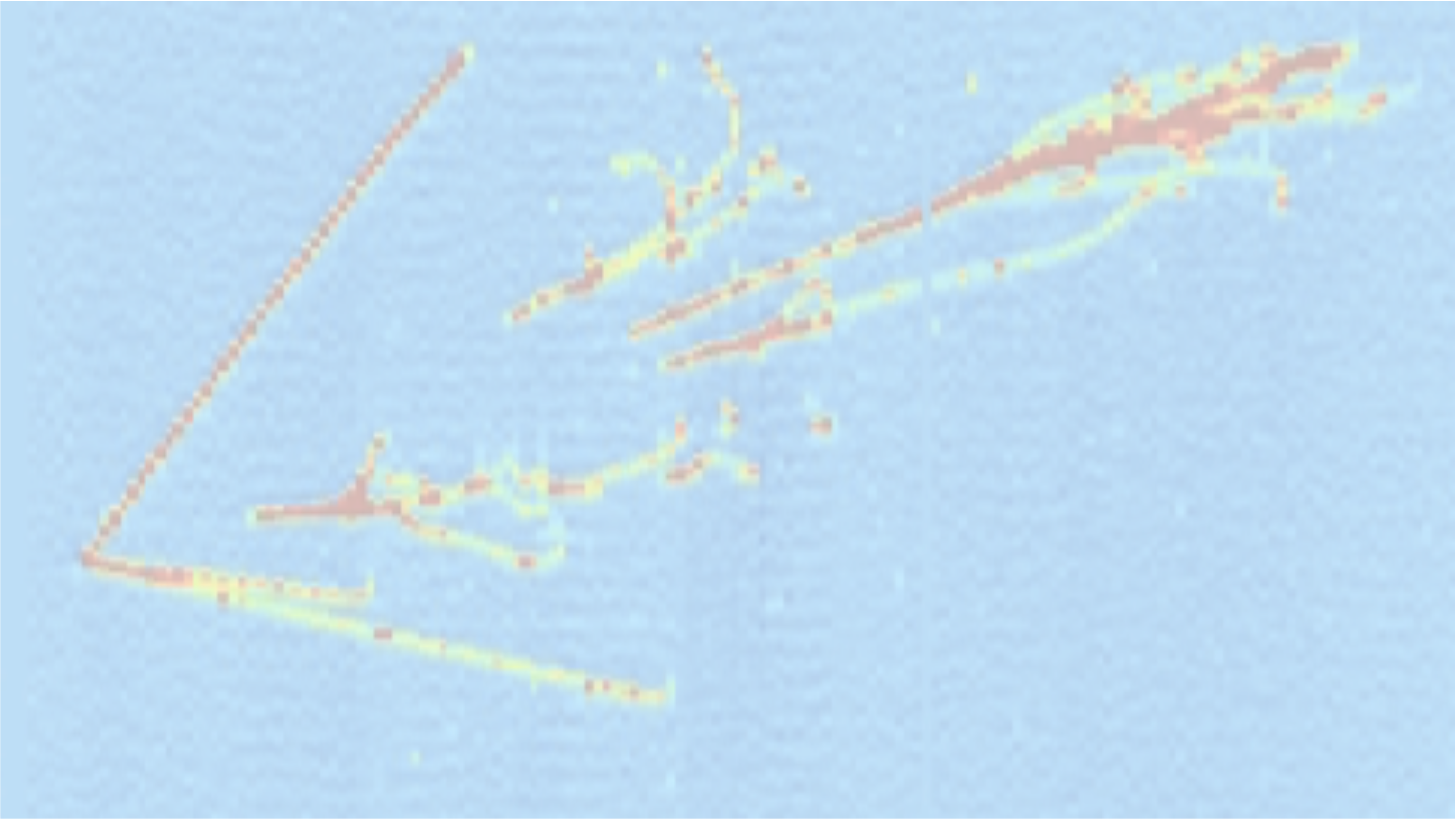
- Full DUNE simulation/reconstruction now in reach







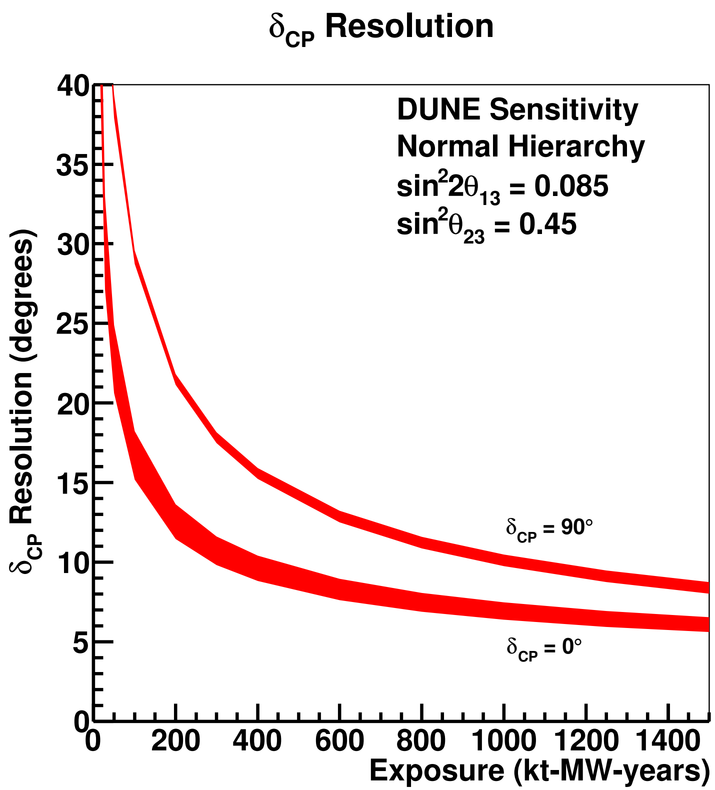
Physics

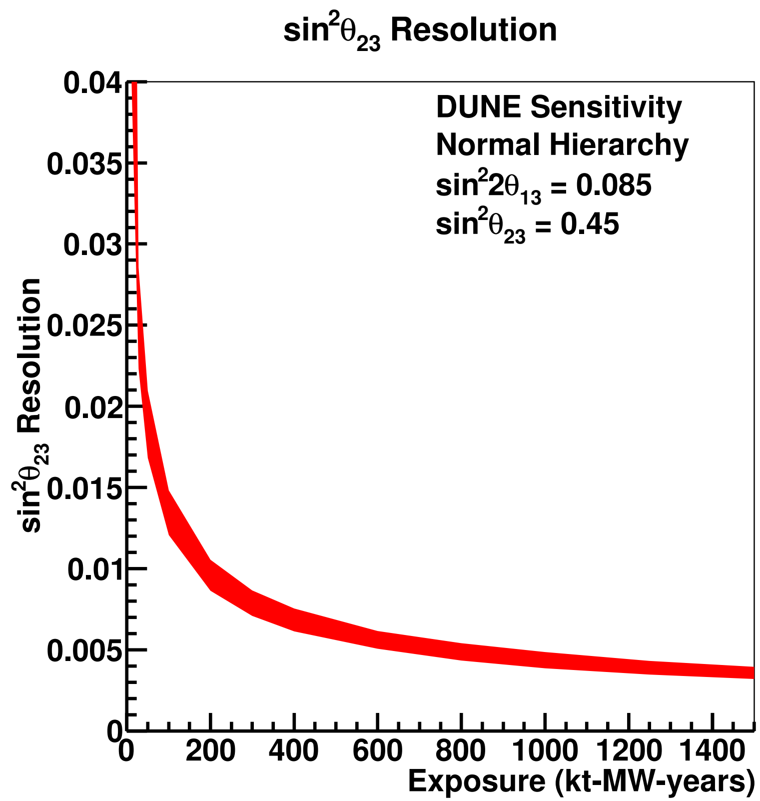


Parameter Resolutions

δ_{CP} & θ_{23}

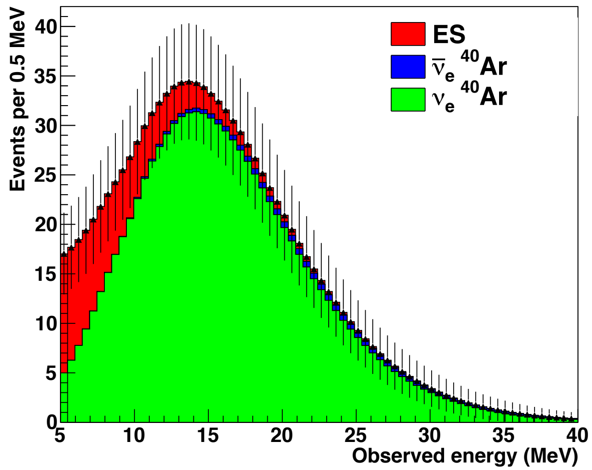
- As a function of exposure

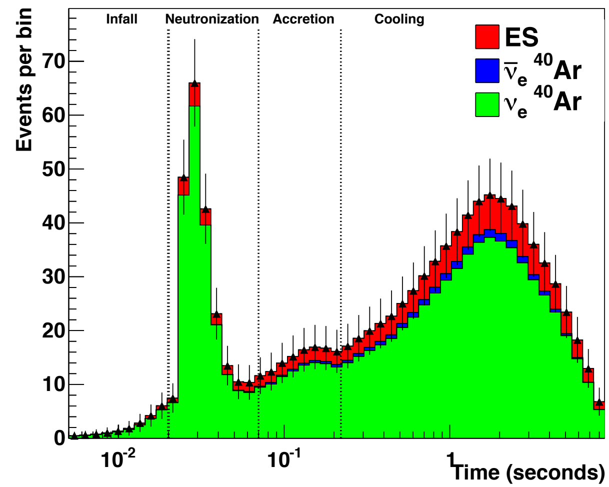




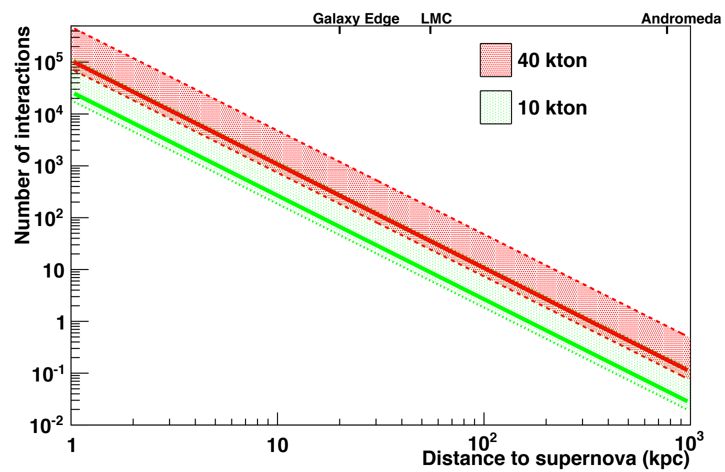
SNB

- Energy and timing sensitive to particle & astrophysics

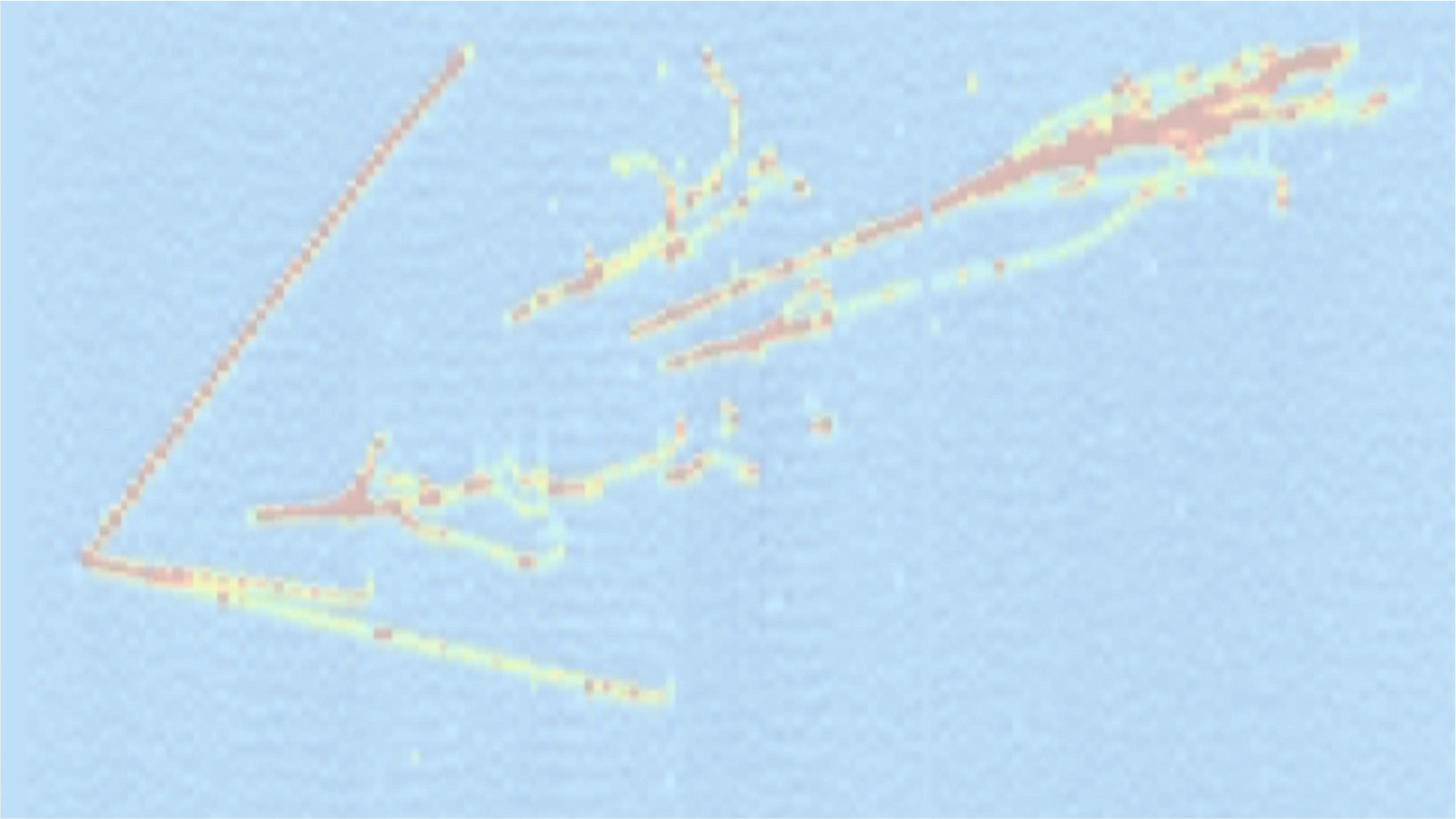




- Event Rates:

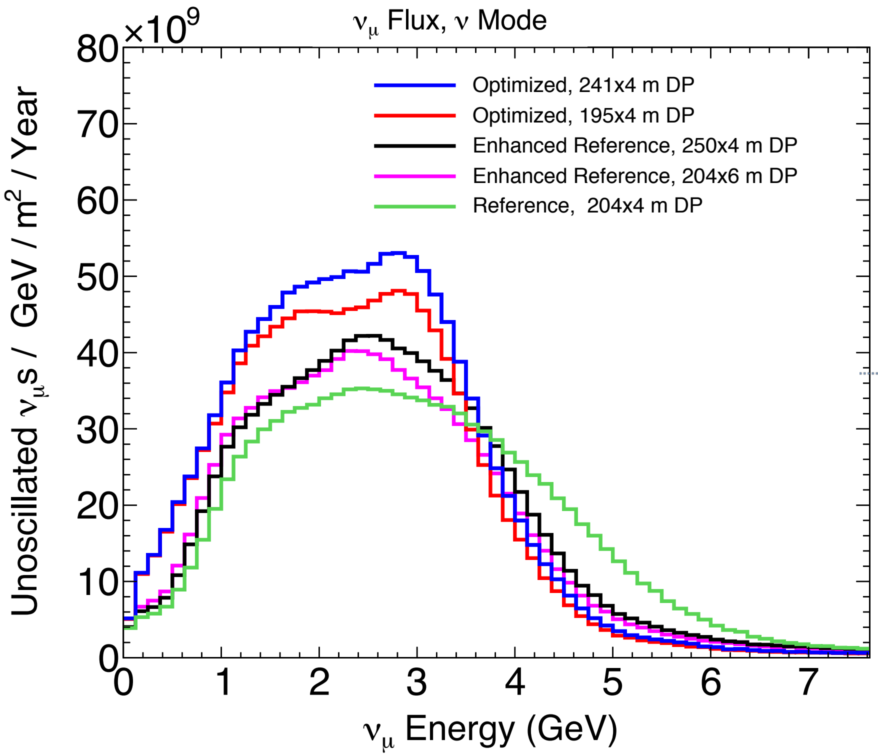


Beam Optimization

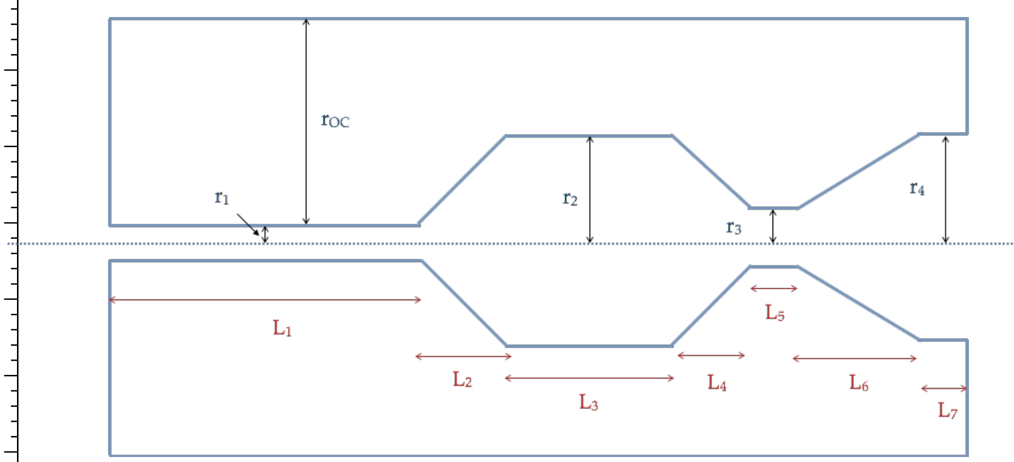


Beam Optimization

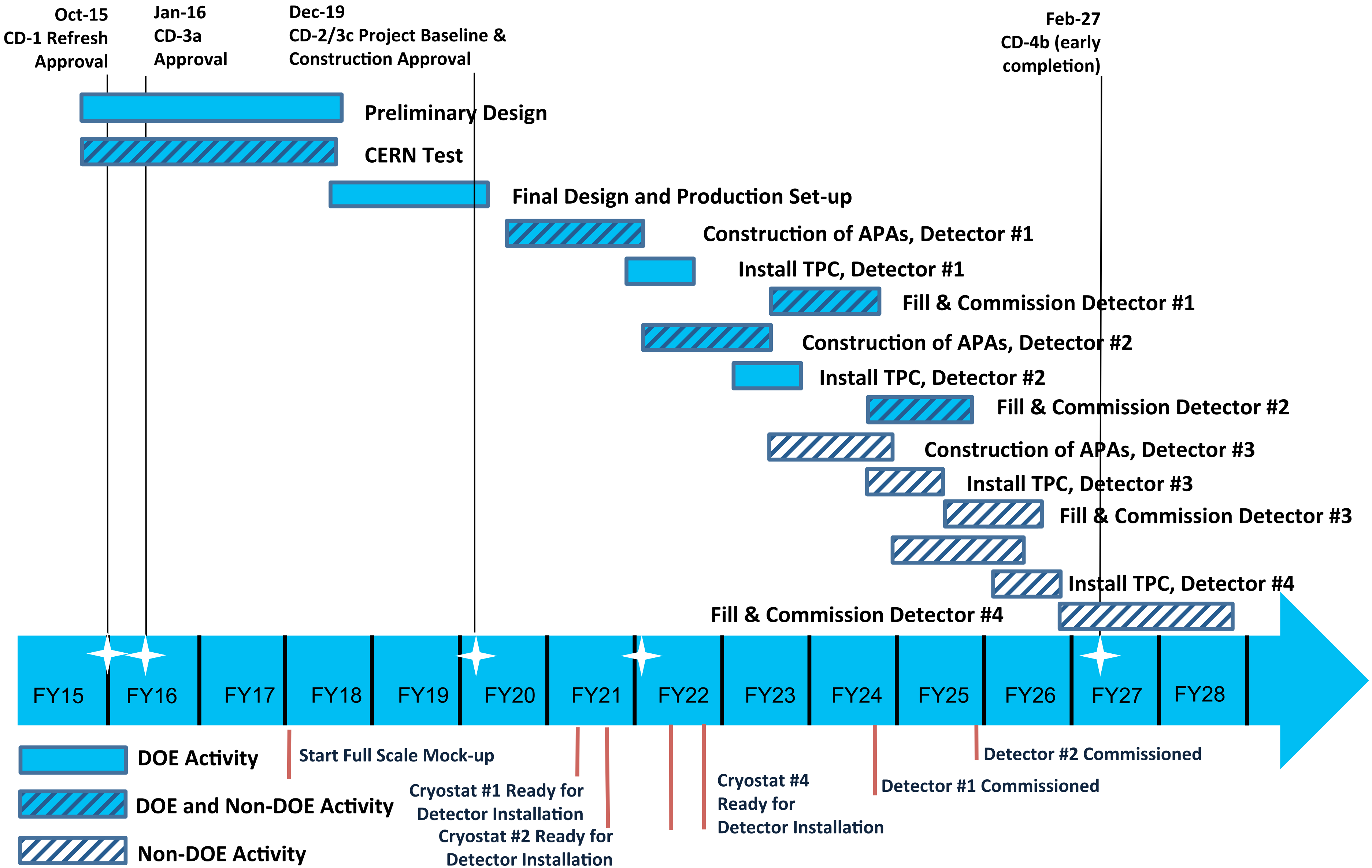
Following LBNO approach, genetic algorithm used to optimize horn design – increase neutrino flux at lower energies



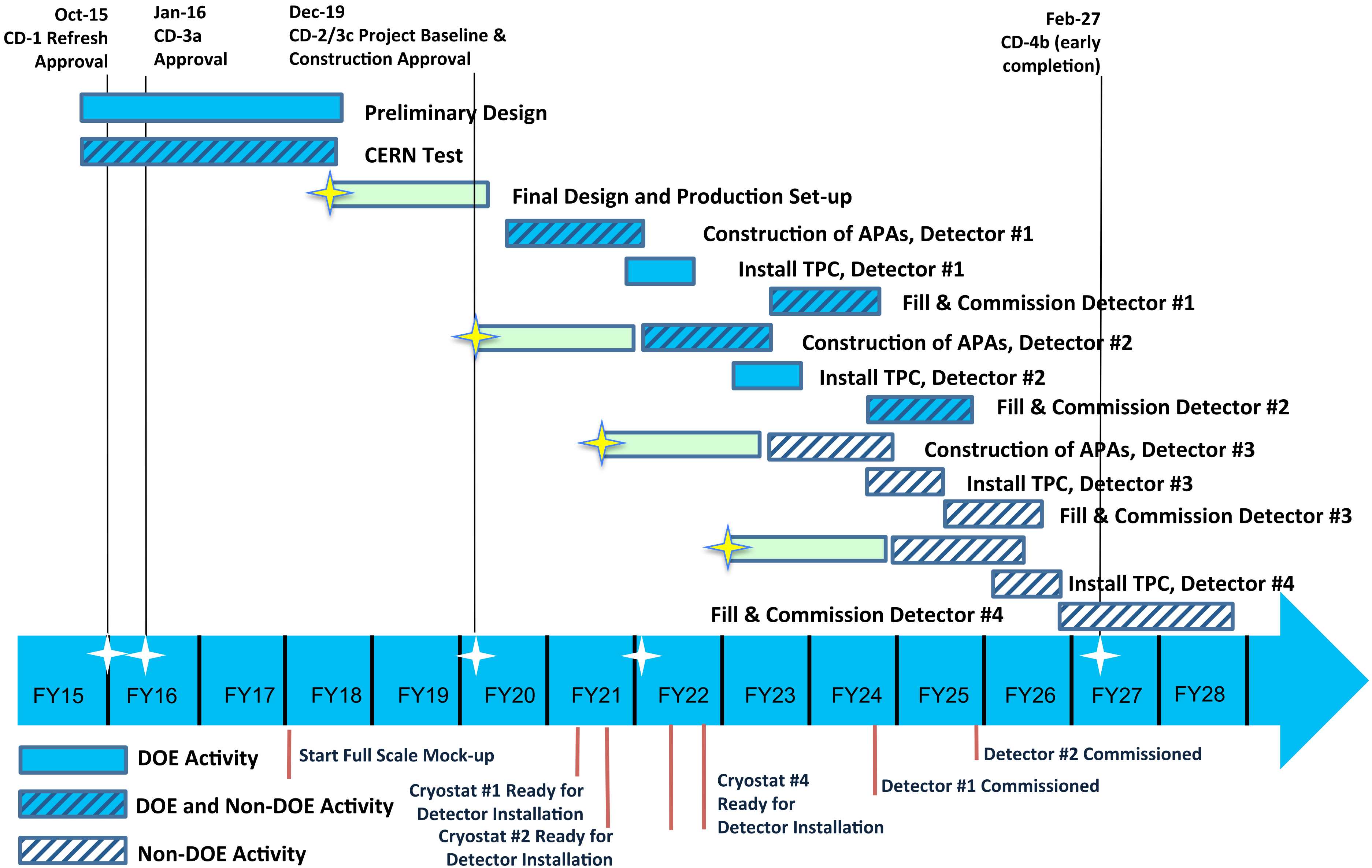
Horn 1



Resource Loaded Schedule



Indicative Far Detector Decision Dates



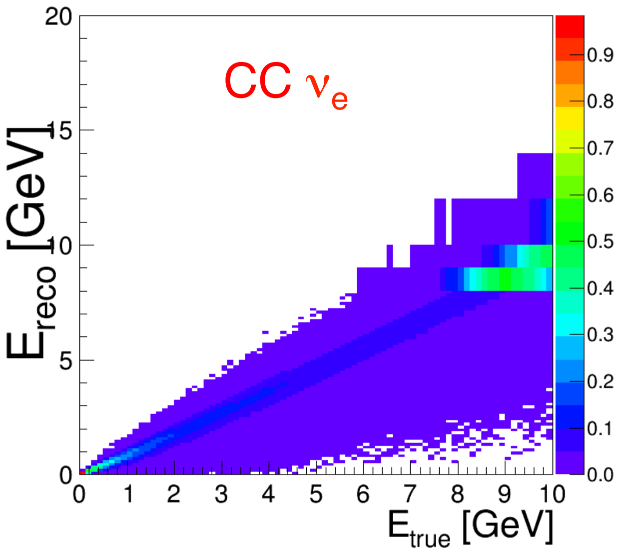
FD Technology Decision Timeline

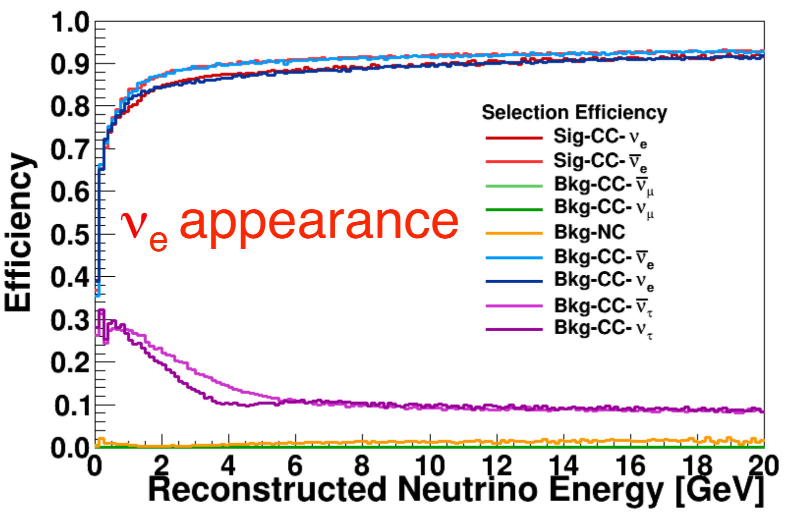
Far Detector Technology Timeline

- **DOE scope is for ~50 % of two 10-kt FD modules**
  - Remaining ~50% from international partners
  - Gives scope for **two** single-phase detectors
  - Timescale for CD-2 is 2019/2020 sets timescale for baseline design
  - Matches the decision time for second 10-kt module
- **Currently, the funding for other two 10-kt FD modules 100 % from non-DOE sources**
  - Opportunity for to attract new international partners with desire to contribute to enhanced designs, e.g. dual phase
  - Flexibility is required: will take 3 – 4 years for international agreements
- **Given schedule – first 10-kt will be single phase (see CDR)**
- **Second and subsequent 10-kt modules:**
  - Details will depend on timescale of demonstration and performance of alternative technologies
  - CERN neutrino platform critical here

Evaluating DUNE Sensitivities II

- **Efficiencies & Energy Reconstruction from "Fast MC"**
  - Generate neutrino interactions in LAr using GENIE
  - **Fast MC** smears response at generated final-state particle level
    - "Reconstructed" neutrino energy
    - kNN-based MV technique used for ν_e "event selection": parameterized efficiencies
  - Used as inputs to GLoBES

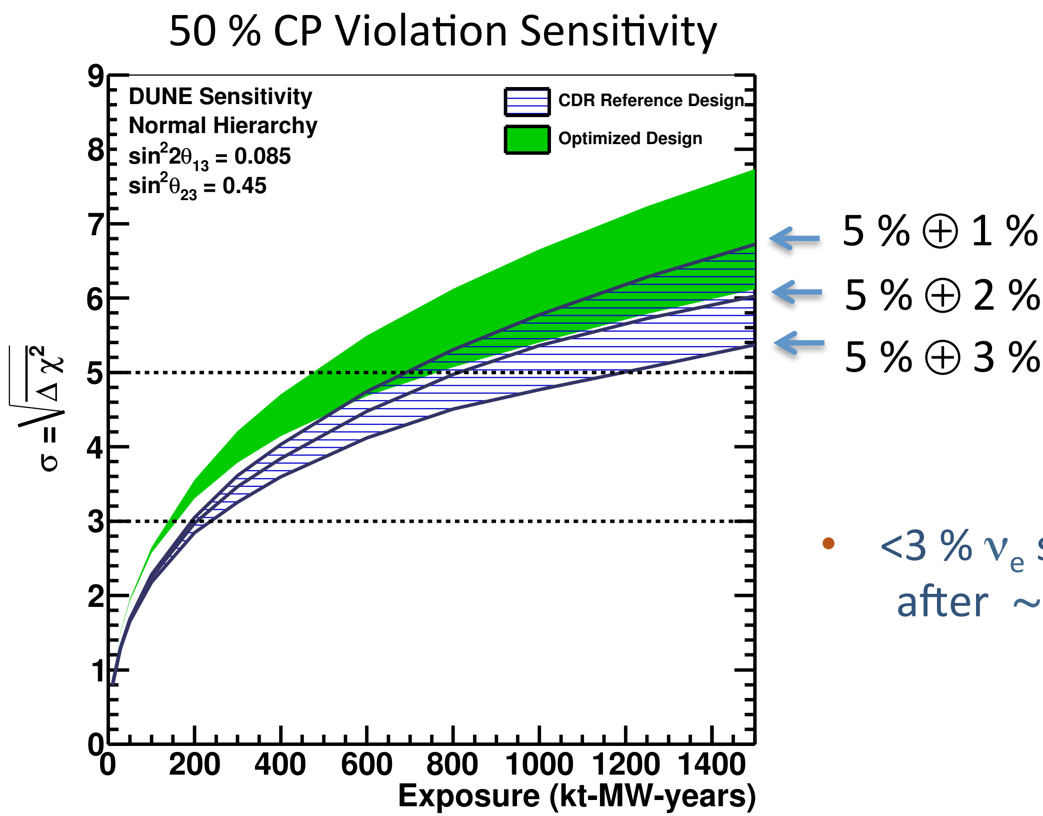




Evaluating DUNE Sensitivities III

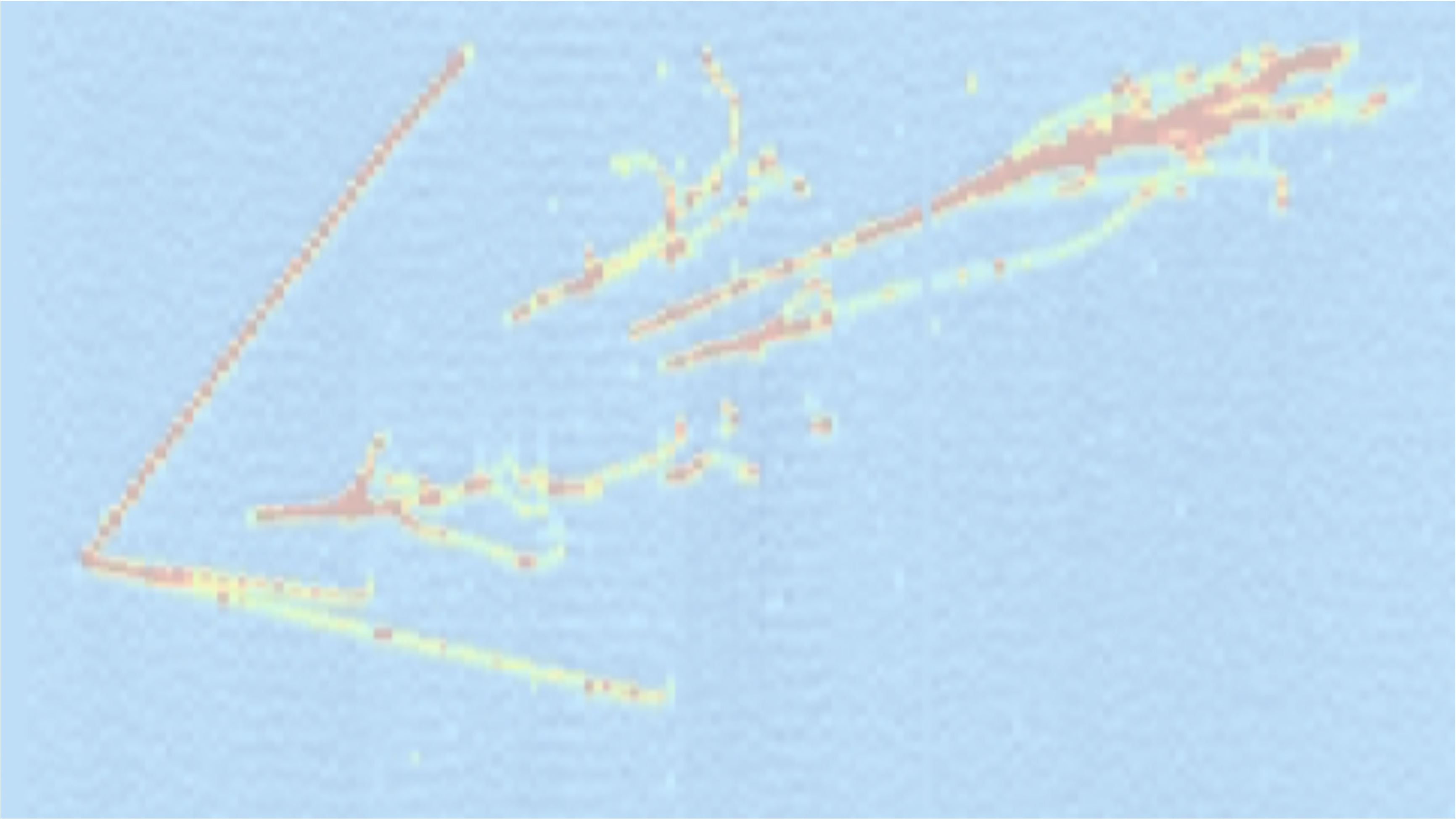
Propagate to Oscillation Sensitivities

using assumptions for systematics (from the ND)



- <3 % ν_e systematics important after ~200 kt.MW.yr

Systematics & Performance



Evaluating DUNE Sensitivities

- **Systematic Uncertainties**
  - Anticipated uncertainties based on MINOS/T2K experience
  - Supported by preliminary fast simulation studies of ND

Source	MINOS ν_e	T2K ν_e	DUNE ν_e
Flux after N/F extrapolation	0.3 %	3.2 %	2 %
Interaction Model	2.7 %	5.3 %	~ 2 %
Energy Scale (ν_μ)	3.5 %	Inc. above	(2 %)
Energy Scale (ν_e)	2.7 %	2 %	2 %
Fiducial Volume	2.4 %	1 %	1 %
Total	**5.7 %**	**6.8 %**	**3.6 %**

- **DUNE goal for ν_e appearance < 4 %**
  - For sensitivities used: 5 % $\oplus$ 2 %
    - where 5 % is correlated with ν_μ & 2 % is uncorrelated ν_e only

Evaluating DUNE Sensitivities

- **Assumed* Particle response/thresholds**
  - Parameterized detector response for individual final-state particles

Particle Type	Threshold (KE)	Energy/momentum Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained: from track length Exiting: 30 %	1^{o}
$\pi^{\pm}$	100 MeV	MIP-like: from track length Contained π-like track: 5% Showering/Exiting: 30 %	1^{o}
$e^{\pm}/\gamma$	30 MeV	$2\% \oplus 15\ \%/\sqrt{(E/GeV)}$	1^{o}
p	50 MeV	$p < 400$ MeV: 10 % $p > 400$ MeV: $5\% \oplus 30\%/\sqrt{(E/GeV)}$	5^{o}
n	50 MeV	$440\%/\sqrt{(E/GeV)}$	5^{o}
other	50 MeV	$5\% \oplus 30\%/\sqrt{(E/GeV)}$	5^{o}

*current assumptions to be addressed by FD Task Force

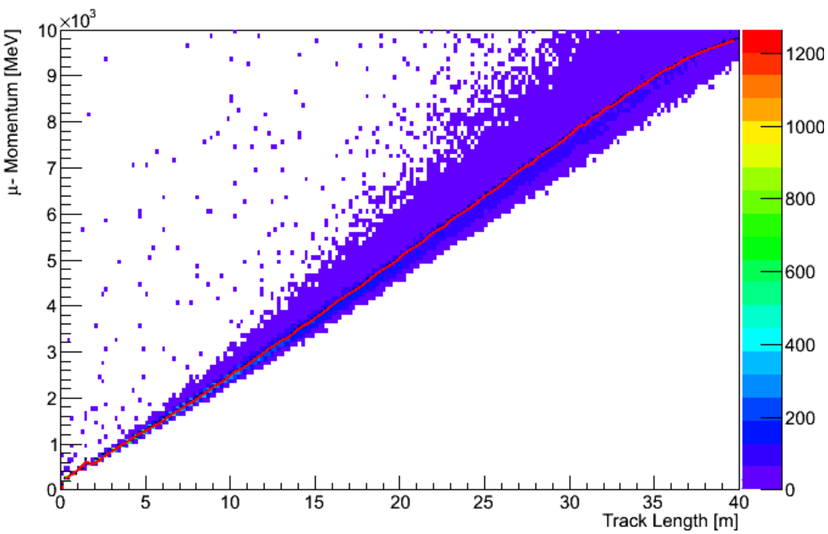
Sensitivity Calculations: FD Resolution

Particle Type	Energy/Momentum Resolution in DUNE Fast Monte Carlo	Achieved Resolution/ Notes
$\mu^{\pm}$	Contained track: track length Exiting track: 30%	See next slide 10-15% (1)
$\pi^{\pm}$	μ-like contained track: track length π-like contained track: 5% Showering or exiting: 30%	See next slide Similar to contained μ 30%/√E [GeV] (2)
$e^{\pm}/\gamma$	2% ⊕ 15%/√E [GeV]	1% ⊕ 3%/√E [GeV] (3)
p	p < 400 MeV/c: 10% p > 400 MeV/c: 5% ⊕ 30%/√E [GeV]	6% (4) 30%/√E [GeV] (3)
n	40%/√E [GeV]	Also assume 40% bias from missing energy
Other	5% ⊕ 30%/√E [GeV]	Similar to protons

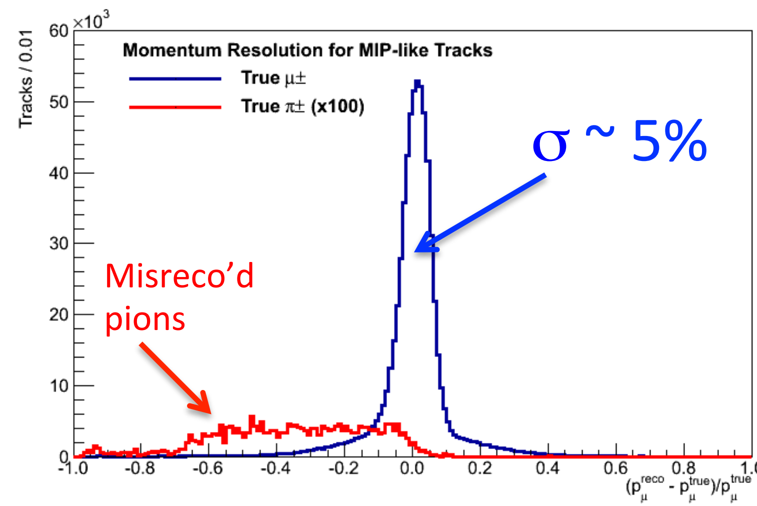
(1) ICARUS Collaboration, Eur.Phys.J. **C48** (2006), arXiv:hep-ex/0606006
(2) ICARUS Collaboration, ICARUS at FNAL, arXiv:1312.7252
(3) ICARUS Collaboration, Acta Phys.Polon, **B41** (2010), arXiv:0812.2373
(4) ArgoNeuT Collaboration, Phys.Rev.D **90** (2014), arXiv:1405.4261

Resolution from Track Length

Muon momentum as a function of track length (GEANT4):



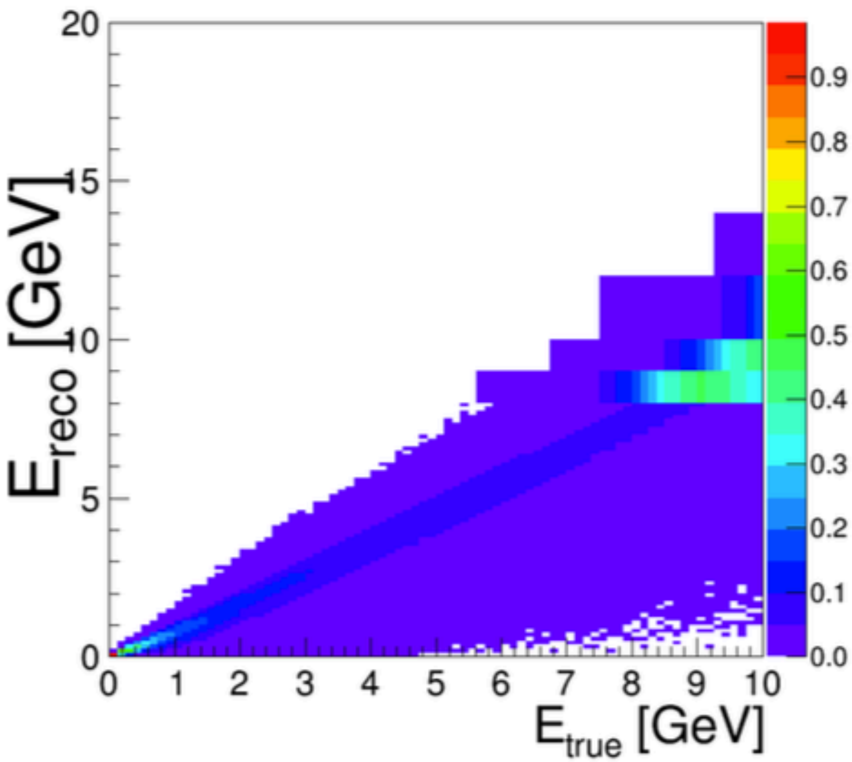
Momentum resolution using track length method:



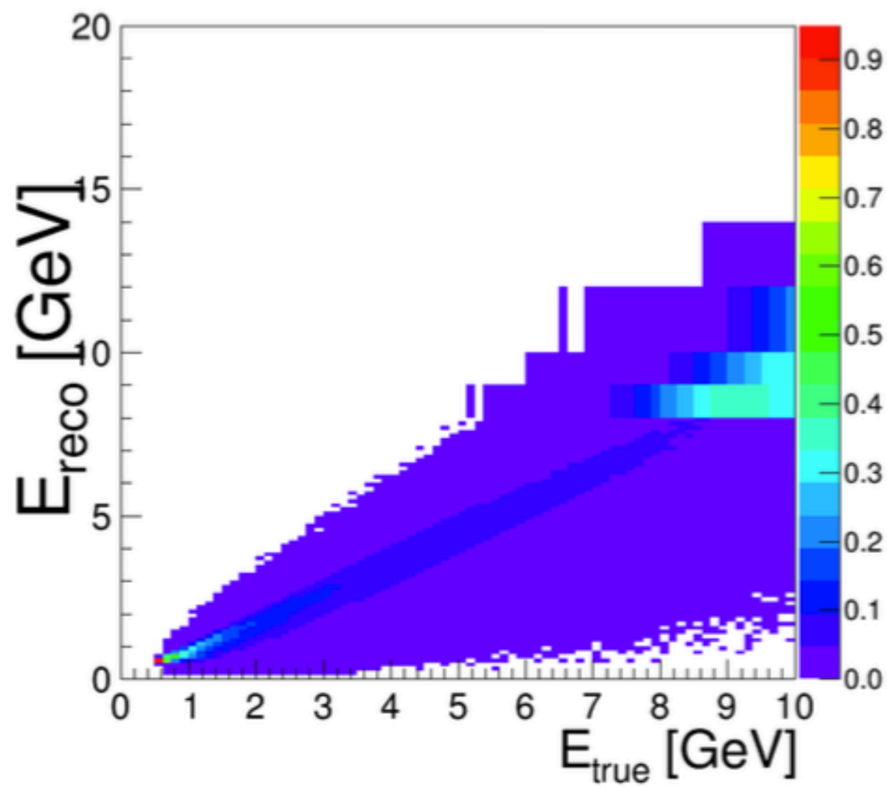
Neutrino Resolution

Neutrino signal resolution from Fast MC based on preceding single particle resolutions

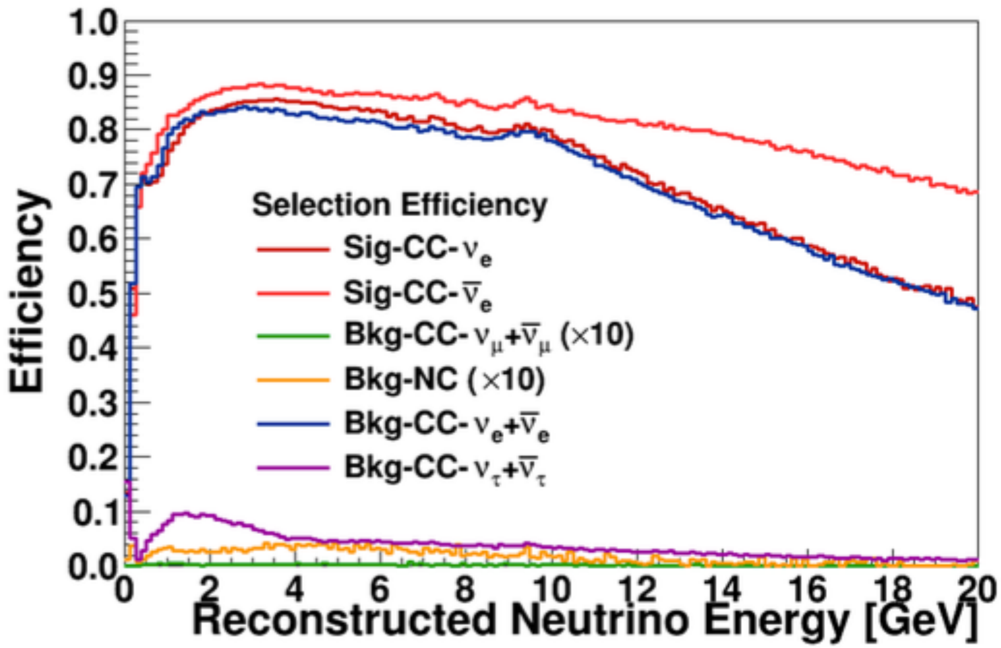
ν_e Appearance Signal:



ν_μ Disappearance Signal:



Sensitivity Calculations: ν_e Efficiency



Low-energy efficiency reduced to match early hand-scan studies of LArSoft simulations (3 mm pitch)

- Did not use dE/dx

e/γ separation based on dE/dx applied using LArSoft simulations (3 mm pitch)

- 95% efficiency/50% purity for E_γ = 250 MeV
- 95% efficiency/92% purity for E_γ > 1.5 GeV
- Effect of pitch next slide

NC/ν_τ background reduction applied using kNN algorithm (based primarily on p_T)

Effect of Wire Pitch on e/γ PID

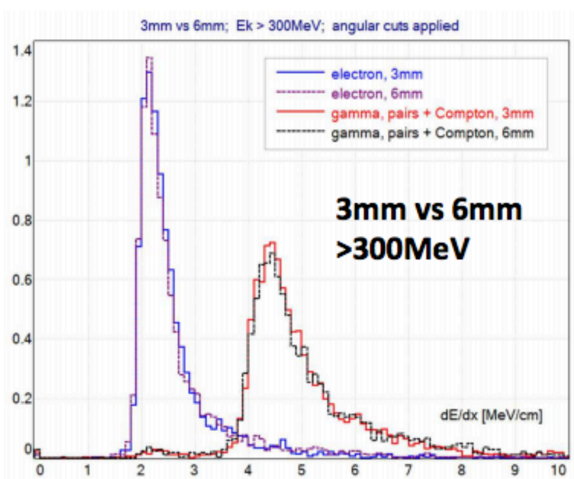
ICARUS MC:

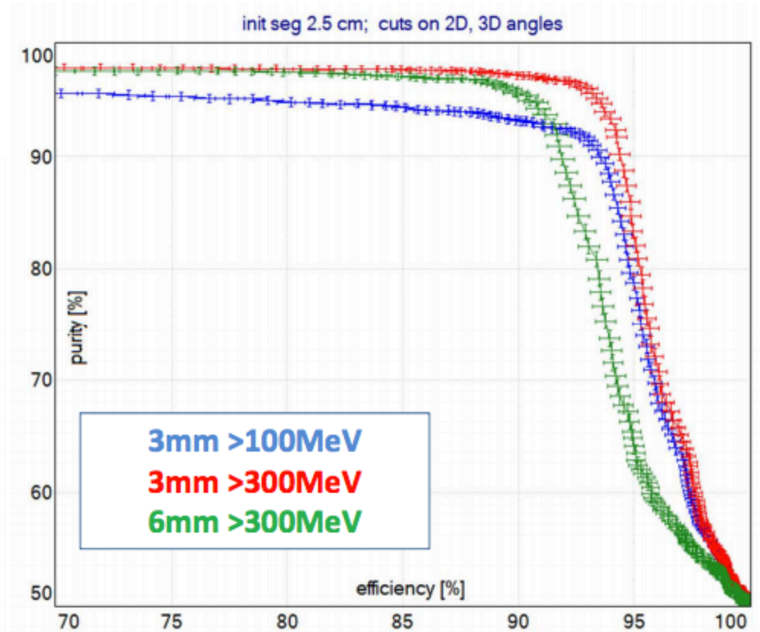
R. Sulej

electron / γ discrimination

Effect of:

- 3mm vs 6mm wire pitch – since large projects are considering different pitch values (=N° channels)
- cascade energy >100MeV and >300MeV

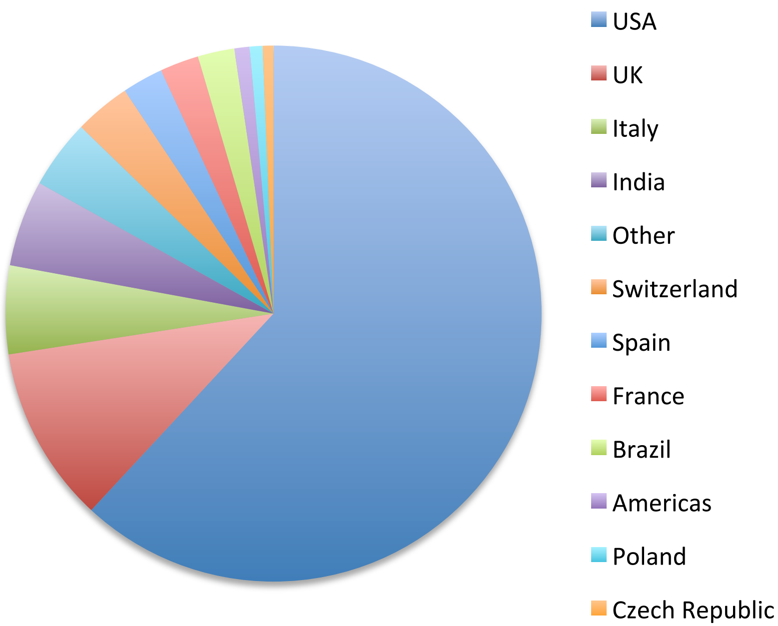




The DUNE Collaboration

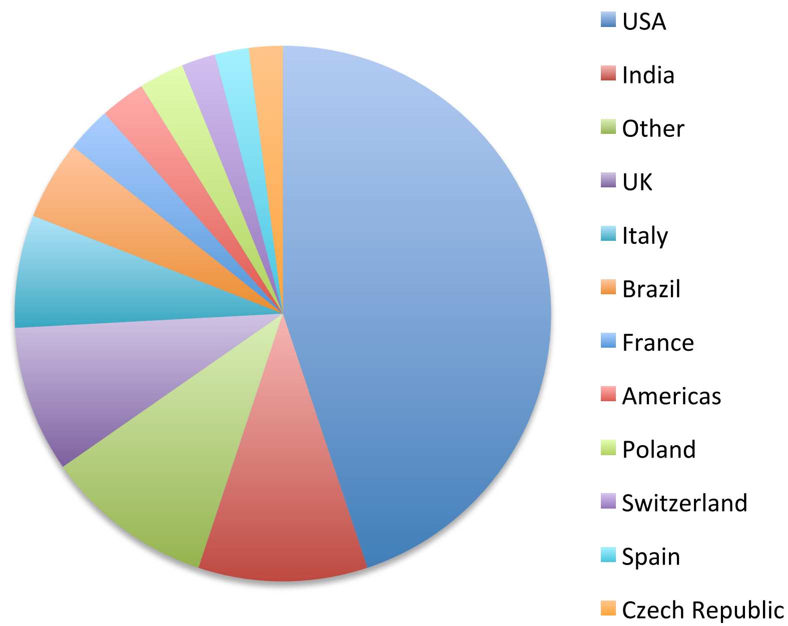
As of today:

776 Collaborators



from

144 Institutes



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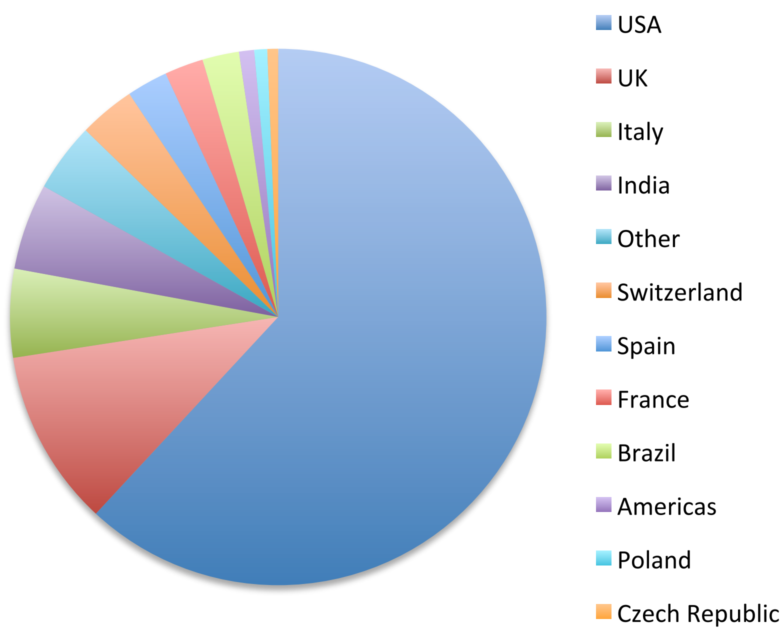


from

26 Nations

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

DUNE already has broad international support

Leading up to DUNE

For over a decade groups around the world have been designing/planning very long baseline neutrino experiments for CP and mass hierarchy measurements: eg. US LBNE, Europe LBNO, Japan T2HK.

2012: Daya Bay measured θ_{13} is non-zero! (CP can be measured!)

2013: European Strategy for Particle Physics updated

Endorsed high priority of neutrino physics

Bottom line: CERN should help the European neutrino community participate in a long-baseline program outside of Europe.

European Strategy for Particle Physics

2014: The US particle physics strategy updated

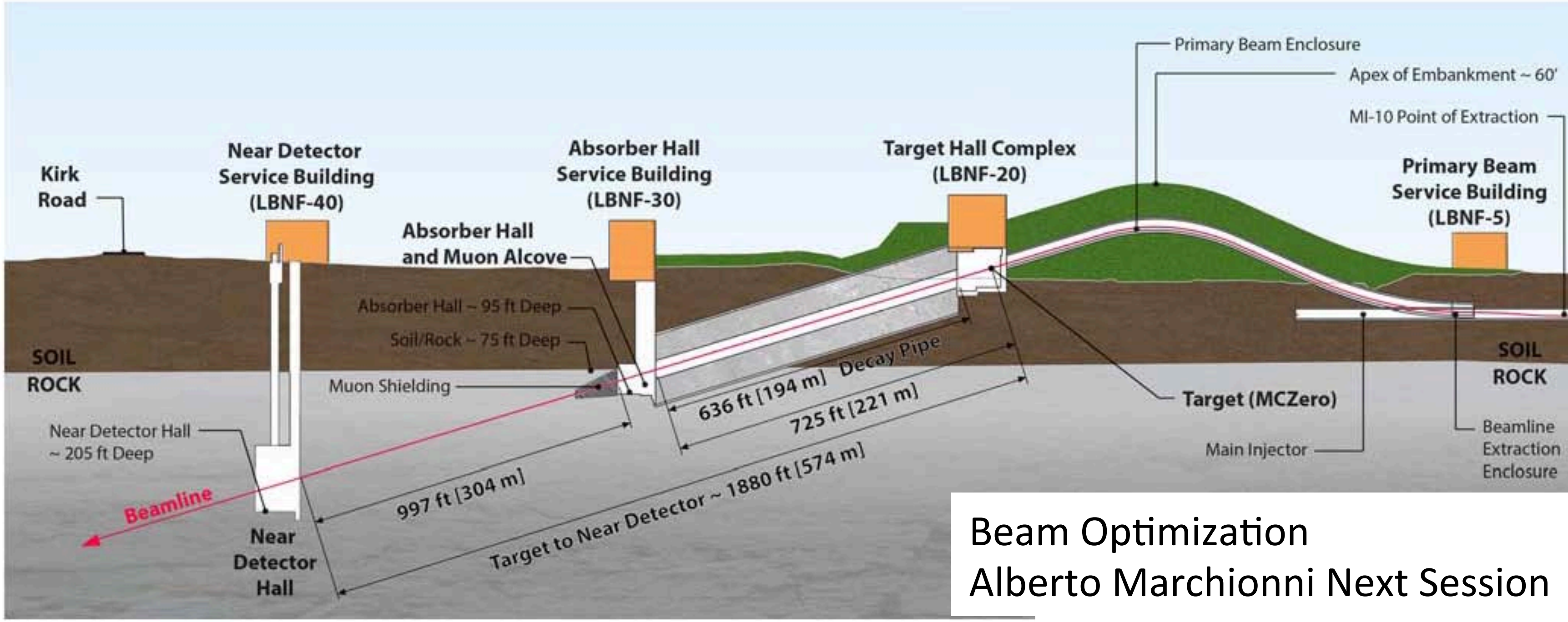
[Particle Physics Project Prioritization Panel (P5)](#)

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

P5 Recommendation 13: 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. LBNF is the highest priority large project in its timeframe.

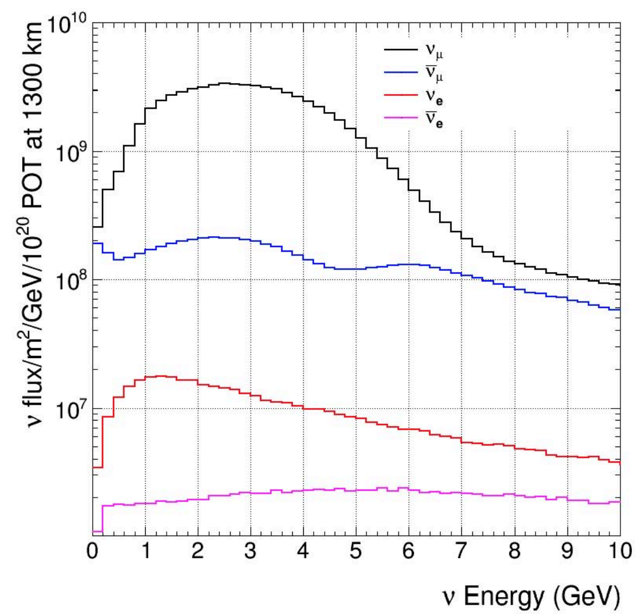
LBNF/DUNE Neutrino Beam



Beam Optimization
Alberto Marchionni Next Session

Parameter	Value	
Energy	60 GeV	120 GeV
Protons per cycle	7.5×10^{13}	7.5×10^{13}
Spill duration	1.0×10^{-5} sec	1.0×10^{-5} sec
Protons on target per year	1.9×10^{21}	1.1×10^{21}
Beam/batch (84 bunches)	12.5×10^{12} nominal; (8×10^{11} commissioning)	
Cycle time	0.7 sec	1.2 sec
Beam Power	1.03 MW	1.2 MW

- FNAL proton improvement program will increase the beam power before the start of DUNE to 1.2 MW!
- Beam upgradable to 2.4 MW



LBNF/DUNE Projects estimate in CORE Accounting

	M & S K $	Labor K Hours
Project Office - LBNF	**$15,569**	
Far Site Facilities	**$545,421**	**23**
Far Site CF	$254,108	
Cryogenics Infrastructure	$291,313	23
Near Site Facilities	**$252,981**	**265**
Near Site CF	$199,046	
Beamline	$53,934	265
LBNF Total	**$813,970**	**288**
Near Detector	**$43,205**	**198**
Far Detector	**$130,383**	**1,261**
DUNE Total	**$173,588**	**1,459**
GRAND TOTAL	**$987,558**	**1,747**