DUNE Near Detector: Physics and System Overview

Dan Dwyer
DUNE Near Detector Conceptual Design Review
7-9 July 2020

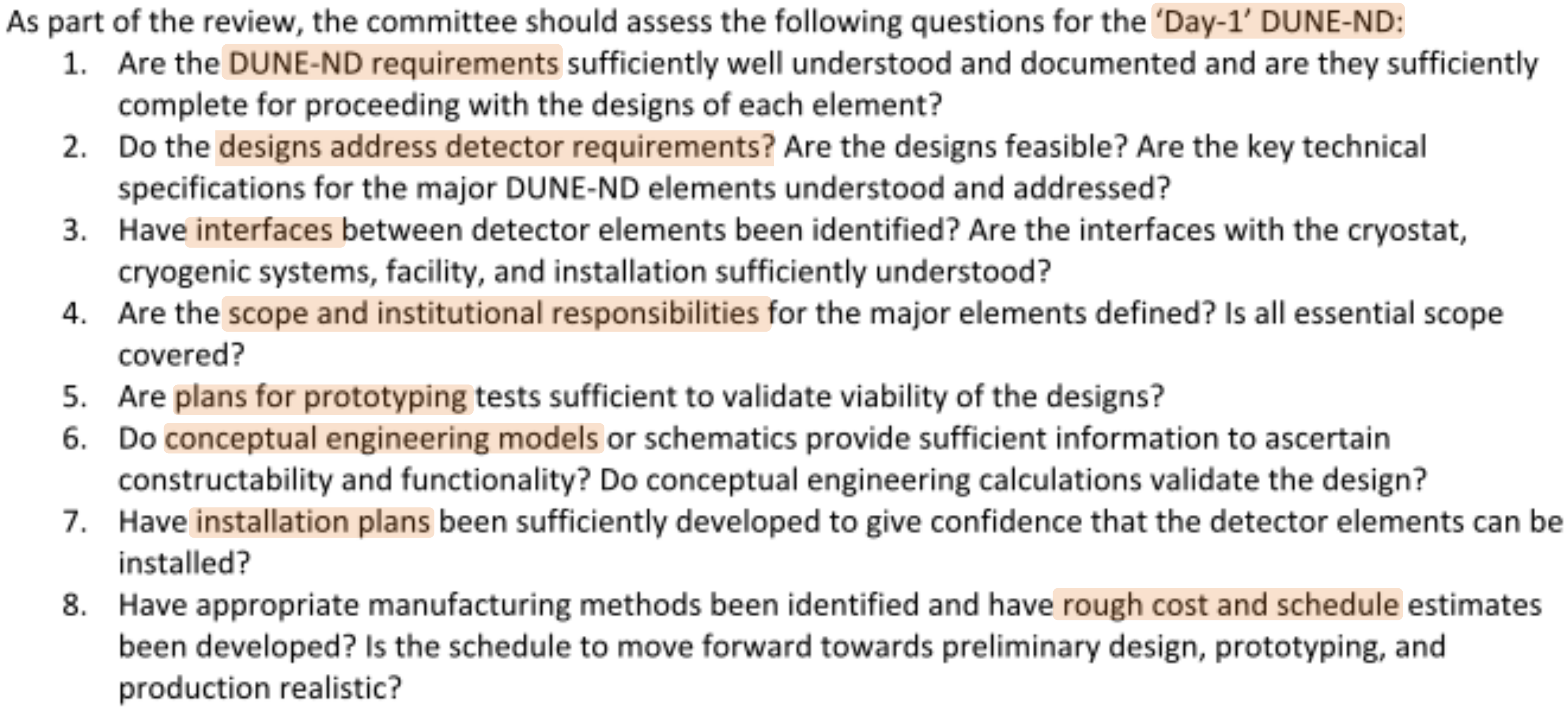
Who am I

- Dan Dwyer
- Staff Scientist, LBNL
  - Technical Coordinator for DUNE ND-LAr Consortium
  - L2 Manager of the DUNE Near Detector
  - DOE Early Career Award for Pixel LArTPC technology
  - Background in ν physics with KamLAND, Daya Bay Experiments
  - APS Primakoff Award for “innovative contributions to neutrino physics”

Outline

- Context
- DUNE Physics
- The role of the Near Detector
- Near Detector Concept
- Scope and Key Design Aspects of Detectors
- Subsystem descriptions
- Near Detector Organization and Management
- Summary

Today’s Charge



As part of the review, the committee should assess the following questions for the ‘Day-1’ DUNE-ND:

1. Are the DUNE-ND requirements sufficiently well understood and documented and are they sufficiently complete for proceeding with the designs of each element?
2. Do the designs address detector requirements? Are the designs feasible? Are the key technical specifications for the major DUNE-ND elements understood and addressed?
3. Have interfaces between detector elements been identified? Are the interfaces with the cryostat, cryogenic systems, facility, and installation sufficiently understood?
4. Are the scope and institutional responsibilities for the major elements defined? Is all essential scope covered?
5. Are plans for prototyping tests sufficient to validate viability of the designs?
6. Do conceptual engineering models or schematics provide sufficient information to ascertain constructability and functionality? Do conceptual engineering calculations validate the design?
7. Have installation plans been sufficiently developed to give confidence that the detector elements can be installed?
8. Have appropriate manufacturing methods been identified and have rough cost and schedule estimates been developed? Is the schedule to move forward towards preliminary design, prototyping, and production realistic?

Context: Near Detector Design Maturity

- **DUNE Near Detector Development:**
  - Formal DUNE ND design effort initiated just over 1 year ago (Apr. 2019)
  - Focus: delivering ND system essential for physics on ‘Day-1’
  - First two DUNE ND Consortia (ND-LAr, SAND) formally initiated May 2020
- **Design Maturity:**
  - ND design is not as mature as Far Detector, but has shown rapid progress
  - Design well-motivated by DUNE physics requirements
  - Scope and Key Design Aspects are well-understood
  - Active and successful prototyping program
  - Institutional partners working together coherently
- **Next Steps:**
  - Complete transition to ND Consortia, initiate Preliminary Design efforts

DUNE Physics and the Near Detector

DUNE Physics:

Accelerator Neutrinos:
- CP Violation
- Mass Ordering
- Precision Mass and Mixing

← *Headline measurements*

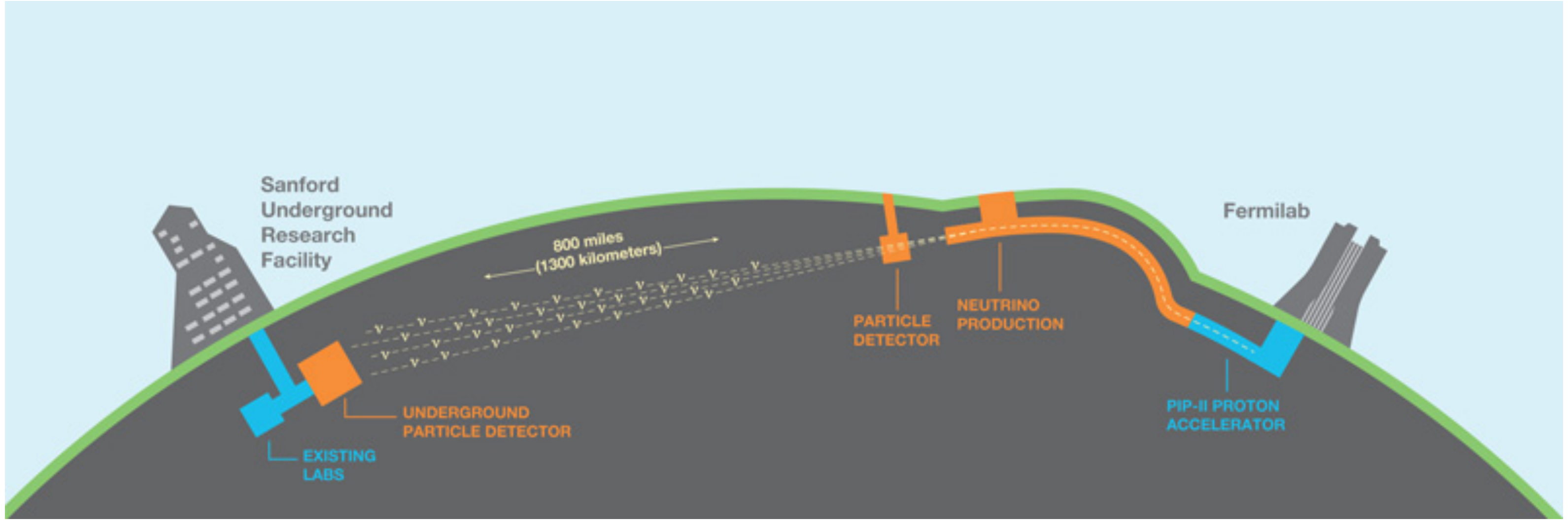
Supernova Neutrino Bursts
Baryon Number Violation
BSM Searches

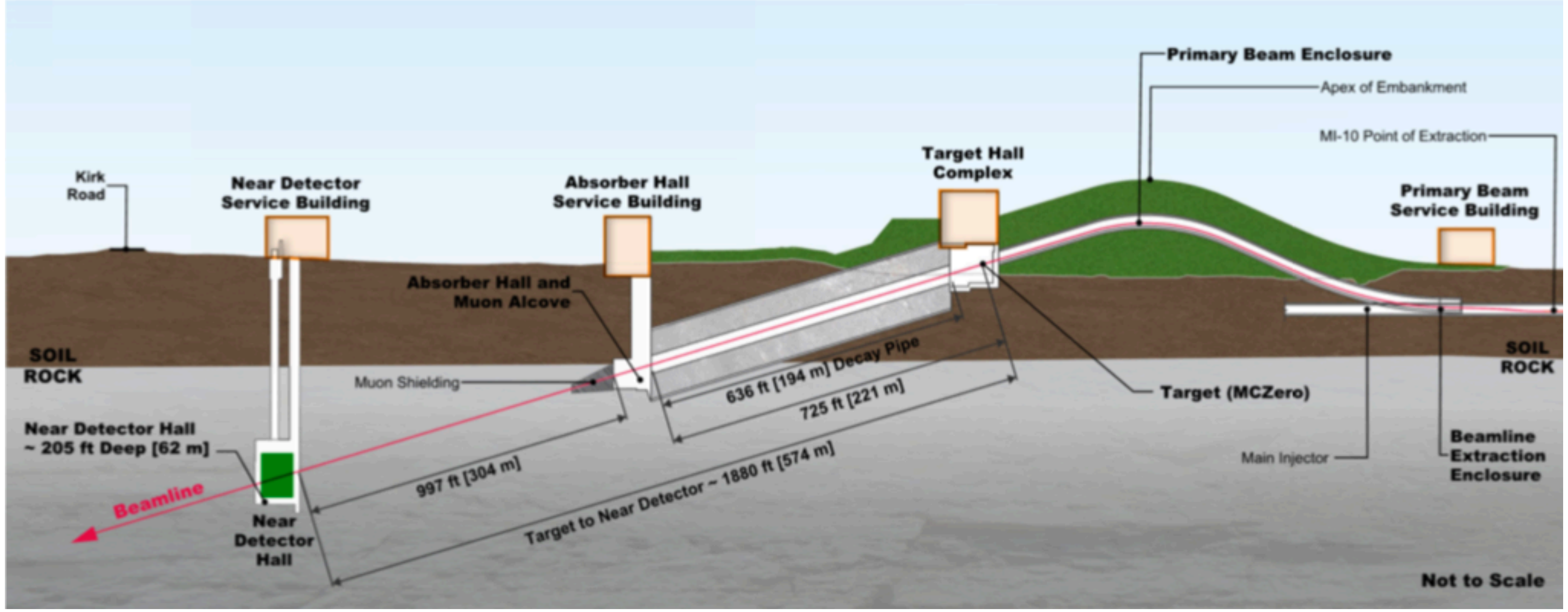
DUNE Near Detector:

- In LBNF Beam (574m from target)
- At new underground site (62m deep)

Key Purpose:
Enable the search for CP Violation

With ~10M neutrino events/yr, it will also provide a rich physics program all on it’s own.





Physics Target for the ‘Day-1’ Near Detector

The ‘Day-1’ Near Detector:

The Near Detector suite/capabilities needed from the start of LBNF neutrino beam operation.

‘Day-1’ System Requirement:

Enable a 3σ observation of maximal CP violation

3σ Max-CPV is difficult:

Only modest variation in ν_e signal

In 3.5 yrs (staged), ν-only operation, NO:

~1100 ν_e appearance events

~300 background

Max CPV:

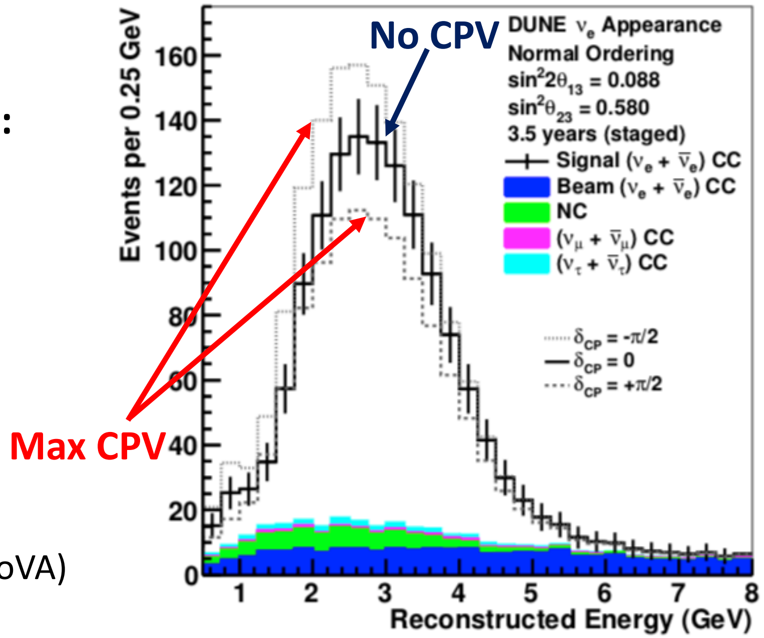
Variation in signal: ~15%

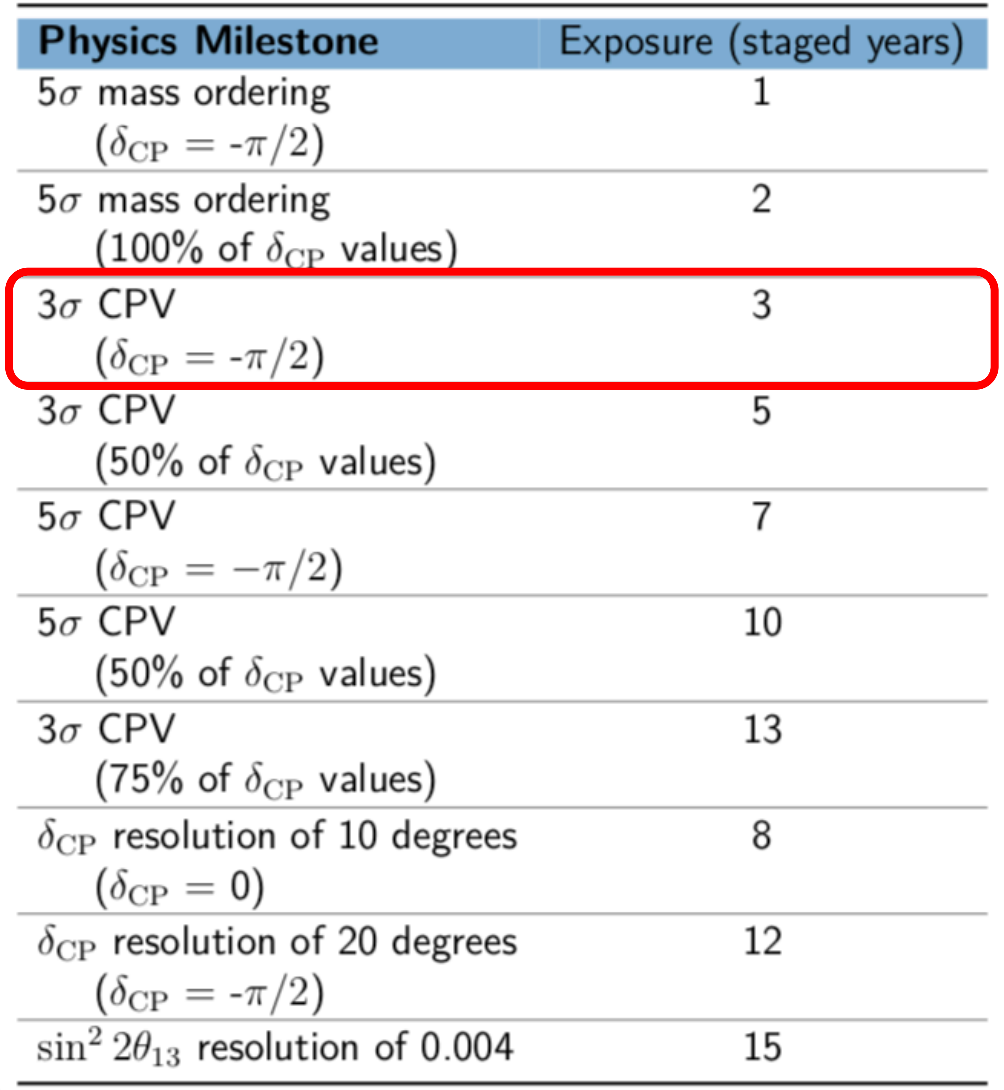
Statistical uncertainty: ~3%

Requires total systematic uncertainty less than ~3%

Compare with state-of-the-art of ~7-8% (T2K, NoVA)

From DUNE TDR





Physics Milestone	Exposure (staged years)
5σ mass ordering ($\delta_{\rm CP} = -\pi/2$)	1
5σ mass ordering (100% of $\delta_{\rm CP}$ values)	2
3σ CPV ($\delta_{\rm CP} = -\pi/2$)	3
3σ CPV (50% of $\delta_{\rm CP}$ values)	5
5σ CPV ($\delta_{\rm CP} = -\pi/2$)	7
5σ CPV (50% of $\delta_{\rm CP}$ values)	10
3σ CPV (75% of $\delta_{\rm CP}$ values)	13
$\delta_{\rm CP}$ resolution of 10 degrees ($\delta_{\rm CP} = 0$)	8
$\delta_{\rm CP}$ resolution of 20 degrees ($\delta_{\rm CP} = -\pi/2$)	12
$\sin^2 2\theta_{13}$ resolution of 0.004	15

Predicting the Far Detector Signal

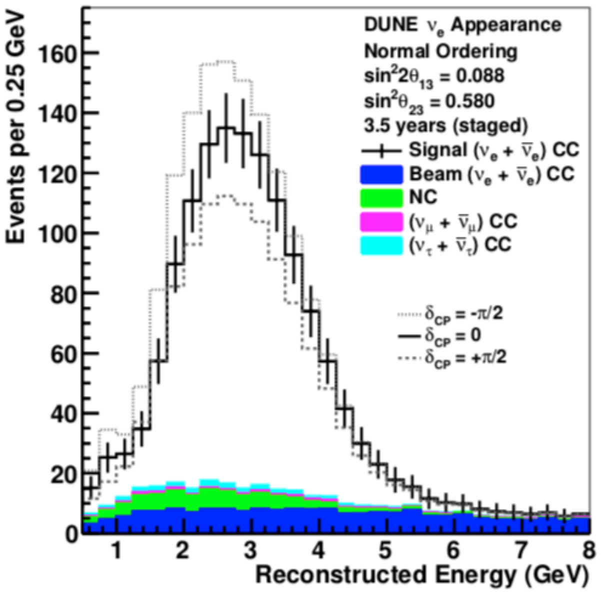
Near Detector:

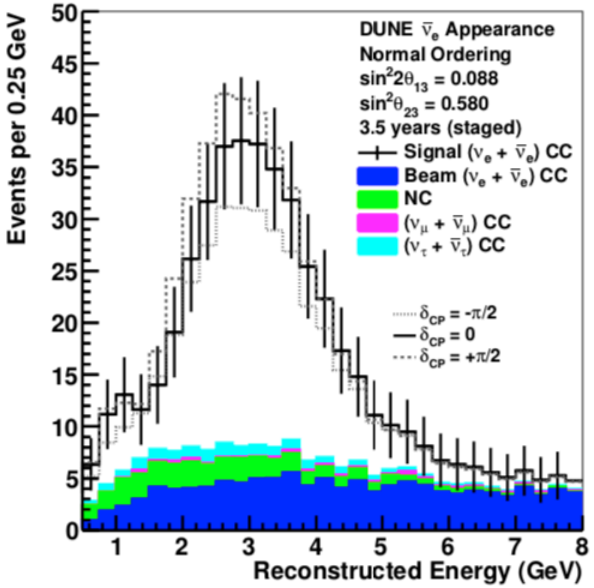
Must enable a precise (better than ~4%) prediction of the FD appearance signal

Far Detector appearance signal:

$$\frac{dN^{\rm far}_{\nu_e}}{dE_{\rm rec}} = \int_{E_\nu} \underbrace{D^{\rm far,inclus.}_{\nu_e-{\rm CC}}(E_{\rm rec};E_\nu)}_{\text{LArTPC response}} \; \underbrace{\sigma^{\rm inclus.,Ar}_{\nu_e-{\rm CC}}(E_\nu)}_{\nu\text{-Ar cross section}} \; \overset{\text{Oscillation}}{\boxed{P_{\mu e}(E_\nu)}} \; \underbrace{\Phi^{\rm far}_{\nu_\mu}(E_\nu)\Big|_{l=0}}_{\text{Beam flux}} \; dE_\nu$$

Existing model uncertainties: ~10% for each





Near Detector: Physics Strategy

Near Detector:

Physics needs dictate detector concept

Far Detector appearance signal:

Oscillation

$$\frac{dN^{\text{far}}_{\nu_e}}{dE_{\text{rec}}} = \int_{E_\nu} D^{\text{far,inclus.}}_{\nu_e-\text{CC}}(E_{\text{rec}}; E_\nu)\ \sigma^{\text{inclus.,Ar}}_{\nu_e-\text{CC}}(E_\nu)\ \boxed{P_{\mu e}(E_\nu)}\ \Phi^{\text{far}}_{\nu_\mu}(E_\nu)\Big|_{l=0}\ dE_\nu$$

Far/Near diff. constrained by detector model

Far/Near diff. constrained by theory

Far/Near diff. constrained by beam model and Near data

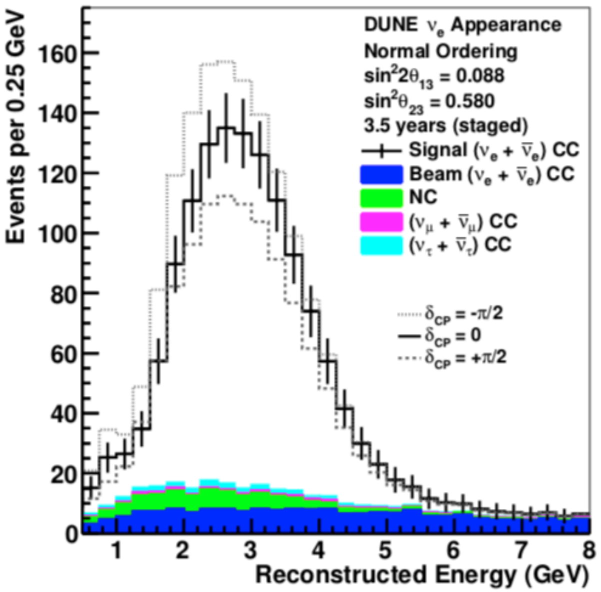
Near Detector signal:

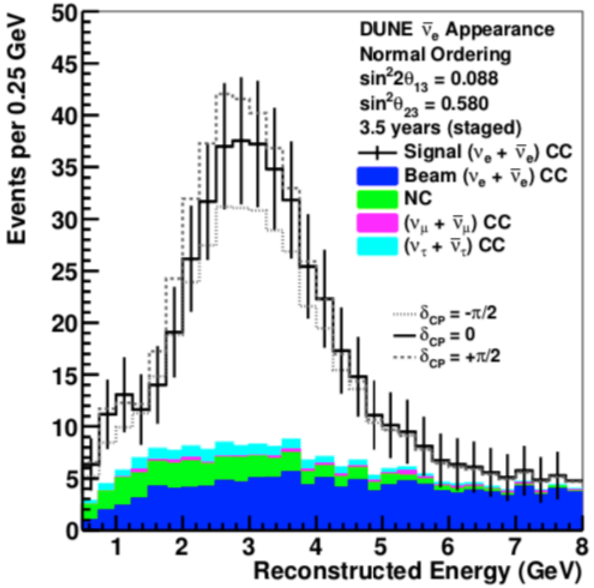
$$\frac{dN^{\text{near}}_{\nu_\mu-\text{CC}}}{dE_{\text{rec}}} = \int_{E_\nu} D^{\text{near}}_{\nu_\mu-\text{CC,inclus.}}(E_{\text{rec}}; E_\nu)\ \boxed{\sigma^{\text{inclus.,Ar}}_{\nu_\mu-\text{CC}}(E_\nu)}\ \Phi^{\text{near}}_{\nu_\mu}(E_\nu)\Big|_{l=l_{\text{near}}}\ dE_\nu$$

Physics Strategies:

Rationale for ND concept

1. Near Detector target is Argon





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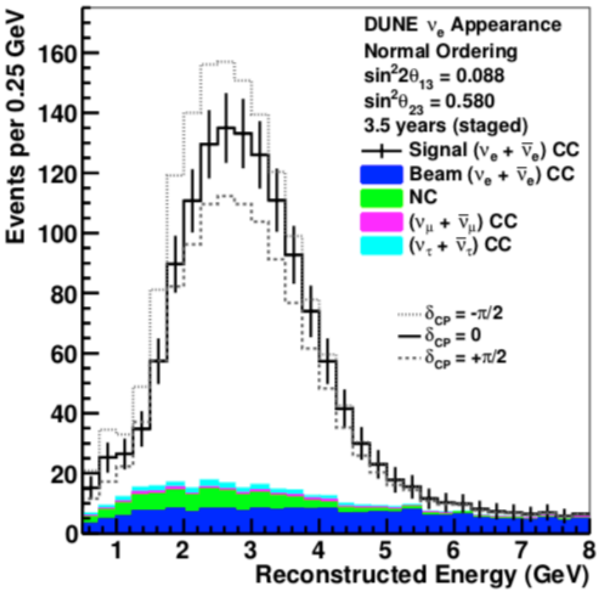
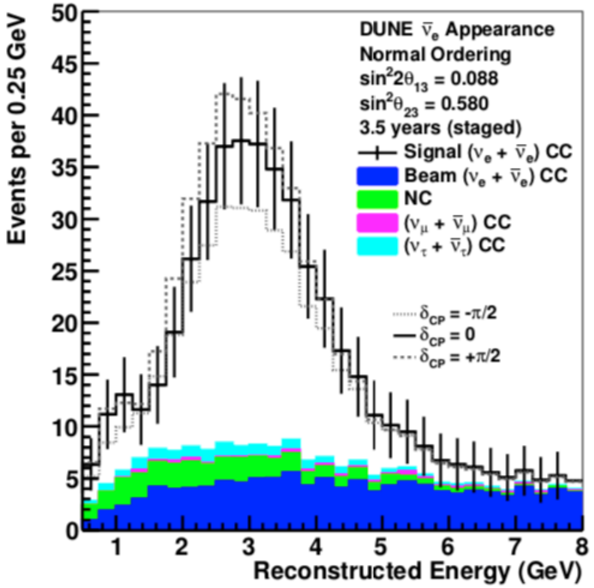
2. Near Detector has an LArTPC

Physics Strategies:

Rationale for ND concept





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Near Detector signal:

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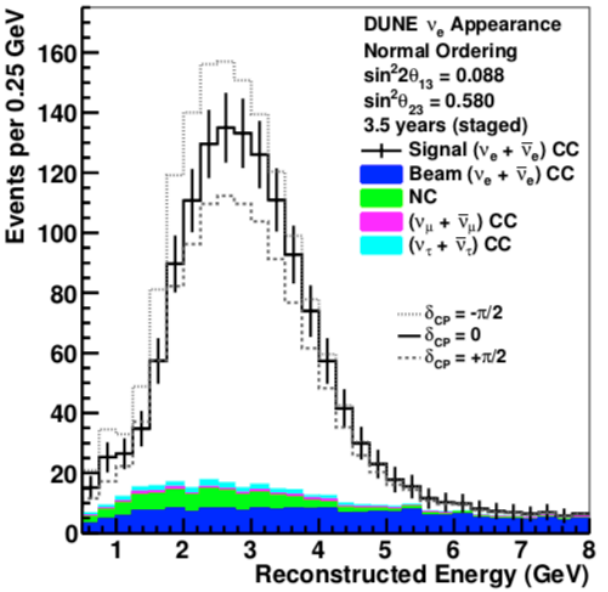
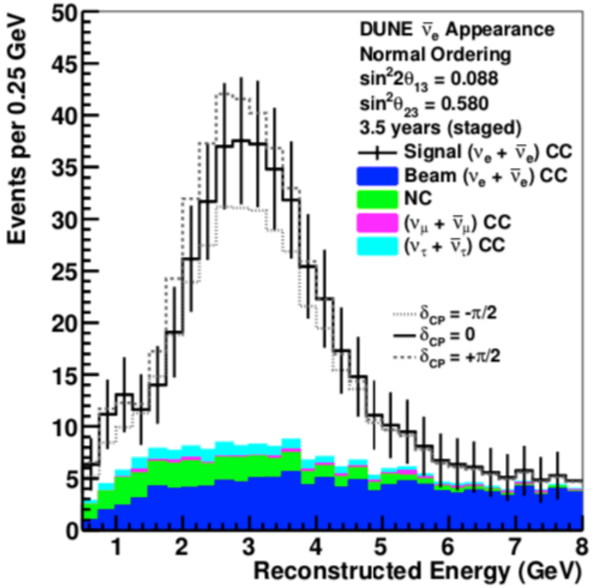
Physics Strategies:

Rationale for ND concept

3. Off-axis data provides beam of 'known' neutrino energy, breaks detector response / cross section degeneracy





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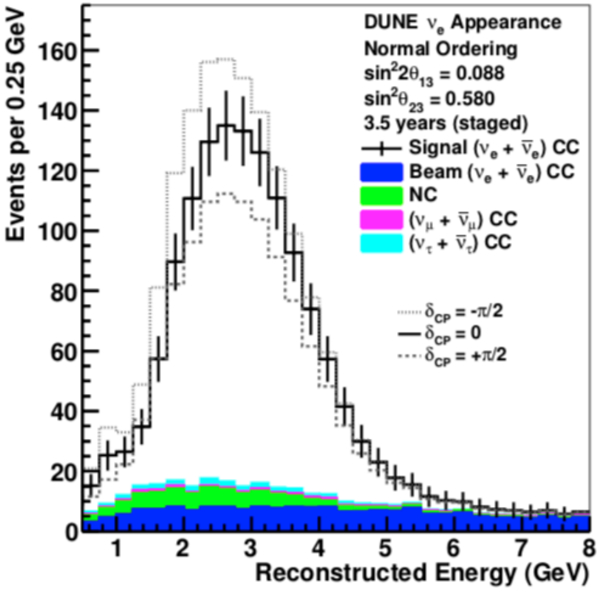
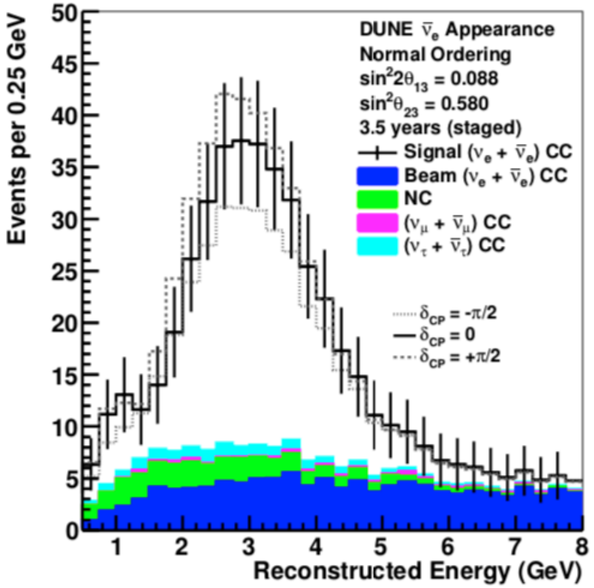
Physics Strategies:

Rationale for ND concept

4. Beam monitoring ensures unforeseen variations in beam flux are identified.

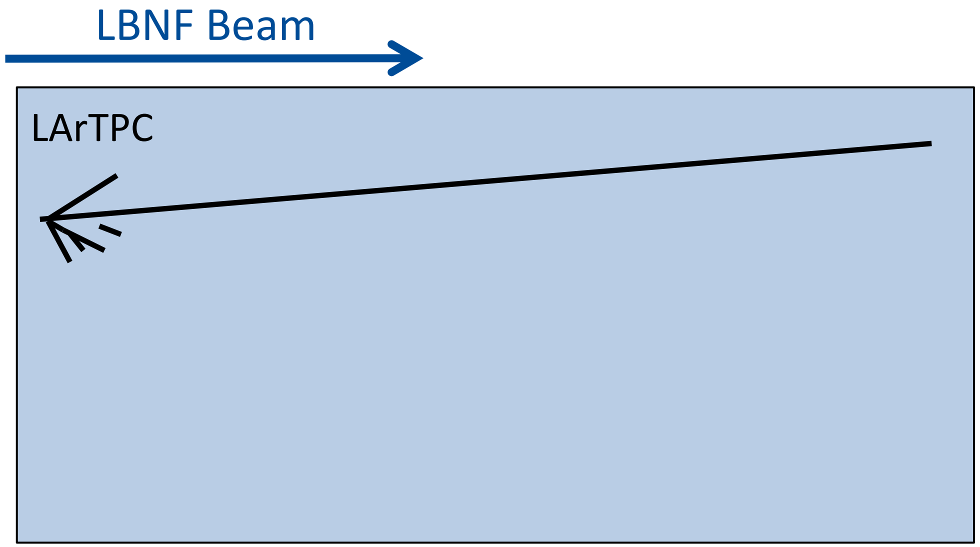




Near Detector: Concept Development

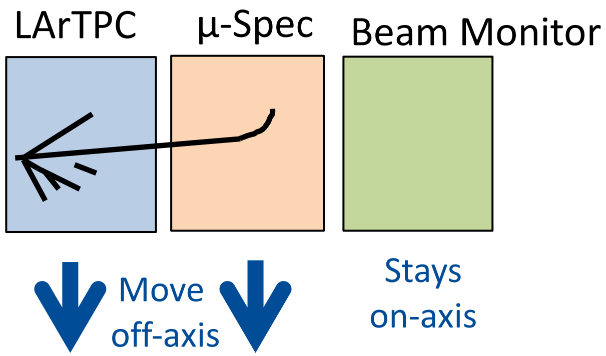
Step 1: Sketch Concept

Construct detector based on preceding physics discussion.
~25m long LArTPC to range ~5 GeV muons.
~30m wide LArTPC to provide off-axis data.



Step 2: Apply simple optimization

Can achieve same goals with a smaller movable LArTPC plus muon spectrometer, with a stationary beam monitor.



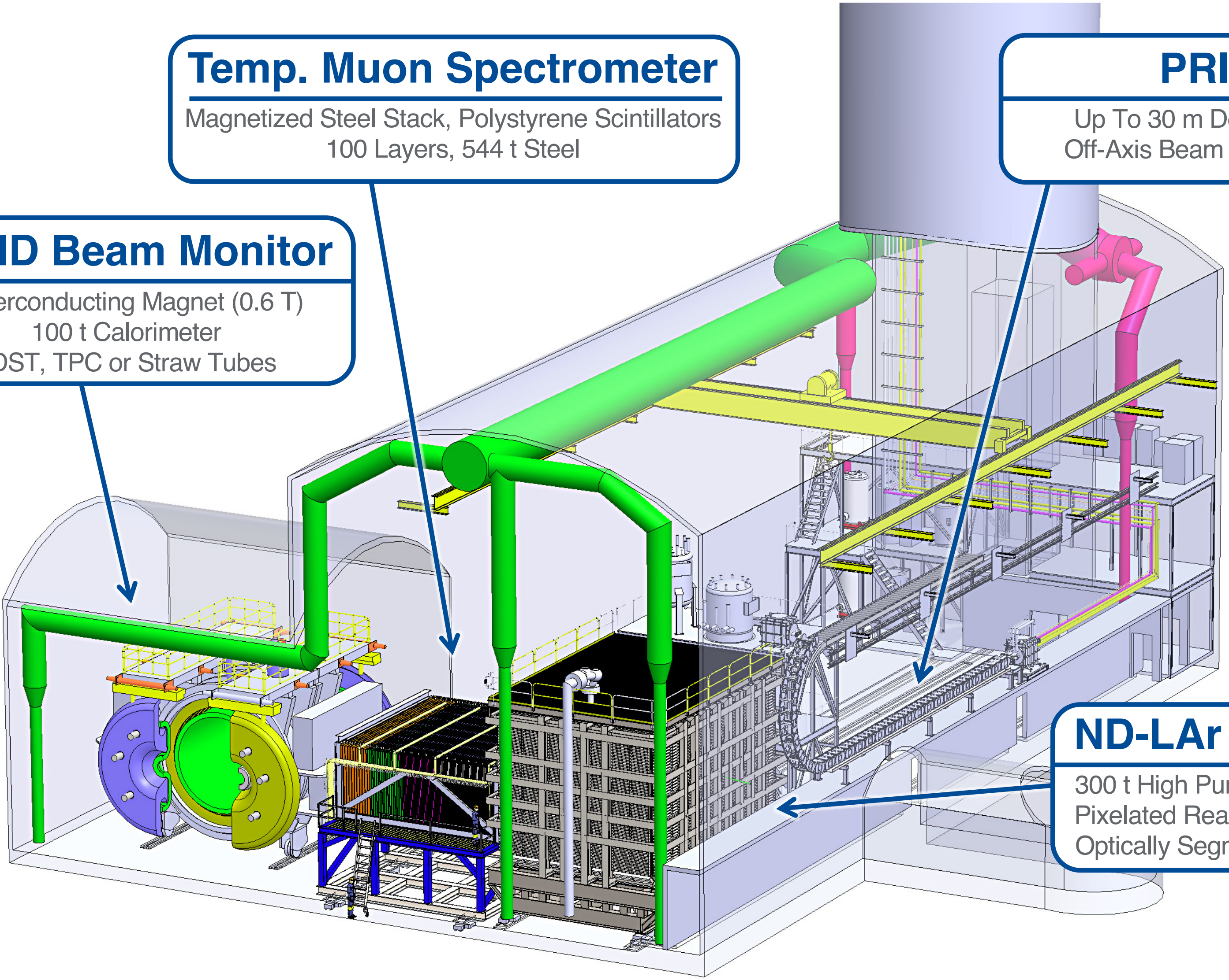
Step 3: Reality Check

Evaluated and endorsed by independent scientific review panel: Long Baseline Neutrino Committee (LBNC).

LBNC Closeout Report, July 2019

> The LBNC strongly endorses the need for a ND containing a movable liquid argon TPC and magnetic spectrometer, and a fixed on-axis beam monitor. These are the minimum elements required for DUNE to achieve its physics goals, and are needed from the start of data-taking.

Near Detector: Day-1 System Design



Temp. Muon Spectrometer

Magnetized Steel Stack, Polystyrene Scintillators
100 Layers, 544 t Steel

PRISM

Up To 30 m Detector Travel
Off-Axis Beam Measurement

SAND Beam Monitor

Superconducting Magnet (0.6 T)
100 t Calorimeter
3DST, TPC or Straw Tubes

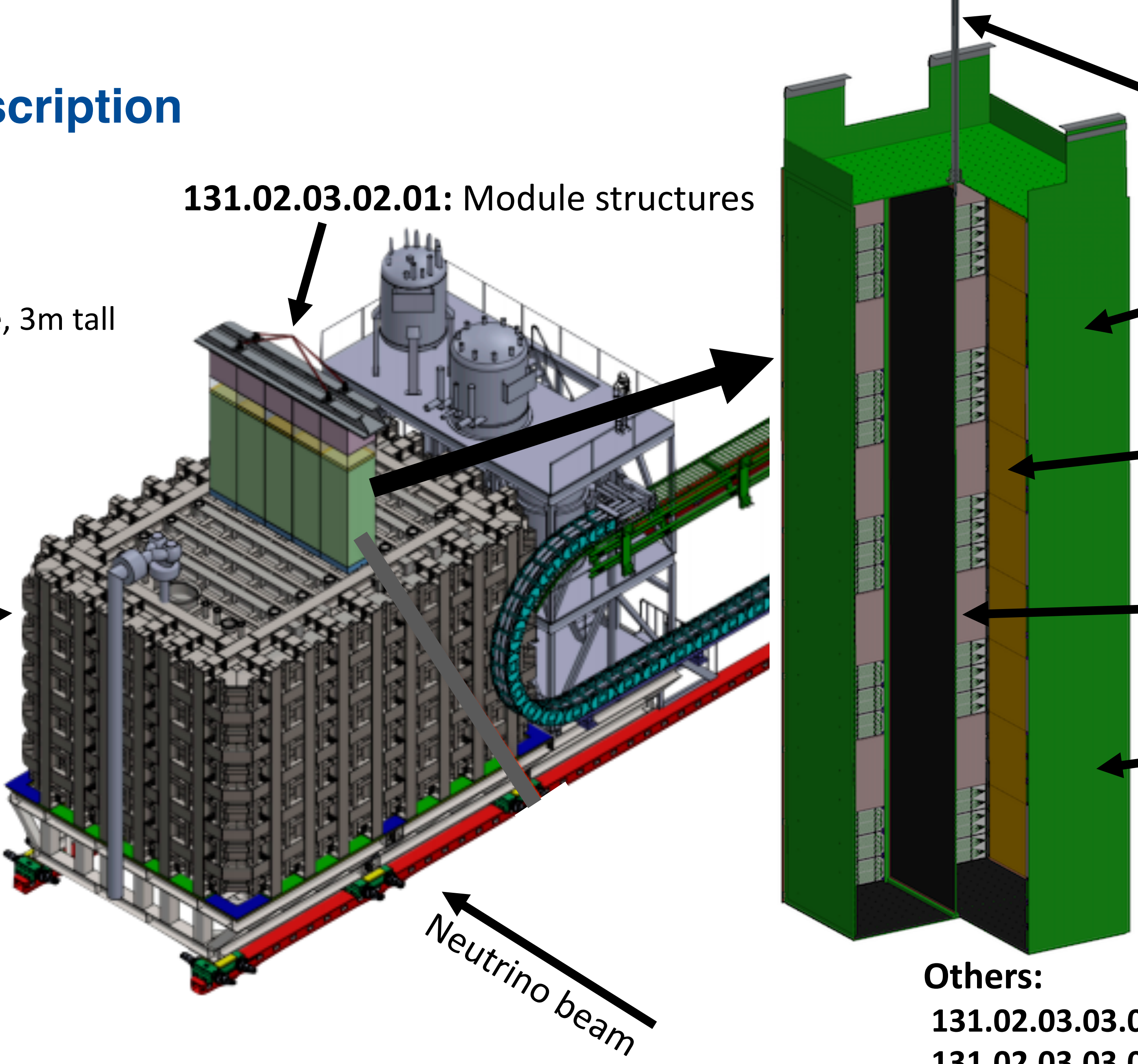
ND-LAr Detector

300 t High Purity Liquid Argon
Pixelated Readout Electronics
Optically Segmented Detector

ND LArTPC: Description

35 Modular LArTPCs:

- 7 banks, 5 modules each
- Each module: 1m x 1m base, 3m tall
- In membrane cryostat



131.02.03.02.01: Module structures

131.02.03.03:
ND Cryostat

131.02.03.02.02:
High Voltage

131.02.03.02.03:
Field Structures

131.02.03.02.04:
Charge Readout System

131.02.03.02.05:
Light Readout System

131.02.03.02.06:
Calibration

Others:

131.02.03.03.07: TPC Module Integ. & Testing
131.02.03.03.08: TPC Module Installation

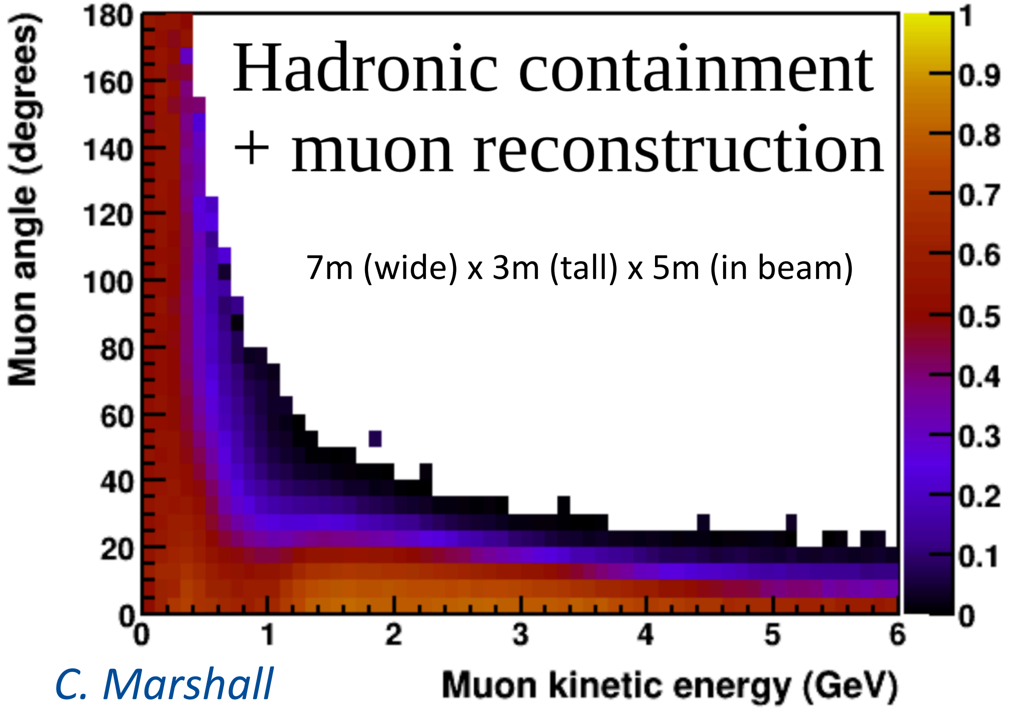
ND LArTPC: Key Design Aspects

LArTPC Minimum Size:

7m wide by 3m tall by 5m deep in beam direction.

Required by coverage of neutrino cross-section, not by simple detector efficiency

Acceptance in lepton kinematic space



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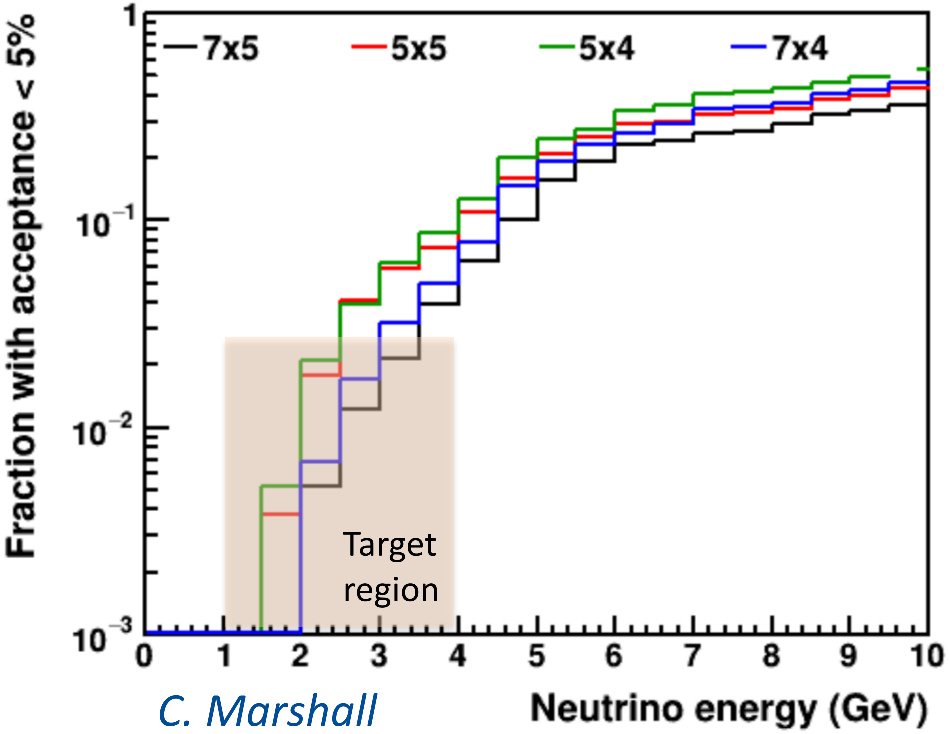
Fraction of events in 'bad' kinematic space (< 5% acceptance)



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ND LArTPC: Key Design Aspects

Near Site Neutrino Intensity:

ND LArTPC must cope with beam neutrino pileup:

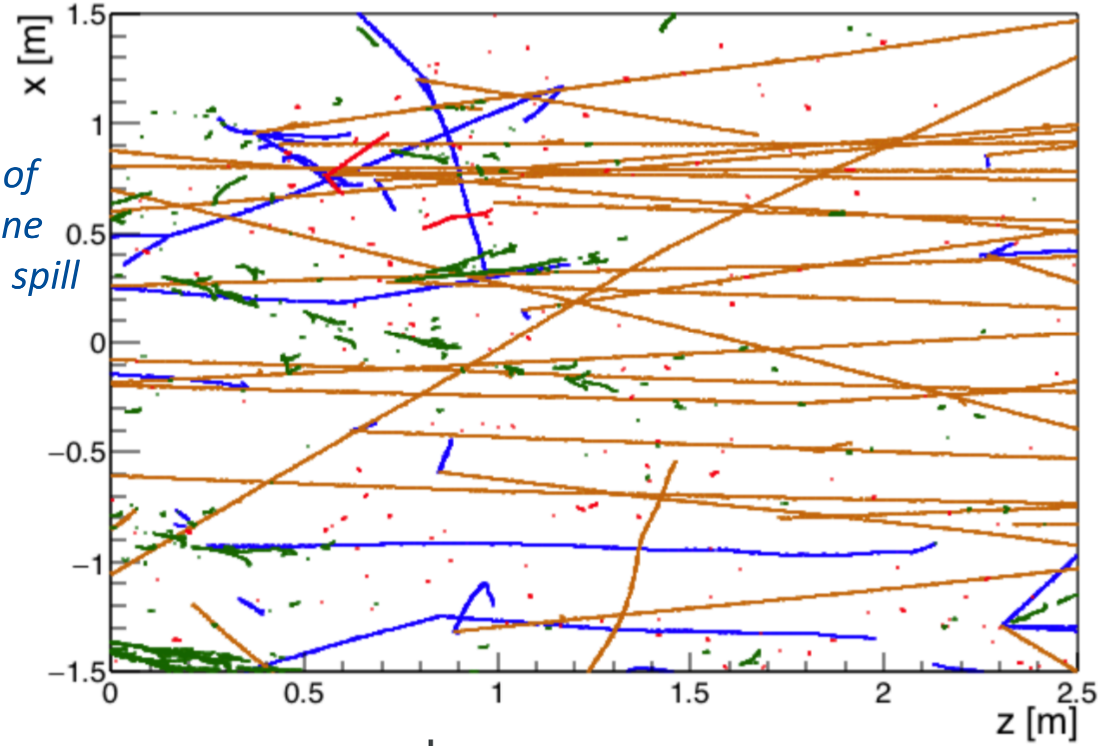
- 20-30 interactions within LArTPC per ~10 μs beam spill
- Many more signals from neutrino interactions outside active region, particularly rock muons.

Charge signals:

Appear ~simultaneous, relative to drift time: ~1.6 mm/μs

Light signals:

Enable ~ns signal separation, if accurately associated with corresponding charge signal



Signal at center of ND LArTPC for one simulated beam spill (~10 μs @ 2MW)

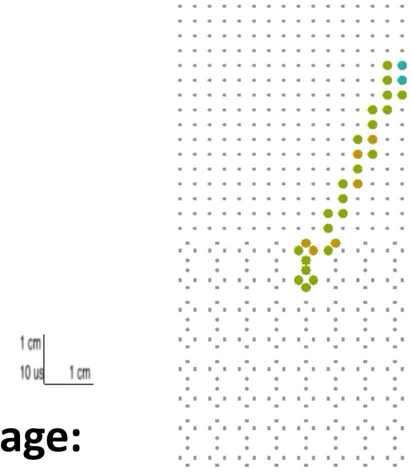
Overcoming Pileup:

Pixelated charge readout (LArPix):

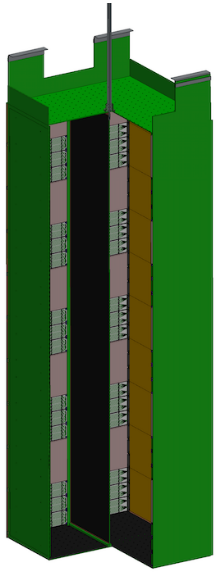
Provides unambiguous 3D charge readout

Optical modularity, high photodetector coverage:

Achieve high efficiency/accuracy for charge-to-light signal association.

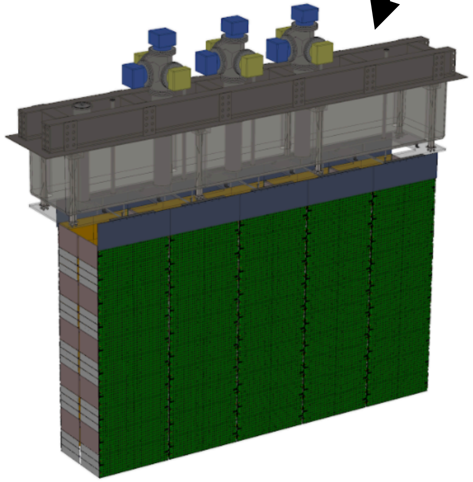


3D cosmic data taken using LArPix-v1

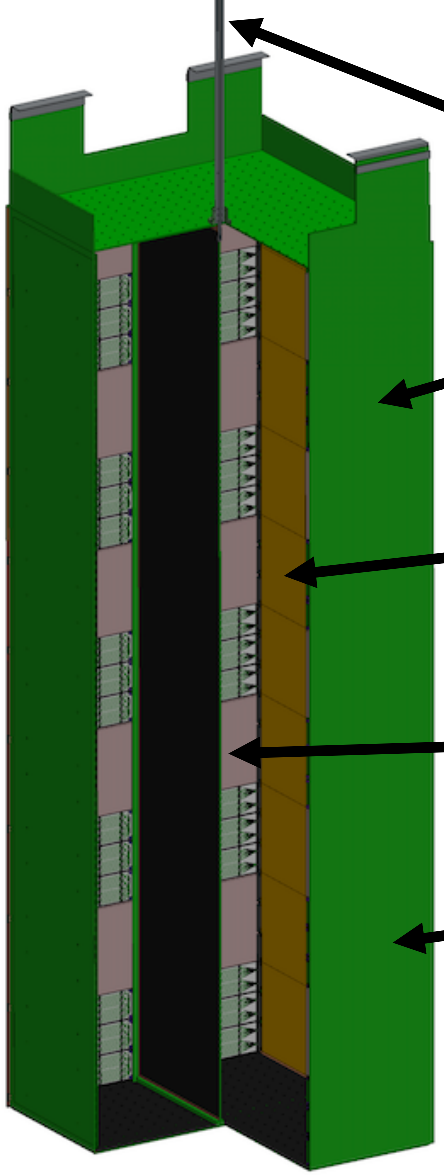


ND LArTPC module: high photocoverage and opaque walls to improve charge-to-light matching.

ND LArTPC: Partners



131.02.03.02.01:
Module structures



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Field Structures

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131.02.03.02.05:
Light Readout System

131.02.03.02.06:
Calibration

Subsystem	Institutions
Module Structure	Univ. of Bern
HV	Univ. of Bern
Field Structure	SLAC, CSU
Charge Readout	LBNL, Caltech, CSU, Rutgers, UC-Davis, UCSB, UPenn, UTA
Light Readout	JINR, Univ. of Bern
Calibration	MSU, JINR, Univ. of Bern
TPC Module Integ.	LBNL, CSU, Univ. of Bern
TPC Module Install.	All

Others:
131.02.03.03.07: TPC Module Integ. & Testing
131.02.03.03.08: TPC Module Installation

Temporary Muon Spectrometer (SSRI): Description

Magnetized Muon Range Stack:

- Sandwich of 100 steel plates & scintillator strip trackers
- 7m (wide) x 3.2m (tall) x 7m (in beam direction)
- Conventional coils to provide magnetic field
- Moves off-axis with ND LArTPC

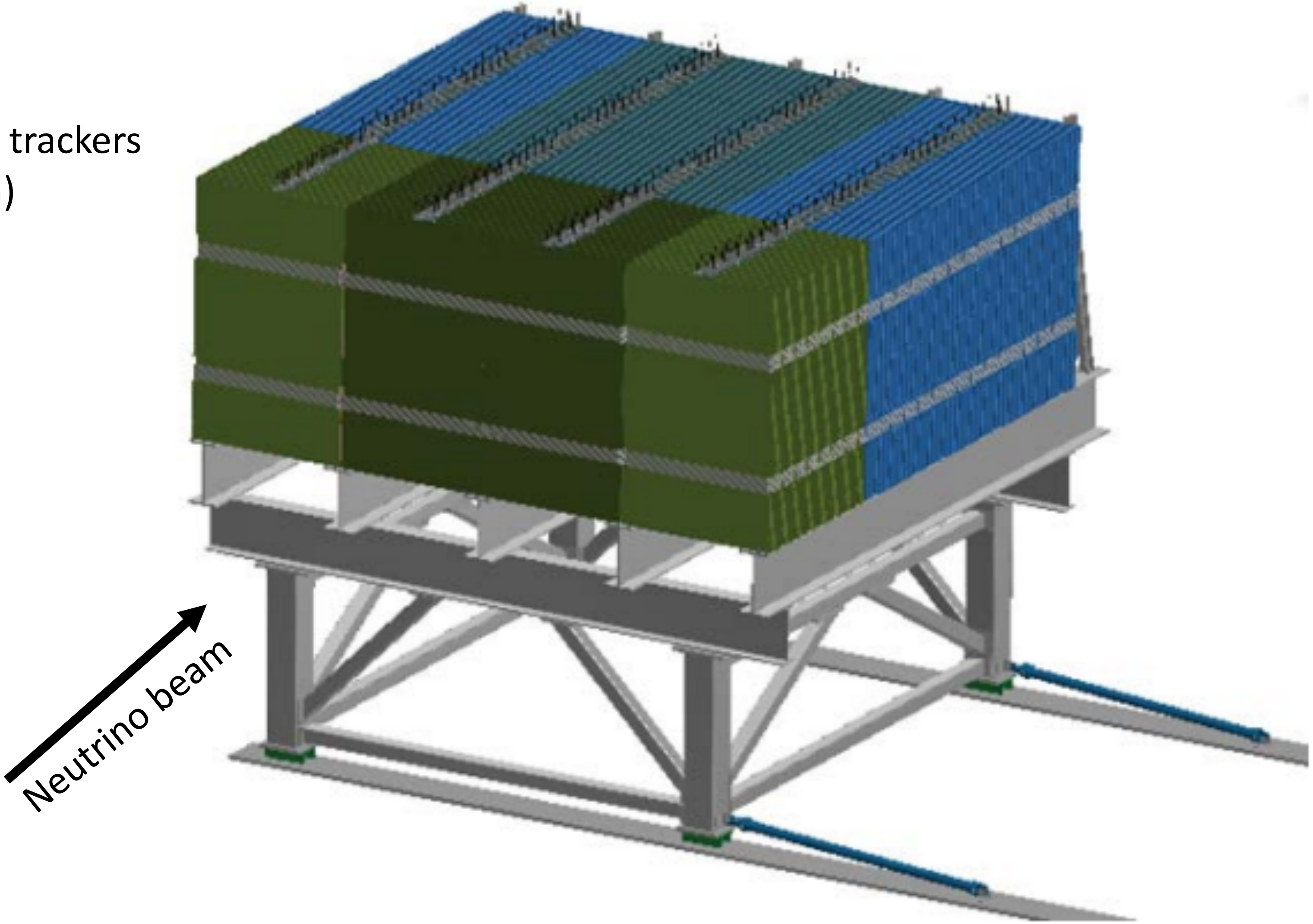
Argonne NATIONAL LABORATORY

THE UNIVERSITY of MISSISSIPPI

UNIVERSITY of ROCHESTER

WICHITA STATE UNIVERSITY

WILLIAM & MARY CHARTERED 1693



Temporary Muon Spectrometer (SSRI): Key Design Aspects

Detector Size:

- Face: 7m (wide) x 3.2m (tall), to match LArTPC
- Depth: 7m (in beam direction), to range 5 GeV muons

Number of tracking planes:

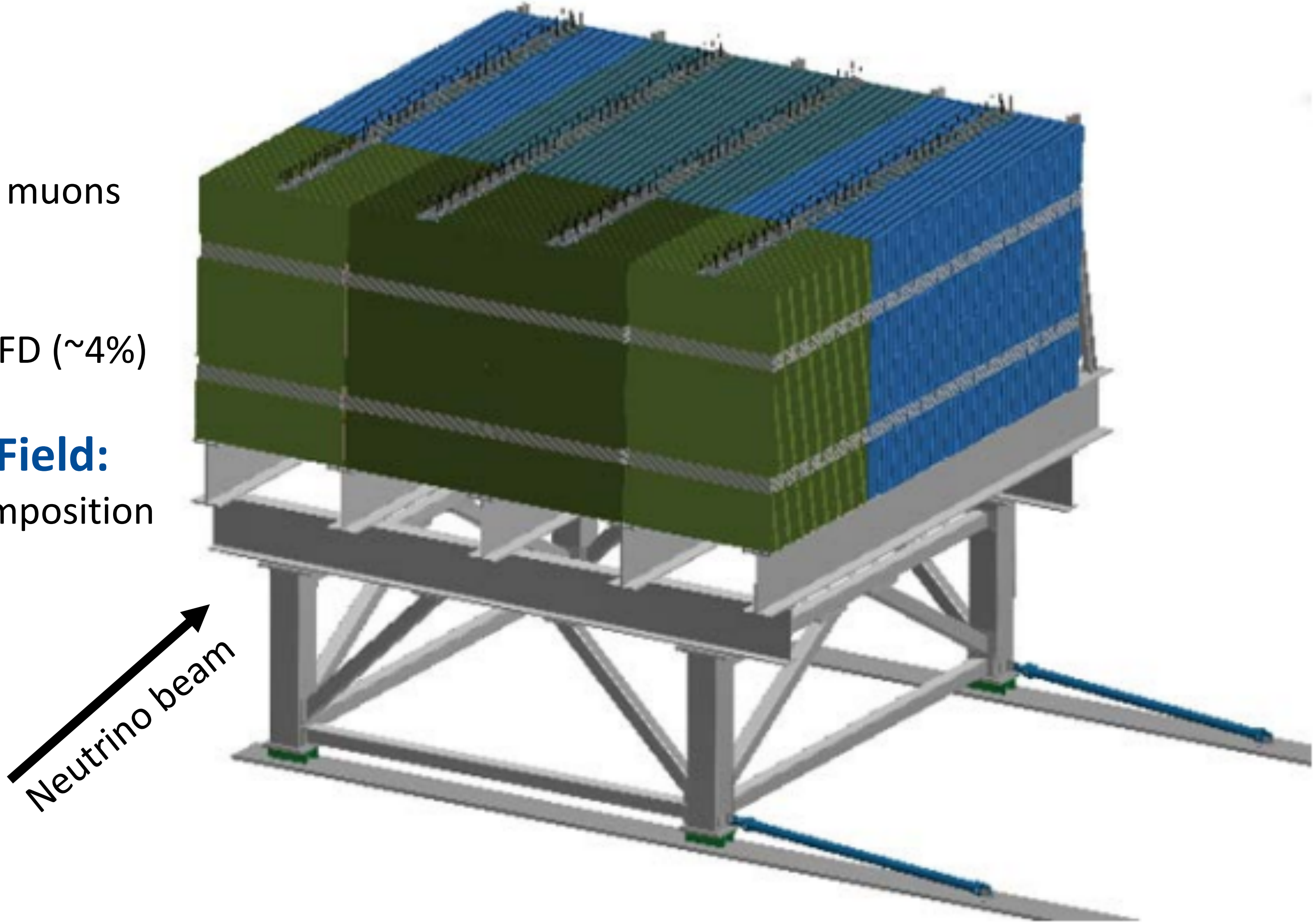
To achieve muon energy resolution on par with FD (~4%)

Tracker Spatial Resolution & Magnetic Field:

To precisely measure neutrino/antineutrino composition

Tracker Time Resolution:

Overcome beam pileup



PRISM: Description

PRISM:

Enable the ND LArTPC and Muon Spectrometer to make measurements away from the beam axis.

Components:

Motorized skates:

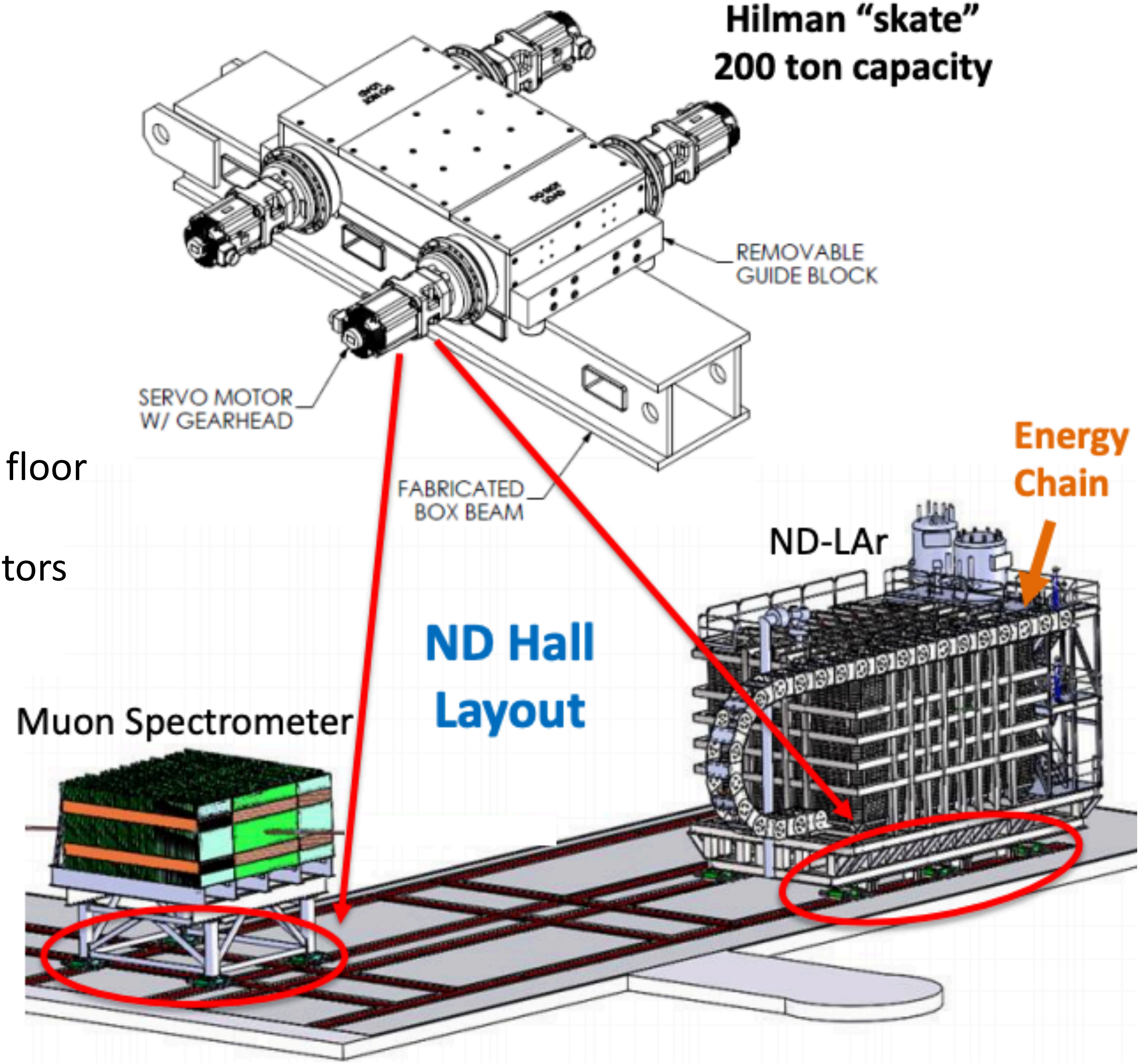
Support and drive detector motion on rails integrated into floor

Energy Chain:

Flexible conduit to maintain utilities (power, cryo) to detectors

Monitoring:

Instruments to track detector position



PRISM: Key Design Aspects

Travel Distance:

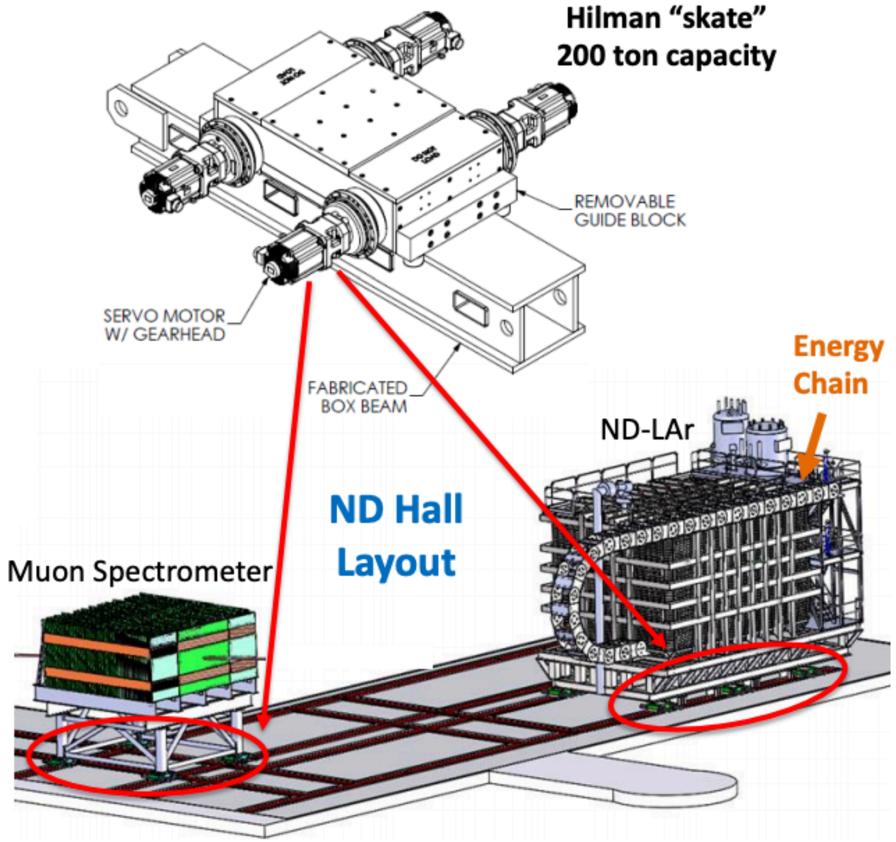
Travel to 30m off-axis covers neutrino energies from 0.5-5 GeV

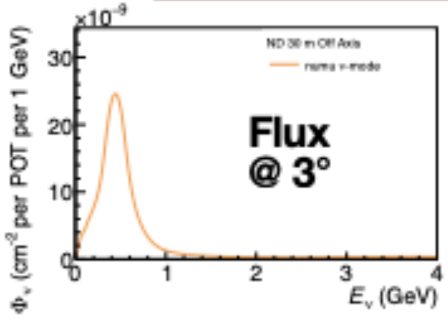
Weight:

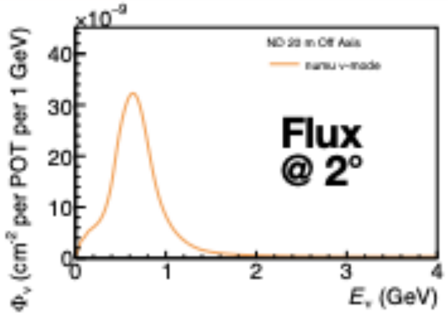
Must support ~700-ton Muon Spectrometer, ~300-ton LArTPC

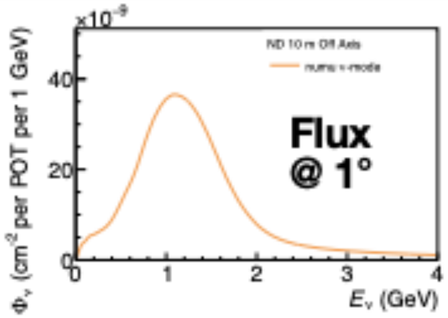
Utilities:

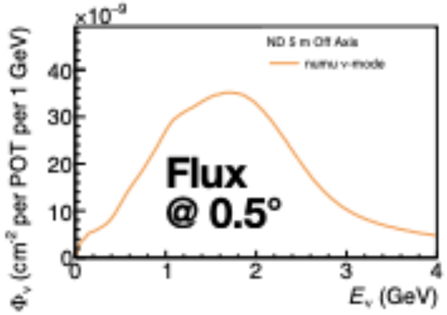
Energy chain must provide detector utilities, LArTPC cooling (LN)

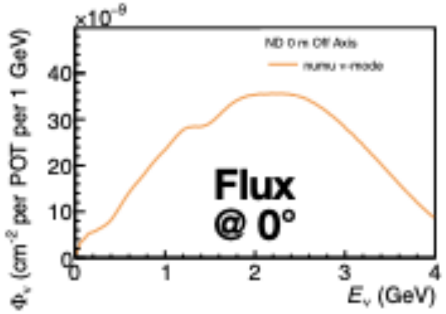












SAND: Description

SAND:

System for on-axis Neutrino Detection.

Purpose:

Monitor stability of neutrino beam intensity, energy spectrum, and spatial profile.

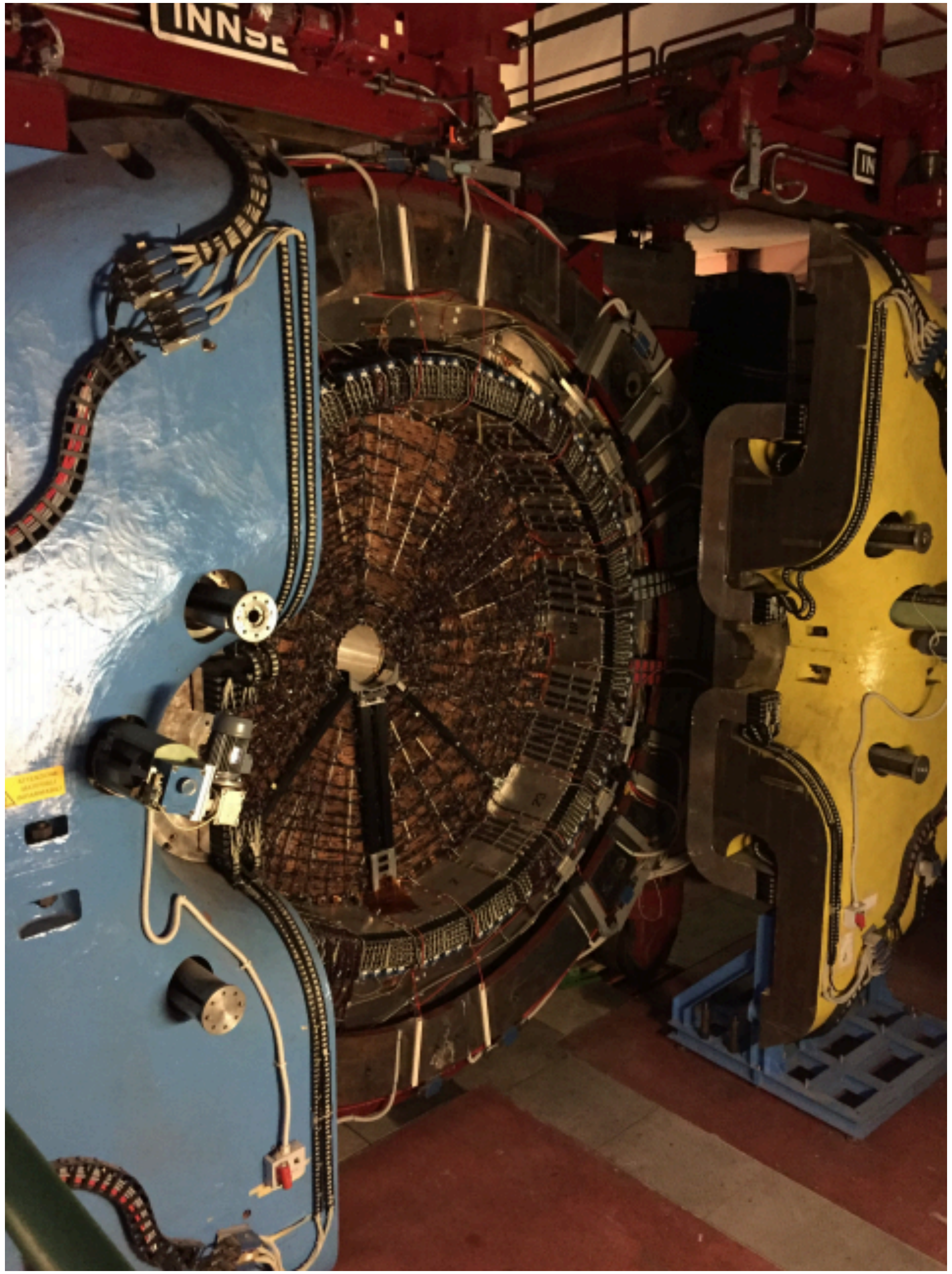
Components:

Reuse Existing KLOE Detector Systems:

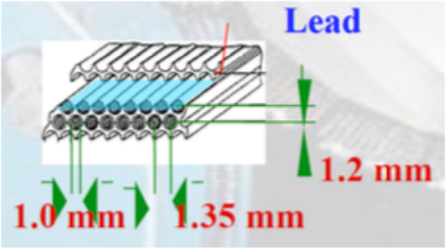
- Electromagnetic Calorimeter
- Superconducting solenoid
- Iron yoke

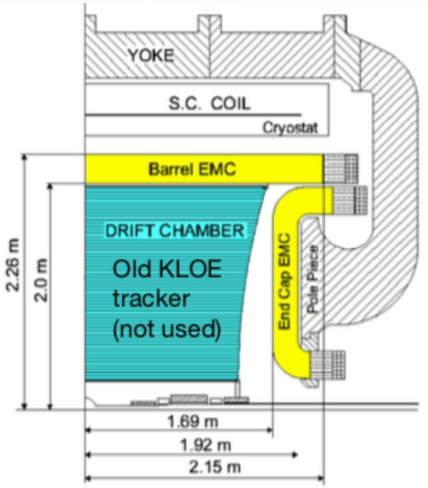
New Tracker:

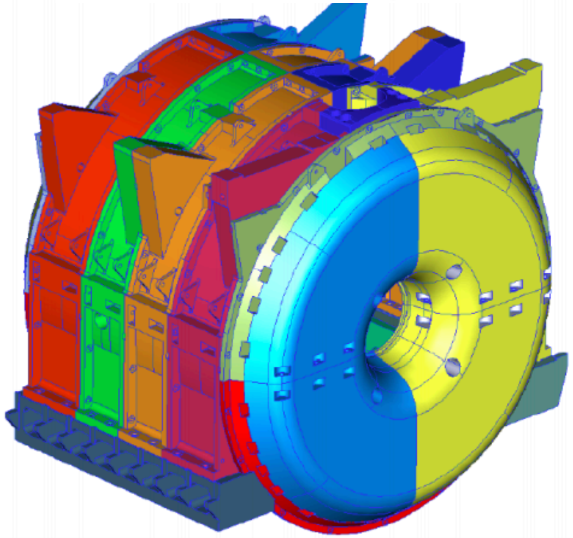
- 3D plastic scintillator tracker
- Straw tubes or TPC



Lead:Fiber:Glue = 42:48:10 (by volume)



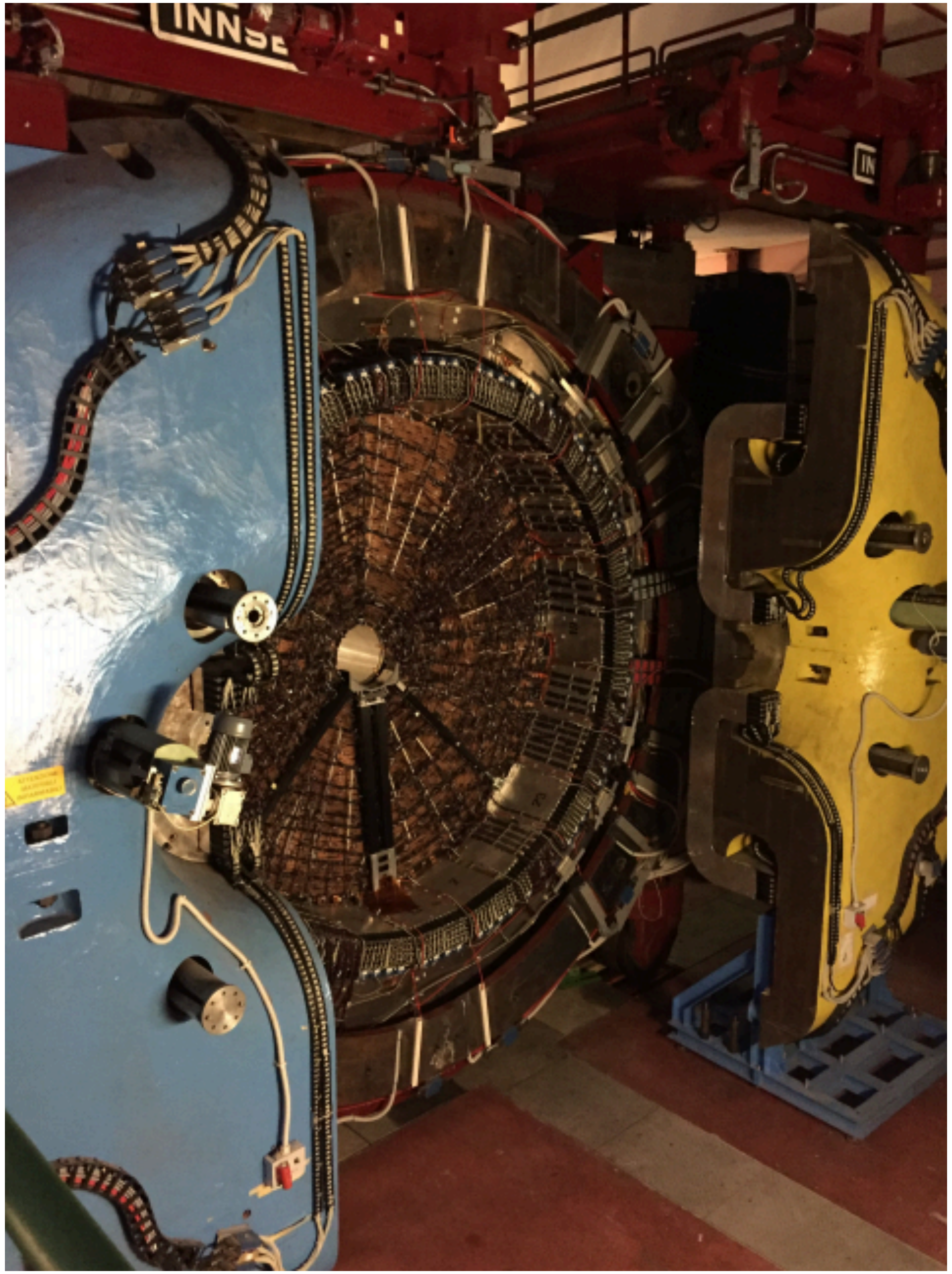




SAND: Key Design Aspects

Beam Monitoring Requirements:

- Identify neutrino interaction position/time
- At minimum: reconstruct muon energy
- If able to reconstruct neutrino energy, the sensitivity to variations improve (i.e. faster, or using less target mass).
- Must tolerate pileup



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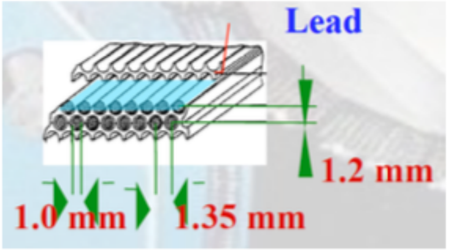
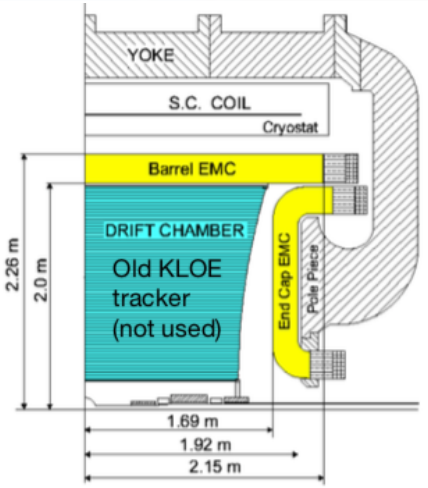
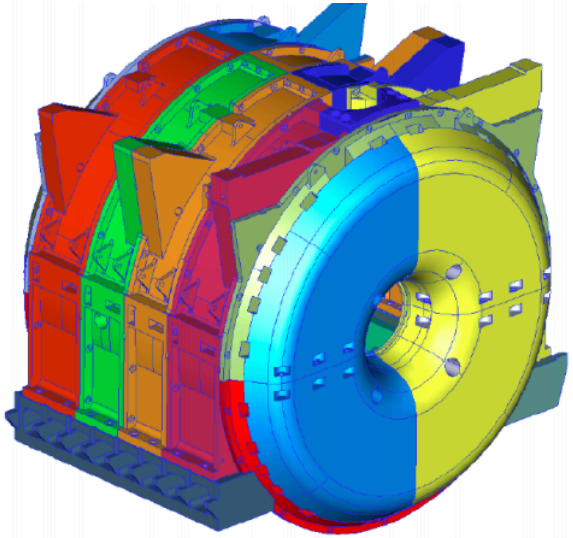






Relation to Near Detector ‘Reference Design’

‘Reference’ Near Detector Design:

DUNE Collaboration goal: Replace the Muon Spectrometer with a more performant detector: ND-GAr

ND-GAr Detector:

Gas argon TPC:

1-ton argon in a ~6m diameter 10-bar pressure vessel

Calorimeter:

Based on CALICE design, located outside pressure vessel

Superconducting Magnet:

Exploring design options

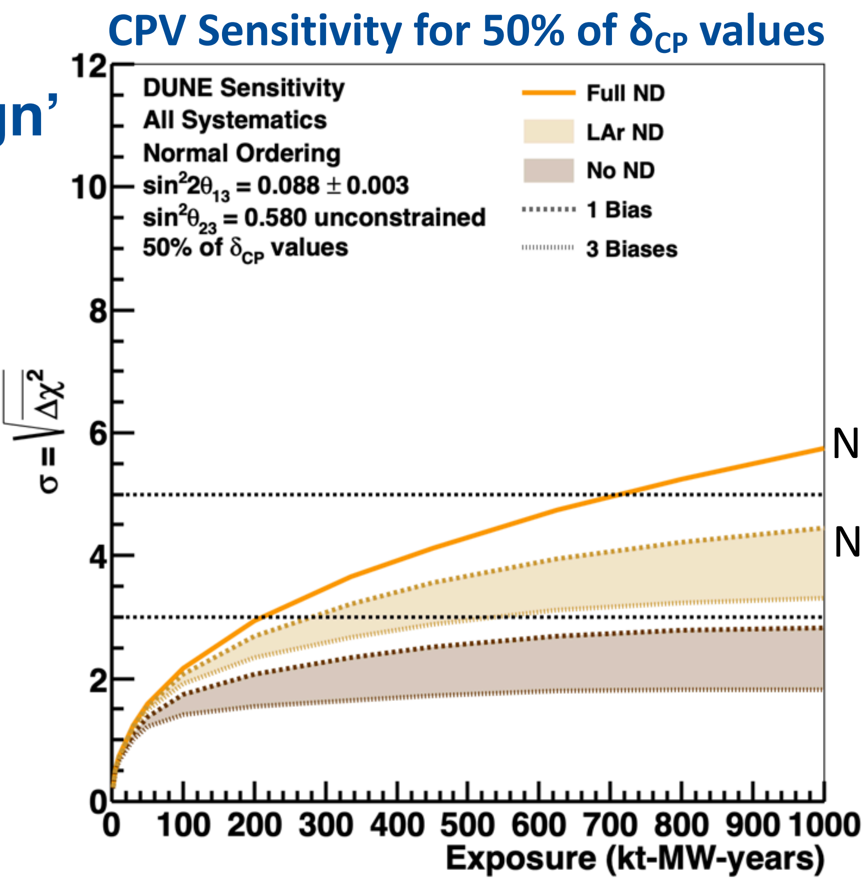
Physics Motivation:

Delivers more precise characterization of ν-Ar interactions, powerful constraint on neutrino interaction models.
Likely needed for ultimate DUNE sensitivity.

DUNE Strategy:

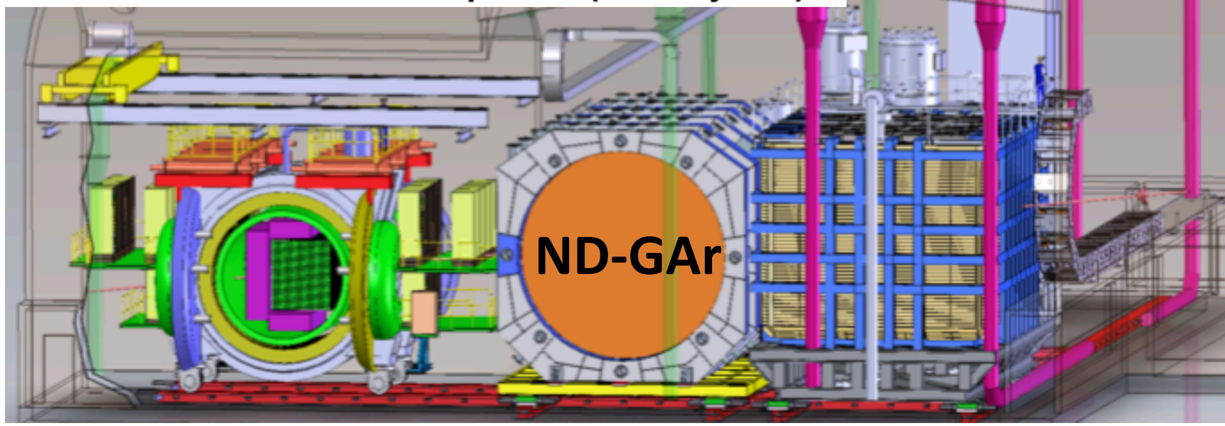
Collaboration will continue to develop ND-GAr design, replace Muon Spectrometer once resources & plan established.

CPV Sensitivity for 50% of δ_{CP} values



ND-LAr + ND-GAr

ND-LAr + μ-Spec.



Near Detector: Organization

Near Detector Consortia / Design Groups:

ND-LAr Consortium:

Consortium Lead: Michele Weber
Technical Lead: Dan Dwyer

ND-GAr/Muon Spectrometer Design Group:

Design Group Leads: Alfons Weber, Alan Bross
Technical Lead: Tom LeCompte

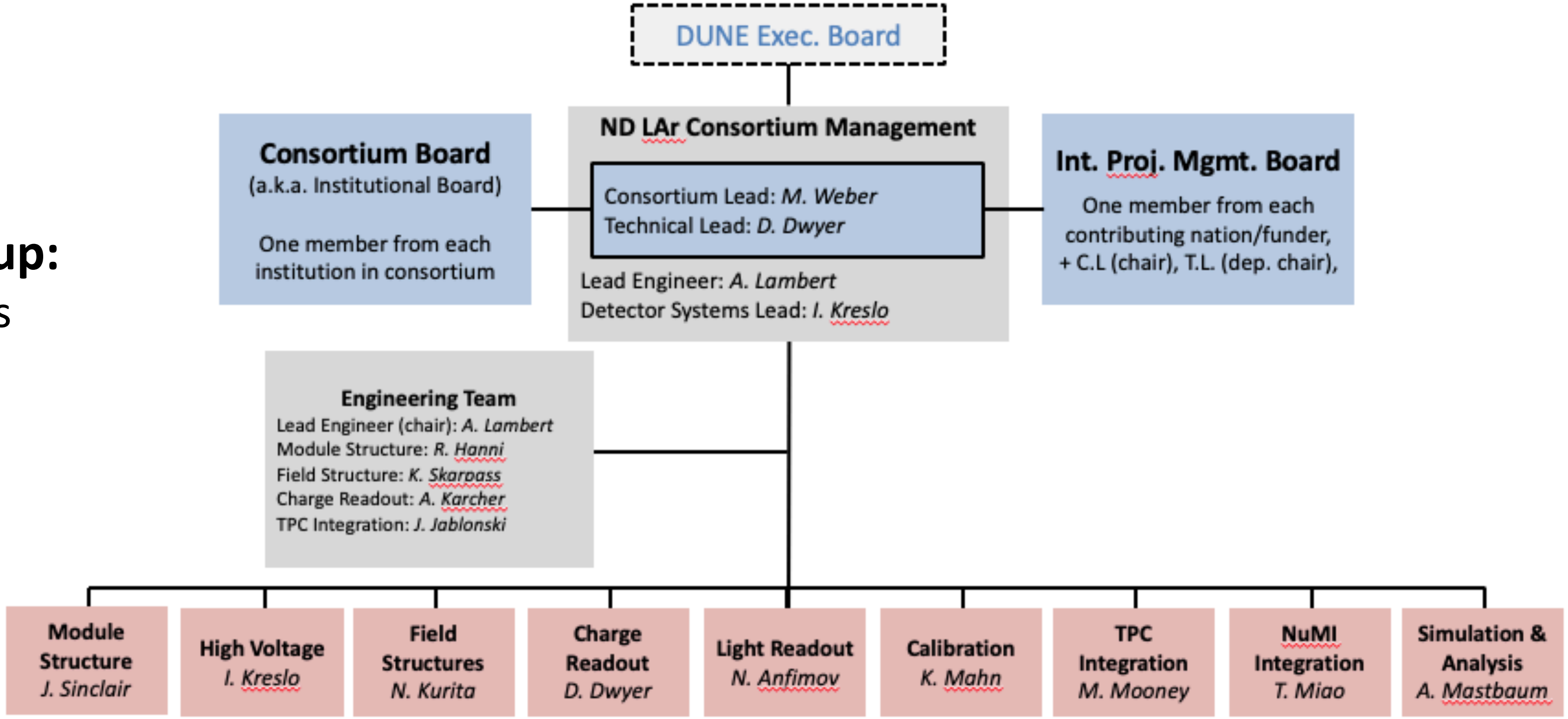
ND Beam Monitor - SAND Consortium:

Consortium Lead: Luca Stanco
Technical Lead: (tbd.)

ND DAQ Task Force:

Task Force Lead: Asher Kaboth

Example Consortium Structure



DUNE Exec. Board

Consortium Board
(a.k.a. Institutional Board)
One member from each institution in consortium

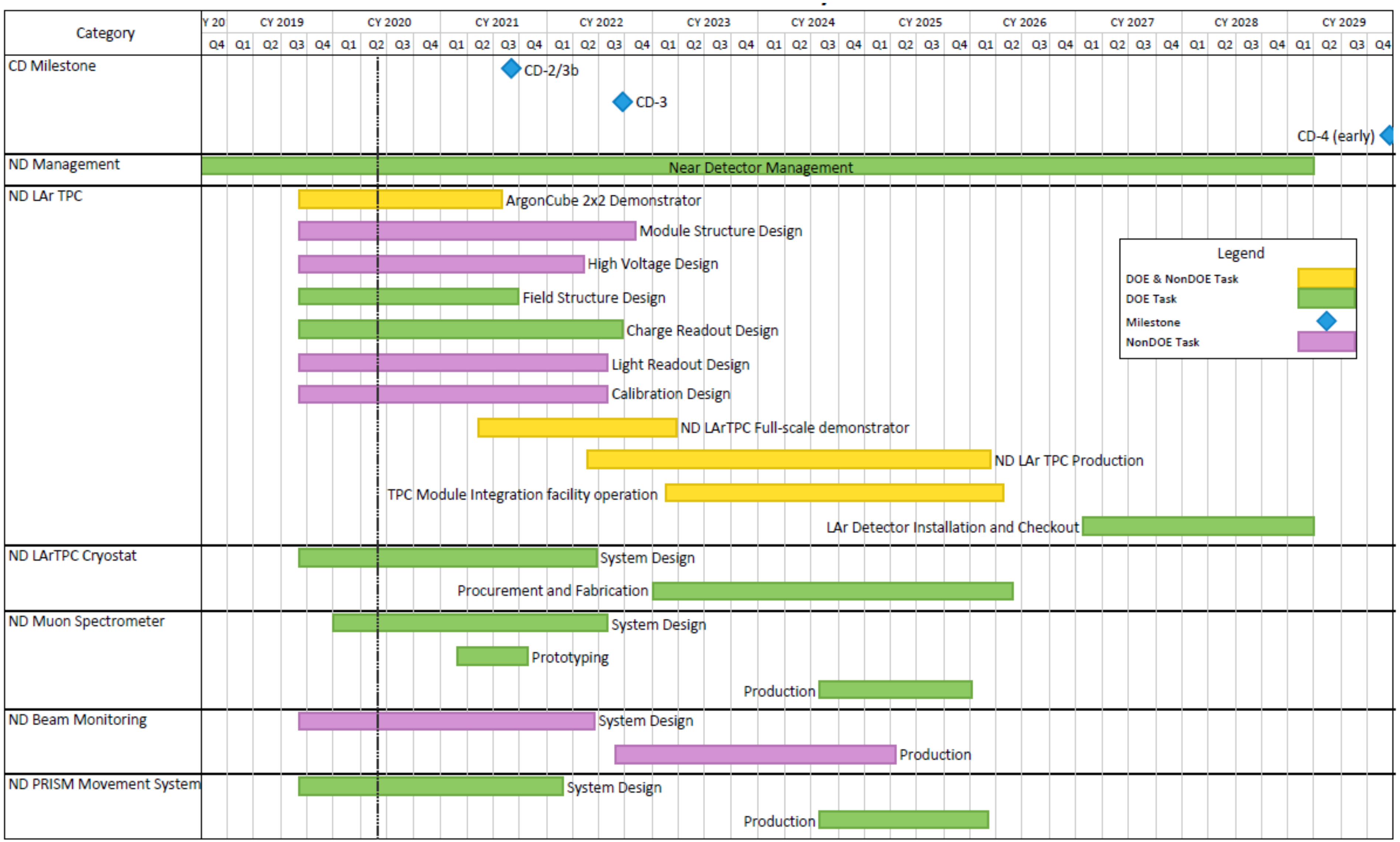
ND LAr Consortium Management
Consortium Lead: *M. Weber*
Technical Lead: *D. Dwyer*
Lead Engineer: *A. Lambert*
Detector Systems Lead: *I. Kreslo*

Int. Proj. Mgmt. Board
One member from each contributing nation/funder, + C.L (chair), T.L. (dep. chair),

Engineering Team
Lead Engineer (chair): *A. Lambert*
Module Structure: *R. Hanni*
Field Structure: *K. Skarpass*
Charge Readout: *A. Karcher*
TPC Integration: *J. Jablonski*

Module Structure *J. Sinclair*
High Voltage *I. Kreslo*
Field Structures *N. Kurita*
Charge Readout *D. Dwyer*
Light Readout *N. Anfimov*
Calibration *K. Mahn*
TPC Integration *M. Mooney*
NuMI Integration *T. Miao*
Simulation & Analysis *A. Mastbaum*

Near Detector: Schedule



Near Detector: Resources

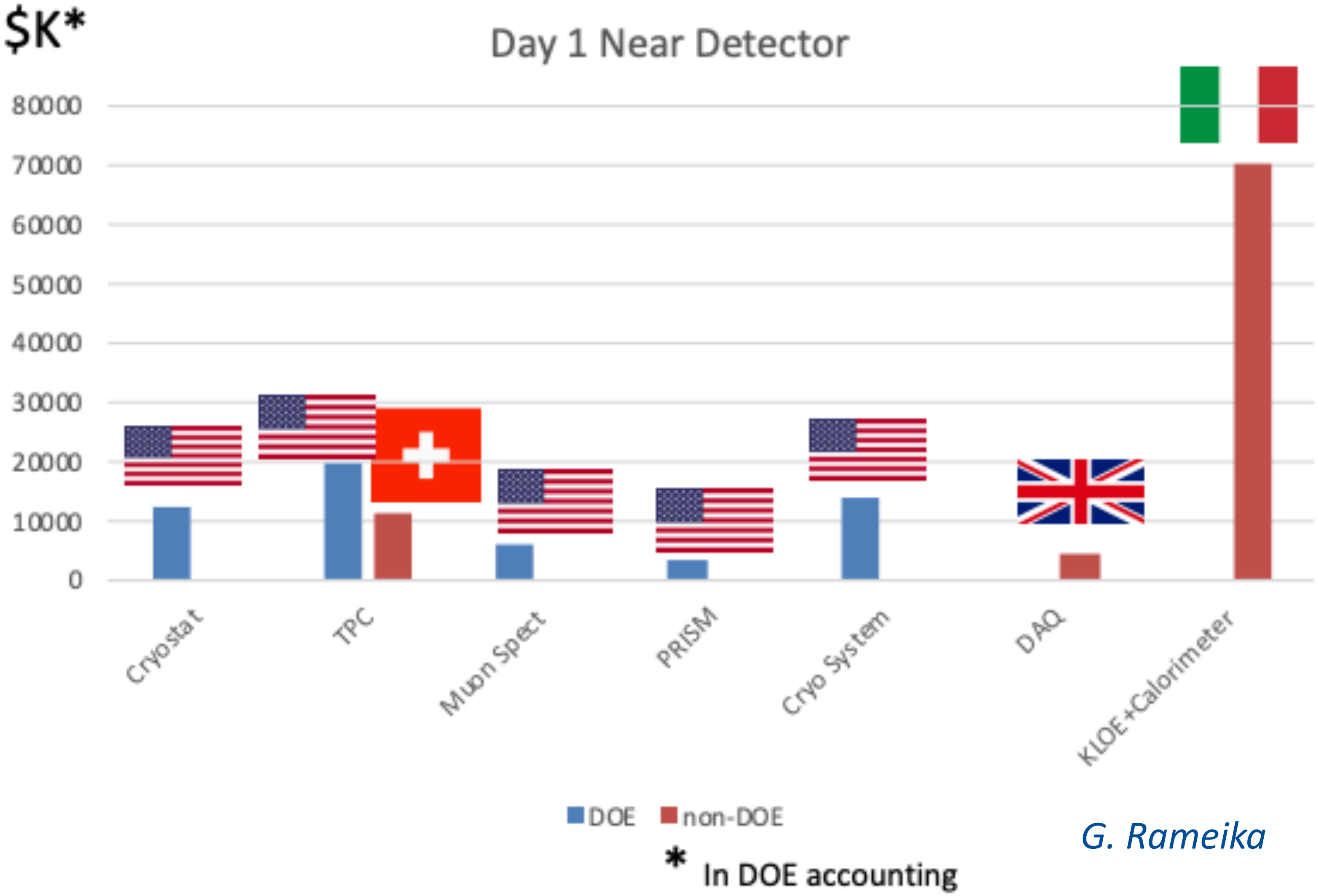
Near Detector Resources:

International resource plan developed.

Next steps: refine plan, initiate MOUs.

Open questions:

- Impact of US ’Value Engineering’ process
- Resource model for new tracking component for SAND.

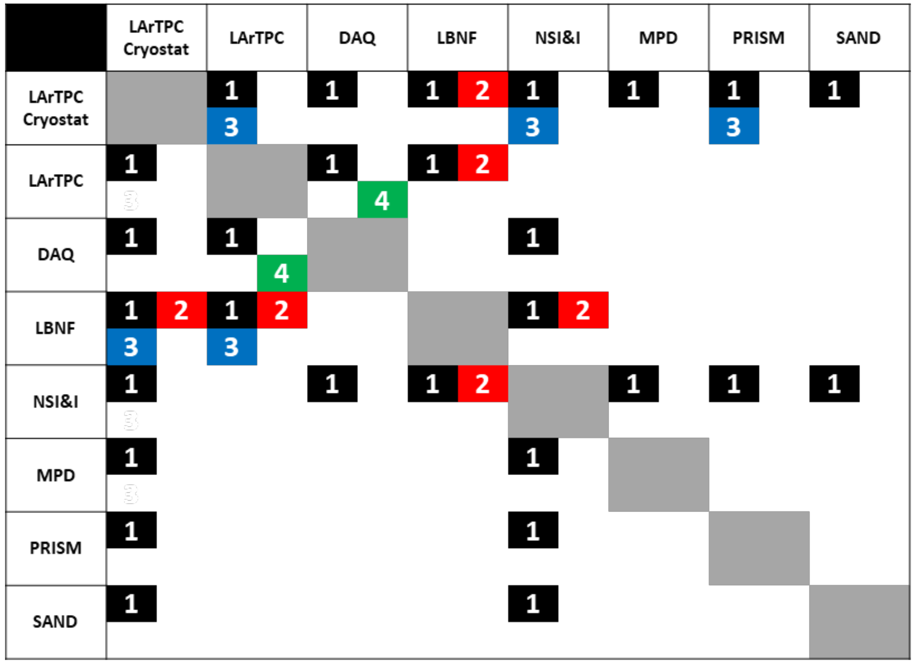


G. Rameika

Near Detector: Interfaces

- **Between Near Detector Subsystems**
  - Detailed interfaces under development
  - Key Items:
    - LArTPC & Muon Spectrometer: Intervening material, joint acceptance, coordinated PRISM
    - Magnetic interactions between systems
- **Near Site Integration (NSI)**
  - Manages interface between Near Detector and NSCF
  - Key Items:
    - Near Hall dimensions/details: Detector sizes, power, crane needs
    - PRISM: Movement technology, interferences, energy chain
    - Installation: NSI provides coordination (install. engineer, general techs), ND provides specialists
- **LBNF Cryogenics**
  - Provides LAr cryogenic system for ND LArTPC, LHe for SAND
  - Key Items:
    - Cryogenics and PRISM movement

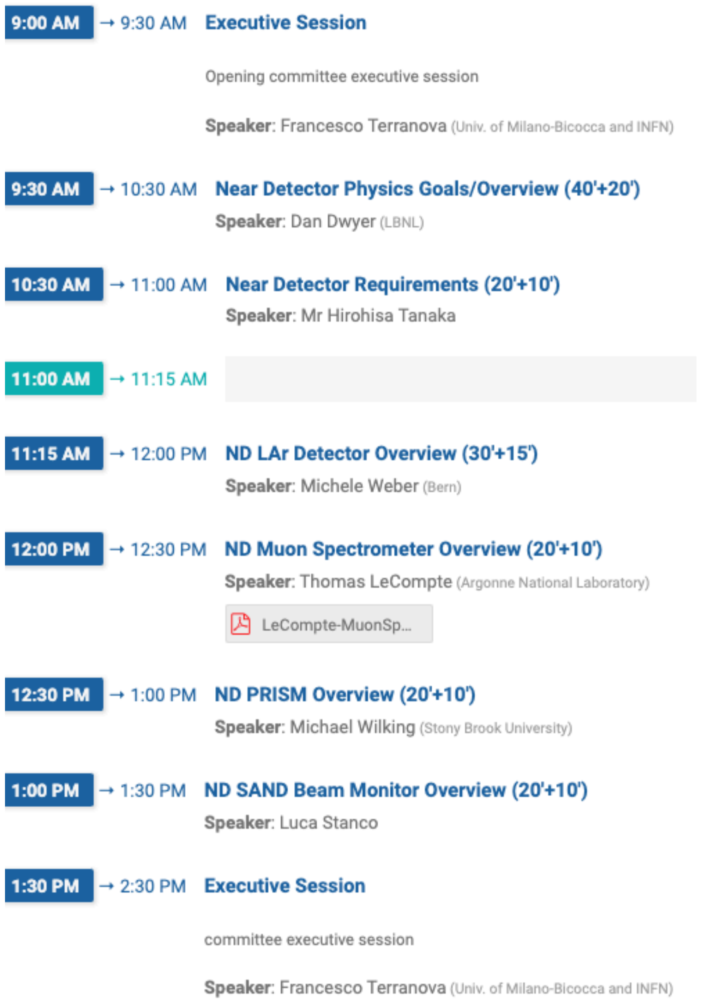
ND Interface Matrix *A. Lambert*



	LArTPC Cryostat	LArTPC	DAQ	LBNF	NSI&I	MPD	PRISM	SAND
LArTPC Cryostat		1 3	1	1 2	1 3	1	1 3	1
LArTPC	1 3		1 4	1 2				
DAQ	1	1 4			1			
LBNF	1 2 3	1 2 3			1 2			
NSI&I	1 3		1	1 2		1	1	1
MPD	1 3				1			
PRISM	1				1			
SAND	1				1			

Review Agenda

Today:
Introduction, Detector Descriptions



9:00 AM → 9:30 AM **Executive Session**

Opening committee executive session

Speaker: Francesco Terranova (Univ. of Milano-Bicocca and INFN)

9:30 AM → 10:30 AM **Near Detector Physics Goals/Overview (40'+20')**

Speaker: Dan Dwyer (LBNL)

10:30 AM → 11:00 AM **Near Detector Requirements (20'+10')**

Speaker: Mr Hirohisa Tanaka

11:00 AM → 11:15 AM

11:15 AM → 12:00 PM **ND LAr Detector Overview (30'+15')**

Speaker: Michele Weber (Bern)

12:00 PM → 12:30 PM **ND Muon Spectrometer Overview (20'+10')**

Speaker: Thomas LeCompte (Argonne National Laboratory)

LeCompte-MuonSp...

12:30 PM → 1:00 PM **ND PRISM Overview (20'+10')**

Speaker: Michael Wilking (Stony Brook University)

1:00 PM → 1:30 PM **ND SAND Beam Monitor Overview (20'+10')**

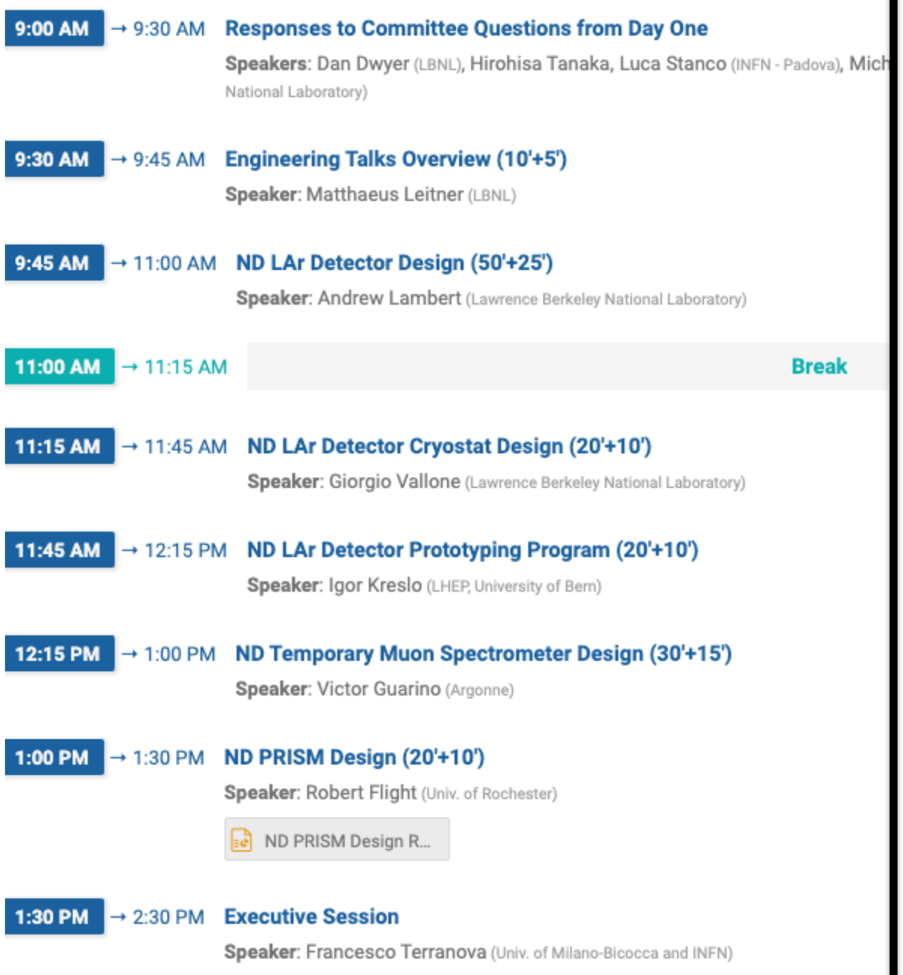
Speaker: Luca Stanco

1:30 PM → 2:30 PM **Executive Session**

committee executive session

Speaker: Francesco Terranova (Univ. of Milano-Bicocca and INFN)

Tomorrow:
System Design and Engineering



9:00 AM → 9:30 AM **Responses to Committee Questions from Day One**

Speakers: Dan Dwyer (LBNL), Hirohisa Tanaka, Luca Stanco (INFN - Padova), Mich
National Laboratory)

9:30 AM → 9:45 AM **Engineering Talks Overview (10'+5')**

Speaker: Matthaeus Leitner (LBNL)

9:45 AM → 11:00 AM **ND LAr Detector Design (50'+25')**

Speaker: Andrew Lambert (Lawrence Berkeley National Laboratory)

11:00 AM → 11:15 AM **Break**

11:15 AM → 11:45 AM **ND LAr Detector Cryostat Design (20'+10')**

Speaker: Giorgio Vallone (Lawrence Berkeley National Laboratory)

11:45 AM → 12:15 PM **ND LAr Detector Prototyping Program (20'+10')**

Speaker: Igor Kreslo (LHEP, University of Bern)

12:15 PM → 1:00 PM **ND Temporary Muon Spectrometer Design (30'+15')**

Speaker: Victor Guarino (Argonne)

1:00 PM → 1:30 PM **ND PRISM Design (20'+10')**

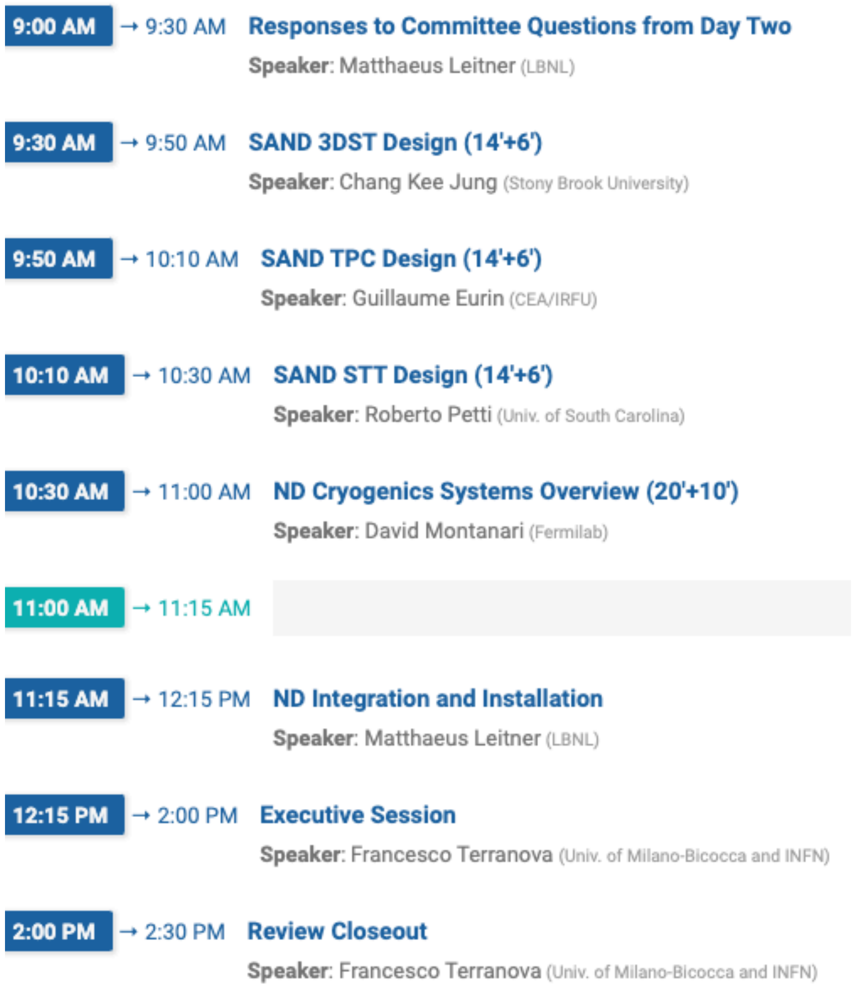
Speaker: Robert Flight (Univ. of Rochester)

ND PRISM Design R...

1:30 PM → 2:30 PM **Executive Session**

Speaker: Francesco Terranova (Univ. of Milano-Bicocca and INFN)

Thursday:
SD&E (cont) and Key Interfaces



9:00 AM → 9:30 AM **Responses to Committee Questions from Day Two**

Speaker: Matthaeus Leitner (LBNL)

9:30 AM → 9:50 AM **SAND 3DST Design (14'+6')**

Speaker: Chang Kee Jung (Stony Brook University)

9:50 AM → 10:10 AM **SAND TPC Design (14'+6')**

Speaker: Guillaume Eurin (CEA/IRFU)

10:10 AM → 10:30 AM **SAND STT Design (14'+6')**

Speaker: Roberto Petti (Univ. of South Carolina)

10:30 AM → 11:00 AM **ND Cryogenics Systems Overview (20'+10')**

Speaker: David Montanari (Fermilab)

11:00 AM → 11:15 AM

11:15 AM → 12:15 PM **ND Integration and Installation**

Speaker: Matthaeus Leitner (LBNL)

12:15 PM → 2:00 PM **Executive Session**

Speaker: Francesco Terranova (Univ. of Milano-Bicocca and INFN)

2:00 PM → 2:30 PM **Review Closeout**

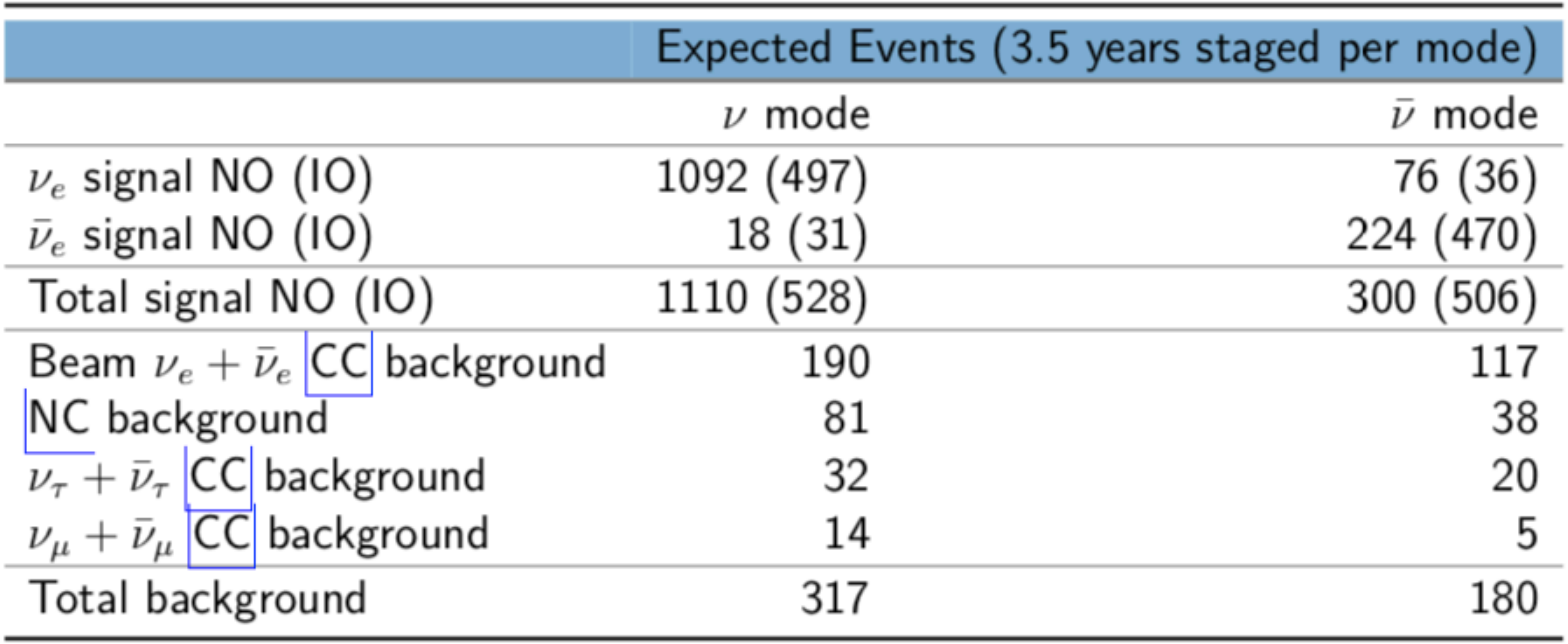
Speaker: Francesco Terranova (Univ. of Milano-Bicocca and INFN)

Summary

- **DUNE Near Detector Development:**
  - Formal DUNE ND design effort initiated just over 1 year ago (Apr. 2019)
  - Focus: delivering ND system essential for physics on ‘Day-1’
  - First two DUNE ND Consortia (ND-LAr, SAND) formally initiated May 2020
- **Design Maturity:**
  - ND design advancing rapidly
  - Day-1 design well-motivated by DUNE physics requirements
  - Scope and Key Design Aspects are well-understood
  - Schedule and costs developed commensurate with conceptual design
  - Institutional partners working together coherently
  - General interfaces established, to be formalized during next phase.
- **Next:**
  - Complete transition to ND Consortia, initiate Preliminary Design efforts

Backup

Electron Neutrino Appearance Rates



	Expected Events (3.5 years staged per mode)	
	ν mode	$\bar{\nu}$ mode
ν_e signal NO (IO)	1092 (497)	76 (36)
$\bar{\nu}_e$ signal NO (IO)	18 (31)	224 (470)
Total signal NO (IO)	1110 (528)	300 (506)
Beam $\nu_e + \bar{\nu}_e$ CC background	190	117
NC background	81	38
$\nu_\tau + \bar{\nu}_\tau$ CC background	32	20
$\nu_\mu + \bar{\nu}_\mu$ CC background	14	5
Total background	317	180