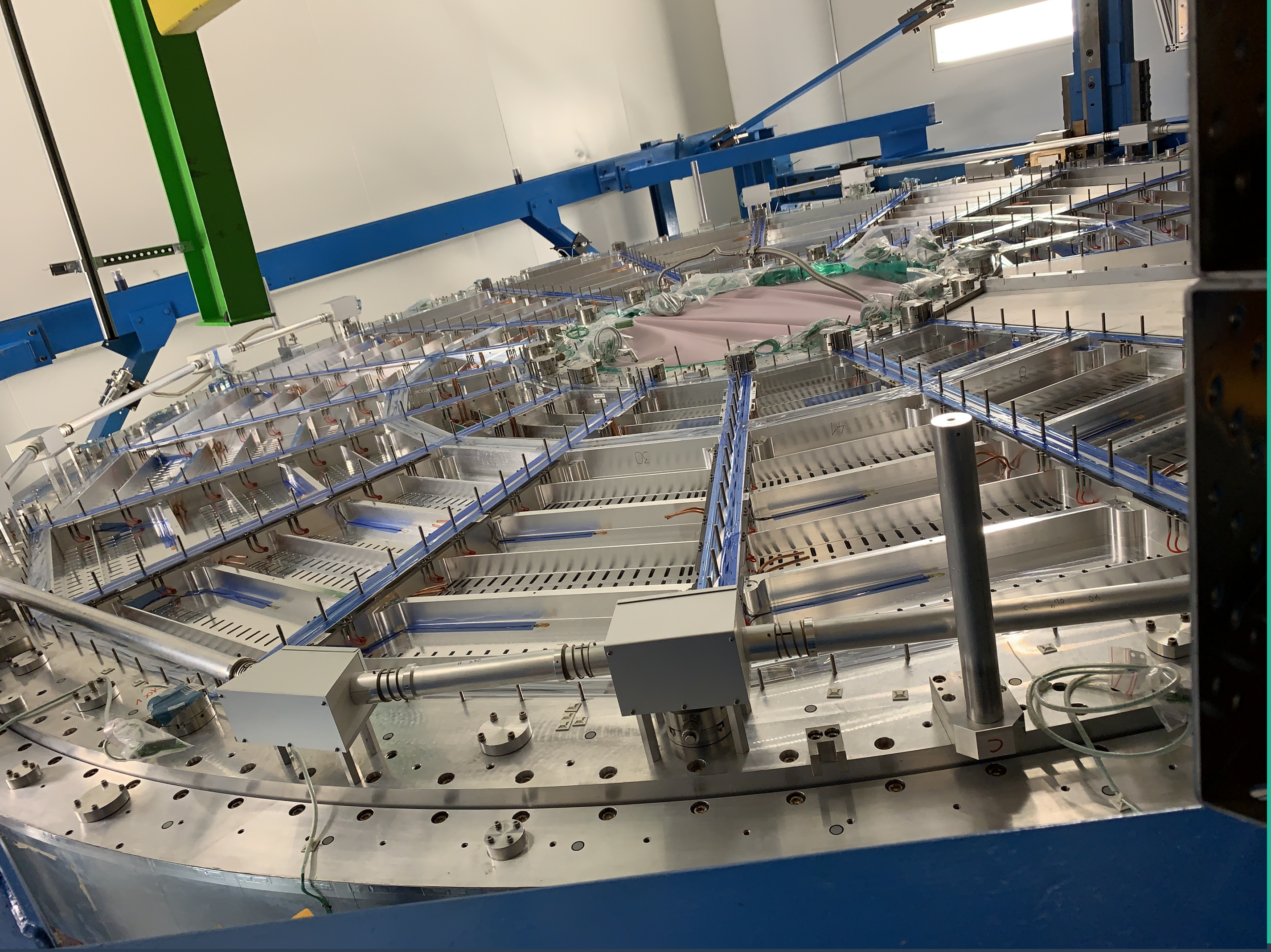


A Gaseous Argon-Based Near Detector to Enhance the Physics Capabilities of DUNE

Tanaz Angelina Mohayai, for the DUNE Collaboration

Snowmass Community Summer Study Workshop

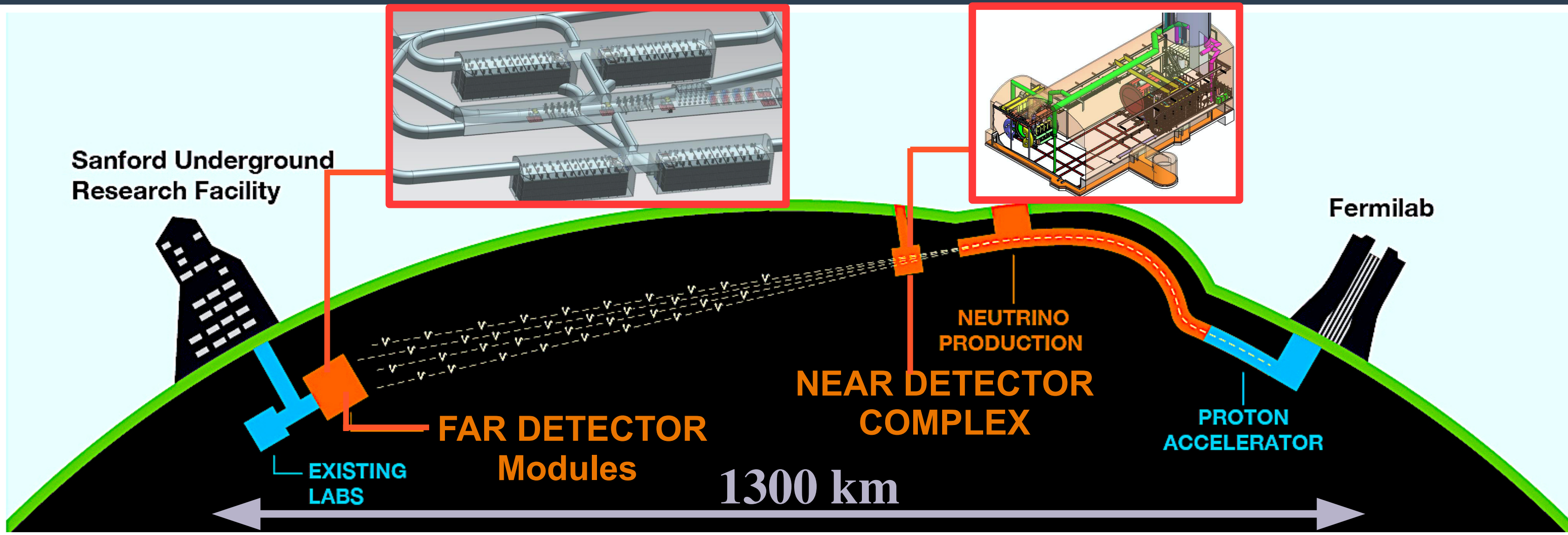
Seattle, WA

July 23, 2022

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Fermilab

DUNE, a Neutrino Oscillation Experiment



- Primary goal is to reduce systematic uncertainties in ν-oscillation probability (hence δCP) to a few %:
  - ★ Observable: ratio of appearance events in the far detector to near detector

measured by FD

what we want

$$\frac{N^{FD}_{\nu_e}(E_{reco})}{N^{ND}_{\nu_\mu}(E_{reco})} = \frac{\int \boxed{P_{\nu_\mu \to \nu_e}(E_\nu)} \times \Phi_{\nu_e}(E_\nu) \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{FD}_{\nu_e}(E_\nu) \times S^{FD}_{\nu_e}(E_\nu \to E_{reco})\, dE_\nu}{\int \Phi_{\nu_\mu}(E_\nu) \times \sigma_{\nu_\mu}(E_\nu) \times \epsilon^{ND}_{\nu_\mu}(E_\nu) \times S^{ND}_{\nu_\mu}(E_\nu \to E_{reco})\, dE_\nu}$$

event rates measured by our detectors

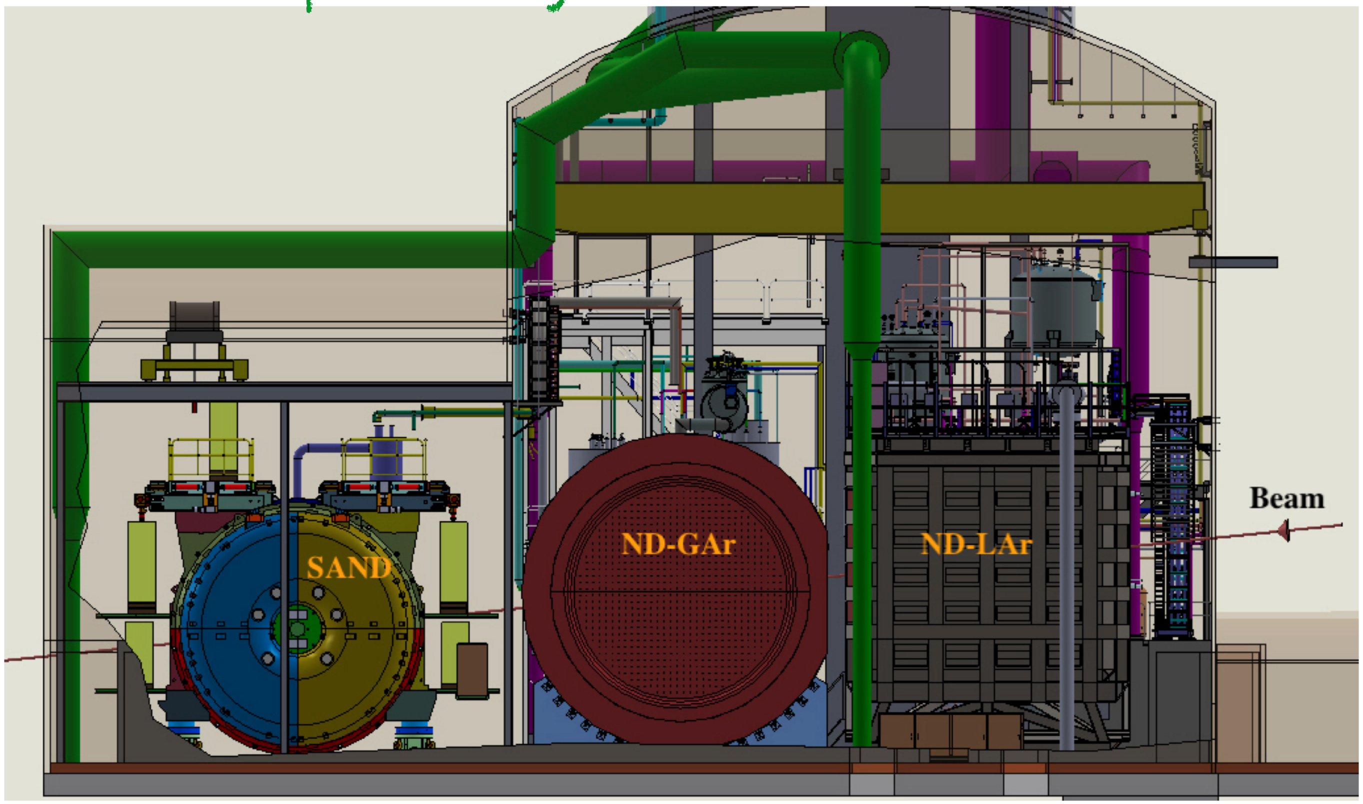
measured by ND

near detector in particular should be able to measure and constrain uncertainties in flux, Φ and cross section, σ + reconstruct neutrino energy very well (via migration matrix S)

Big Picture

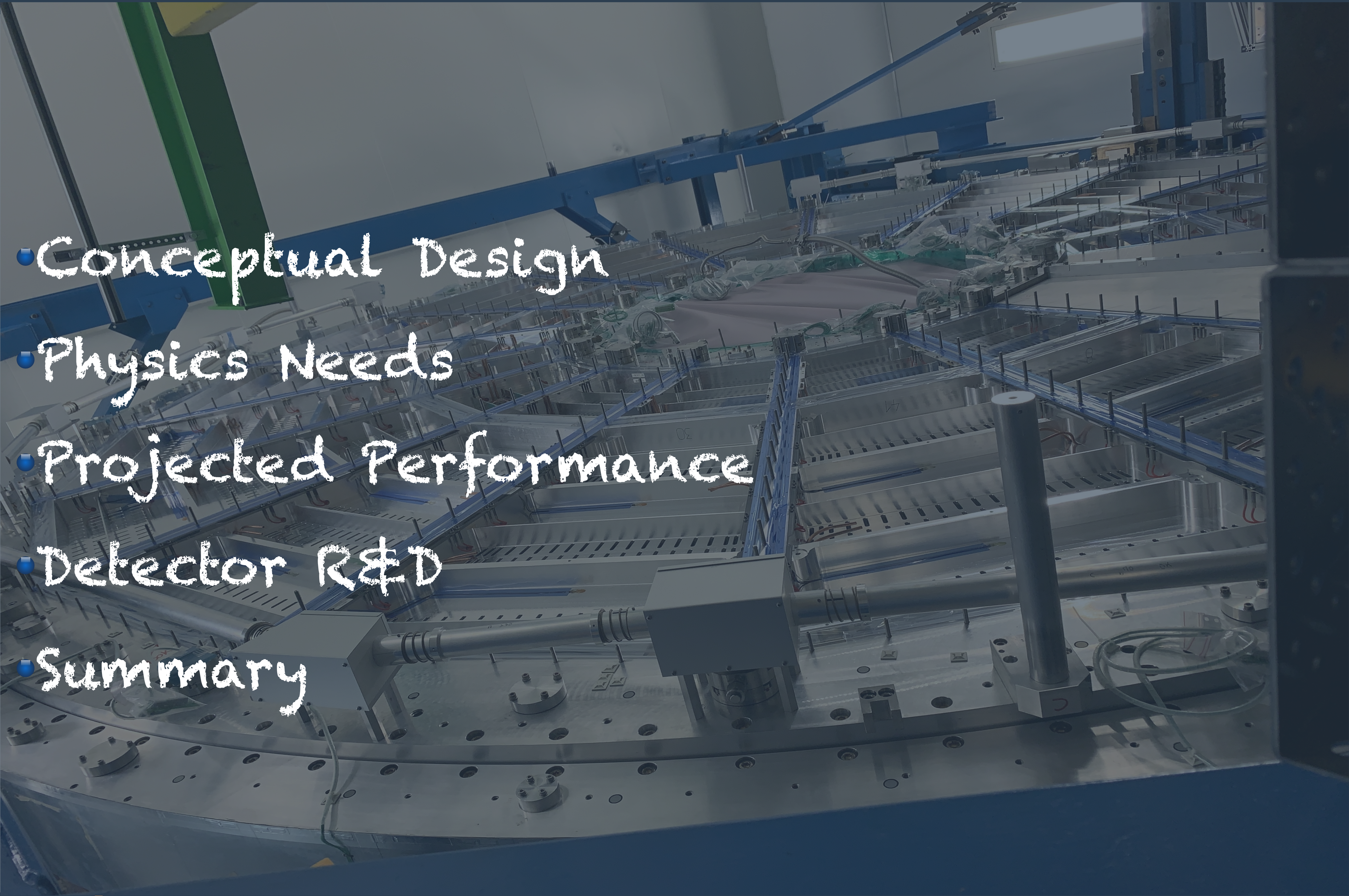
- DUNE needs **complementary detectors at the near site** to constrain the uncertainties in the neutrino oscillation measurement
- To reach **5σ sensitivity to CP violation** & enable a comprehensive BSM physics program, DUNE needs the low threshold, high resolution **gaseous-argon based near detector, ND-GAr** (Phase II ND upgrade)

complementary detectors at the near site



in the early running, a simpler downstream detector can reconstruct muon tracks exiting ND-LAr (Phase I) – more on the slides that follow

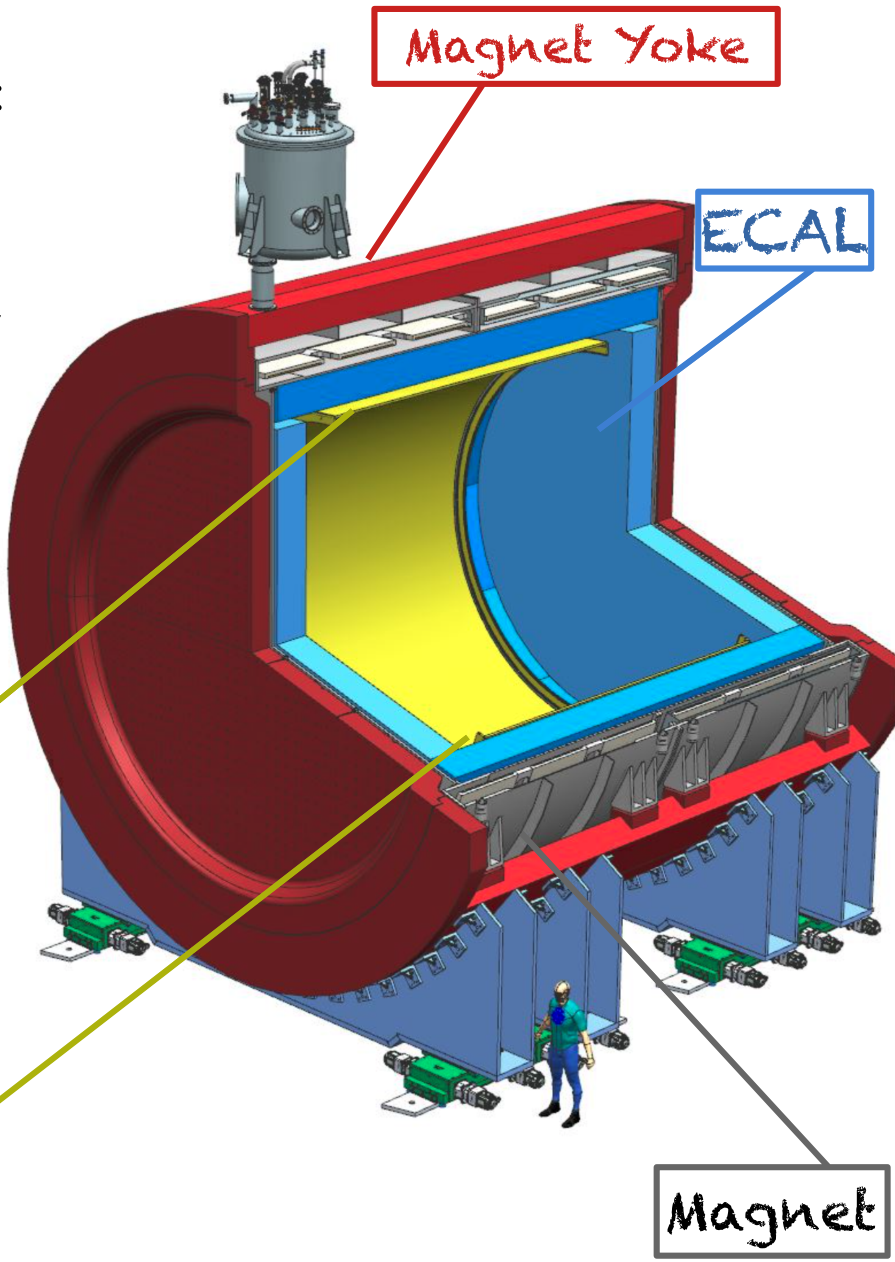
Outline



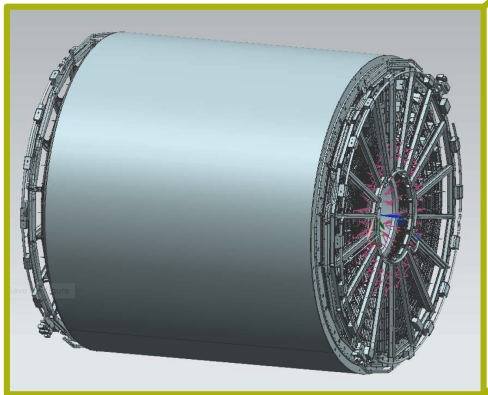
- Conceptual Design
- Physics Needs
- Projected Performance
- Detector R&D
- Summary

ND-GAr Concept

- Design is a **magnetized High Pressure Gas Argon TPC, HPgTPC** surrounded by an **ECAL** calorimeter:
  - Reference design repurposes ALICE multi-wire chambers & covers the entire endcaps except the central regions
  - Other designs could be considered especially for the central regions, e.g. Gas-Electron Multipliers
- Main capabilities enabled by ND-GAr's design:
  - Identifying and resolving discrepancies in neutrino-nucleus interaction models
    - Leads to a more accurate reconstruction of neutrino energy & a better constraint of cross-section uncertainties
  - A better constraint of backgrounds for a comprehensive BSM search



HPgTPC



ALICE engineering drawing

Physics Need

T2K https://doi.org/10.1038/s41586-020-2177-0

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

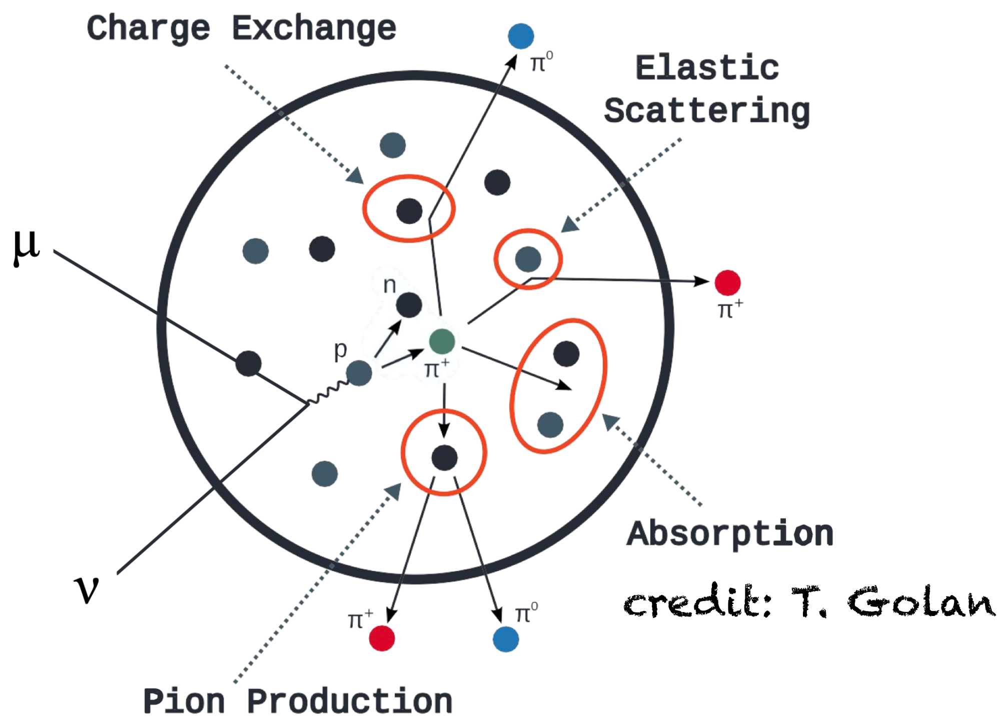
NOvA https://doi.org/10.1103/PhysRevLett.123.151803

Source	ν_e Signal (%)	ν_e Bkg. (%)	$\bar{\nu}_e$ Signal (%)	$\bar{\nu}_e$ Bkg. (%)
Cross-sections	+4.7/-5.8	+3.6/-3.4	+3.2/-4.2	+3.0/-2.9
Detector model	+3.7/-3.9	+1.3/-0.8	+0.6/-0.6	+3.7/-2.6
ND/FD diffs.	+3.4/-3.4	+2.6/-2.9	+4.3/-4.3	+2.8/-2.8
Calibration	+2.1/-3.2	+3.5/-3.9	+1.5/-1.7	+2.9/-0.5
Others	+1.6/-1.6	+1.5/-1.5	+1.4/-1.2	+1.0/-1.0
Total	+7.4/-8.5	+5.6/-6.2	+5.8/-6.4	+6.3/-4.9

Dominant sources of uncertainties in neutrino oscillation measurements: **cross sections/neutrino interaction models**

Physics Need

- Nucleus is a complicated environment (e.g. when using heavy nuclei as target):
  - ★ Nuclear effects, e.g. final state interactions not yet fully understood
  - ★ Different **interaction channels** may lead to the same **final topology** in our detectors, introducing uncertainties in neutrino energy reconstruction and neutrino event rate estimation

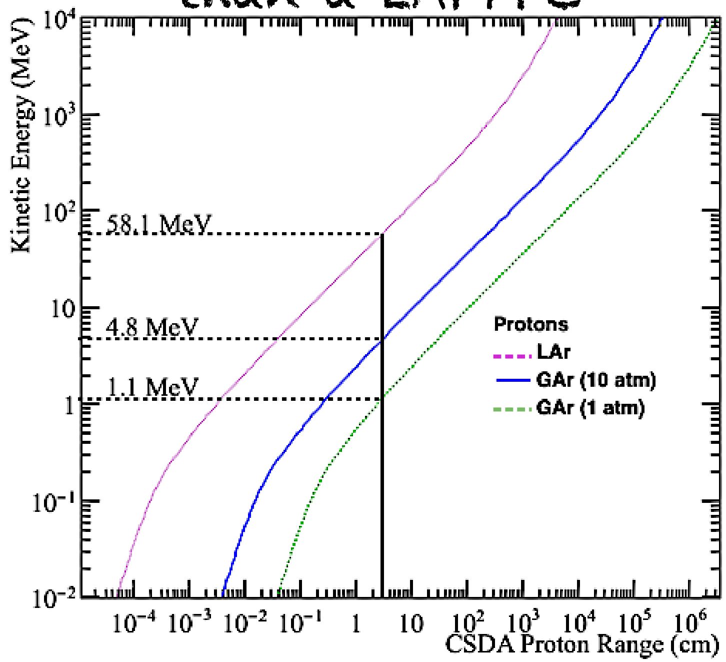


  - ★ A wealth of LArTPC data exists to help with tuning the neutrino-argon interaction models, but mis-modelings persist e.g. for low-energy nucleons below LArTPC detection threshold

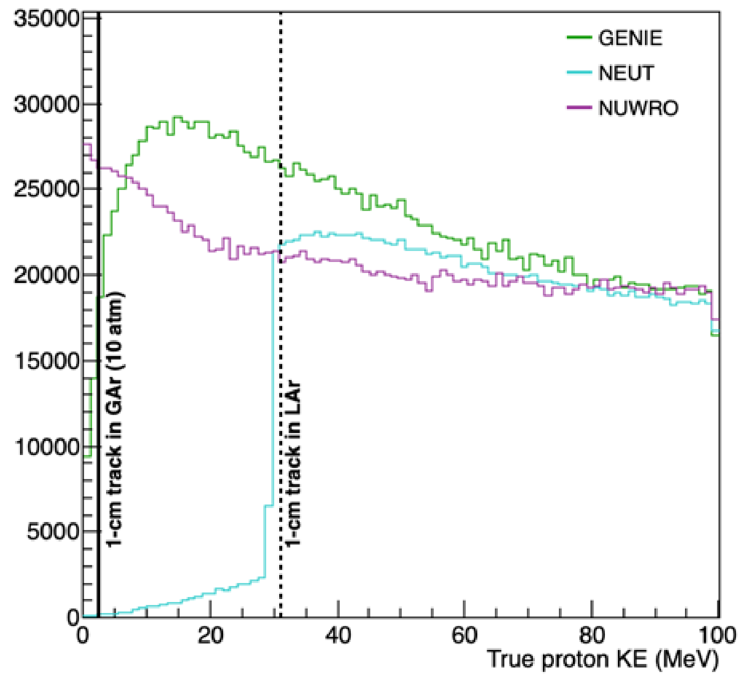
Physics Need

- **ND-GAr's HPgTPC** has a lower density ($\rho_{LAr}/\rho_{GAr} \approx 85$ for 10 atm GAr), therefore a lower detection threshold than a **LArTPC**
  - Leads to a higher sensitivity to lower energy protons or pions compared to a LArTPC
  - Reveals discrepancies between neutrino event generators, getting us closer to choosing more accurate neutrino-nucleus interaction models

A GAr-based detector sees lower KE protons than a LArTPC

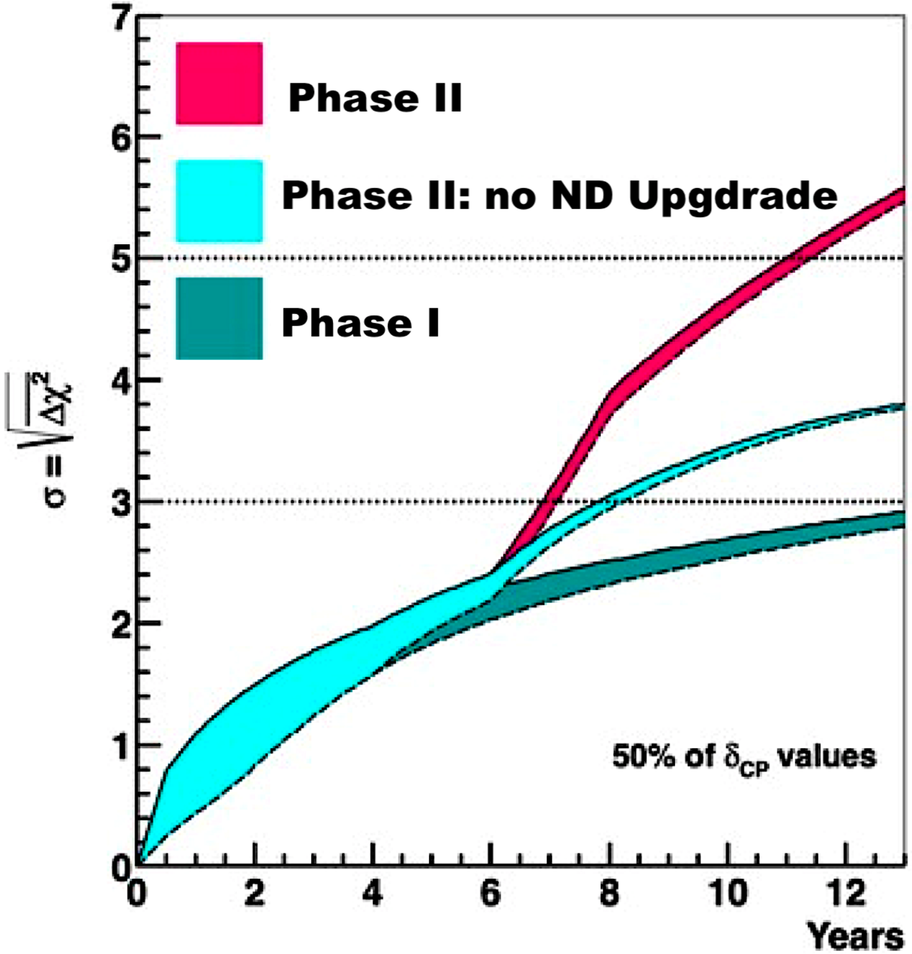


neutrino generator discrepancies at low proton KE, accessible with a GAr-based detector

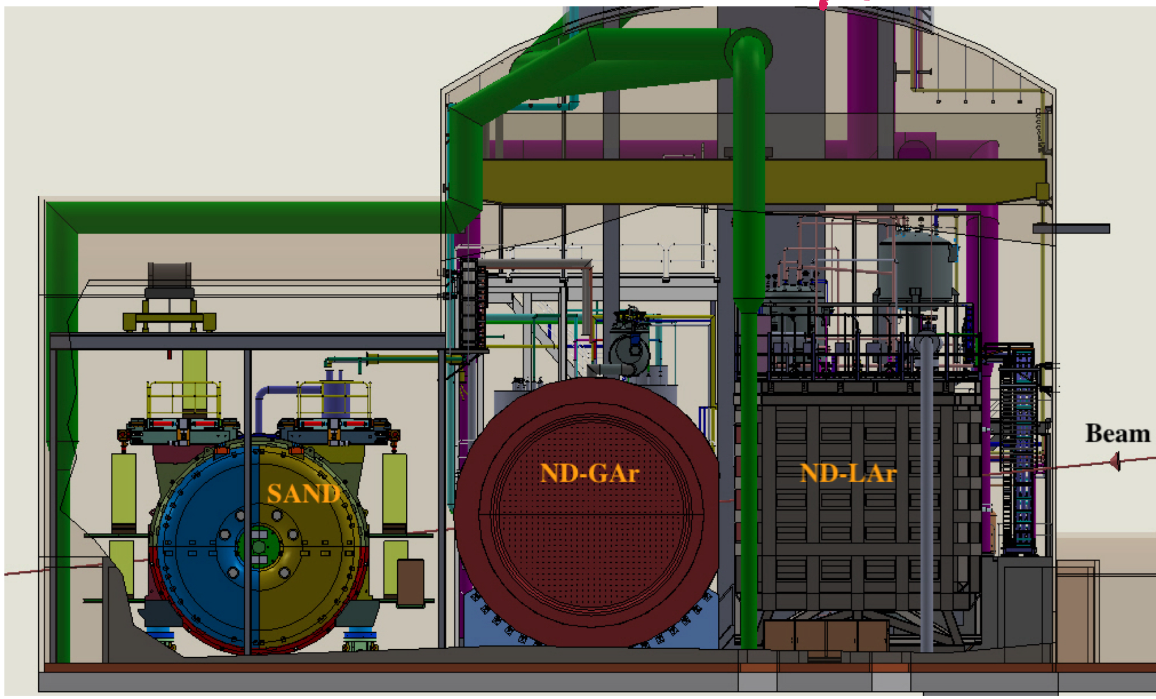


Projected Performance

- DUNE aims to reach 5σ sensitivity to CP violation and achieve the ultimate precision physics measurement:
  - ★ Only possible with a **Phase II** design that includes an **ND upgrade to ND-GAr** (after the initial DUNE running with **phase I**)



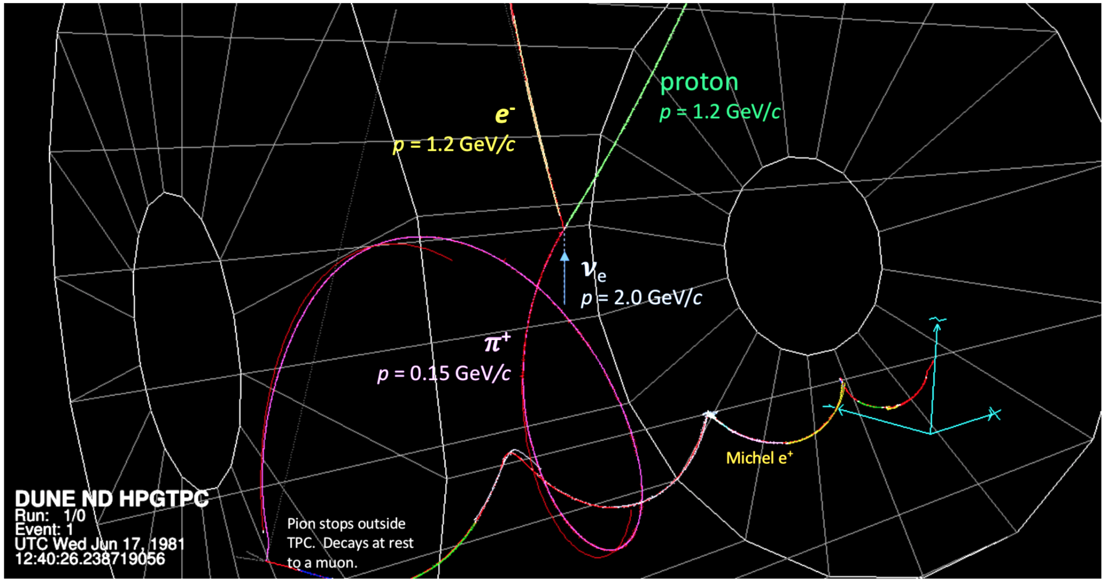
Phase II with ND Upgrade



Projected Performance

1 ton fiducial mass for 1 year of ν-mode running

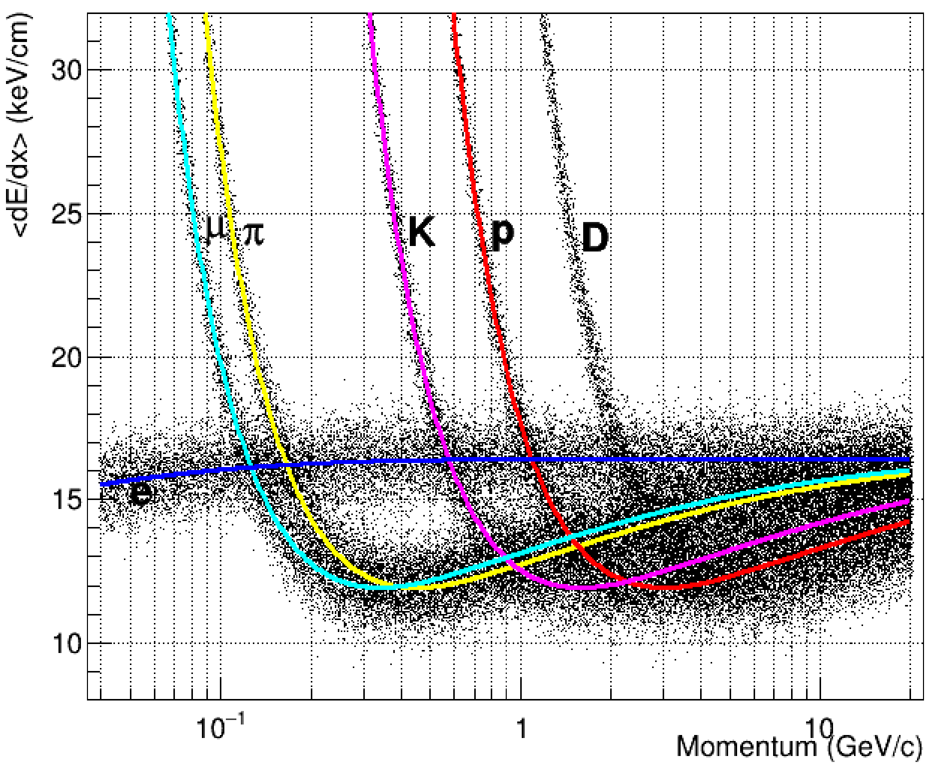
Event class	Number of events per ton-year
ν_μ CC	1.6×10^6
$\overline{\nu}_\mu$ CC	7.1×10^4
$\nu_e + \overline{\nu}_e$ CC	2.9×10^4
NC total	5.5×10^5
ν_μ CC0π	5.9×10^5
ν_μ CC$1\pi^\pm$	4.1×10^5
ν_μ CC$1\pi^0$	1.6×10^5
ν_μ CC2π	2.1×10^5
ν_μ CC3π	9.2×10^4
ν_μ CC other	1.8×10^5

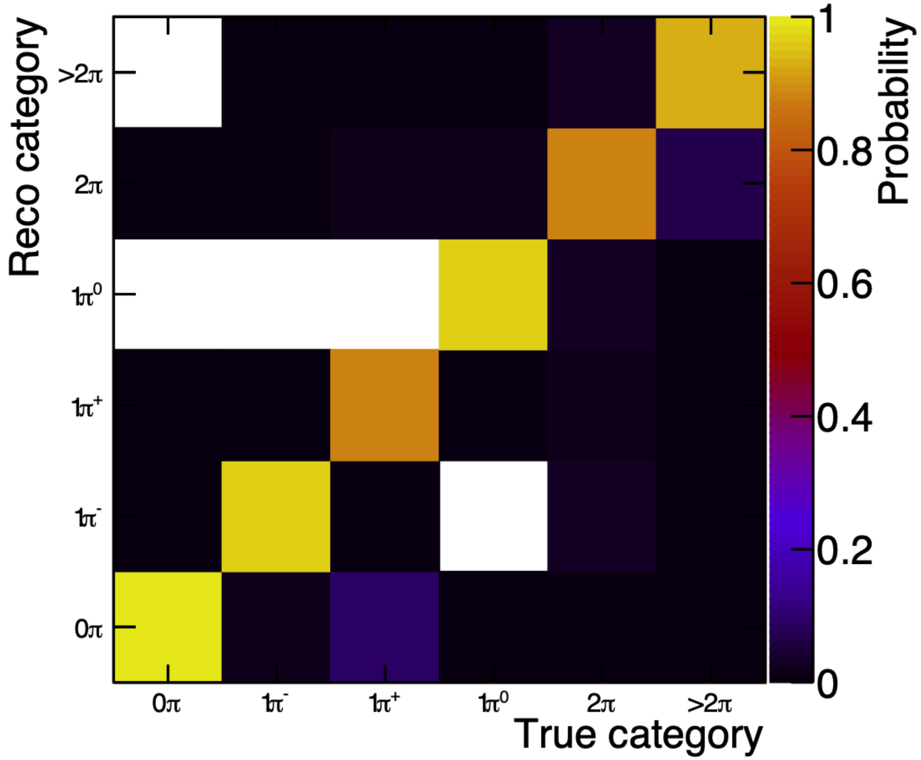


- Collect independent sample of ν-interactions on argon, the same target nucleus as ND-LAr and the DUNE far detector, enabling a rich cross-section physics program
  - e.g. high statistics sample of exclusive final-state measurements with **different particle species multiplicities e.g. pions**

Projected Performance

dE/dx based on PEP-4

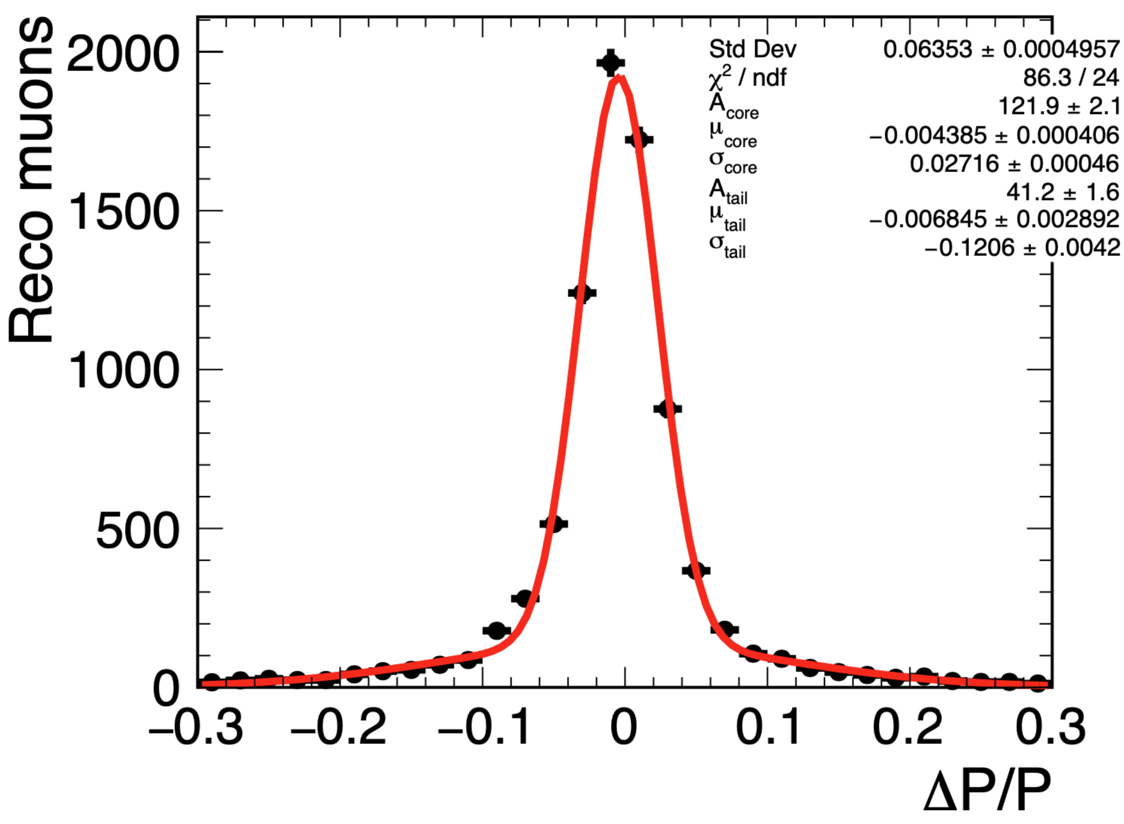


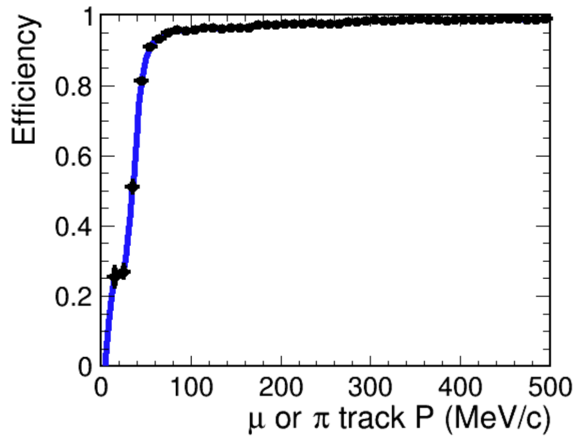


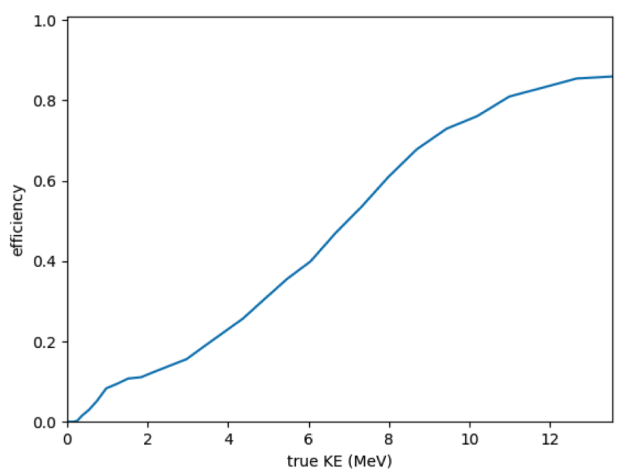
- And thanks to ND-GAr's excellent PID, we can identify the **different particle species multiplicities e.g. pions** very well
- dE/dx resolution 0.8 keV/cm

Projected Performance

- A full end-to-end simulation and reconstruction software GArSoft is currently under development and further improvements are expected:
  - ★ Momentum resolution (left) for μs from a sample of ν_μ CC events = 2.7%, tracking efficiency for muons or pions is from the same sample
  - ★ Proton tracking efficiency, based on a sample of isotropic protons at the vertex: ~80% for 10 MeV protons

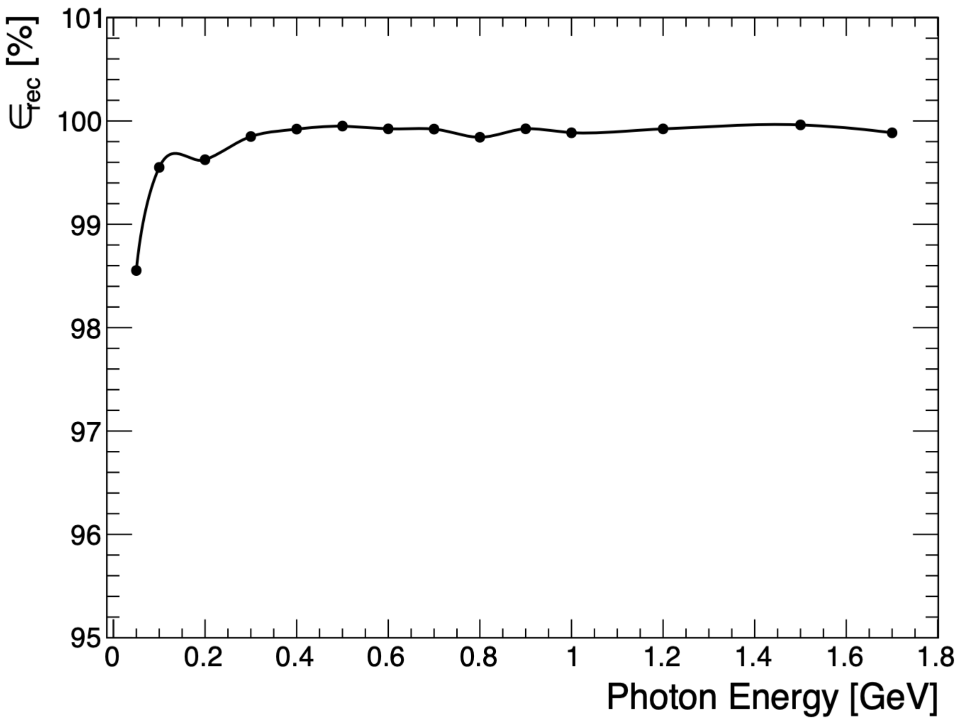


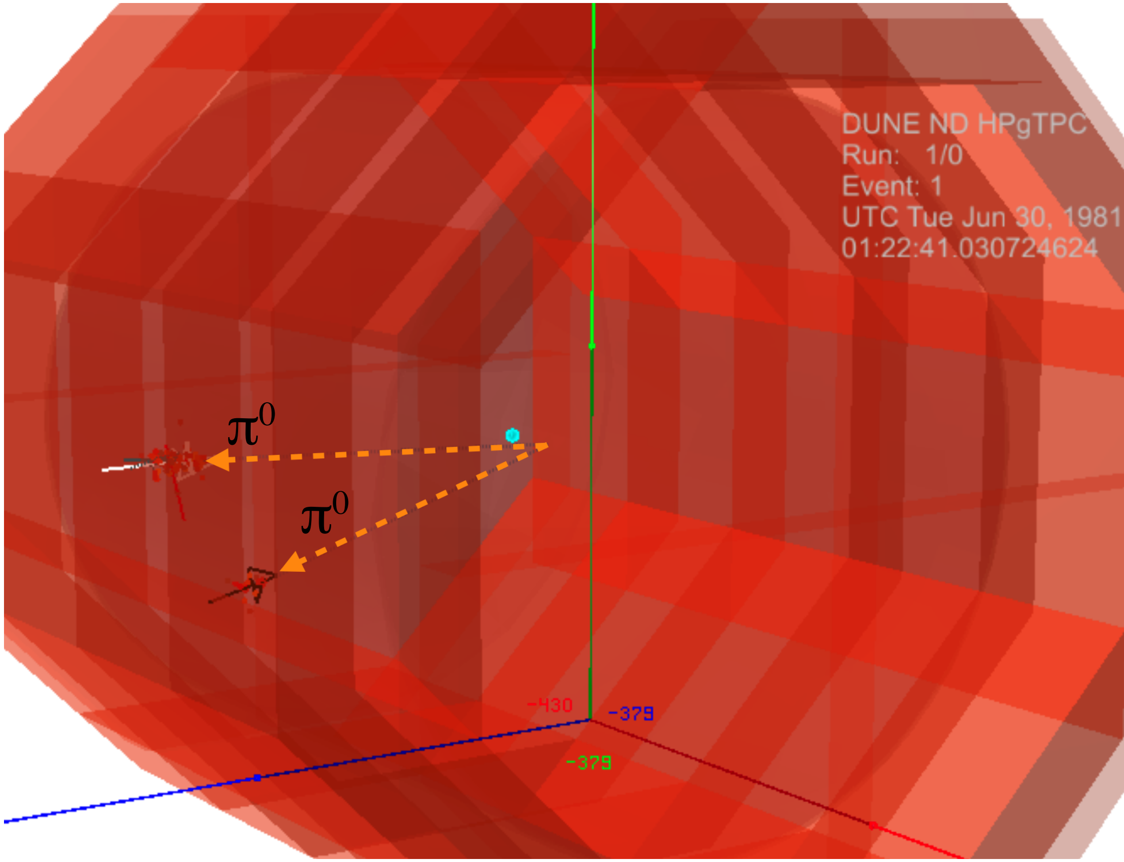




Projected Performance

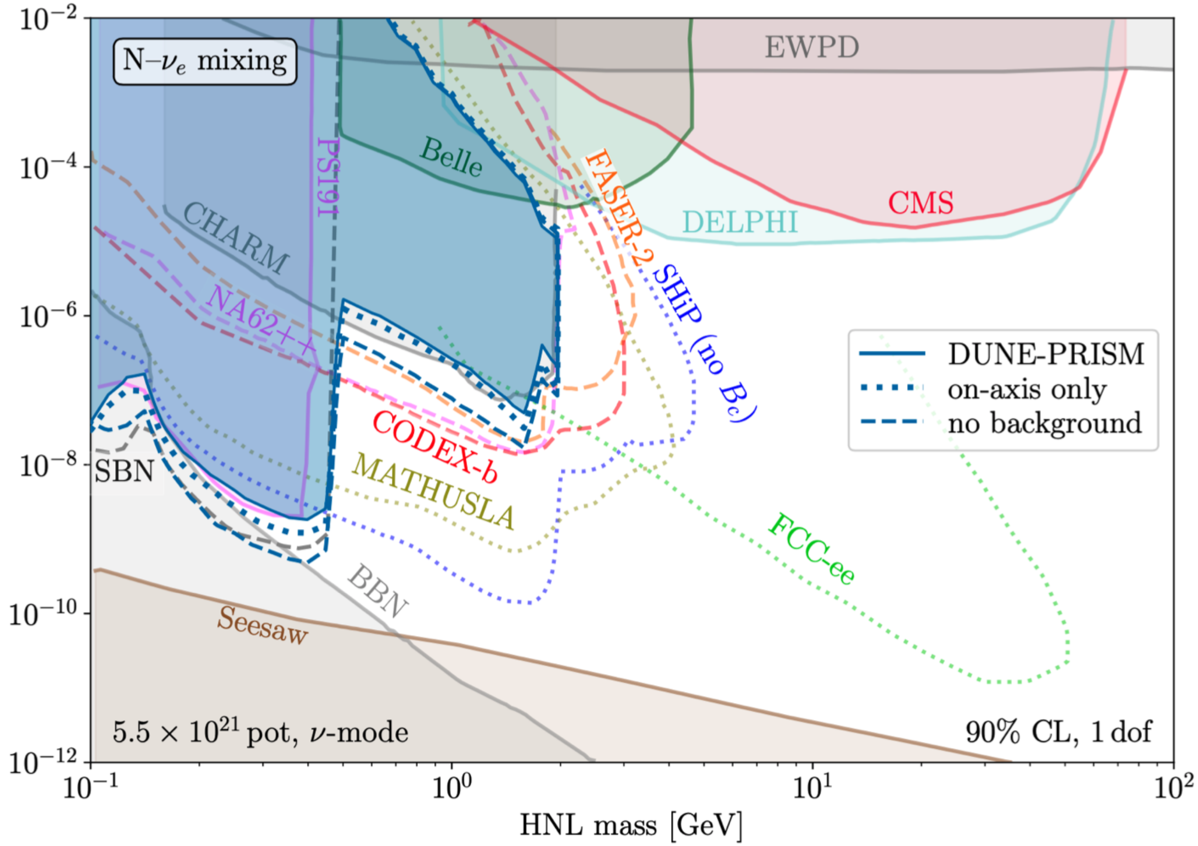
- ECAL helps tag/reject neutral particles, including π^0, γs (background to electron-neutrinos), & neutrons
- Can also Tag/reject outside of fiducial volume backgrounds using timing





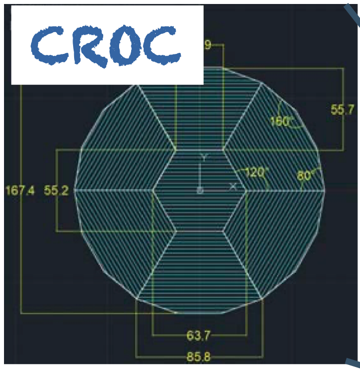
Projected Performance

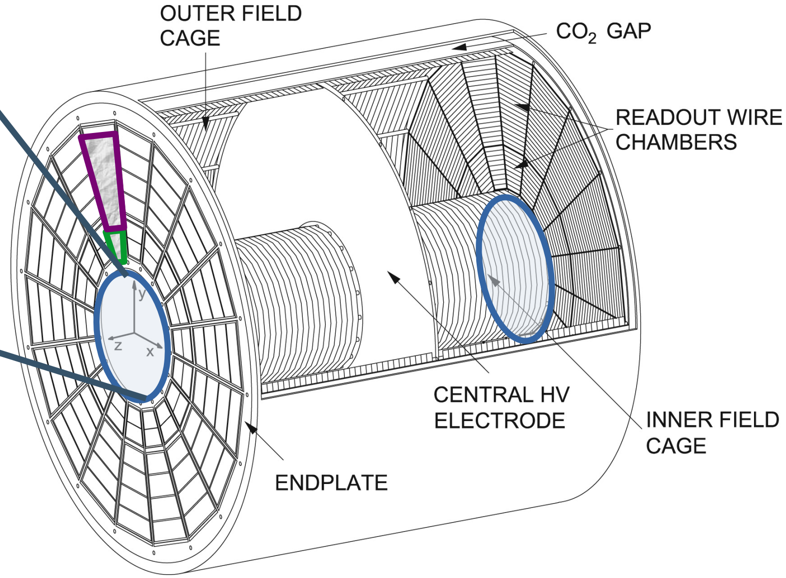
- Thanks to its strong constraint of backgrounds, ND-GAr enables a rich BSM physics program in DUNE, e.g. in rare event searches such as:
  - Neutrino tridents
  - Heavy neutral leptons, HNL
  - Light dark matter
  - Heavy axions
  - Tau neutrinos



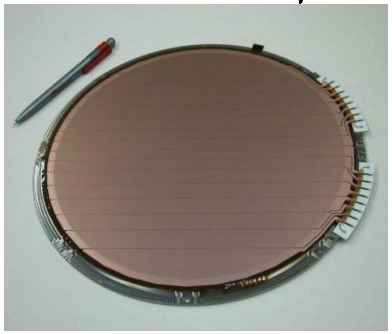
M. Breitbach, L. Buonocore, C. Frugiuele, J. Kopp and L. Mittnacht, Searching for physics beyond the standard model in an off-axis dune near detector, 2102.03383

R&D Efforts



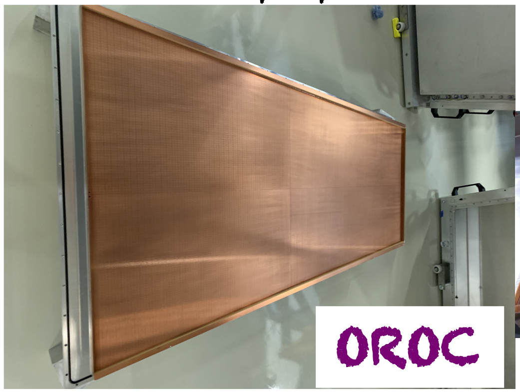


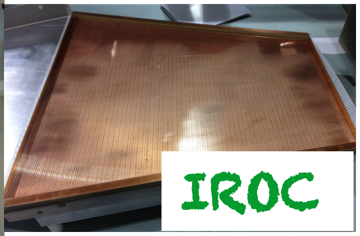
e.g. a circular-shaped GEM

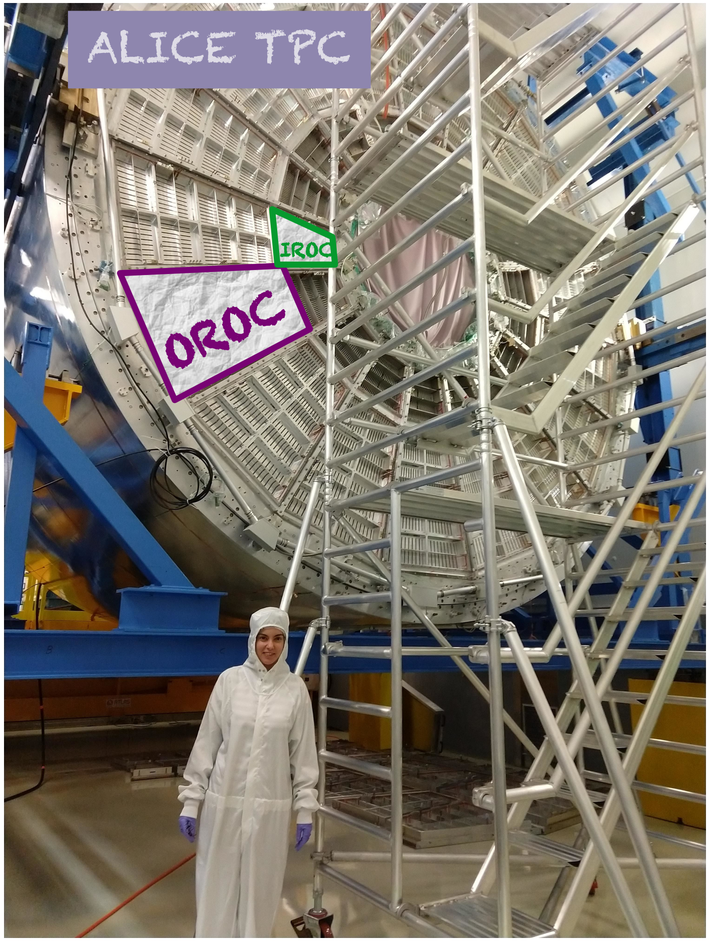


Danilo Domenici, LNF Frascati Detector School lecture

ALICE readout chambers are multi-wire proportional chambers







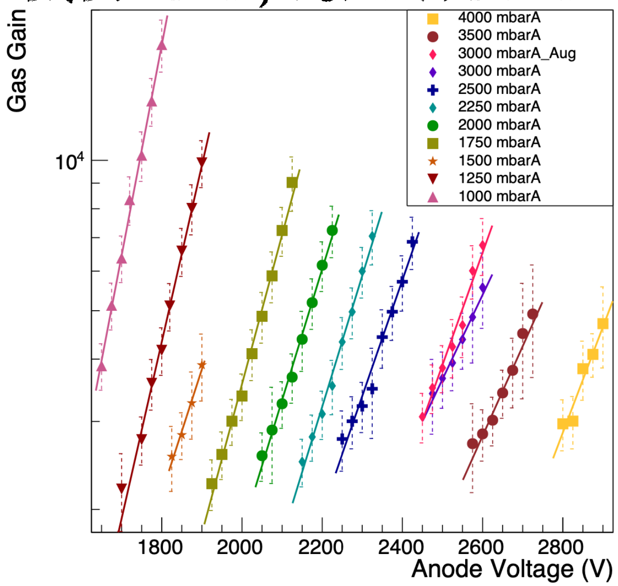
- Bulk of the R&D is focused on the optimization of the acquired ALICE **inner (IROC)** and **outer (OROC)** readout chambers
- We have to build the **central readout chambers, CROC** – opportunities for exploring alternate designs, such as **Gas-electron multipliers, GEMs**

R&D Efforts

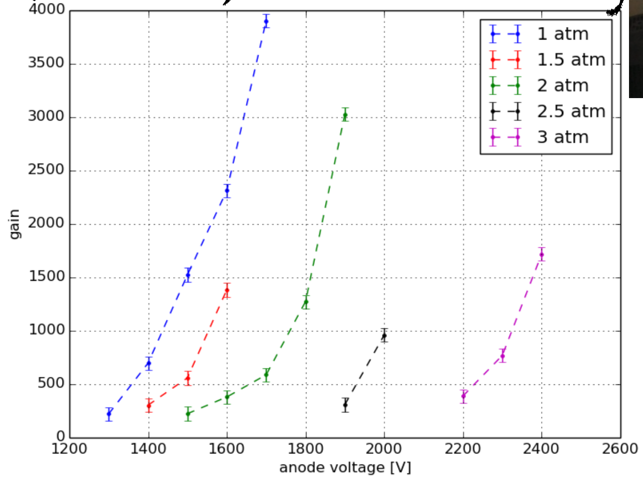
- What is involved in the readout chamber optimization studies:
  - Testing the chambers @ various pressures up to 10 atm (e.g. ALICE chambers previously operated at 1 atm)

Fermilab Test Stand, housing an IROC

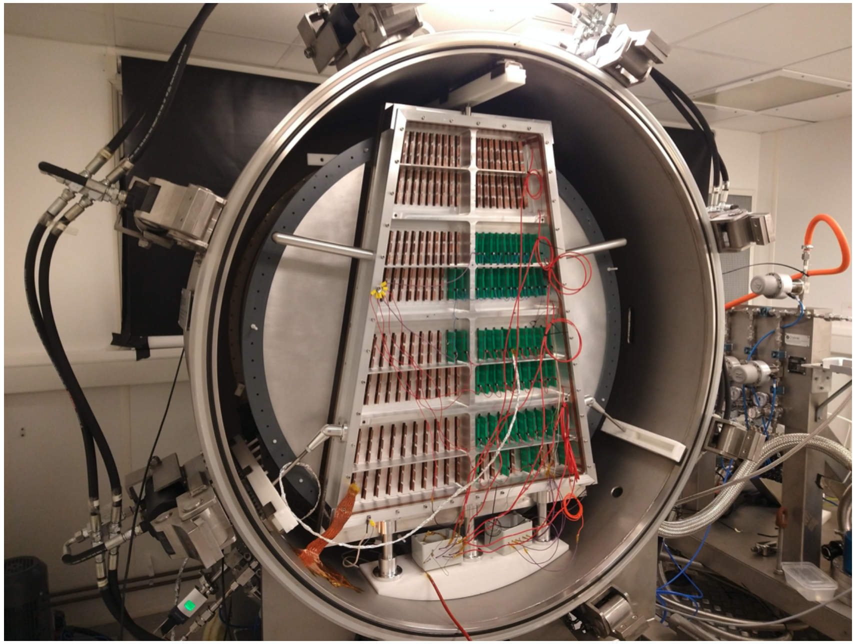
OROC Gain, DUNE Preliminary



IROC Gain, DUNE Preliminary



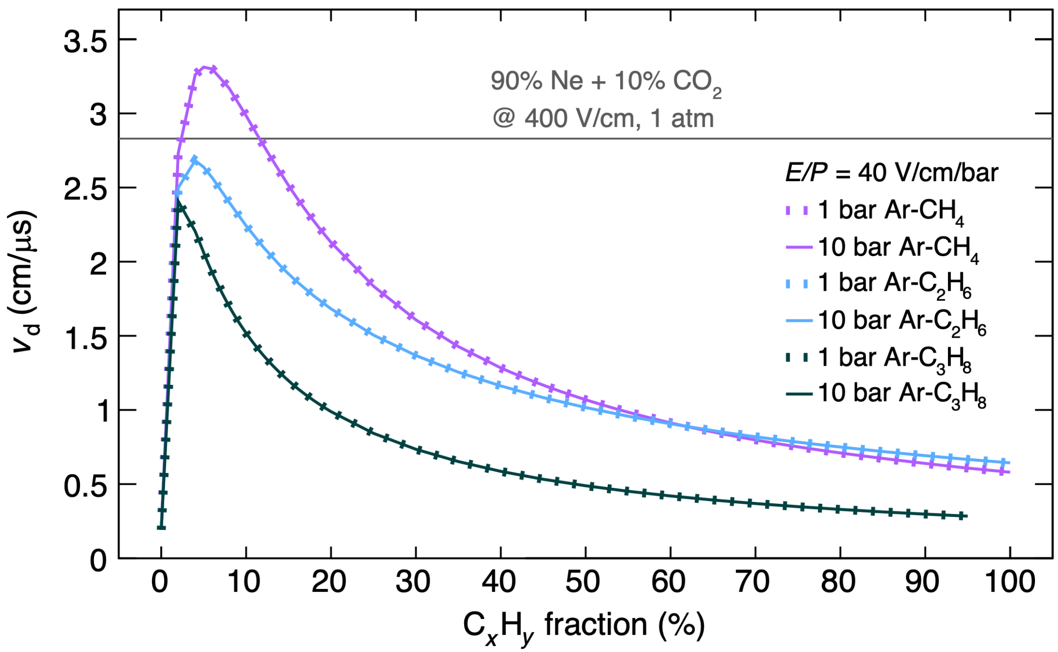
Royal Holloway Test Stand, housing an OROC

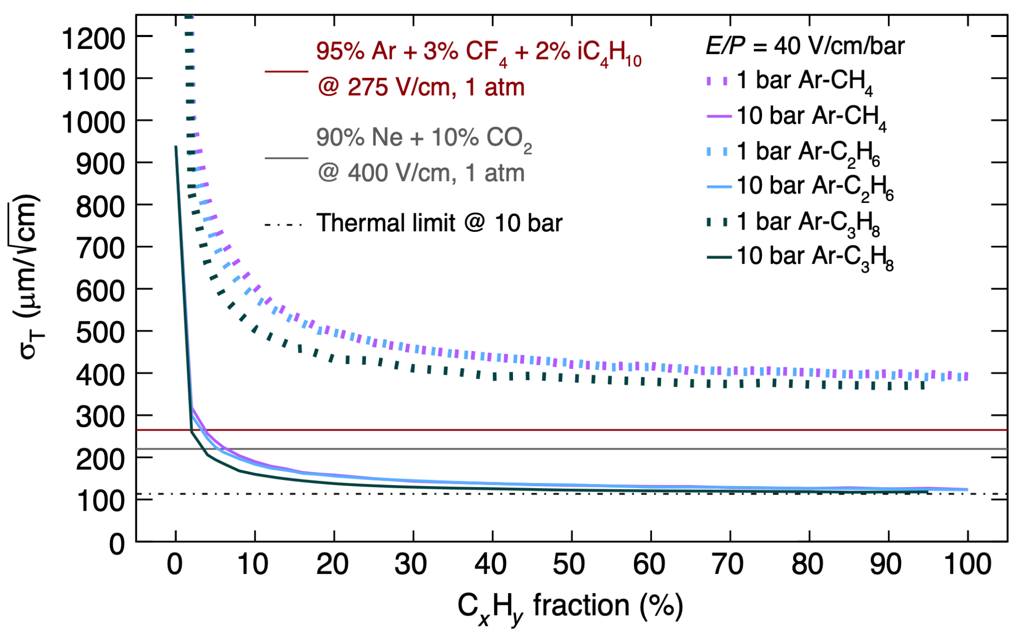


Soon to be placed in Fermilab Test Beam

R&D Efforts

- What is involved in the readout chamber optimizations:
  - Testing the chambers @ various pressures up to 10 atm (e.g. ALICE chambers previously operated at 1 atm)
  - Defining a base gas mixture – reference gas is Ar-CH_4 (97% of interactions on Ar) but can be optimized to:
    - Control pile up (drift velocity) and improve spatial resolution (diffusion)





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

R&D Efforts

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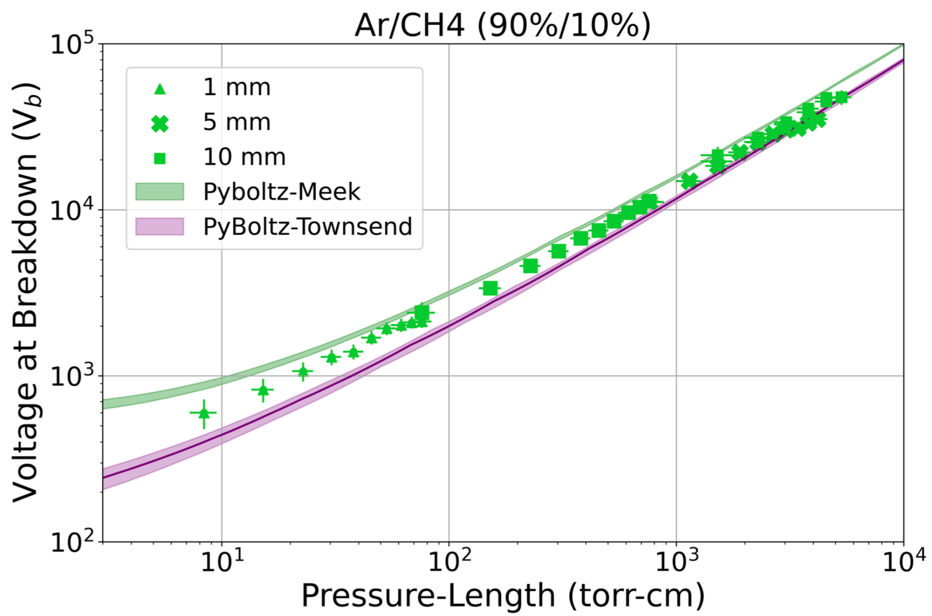
    - Control pile up (drift velocity) and improve spatial resolution (diffusion)
    - Maximize gas gain, while minimizing gas electrical breakdown



Projected Breakdown Voltage at 10 bar, 1 cm (kV)							
	Ar	Xe	Ar-CF_4	Ar-CH_4	Ar-CO_2	CO_2	CF_4
Townsend	**52.6**	**75.4**	61.7	63.9	68.6	129.5	179.7
Meek	69.9	98.9	72.1	80.3	87.3	**171.2**	**212.2**

Norman, L. *et al.* Dielectric strength of noble and quenched gases for high pressure time projection chambers. *Eur. Phys. J. C* **82**, 52 (2022).

R&D Efforts

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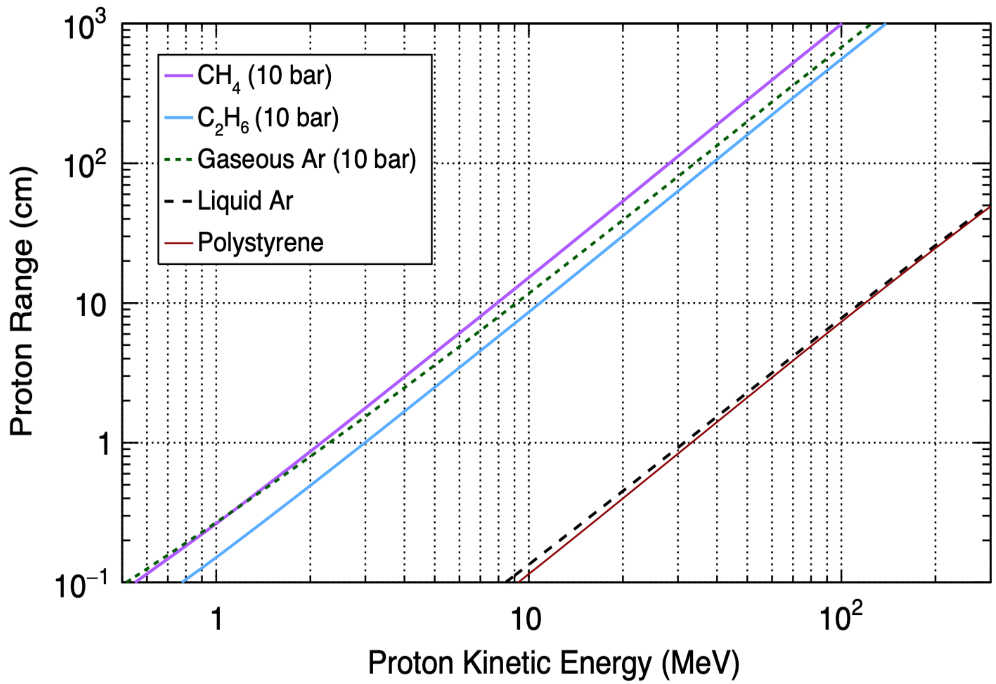
    - Ability to operate with a hydrogen-rich gas mixture to probe more fundamental neutrino-hydrogen interactions



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

R&D Efforts

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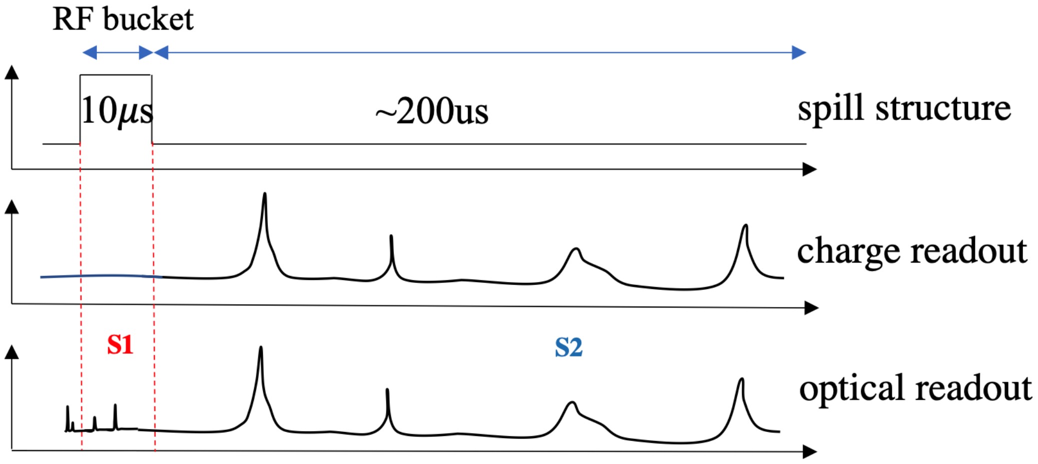
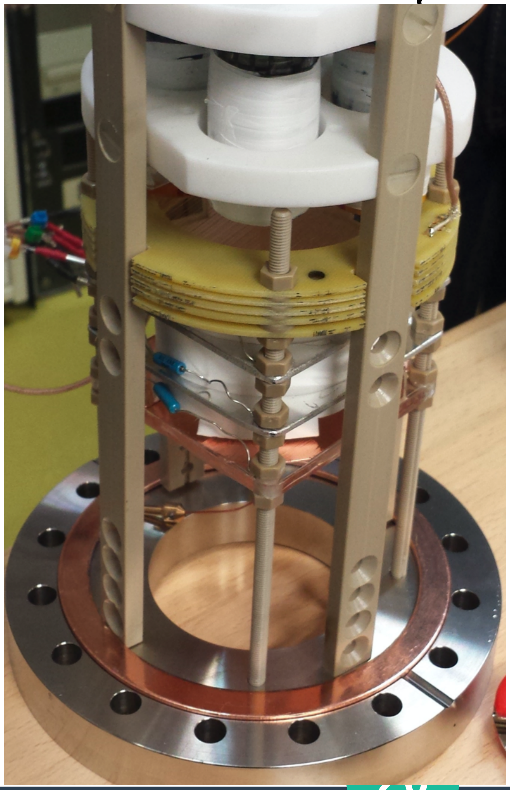
    - Maximize gas gain, while minimizing gas electrical breakdown
    - Ability to operate with a hydrogen-rich gas mixture to probe more fundamental neutrino-hydrogen interactions
- Light collection:
  - t0 time-tag and an improved track matching with ND-LAr
  - Neutral particle reconstruction via time-of-flight



IGFAE test setup



Summary

- DUNE needs the full ND-GAr to reach the 5σ sensitivity in CP violation measurement

- The DUNE ND-GAr design includes a number of capable components to primarily enable:
  - A precise view of ν-Ar interactions with low detection threshold to enable a precise to identify and resolve discrepancies in neutrino-nucleus interaction models
  - A strong constraints on backgrounds to search for rare particles and symmetries beyond the standard model

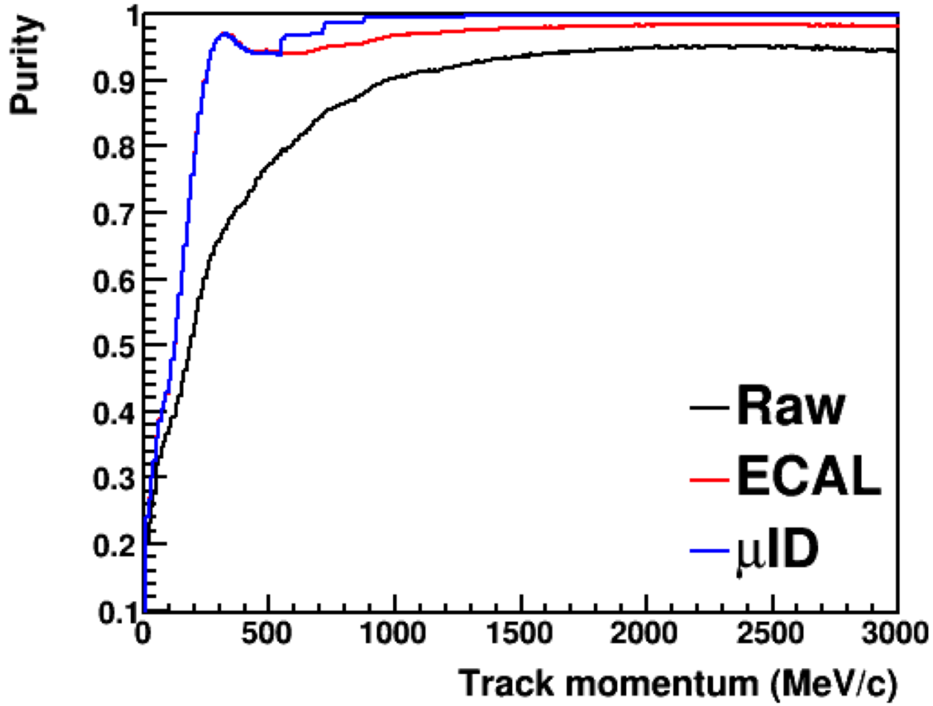
- We are conducting a wide variety of detector R&D projects in building a highly-capable ND-GAr:
  - In addition to the R&D on the acquired ALICE readout chambers, there are on-going novel detector R&D efforts, such as optical readout

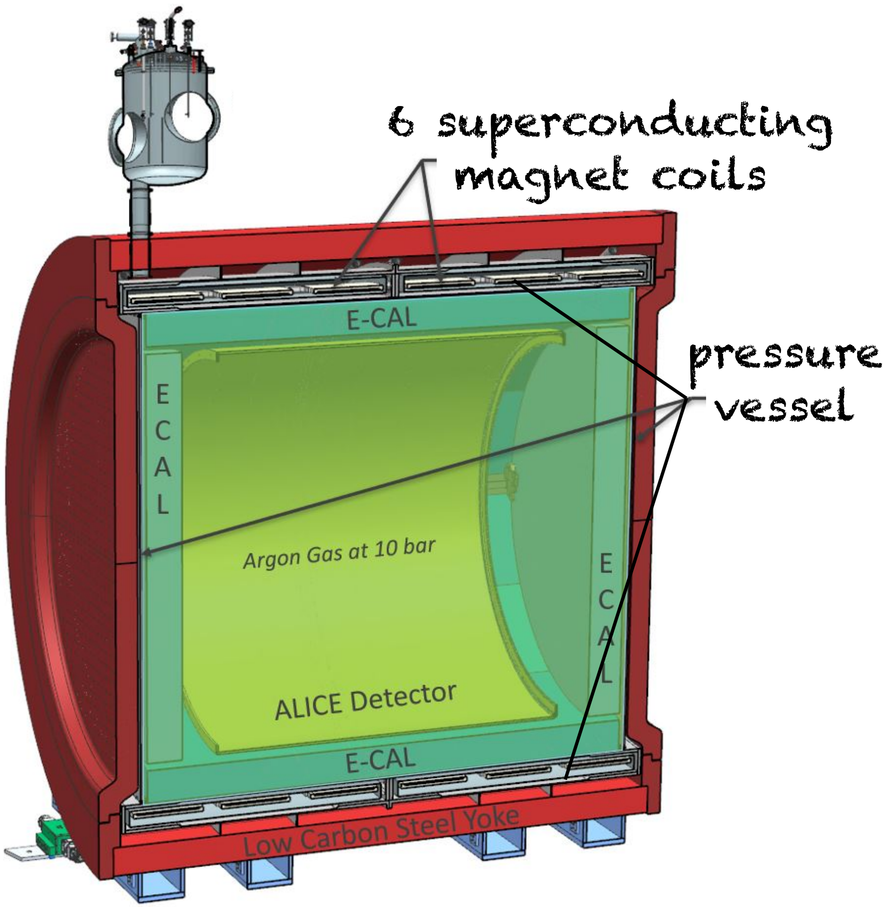
Thank You

Additional Slides

Projected Performance

- High-momentum muons and pions will range out of ECAL
- A muon tagger can achieve a purity of 100% above 1 GeV/c





magnet yoke instrumented with a muon tagger, μID