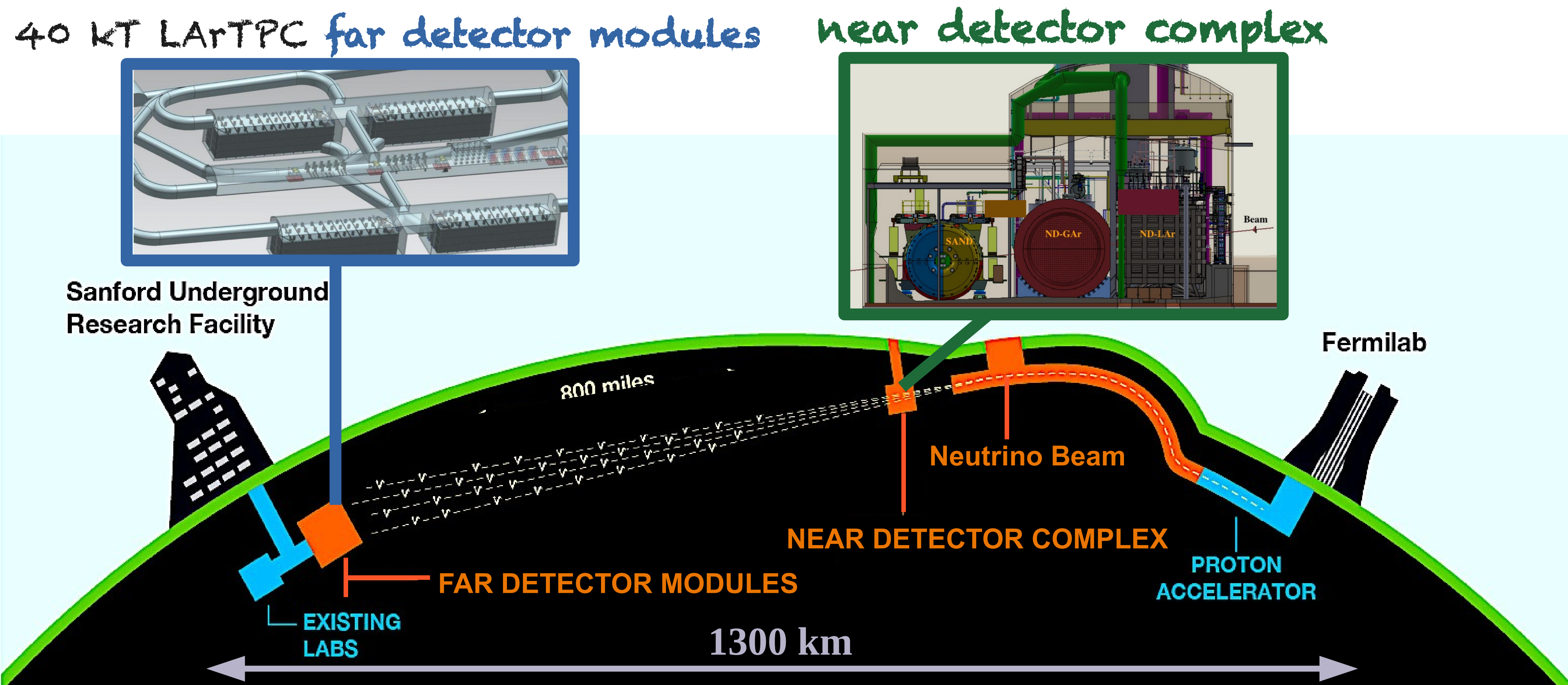
A Gaseous-Ar Based Near Detector for DUNE Phase II

Tanaz A. Mohayai, Indiana University
for the DUNE Collaboration
2023 CPAD Workshop, SLAC
Nov. 9, 2023

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Deep Underground Neutrino Experiment

- A comprehensive physics program:
  - ★ High precision measurements of neutrino mixing & the CP violation, and searches for BSM physics, baryon number violation, and supernova neutrinos
- Key components:
  - ★ 1.2 MW, upgradable to 2.4 MW high-intensity, wide-band **neutrino beam**
  - ★ 40 kT liquid Argon time projection chamber, LArTPC **far detector, FD**
  - ★ **Near detectors, ND**



Compared to Existing Neutrino Experiments

- **Cross sections/neutrino interaction model uncertainties** from existing experiments too large for DUNE
- DUNE needs to do better!

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

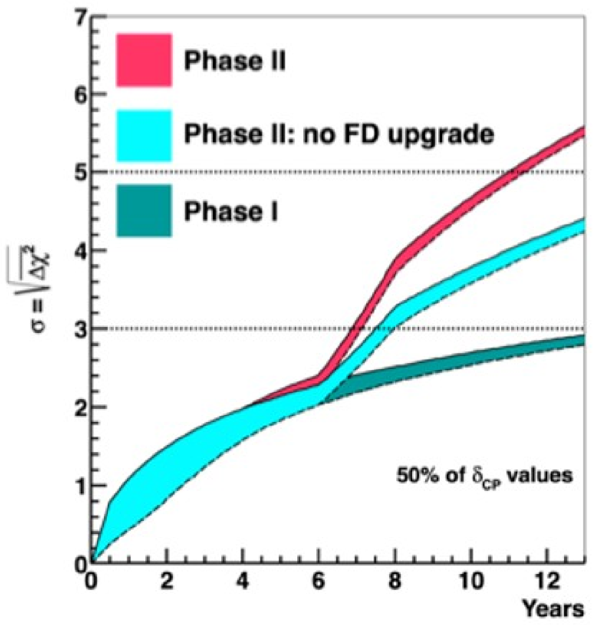
Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal 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

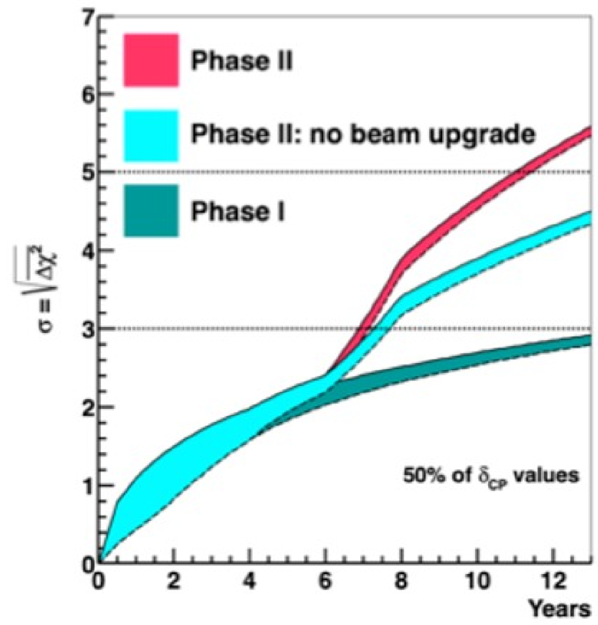
NOvA https://doi.org/10.1103/PhysRevLett.123.151803

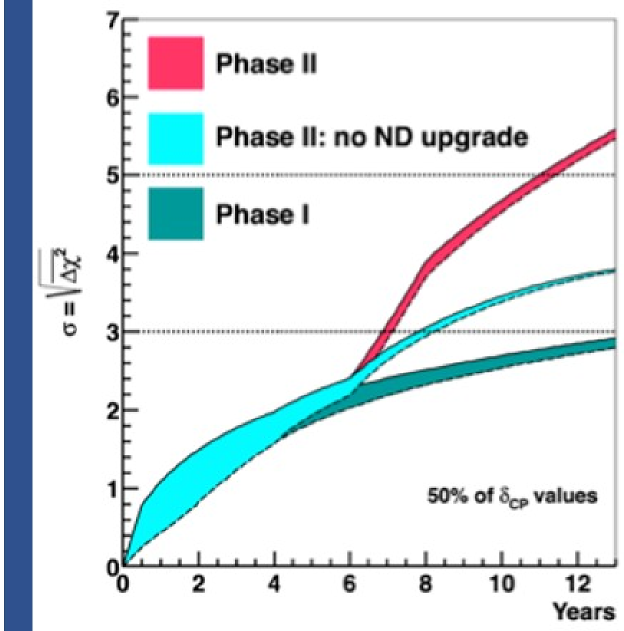
Source	ν_e Signal (%)	ν_e Bkg. (%)	$\bar{\nu}_e$ Signal (%)	$\bar{\nu}_e$ Bkg. (%)
Cross-sections	+4.7/-5.8	+3.6/-3.4	+3.2/-4.2	+3.0/-2.9
Detector model	+3.7/-3.9	+1.3/-0.8	+0.6/-0.6	+3.7/-2.6
ND/FD diffs.	+3.4/-3.4	+2.6/-2.9	+4.3/-4.3	+2.8/-2.8
Calibration	+2.1/-3.2	+3.5/-3.9	+1.5/-1.7	+2.9/-0.5
Others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

DUNE Phase II

- **Phase II** of DUNE will include upgrades to ND, FD, and beam to enable the ultimate **5σ sensitivity to CP violation**
- But only **ND upgrade** specifically targets systematics
  - ★ Largest bias observed **without an ND upgrade**

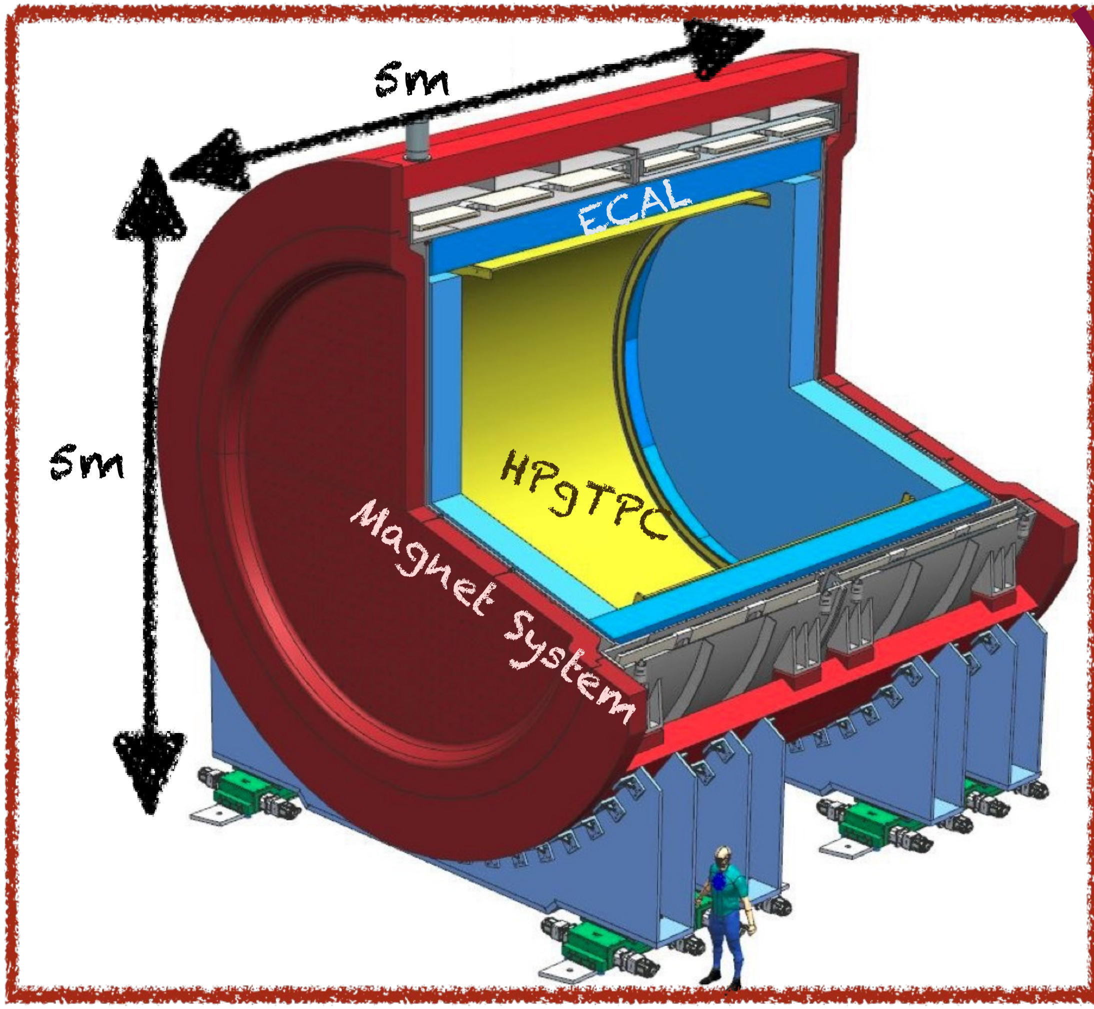




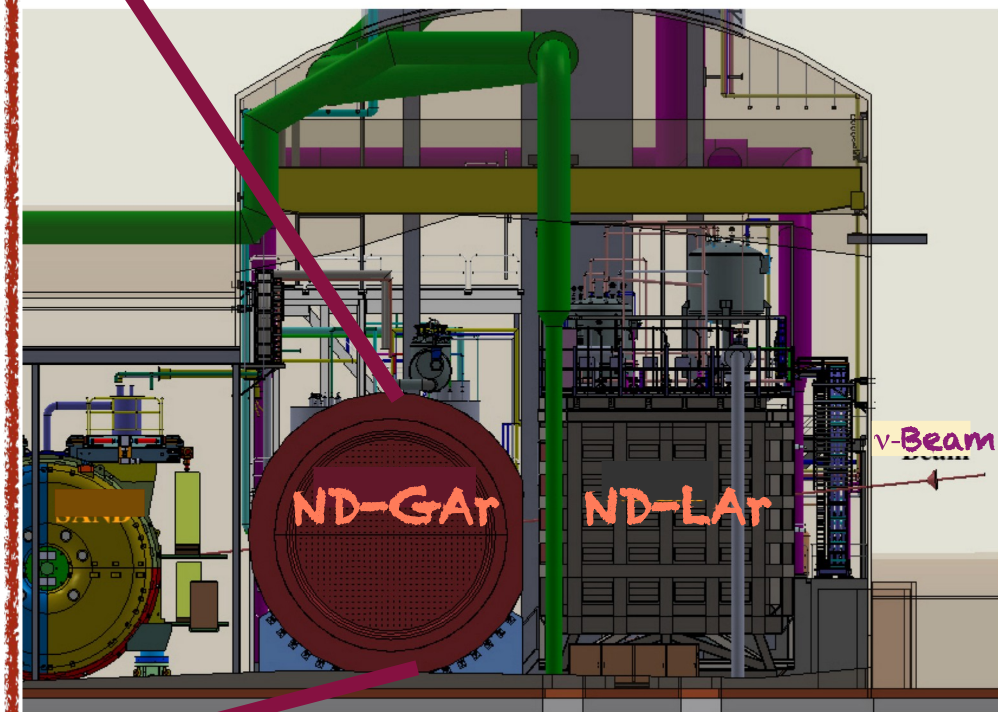


DUNE Collaboration, A. A. Abud et al. in 2022 Snowmass Summer Study. 3, 2022. arXiv:2203.06100 [hep-ex]

Near Detector Upgrade for DUNE Phase II



The phase I muon spectrometer will be replaced by ND-GAr in DUNE Phase II

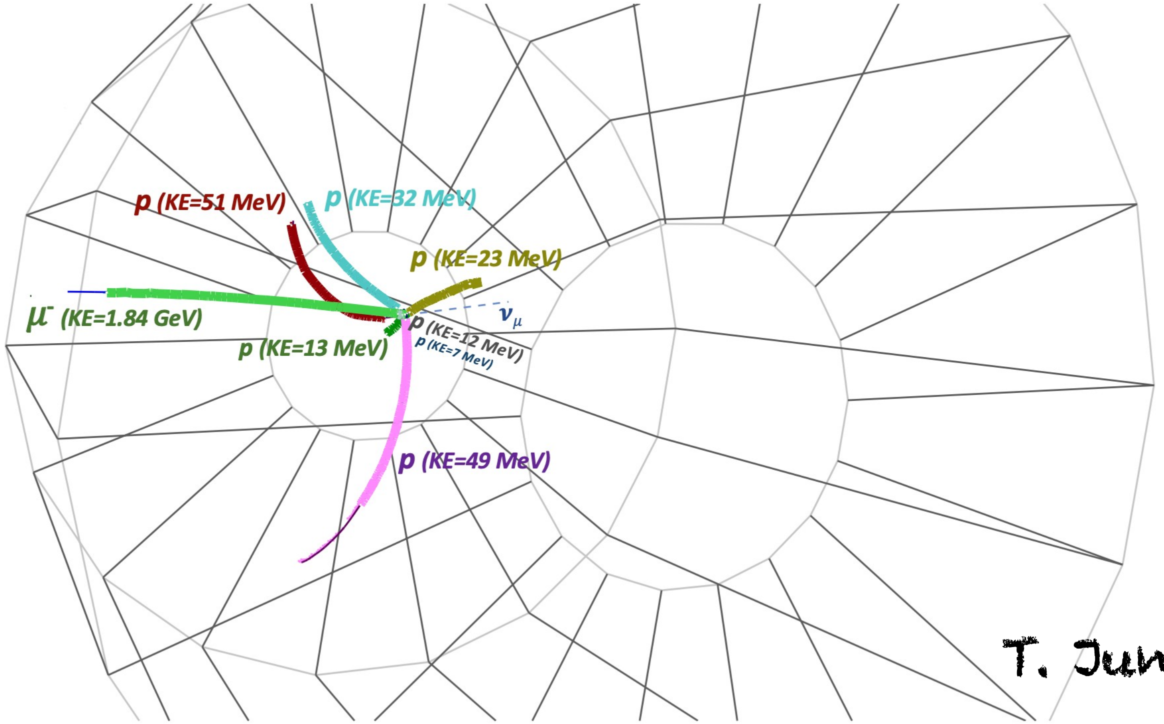


- ND-GAr, a **magnetized** **High Pressure <u>(10 atm)</u> Gas Argon TPC (HPgTPC)** surrounded by **ECAL** will be the DUNE ND Phase II upgrade
  - ★ **A low threshold detector** with excellent PID, tracking efficiency, and momentum resolution

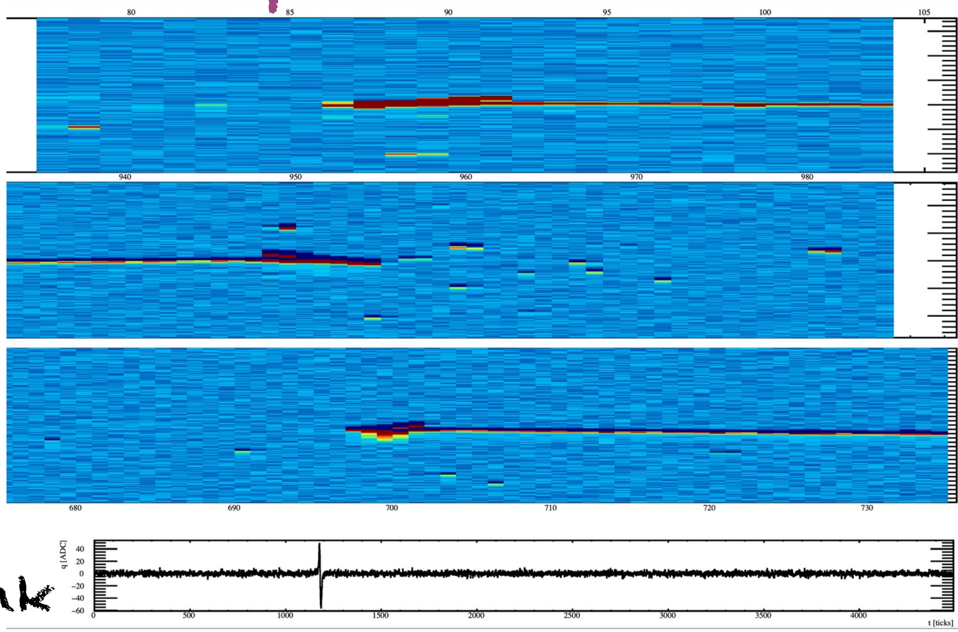
Impact of a Low Threshold Detector

- **Lower threshold of HPgTPC** compared with a **LArTPC** leads to a data-driven constraint on uncertainties in neutrino energy estimation

ND-GAr's HPgTPC



same simulated neutrino event with 7 protons in a LArTPC



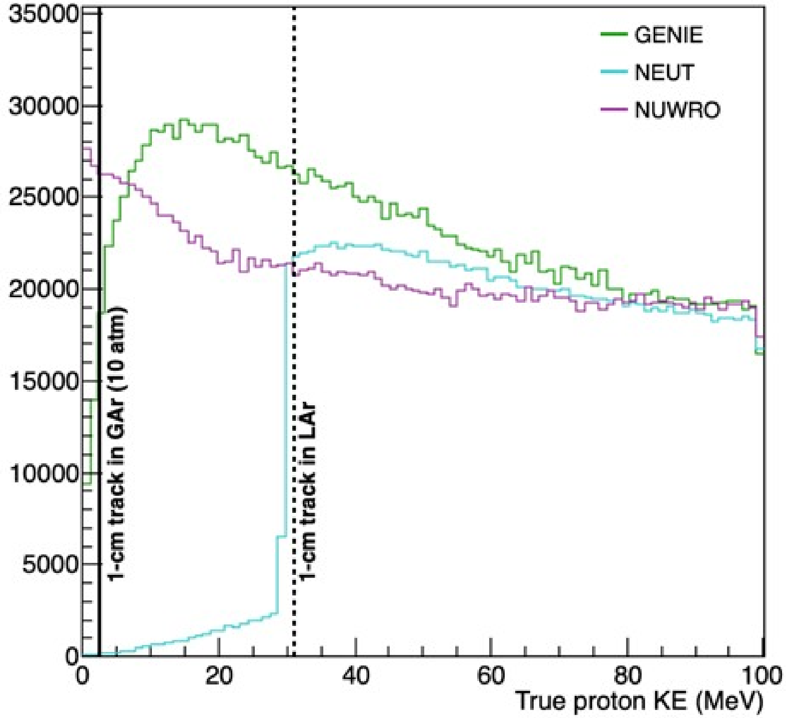
T. Junk

from the ND-GAr software, GArSoft with end-to-end reconstruction

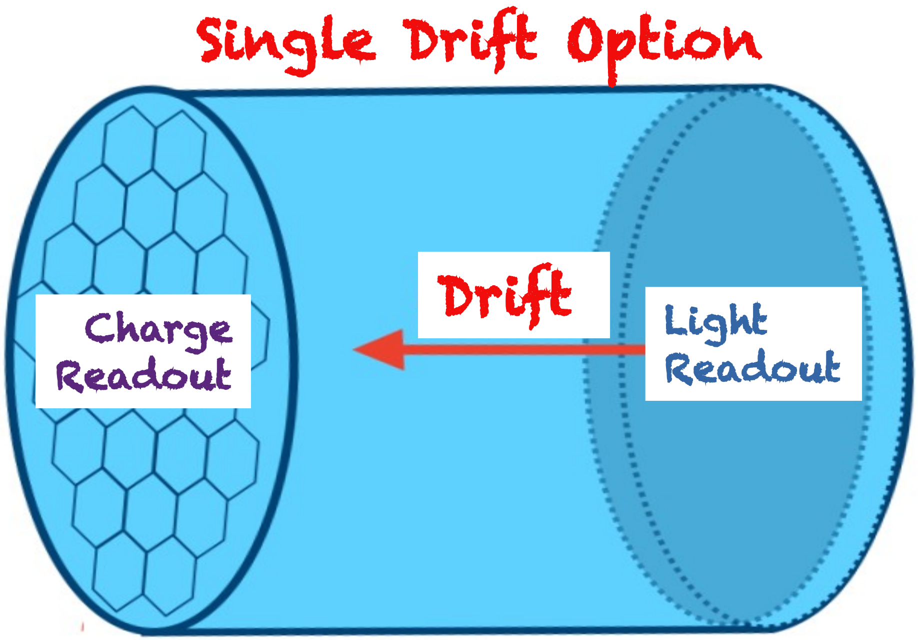
Impact of a Low Threshold Detector

- The low energy threshold of HPgTPC also allows DUNE to be more sensitive to **low energy hadrons** where neutrino interaction models are at odds, helping to resolve these disagreements

HPgTPC gives access to inaccessible regions of proton energy thanks to its low energy threshold



R&D Efforts

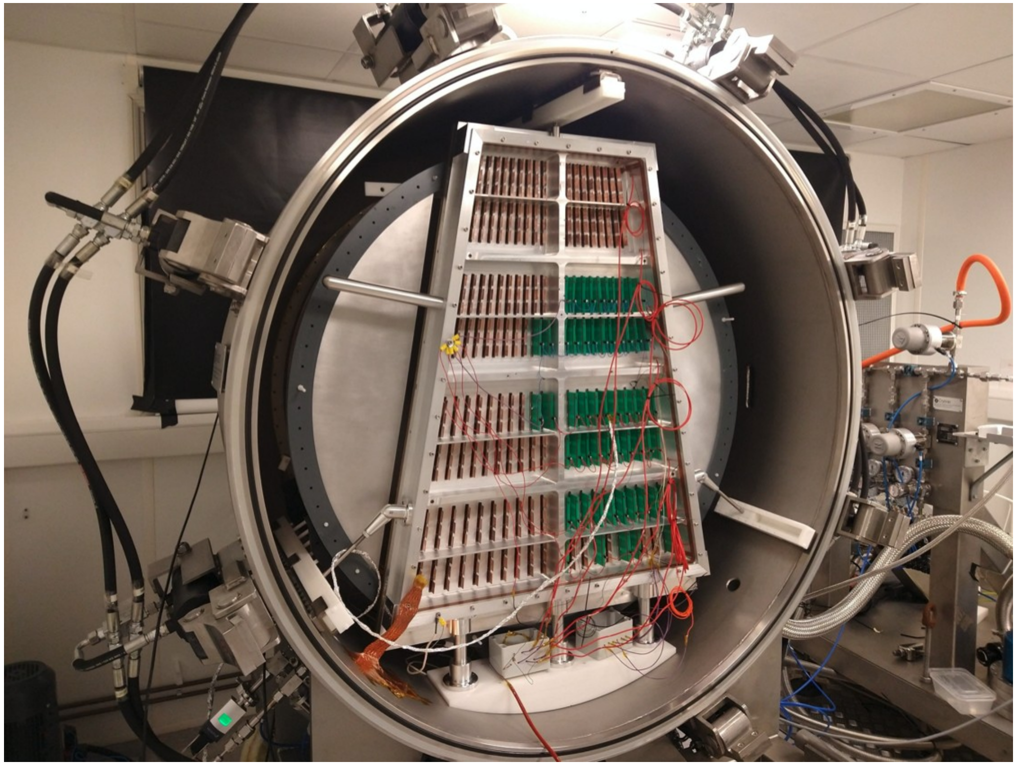


- On-going R&D thrusts of HPgTPC:
  - ★ TPC amplification, options include acquired ALICE MWPC, GEMs
  - ★ TPC readout, options include SAMPA, LArPix, SiPMs, LAPPDs
  - ★ Gas mixture optimizations

R&D Efforts - TPC Amplification

- MWPCs in the context of re-purposed ALICE chambers
  - Two efforts in US and UK completed a pressure scan of the chambers

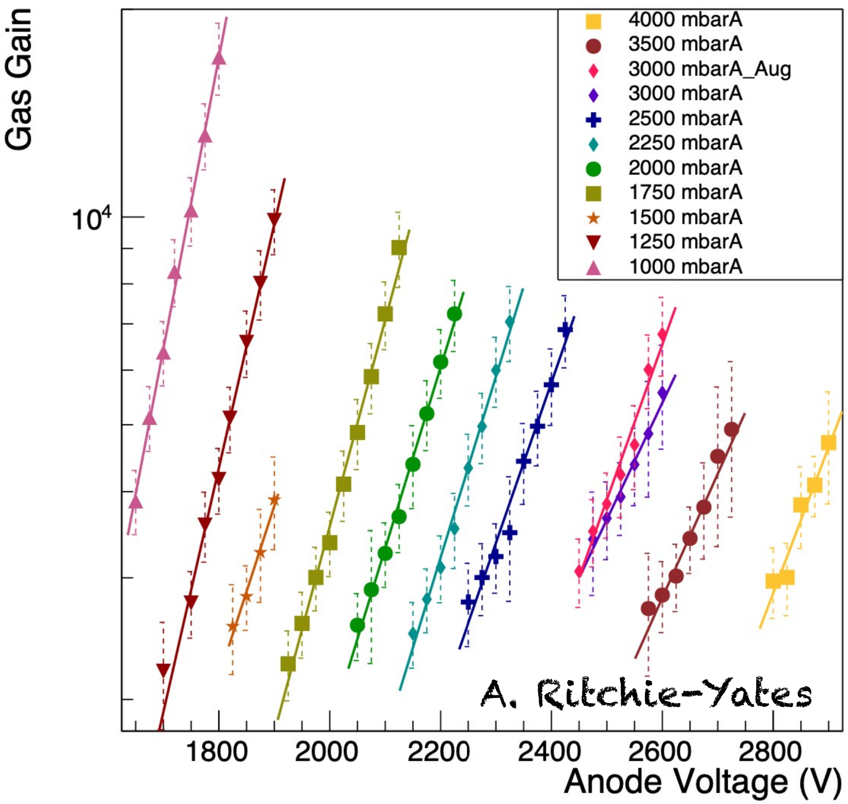
Royal Holloway Test Stand, housing an OROC, recently moved to Fermilab Test Beam, now named TOAD

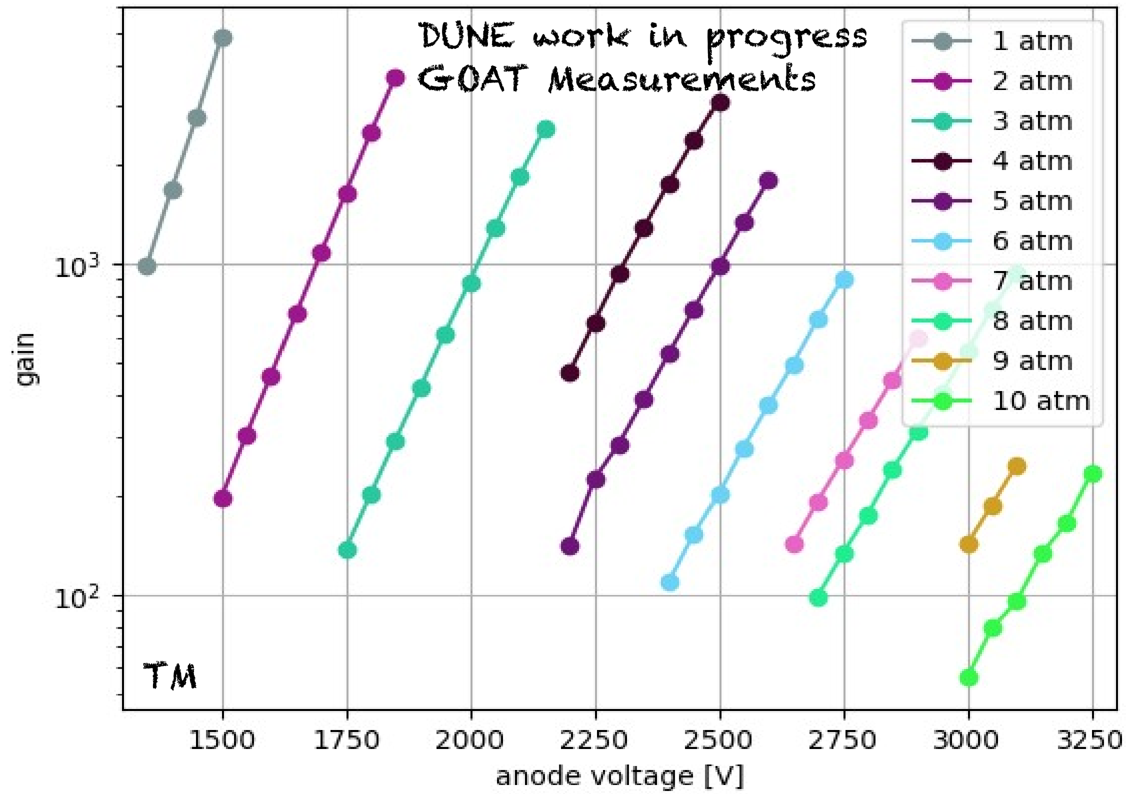


Fermilab Test Stand, housing an IROC, also named GOAT, now re-branding to GORG

R&D Efforts – TPC Amplification

- MWPCs in the context of re-purposed ALICE chambers
  - Two efforts in US and UK completed a pressure scan of the chambers
  - Chambers able to maintain their **gain** with increasing pressure

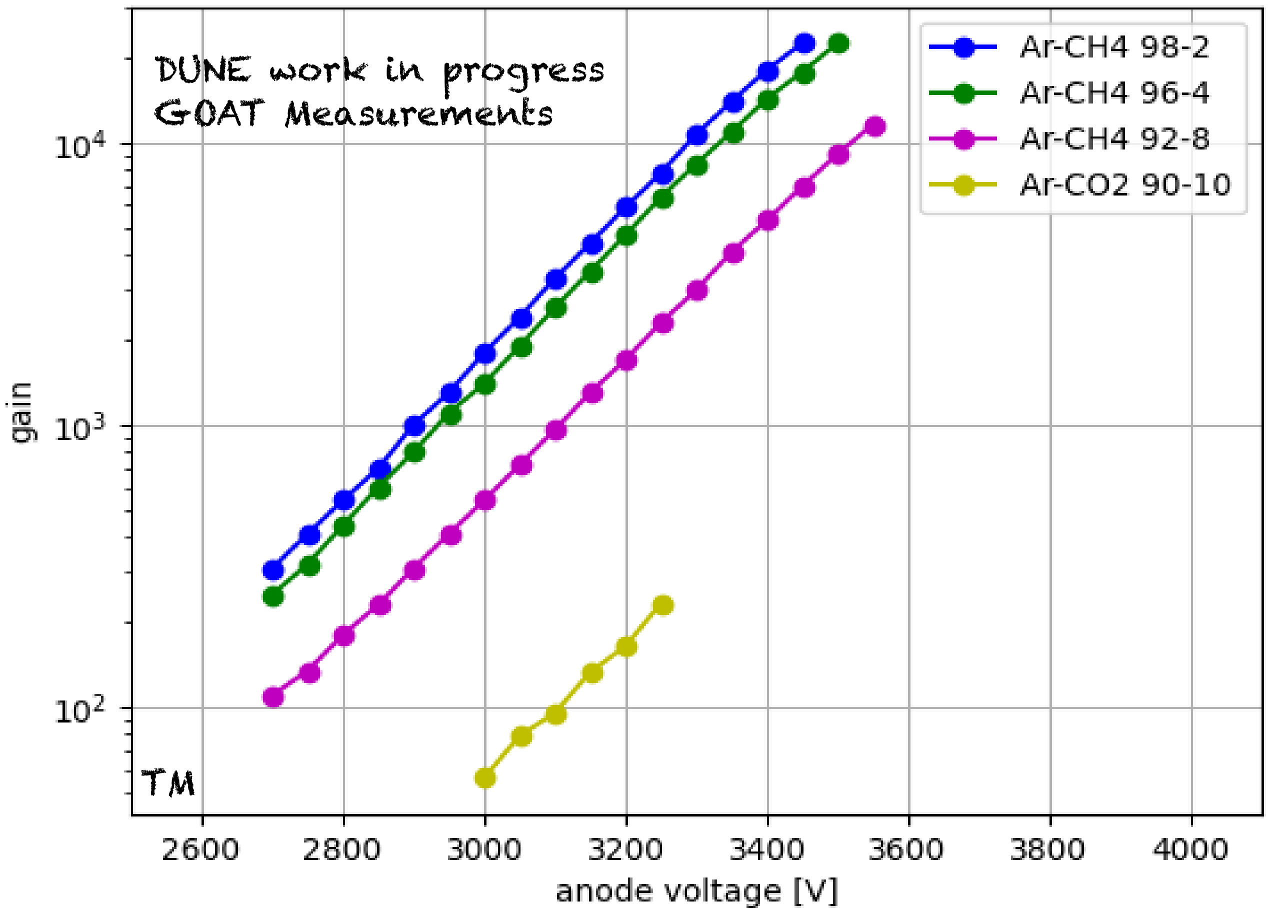




https://doi.org/10.48550/arXiv.2305.08822

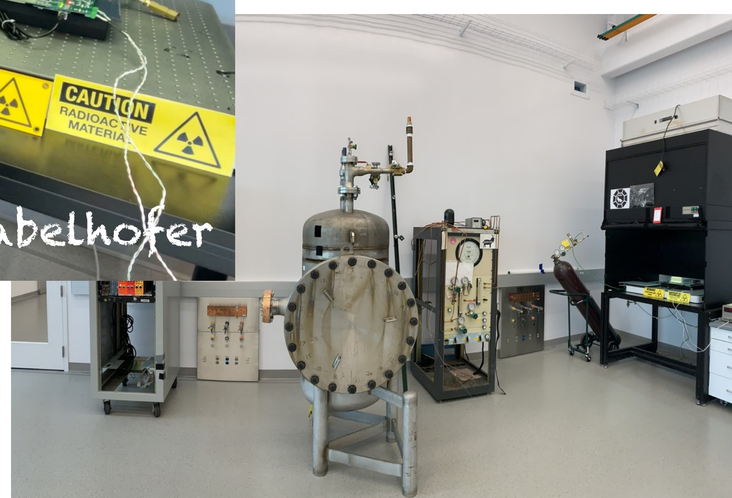
R&D Efforts – TPC Amplification & Gas Mixture Choices

- MWPCs in the context of re-purposed ALICE chambers
  - Two efforts in US and UK completed a pressure scan of the chambers
  - Chambers able to maintain their **gain** with increasing pressure
  - Using an Ar-CH_4 mixture, chambers can operate at a gain of 1k with an anode voltage below 3kV

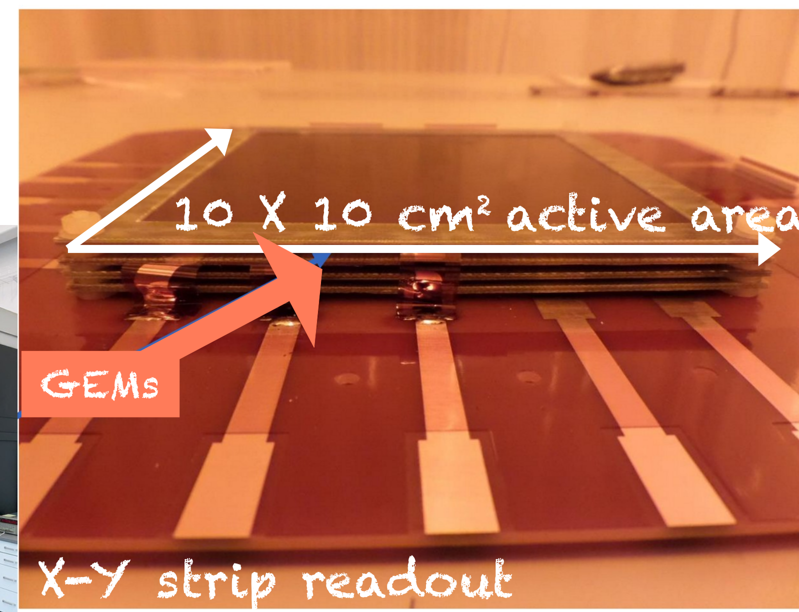


R&D Efforts – TPC Amplification

- Other options being considered are GEMs, testing them at high pressure requires R&D
  - On-going efforts include a series of calibration tests at Fermilab as part of the GORG effort (continuation of TM's New Initiatives award) and work that is starting up at Indiana University



Led by Indiana



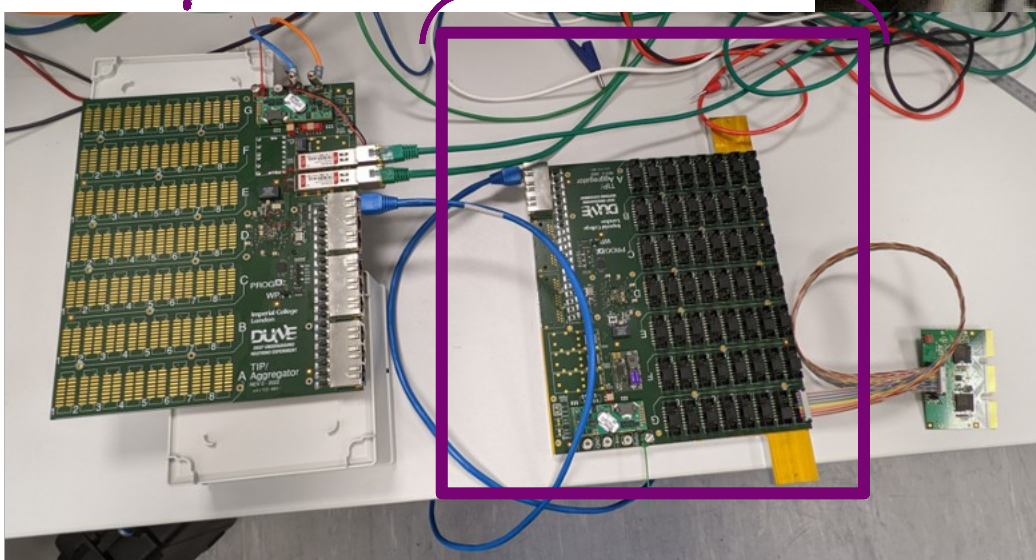
R&D Efforts - TPC Amplification

- Other options being considered are GEMs, testing them at high pressure requires R&D
  - On-going efforts include a series of calibration tests at Fermilab as part of the GORG effort (continuation of TM's New Initiatives award) and work that is starting up at Indiana University
- ThickGEMs are also being considered, led by Liverpool

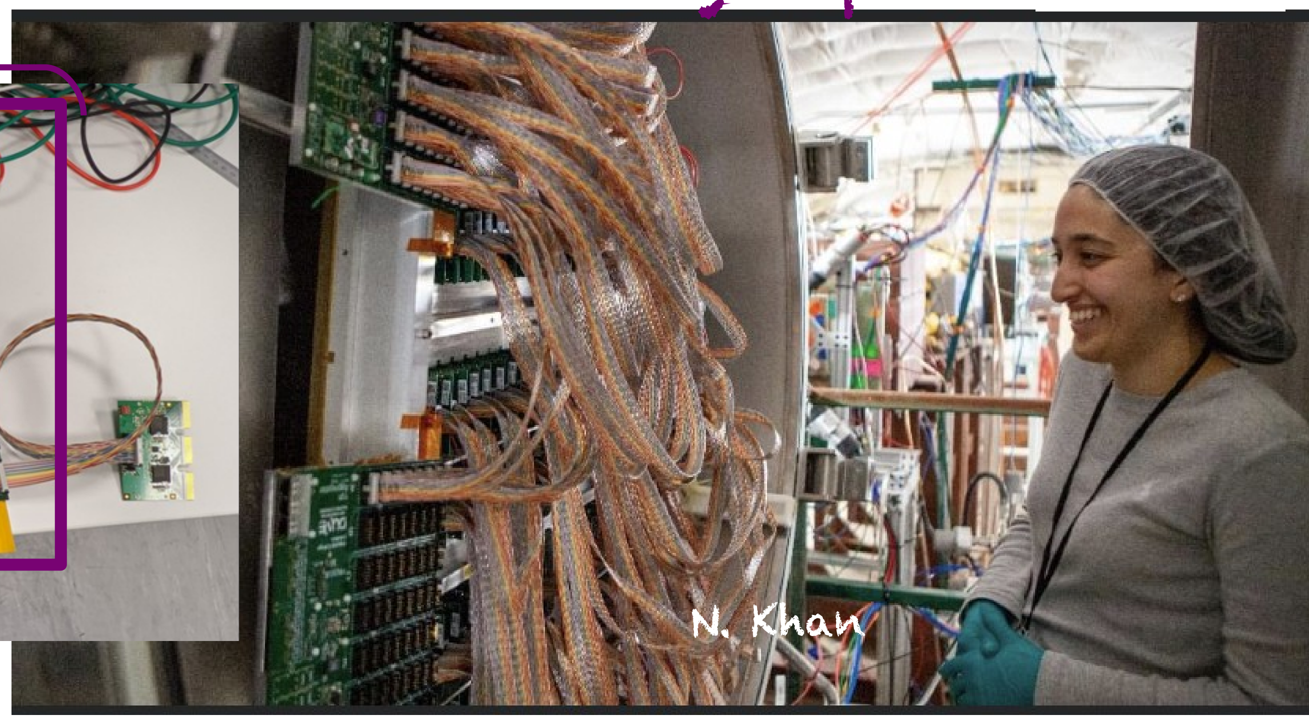
R&D Efforts – TPC Readout

- Beam prototype, TOAD, is scheduled to make a full slice test of the ALICE-based SAMPA cards
- Will also evaluate the long-term operation of ALICE chambers in a beam
- The prototype is in Fermilab Test Beam and a full chain of DAQ and electronics are being installed and tested

placed inside the pressure vessel

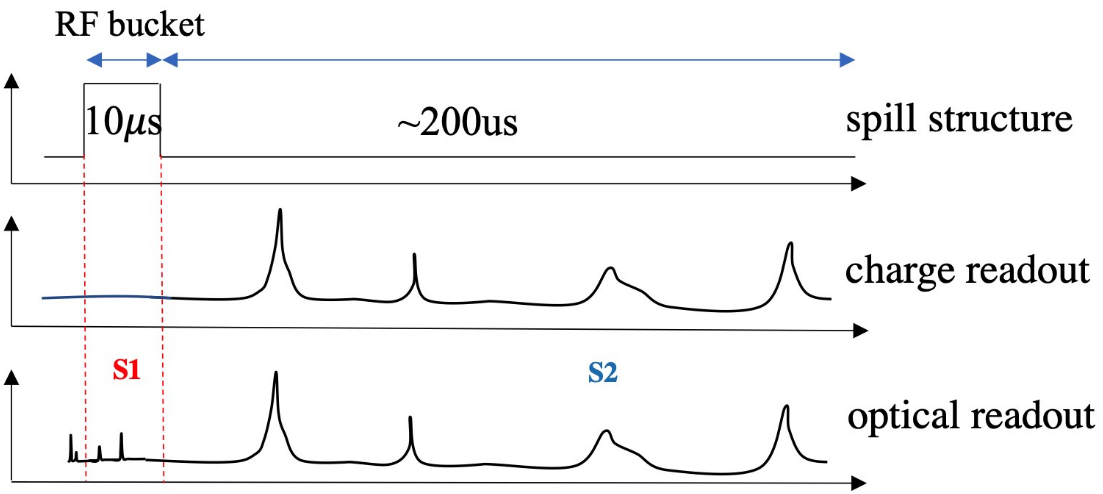


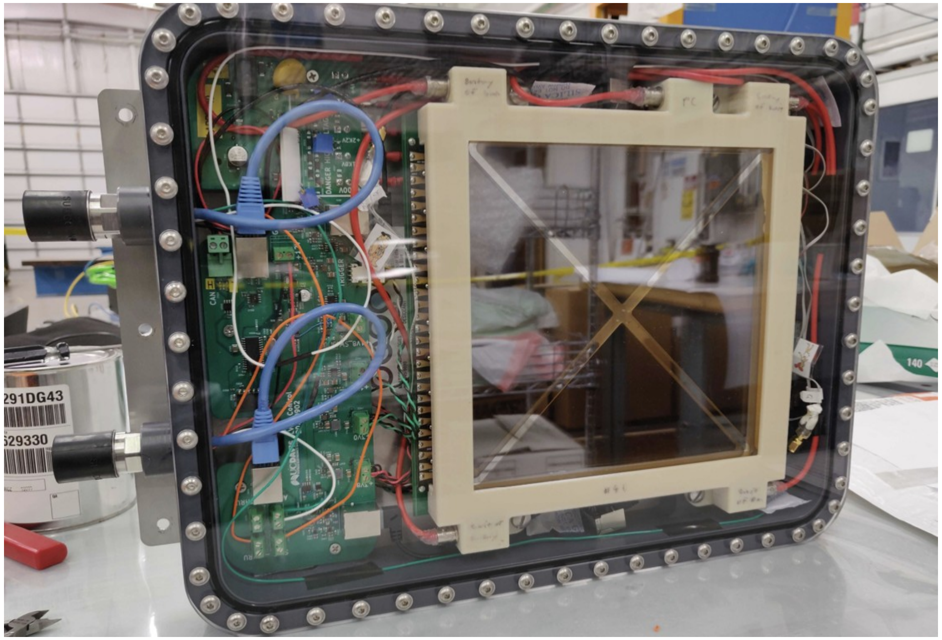
Led by Imperial



R&D Efforts – TPC Readout & Gas Mixture Choices

- Another key part of the R&D is the ability to read out both light and charge
  - Light readout is instrumental for background suppression & triggering
  - Options include SiPMs or LAPPDs
- Choosing an admixture/dopant that will not quench the scintillation signal also crucial
  - Initial studies carried out at IGFAE focuses on **CF4**

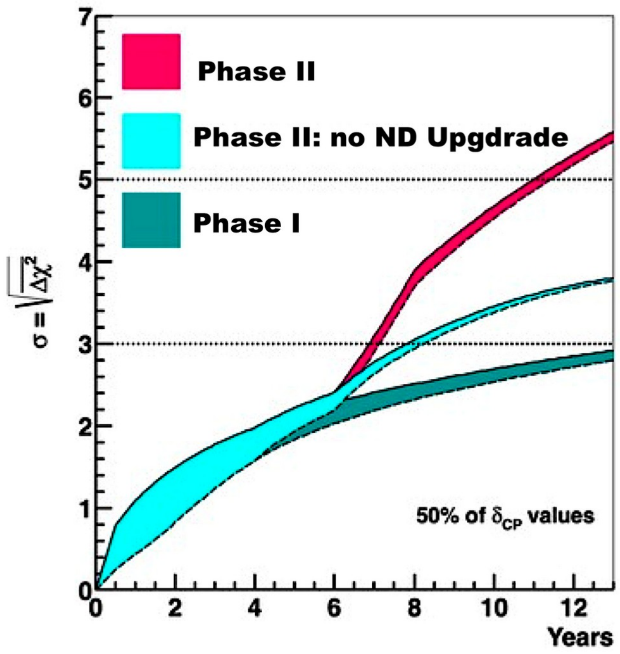


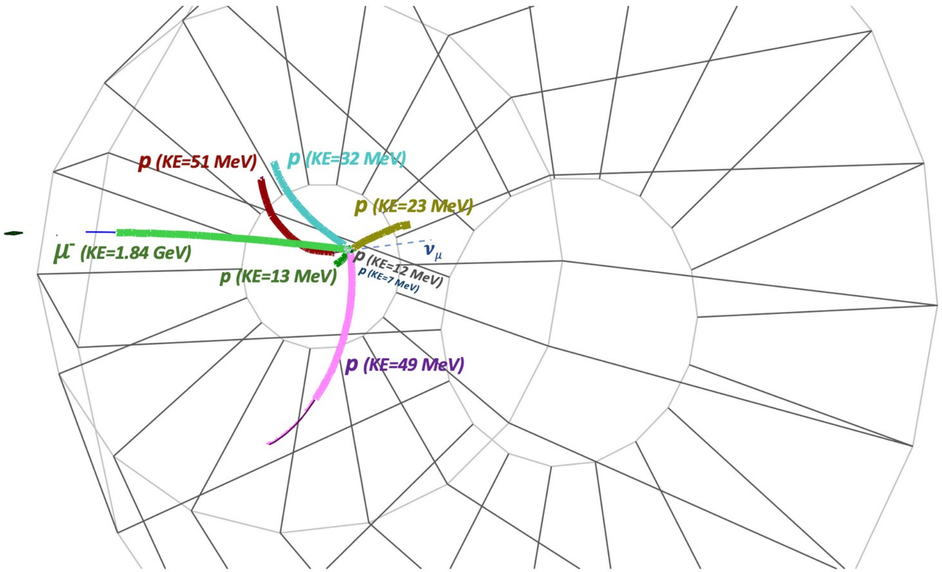


Summary

- The DUNE ND-GAr's unique design includes highly capable components that enable:
  - DUNE to reach a 5σ sensitivity to CP violation after ~5 years of running
  - Examining ν-Ar interactions up close to establish a robust constraint on systematics.

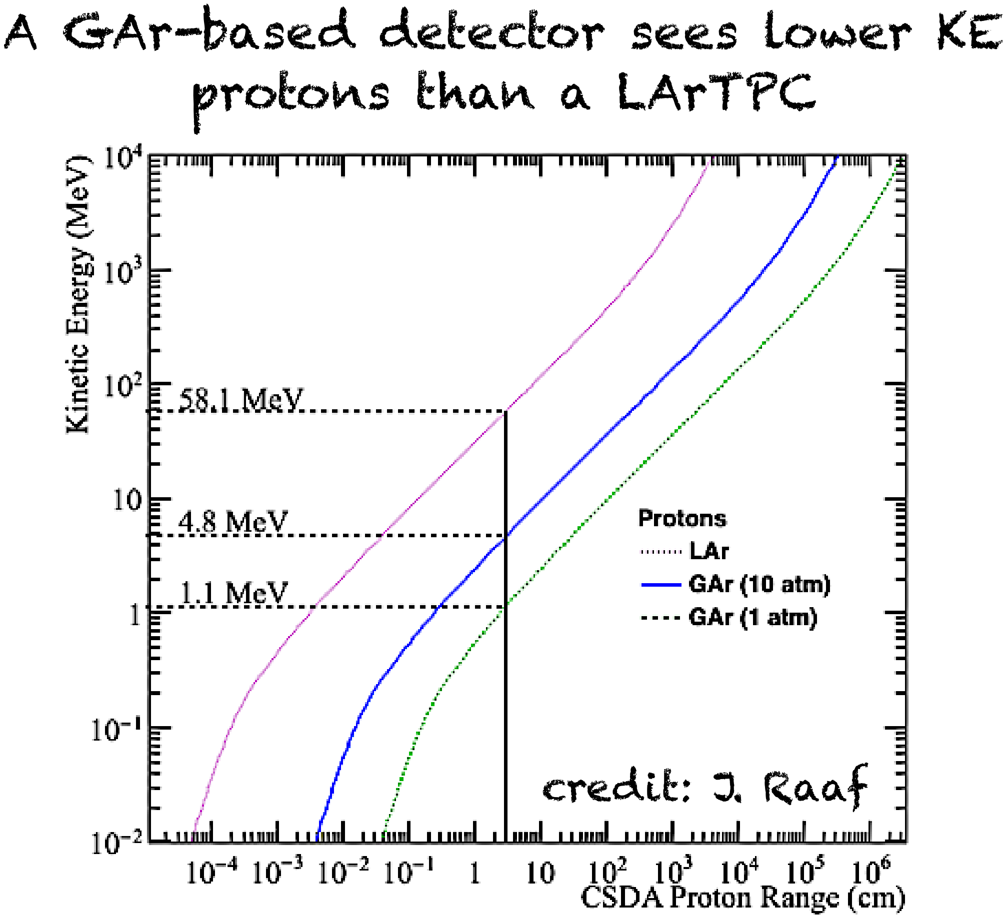
- A wide range of detector R&D efforts are underway to build this highly capable gas-based argon detector:
  - Besides R&D on the acquired ALICE MWPCs, we are exploring various new detector R&D areas, including MPGDs and light readout
  - Our R&D endeavors offer synergies across diverse communities, and we welcome participation from new institutions!





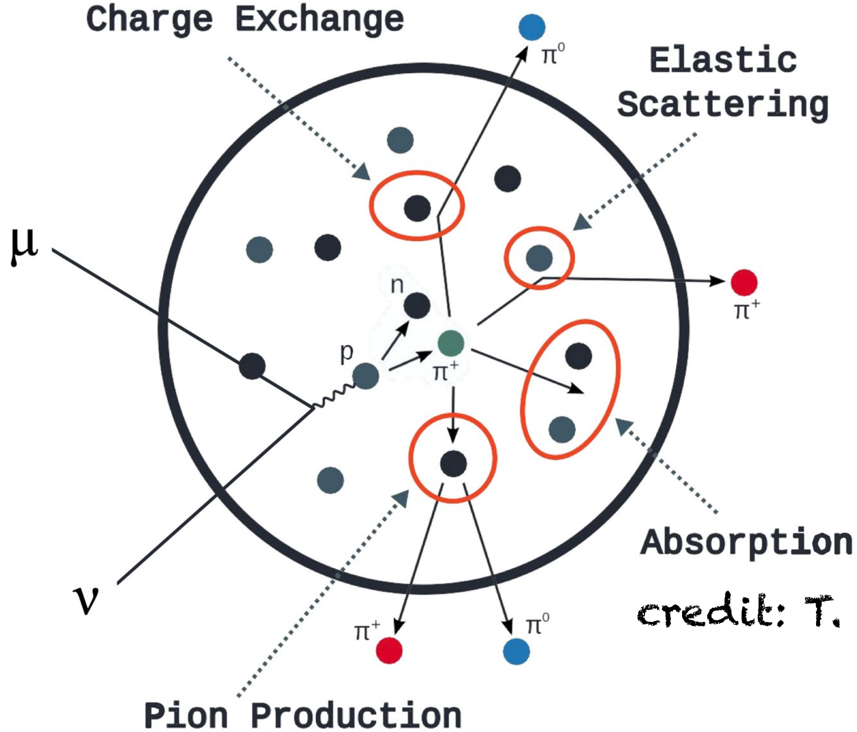
Low Threshold ND-GAr

- Lower threshold of **ND-GAr's HPgTPC** than **ND-LAr**:
  - Leads to a high sensitivity to low energy protons or pions:



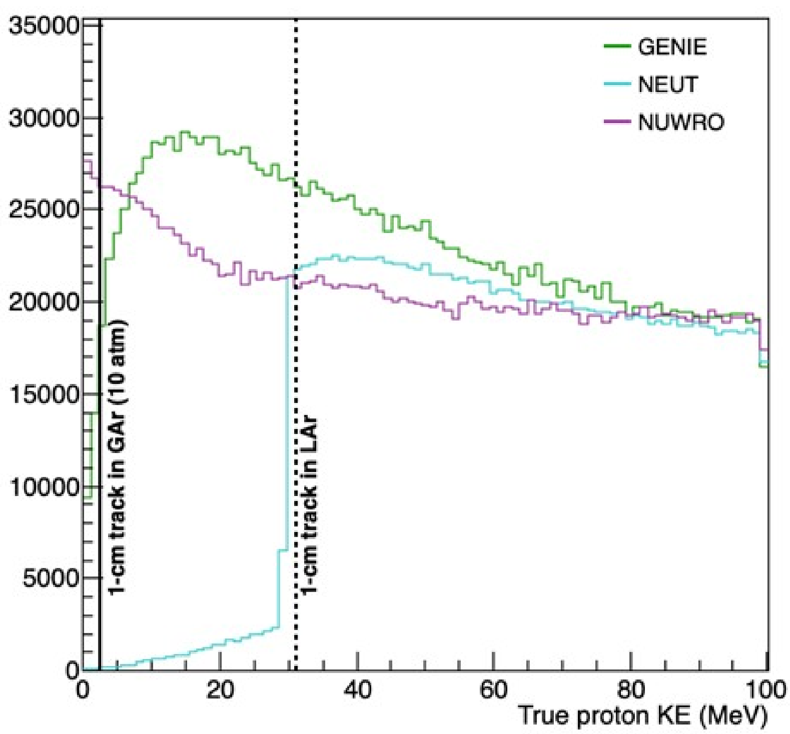
Low Threshold ND-GAr

- Nucleus is a complicated environment (e.g. specially problematic when using heavy nuclei as target):
  - Nuclear effects, e.g. final state interactions not yet fully understood
  - Tuning the nuclear models with data can help improve it, HPgTPC in ND-GAr can provide access to a previously un-explored energy regions



credit: T. Golan

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



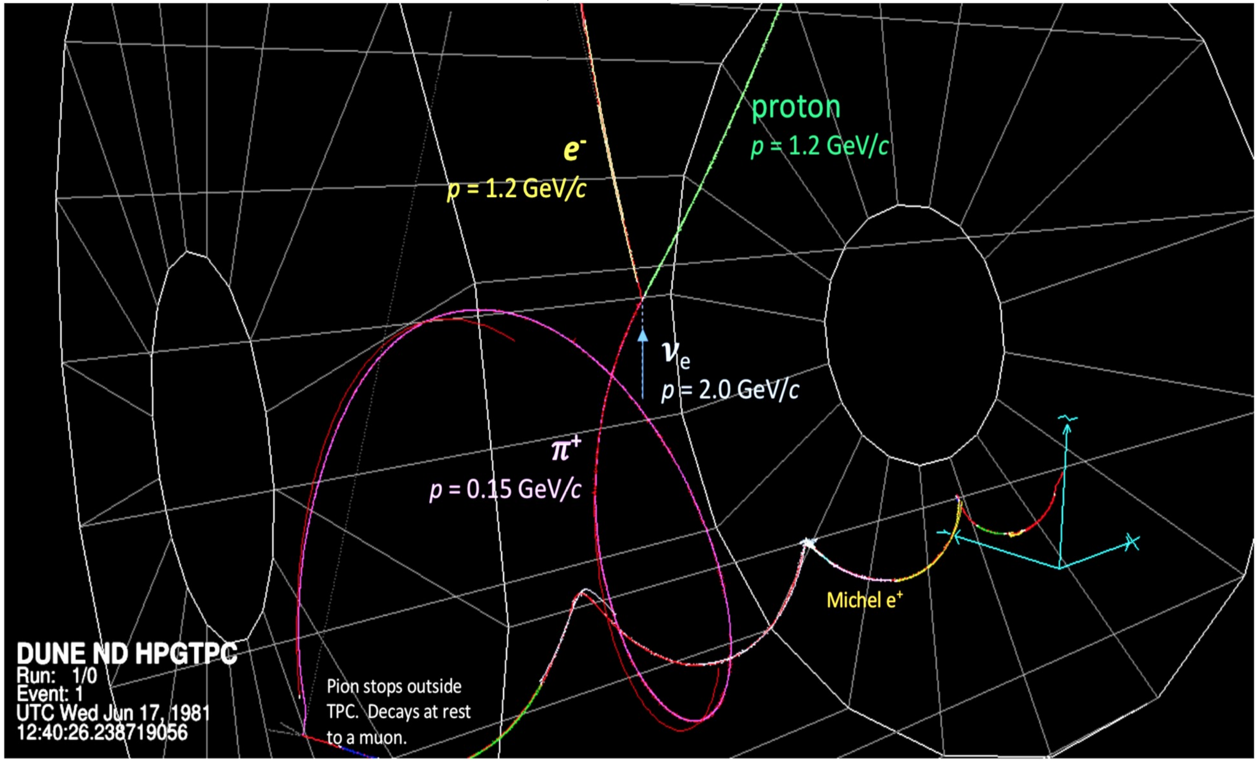
A Wealth of ν-Argon Interaction Data

- Using high-pressure gas-argon as detecting medium allows for an independent sample of ν-interactions on argon and constrains the cross-section systematic uncertainties to the level needed by the oscillation analysis
  - e.g. high statistics sample of exclusive neutrino interactions without a **pion** or **with some number of pions in final state**

1 ton fiducial mass for 1 year of ν-mode running with a 1.2MW Beam Power

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 CC1$\pi^\pm$	4.1×10^5
ν_μ CC1π^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

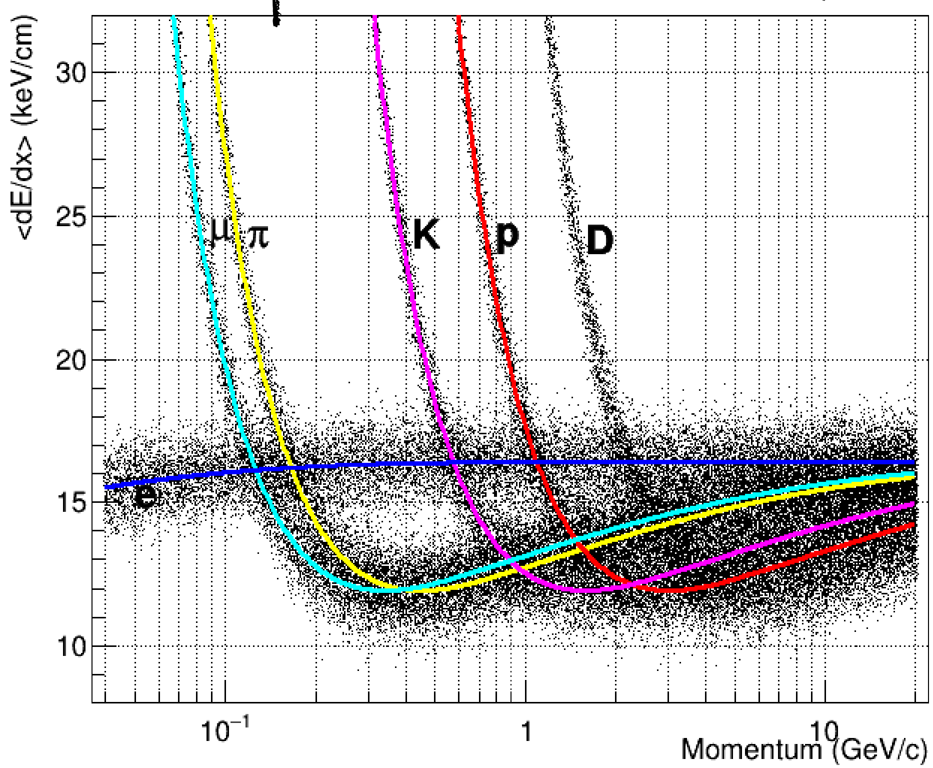
A detailed view of the ν-interaction vertex

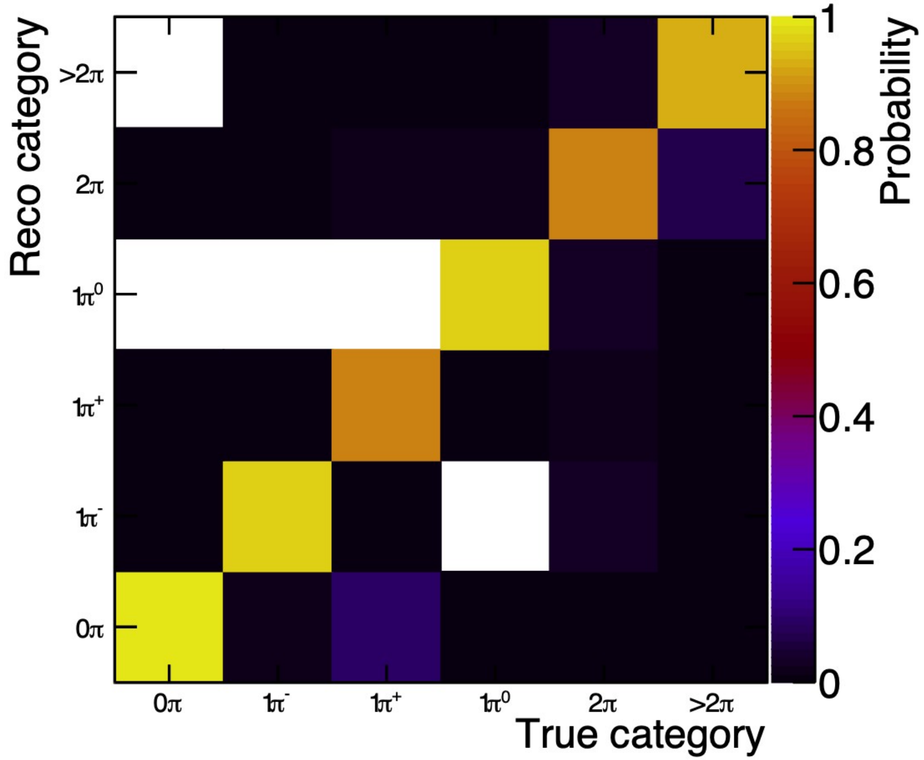


Superb PID for ν-Ar Interaction Measurements

- dE/dx resolution: 0.8 keV/cm
- Excellent PID combined with low threshold feature allows ND-GAr to help with correctly identifying the **different final state topologies e.g. pion multiplicities** very well

dE/dx-based PID will be comparable to PEP-4's

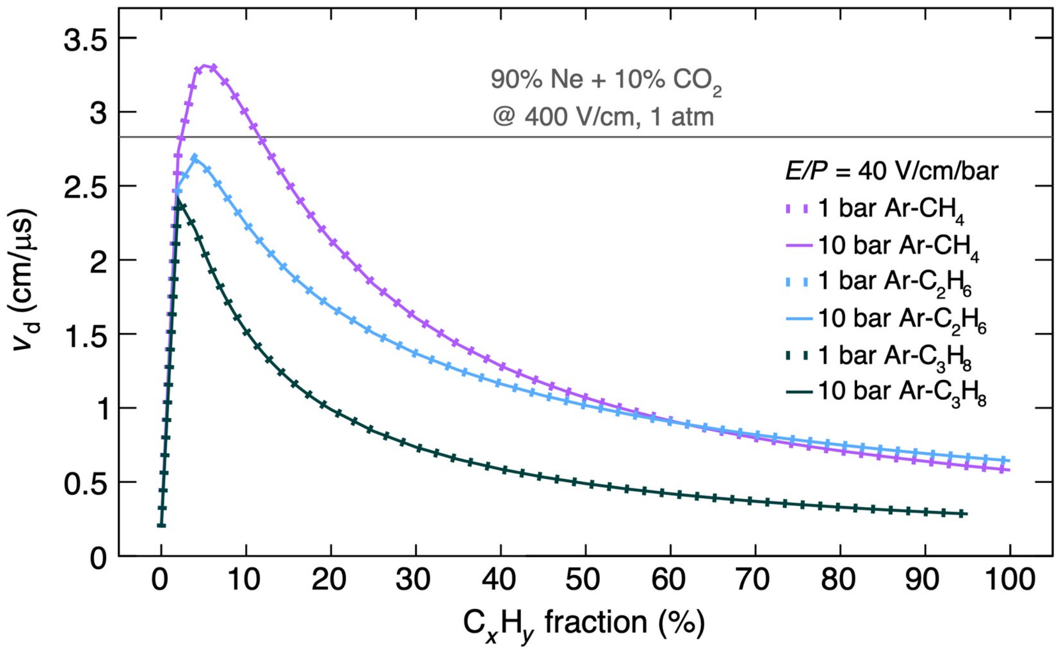


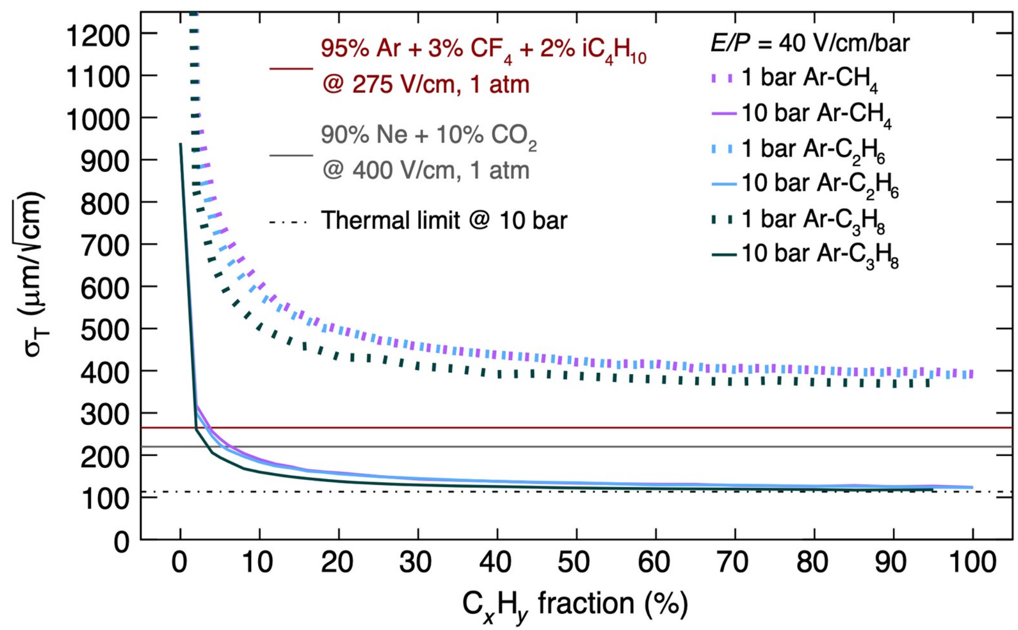


DUNE Collaboration, A. Abed Abud et al. Instruments 5 no. 4, (2021) 31, arXiv:2103.13910 [physics.ins-det].

R&D Efforts

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

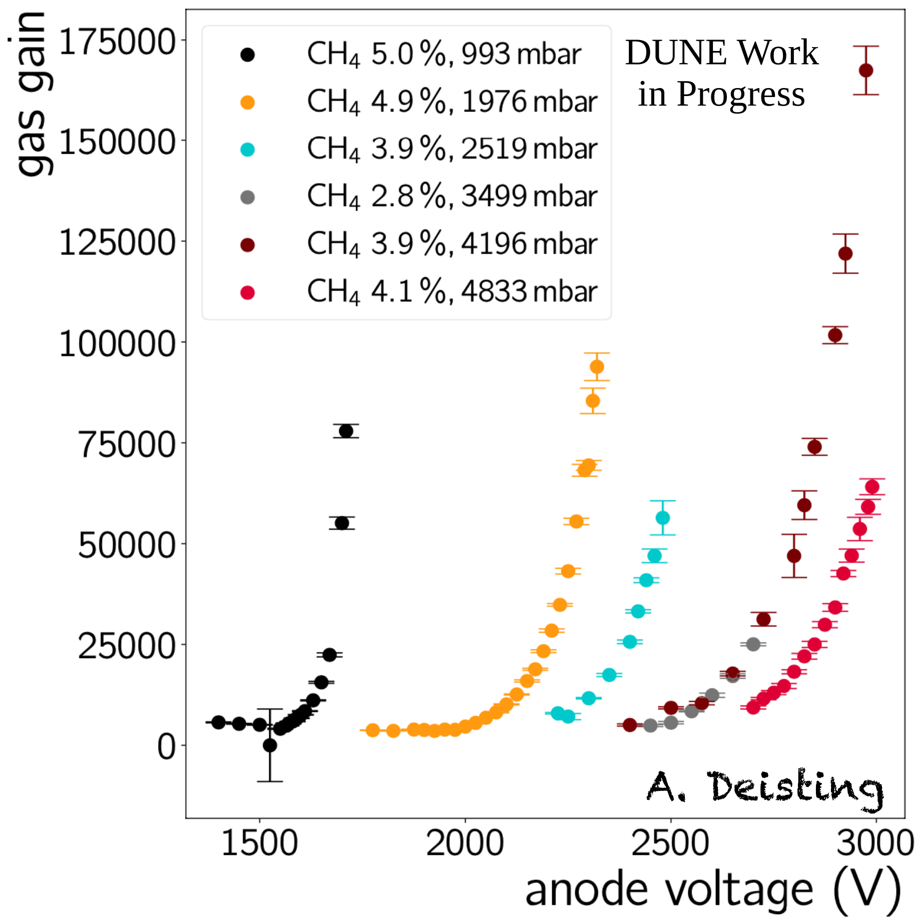




P. Hamacher-Baumann et al., Phys. Rev. D 102, 033005 (2020)

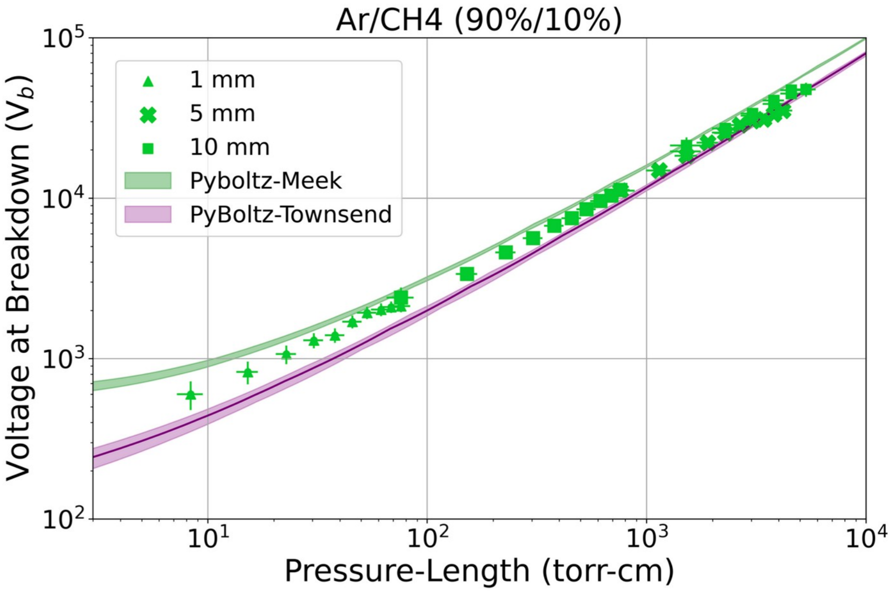
R&D Efforts

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



R&D Efforts

- What is involved in the charge readout optimization studies:
  - Testing the chambers @ various pressures up to 10 atm (e.g. ALICE chambers previously operated at 1 atm)
  - Defining a base gas mixture – reference is argon-based gas with 10% CH_4 admixture (97% of interactions on Ar) but can be optimized to:
    - Control pile up (drift velocity) and improve spatial resolution (diffusion)
    - Maximize gas gain, while minimizing gas electrical breakdown

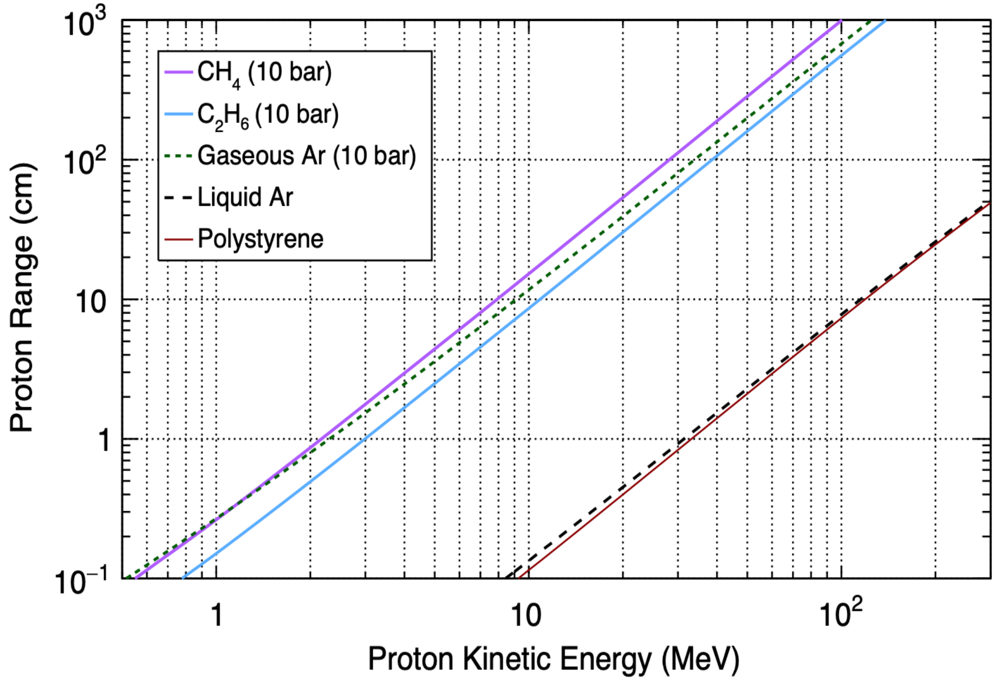


Norman, L. *et al.* Dielectric strength of noble and quenched gases for high pressure time projection chambers. *Eur. Phys. J. C* **82**, 52 (2022)

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**

R&D Efforts

- What is involved in the charge readout optimization studies:
  - Testing the chambers @ various pressures up to 10 atm (e.g. ALICE chambers previously operated at 1 atm)
  - Defining a base gas mixture – reference is argon-based gas with 10% CH_4 admixture (97% of interactions on Ar) but can be optimized to:
    - Control pile up (drift velocity) and improve spatial resolution (diffusion)
    - Maximize gas gain, while minimizing gas electrical breakdown
    - 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)

Light Readout R&D

- A demonstrator is being built at IGFAE and IFIC in Spain with an aim to optimize an argon-based gas mixture and light collection

GAT0