A Gaseous-Ar Based Near Detector (ND-GAr) for DUNE Phase II

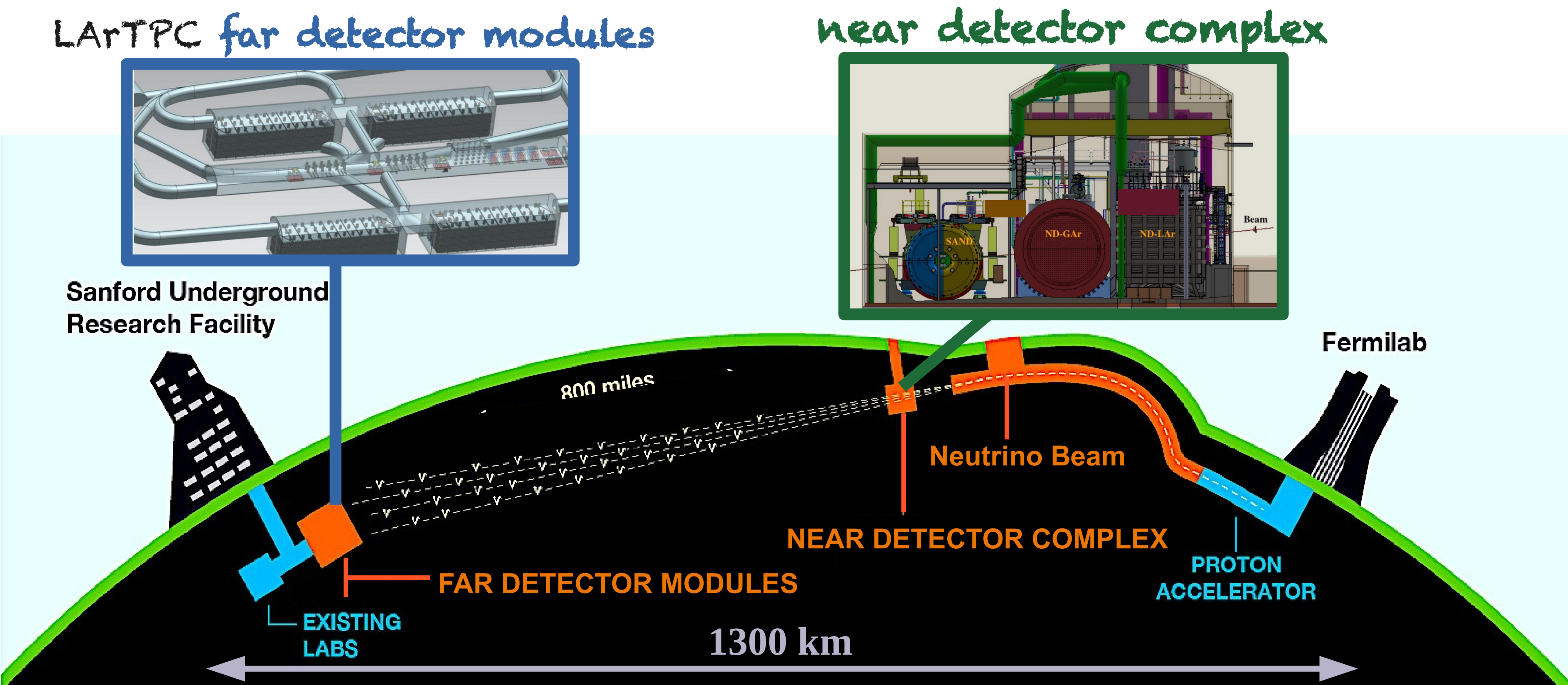
Tanaz A. Mohayai, Indiana University
for the DUNE Collaboration

ICHEP24, Prague, Czech Republic
July 19, 2024

DEEP UNDERGROUND NEUTRINO EXPERIMENT

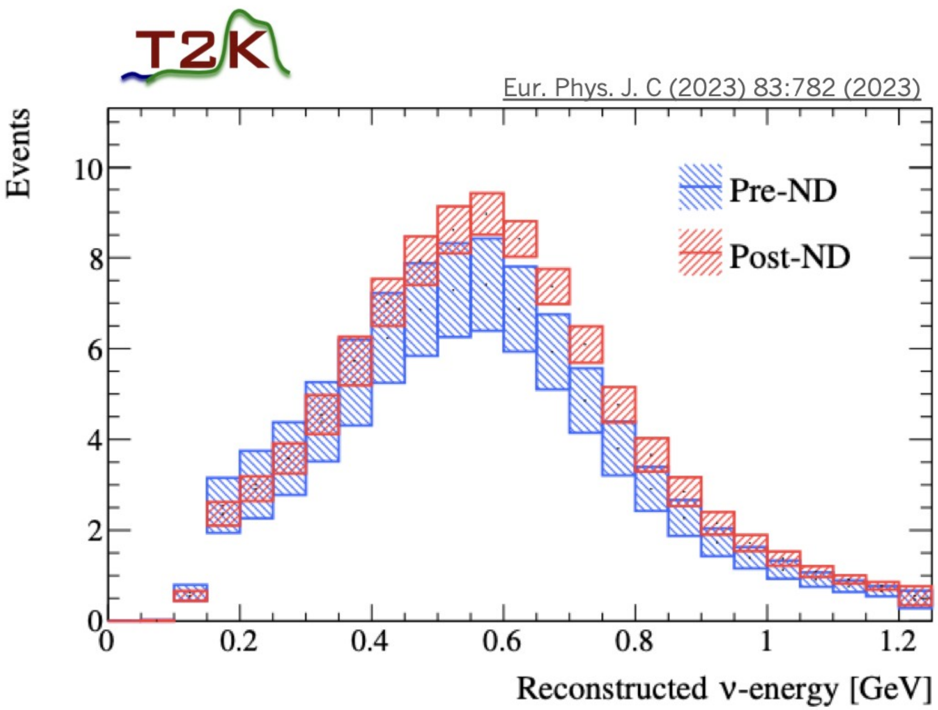
Deep Underground Neutrino Experiment

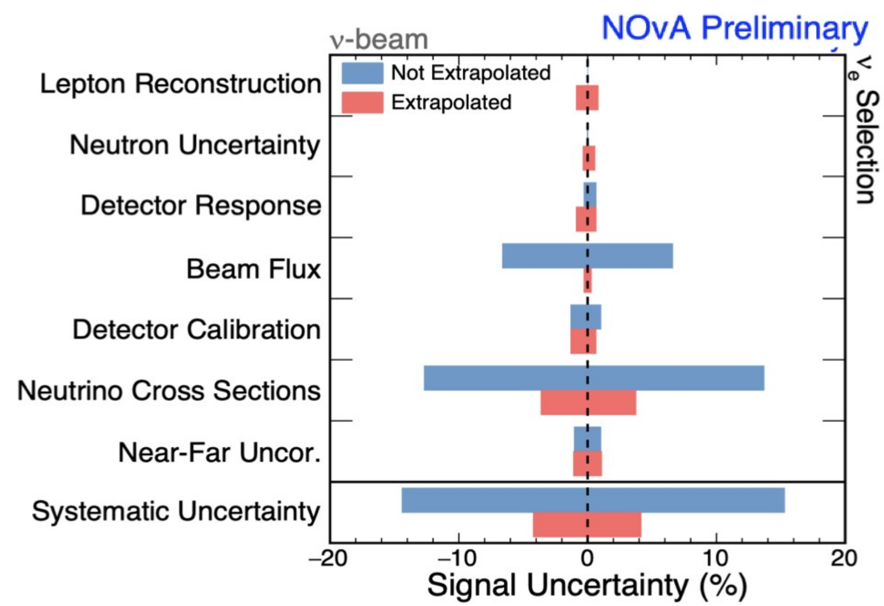
- A comprehensive physics program:
  - High precision measurements of neutrino mixing & the CP violation, and searches for BSM physics, baryon number violation, and supernova neutrinos
- Key components:
  - 1.2 MW, upgradable to 2.4 MW high-intensity, wide-band **neutrino beam**
  - **Near detectors,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



Compared to Existing Neutrino Experiments

- **Cross sections/neutrino interaction model uncertainties are the most dominant**, those from existing experiments too large for future precision neutrino physics:
  - T2K uncertainty ~5% (after applying constraints from ND data fit)
  - NOvA uncertainty ~4%
- DUNE can rise to the challenge (aim is ~% level precision)!

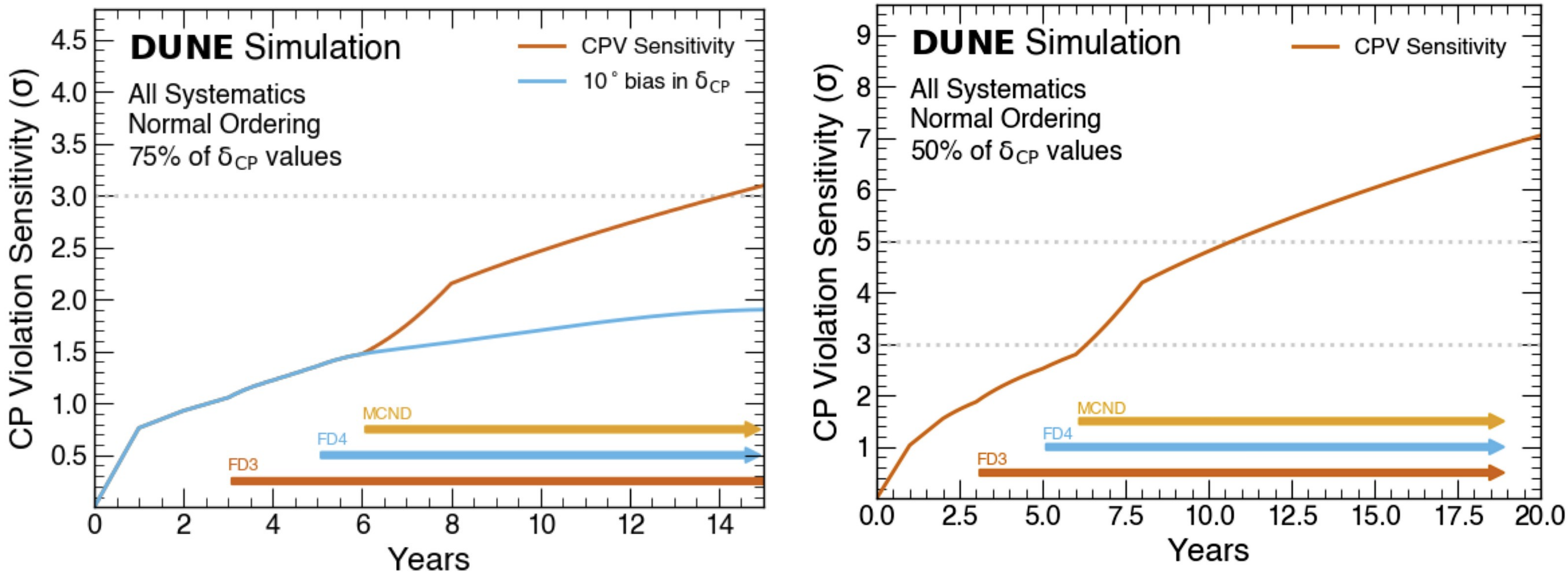




From Z. Vallari Wine & Cheese Seminar at FNAL

DUNE Phase II

- **Phase II** of DUNE will have upgrades to ensure the full scope of DUNE is met – includes **ND**, FD, and beam upgrades for higher statistics
  - ★ But only **ND upgrade to MCND (more capable near detector)**, a high pressure gas argon TPC with ECAL and B-field (*ND-GAr*) targets neutrino interaction systematics



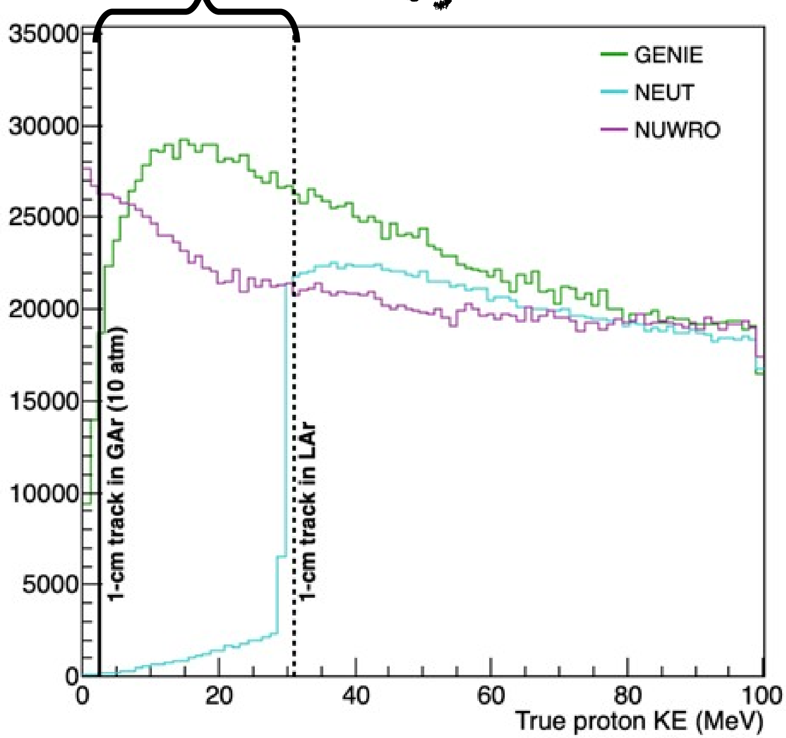
The phase I muon spectrometer will be replaced by ND-GAr in DUNE Phase II

2006.16043, Eur. Phys. J. C 80, 978 (2020), 2109.01304, Phys. Rev. D 105, 072006 (2022), 2002.03005

How a Gas-based ND-GAr helps

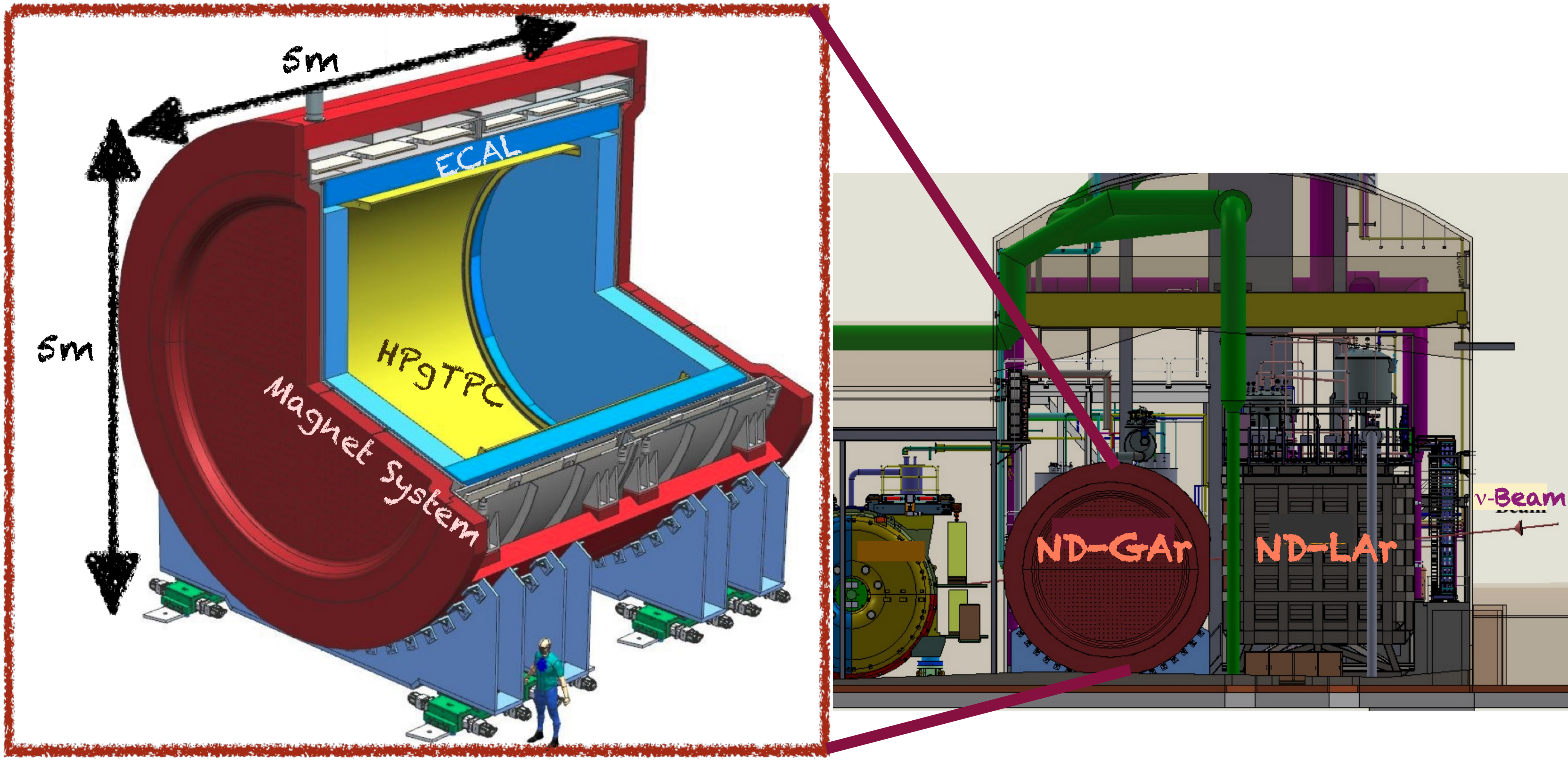
- Large uncertainty in neutrino interaction stems from inability to predict **low energy hadrons**
- The low energy threshold of a high-pressure gas TPC allows DUNE to be more sensitive to **low energy hadrons** where neutrino interaction models are at odds, helping to resolve these disagreements

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



Instruments 2021, 5(4), 31; https://doi.org/10.3390/instruments5040031

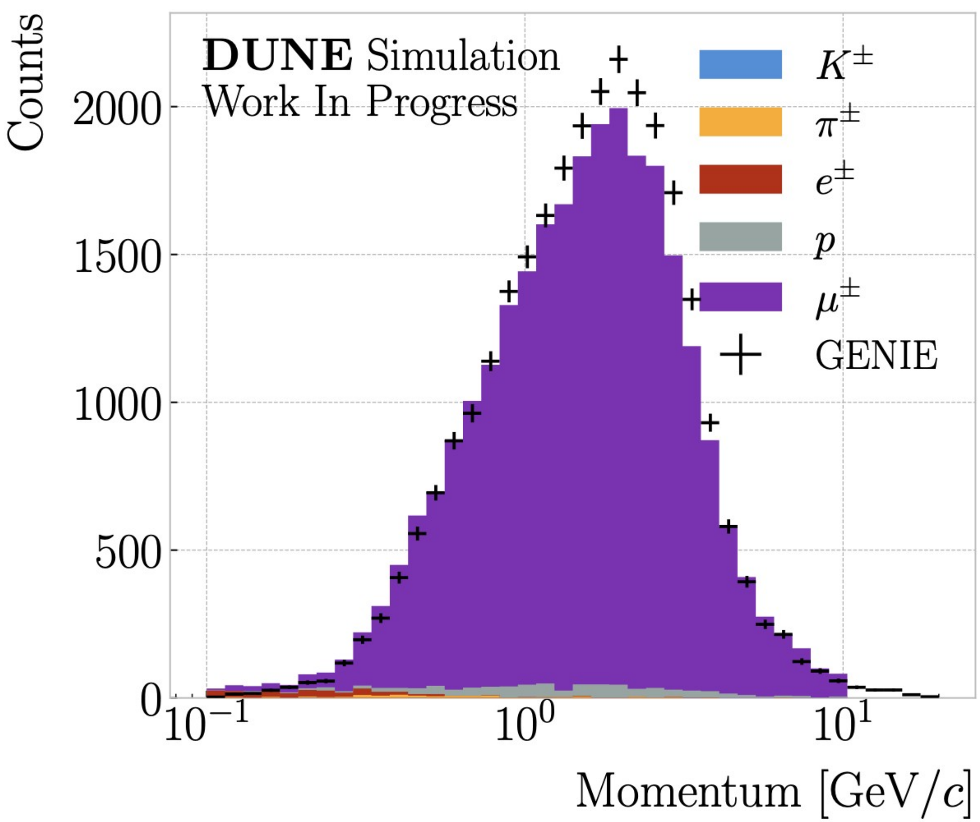
ND-GAr Design Details

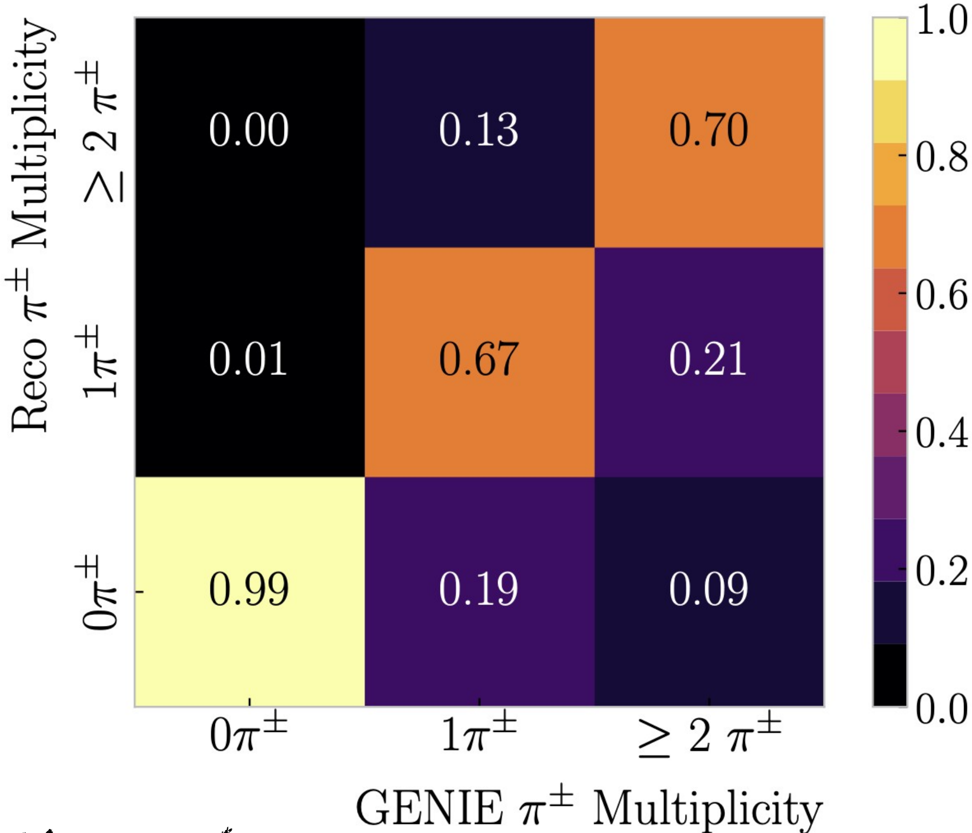


- ND-GAr, a **magnetized** **High Pressure <u>(10 atm)</u> Gas Argon TPC (HPgTPC)** (can collect a million muon neutrino interactions on Ar) surrounded by **ECAL** will be the DUNE ND Phase II upgrade
  - ★ **A low threshold detector** with excellent PID and momentum resolution

Detector Performance

- Mature hadron reconstruction in current end-to-end software targeting neutrino interactions in DUNE-relevant energy ranges where multi-pion final states are common



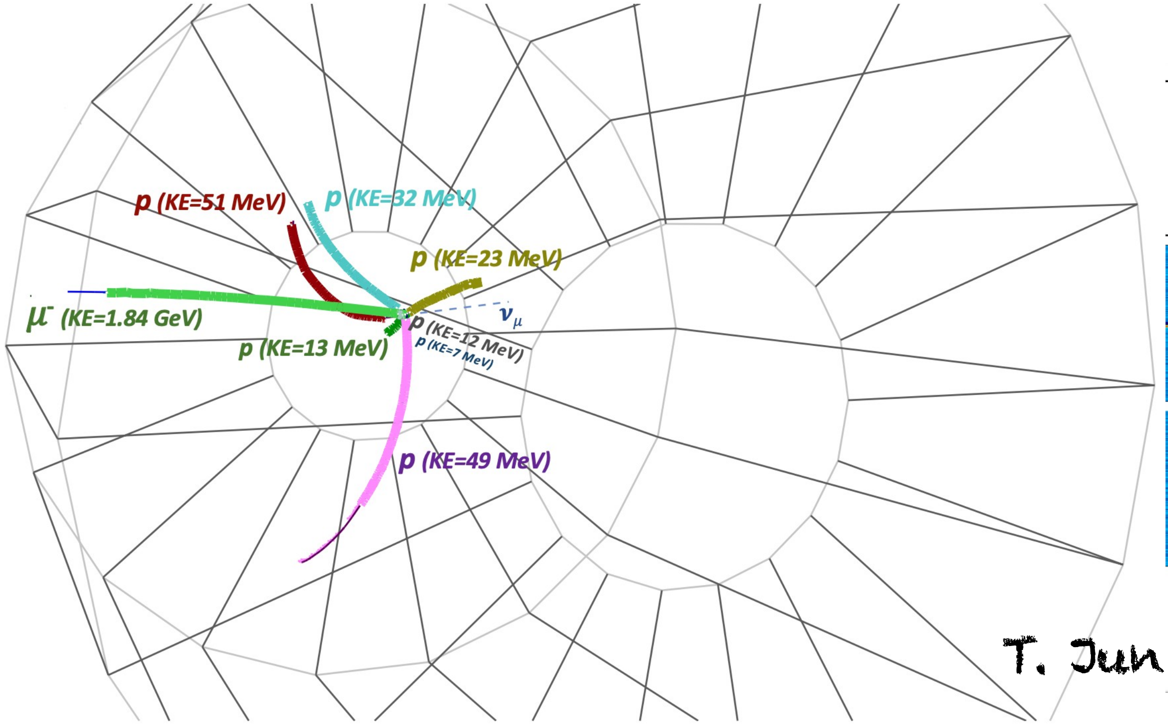


from the ND-GAr software, GArSoft with end-to-end reconstruction

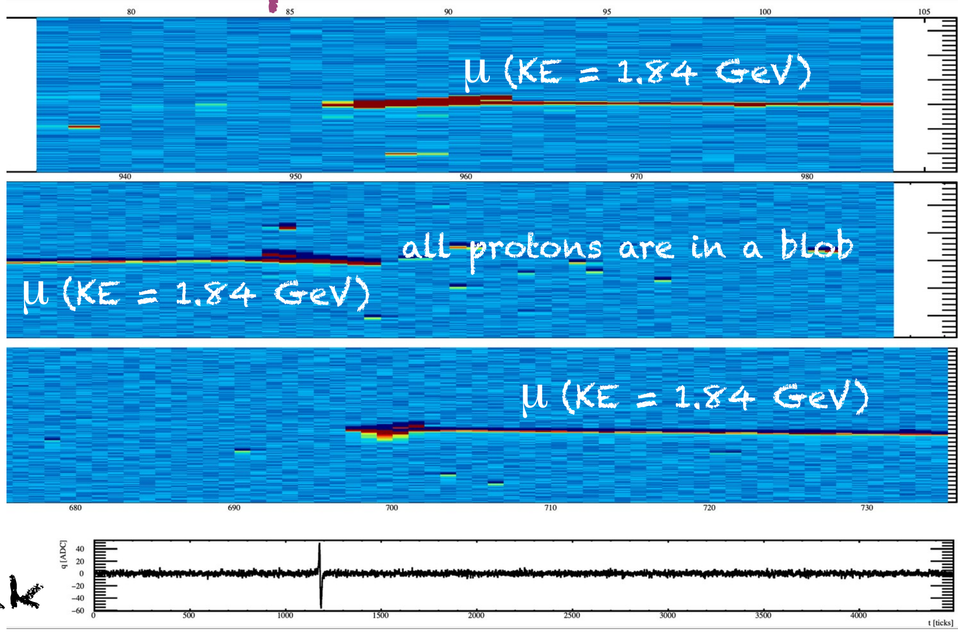
F. Martínez López

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

ND-GAr's HPgTPC



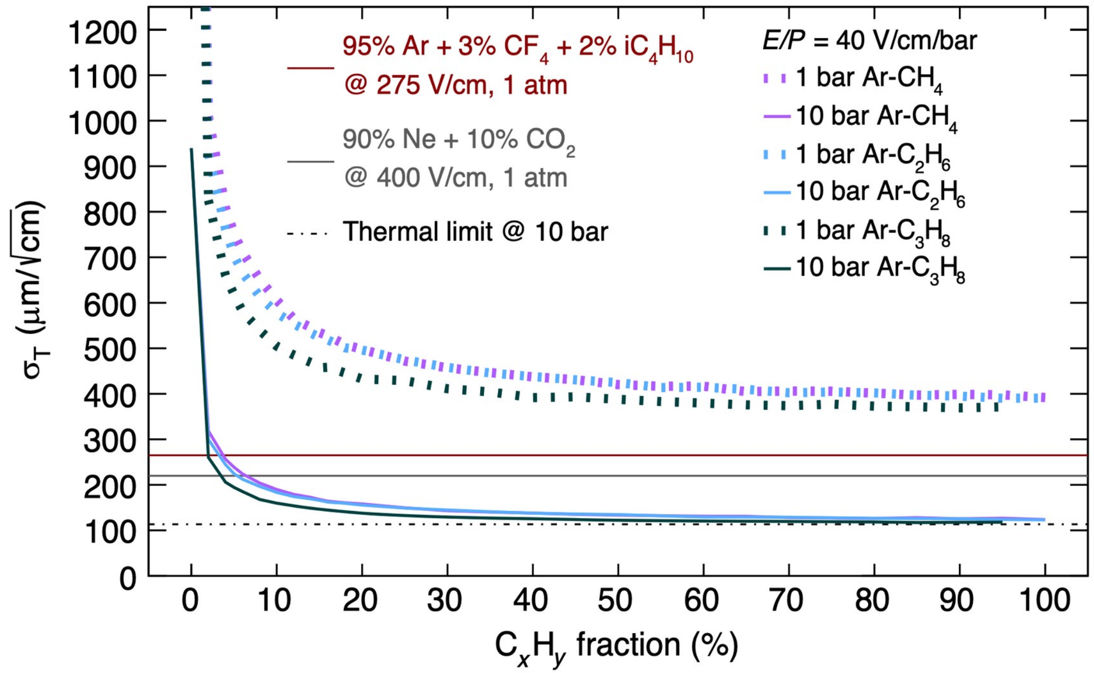
same simulated neutrino event with 7 protons in a LArTPC



T. Junk

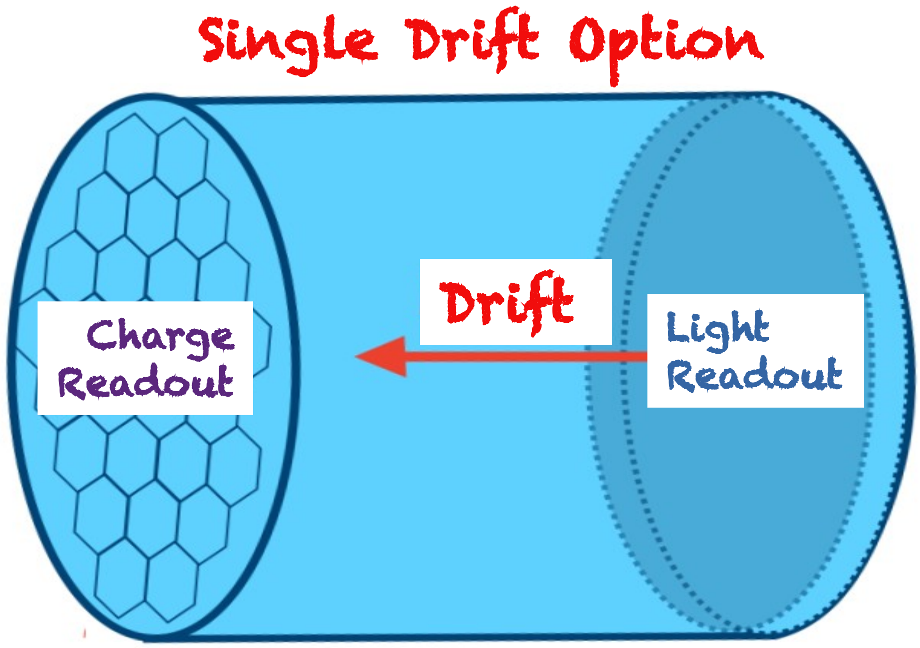
Advancing DUNE's Physics Goals through R&D

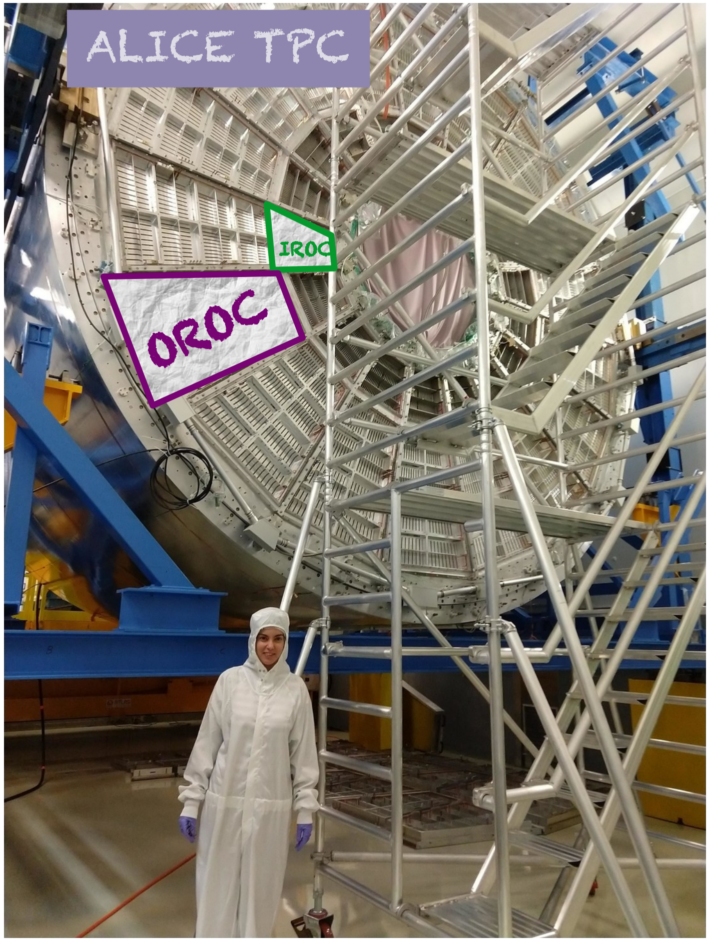
- Design can be optimized to fulfill given physics requirement/s, such as
  - Adjusting the multiplication gain to optimize the energy thresholds
  - Fine-tuning the granularity and pixelization in the readout systems to lower the tracking thresholds
  - Optimizing the pad response function and diffusion to achieve sub-mm spatial resolution



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

So far, the majority of the R&D has focused on the HPgTPC component of ND-GAr



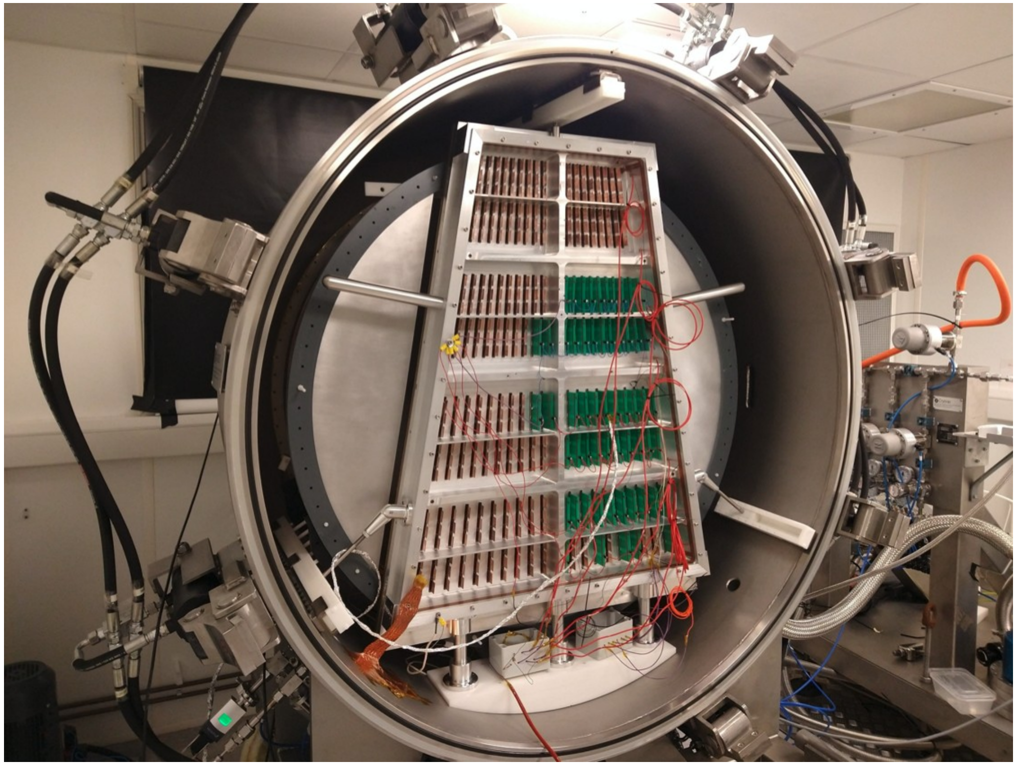


- On-going R&D thrusts of HPgTPC:
  - TPC amplification, options explored include acquired ALICE MWPCs (inner and outer readout chambers, IROC and OROCs), GEMs, THGEMs, and room for additional designs, e.g. Micromegas
  - TPC readout, options include SAMPA, LArPix, SiPMs, LAPPDs
  - Gas mixture optimizations

R&D Efforts – TPC Amplification

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

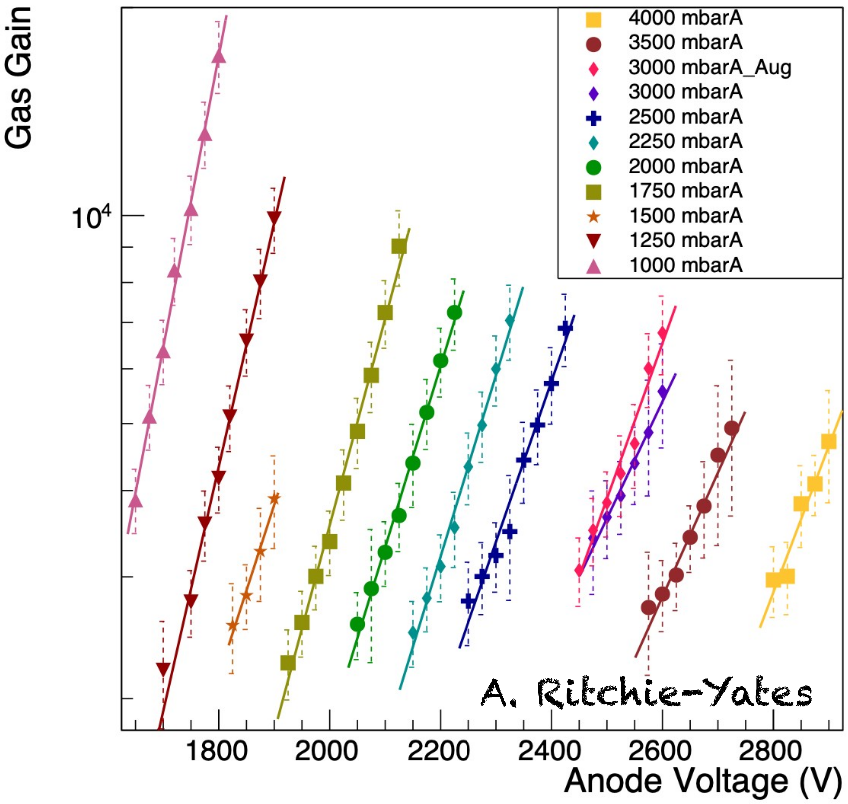
Royal Holloway Test Stand, housing an OROC, recently moved to Fermilab Test Beam, now named TOAD

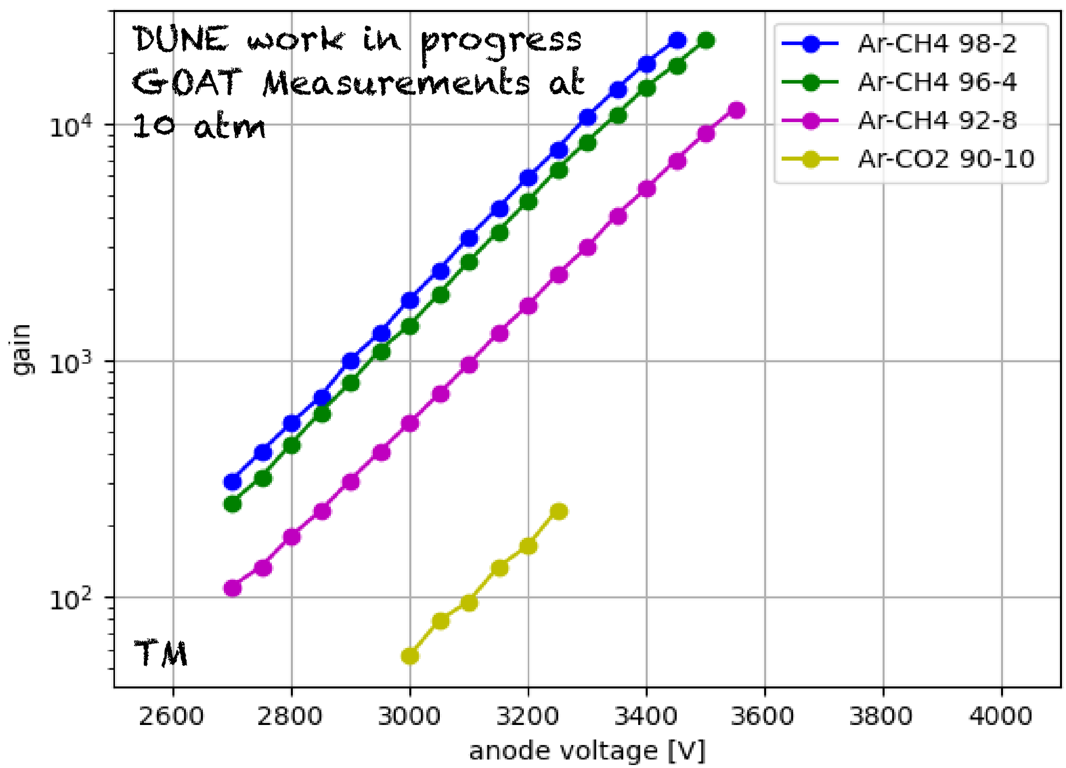


Fermilab Test Stand, housing an IROC, also named GOAT, now re-branding to GORG

R&D Efforts – TPC Amplification

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

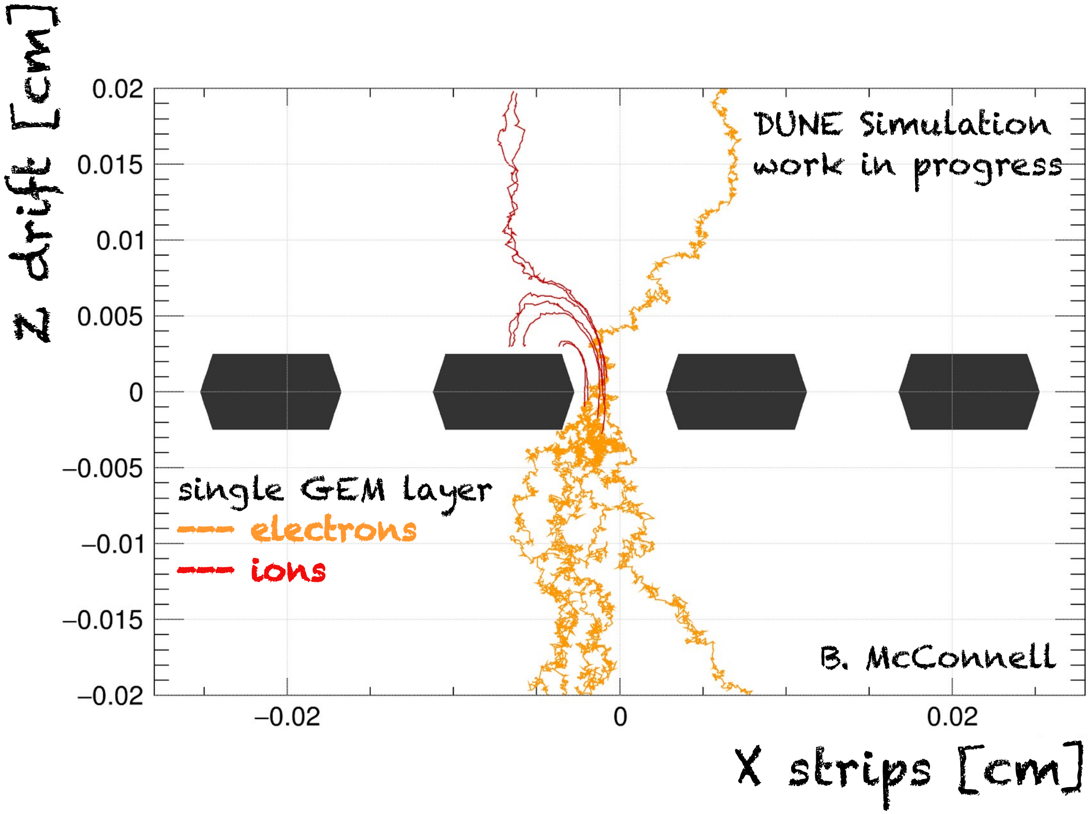




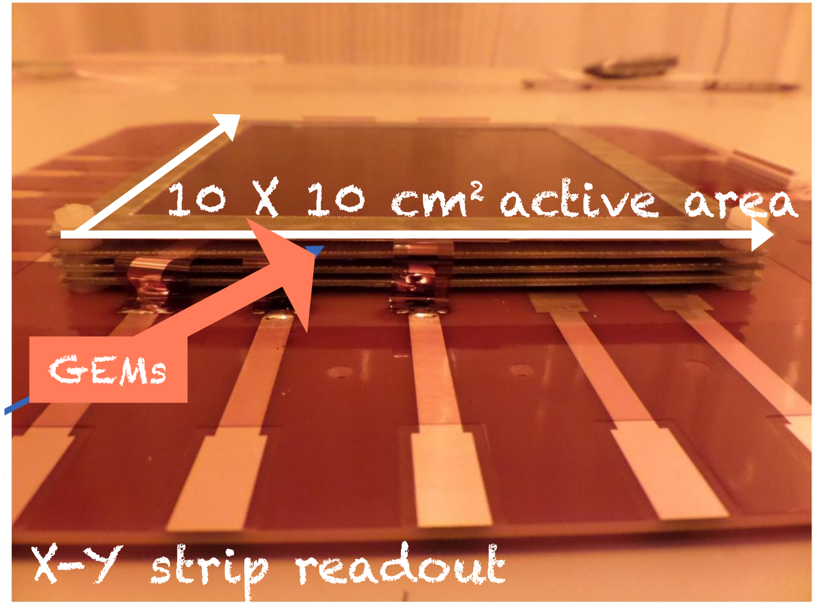
https://doi.org/10.48550/arXiv.2305.08822

R&D Efforts - TPC Amplification

- Other options being considered are GEMs, testing them at high pressure requires R&D
  - On-going efforts include tests as part of the GORG effort (continuation of the speaker's New Initiatives award)

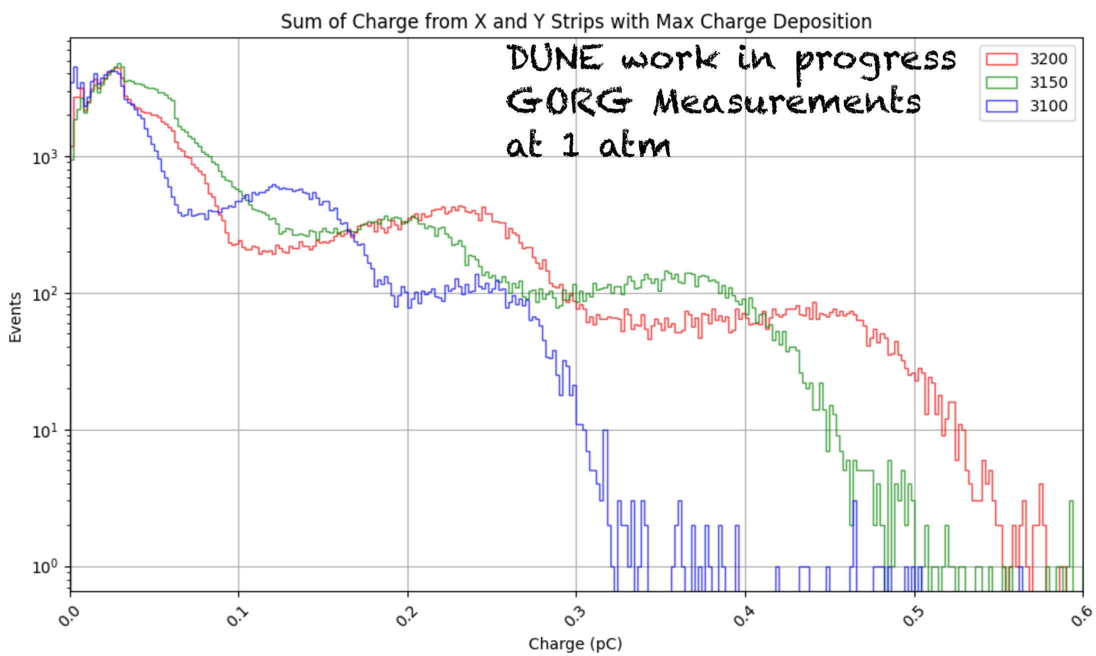


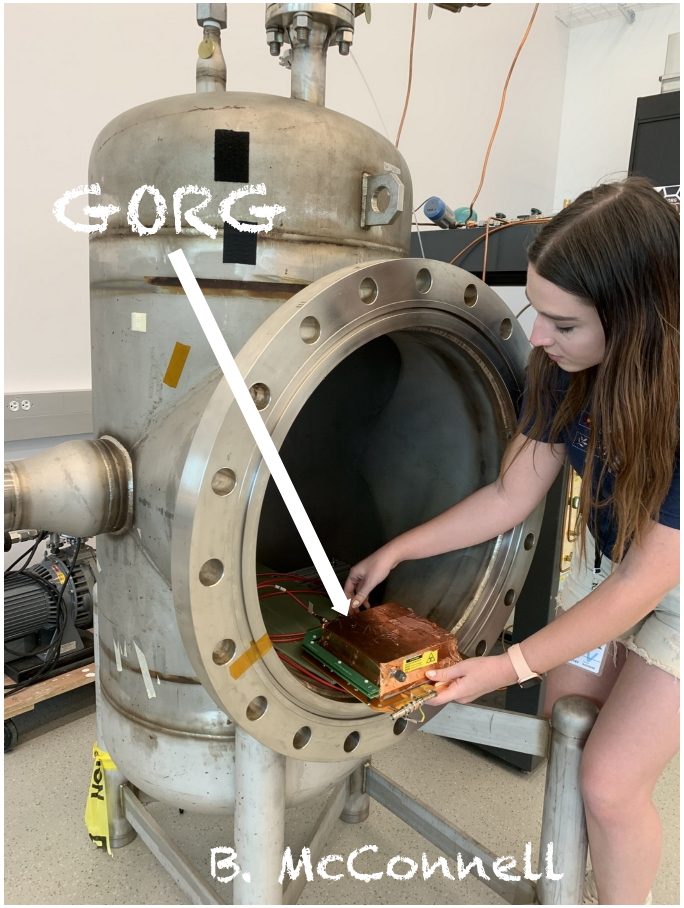
GORG



R&D Efforts – TPC Amplification

- Other options being considered are GEMs, testing them at high pressure requires R&D
  - ★ On-going efforts include tests as part of the GORG effort (continuation of the speaker's New Initiatives award)
  - ★ Bench tests carried out in a clean bench show the pulse height distribution at 1 atm – pressure tests are underway!

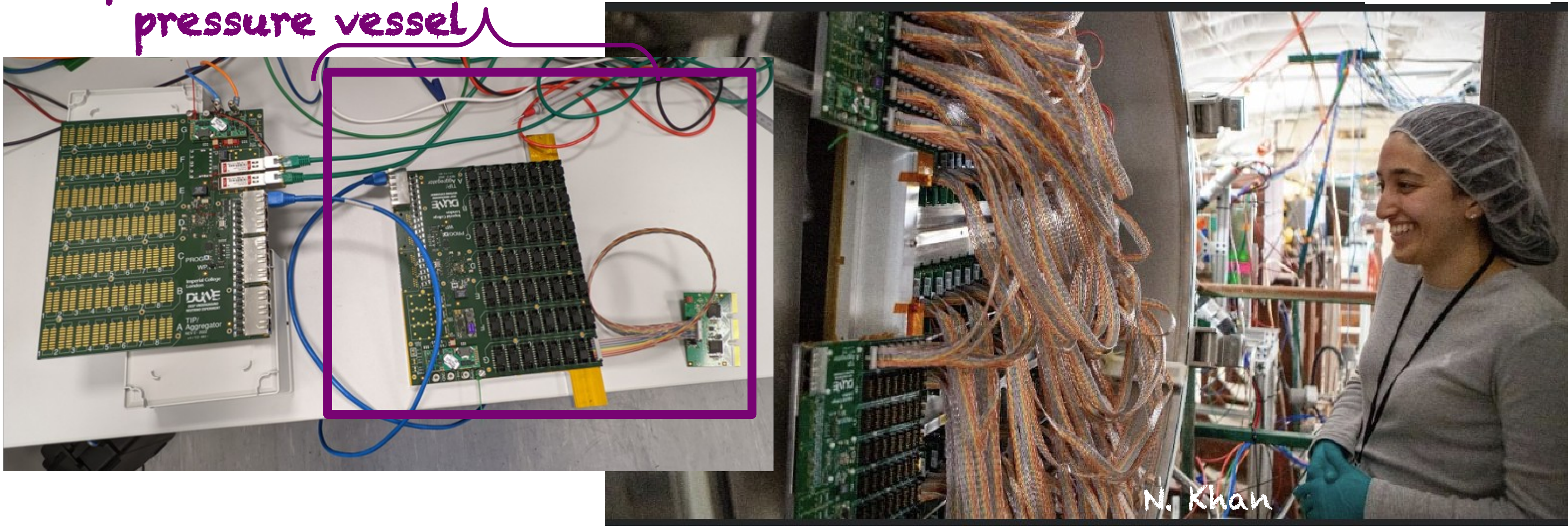




R&D Efforts - TPC Readout Electronics

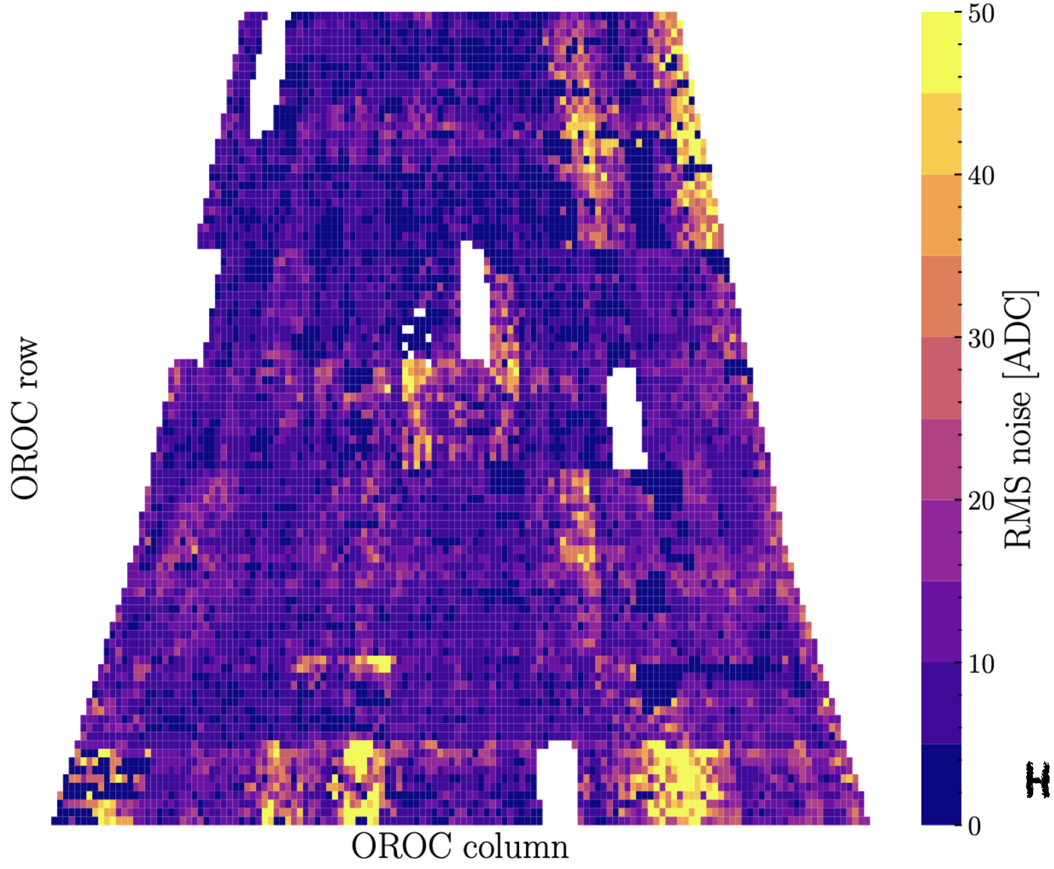
- Beam prototype, TOAD, is making a full slice test of the electronics in high pressure (starting with ALICE-based SAMPA cards)
- The prototype is in Fermilab Test Beam and a full chain of DAQ and electronics are being installed and tested

placed inside the pressure vessel

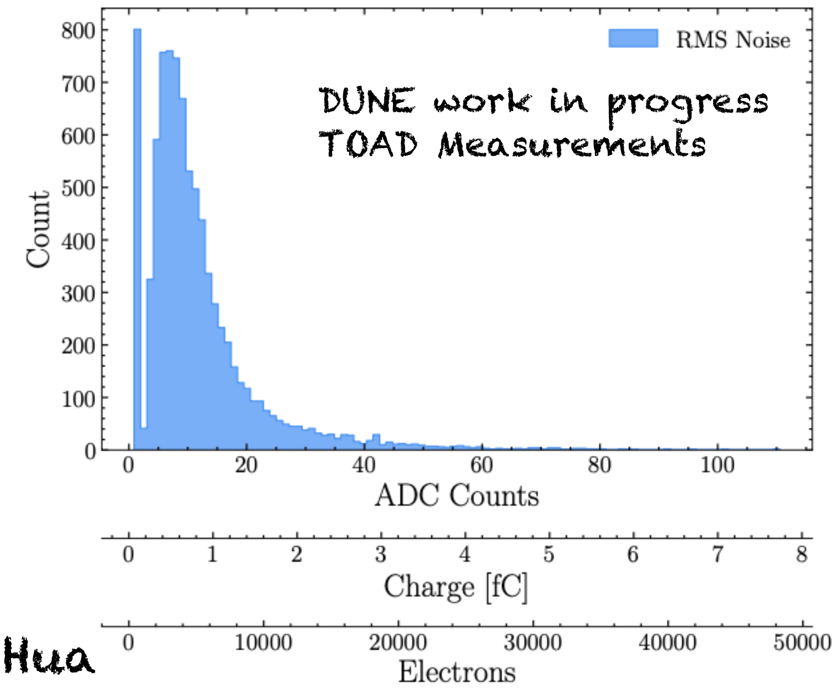


R&D Efforts - TPC Readout Electronics

- Status of TOAD:
  - Noise measurement at 4.5 bar Ar-CH4 (96:4) – demonstrated that electronics can operate under this pressure
  - Detailed pressure, volume, temperature (PVT) studies carried out – will be integrating additional systems, e.g. active cooling and Temperature and gas quality sensor

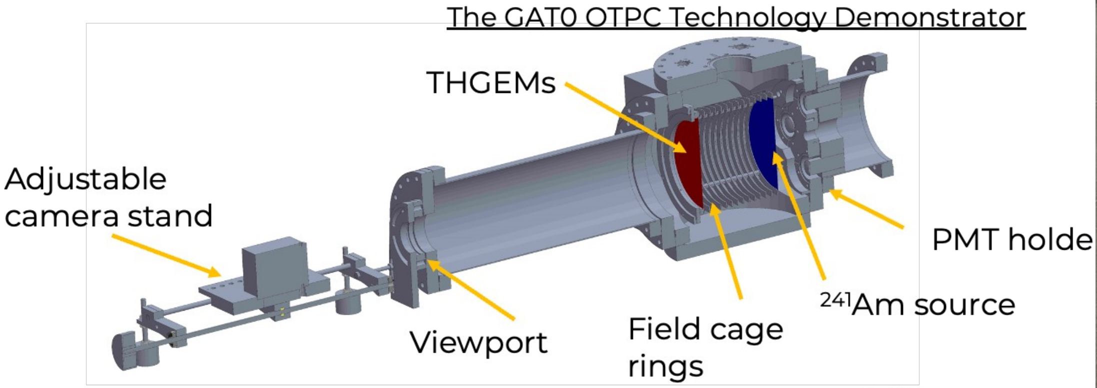


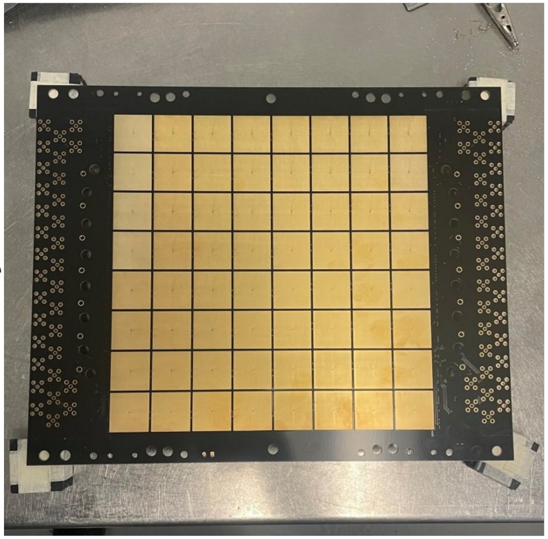
H. Hua



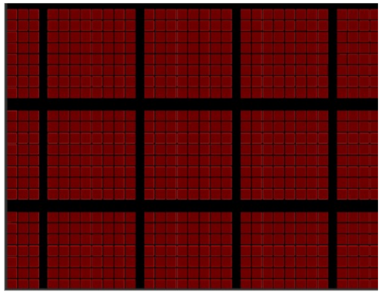
R&D Efforts – TPC Readout & Gas Mixture Choices

- 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, LAPPDs
- Choosing an admixture/dopant that will not quench the scintillation signal also crucial
- Initial studies being carried out at IGFAE (in Spain) with focus on **CF4** through the GAT0 effort





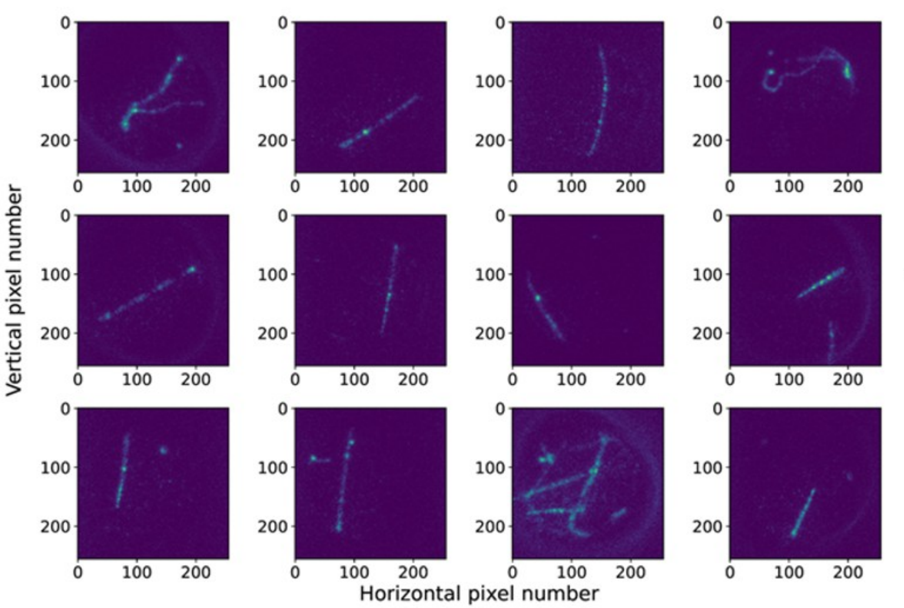
LAPPD Simulation

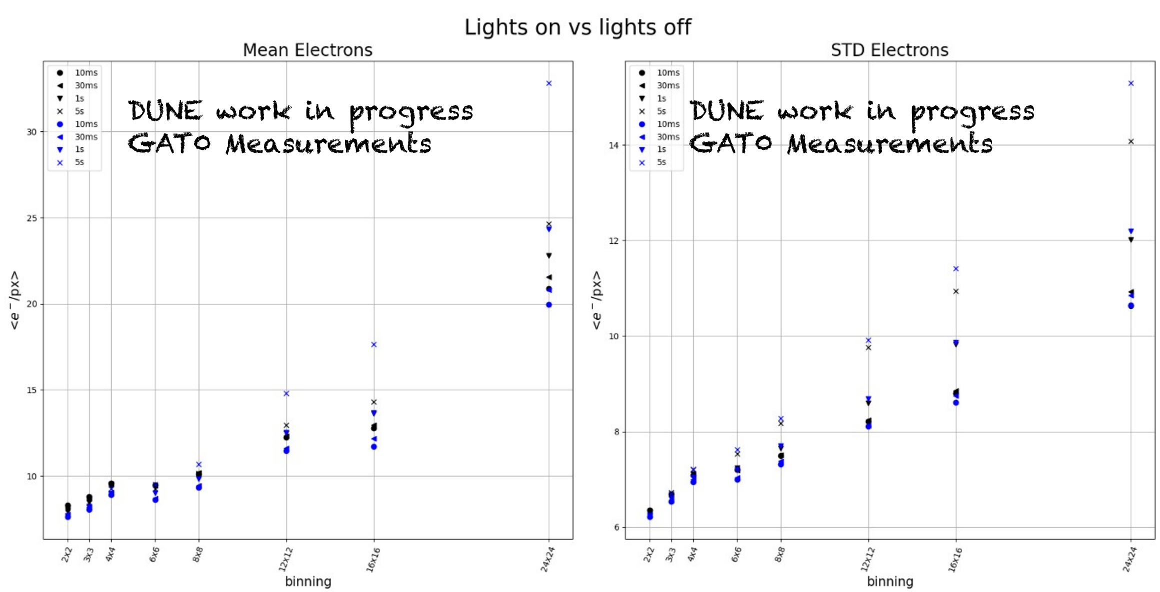


M. Adil Aman

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, LAPPDs
- Choosing an admixture/dopant that will not quench the scintillation signal also crucial
- Initial studies being carried out at IGFAE (in Spain) with focus on **CF4** through the GAT0 effort
  - ★ Optical gain of 10^6 ph/e at 1 bar Ar/CF4 and CCD camera noise characterized



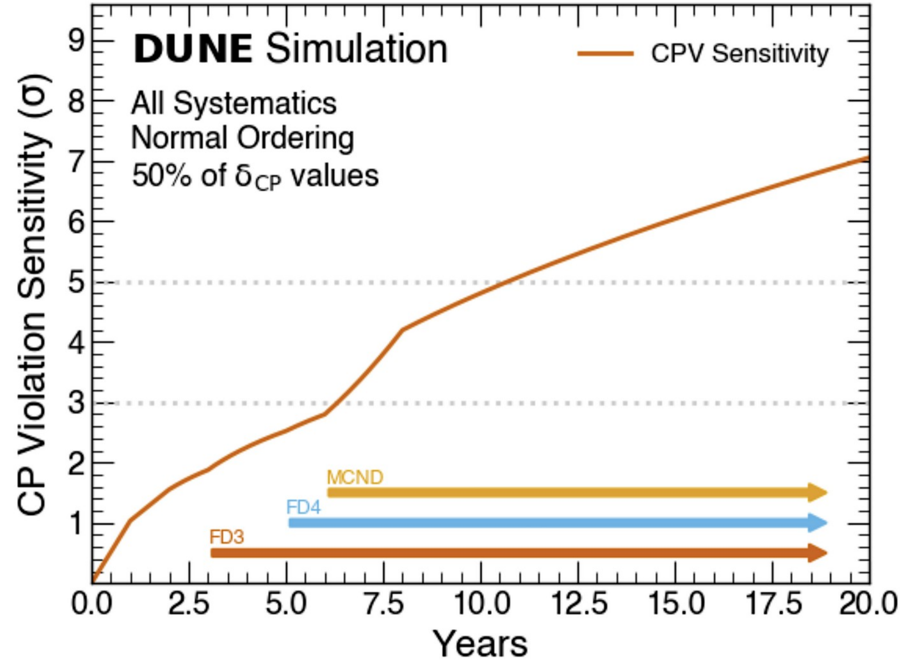


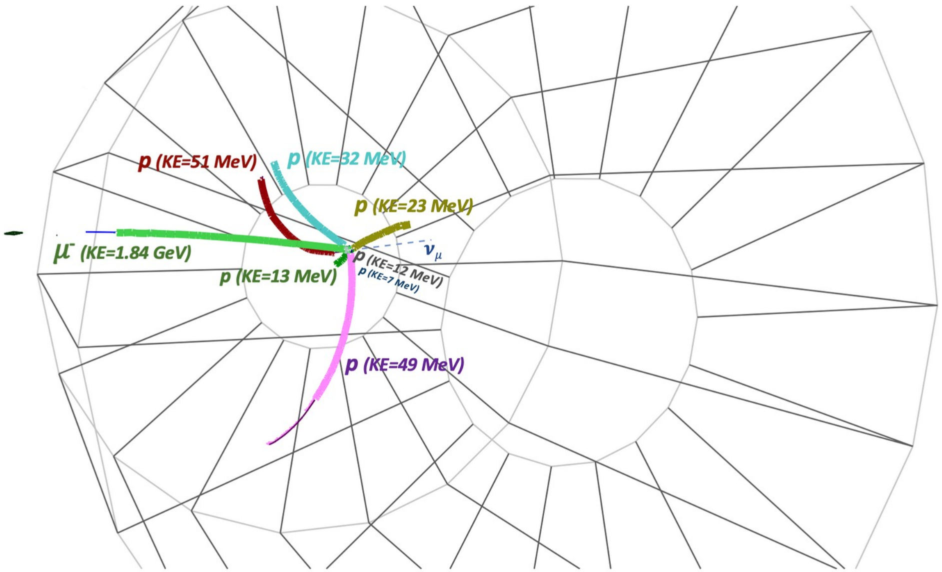
R. Hafeji

Summary

- The DUNE ND-GAr's unique design includes highly capable components that enable:
  - ★ DUNE to reach a 5σ sensitivity to CP violation
  - ★ 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!



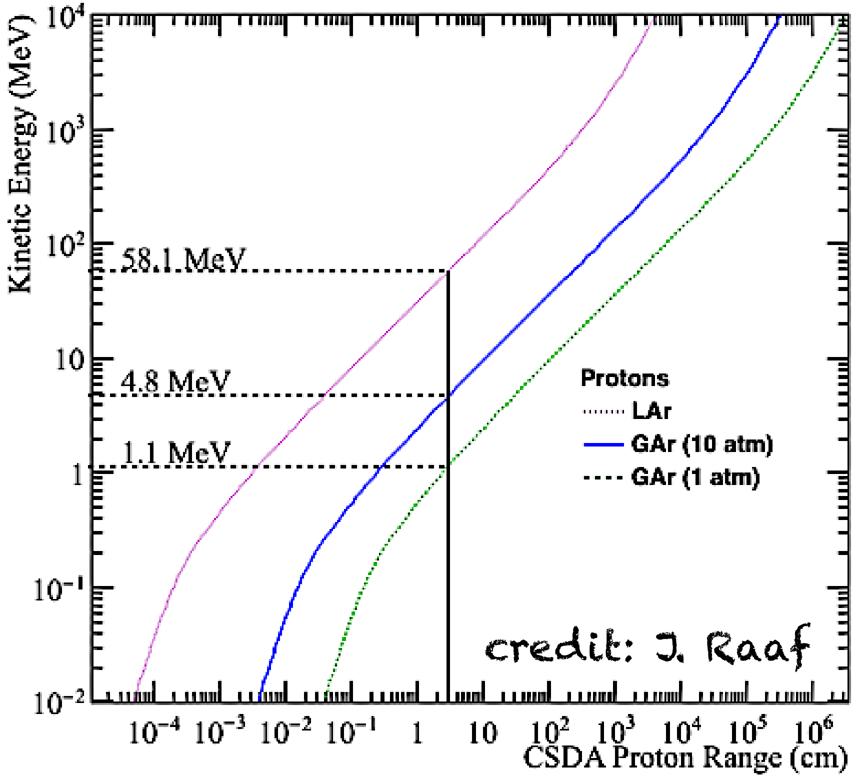


Additional Slides

Low Threshold ND-GAr

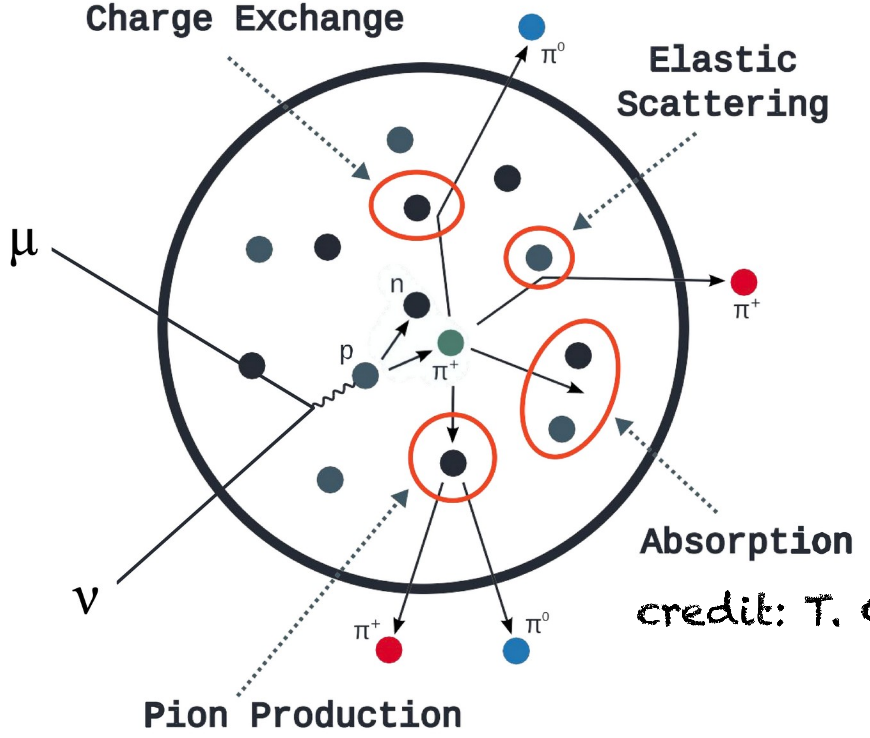
- Lower threshold of **ND-GAr's HPgTPC** than **ND-LAr**:
  - ★ Leads to a high sensitivity to low energy protons or pions:

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



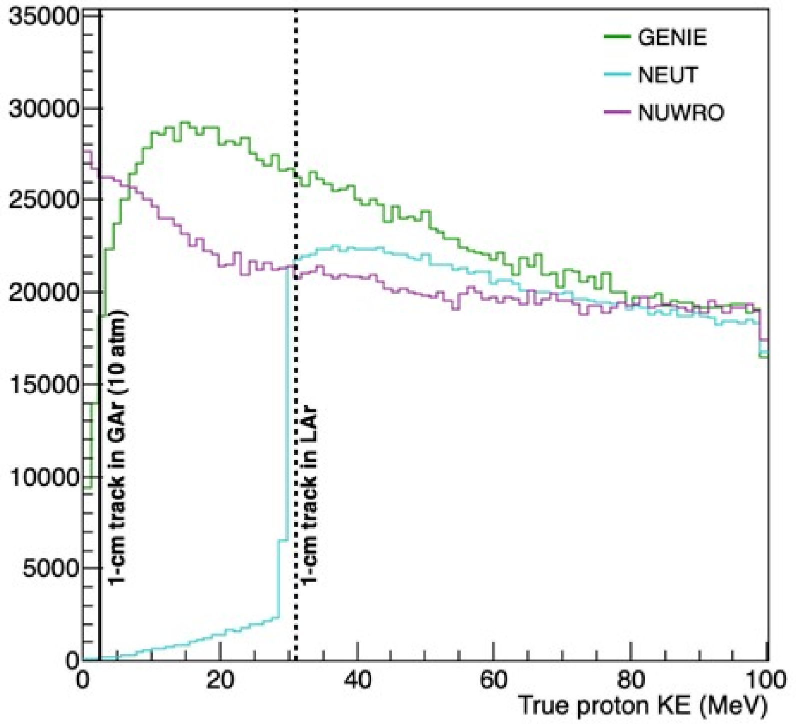
Low Threshold ND-GAr

- 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



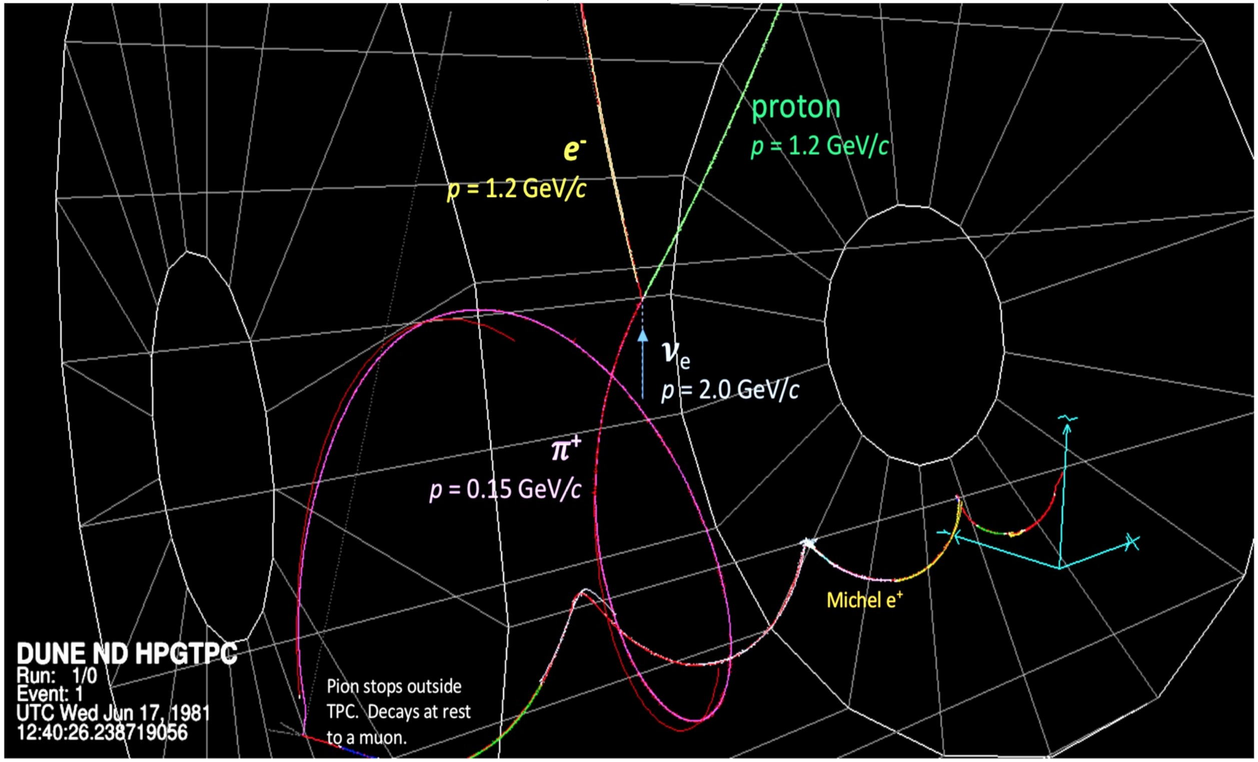
A Wealth of ν-Argon Interaction Data

- 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 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

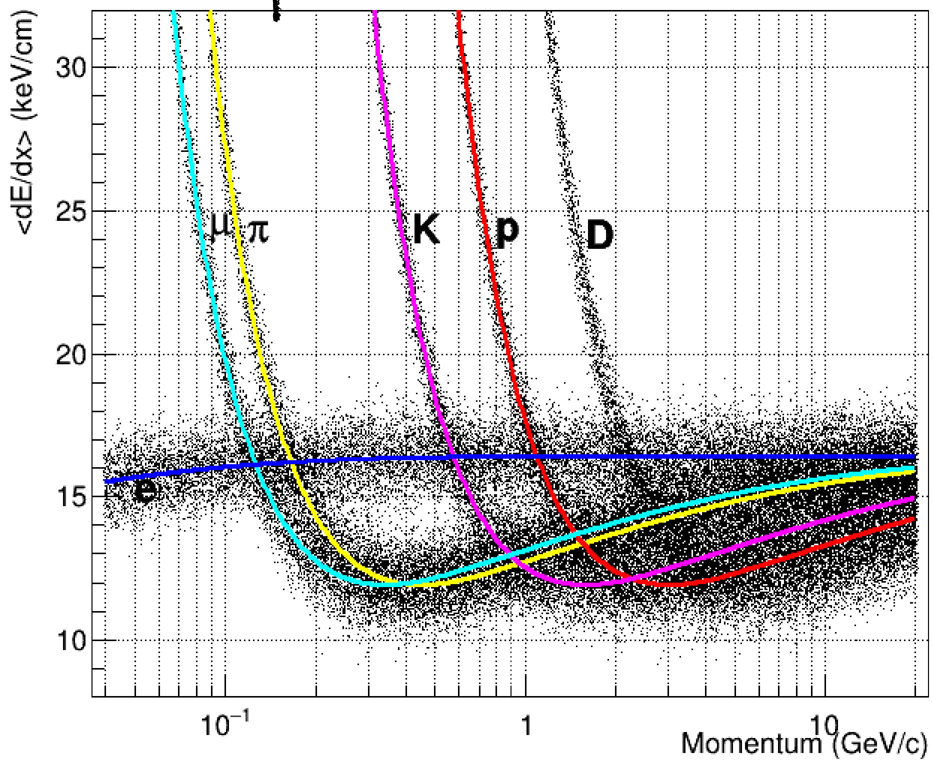
A detailed view of the ν-interaction vertex



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

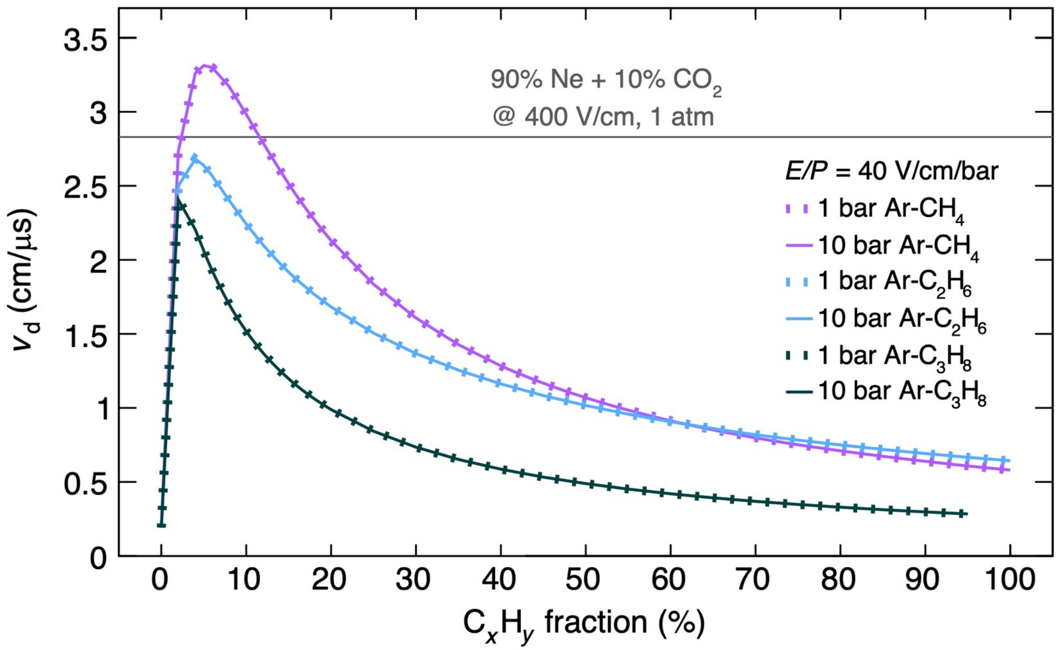
dE/dx-based PID will be comparable to PEP-4's

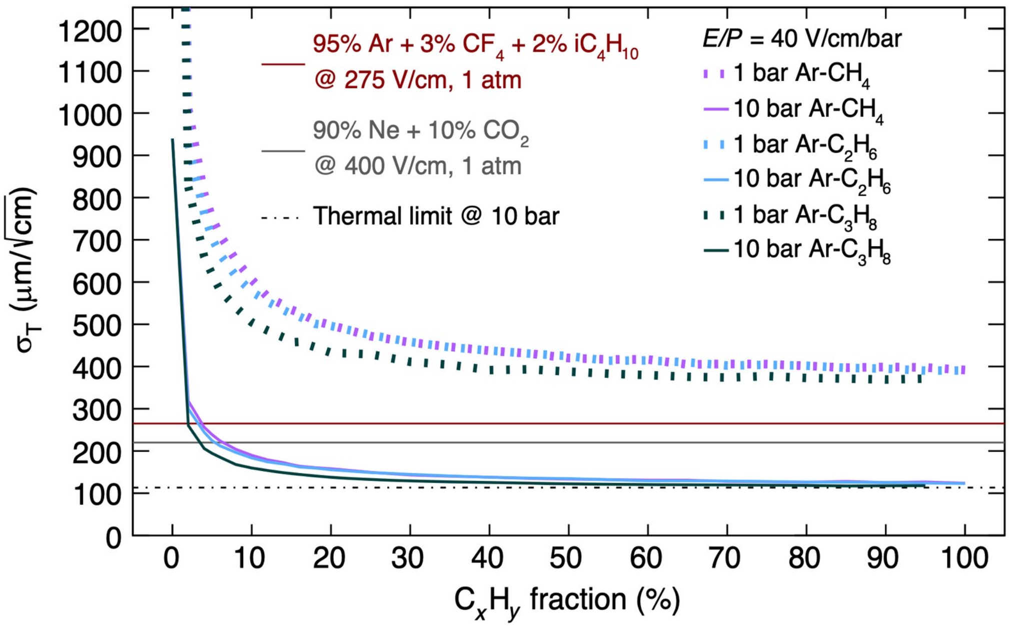


DUNE Collaboration, A. Abed Abud et al. Instruments 5 no. 4, (2021) 31, arXiv:2103.13910 [physics.ins-det].

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)

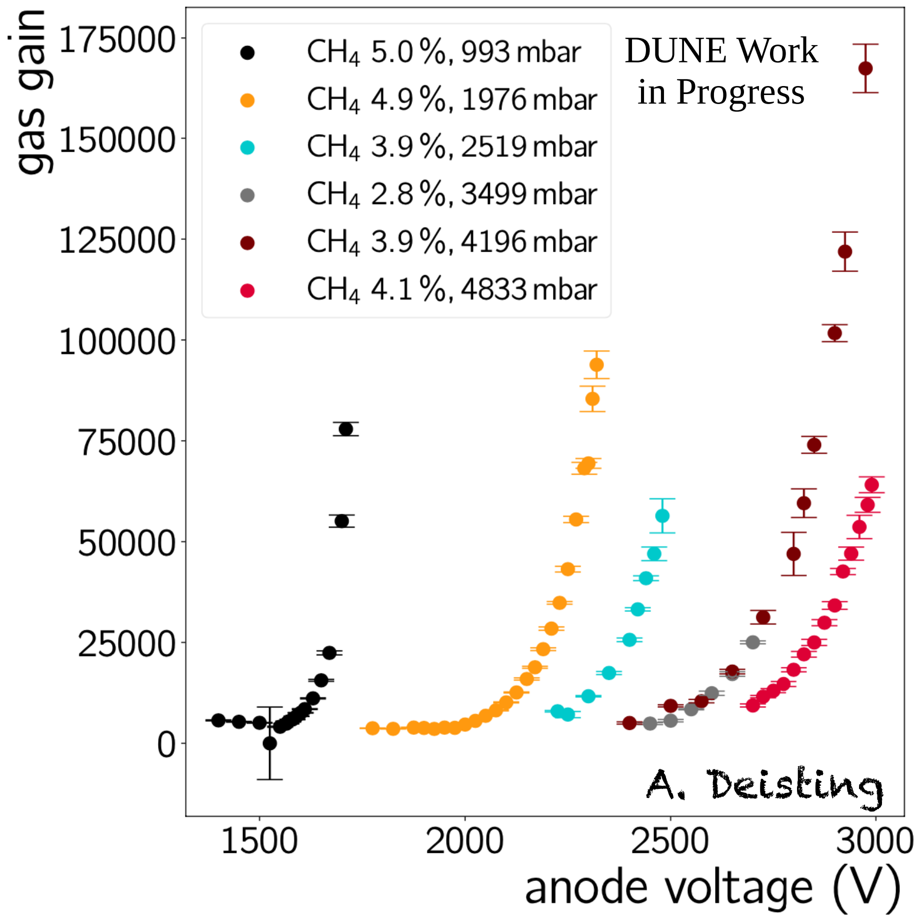




P. Hamacher-Baumann et al., Phys. Rev. D 102, 033005 (2020)

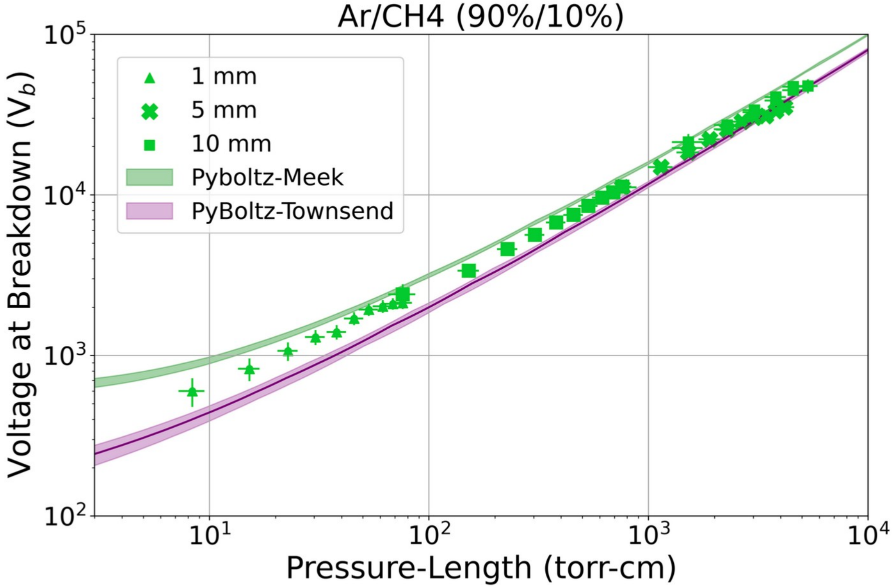
R&D Efforts

- 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

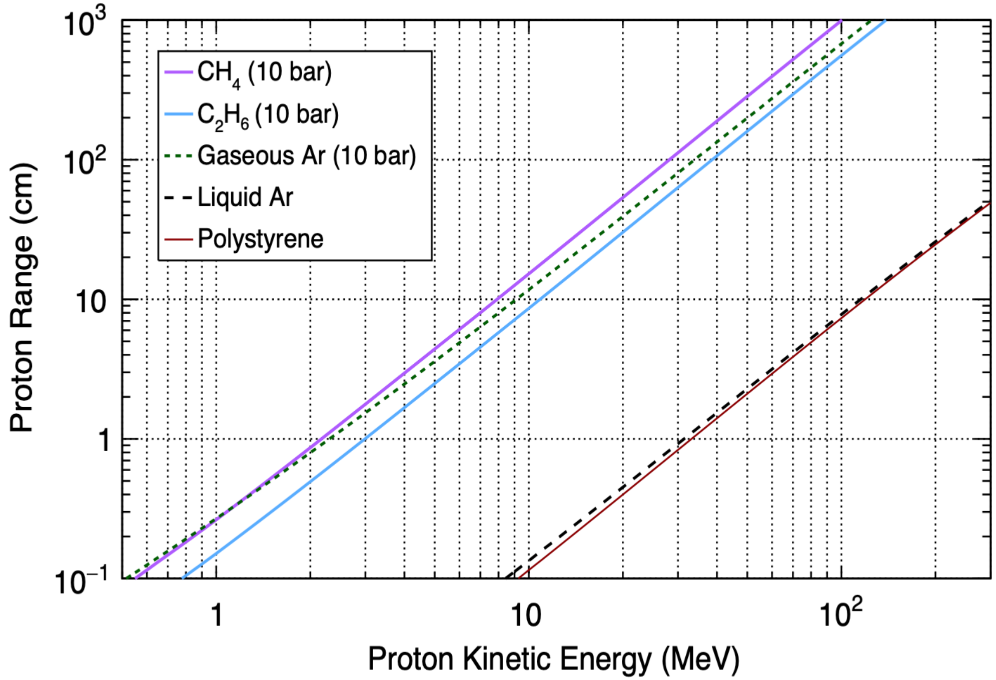


Norman, L. *et al.* Dielectric strength of noble and quenched gases for high pressure time projection chambers. *Eur. Phys. J. C* **82**, 52 (2022)

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