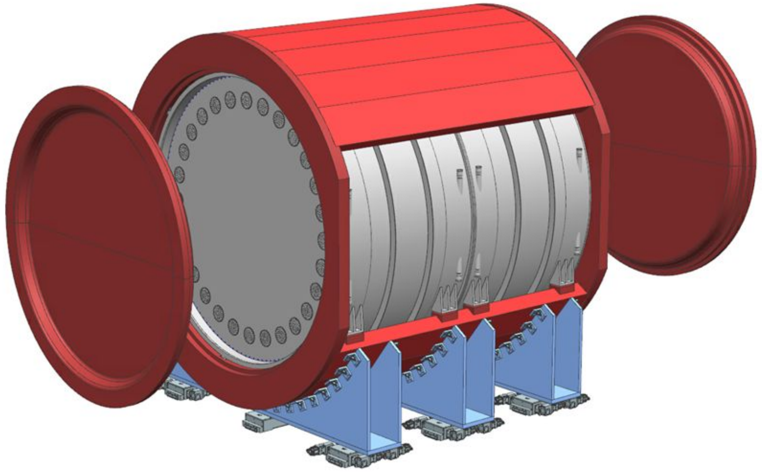
A magnetized high-pressure gaseous argon time projection chamber (ND-GAr) for the Phase II DUNE Near Detector

Andrew Cudd on behalf of the DUNE Collaboration

SLAC FPD Experimental Seminar
2023/04/25



University of Colorado Boulder

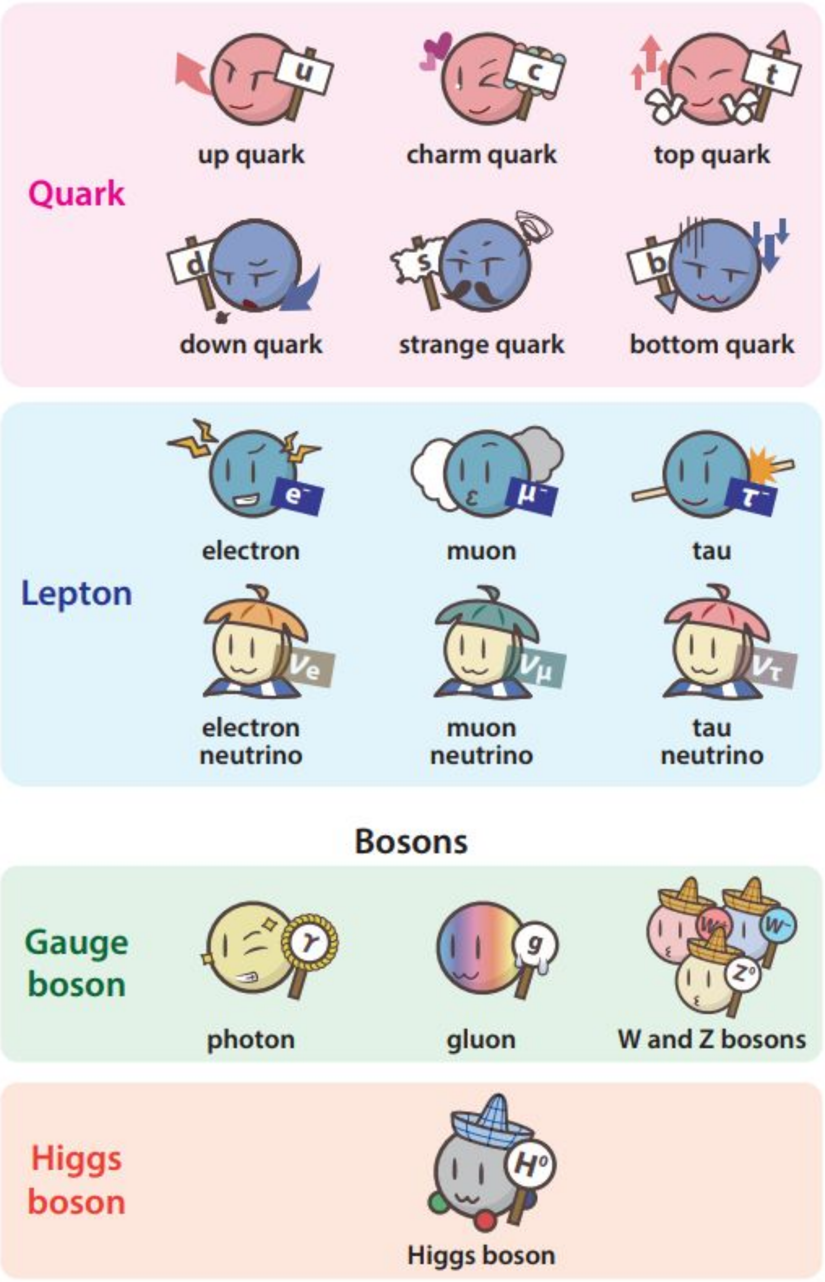
Neutrino Physics

Key Neutrino Facts:

- Neutral particles
- Primarily interact weakly

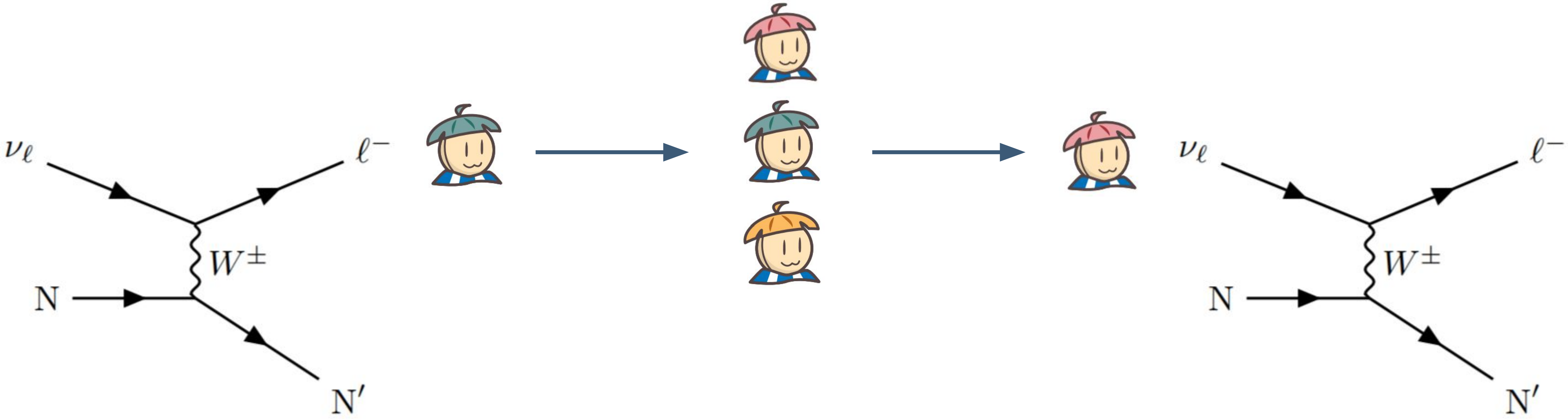
Other Neutrino Facts:

- Nearly massless
- Spin ½ leptons
- Only left-handed



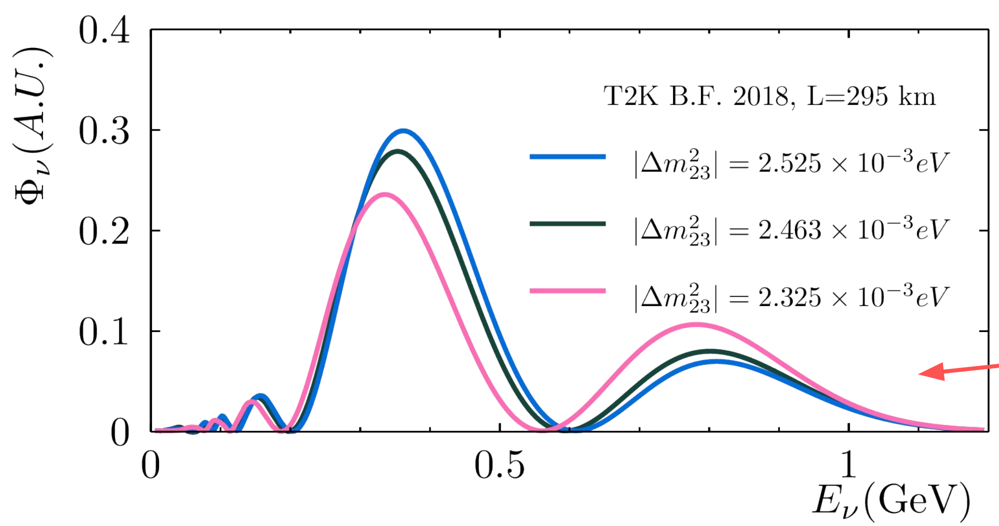

Character illustrations by AKIMOTO Yuki @ higgstan.com
https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/files/NF-pamph-EN.pdf

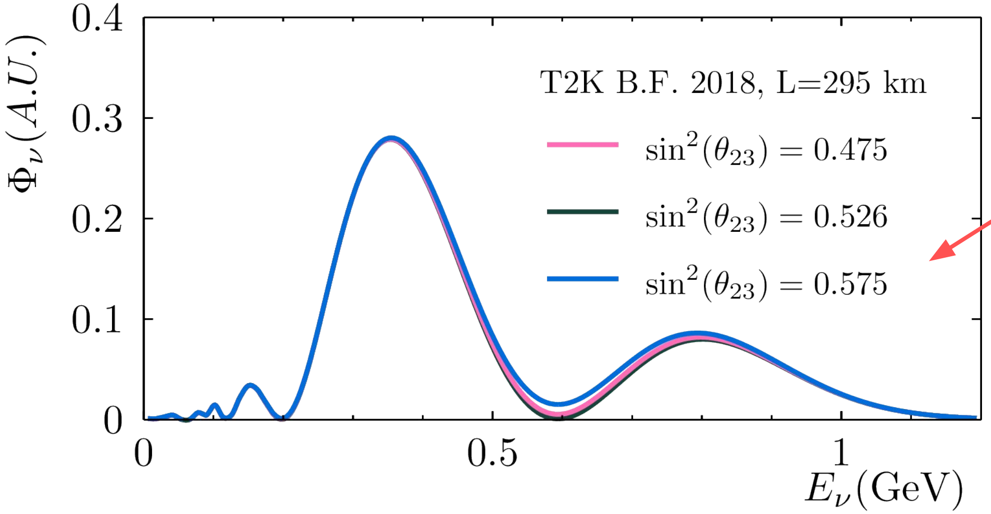
Neutrino Oscillations 101



- Neutrinos interact with matter as a definite flavor
- But travel through space as a superposition of all three flavors
- This flavor change is referred to as neutrino oscillation

Neutrino Oscillations Example

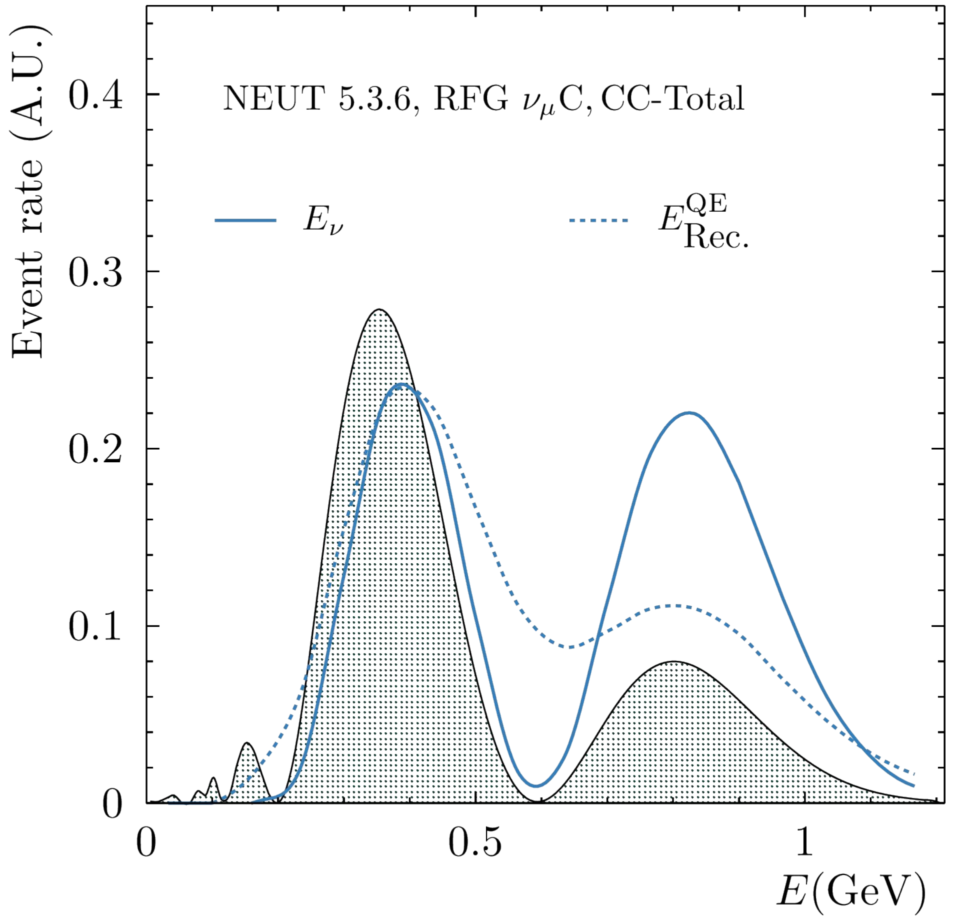




- Muon neutrino disappearance.
- Changing the **mass parameter** changes the **position** of the minimum.
- Changing the **angle parameter** changes the **depth** of the minimum.
- Oscillation probability is a function of **neutrino energy** (and propagation distance)

Measuring Neutrino Energy

- Unable to measure neutrino energy directly
- Need to extract oscillation probability as a function of energy
- Must be reconstructed from observed particles
- Neutrino interaction model provides the mapping from observed variables to energy

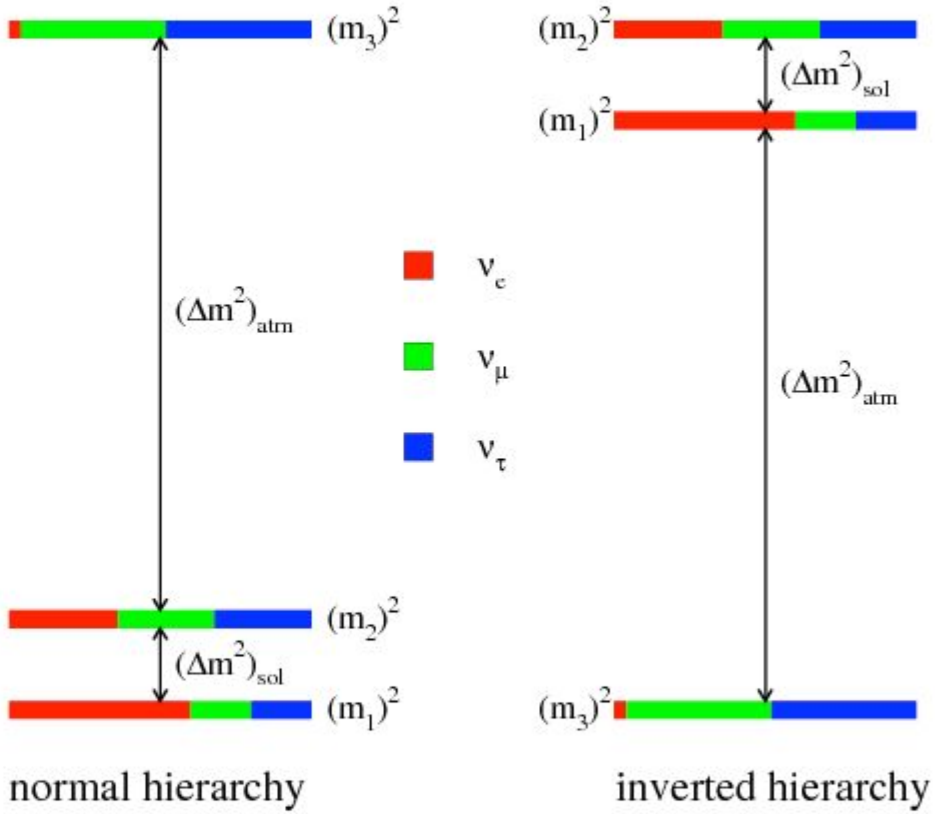


$$E^{QE}_{rec} = \frac{2M_N E_\ell - M_\ell^2 + M_{N'}^2 - M_N^2}{2\left(M_N - E_\ell + |\vec{p}_\ell| \cos\left(\theta_\ell\right)\right)}$$

Unanswered Questions

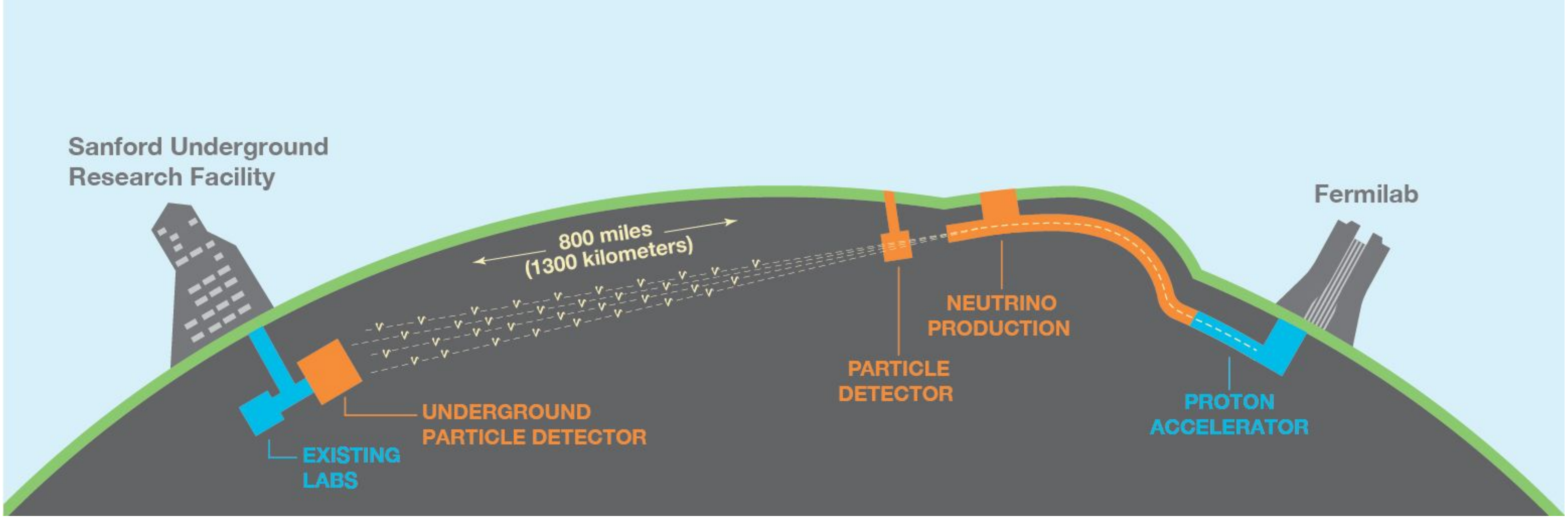
- The neutrino oscillation formula has a term that violates charge-parity symmetry if it is non-zero → not been definitively measured (yet)

- The ordering of the neutrino mass states is undetermined → two possible arrangements exist



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

DUNE: Deep Underground Neutrino Experiment



DUNE is a next-generation long-baseline neutrino oscillation experiment:

- High-intensity (MW-scale) neutrino beam is produced at Fermilab as part of LBNF
- Travels nearly 1300 km to a far detector (FD) at the Sanford Underground Research Facility
- Measured by a suite of near detectors (ND) about 0.5 km from the production target

Physics of DUNE

DUNE has a wide variety of physics goals, both with neutrinos and other physics

- Measurement of neutrino oscillations from both accelerator and atmospheric neutrinos
  - Increase precision of the known oscillation parameters
  - Determine the neutrino mass hierarchy
  - Measure the value of δ_{cp}
- Diverse program of neutrino interaction measurements for different channels, targets, etc.
- Detection of solar neutrinos and neutrinos from a core-collapse supernova
- Searches for beyond the standard model physics
- Searches for proton decay
- Searches for dark matter particles

Role of the DUNE Near Detectors

- The DUNE near detectors have three main goals:
    - Constrain systematic uncertainties for the oscillation physics program
    - Measure and monitor the beam
    - Provide input for the neutrino interaction model

- To achieve these goals, the near detector has several overarching requirements:
    - ND must have a (liquid) argon target to match the FD
    - ND must employ similar technology, i.e. a LArTPC, as the FD
    - ND must be able to promptly detect changes in the beam conditions
    - ND must have similar or better kinematic coverage as the FD
    - ND must be able to operate in the high-intensity environment close to the target

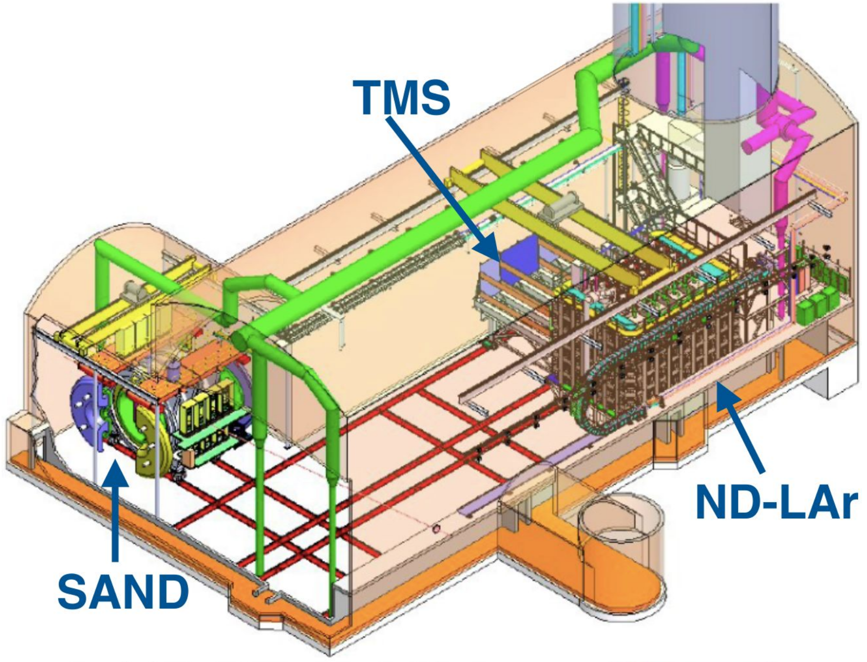
DUNE Near Detector Complex

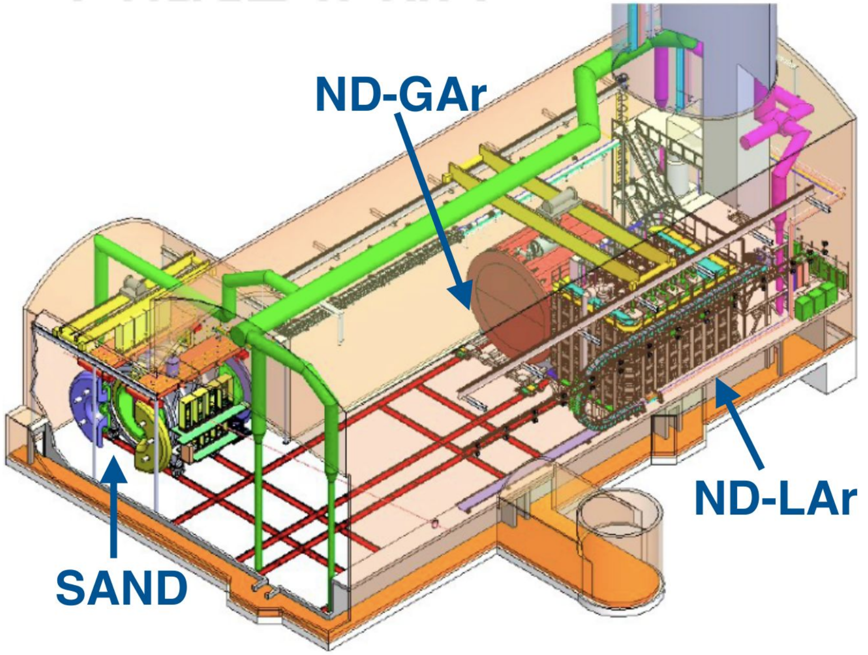
- Dune ND complex has three primary components:
  - ND-LAr: modular liquid argon TPC
  - Magnetized tracker:
    - Phase 1 – The Muon Spectrometer (TMS): a magnetized muon range detector
    - Phase 2 – Upgraded tracker: for example, a magnetized high-pressure TPC (ND-GAr)
  - SAND: System for on-Axis Neutrino Detection

- ND-LAr and the magnetized tracker will be movable off-axis → DUNE PRISM

- DUNE will be built in two phases, with Phase II featuring an upgrade of the near detector complex

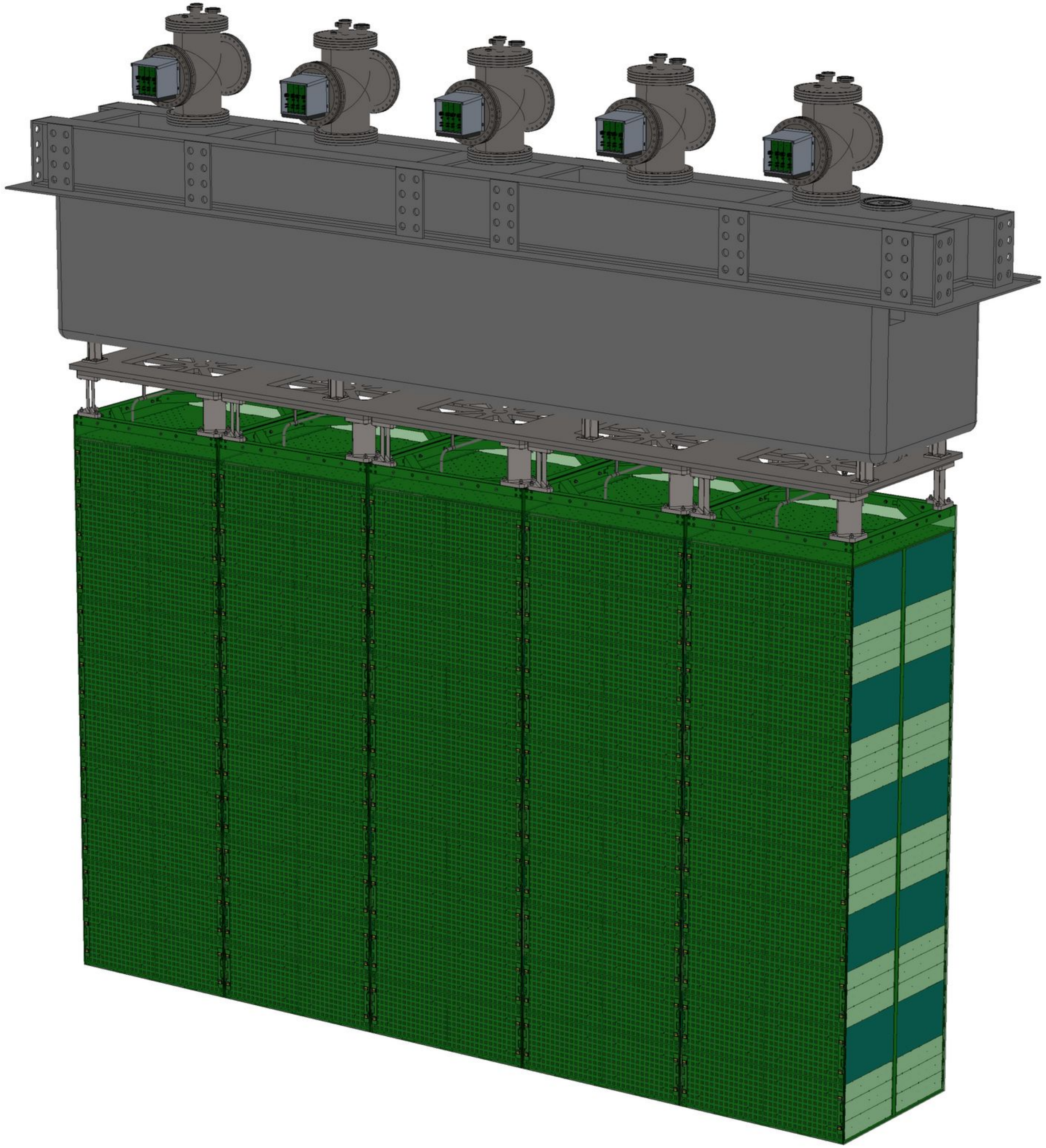
DUNE ND CDR:
https://doi.org/10.3390/instruments5040031





ND-LAr

- Liquid argon TPC based on the ArgonCube design
- Pixel-based readout and optically separated modules to handle the high event rate and track multiplicity in the ND hall
- Light readout for measuring scintillation light from interactions in the liquid
- Composed of 35 modules measuring 1 m x 1 m x 3 m (LxWxH) each all placed in a single cryostat



DUNE ND CDR:
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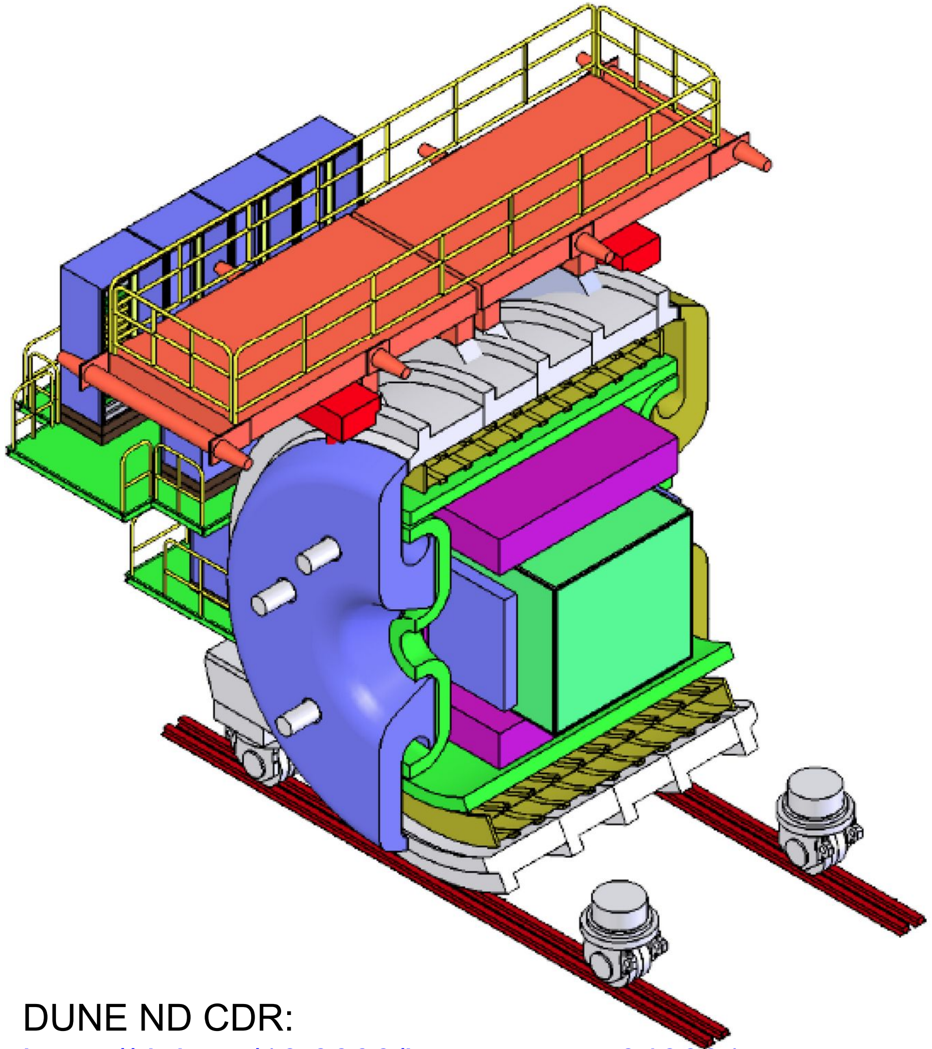
System for on-Axis Neutrino Detection (SAND)

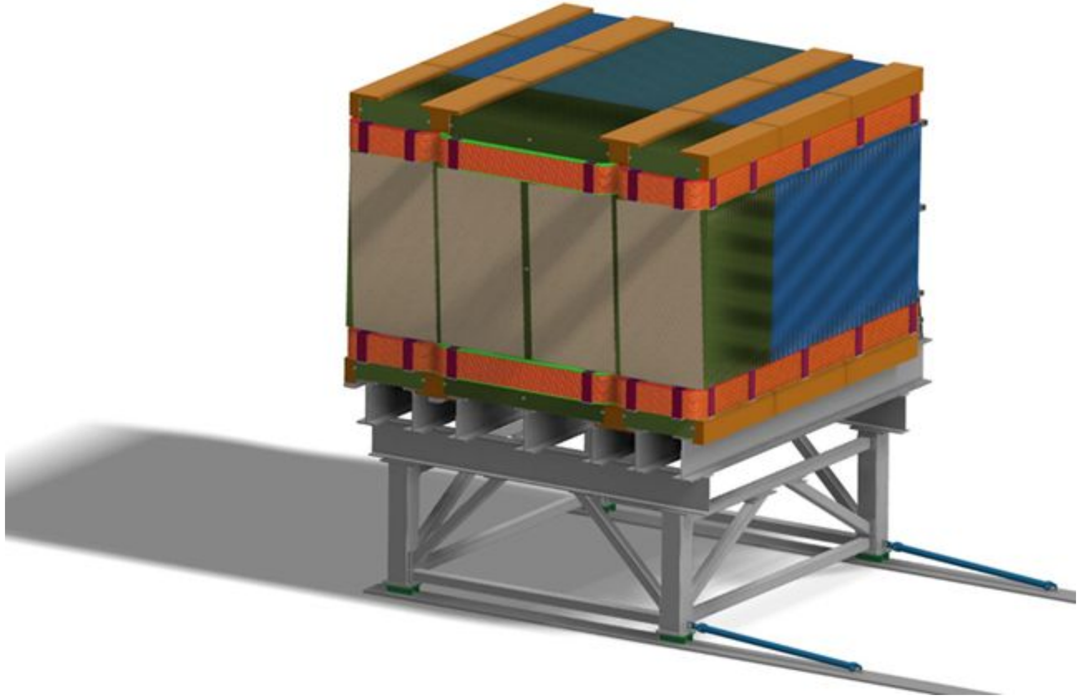


- Primary beam monitor for the ND complex → will remain permanently on-axis
- Repurposing the ECAL and magnet from KLOE experiment
- New central straw tube tracker with (hydro-)carbon target foils and orthogonal planes of Xe-CO2 or Ar-CO2 tubes
- Proposed option of including a small active LAr target in the magnetized region in front of the tracking region

DUNE ND CDR:
https://doi.org/10.3390/instruments5040031

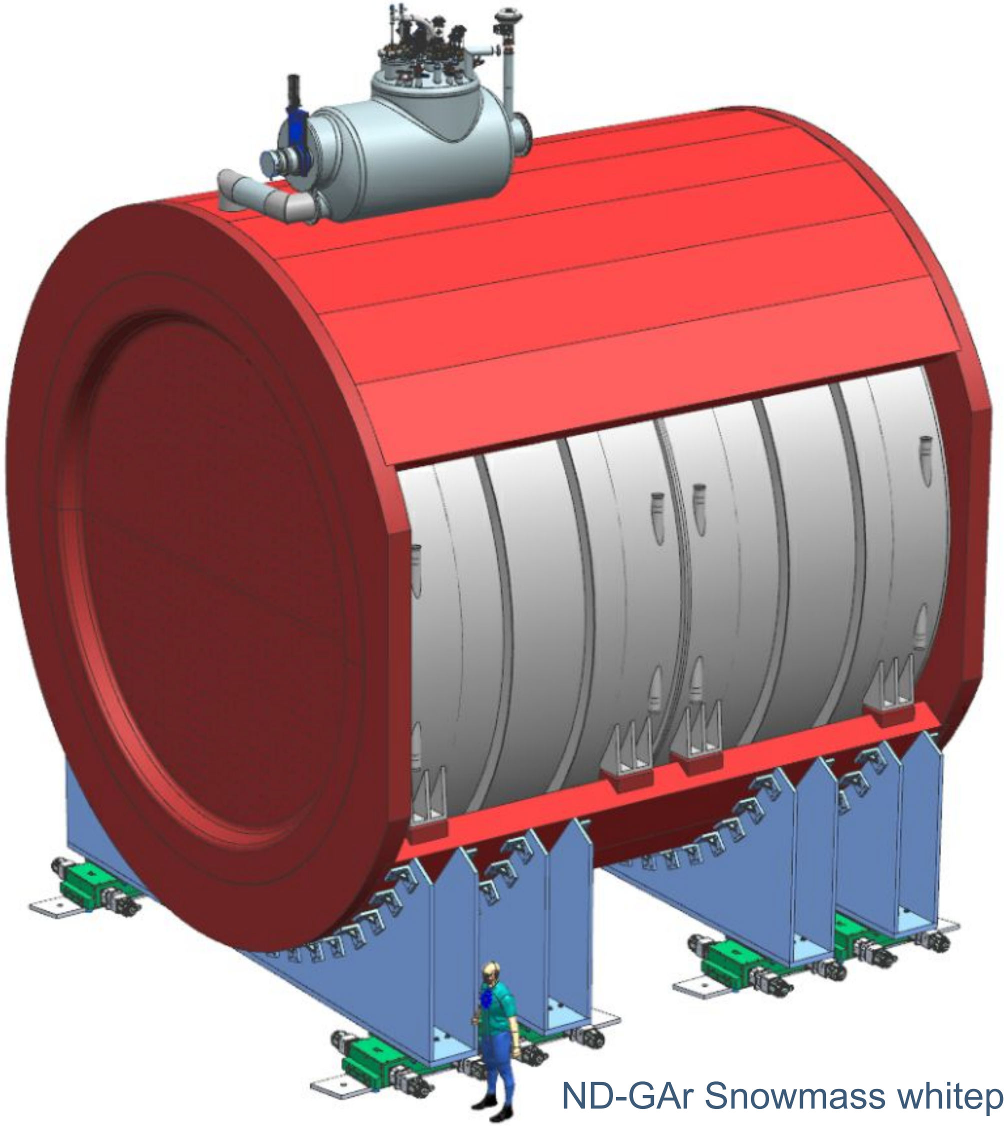
The Muon Spectrometer (TMS)

- Phase I tracker for muons that exit ND-LAr
- Muons above ~1 GeV/c will exit ND-LAr and require a downstream tracker to measure the momentum
- Magnetized muon range detector
    - Momentum by range → resolution comparable to the FD
    - Magnetic field allows for sign-selection with 95+% accuracy
- Will move with ND-LAr as part of PRISM



ND-GAr

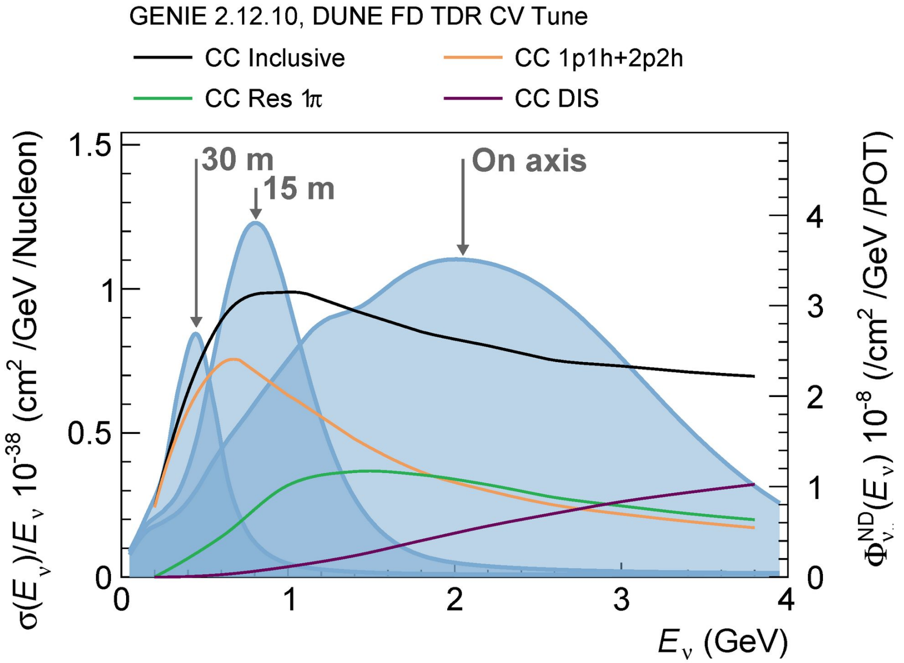
- High-pressure magnetized gaseous argon TPC with calorimeter as an option for the upgraded Phase II near detector
- Still functions as the tracker for muons that exit the ND-LAr → measure momentum and charge
- Gaseous argon provides a low density medium to track charged particles
  - Lower tracking threshold than liquid argon
  - Less multiple scattering of particles
- High-pressure to provide a total 1-ton fiducial volume of argon as a target

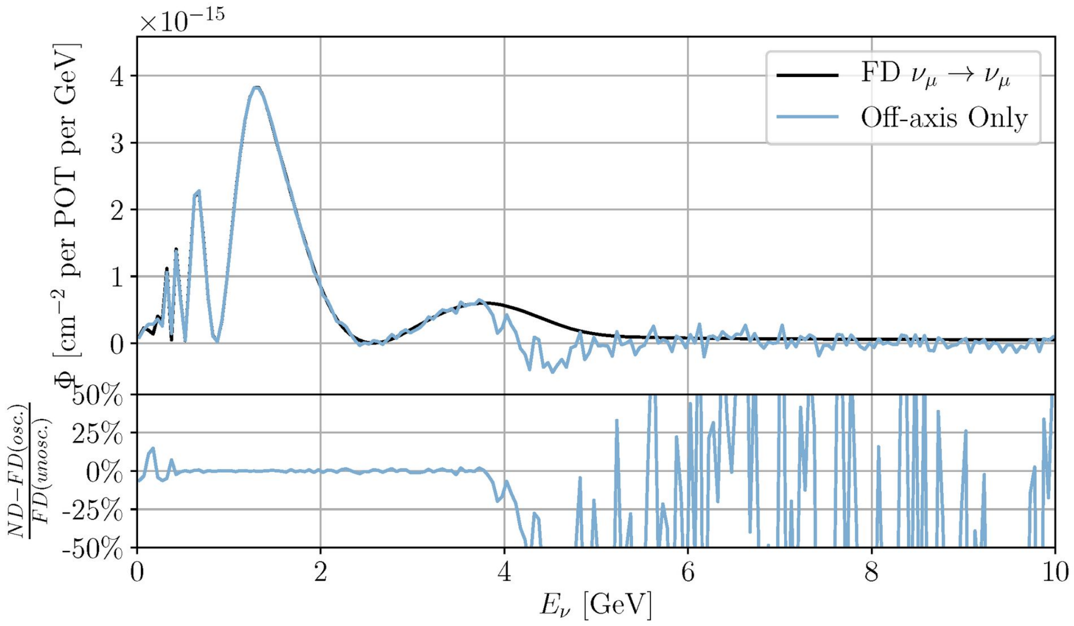


ND-GAr Snowmass whitepaper: https://arxiv.org/abs/2203.06281

DUNE PRISM

- Neutrino energy spectra changes as a function of off-axis angle
- ND-LAr plus the magnetized tracker will be able to travel ~30 m transverse to the beam to sample different off-axis angles
- Linear combinations of off-axis fluxes can be used to construct the far detector flux or Gaussian beam profiles
- Can separate the effects of flux and cross-section uncertainties





DUNE ND CDR:
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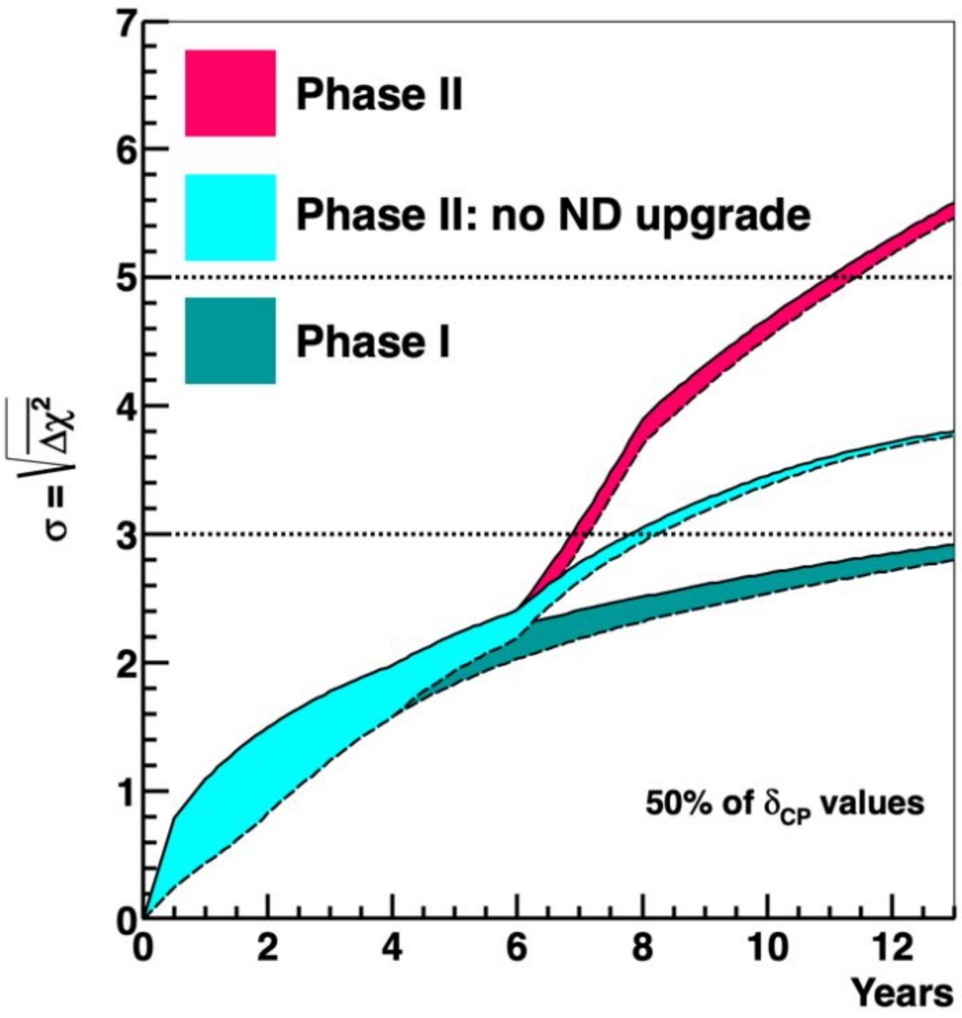
Motivation for ND Upgrade



- Phase I near detector is sufficient for mass ordering and nearly maximal δ_{CP}
- However ND upgrade is required to achieve ultimate 5σ sensitivity
- Without the ND upgrade, the uncertainty from the interaction model will become the limiting factor

Snowmass white paper “DUNE Physics Summary”, arXiv:2203.06100

ND-GAr Performance Requirements

- Classify interactions and measure particles exiting ND-LAr with performance comparable or exceeding the far detector → sign-select particles with a muon momentum resolution of <4% and constrain the energy scale to <1%

- Measure the energy spectrum and multiplicity of protons produced in neutrino interactions

- Measure the energy spectrum and multiplicity of charge pions, particularly up to three pion final states, produced in neutrino interactions

- Detect and measure the rate of neutral pion production for the same energy/momentum range for charged pions

ND-GAr Concept Overview

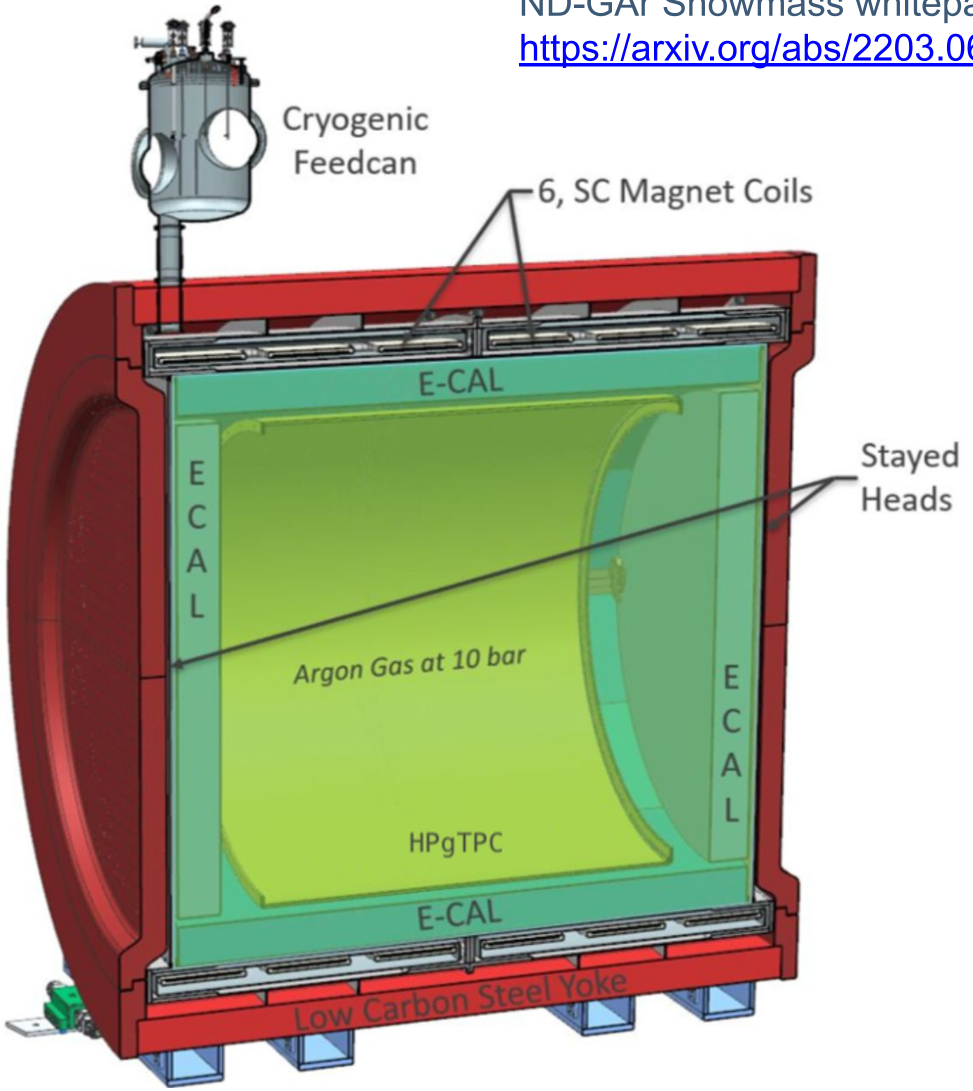
- High-pressure gas TPC (HPgTPC)
    - Argon-gas mixture at 10 atm
    - 5 m diameter x 5 m length cylinder
    - 1 ton fiducial target mass

- Calorimeter surrounding the TPC (barrel plus end caps)

- Superconducting solenoid magnet with partial return yoke (SPY) with a nominal field of 0.5 T

- External muon tagging system

ND-GAr Snowmass whitepaper:
https://arxiv.org/abs/2203.06281

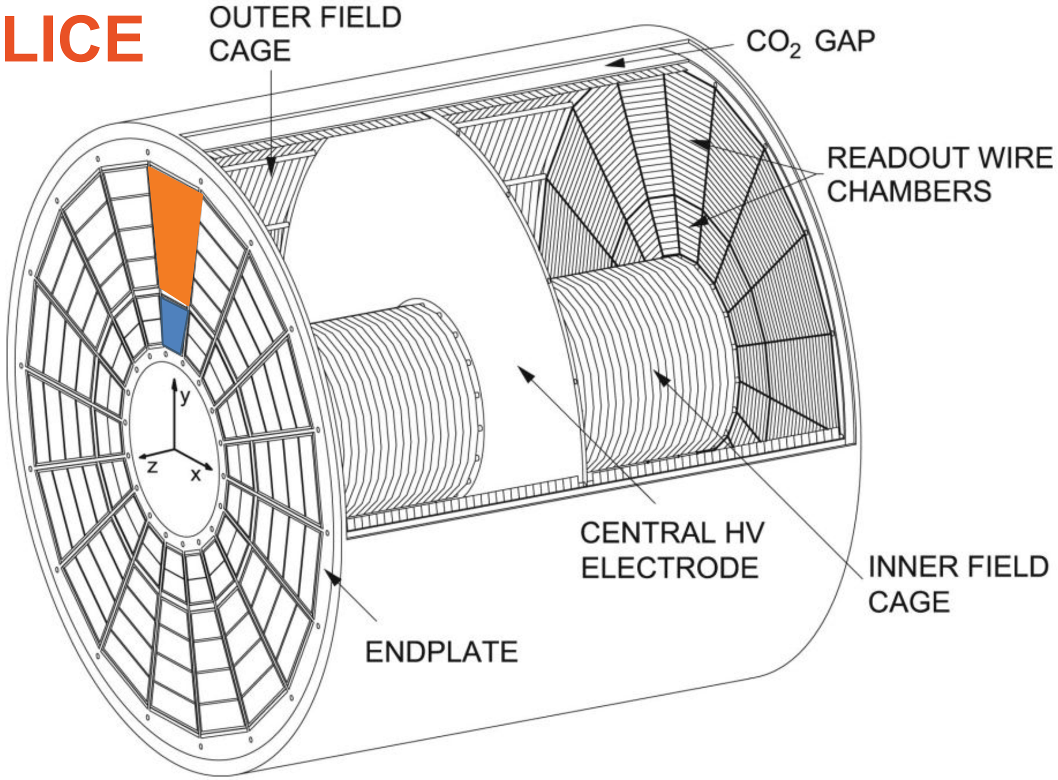


ALCIE NIM https://doi.org/10.1016/j.nima.2010.04.042

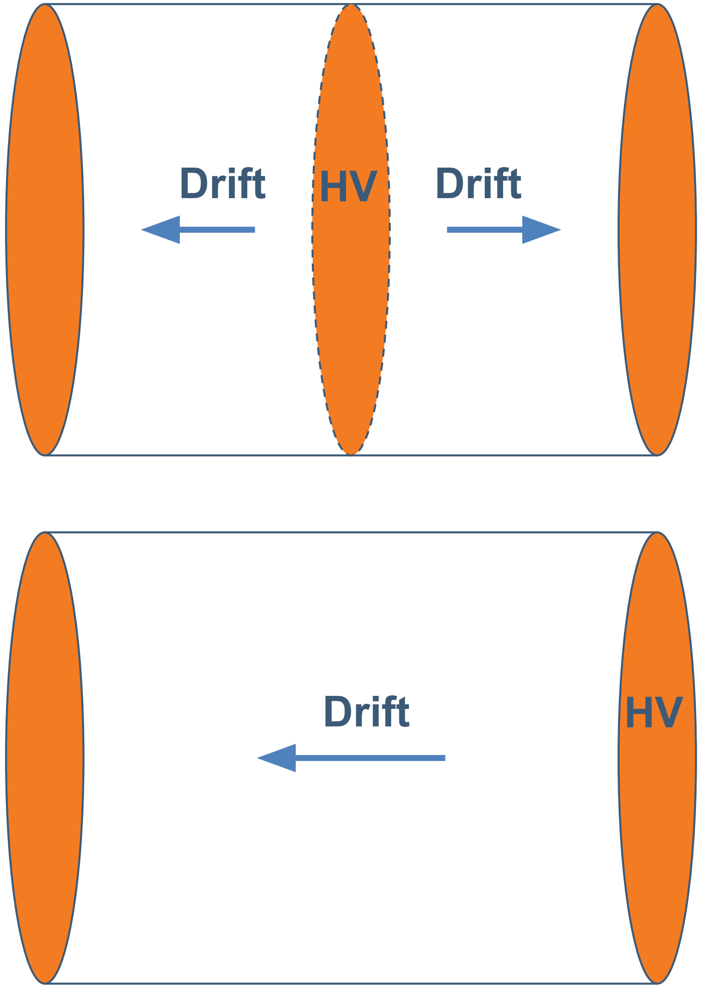
Baseline HPgTPC design

- Based on the ALICE TPC design:
  - 5 m diameter x 5 m length cylinder
  - Double-sided readout and drift
  - Multi-wire proportional readout chambers
- ALICE **inner** and **outer** readout chambers available for use/repurpose after ALICE upgrade
- Opportunity to design new readout chambers using different technology
- Central readout chambers need to be designed and built regardless

ALICE



ND-GAr readout technology



- Repurposing the ALICE wire readout chambers is an option, plus constructing new central chambers
- Could design all new chambers, either still wire chambers or new technology (e.g. GEMs, MicroMegas, etc.)
- Considering the option of a single-sided readout and drift region → reduces number of required chambers and allows for optical readout
- Studying adding an optical readout component to measure light produced from the interactions

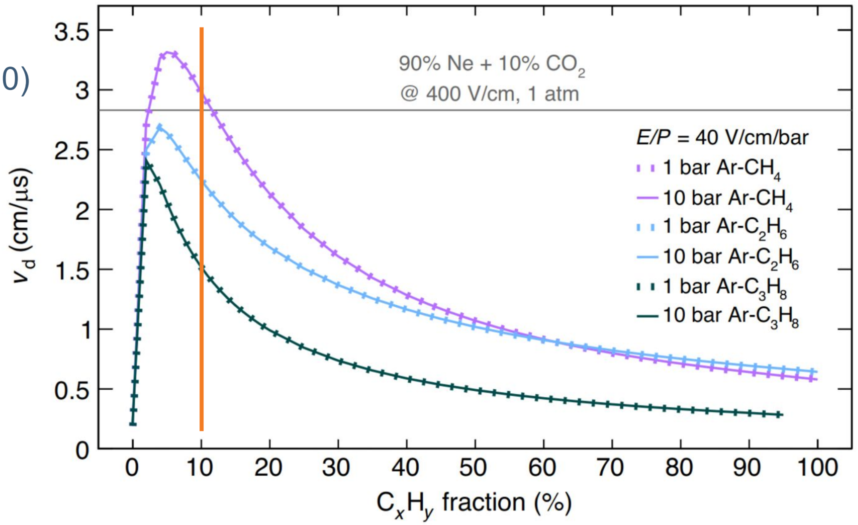
ND-GAr gas mixture

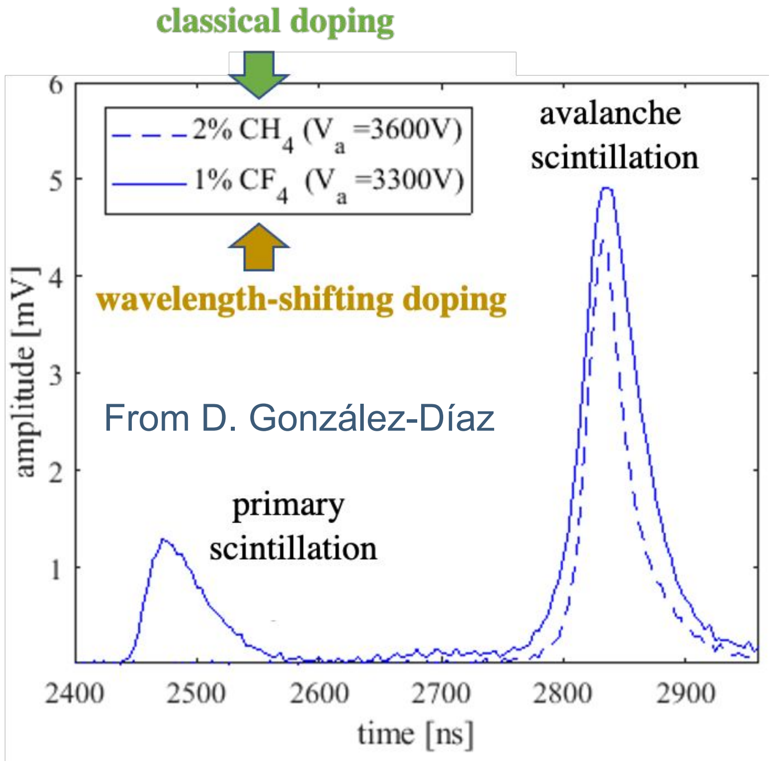
- Gas mixture still being finalized → optimizing gain, quenching, flammability, scintillation light, etc.

- Ar-CH$_4$ (e.g. 90-10) mixture nominal design choice
  - At 10 atm the drift velocity at nominal electric field is a few cm/μs
  - Tune the methane fraction for different drift velocity characteristics and flammability requirements

- Noble gases scintillate in VUV band → photoelectric effect from UV photons causes instability in the wire chambers
  - Dopant gases like methane added to quench the scintillation and increase gain
  - Explore other mixtures such as Ar-CF$_4$ to produce useful scintillation light

P. Hamacher-Baumann et al.,
Phys. Rev. D 102, 033005 (2020)

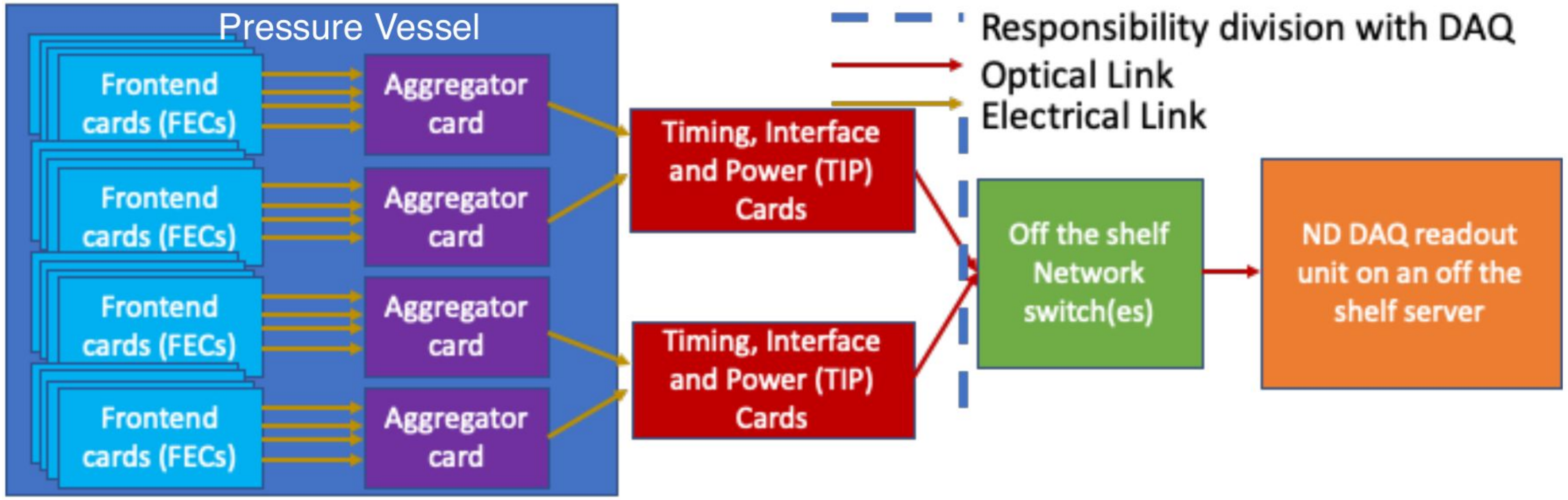




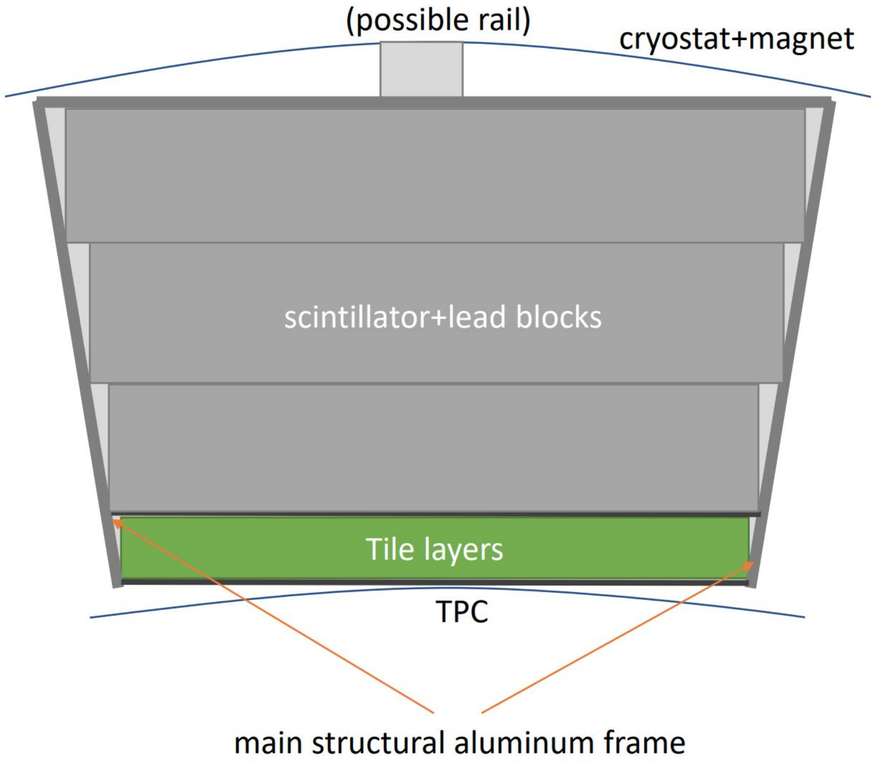
From D. González-Díaz

Charge readout electronics and DAQ

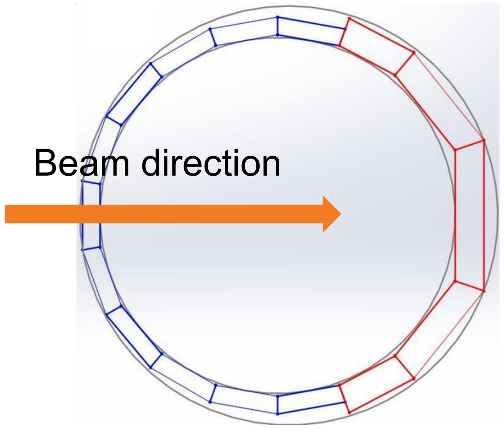
- Digitization at the readout chamber using ALICE SAMPA ASIC-based card (FNAL/Pittsburgh) → ASIC can digitize whatever readout chosen for ND-GAr
- FPGA-based aggregator boards minimize the number feedthroughs in vessel (Imperial)
- Timing, interface, and power (TIP) cards aggregate signal further (Imperial)
- Lower occupancy than heavy-ion collider needs many fewer FPGAs for buffering
- First versions of all these boards have been built and total cost estimate for full ND-GAr would be ~£2M, down from ~$150M using heavy-ion-collider-like system

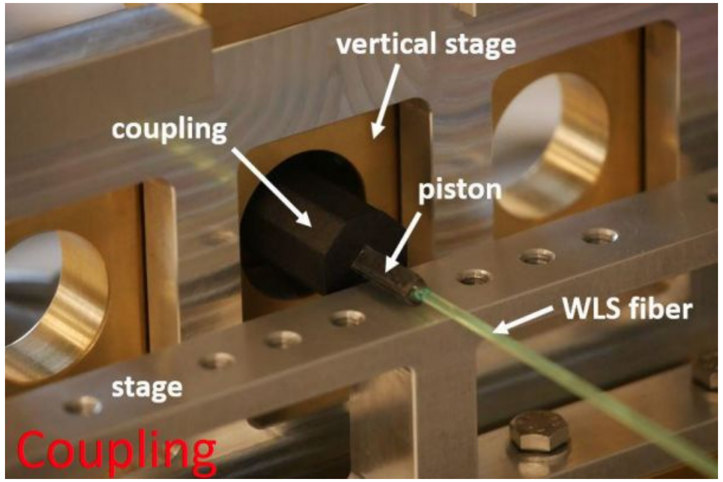


Calorimeter



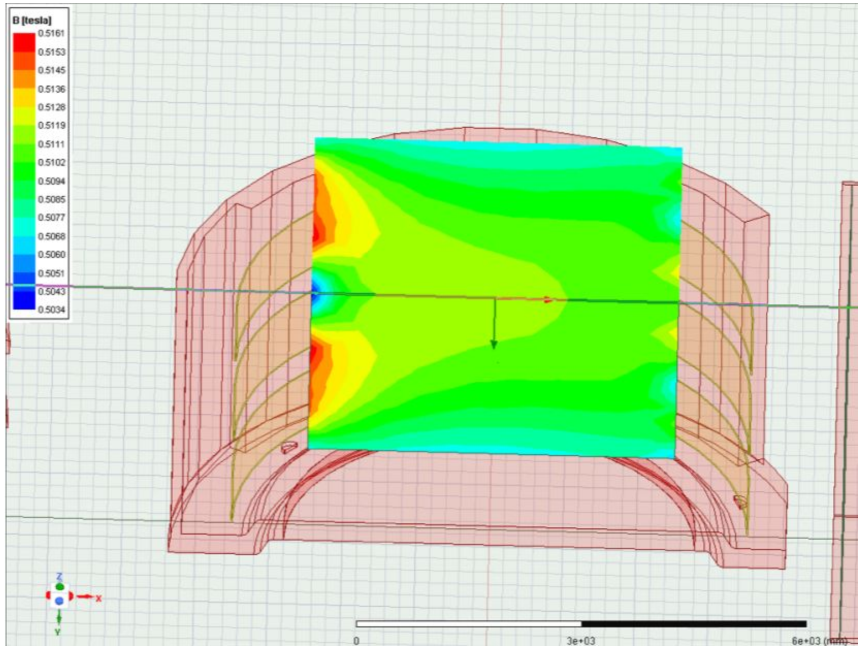
- Based on CALICE analog hadron calorimeter concept
- Two types of lead–scintillator sandwich layers
  - About 32 layers with crossed scintillator strips
  - About 8 layers using tiles for finer granularity
- Studying the physics performance of a symmetric or asymmetric arrangement/design for the modules
- Research and development at MPP and Mainz to design and prototype modules and optimize WLS fiber-to-SiPM coupling

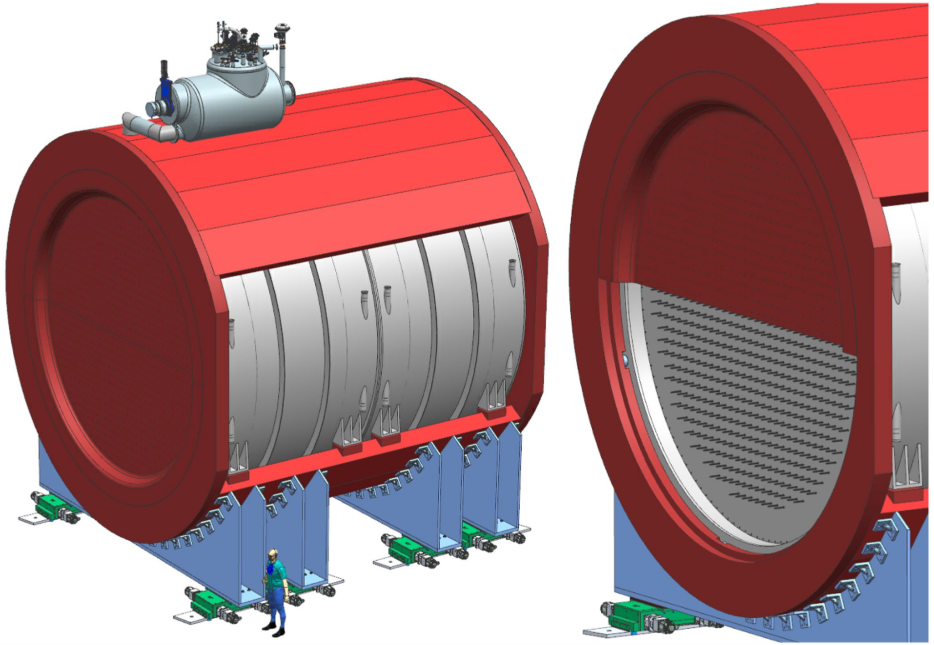




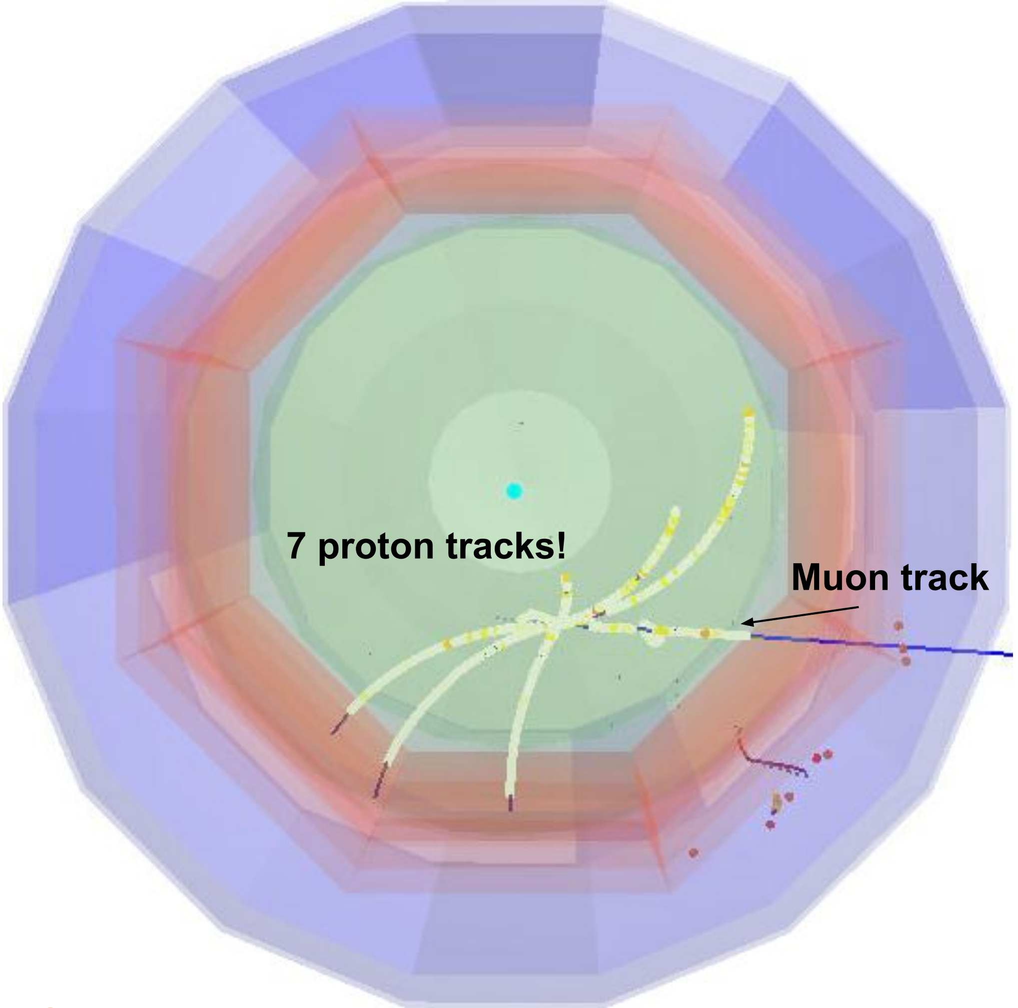
Superconducting magnet

- Solenoid design with a partial return yoke, designed by INFN Genova and FNAL
- Return yoke has “window” cut out to minimize material between the TPC and ND-LAr
- Nominal 0.5 T field with 1% field non-uniformities
- Pressure vessel integrated into the magnet yoke
- Negligible stray field in SAND, a few gauss in ND-LAr





Simulation and reconstruction



ND-GAr event display

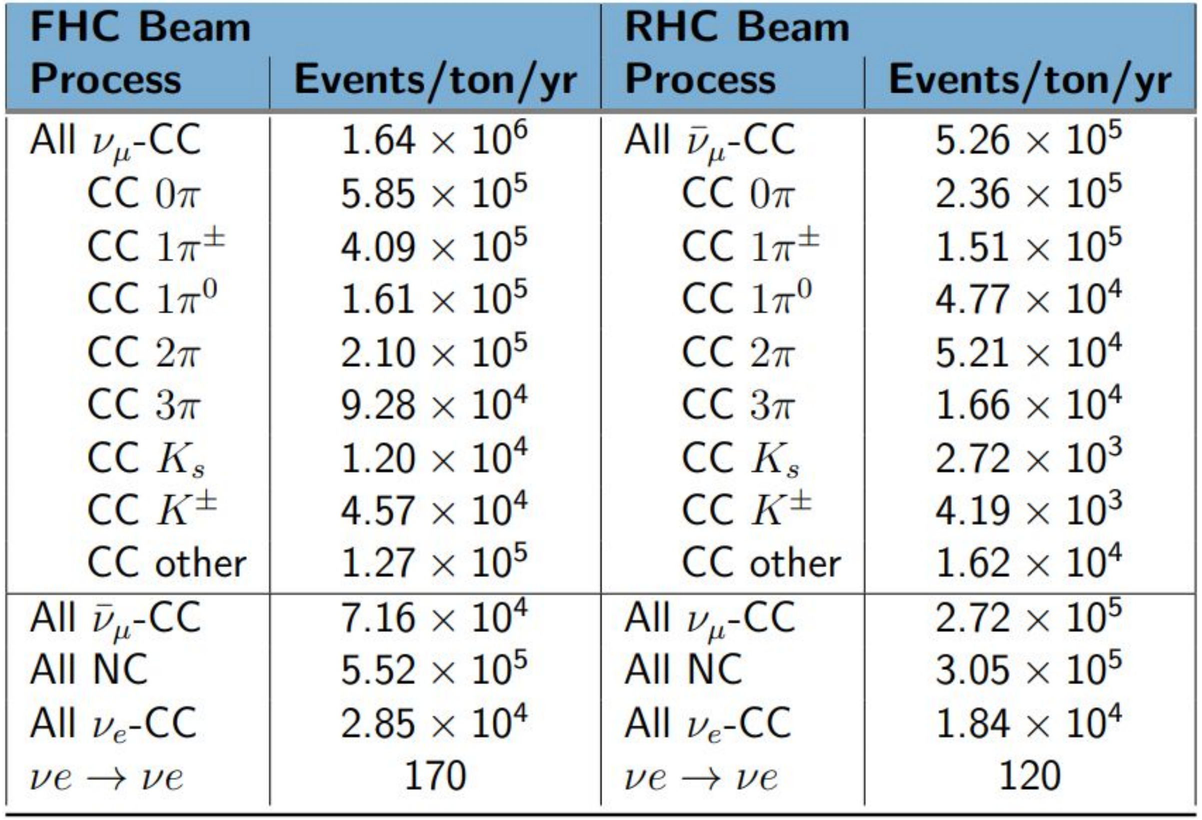
- Full end-to-end simulation and reconstruction software, GAr-Soft, is being used to study and characterize performance

- Muon momentum resolution from charged-current neutrino interactions ~2.7%

- GEANT4 optical simulations also being performed to study optical readout capabilities

- New developments include a tuned Kalman filter for track fitting

Event rate and planned statistics



FHC Beam		RHC Beam	
Process	**Events/ton/yr**	**Process**	**Events/ton/yr**
All ν_μ-CC	1.64×10^6	All $\bar{\nu}_\mu$-CC	5.26×10^5
CC 0π	5.85×10^5	CC 0π	2.36×10^5
CC $1\pi^\pm$	4.09×10^5	CC $1\pi^\pm$	1.51×10^5
CC $1\pi^0$	1.61×10^5	CC $1\pi^0$	4.77×10^4
CC 2π	2.10×10^5	CC 2π	5.21×10^4
CC 3π	9.28×10^4	CC 3π	1.66×10^4
CC K_s	1.20×10^4	CC K_s	2.72×10^3
CC $K^\pm$	4.57×10^4	CC $K^\pm$	4.19×10^3
CC other	1.27×10^5	CC other	1.62×10^4
All $\bar{\nu}_\mu$-CC	7.16×10^4	All ν_μ-CC	2.72×10^5
All NC	5.52×10^5	All NC	3.05×10^5
All ν_e-CC	2.85×10^4	All ν_e-CC	1.84×10^4
$\nu e \rightarrow \nu e$	170	$\nu e \rightarrow \nu e$	120

DUNE ND CDR:
https://doi.org/10.3390/instruments5040031

- The planned 1.2 (2.4) MW neutrino beam will produce tens to hundreds of thousands of events for a variety of exclusive channels *per year*
- Statistical uncertainties to be insignificant for most channels (eventually)
- Enables precise measurements using very fine kinematic binning or measurements with several dimensions

Low momentum tracking

- Gaseous argon target provides a low-density medium for particle tracking
- Proton tracking threshold is currently estimated to be ~5 MeV kinetic energy (roughly corresponds to ~1 cm track length in ND-GAr)
- Very important for discrimination between neutrino interaction generators
- Improve neutrino energy reconstruction by identifying low energy protons (or pions)

DUNE ND CDR:
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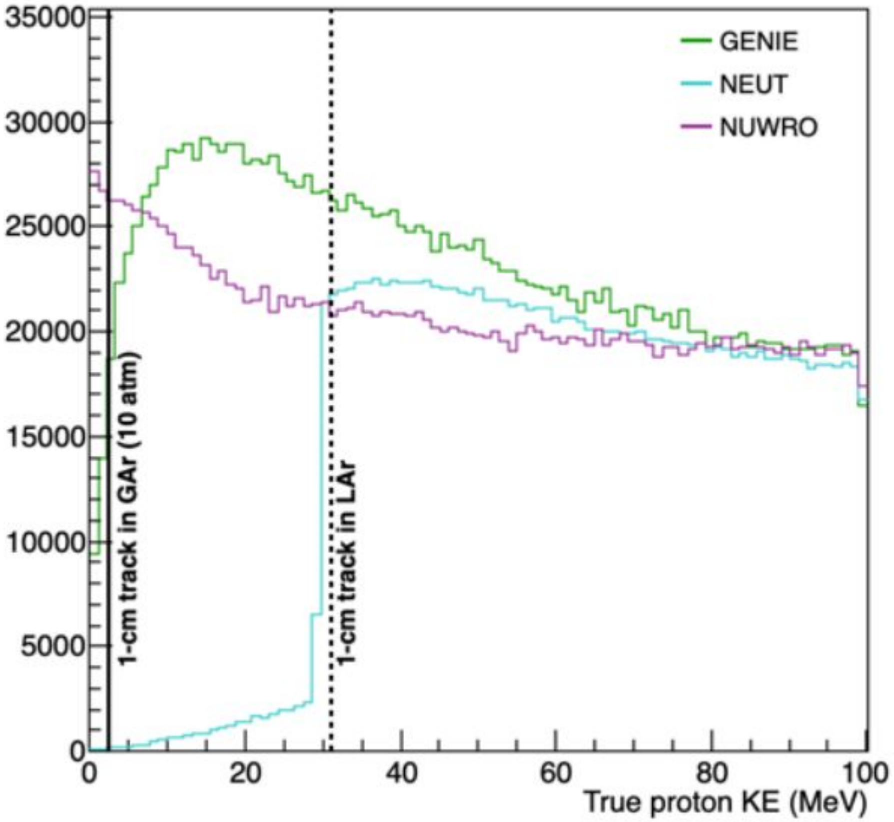
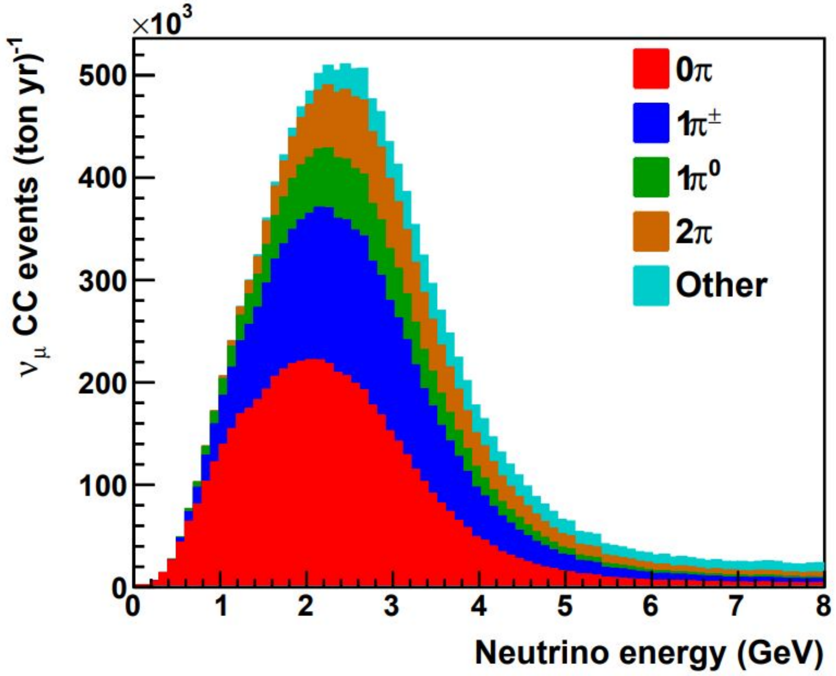
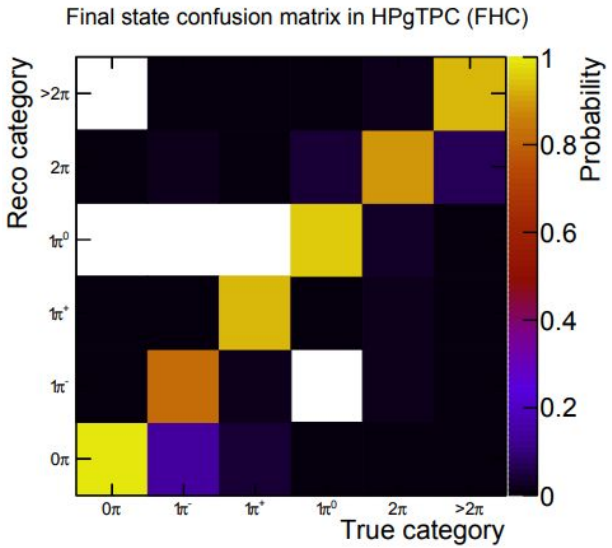


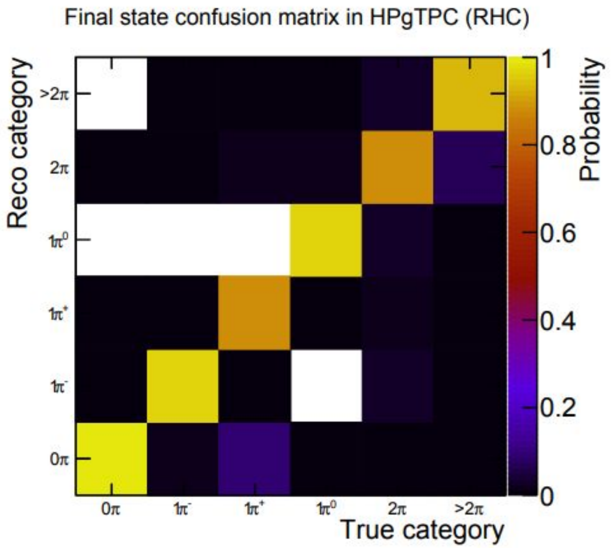
DUNE ND CDR: https://doi.org/10.3390/instruments5040031

Pion multiplicity tracking

- Many different pion production channels due to the wide-band beam
- Migrations between pion channels and missing pions can cause biases in the neutrino energy reconstruction
- ND-GAr offers excellent pion type and multiplicity identification:
  - Tracks from low momentum pions easily visible
  - Great two-track separation to count multiple pions
  - ECAL for identifying neutral pions
  - TPC PID to separate pions from protons

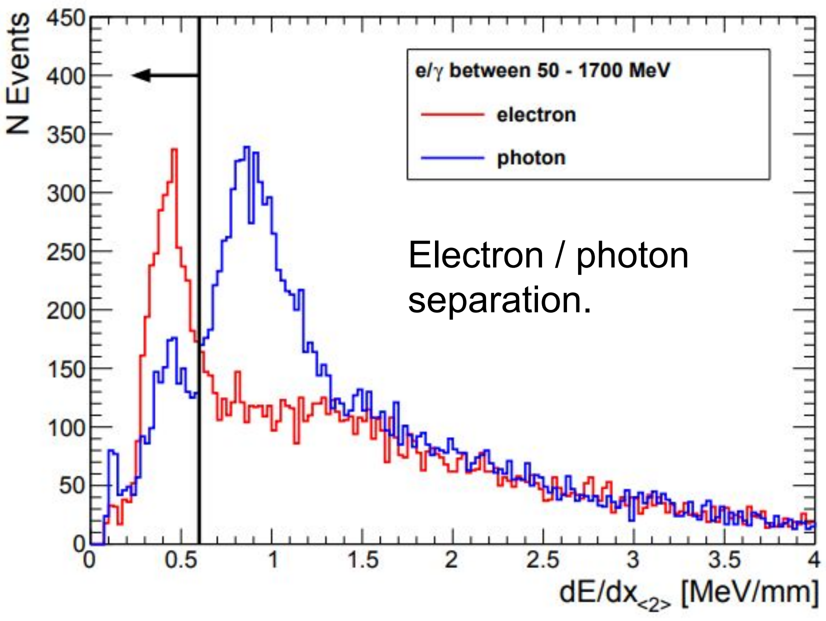




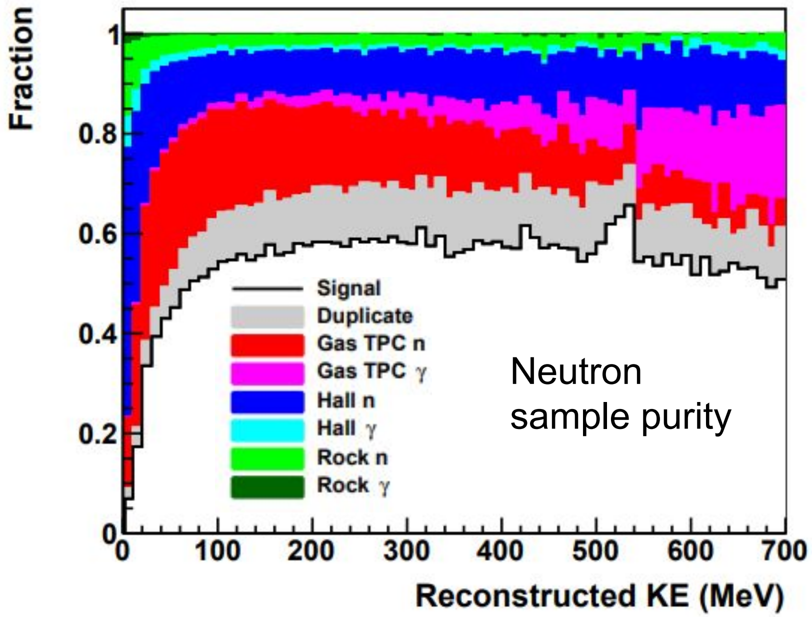


Neutral particle detection

- ECAL provides efficient identification of photons and neutral pions → measure neutral pion production rate.
- Conversions from photons (either from interactions or neutral pions) can mimic an electron neutrino appearance event.
- Additionally the ECAL can identify neutrons produced from neutrino interactions.
- Currently neutron samples with ~45% efficiency and 40-55% purity can be selected with the ECAL.



Electron / photon separation.



Neutron sample purity

DUNE ND CDR:
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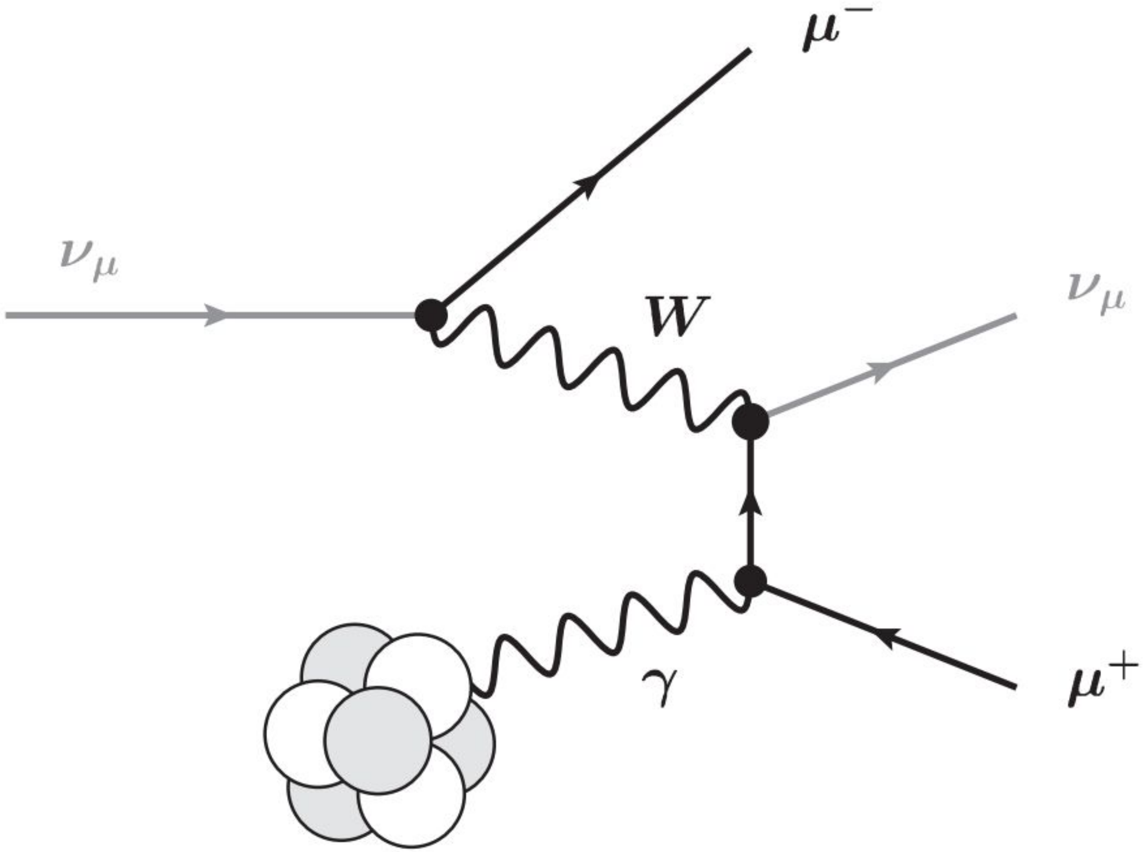
Physics Beyond the Standard Model

- A variety of beyond the standard model signatures can be searched for, such as:
  - Neutrino tridents
  - Heavy neutral leptons
  - Light dark matter
  - Axions (and axion-like particles)
  - Anomalous tau neutrinos

- Backgrounds for these rare processes typically scale with mass whereas the signal scales with volume

- ND-GAr as a large-volume and low-density detector well suited for BSM searches

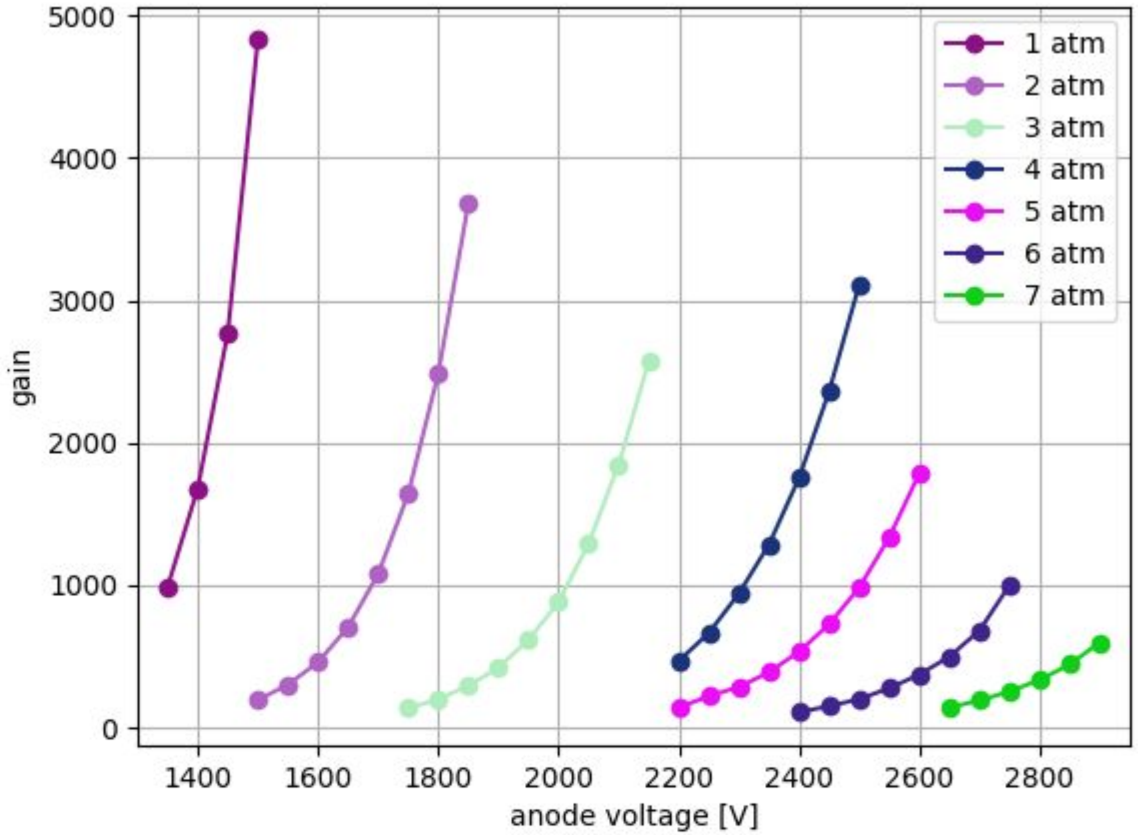


From PRD 100, 115029 (2019)

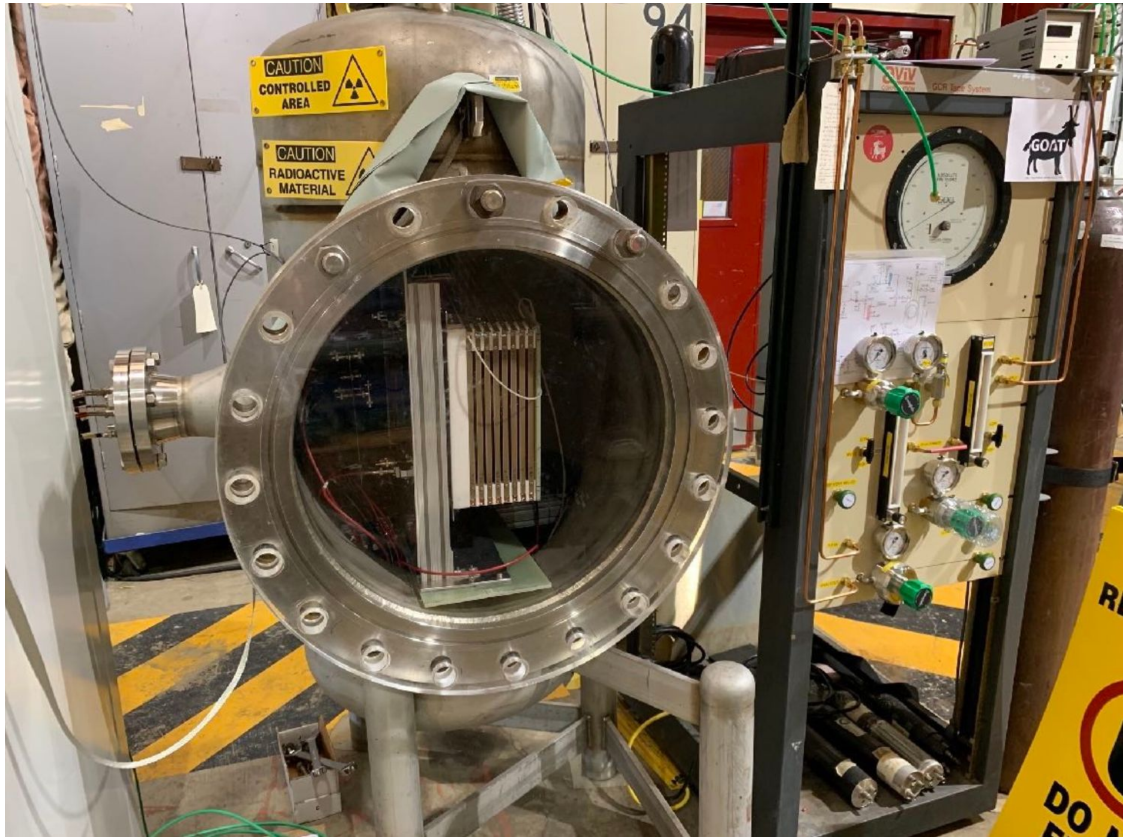
Gaseous-argon Operation of an ALICE TPC (GOAT)

- Test stand for operating an ALICE inner readout chamber with argon-gas mixture at high pressure → up to 10 atm
- Collected data with Ar-CO_2 and Ar-CH_4 at multiple pressure settings
- Gain measured using a reference pulse and an ^{55}Fe source
- Analysis on-going for Ar-CO_2 higher than 7 atm and the Ar-CH_4 dataset

Ar-CO_2 (90-10)

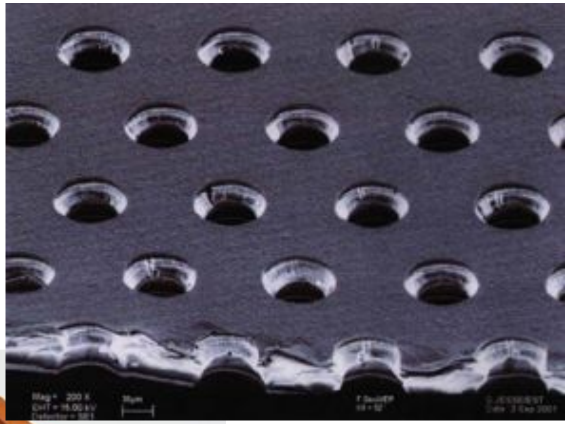


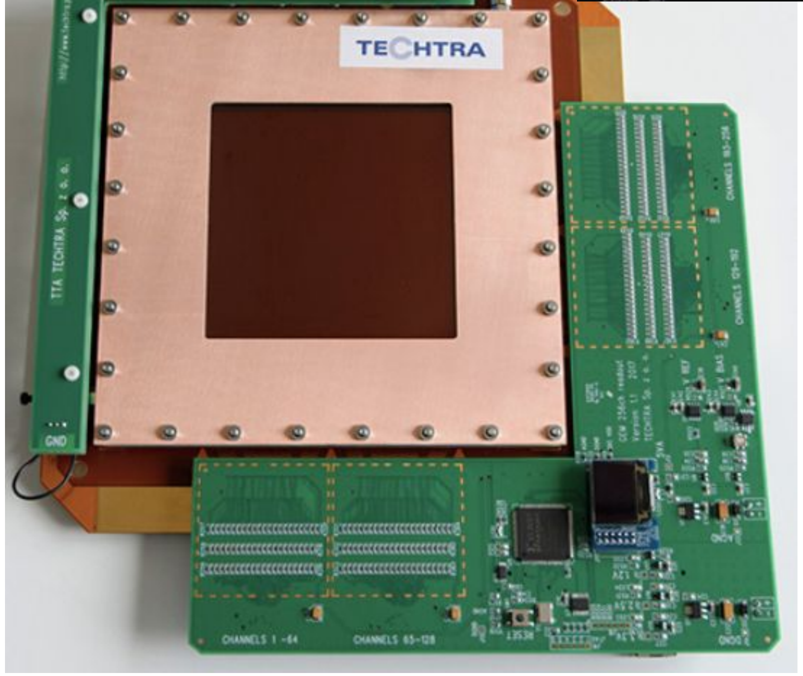
Pictures of GOAT



- Located at FNAL proton assembly building

GEM Over-pressured with Reference Gases (GORG)





- Evolution of GOAT to GORG → test the operation of gas-electron multiplier (GEM) readout at high pressure
- Calibrate GEM gain at high pressure
- Demonstrate comparable gain to the ALICE wire-based readout chambers
- GOAT chamber in the process of being repurposed for GEM operation at Fermilab

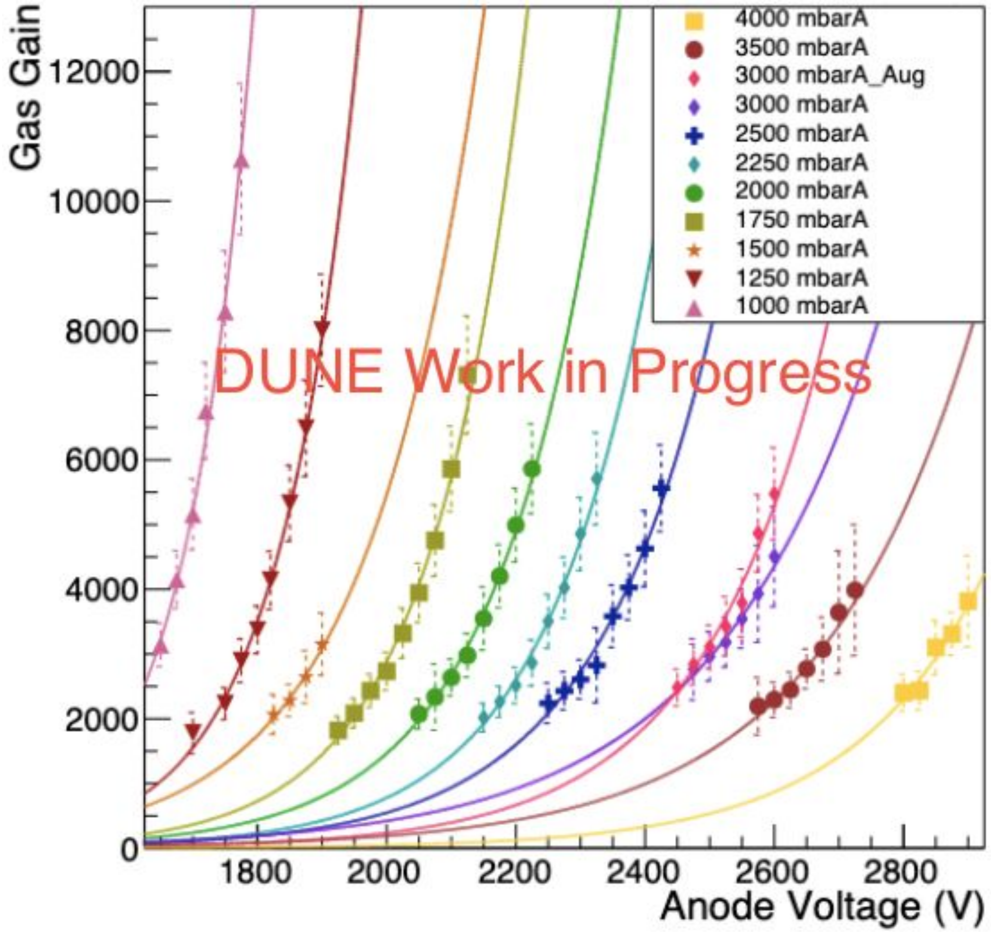
Test stand of an Overpressurized Argon Detector

- Test stand to study and operate multiple components for ND-GAr
- Perform a full slice test of the electronics and DAQ for a single ALICE outer readout chamber
- Reconstruction of tracks with entire electronics chain and software
- Demonstrate long-term operation of electronics and chamber at high pressure
- Observe kinked tracks from hadronic interactions on argon
- Measure proton and pion scattering on argon at high pressure

Gain studies with TOAD

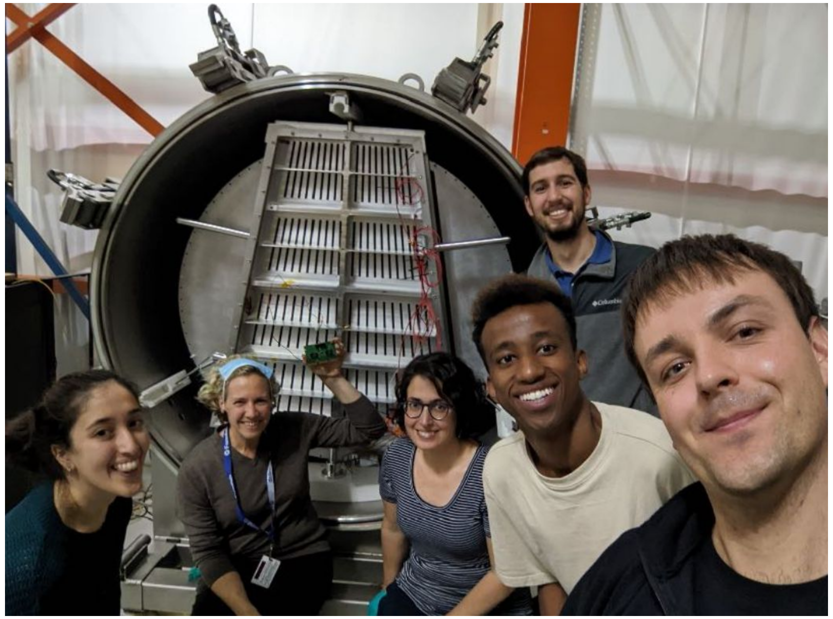
- Performed gain studies of an ALICE outer readout chamber at high pressure
- Used an Ar-CO_2 (90-10) mixture up to 4 atm
- Data collected with several radioactive sources
- Also used to study optical readout of interactions in the gas
- See Deisting, Waldron et al., Instruments 2021, 5(2), 22

Ar-CO2 (90-10)



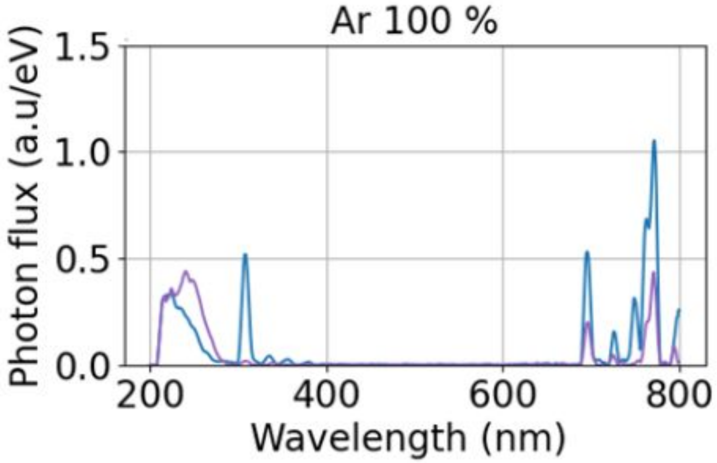
TOAD in a Test Beam

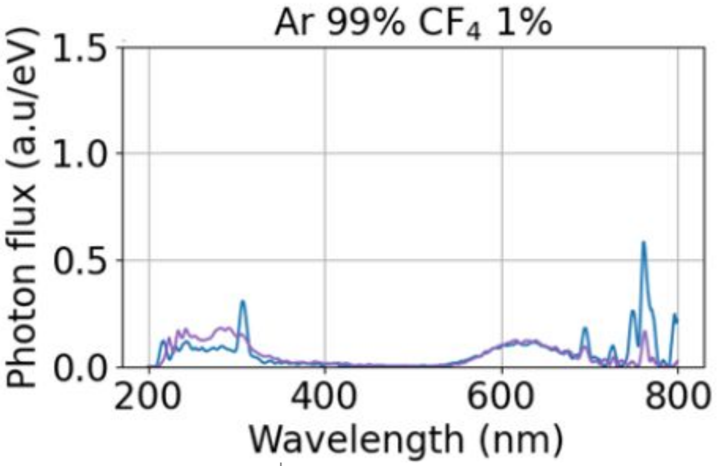
- Shipped to FNAL and arrived last fall
- Planned to operate in a test beam this year
- Has been fully reassembled and is in the process of being recommissioned
- Will operate using an $Ar\text{-}CH_4$ mixture up to 5 atm
- Groups involved include Imperial, Royal Holloway UL, FNAL, Pittsburgh, Queen Mary UL, Oxford, Warwick, U College London, Colorado Boulder, Minnesota Duluth



Argon gas scintillation

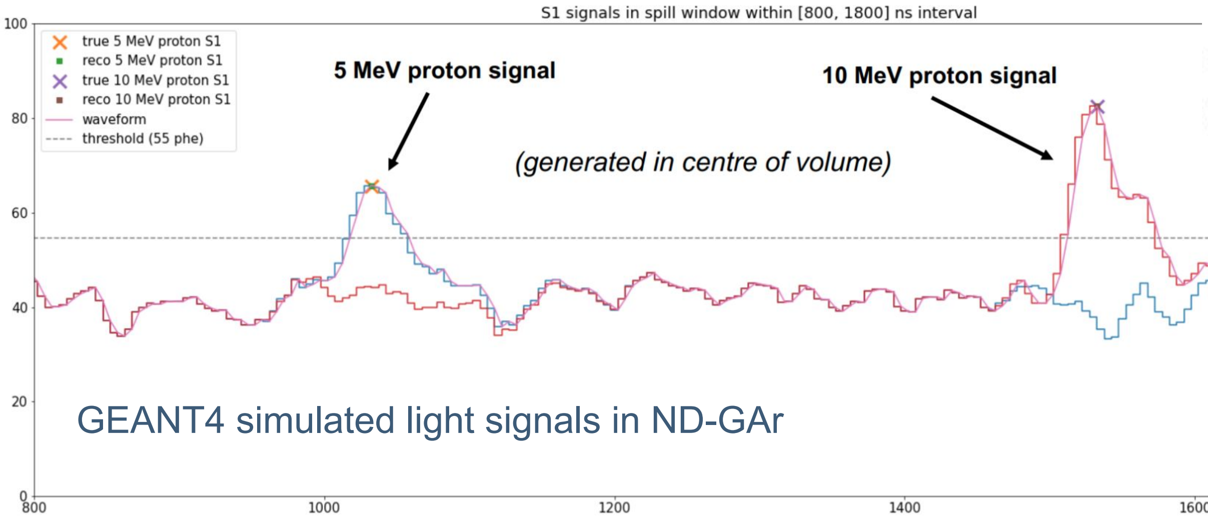
- R&D underway at IGFAE and IFIC in Spain to characterize scintillation of argon gas mixtures and optimize light collection
- Performed measurements of light yield and resolution using an Ar-CF_4 (99-1) mixture
- CF_4 acts as a wavelength-shifter producing light in the visible band





GATO

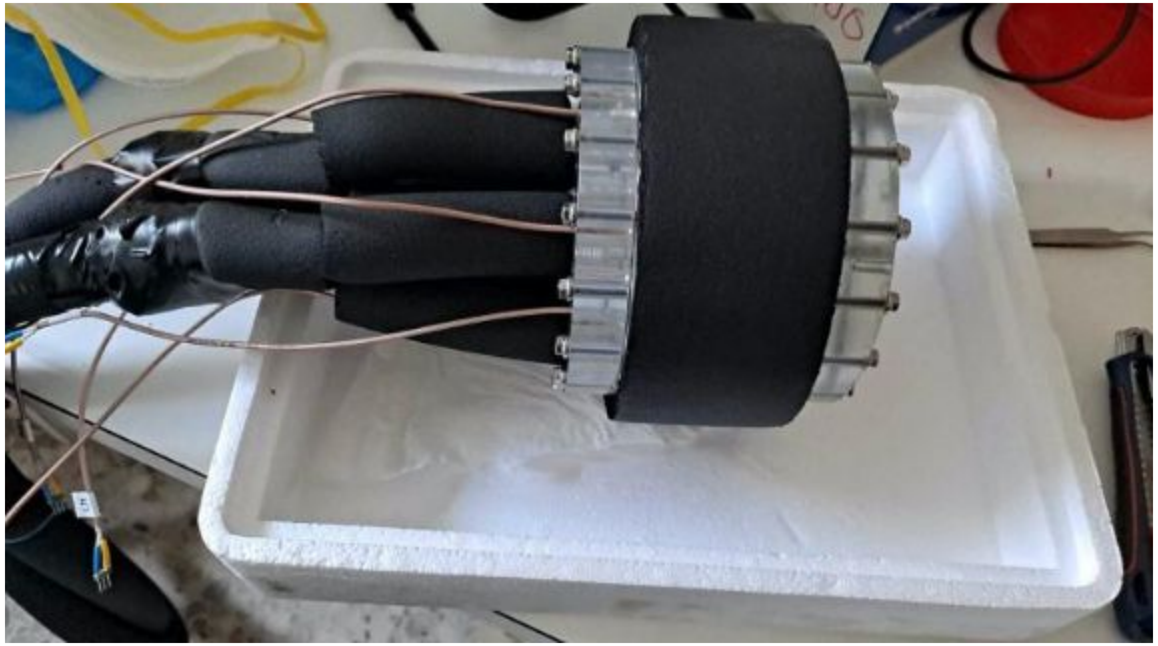
ND-GAr T0 demonstrator

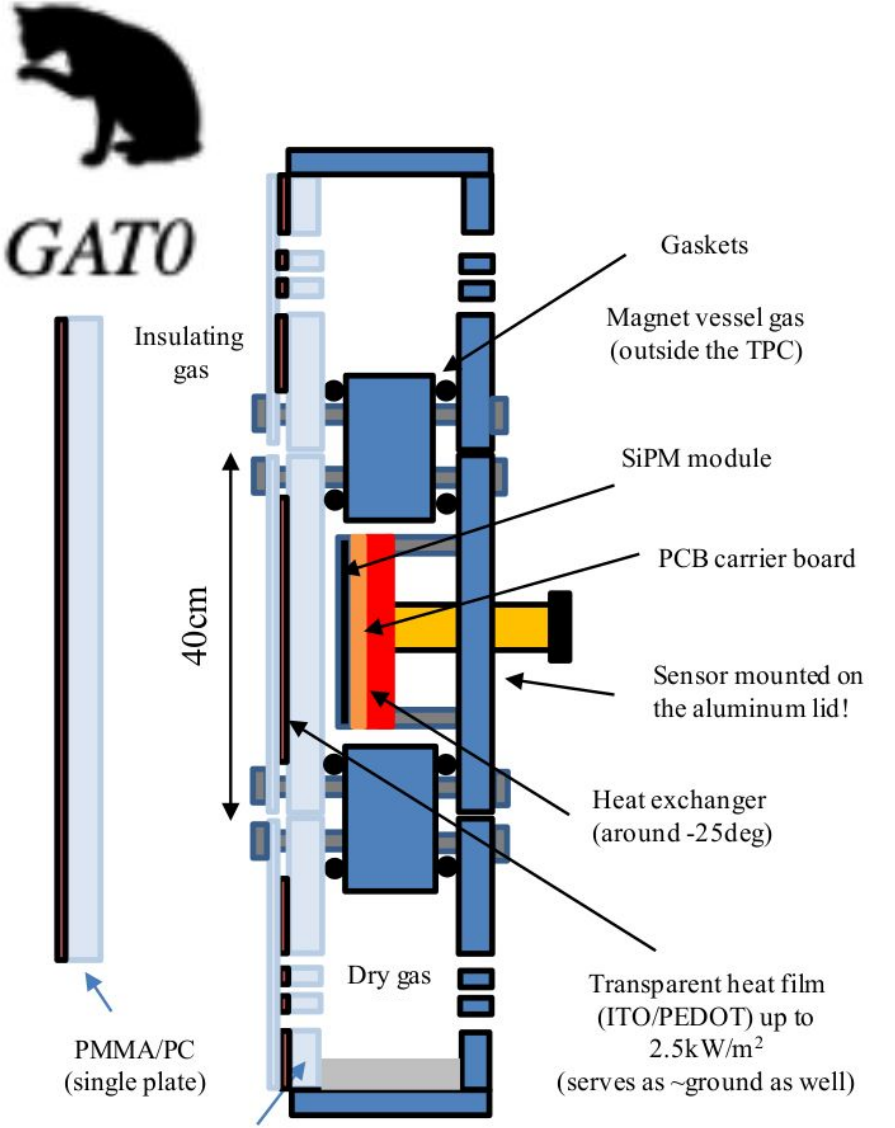


GEANT4 simulated light signals in ND-GAr

Light collection and readout R&D

- Light currently measured with PMTs, but a prototype chamber with a cooled SiPM plane is in development
- Reduce dark count rate to achieve lower tracking threshold





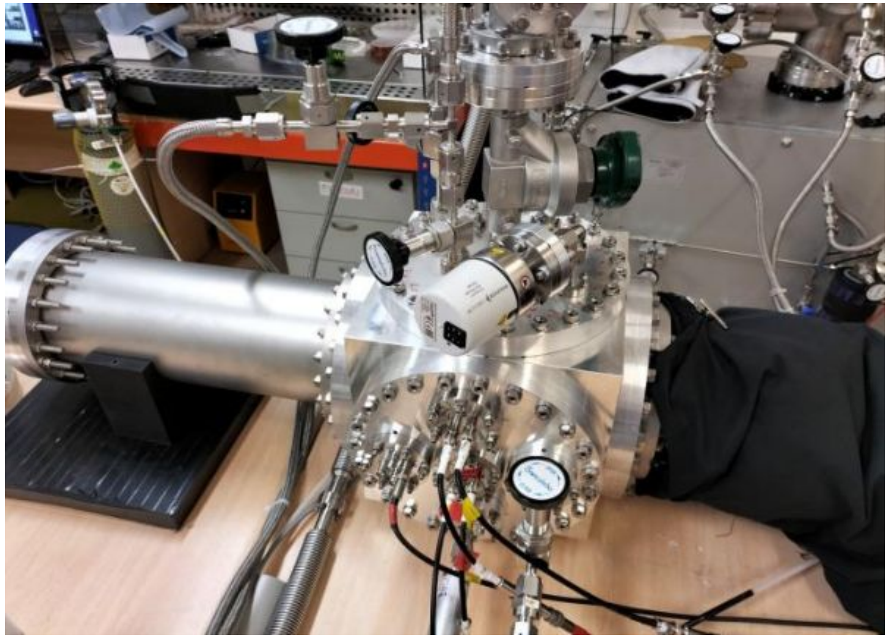
Using individual PMMA/PC windows (20mm-thick) to minimize thermal stress (due to TEC) down to manageable levels

* Not to scale

GAT0 First Light

GAT0

- Chamber was successfully operated with Ar-CF_4 (99-1) at 1 bar with a double thick-GEM structure
- S1 and S2 light signals read with PMTs



10mV/ -25.000mV
2mV/ 1.4250mV
5mV/ -7.2500mV
500.0ns/ -2.000us
1 -82.8mV Stop

Summary
Acquisition
Normal
2.50GSa/s 200MHz
Channels
DC 50Ω 1.00:1
DC 50Ω 1.00:1
DC 50Ω 1.00:1
DC 50Ω 1.00:1

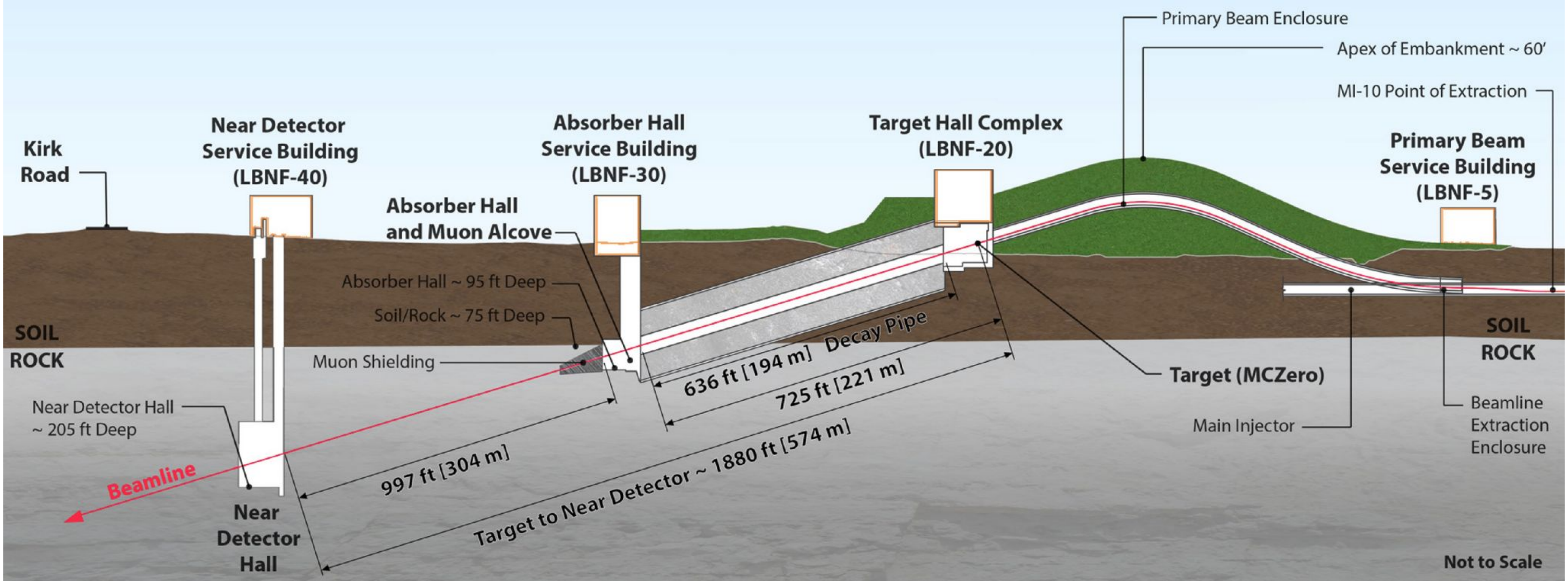
This material is based upon work supported by the U.S. Department of Energy, Office of Science.

Summary

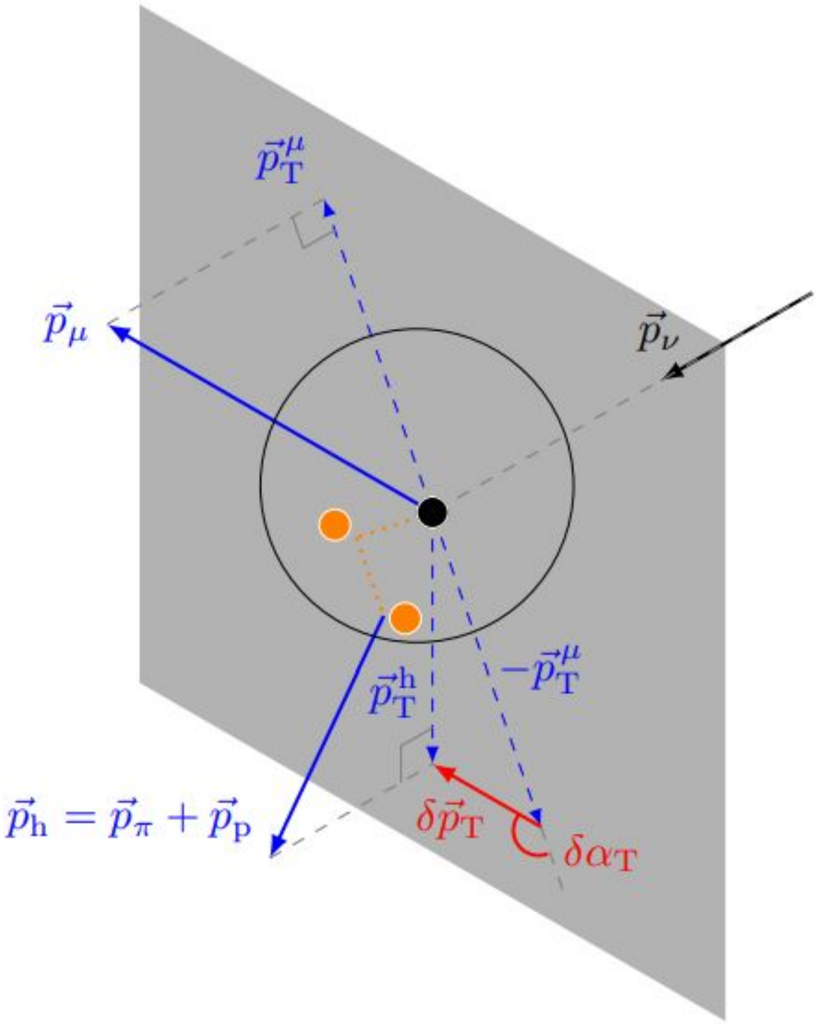
- The Phase II upgrade is required to achieve the ultimate sensitivity of DUNE
- An upgraded near detector, such as ND-GAr, is a critical part of the upgrade
- ND-GAr also supports a rich physics program of neutrino interaction measurements and BSM searches in parallel to supporting the oscillation physics program
- Several prototyping and R&D efforts are in progress such as TOAD and GOAT/GORG at FNAL, GAT0 in Spain, and the calorimeter development in Germany

BACKUP SLIDES

DUNE Near Detector Complex



Transverse kinematic imbalance



- Transverse kinematic imbalance (TKI) is a powerful probe of the underlying nuclear dynamics.

- ND-GAr provides an excellent environment to measure these events with:
  - Low momentum tracking to see all the outgoing hadrons
  - Excellent track separation and PID to identify each hadron
  - 4π angular coverage