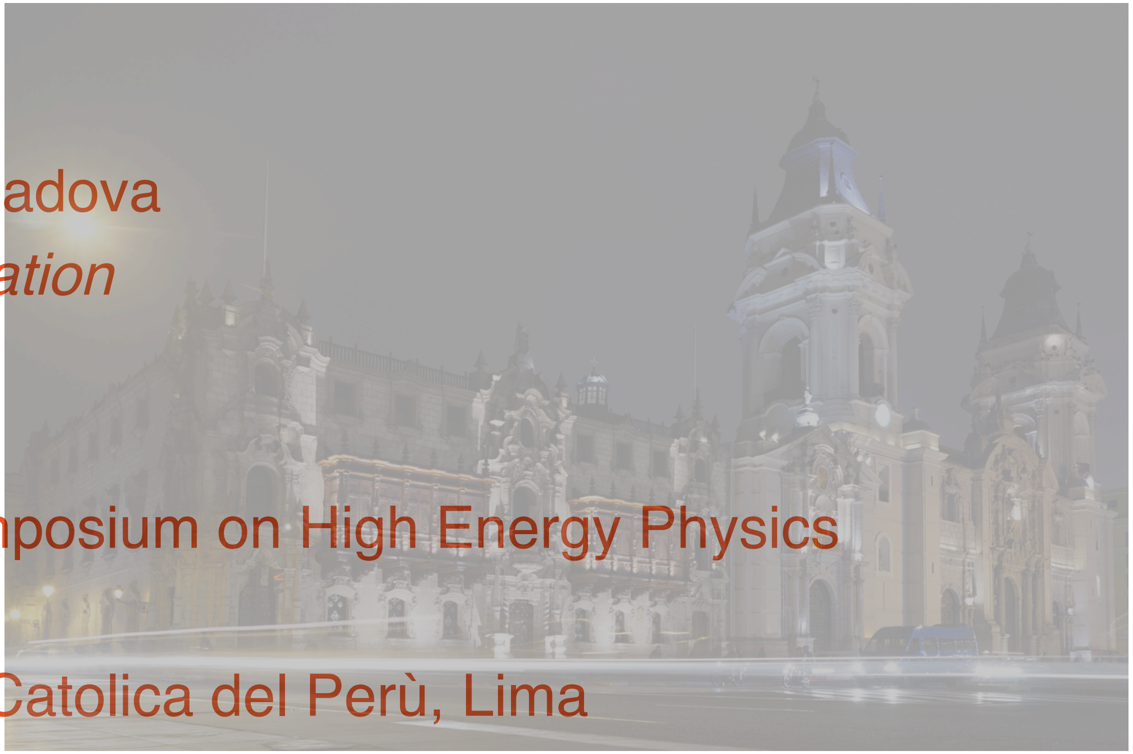
DUNE: Science, Status and perspectives



Luca Stanco, INFN – Padova
for the DUNE Collaboration

XII Latin American Symposium on High Energy Physics
November 27th, 2017
Pontificia Universidad Catolica del Perù, Lima

Content

- Standard Neutrino Oscillation ①
- LBNF project
- The DUNE experiment - status of the project ②
- Near Detector
- On-going R&D studies
- Perspectives for
    - MH and δ_{CP} determinations ③
    - astronomical neutrinos (SuperNovae)
    - solar neutrinos
    - …

①

Neutrino Physics

Standard Neutrino Oscillations

The recent Neutrino History

1998

1rst Annus Mirabilis

Oscillations :
- Observation by *SuperK*
- Reactor exclusion by *Chooz*

2002

2nd A. M.

3 x 3 matrix :
- Solar by *SNO*
- Reactor by *KAMLAND*

2012

3rd A. M.

θ_{13}:
- Reactor by *Daya Bay*, *RENO, Double Chooz, T2K*…

2019-20 ?

4th A. M. ?

- Hints for Mass Hierachy by *NOvA/T2K*
- CPV by *T2K*

≥ 2020 ? ——— δ_{CP} ?

L. S., Rev. in Phys. 1 (2016) 90

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The present scenario

From masses to flavours:

$$\left|\nu_e\right\rangle = U_{e1}\left|\nu_1\right\rangle + U_{e2}\left|\nu_2\right\rangle + U_{e3}\left|\nu_3\right\rangle$$

$$\left|\nu_\mu\right\rangle = U_{\mu 1}\left|\nu_1\right\rangle + U_{\mu 2}\left|\nu_2\right\rangle + U_{e\mu 3}\left|\nu_3\right\rangle$$

$$\left|\nu_\tau\right\rangle = U_{\tau 1}\left|\nu_1\right\rangle + U_{\tau 2}\left|\nu_2\right\rangle + U_{\tau 3}\left|\nu_3\right\rangle$$

U is the 3 × 3 Neutrino Mixing Matrix, mixing given by 3 angles, θ_{23}, θ_{12}, θ_{13} and one phase δ (CPV for $\delta \neq 0, \pi$).

Oscillations have amplitudes driven by the mixing angles and frequencies by $\delta m^2_{solar} = \Delta m^2_{21}$

$\Delta m^2_{atm} = |\Delta m^2_{31}| \approx |\Delta m^2_{32}|$

(and L, E experimental parameters)

E.g. if only two flavours are taken, at leading order, neglecting interference terms, and taking some approximations:

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

APPEARANCE

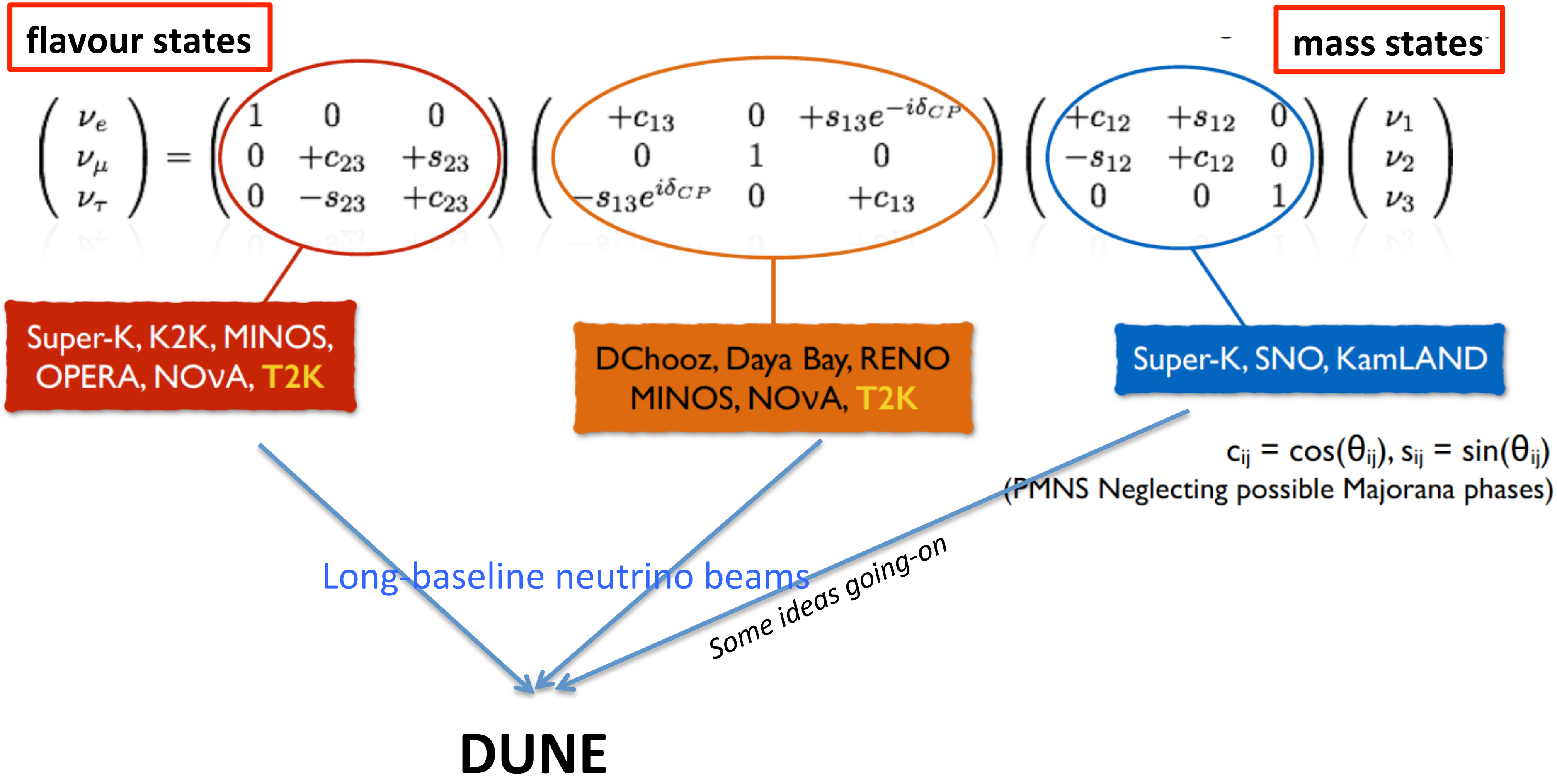
$$P\left(\nu_\alpha \to \nu_\alpha\right) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

DISAPPEARANCE

↑ amplitude

↖ frequency

up till now…



flavour states

mass states

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1&0&0\\0&+c_{23}&+s_{23}\\0&-s_{23}&+c_{23}\end{pmatrix}\begin{pmatrix}+c_{13}&0&+s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{i\delta_{CP}}&0&+c_{13}\end{pmatrix}\begin{pmatrix}+c_{12}&+s_{12}&0\\-s_{12}&+c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Super-K, K2K, MINOS, OPERA, NOvA, T2K

DChooz, Daya Bay, RENO MINOS, NOvA, T2K

Super-K, SNO, KamLAND

$c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

(PMNS Neglecting possible Majorana phases)

Long-baseline neutrino beams

Some ideas going-on

DUNE

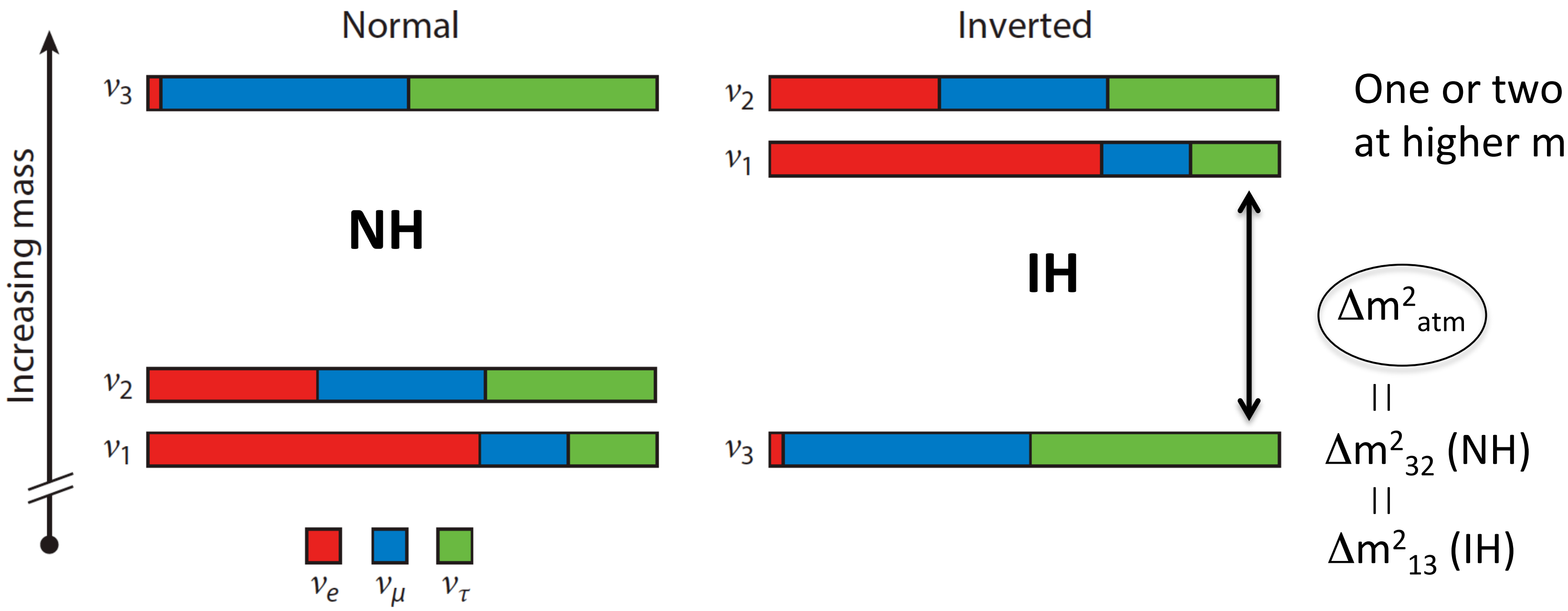
The wonderful frame pinpointed for the 3 standard neutrinos, beautifully adjusted by the θ_{13} measurement, left out some relevant questions:

- Mass ordering: **MH**
- Leptonic CP violation: δ_{CP}
- Anomalies and discrepancies in some measurements,
- Mass values
- **…**
- Dark Matter
- …

The present scenario (cnt.)

We are entering in the precision era, but there are still 4 results to be obtained, at least at first order :

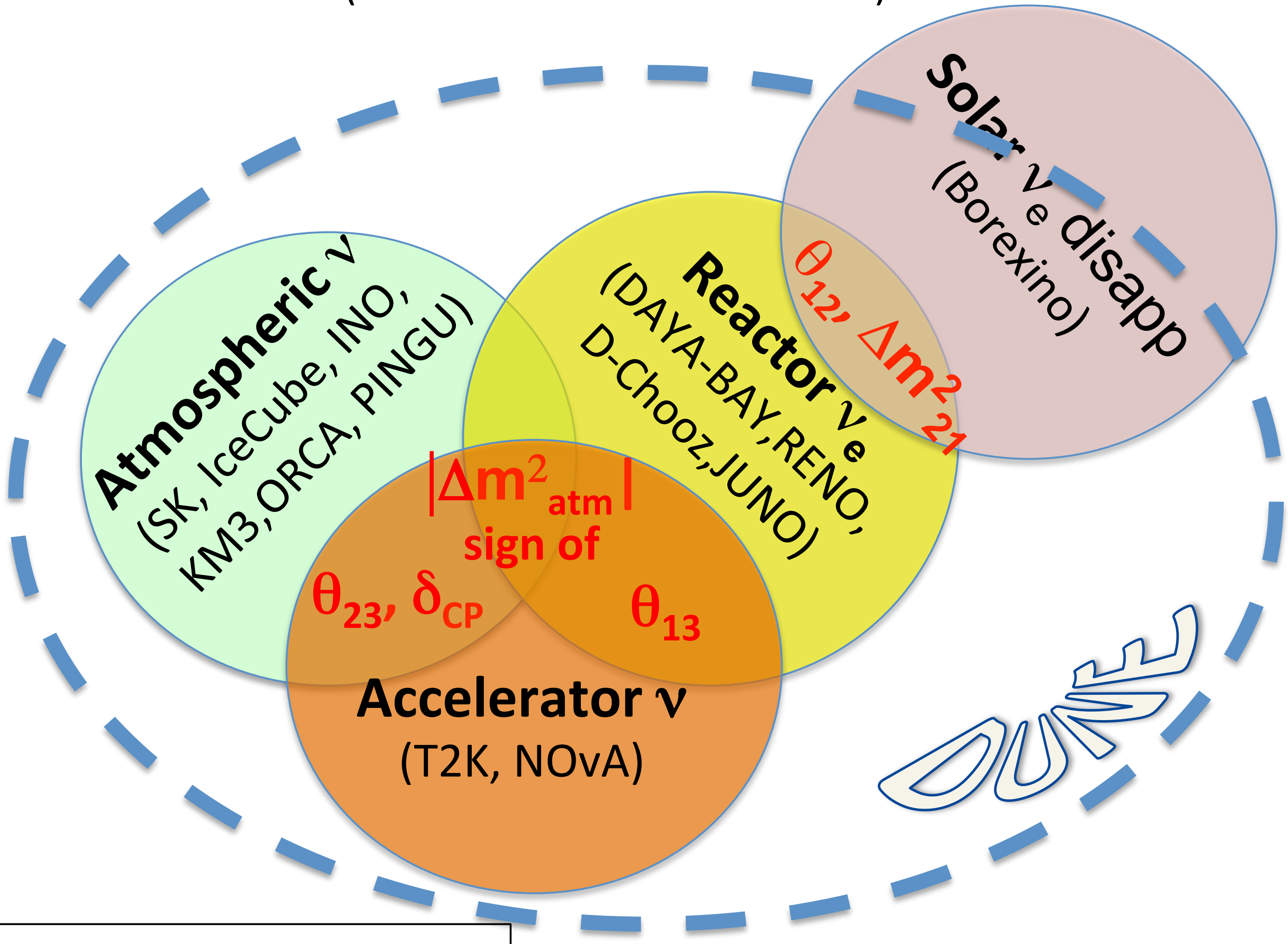
1) Leptonic CP violation (phase δ_{CP})
2) Mass ordering (MO)
3) (θ_{23} octant)
4) Presence or not of more (sterile ?) neutrinos states



One or two states at higher mass ?

Neutrino Oscillation industry

(in the 3 neutrino framework)



Atmospheric ν
(SK, IceCube, INO, KM3,ORCA, PINGU)

Reactor ν_e
(DAYA-BAY,RENO, D-Chooz,JUNO)

Solar ν_e disapp
(Borexino)

Accelerator ν
(T2K, NOvA)

$\theta_{12}, \Delta m^2_{21}$

$|\Delta m^2_{atm}|$
sign of

θ_{23}, δ_{CP}

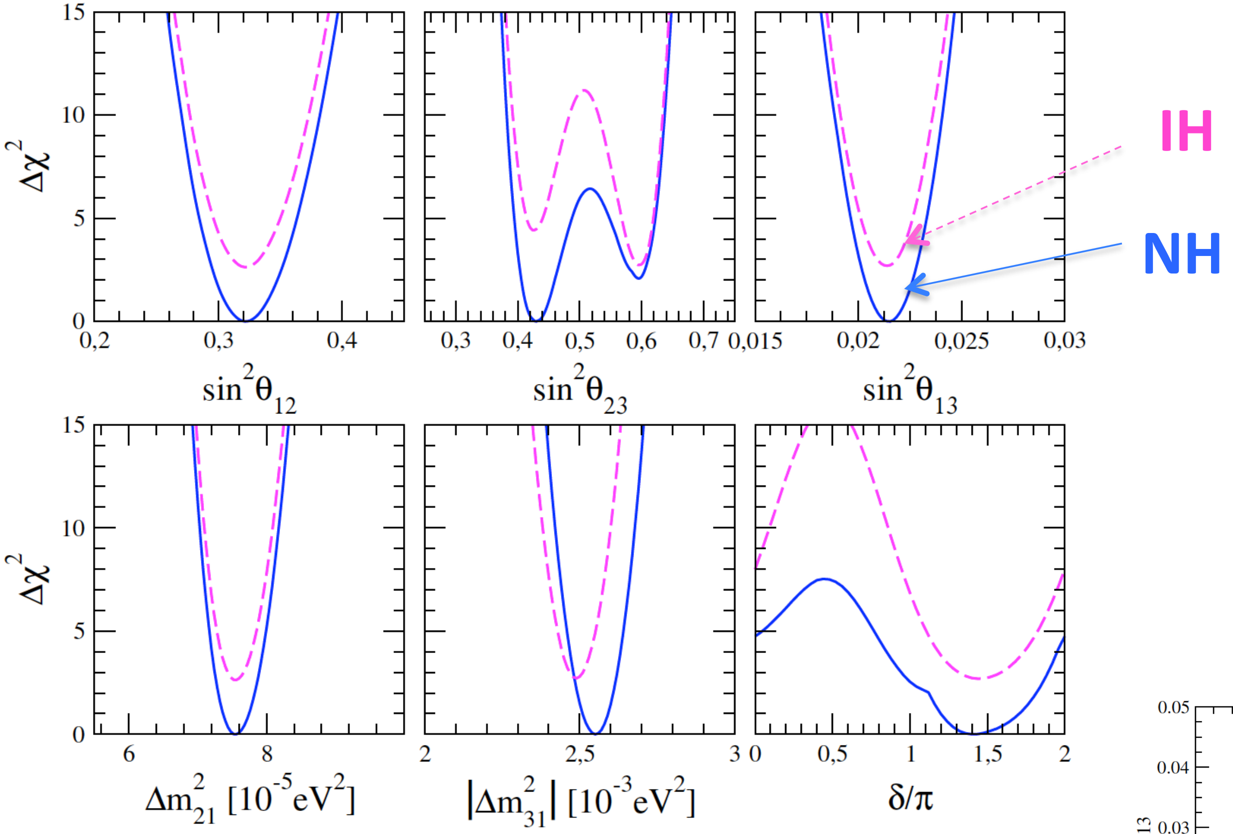
θ_{13}

From a Maxim Gonchar (DLNP) picture

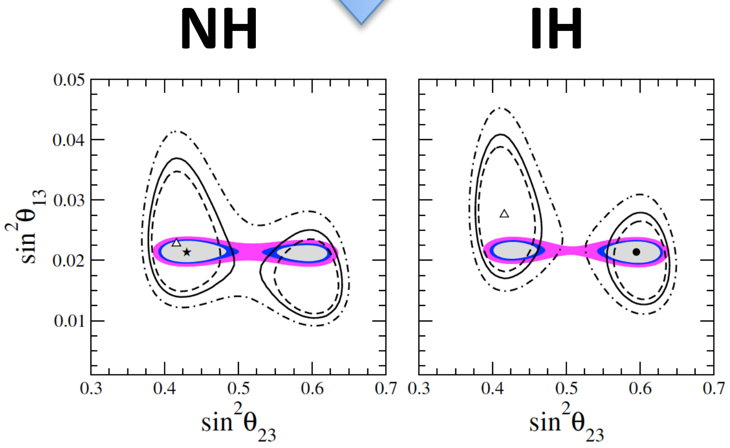
disclaimer: major actors only, not a full list…

Global fits of neutrino data

(de Salas+ 1708.01186)



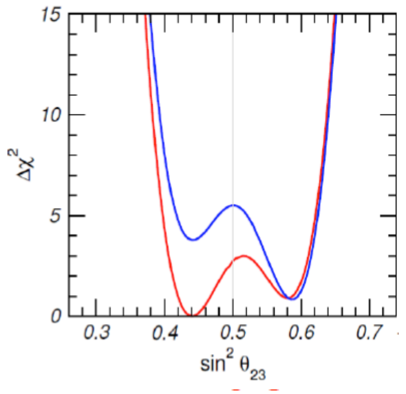
Tension with θ_{23} octant

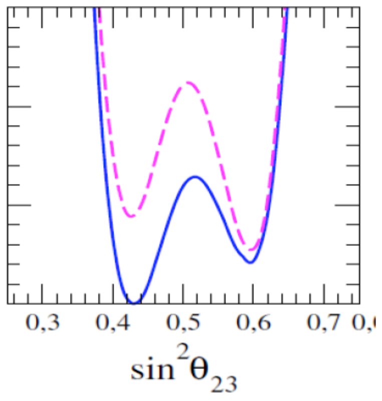


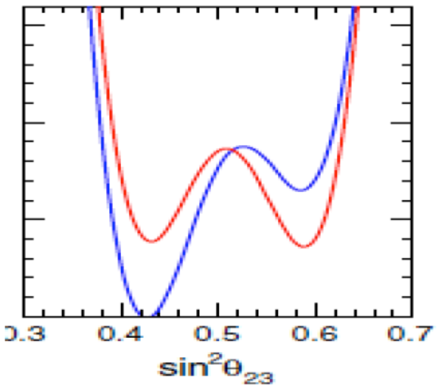
$\Delta\chi^2$(IO-NO)=2.7

Overall, the three GF groups find similar results:

Nu-fit	**Valencia**	**Bari**
Esteban+, 1611.01514		Capozzi+, 1703.04471



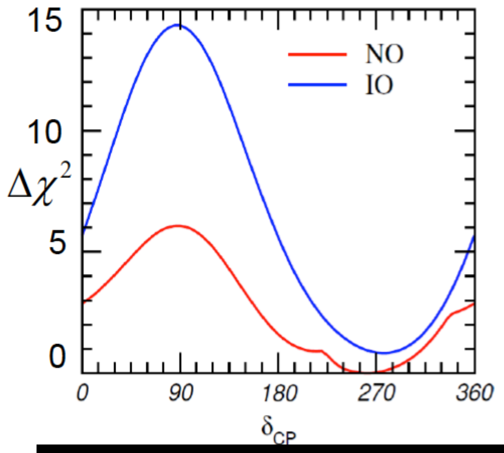


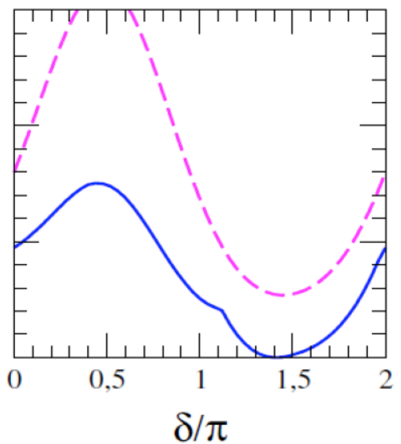


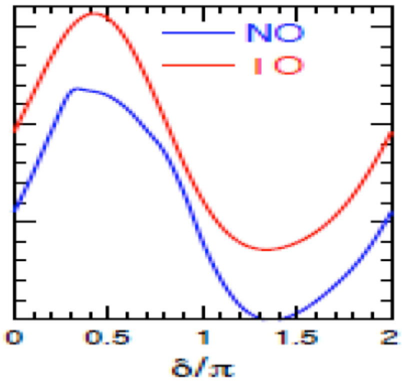
➔maximal θ_{23} disfavored

$\Delta\chi^2$=0.8 **2.7** **3.6**

➔preference for NH







➔$\sin\delta_{CP} \geq 0$ disfavored

Although, … "we are still quite far from a robust measurement"

The importance of measuring δ_{CP}

- *Matter/antimatter asymmetry in the Universe requires CP violation*

- CP violation in the quark sector has been measured the first time 54 years ago, but this violation does not help very much in understanding what happened soon after the Big Bang ($J_{CKM} \approx 3 \times 10^{-5}$)

- *Through leptogenesis, theory links the* ν *−mass generation to the generation of baryon asymmetry of the Universe (Fukugita and Yanagida, 1986).*

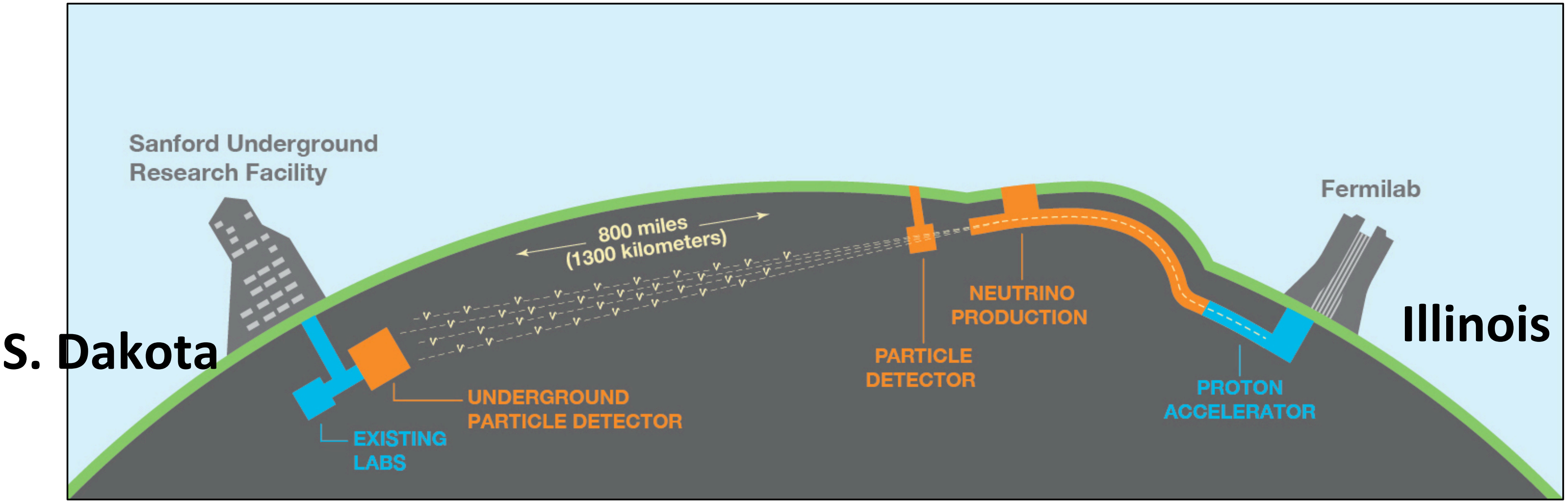
- *The Dirac phase* δ_{CP} *can be one of the ingredients of these mechanisms (and* $J_{PMNS} \approx 0.033 \sin\delta_{CP}$*)*

- It is mandatory to measure its value… also because it is one of the few unknowns of the Standard Model (together with neutrino masses)

②

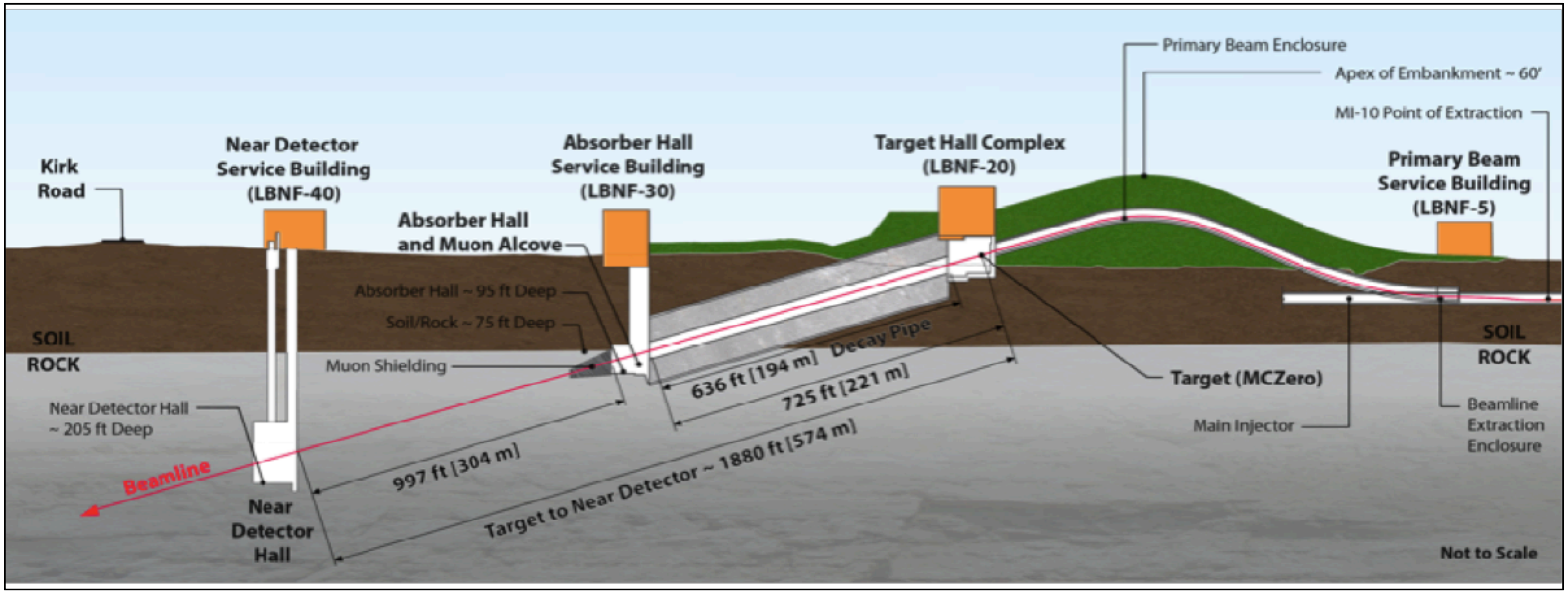
The LBNF/DUNE project

Long Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE)



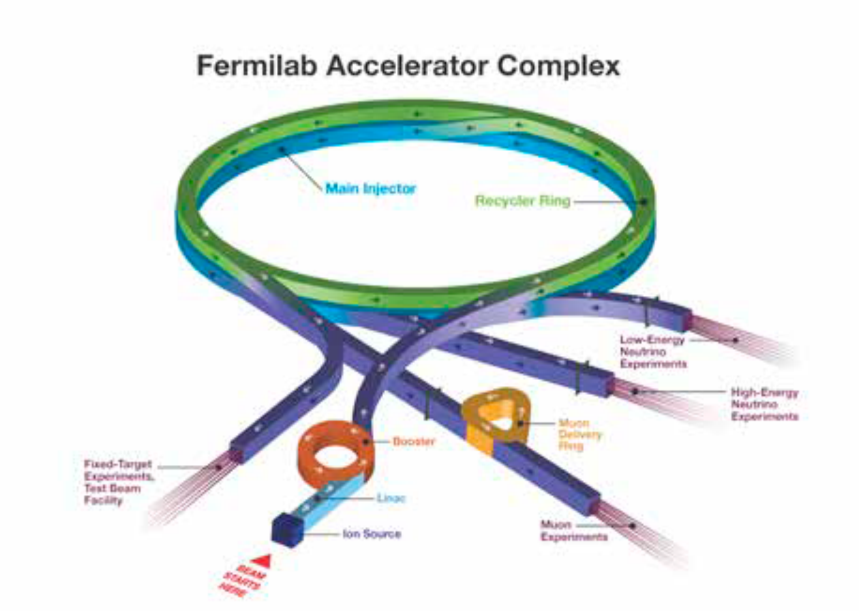
- ✓ Will measure ν_e appearance and ν_μ disappearance in a wideband neutrino beam at 1300 km
- ✓ Access to CP violation, mass hierarchy, and multiple neutrino mixing parameters in a single experiment
- ✓ Large, underground detector will provide sensitivity to nucleon decay, supernova burst, atmospheric neutrinos…

Long Baseline Neutrino Facility (LBNF) Neutrino Beam

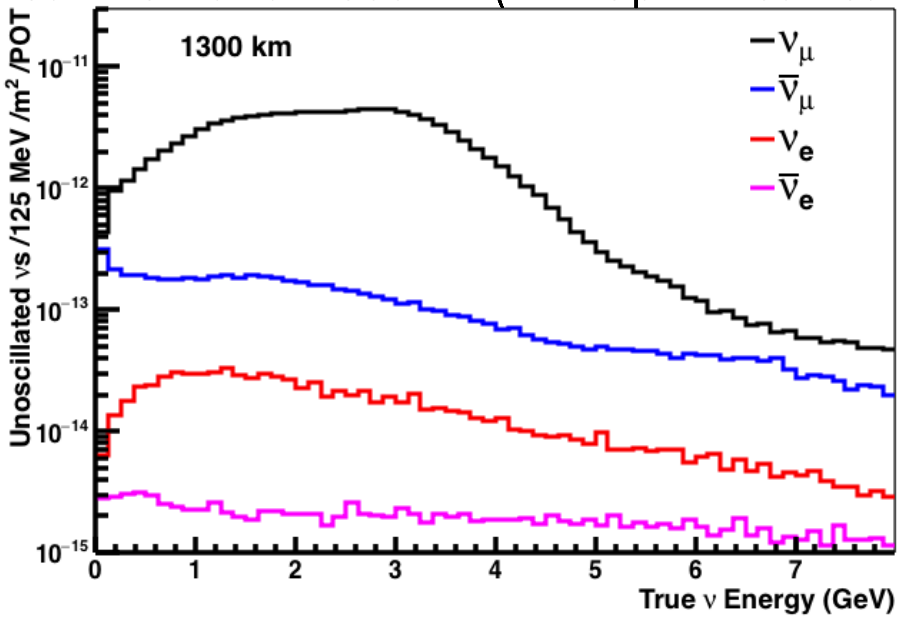


- ✓ LBNF will house and deliver beam to detectors built by DUNE Collaboration
- ✓ 60-120 GeV protons from Fermilab's Main Injector
- ✓ Initial power: 1.2 MW (@120 GeV); plan to upgrade to 2.4 MW
- ✓ 200 m decay pipe, angled at South Dakota (Sanford Underground Research Facility- SURF)
- ✓ Separate ν and ν-bar and running modes

LBNF beam

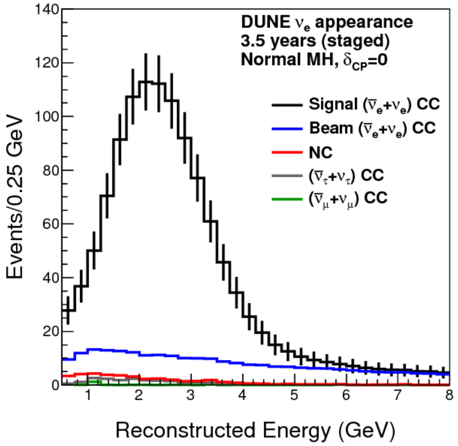


Neutrino Flux at 1300 km (CDR Optimized Beam)

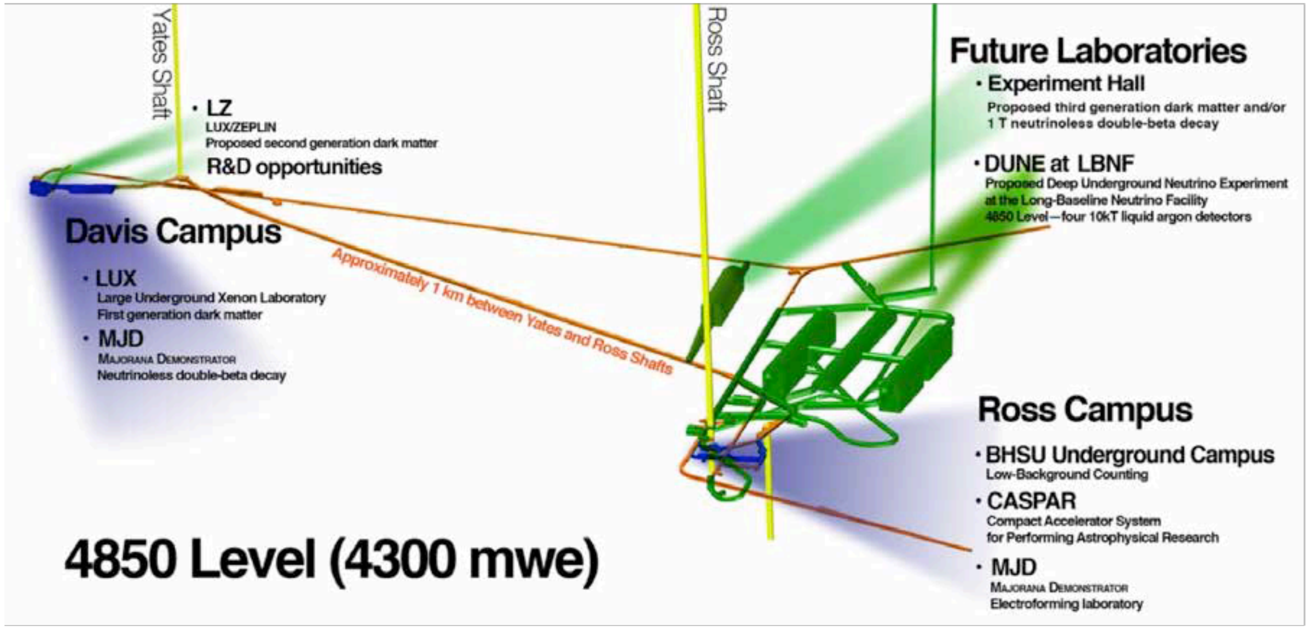


- Horn-focused neutrino beam line optimized for CP violation sensitivity using genetic algorithm
- Engineering design of 3-horn focusing system based on optimized parameters in progress

(DUNE CDR)

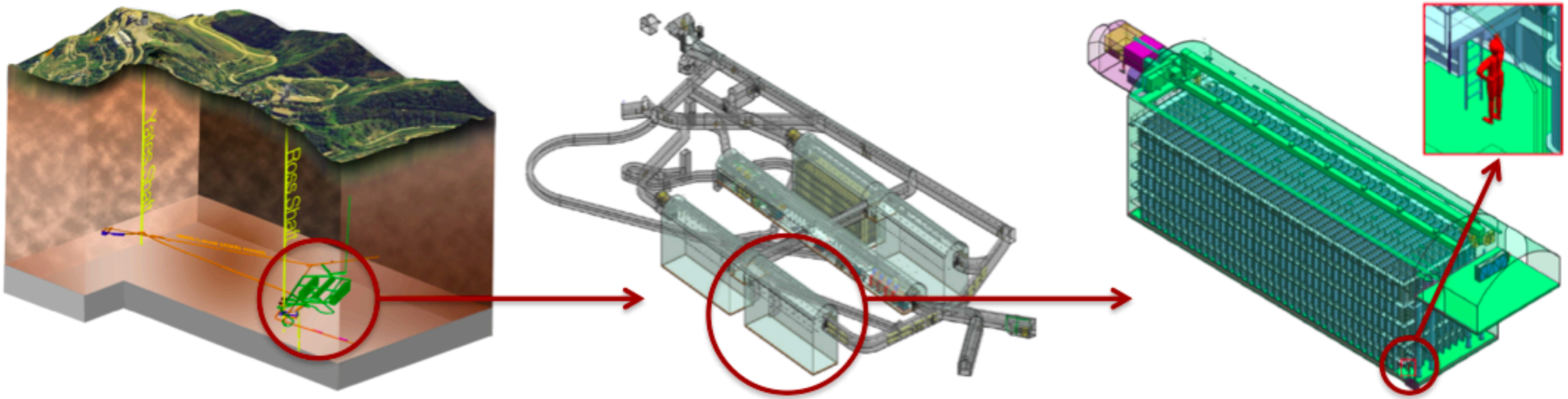


SURF



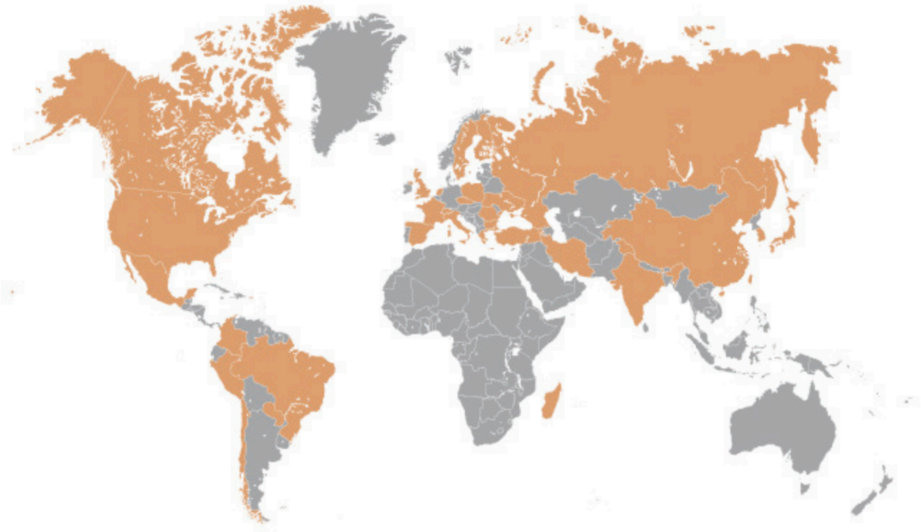
Previously known as Homestake (gold) Mine close to Lead,
in the Black Hills (South Dakota),
50 miles from Mount Rushmore and Crazy Horse statues

Sanford Underground Research Facility (SURF)



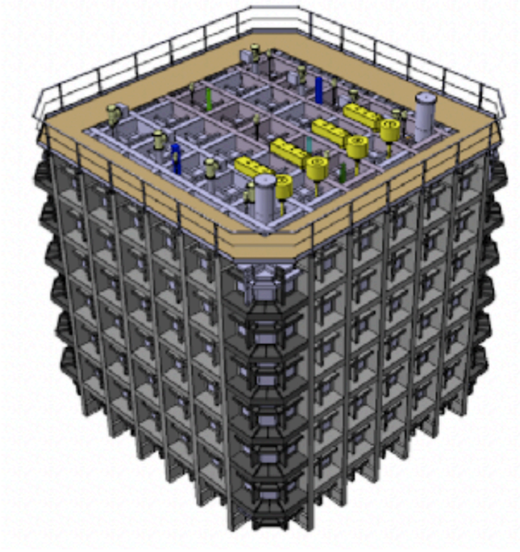
875,000 tons of rock to be excavated

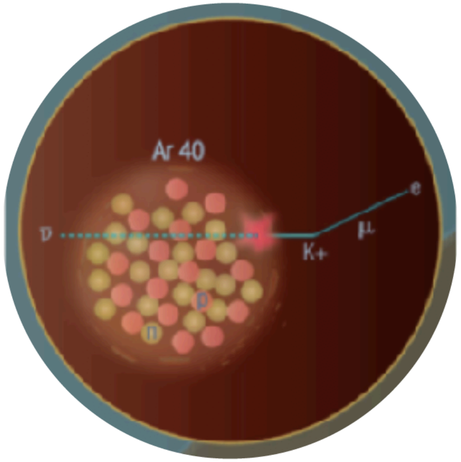
DUNE collaboration



Over 1,200 scientists from 32 nations!

Project timeline





July 2017

Groundbreaking for LBNF/DUNE

Autumn 2018

ProtoDUNE detectors online at CERN

2019

Begin main cavern excavation in South Dakota

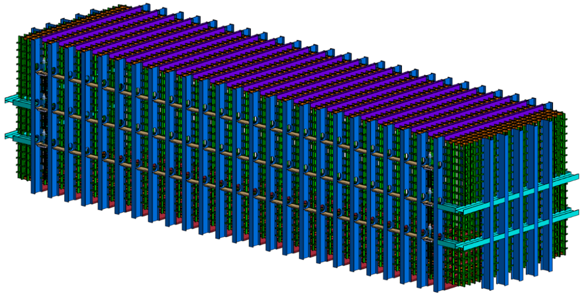
2022

Begin installing the first DUNE detector

2026

Fermilab's high-energy neutrino beam to South Dakota operational with two DUNE detectors online

DUNE status



Scale of a single cryostat housing 17.5 kton LAr TPC

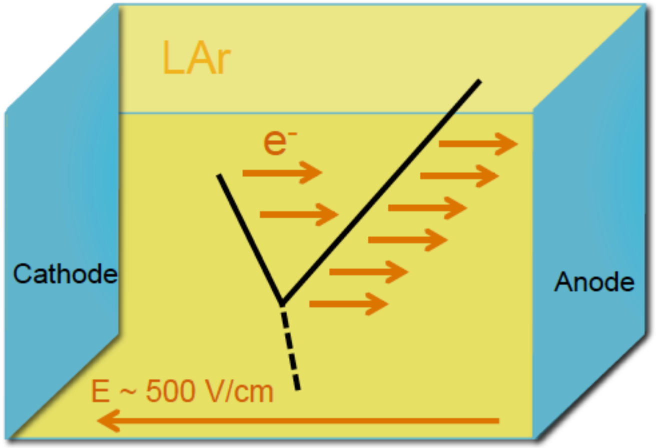
7 story
building 156 at CERN

DUNE Far Detector (FD)

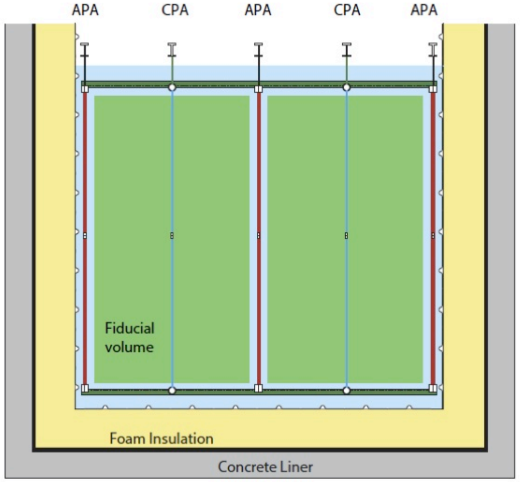
DUNE Far Detector Interim Design Reports are available (arXiv:1807.10334, 1807.10327,1807.10340)

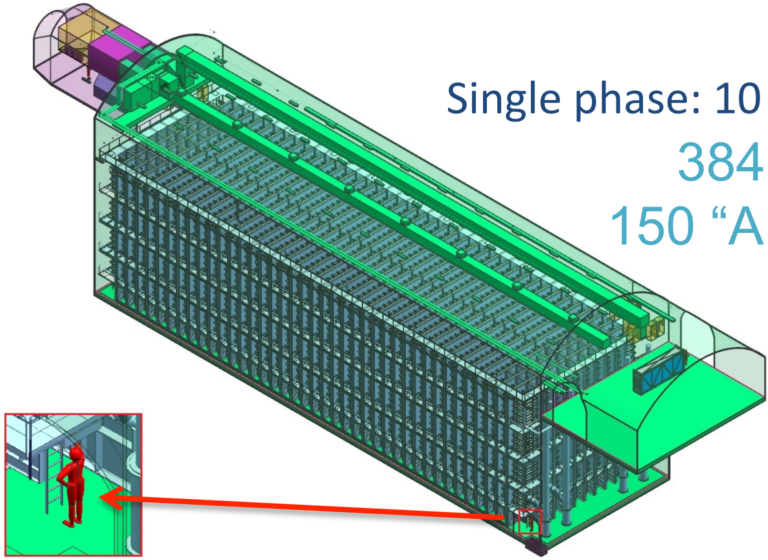
Four 10-kt (fiducial) liquid argon TPC modules
- **Single**- and **dual**-phase detector designs (1st module will be single phase)
- Integrated photon detection
- Modules will not be identical

TPC Critical features:
- LAr ultra-high purity
- E Field: *uniformity* and *stability*



Single phase: modular wire-plane readout



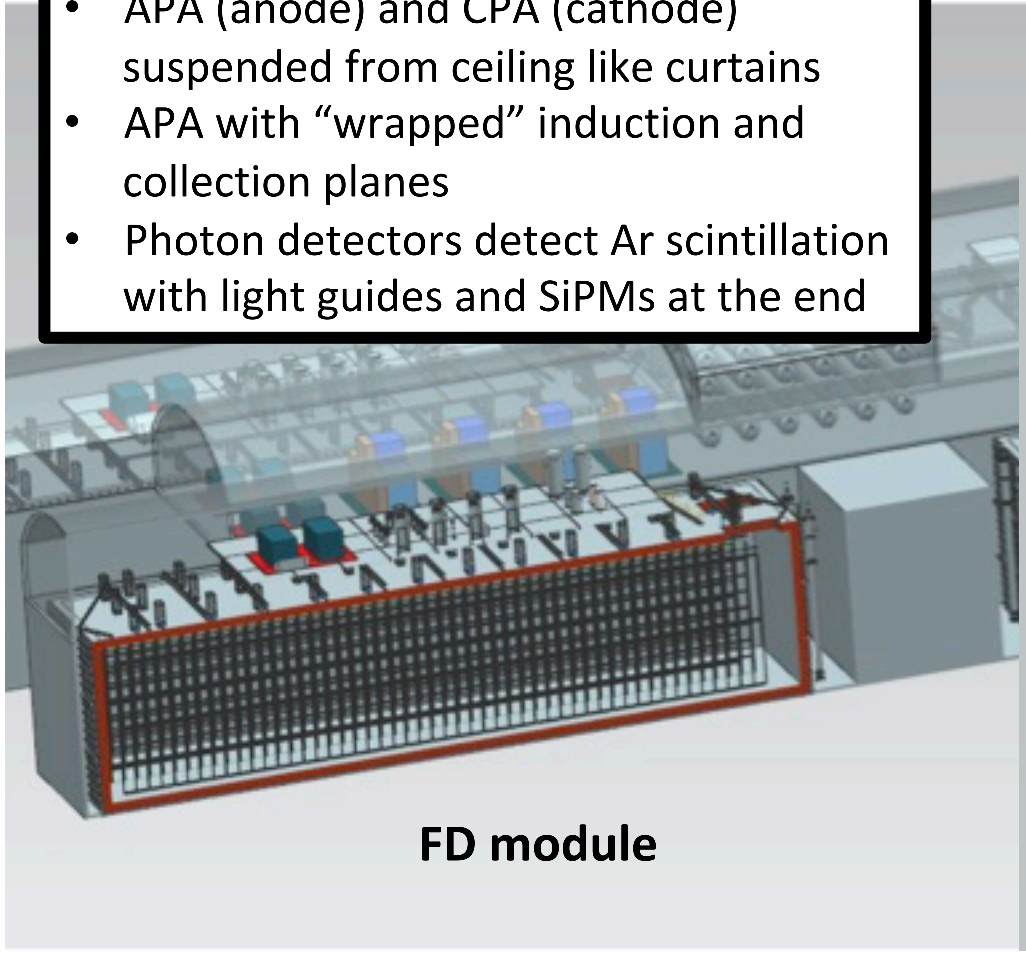


Single phase: 10 kt module

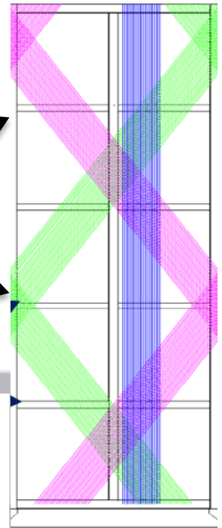
384,000 readout wires
150 “APAs” (2.3 m x 6 m)
12 m high
15.5 m wide
58 m long

FD design: Single Phase LAr TPC

- Design *fixed* for the first 17 kton total (10 kton fiducial) module ➔ based on LBNE modular drift cell design
- APA (anode) and CPA (cathode) suspended from ceiling like curtains
- APA with “wrapped” induction and collection planes
- Photon detectors detect Ar scintillation with light guides and SiPMs at the end



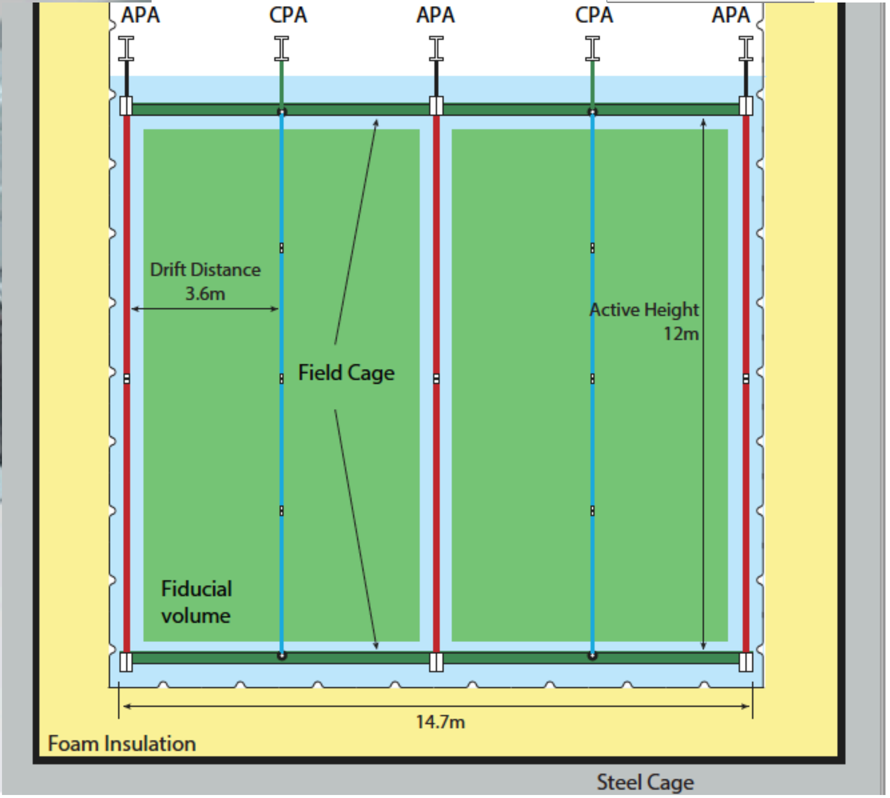
FD module



APA “wrapped”

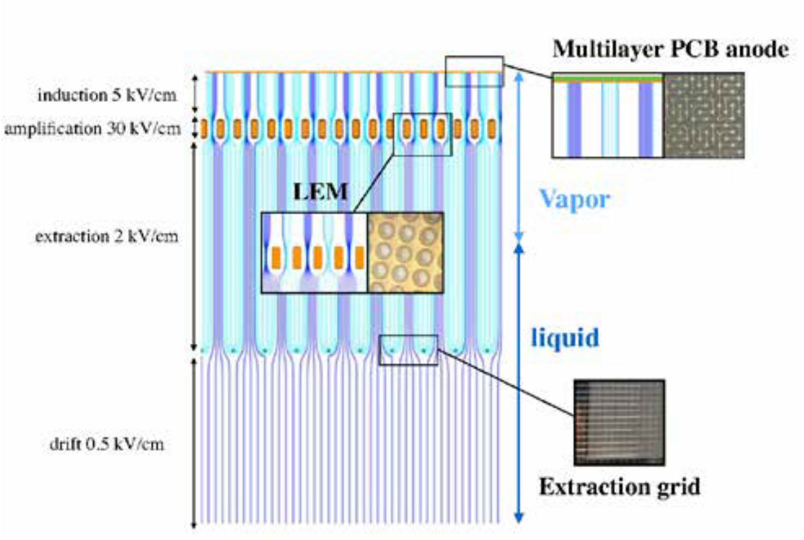
Photon detectors APA planes

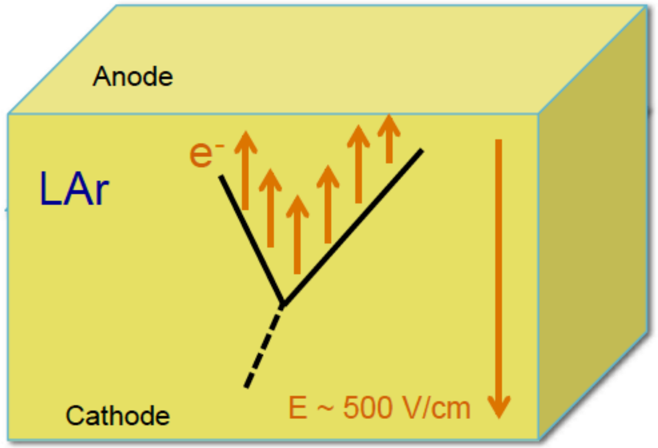
APA: 2 x 6 x 2.3 m
Paired top to bottom



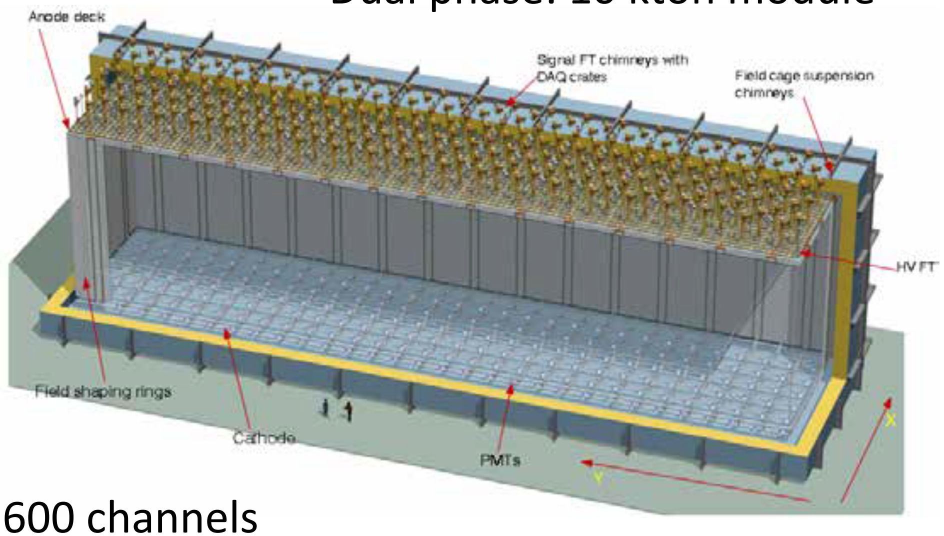
FD design: Dual Phase LAr TPC concept

Dual phase: signal extracted and amplified in gas phase





Dual phase: 10 kton module



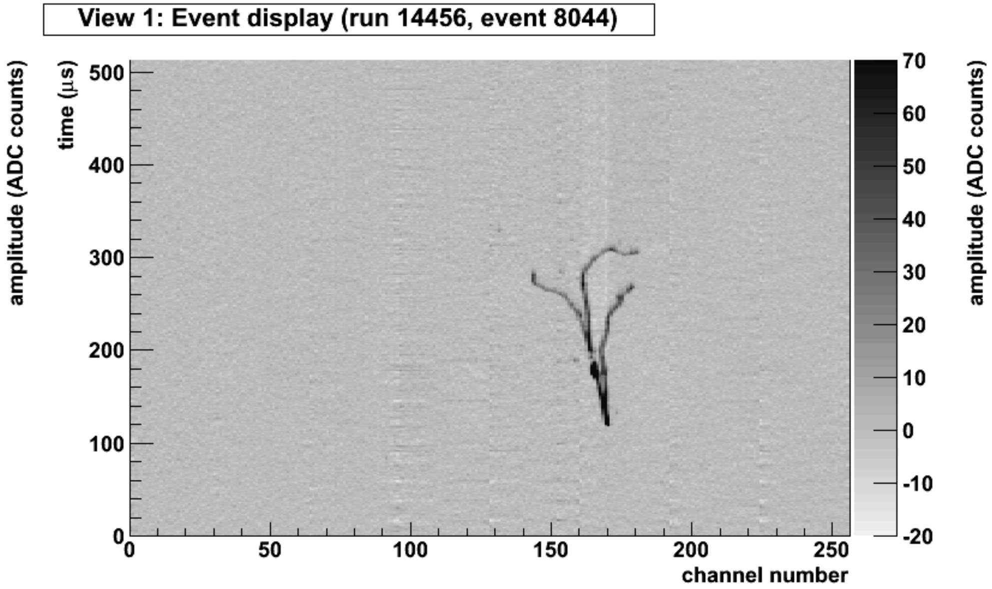
153,600 channels

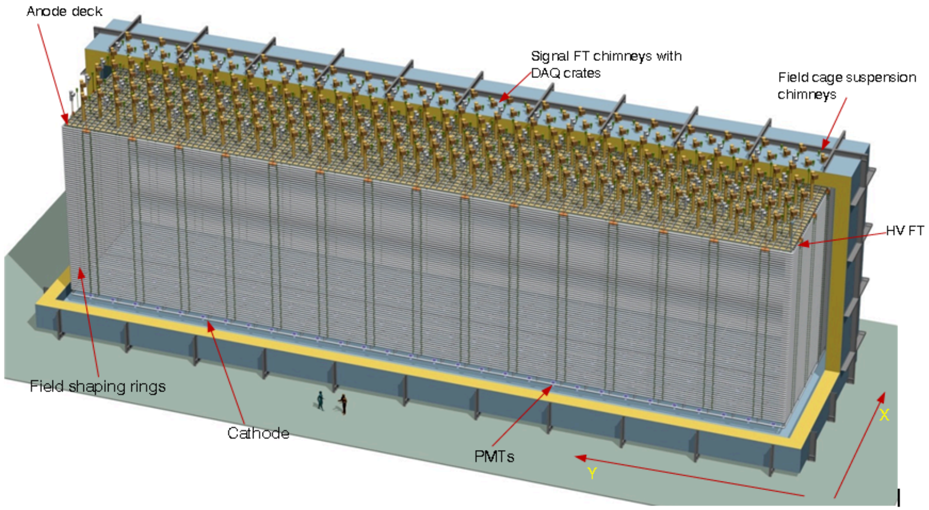
80 3x3 m^2 “CRPs” (Charge Readout Planes)

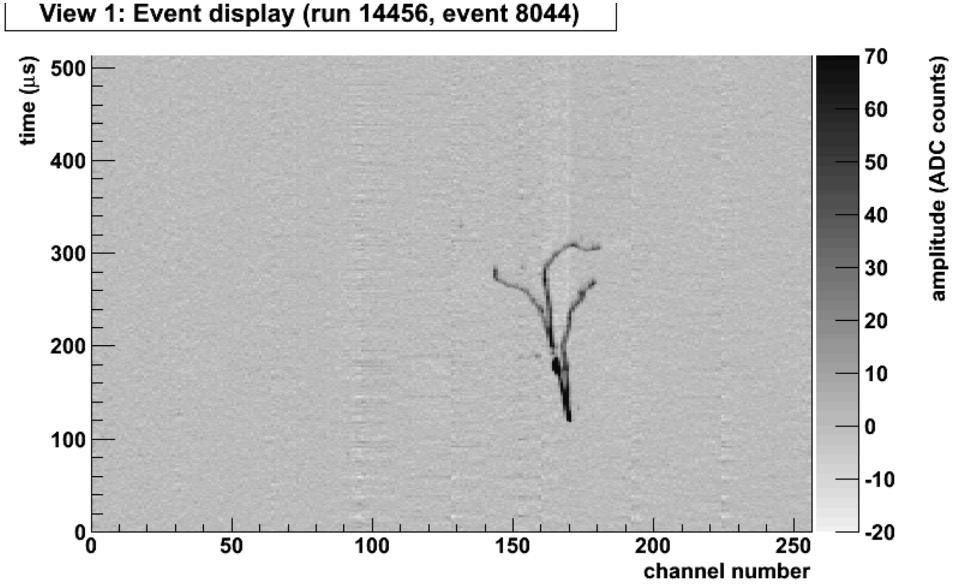
DUNE Dual-Phase LArTPC FD Design

Single TPC volume with amplification in gas phase (LBNO design):

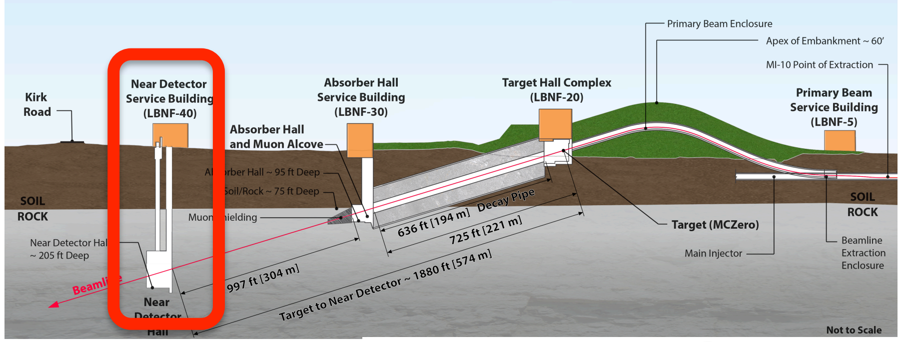
- 12m max drift (vertical), LEM (Large Electron Multiplier) read-out
- Features high S/N: ~100/1
- Excellent 3D reconstruction combining light and charge readout



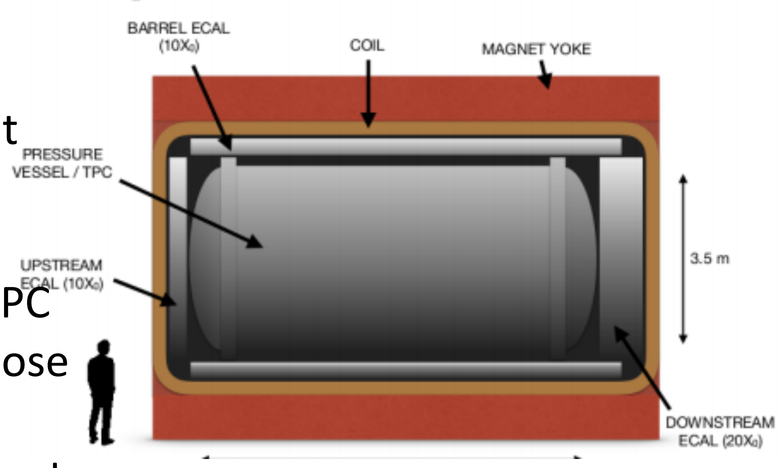


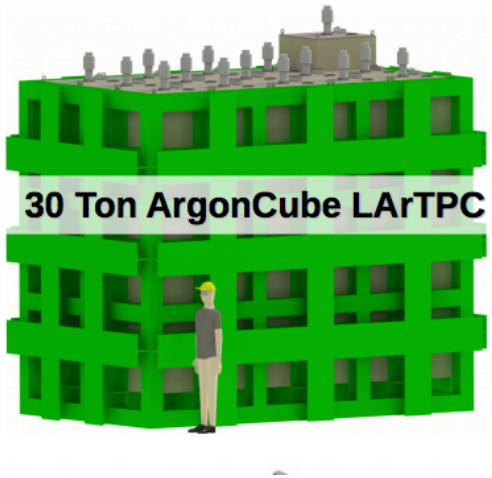


Near Detector (ND)



- Role: constrain systematic uncertainties important to oscillation analyses
  - Measure unoscillated beam flux
  - Measure multiple interaction cross-section channels
- Hall location
  - 574 m from LBNF target
  - ~60 m underground
- Near detector options
  - Highly segmented LArTPC
  - Magnetized multi-purpose tracker
  - Electromagnetic calorimeter
  - Muon chambers
- Conceptual design will preserve option to move ND for off-axis measurements



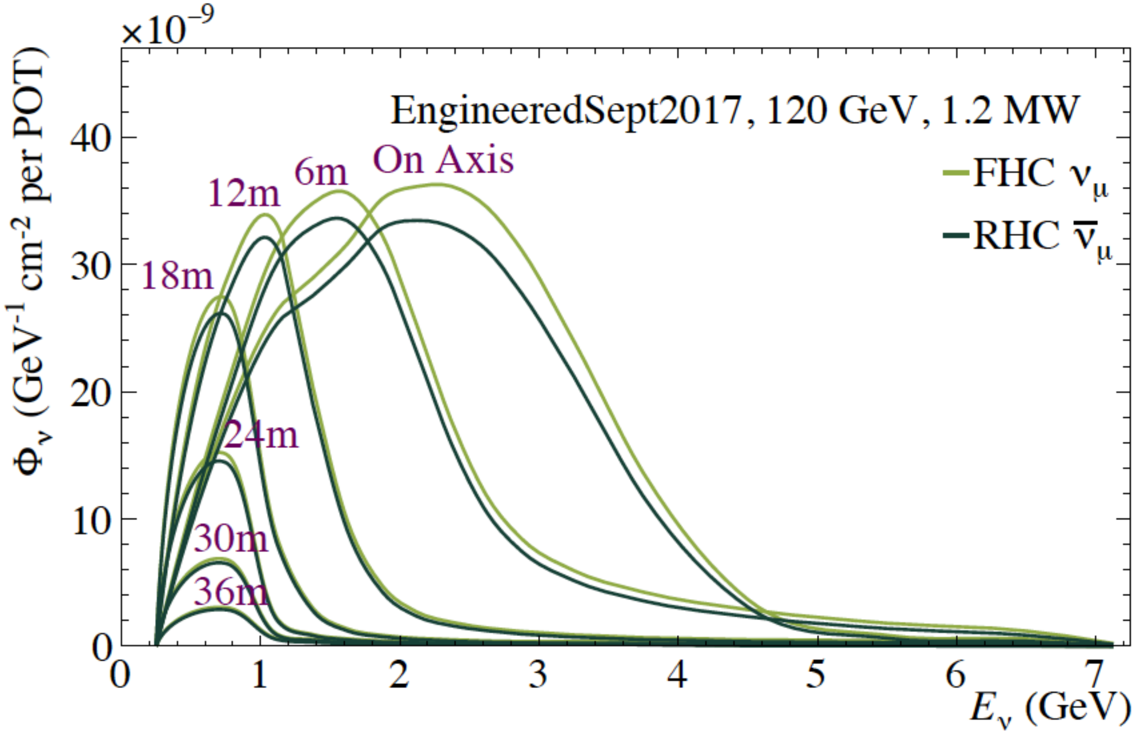


ND CDR expected in 2019

Finalizing Technology choice...

DUNE ND options

>100 million interactions will enable a rich non-oscillation physics program



Capability to move ND for off-axis measurements (DUNE-Prism)

Proto-DUNE detectors R&D and goals

- Prototyping production and installation procedures for DUNE Far Detector Design

  many of the components for the far detector prototyping at 1:1 scale
- Validating design from perspective of basic detector performance
- **Accumulating test-beam data to understand/calibrate response of detector to different particle species**
- Demonstrating long term operational stability of the detector

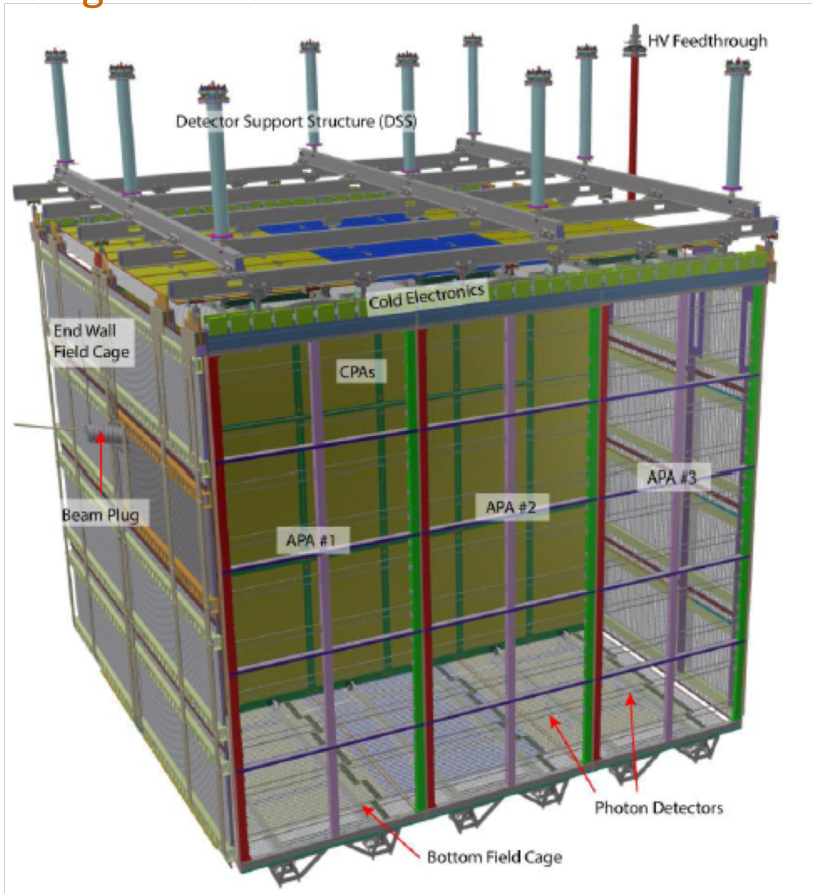
1 kton massive Liquid Argon detectors

On going R&D

Single & Dual Phase Prototypes

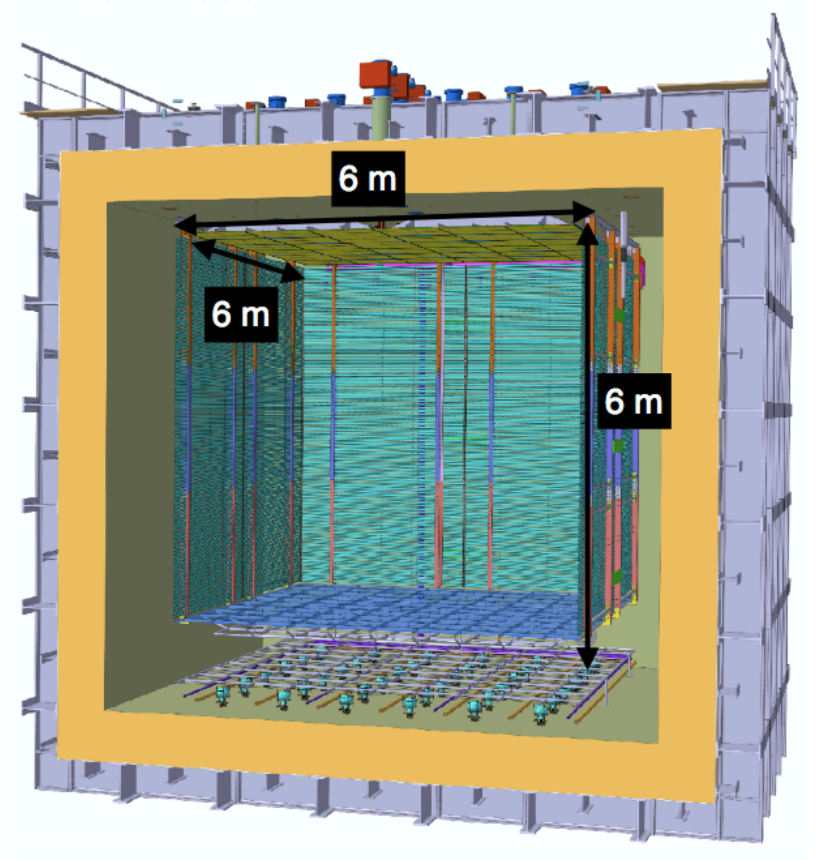
Enabled by CERN Neutrino Platform

Single Phase:



Active volume 6.9 x 7.2 x 6 m^3

Dual Phase:



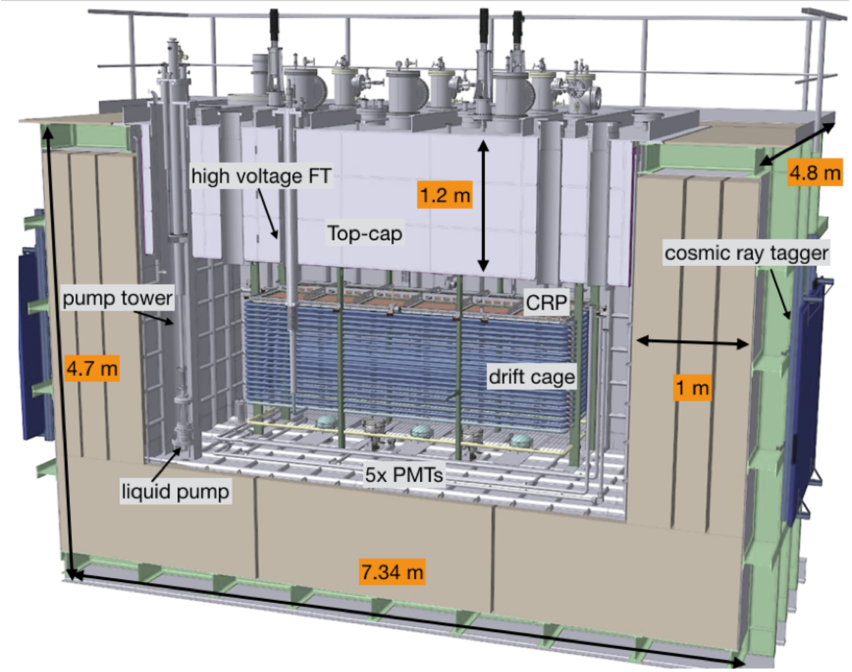
Active volume 6 x 6 x 6 m^3

EHN1 at CERN

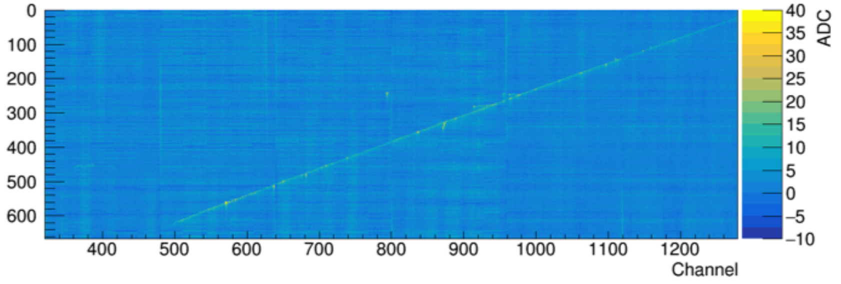

Neutrino Platform at CERN
Dual phase cryostat
Single phase clean room and cold box
Single phase cryostat

3x1x1 Dual Phase Prototype

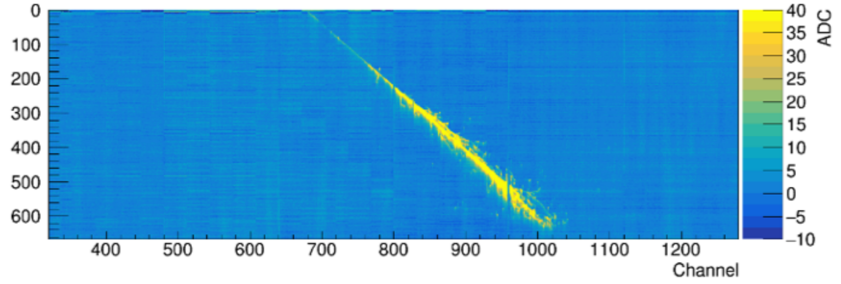
3x1x1 m^3 prototype:



Thru-going muon:



EM Shower:

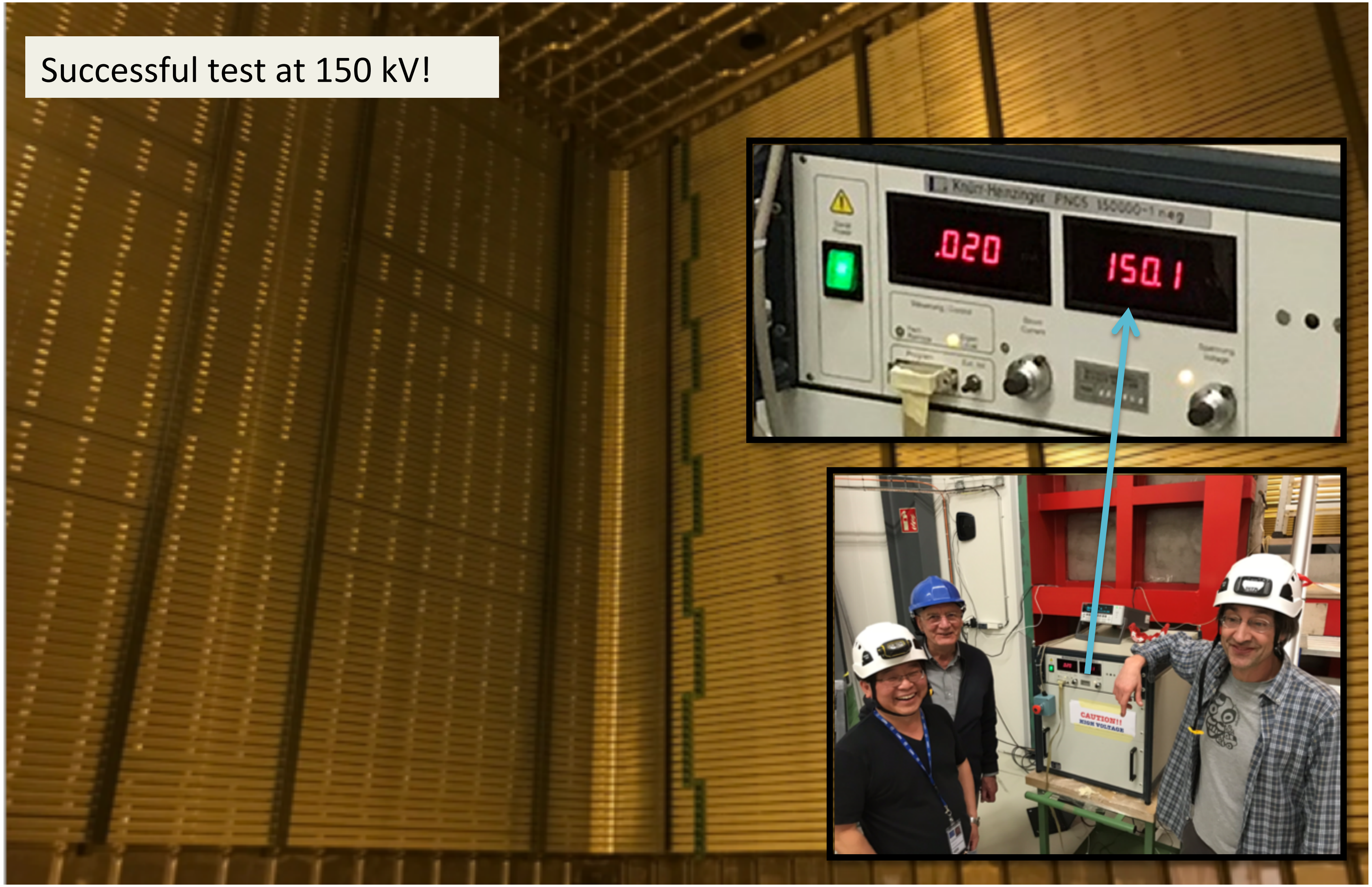


- 3x1x1 prototype ran from June to November 2017
- Successful demonstration of dual phase LArTPC concept
- ENC <1800 e$^-$ (S/N ~100 for a MIP)
- Led to improved designs for protoDUNE dual phase

protoDUNE-DP Field Cage


Field Cage completed: April 2018

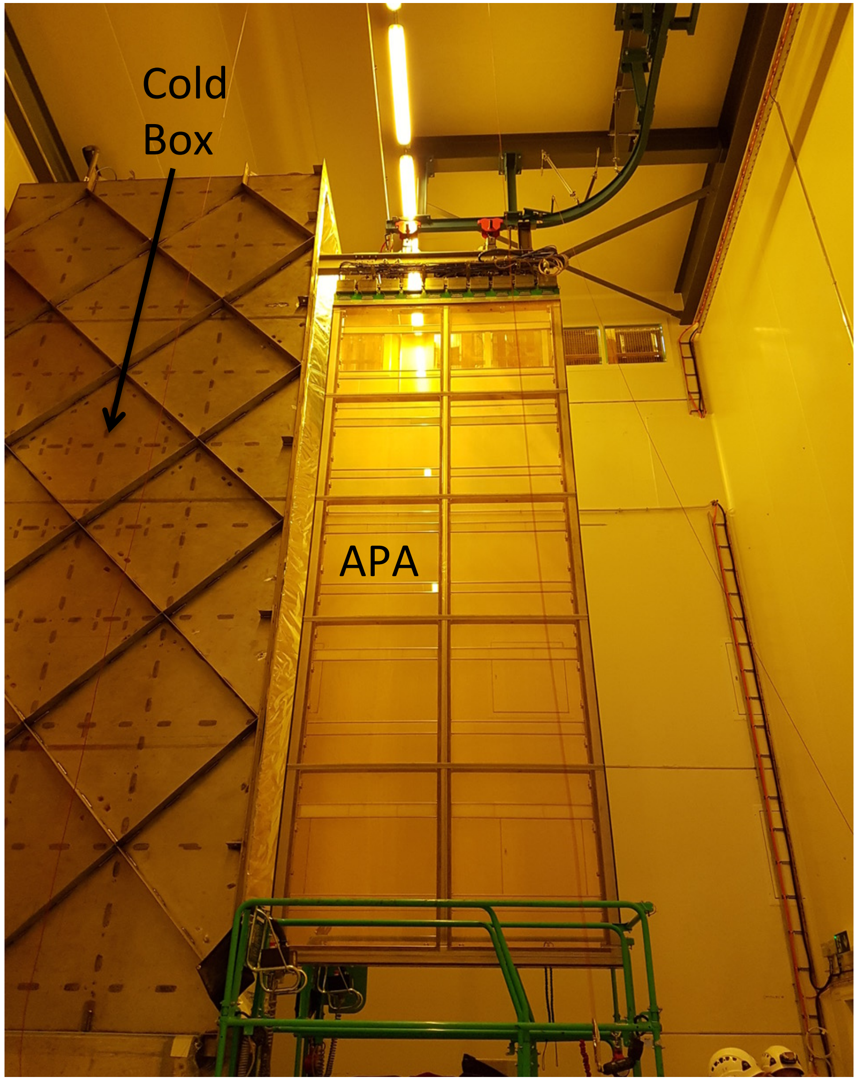
protoDUNE-DP Field Cage


Successful test at 150 kV!

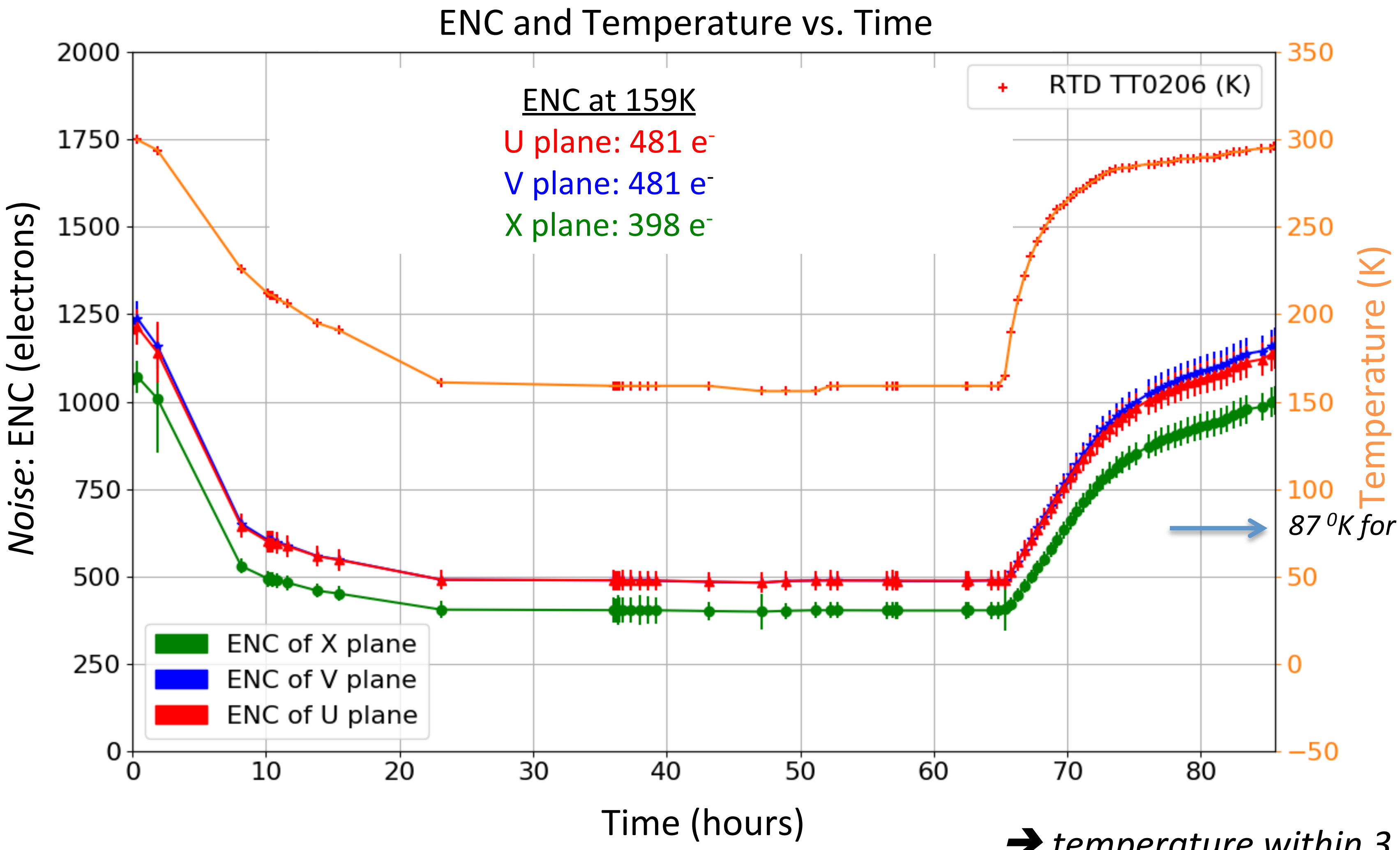
protoDUNE-SP Cold Box

- ➢ **Anode Plane Assemblies (APA)**
- ➢ **with integrated Cold Electronics**
- ➢ **and Ph.Detector modules**

- Allows testing of assembled APA and electronics immediately before installation into protoDUNE cryostat
- Incorporates feed-thru, cabling, and readout system identical to protoDUNE
- Filled with cold nitrogen gas for testing at "cool" temperature (~160 K)
- Successful demonstration of required noise levels at cryogenic temperature



protoDUNE-SP Cold Box Results



ENC at 159K

U plane: 481 e$^-$

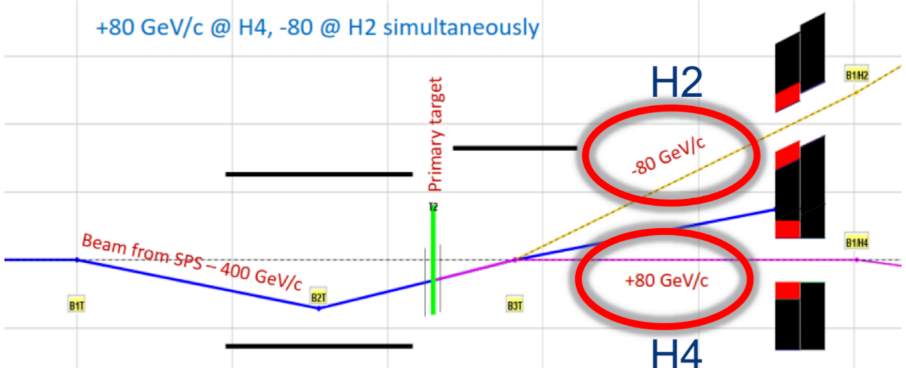
V plane: 481 e$^-$

X plane: 398 e$^-$

87 ^{0}K for LAr

➔ *temperature within 3 mK*

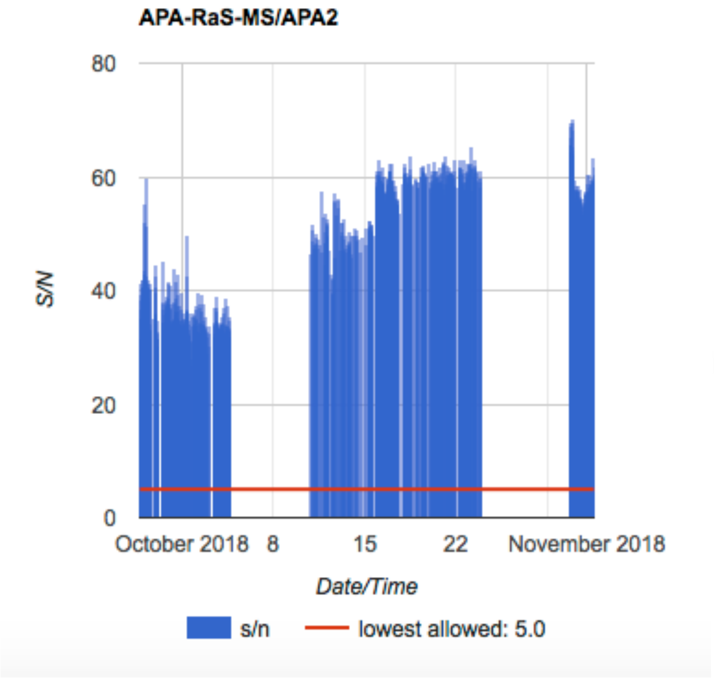
protoDUNE SP: first achievements

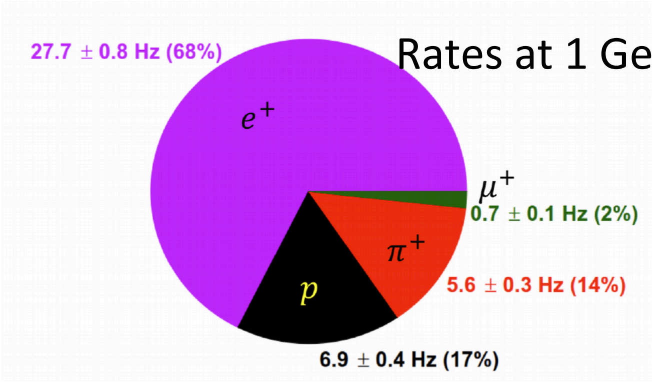


400 GeV/c P beam from SPS

80 GeV/c secondary π+ beam

~0.5 – 7 GeV/c tertiary
e, p, μ+,π+ beam

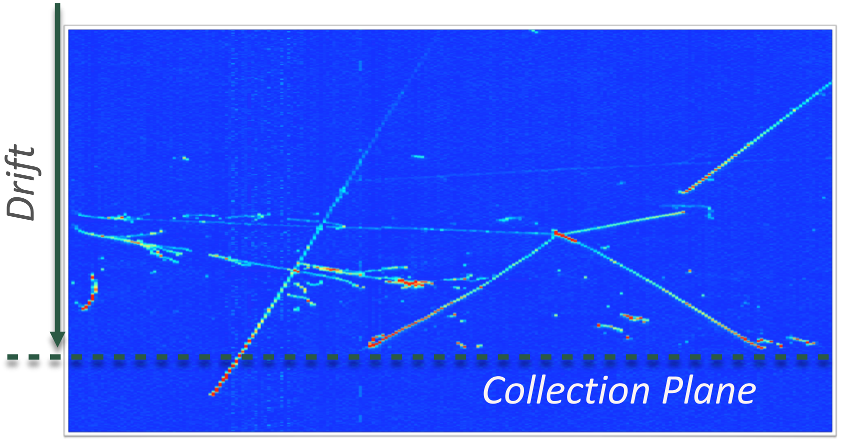




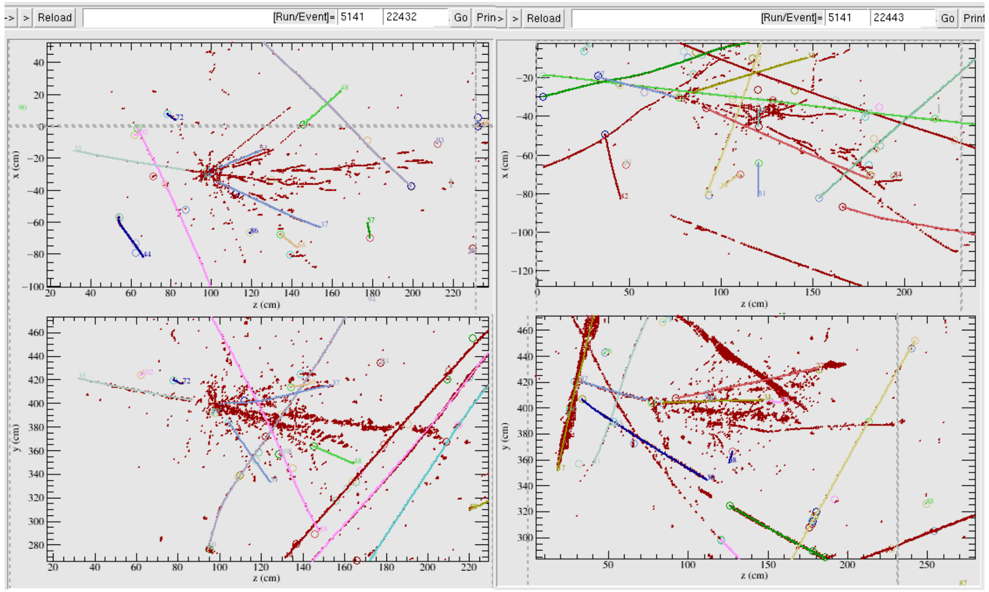
Rates at 1 GeV/c

First tracks seen on September 21rst, 2018

Some real events !



EM showers from pion-0
and a pion interaction with
4 prongs, Run 4696, Ev 103



(preliminary)

First look at data looks very promising:
very low noise level
and very high signal-to-noise ratio

- Stable HV at 180 kV (ie EF at 500 V/cm)
- TPC wires with 99.7% of 15,360 channels alive
- Readout systems successful to sustain full readout (≈ 450 Gb/s) and up to 60 Hz triggered output
- Purity is good (lifetime ≈ 300 μs)
- 1PB of local storage available

Note: ≈ 70 cosmic rays per pulse

protoDUNE's Status

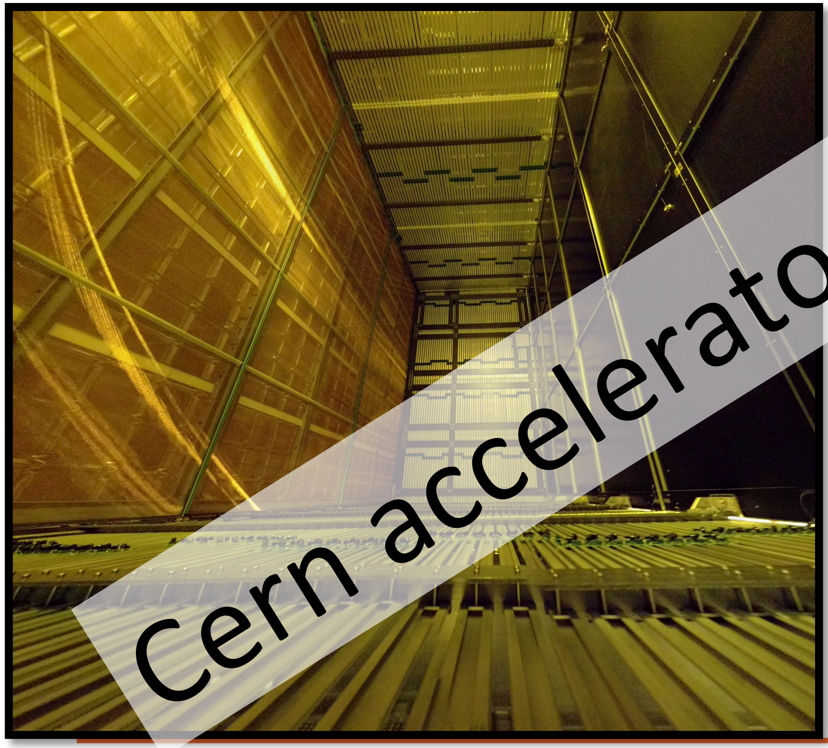
a successful rush !

Single Phase Installation Complete: May 2018

Single Phase Cooldown: July 2018

Single Phase Beam: August-November 2018

Dual Phase Installation Complete: Fall 2018



Cern accelerators shutdown…

③

Perspectives

Perspectives…

“Experiments” in running:

- NOvA
- T2K
- Cosmology
- SuperNovae

Future:

- JUNO ➔ *Reactor neutrinos*

- ORCA (KM3Net)
- PINGU (IceCube)
- INO
- HK

➔ *Atmospheric neutrinos*

- NOvA+T2KII
- **DUNE**
- HK (T2KK)

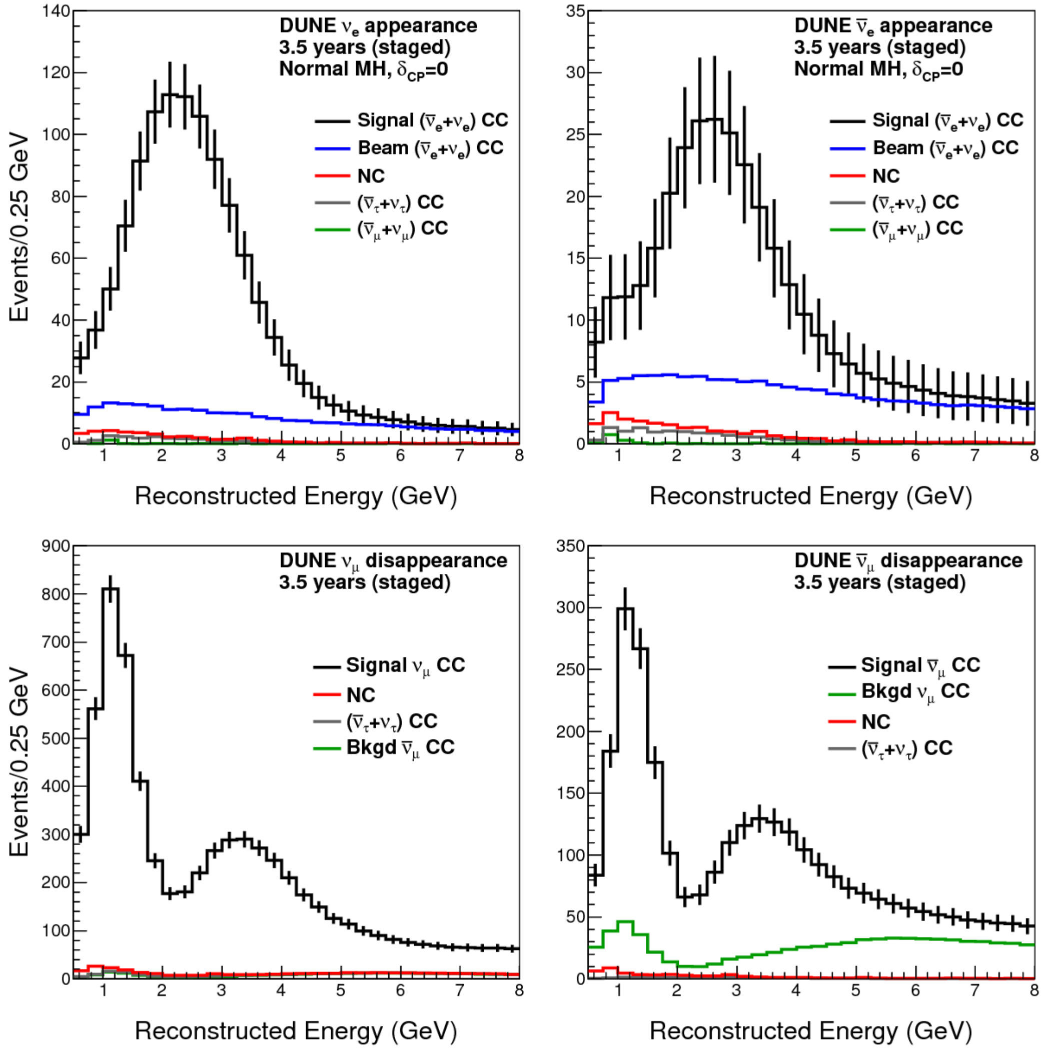
➔ *Long baseline*

Oscillation Sensitivity for DUNE

DUNE Conceptual Design Report (CDR)
arXiv:1512.06148

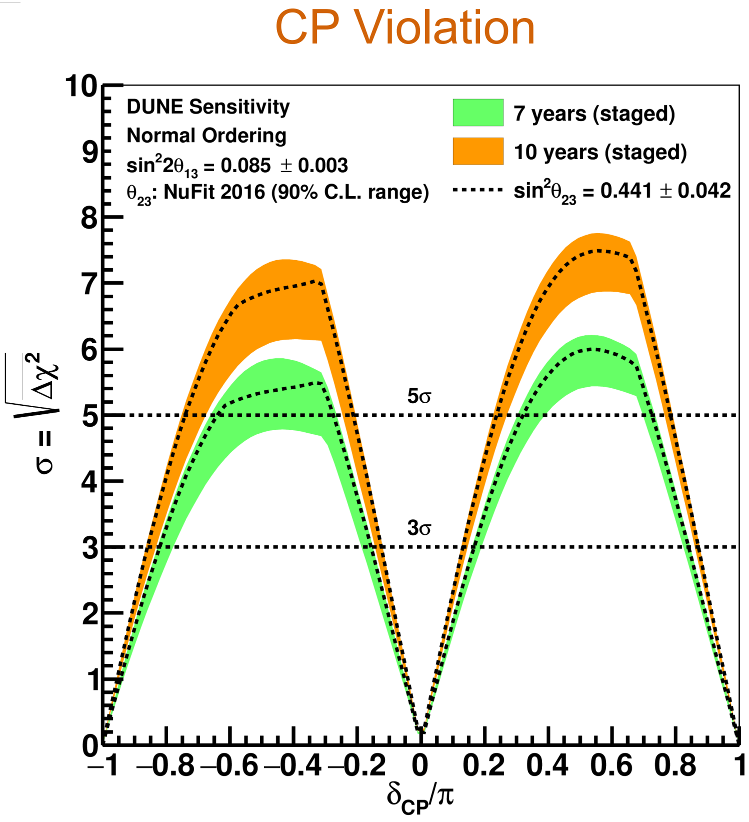
Order 1000 ν_e appearance events in ~7 years of equal running in neutrino and antineutrino mode

Simultaneous fit to four spectra to extract oscillation parameters

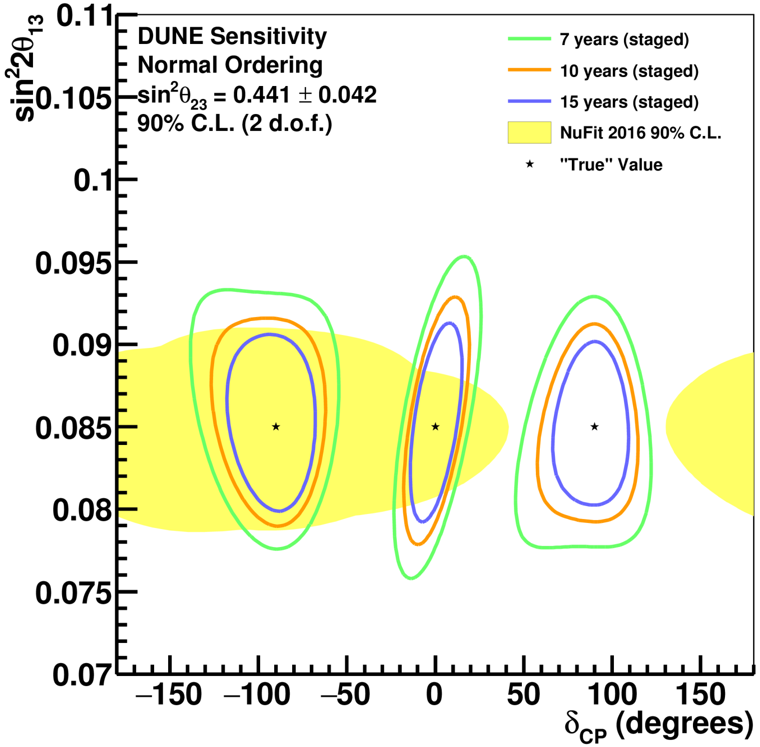


Sensitivity to CPV for DUNE

DUNE CDR:



Width of band indicates variation in possible central values of θ_{23}



Simultaneous measurement of neutrino mixing angles and δ_{CP}

Perspectives for MH

Many different ways to define "sensitivity"

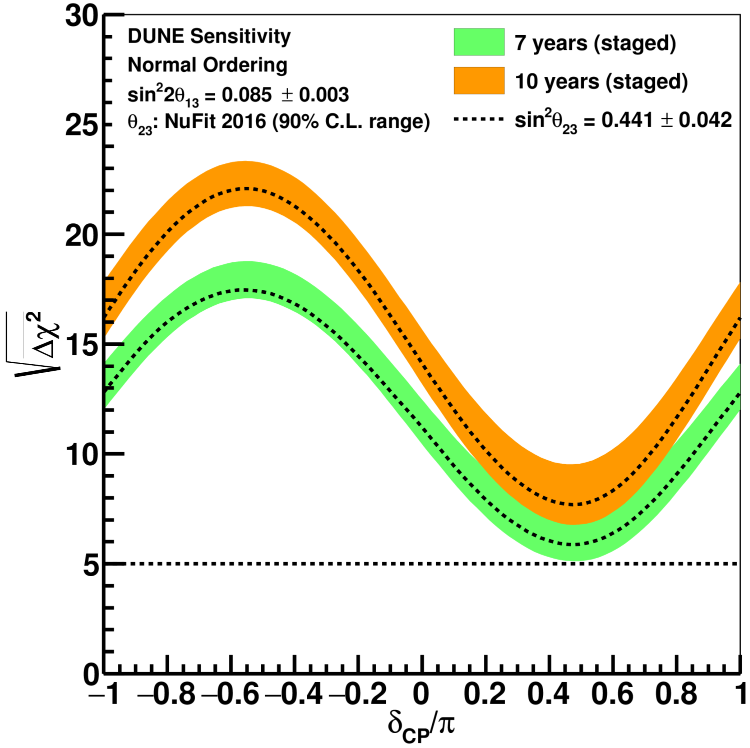
Only above 5 σ
we are "unsensitive"
to methodology

- NOvA: Degeneracy with δ_{CP} ?
- PINGU/ORCA: funded ? systematics ?
  Degeneracy with δ_{CP} and θ_{23} ?
- INO: really ?
- JUNO: technical challenge on energy resolution ?
  Degeneracy with Δm^2_{atm} ?

DUNE: ok, it will get it

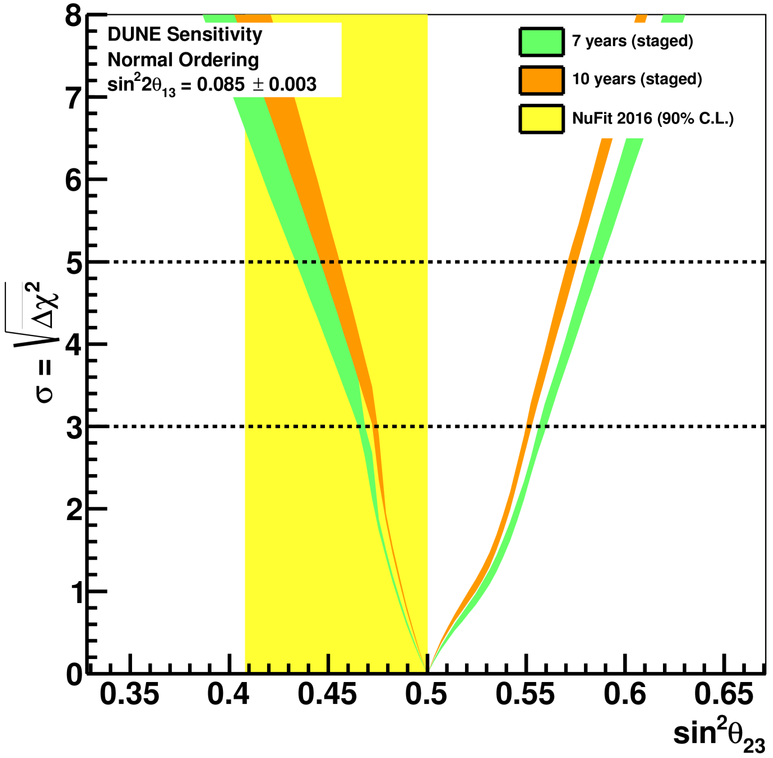
MH and θ_{23} Oscillation Physics

DUNE CDR Mass Ordering



Width of band indicates variation in possible central values of θ_{23}

DUNE CDR Octant

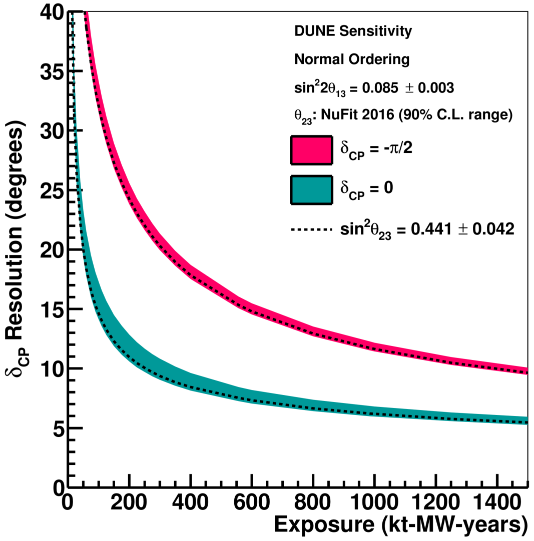


Width of band indicates variation in possible true value of δ_{CP}

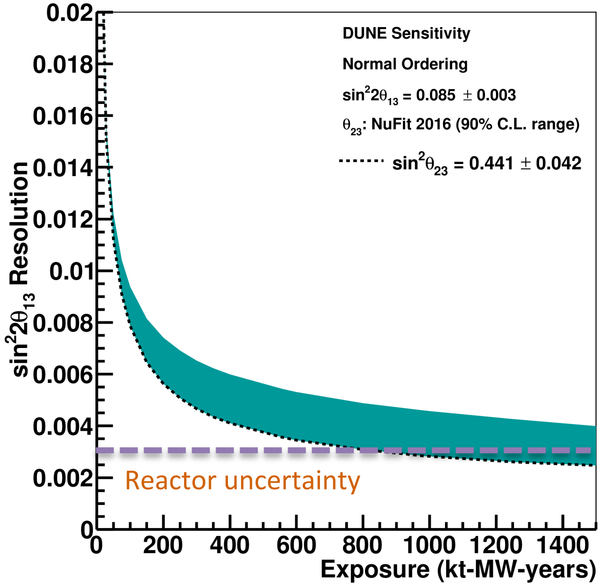
Oscillation Parameter Sensitivity

DUNE CDR:

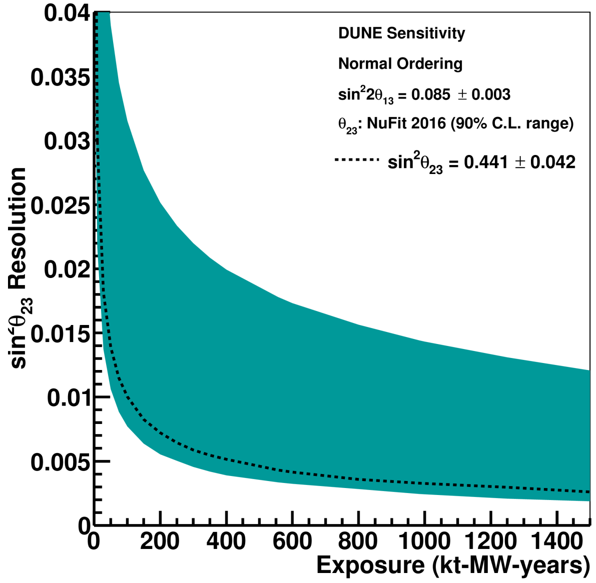
δ_{CP} Resolution



$\sin^2 2\theta_{13}$ Resolution



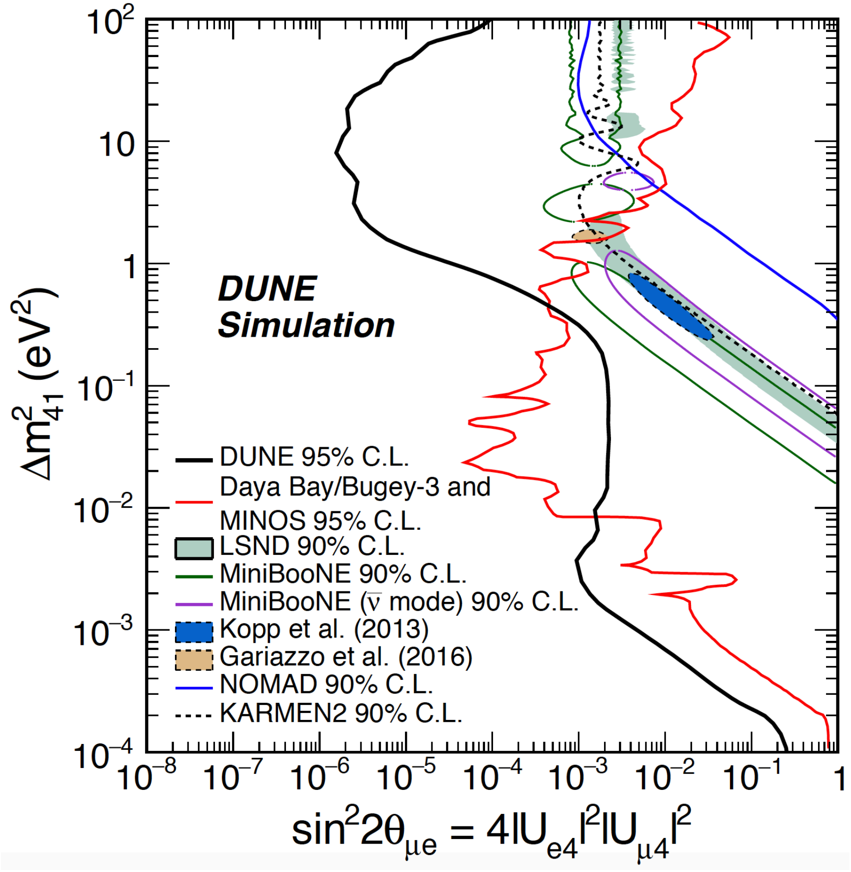
$\sin^2\theta_{23}$ Resolution



BSM searches

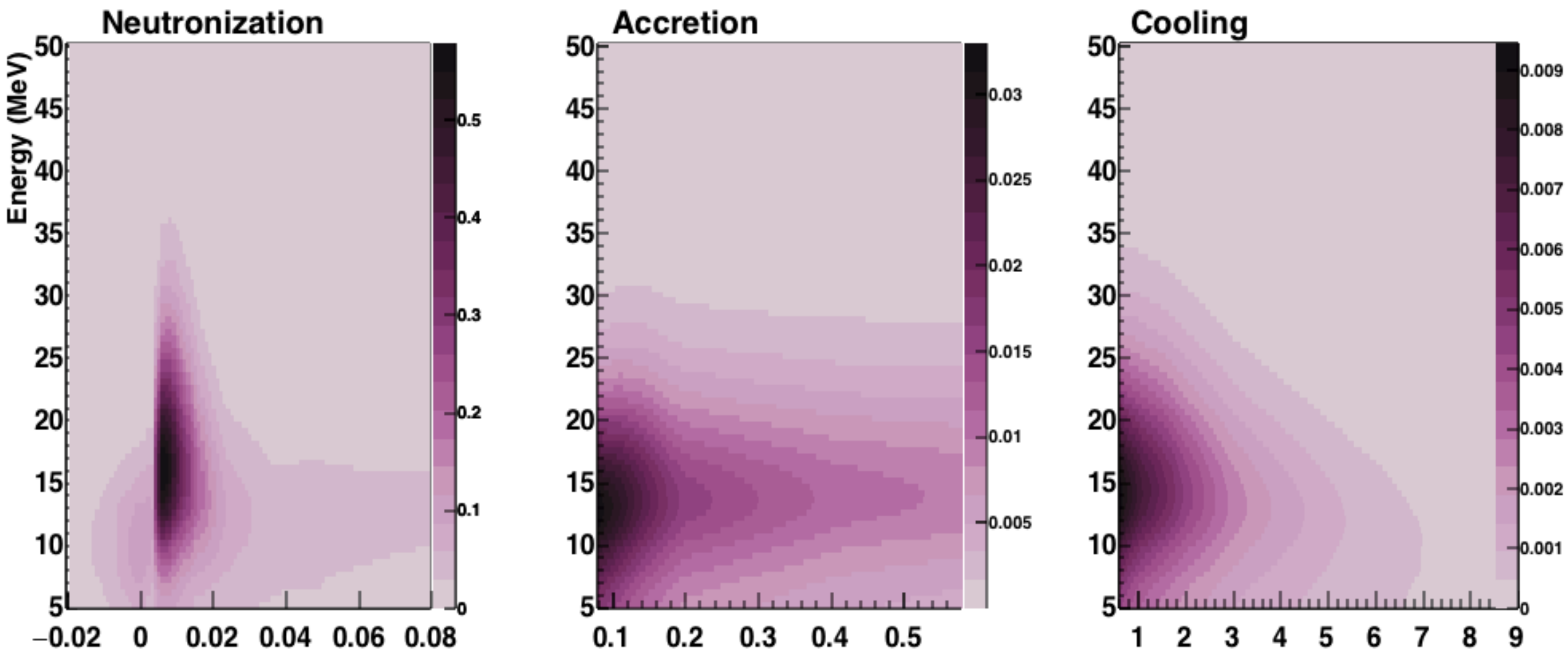
- DUNE sensitive to many BSM particles and processes
  - *Light dark matter*
  - *Boosted dark matter*
  - *Sterile neutrinos*
  - *Non-standard interactions, non-unitary mixing, CPT violation*
  - *Neutrino trident searches*
  - *Large extra dimensions*
  - *Neutrinos from dark matter annihilation in sun*
- Active area of research within phenomenology community as well as the DUNE collaboration
- GLoBES configurations arXiv: 1606.09550

Sterile Neutrino Sensitivity (ν_e CC appearance at ND)



SBN neutrinos

In LArTPC, SNB signal dominated by electron neutrinos: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$



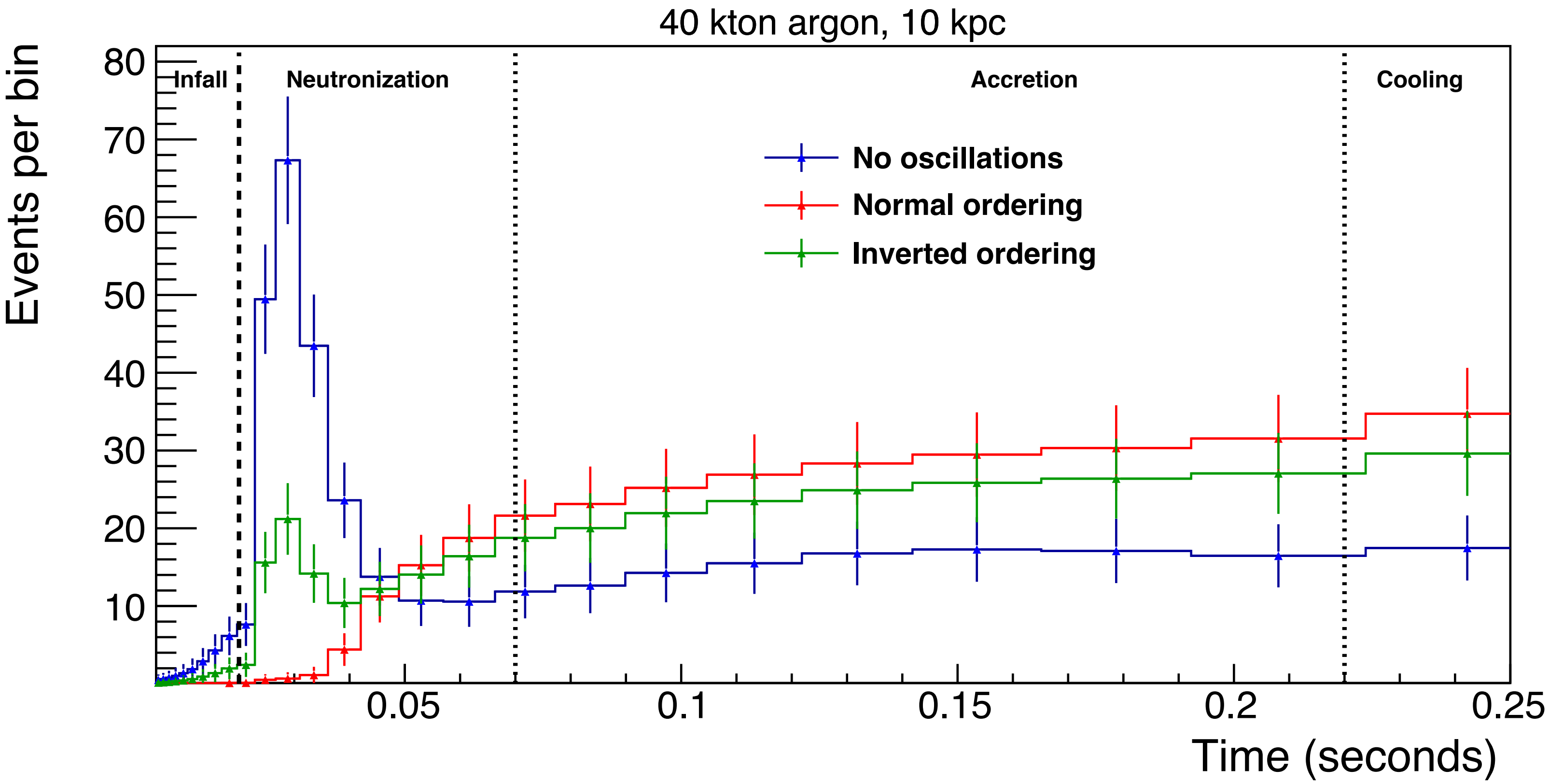
Time (s)

Events per 0.5 MeV per ms, 40 kton @10 kpc

SBN neutrinos

In LArTPC, SNB signal dominated by electron neutrinos:

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

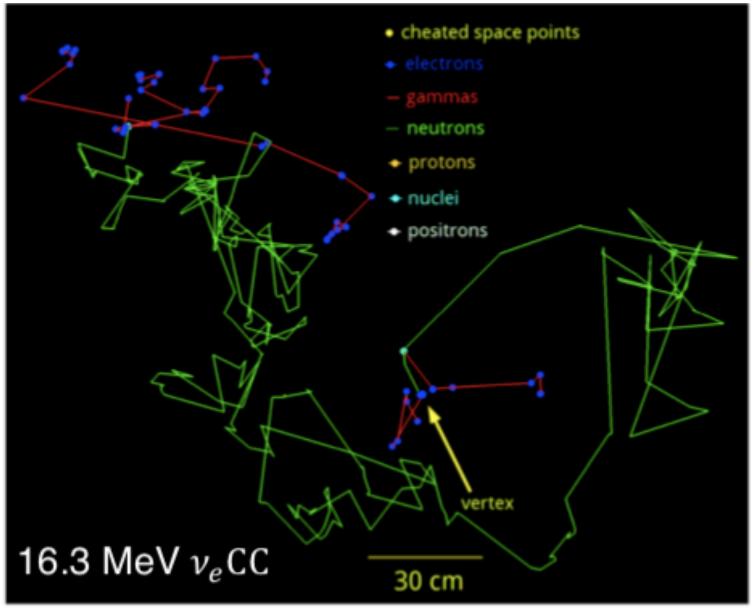


Observation of early time development yields sensitivity to neutrino mass ordering and details of SNB model.

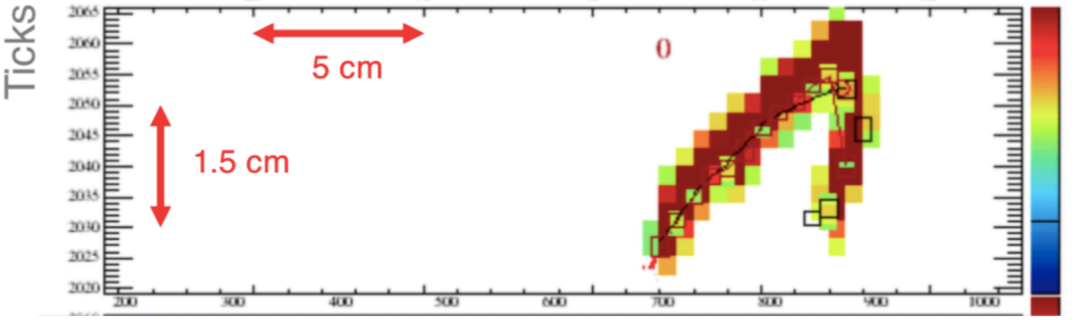
SNB ν Simulation & Reconstruction

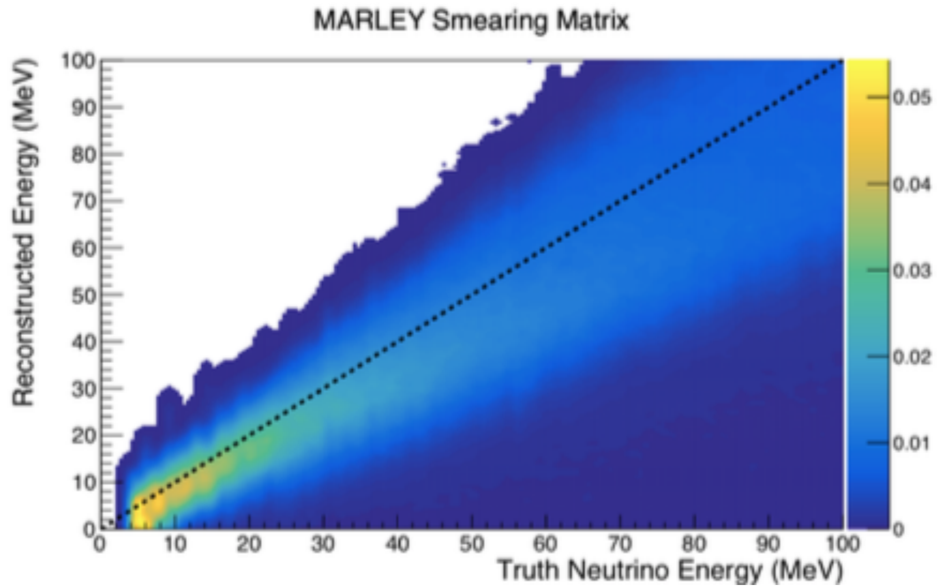
Work underway on improved event reconstruction and tagging of 5-100 MeV events+ DAQ/triggering

MARLEY event generator: marleygen.org



DUNE Simulation 30.25-MeV ν

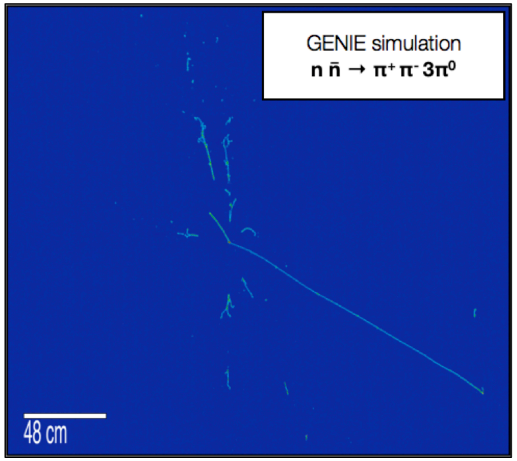




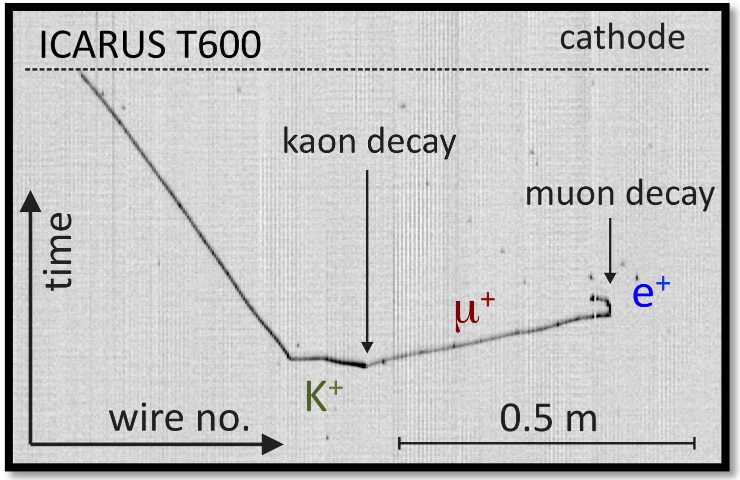
Baryon Number Violation

- Deep underground location and precise particle tracking facilitate DUNE sensitivity to many baryon number violating processes including:
  - Neutron-antineutron oscillation
  - $\bar{p}$->νK^+, n→K^+e^-
  - p→$\pi^0 e^+$

$n\bar{n}$ MC:



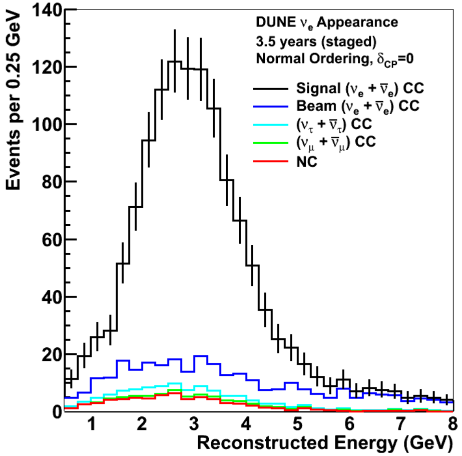
Cosmogenically induced K^+ event:



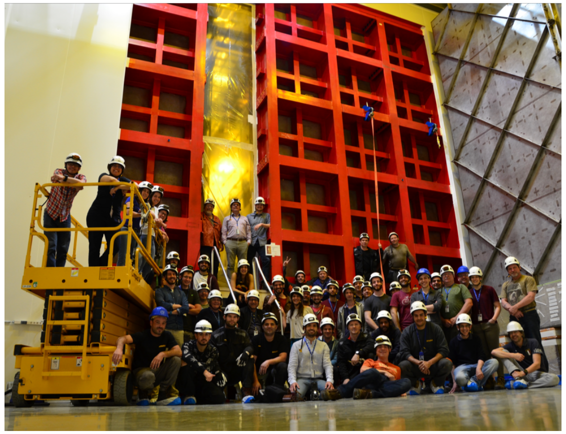
- Sensitivity based on full MC and automated reconstruction and event selection in progress (planned for TDR in 2019)
  - Challenges include atmospheric neutrino background and final state interactions within the argon nucleus

Summary

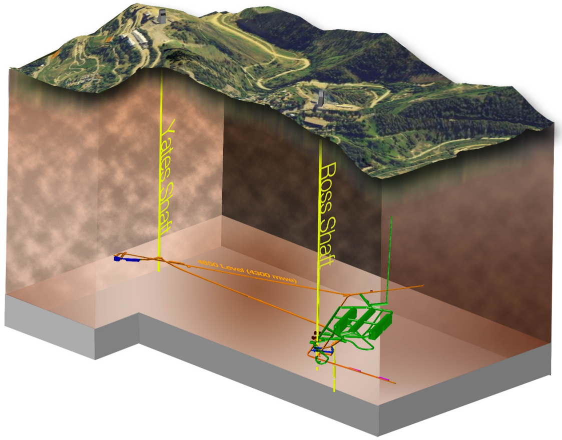
New Analysis



protoDUNE



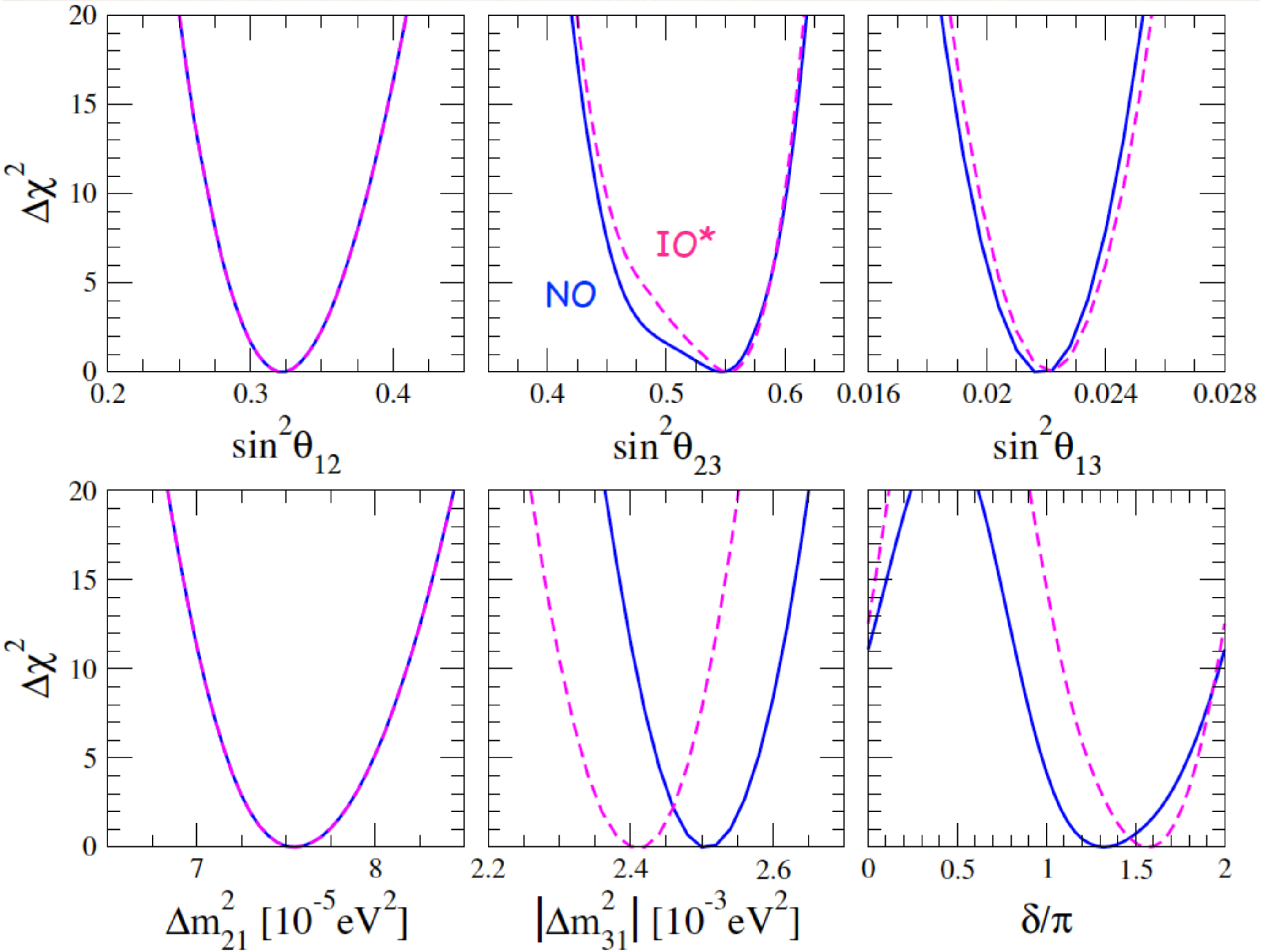
Coming Soon...



- LBNF/DUNE: the ultimate neutrino facility/observatory
- LBNF and DUNE making rapid progress on facility construction, detector design, and physics analysis
- New MC-based oscillation sensitivity analysis exceeds CDR-level sensitivity to δ_{CP}
- First look at protoDUNE pre-commissioning data is very promising!
- DUNE Technical Design Report and protoDUNE SP and DP results in 2019!
- Expect first DUNE FD data in ~2026…

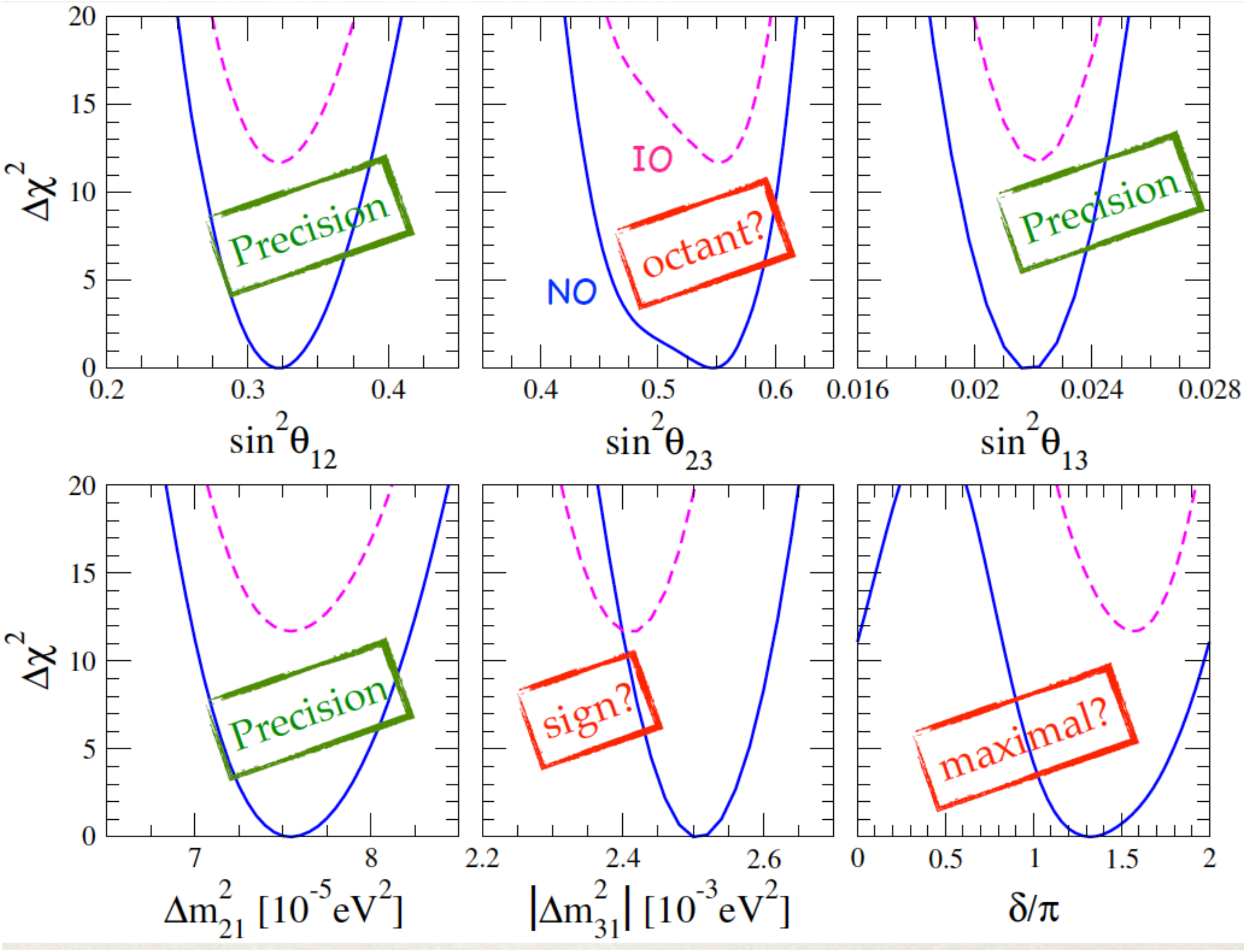
Backup slides

Global fit to neutrino oscillations



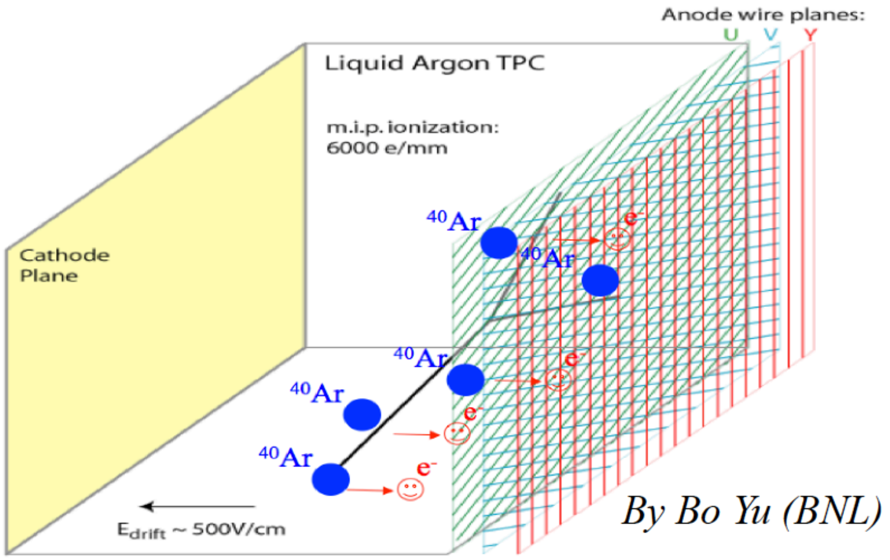
* wrt local minimum in IO

deSalas et al, 1708.01186 (May 2018)

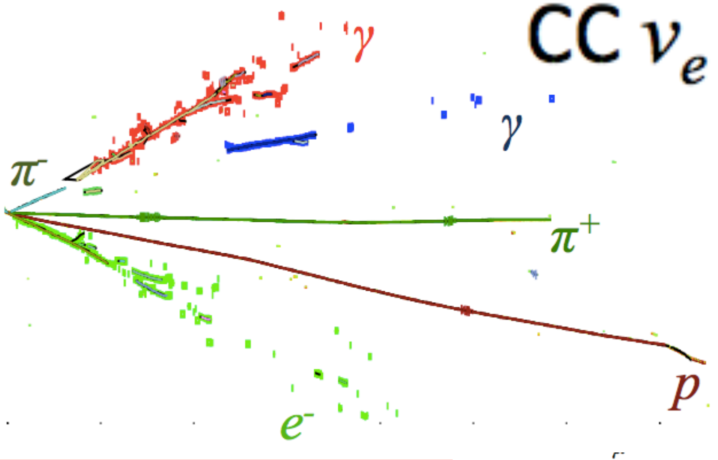


deSalas et al, 1708.01186 (May 2018)

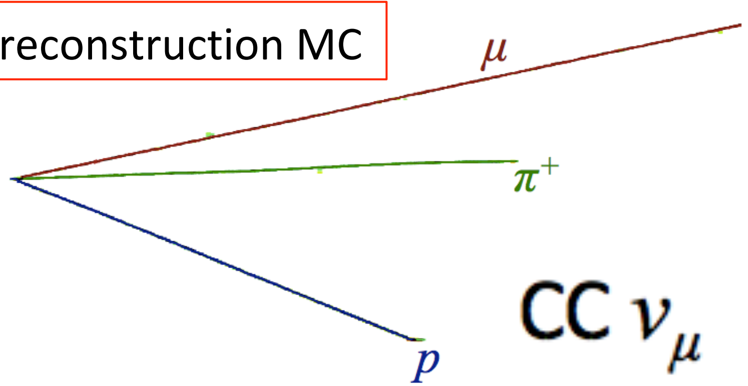
Far Detector Single Phase Technology – Liquid Argon Time Projection Chamber



By Bo Yu (BNL)



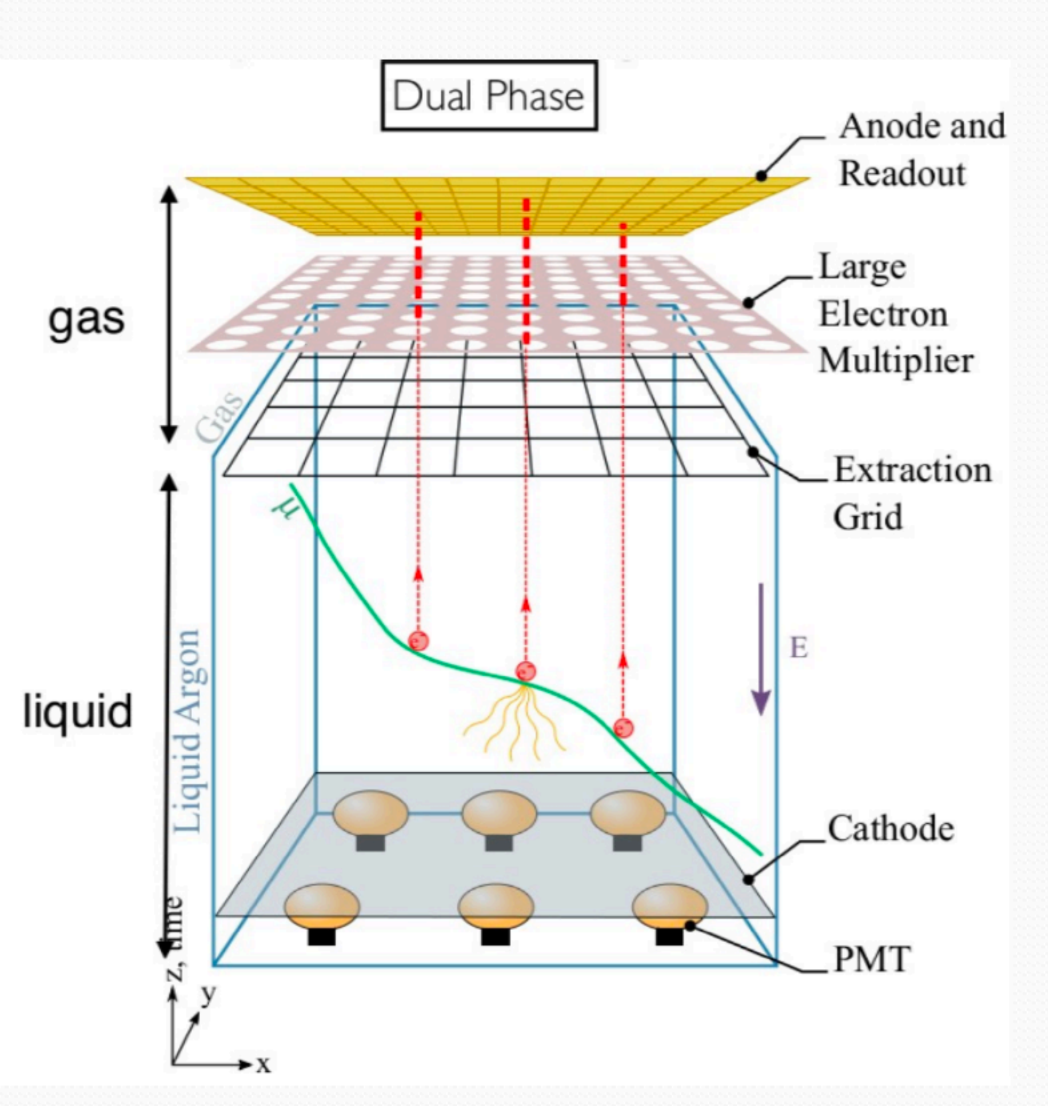
FD reconstruction MC



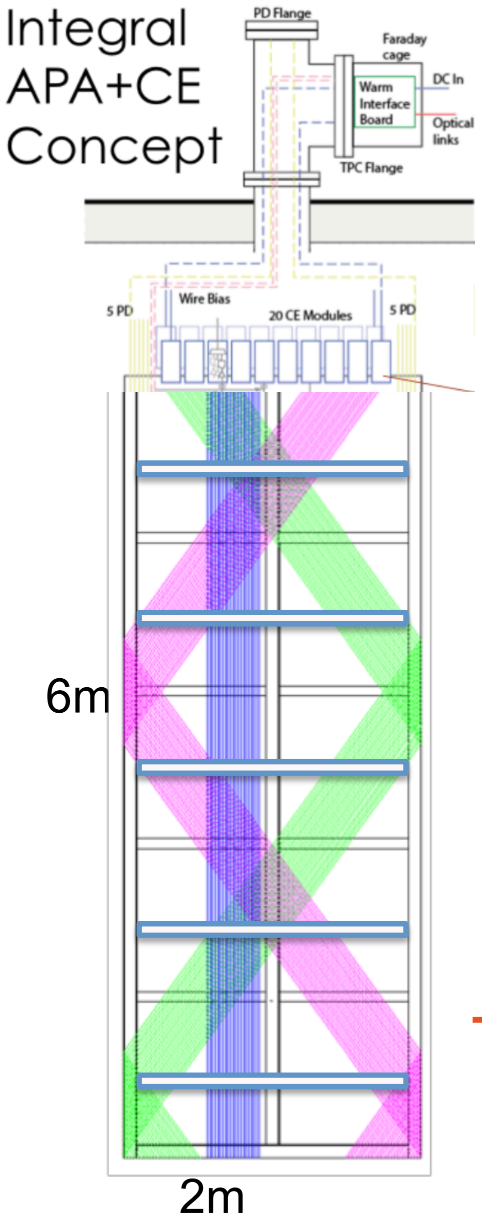
- LAr TPC: excellent tracking and calorimetry
- Suitable for very large detectors – high signal eff. and bkg. discrimination
- High resolution 3D reconstruction – charged particles ionize Ar; electrons drift to anode wires (~ms) for xy coordinate; drift time – z coordinate
- Ar scintillation light (~ns) detected by photon detectors – provides t0

FD Dual Phase Technology Ar TPC

- Ionization readout:
  - Ionization electrons extracted into gas phase
  - Charge amplification via large electron multipliers
  - Charge readout by 2D segmented anode
- Easy access for electronics maintenance even during operation
- Excellent 3D reconstruction
- **Very high HV required**
- Scintillation light collected by Photomultipler Tubes (PMTs)



APA concept



Core detector element: Anode Plane Assemblies (APA) with integrated Cold Electronics Boards and Ph.Detector modules

Each APA : 960 X, 800 V, 800 U, 960 G (un-instrumented) wires

10 Photon Detectors are installed into each APA frame

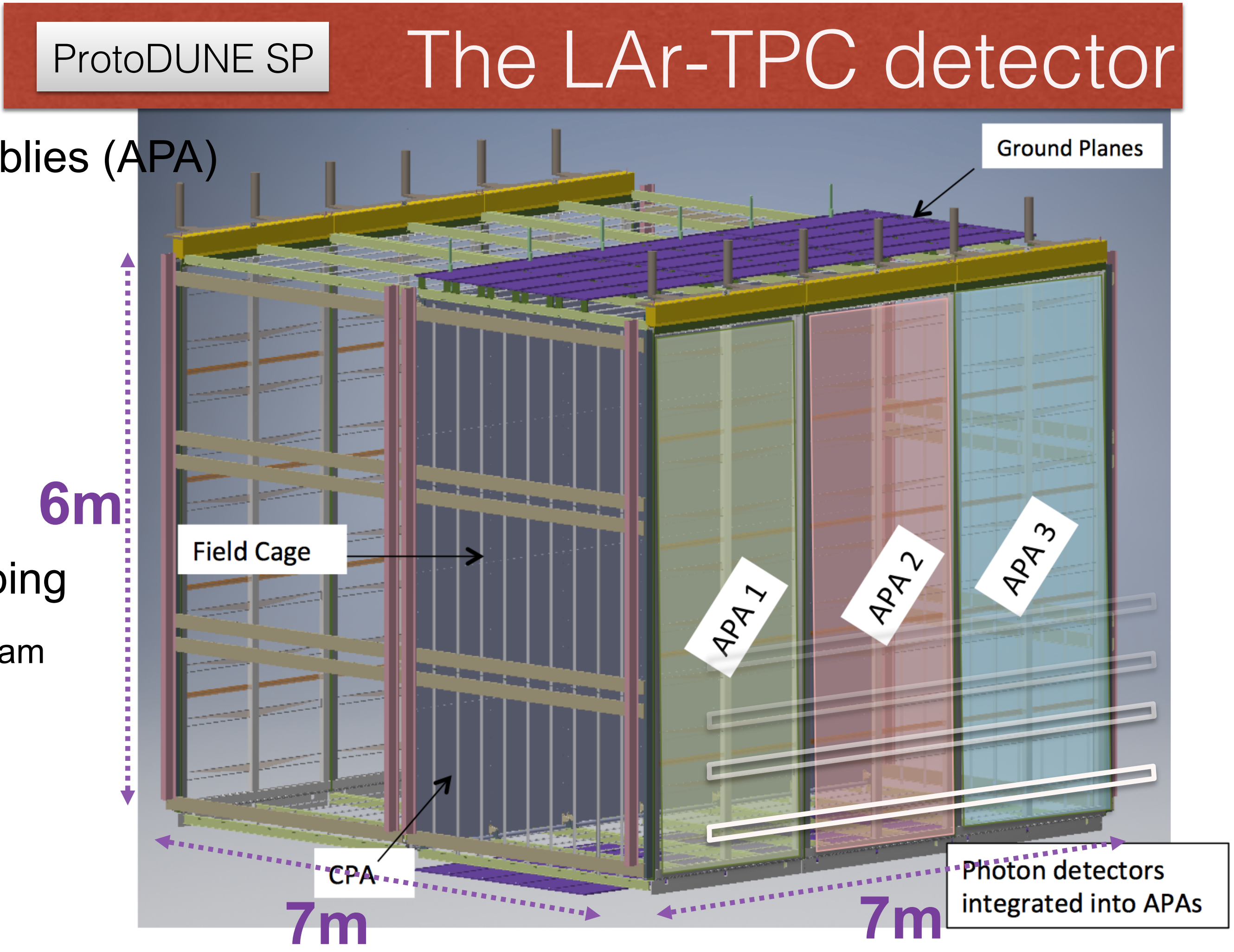
20 ColdElectronics Boxes mounted onto the APA frame and connected to the wires - 2560 Channels-Wire

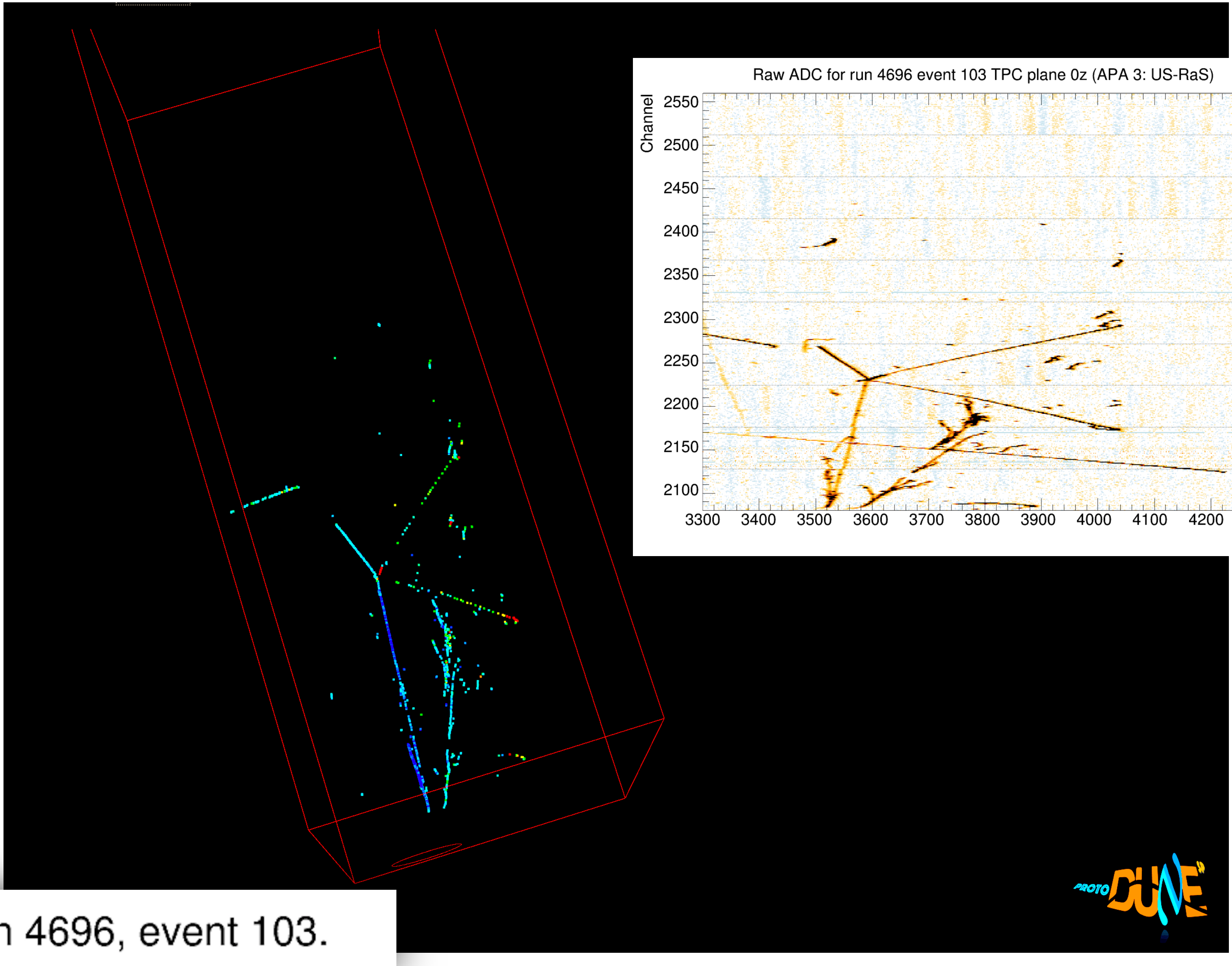
- The modular approach to detector construction enables the construction of detector elements to take place in parallel and at multiple sites.

This will be an essential approach for the DUNE Far Detector

The ProtoDUNE SP Detector

- Six Anode Plane Assemblies (APA)
  - 3 APAs on each side
- Central cathode plane
  - -180 kV nominal
- Field Cage for field shaping
  - shaped profiles / G-10 I-Beam
  - Constructed in panels
- Ground Planes





Run 4696, event 103.

DUNE Systematics: TDR

- Systematics analysis building on expertise developed in MINERvA, T2K, and NOvA
  - "DUNEResponse" ← "T2KReweight"
- CAFAna fitting framework facilitates more sophisticated treatment of systematic uncertainty than was possible for CDR
  - Systematic uncertainties in TDR will be based on detailed evaluation of flux, neutrino interaction, and detector uncertainties
  - Sensitivity calculations will be based on fits combining information from near and far detectors
- Flux and interaction systematics evaluated using reweighting technique (including GENIE and non-GENIE reweights)
  - Impact of systematic variations propagated through full analysis chain
  - Ability to consider systematics impacting kinematic distributions as well as normalization
- Detector systematics evaluated within the fit
  - Detector calibration task force evaluating magnitude and sources of detector uncertainty