Charge Readout Prototyping for ND-GAr

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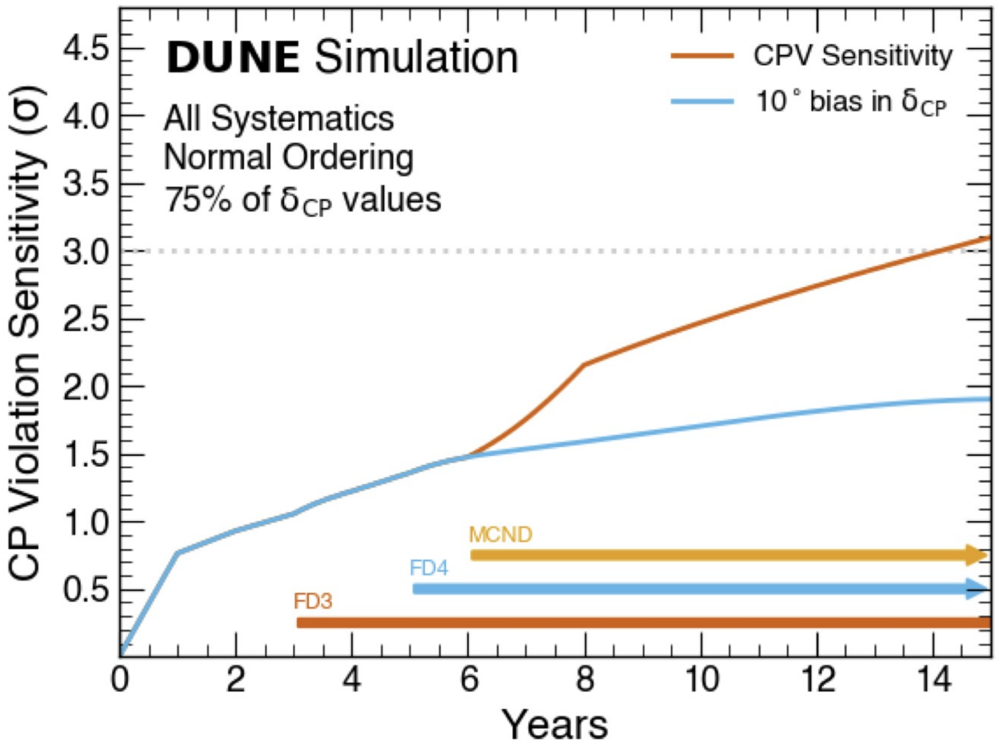
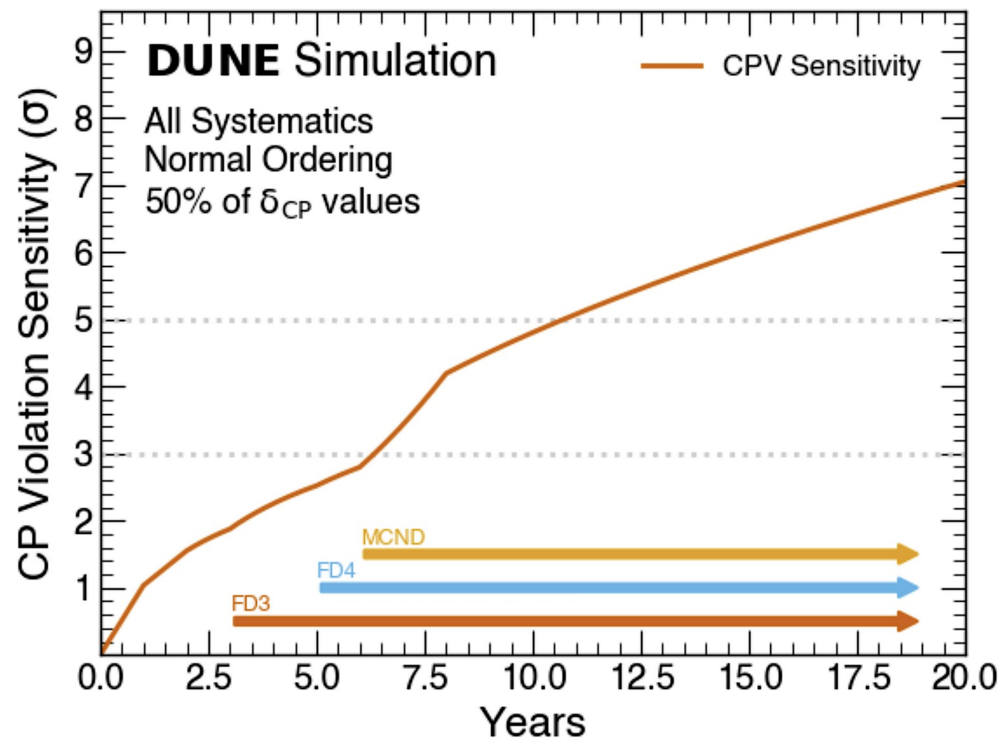
DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE Phase II

- **Phase II** of DUNE includes upgrades to achieve its full scope – includes **ND**, FD, and beam upgrades for higher statistics
  - But only the ND upgrade to ND-GAr (referred to as MCND in the plot), leveraging a gas argon TPC-based design, specifically addresses neutrino interaction systematics and detector acceptance systematics



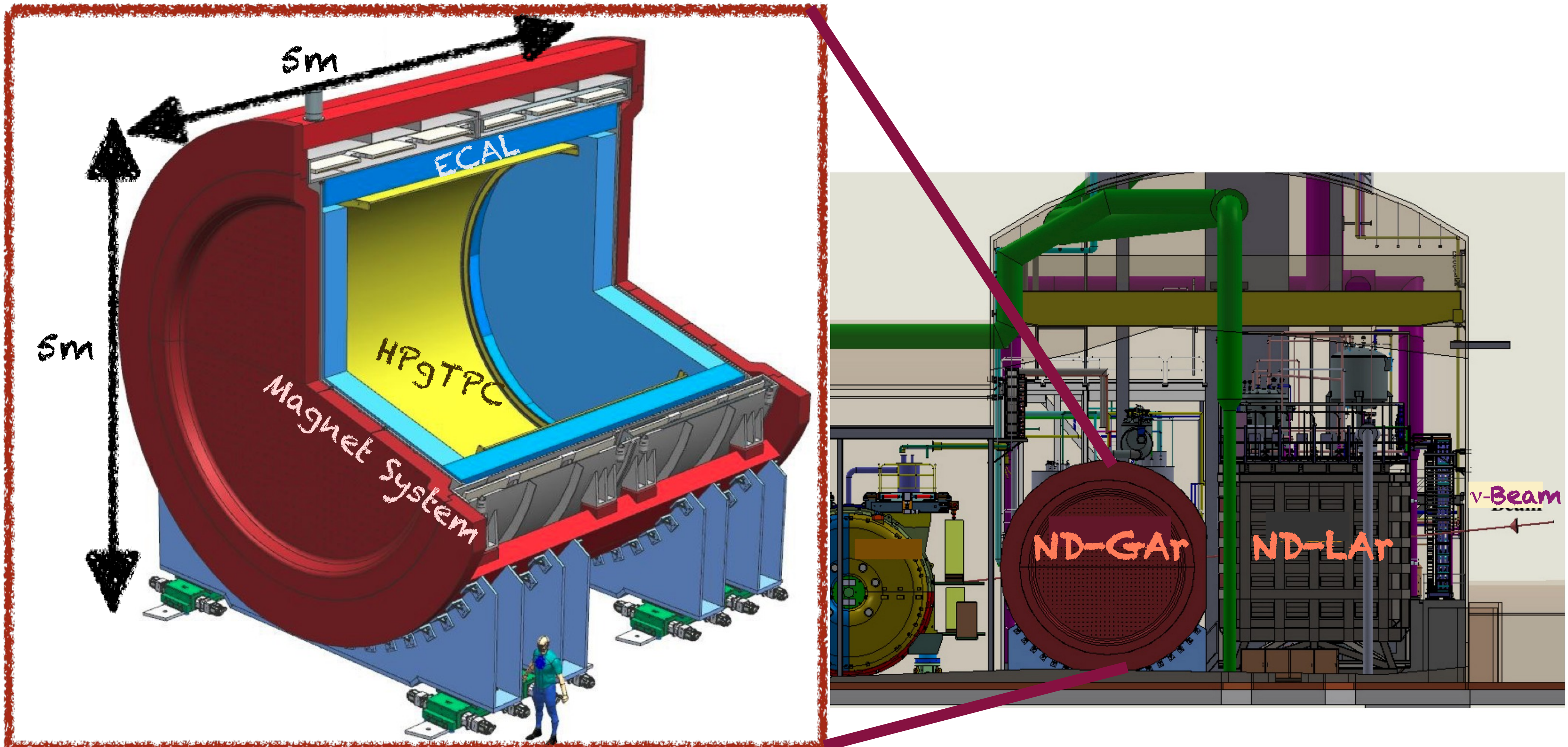


The phase I muon spectrometer will be replaced by ND-GAr in DUNE Phase II

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

Design Features of ND-GAr

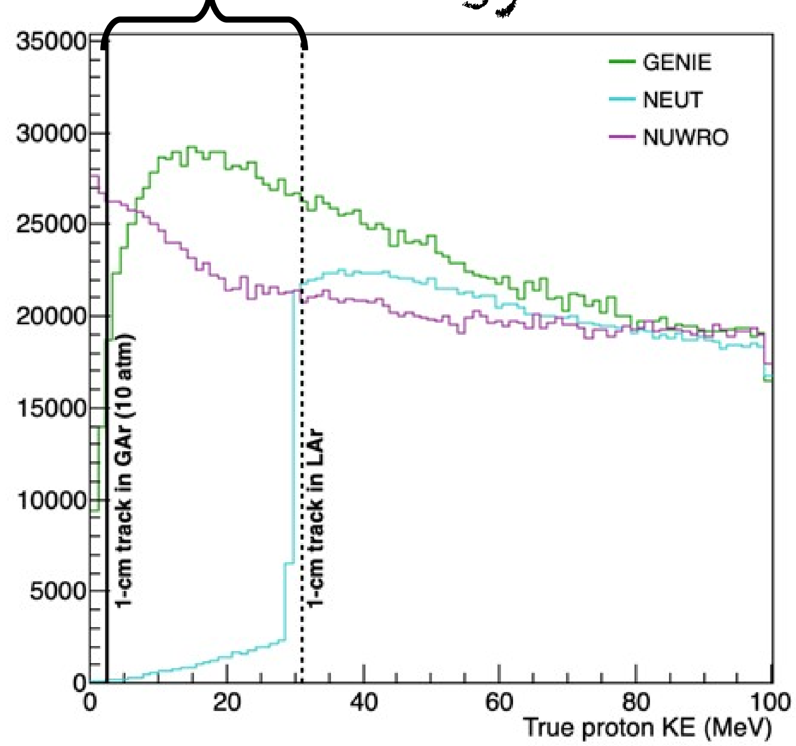
- Key design features recommended by P5 include a high-pressure gaseous argon detector, an ECAL, and a magnetized
- Test beams validate evolving design aspects like pixelization, amplification, and granularity to align with physics goals



Role in Reducing ν-Interaction Systematics

- Addressing neutrino interaction systematics requires resolving discrepancies in interaction models, especially in regions dominated by low-energy hadrons
- The low energy threshold of a high-pressure gas TPC allows DUNE to be more sensitive to **these regions**

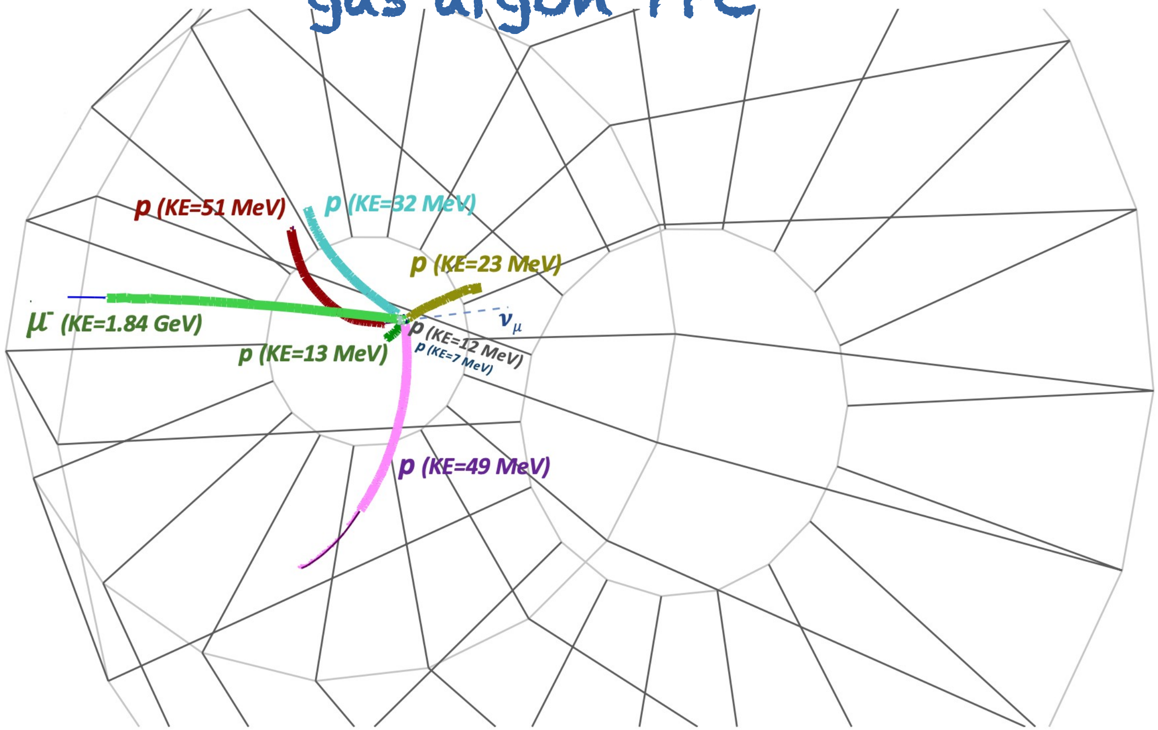
HPgTPC gives access to inaccessible regions of proton energy thanks to its low energy threshold



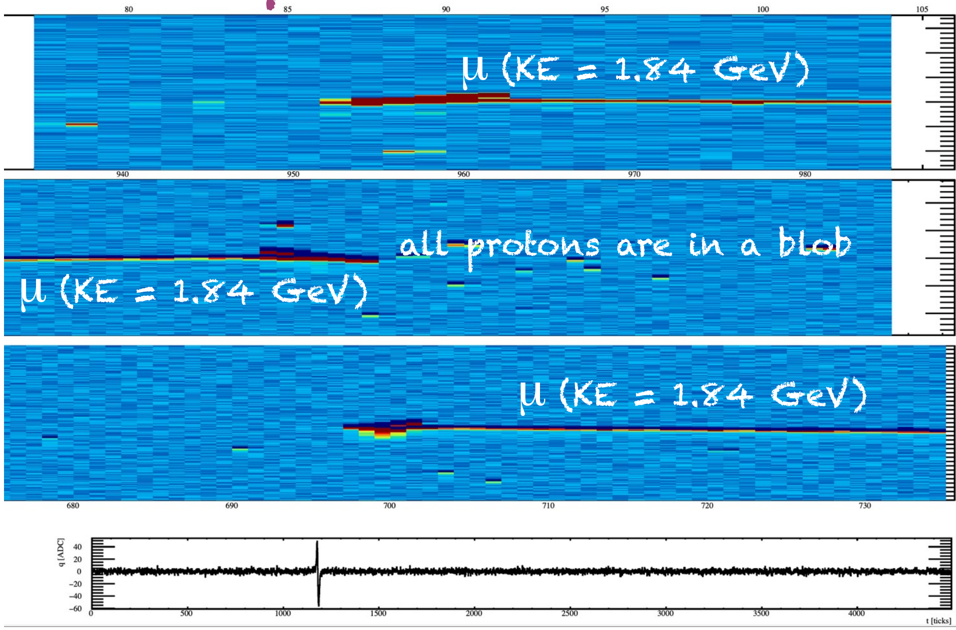
Instruments 2021, 5(4), 31; https://doi.org/10.3390/instruments5040031

Detector Performance in Event Display - GAr vs LAr

ND-GAr's high pressure gas argon TPC



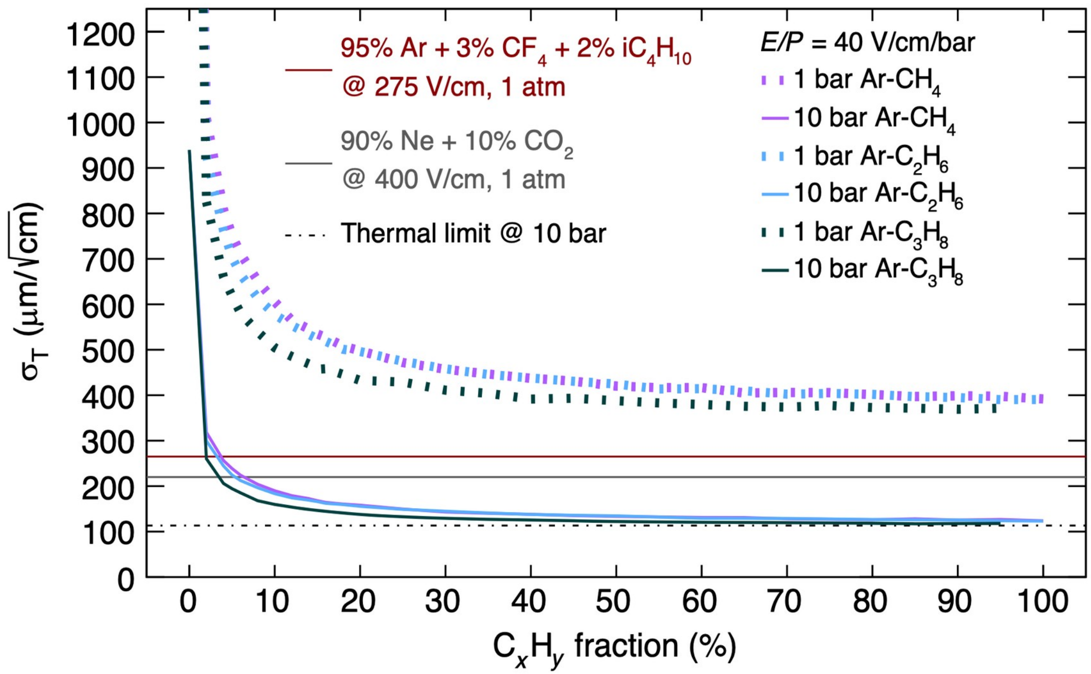
same simulated neutrino event with 7 protons in a LArTPC



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

Bridging Physics and Design

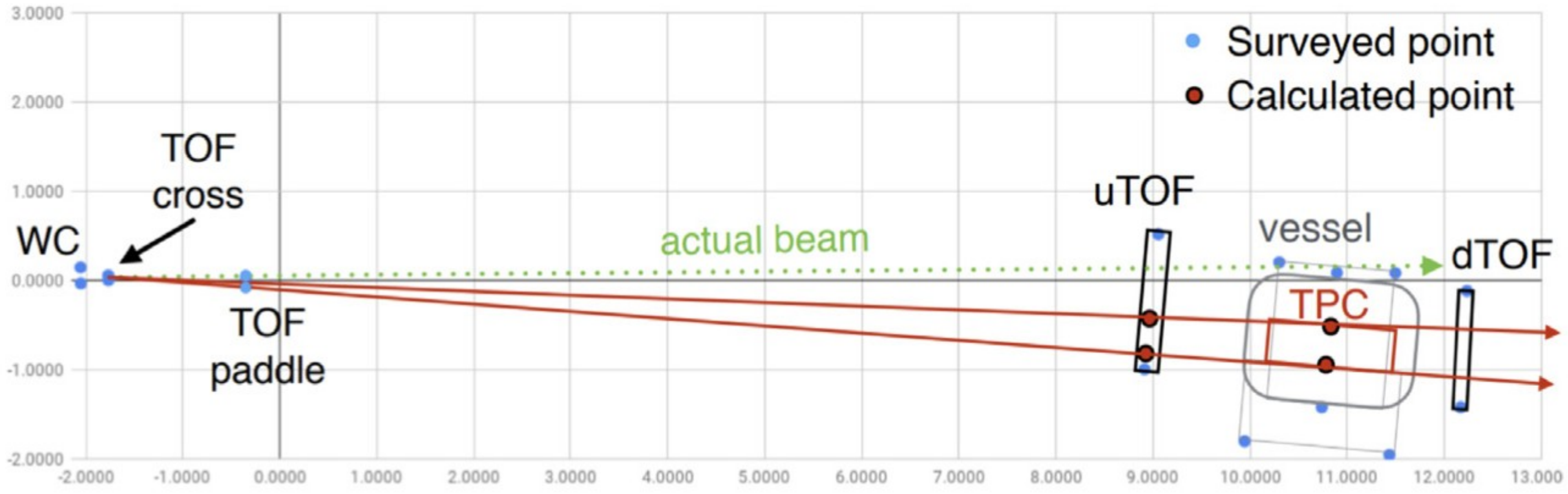
- Evolving design aspects must align with physics requirements:
  - Adjusting the multiplication gain to optimize the required energy threshold
  - Optimizing the granularity and pixelization in the readout systems to reach the required tracking thresholds
  - Optimizing the pad response function and diffusion to achieve sub-mm spatial resolution



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

Bridging Physics and Design – Test Beams

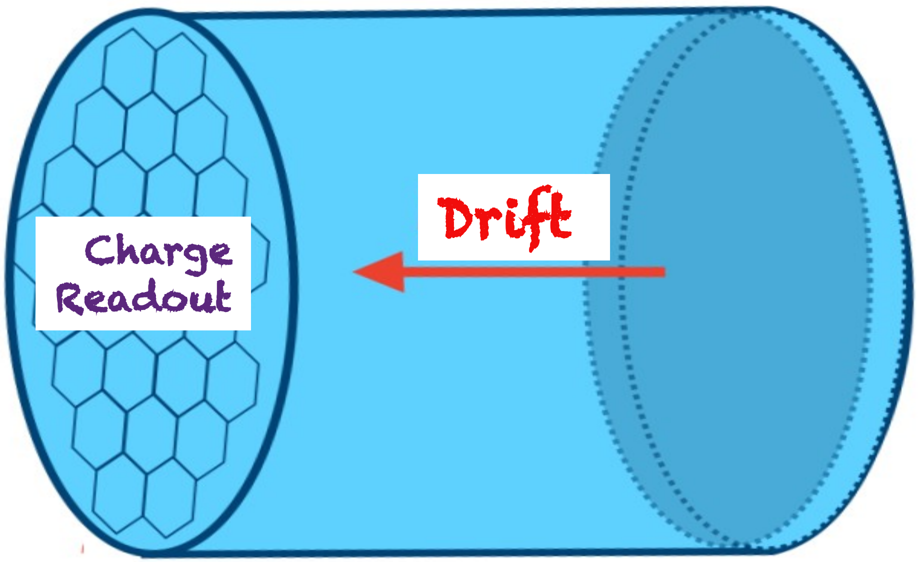
- Test beams → a platform to validate design concepts and physics performance under controlled conditions
- First ND-GAr, neutrino-TPC test beam was carried out at CERN's T10 beamline– focus was on the low-momentum proton beam (≤ 0.5 GeV), provides important lessons learned

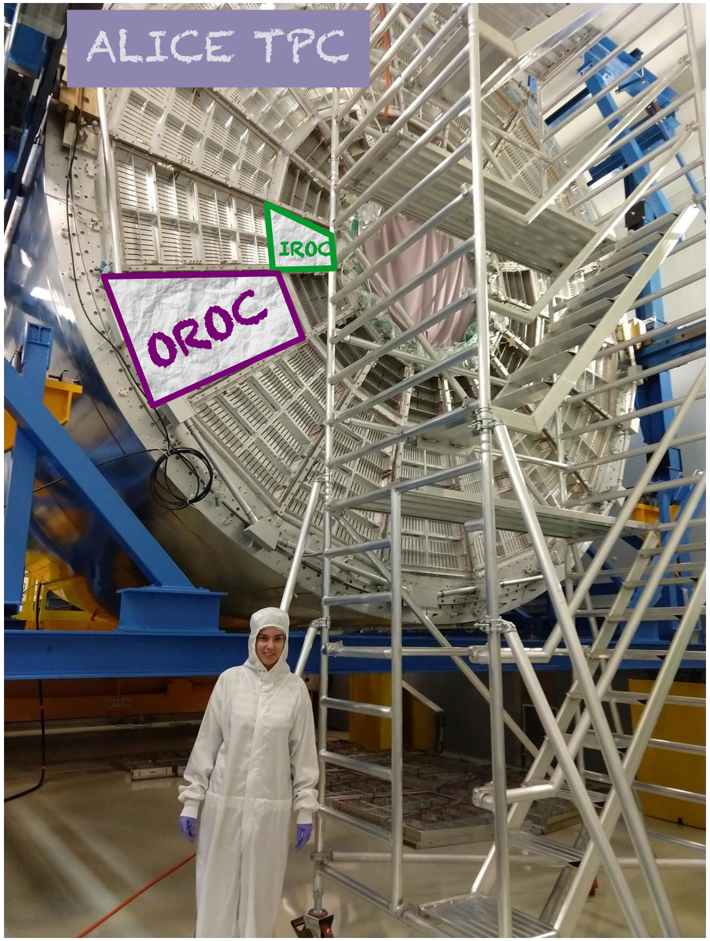


Deisting, A et al. Commissioning of a High Pressure Time Projection Chamber with Optical Readout. Instruments 2021, 5, 22. https://doi.org/10.3390/instruments5020022

Advancing R&D Post-CERN Test Beam

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



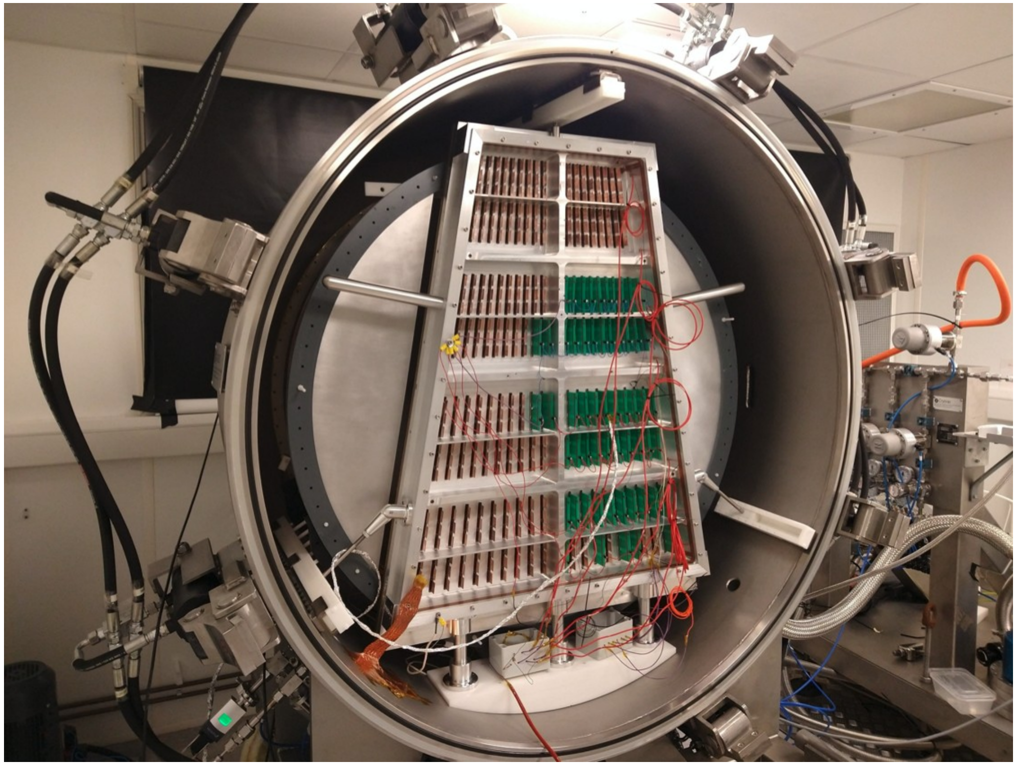


- On-going R&D thrusts:
  - TPC amplification, initial focus on acquired ALICE MWPCs (IROC and OROCs), current emphasis on MPGDs e.g. GEMs, with room for exploring additional designs, e.g., Micromegas
  - TPC readout options explored to date: SAMPAs
  - Gas mixture optimizations

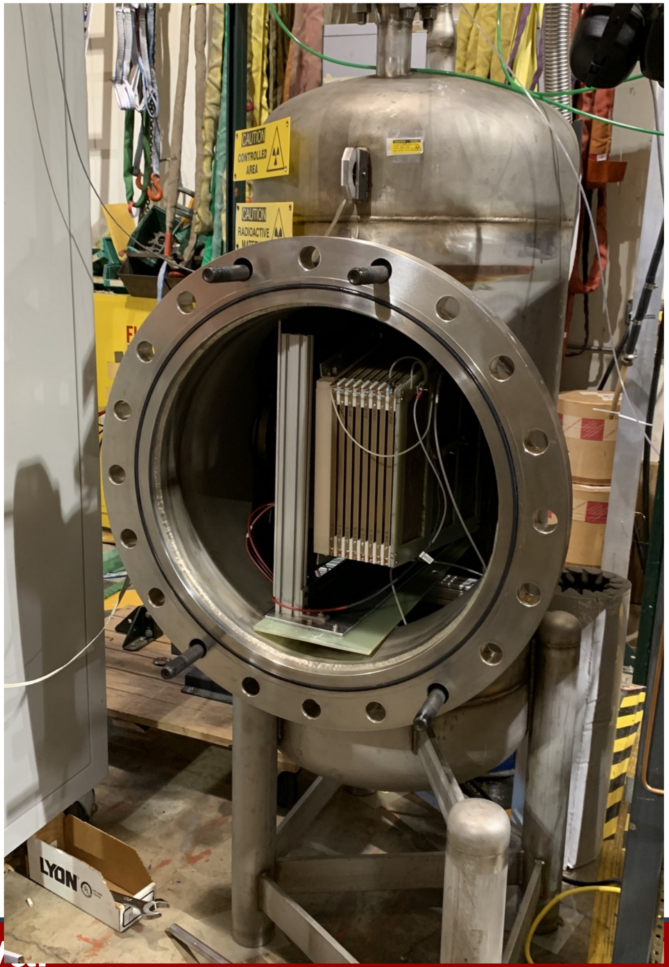
R&D Efforts – TPC Amplification

- A starting point was MWPCs acquired from ALICE
  - ★ Two efforts in US (GOAT) and UK (TOAD) completed a pressure scan of the chambers
  - ★ UK effort used the same pressure vessel from the CERN test beam

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

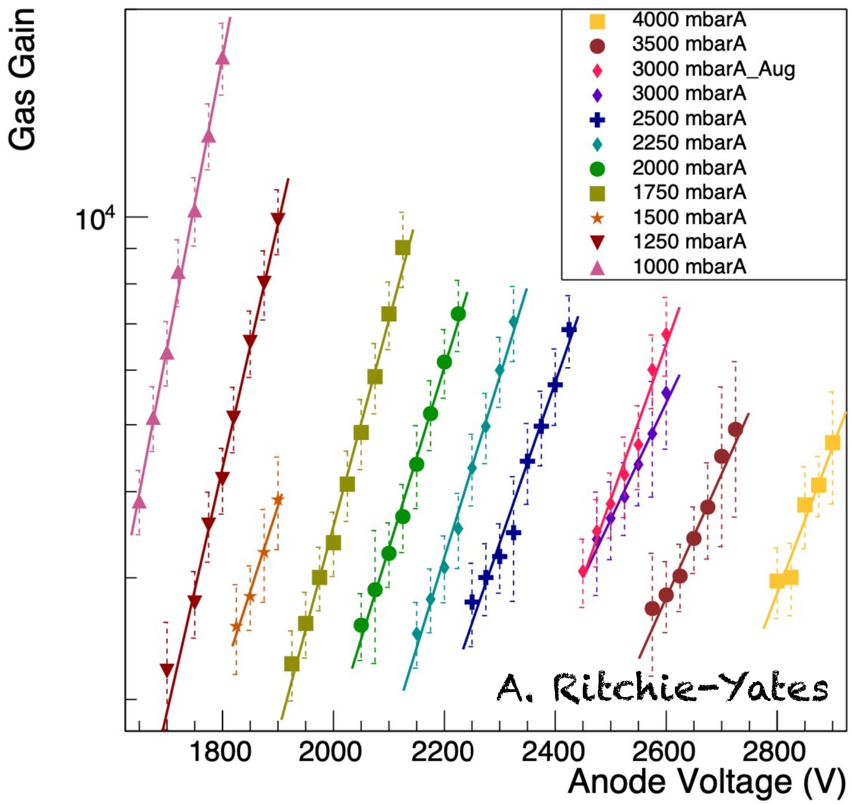


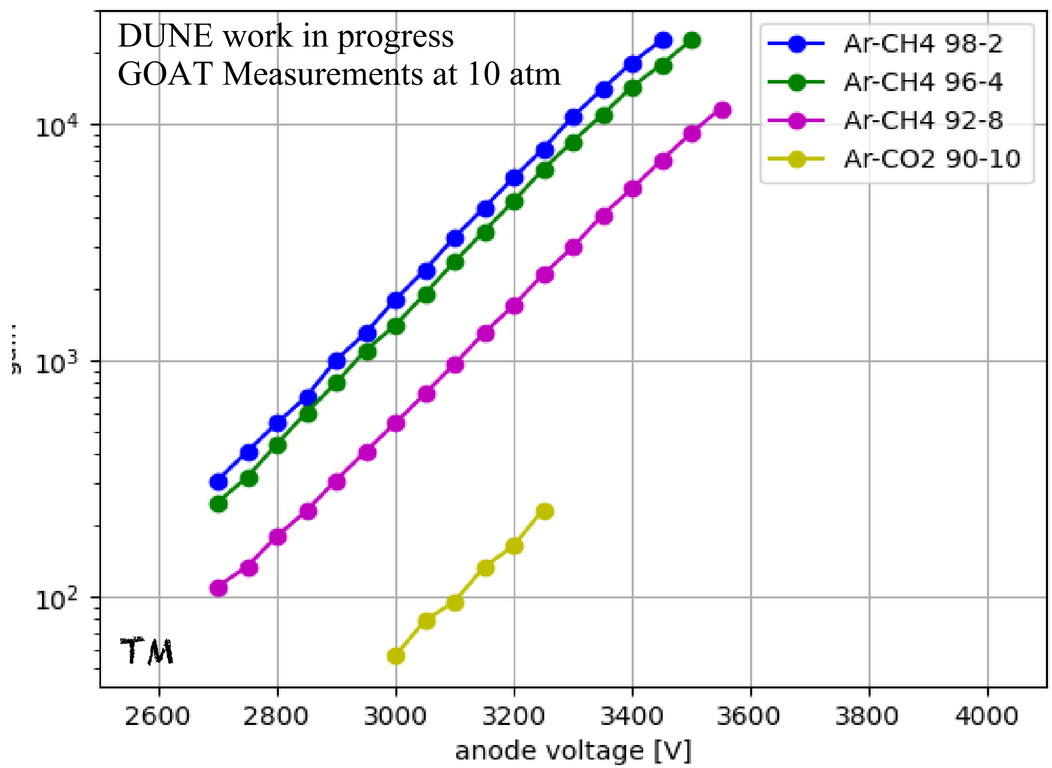
Fermilab Test Stand, housing an IROC, also named GOAT, now re-branding to GORG



R&D Efforts – TPC Amplification

- A starting point was MWPCs acquired from ALICE
  - 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 to the chambers
  - Using an Ar-CH4 mixture, the chambers achieve a gain of 1k with ~3kV, deemed the safe operational limit by ALICE

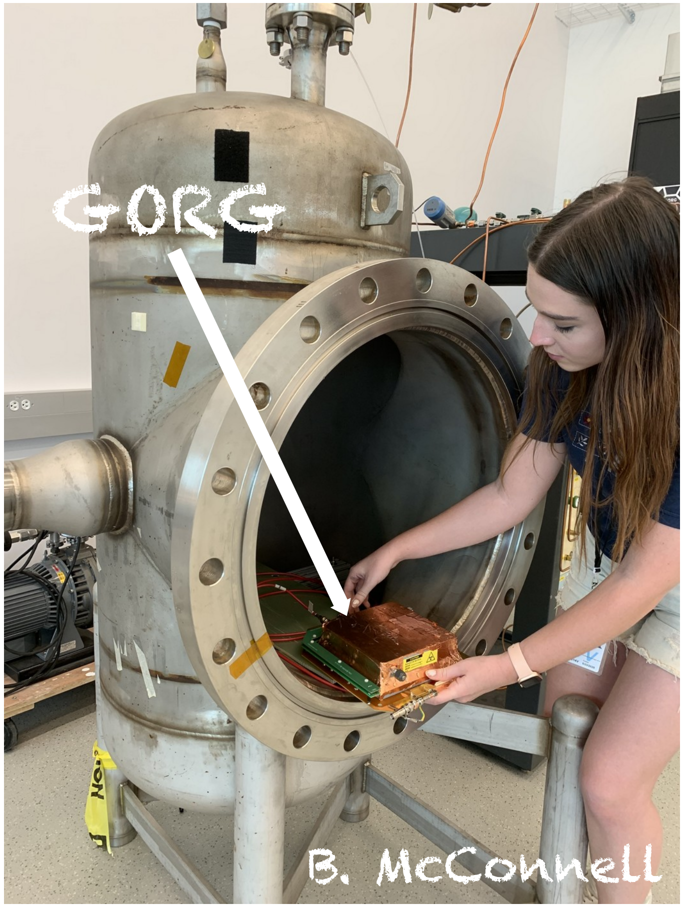


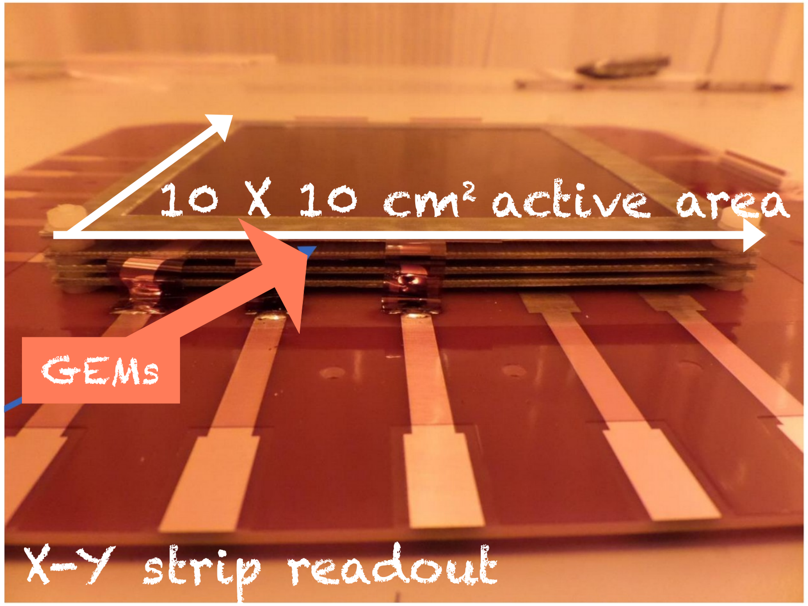


https://doi.org/10.48550/arXiv.2305.08822

- Testing GEMs, operating them at high pressure requires extensive R&D before moving onto a test beam
  - On-going efforts include tests as part of the GORG effort (continuation of TM's New Initiatives award)

same pressure vessel as GOAT being considered for initial pressure tests of GEMs

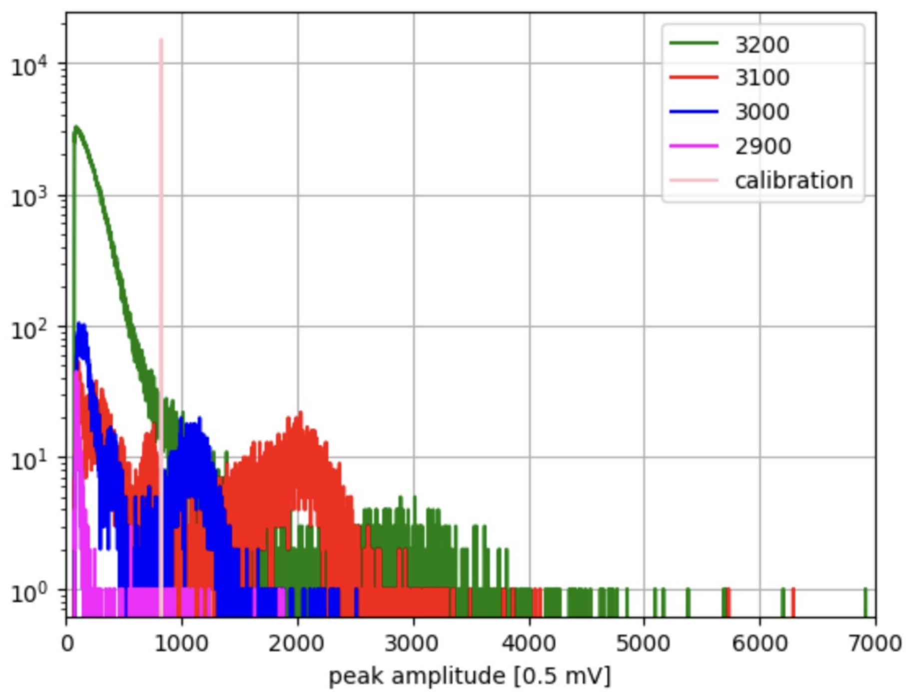




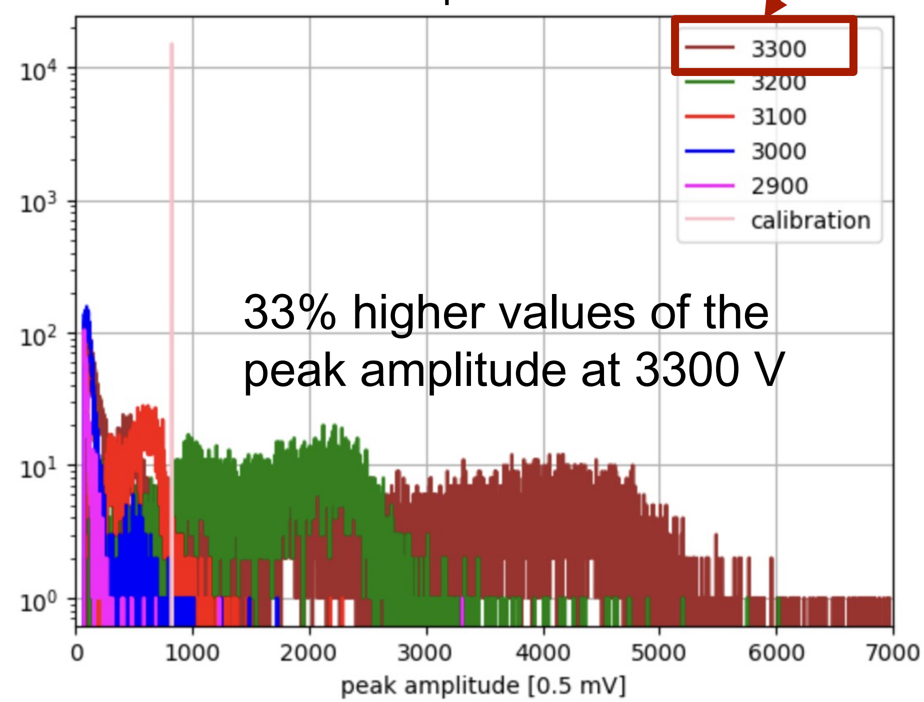
- Bench tests indicate the expected trend with the Fe-55 pulse height distribution at 1 atm; pressure scans are next!
- Define optimized GEM parameters for a larger triple-GEM structure for use in a test beam

improved voltage stability enables higher voltage supply to the GEMs

Ar:CO_2 90:10

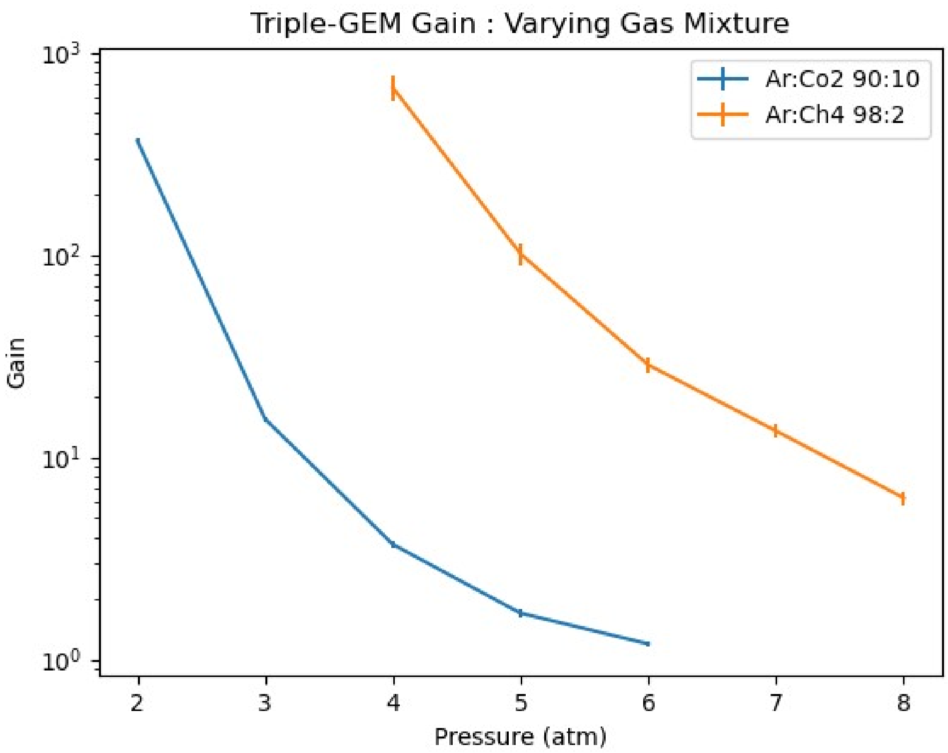


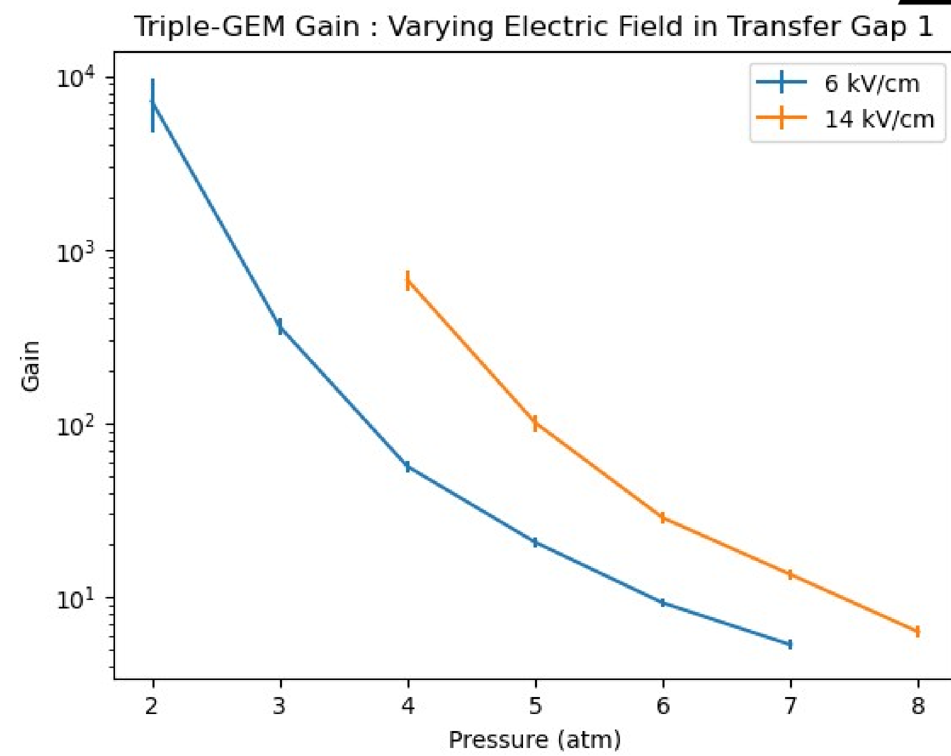
Ar:CH_4 98:2



R&D Efforts – TPC Amplification

- Ahead of pressure scans, detailed simulation studies are refining triple-GEM parameters, exploring both adjustable operational settings—such as **choice of gas mixture, transfer field strengths,** and gap configurations—and design-level modifications requiring a re-engineered triple-GEM stack (e.g. hole pitch)





B. McConnell

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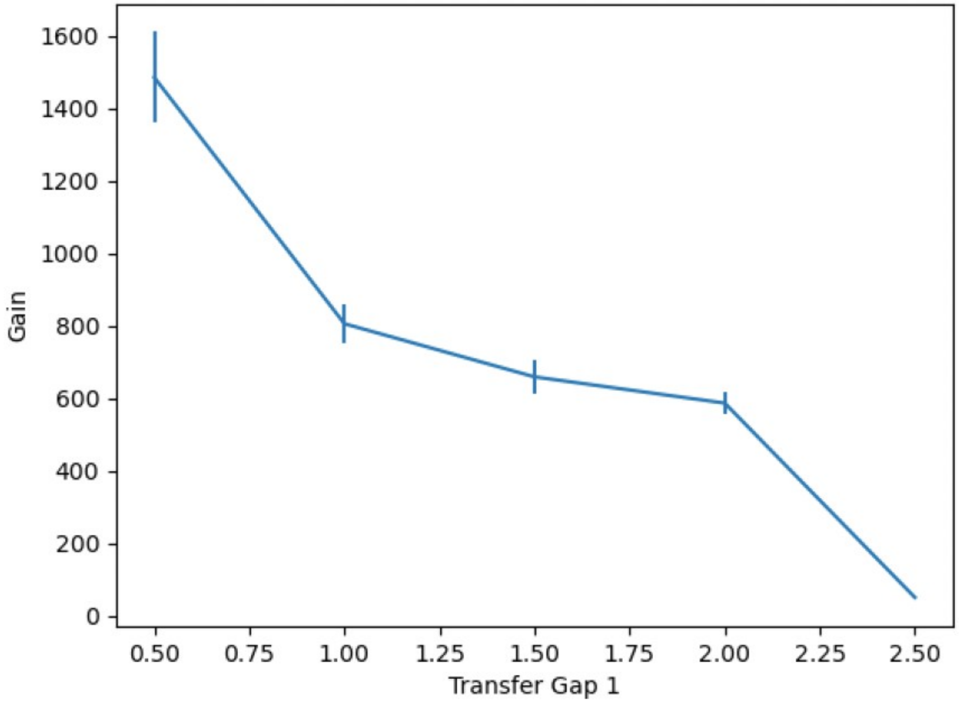
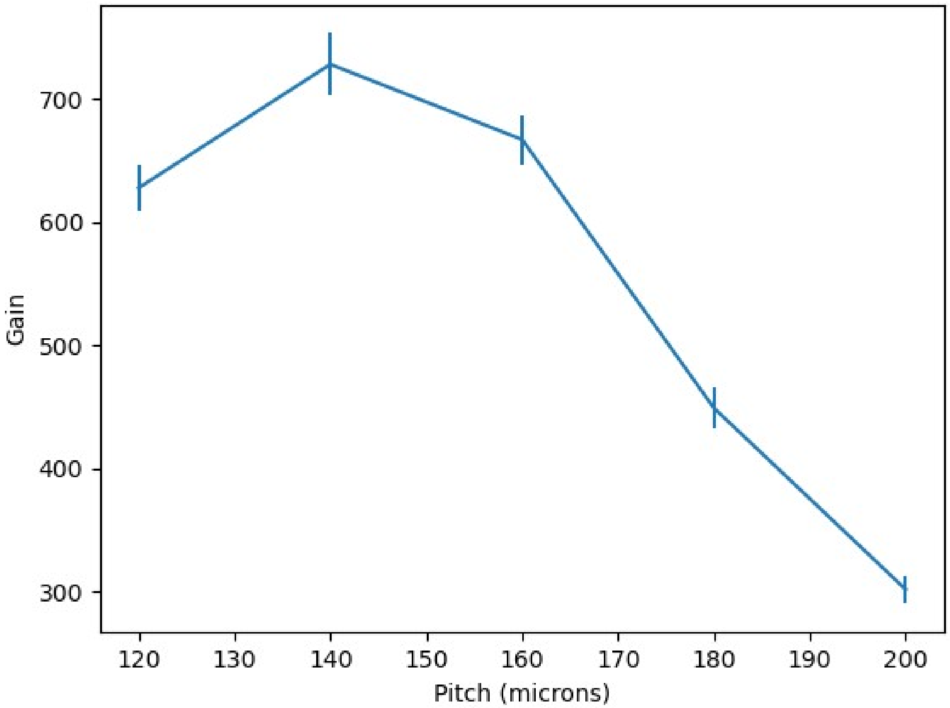


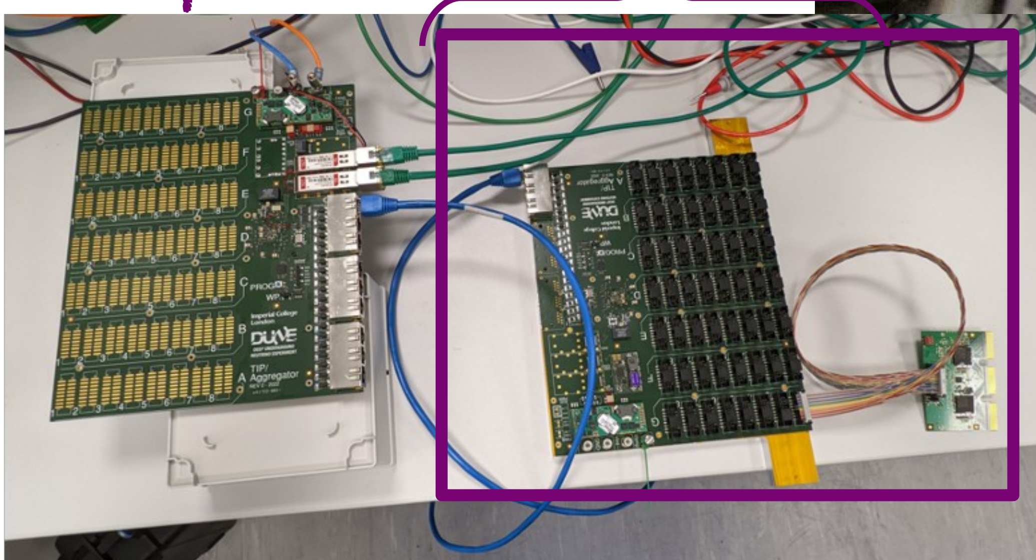


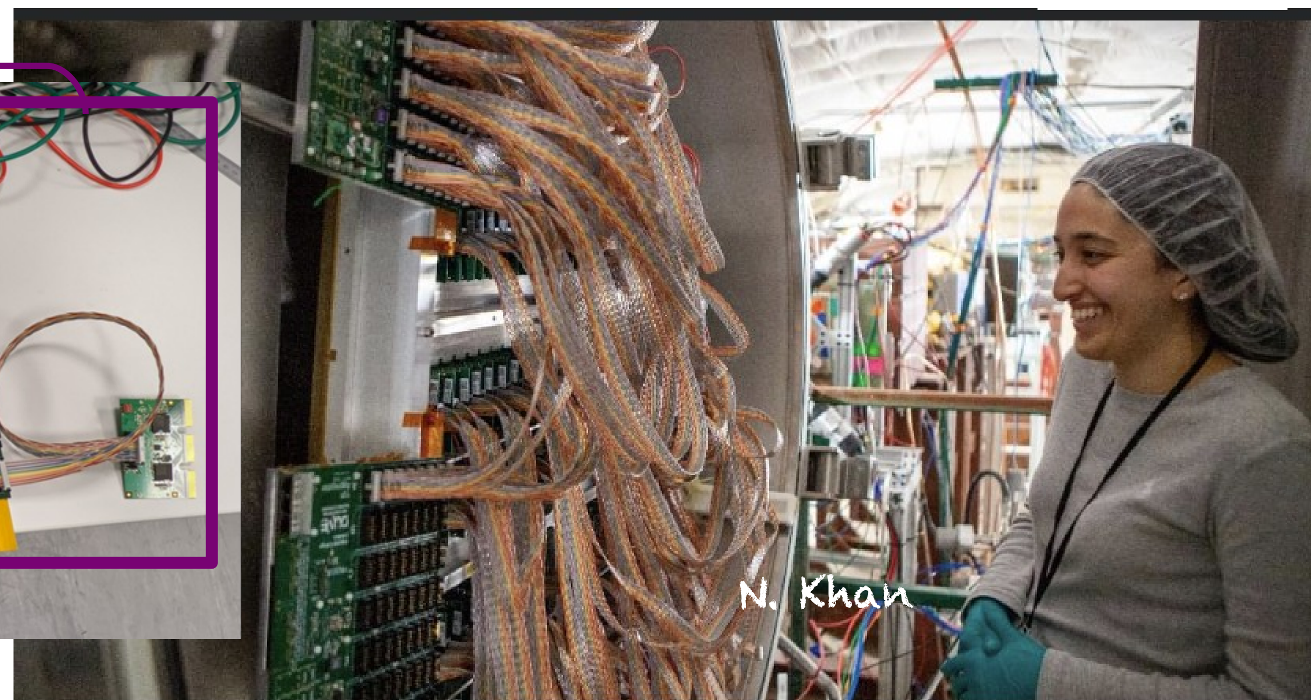
B. McConnell

Latest Test Beam on Readout Electronics

- Beam prototype TOAD carried out a full slice test of electronics under high pressure and in test beam environment with ALICE-based SAMPA cards, using the same pressure vessel from the CERN beam test
  - Tests carried out at Fermilab Test Beam
  - Established a clear path to delivering the readout system for ~$2M, making SAMPAs a cost-effective option for the future ND-GAr

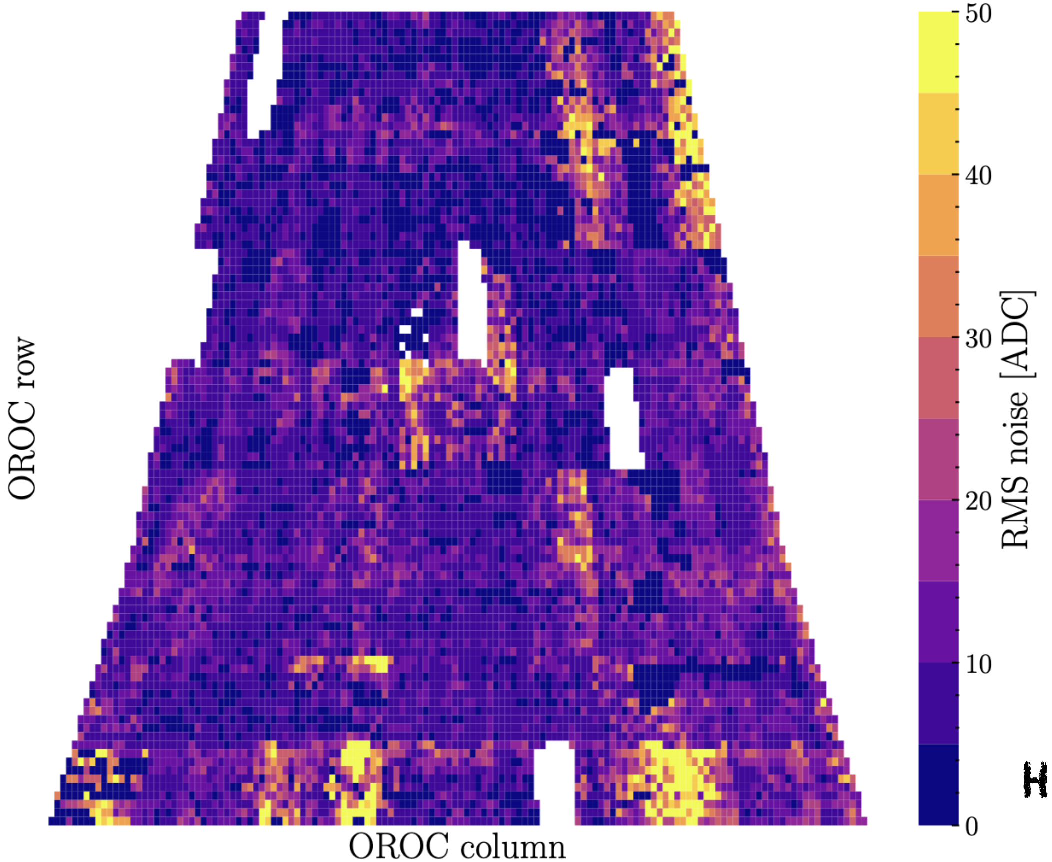
placed inside the pressure vessel



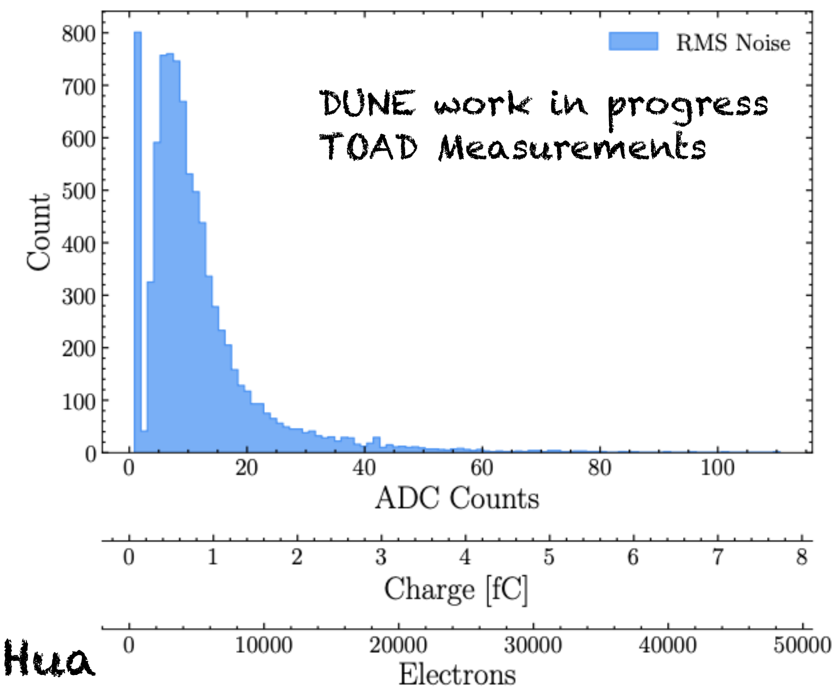


R&D Efforts – TPC Readout Electronics

- Additional measurements were noise measurement of electronics at 4.5 bar Ar-CH_4 (96:4) – demonstrated that electronics can operate under this pressure for the first time
- Detailed pressure, volume, temperature (PVT) studies carried out



H. Hua



Integration in a Future Test Beam

- The primary objectives:
  - Demonstrate long-term operation of the GEMs with SAMPA readout electronics at high pressure
  - Demonstrate reconstruction of low energy tracks
  - Probe the low-momentum region where models are in disagreement
- CERN Neutrino Platform a potential site for this:
  - Focus would be on low energy beams
- Existing pressure vessel, TOAD, tested at CERN and Fermilab, a viable platform:
  - Requires upgrades, such as active cooling, temperature monitoring, sensors

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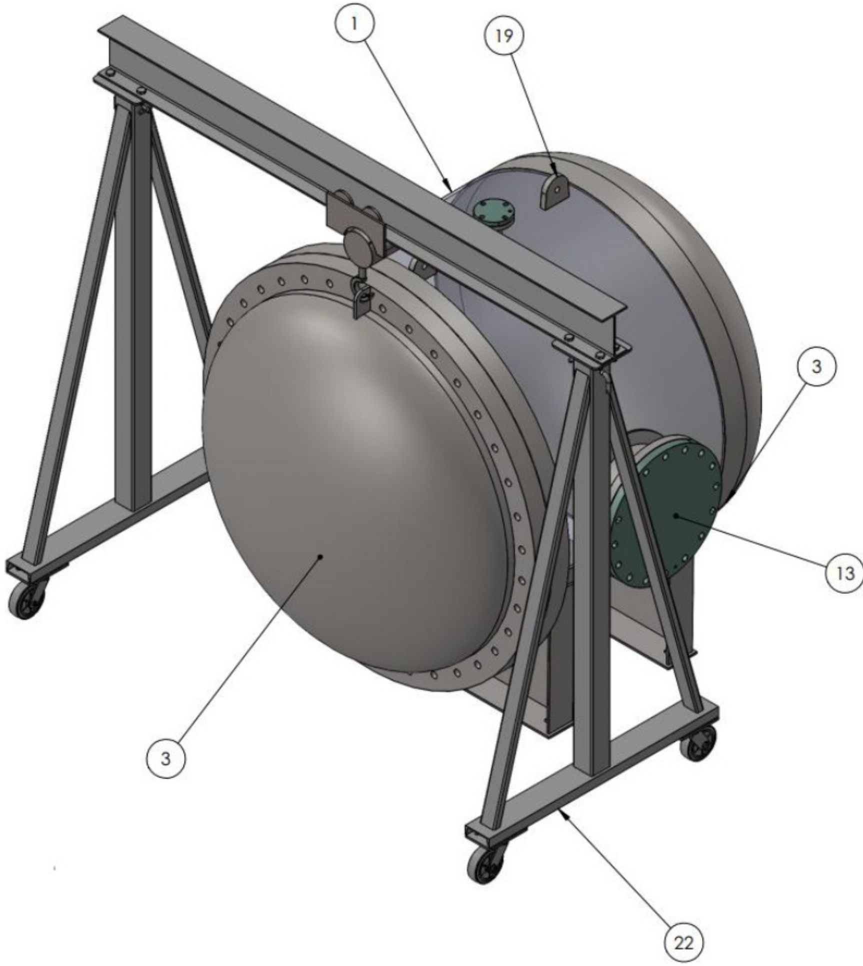
A key advantage of a prototype at CERN is the GDD group, who can offer invaluable expertise for many of the GEM prototyping activities

Additional Test Beam Campaign

- CERN beam tests could also include neutron beam campaign:
  - ★ n_TOF as a potential site
- Indiana University is in the process of procuring a pressure vessel for neutron beam tests of GEMs at the former Cyclotron Facility at the university
- Pressure vessel size (> TOAD) is optimized to maximize neutron interactions on argon
  - Protons with energies < 500 MeV are unlikely to pass through the pressure vessel walls → proton tracks from neutron scatters on argon provide a valuable tool for validating low-energy hadron reconstruction
  - Insights from these tests help identify gaps in neutron reconstruction performance, informing design requirements for ND-GAr's ECAL

IU Pressure Vessel being procured for neutron beam tests



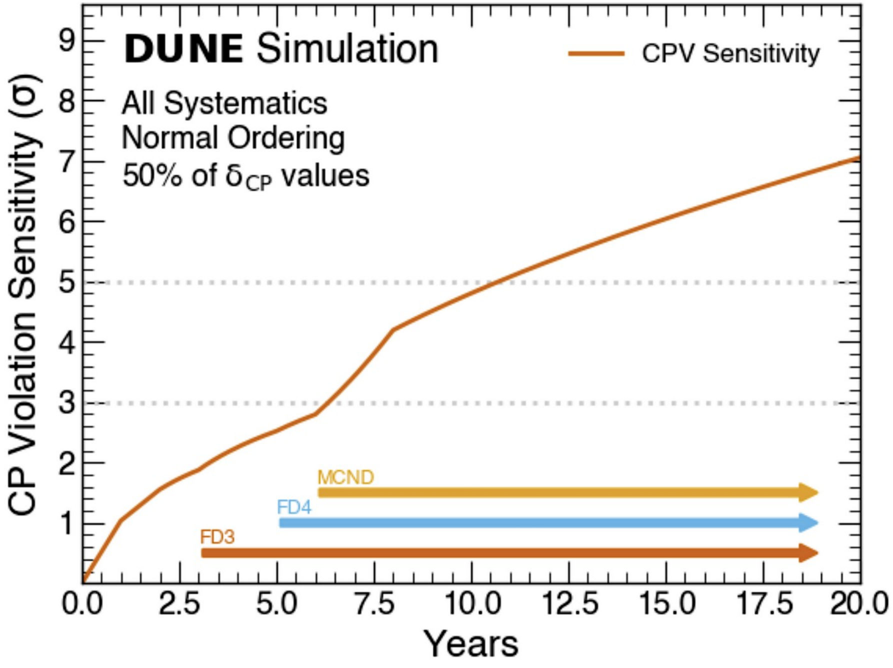
Possible Timeline

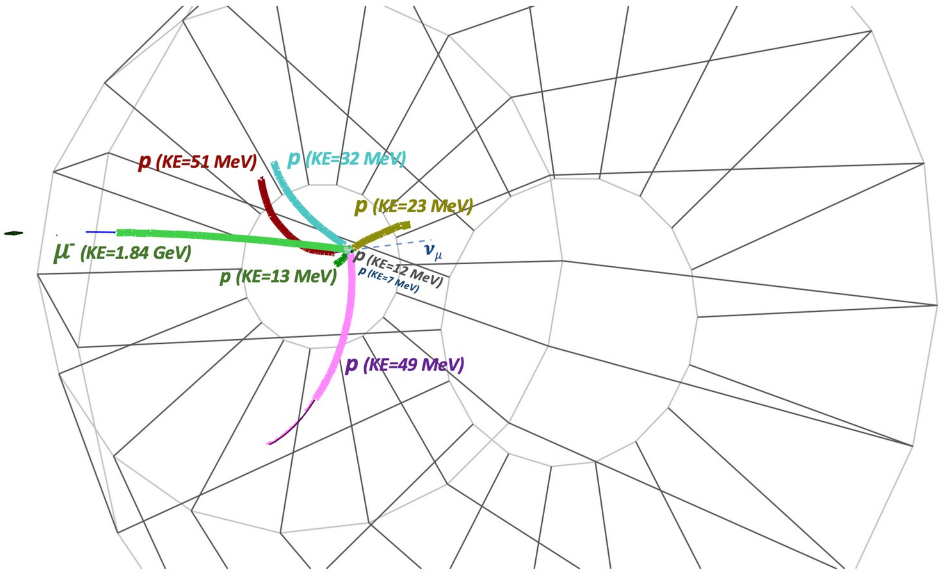
2025 Q1-Q2	Simulation studies for GEM optimizations
2025 Q3	Pressure Scans and SAMPA Integration Preparation
2025 Q4	Medium-scale GEM Prototype Assembly
2026 Q1-Q3	Analysis and Development of Larger GEM Prototype
2026 Q3-Q4	Neutron Beam Studies with IU Pressure Vessel and Optimizations of GEM+electronics from the neutron beam test and analysis of GEM pressure scans
2027 Q1-Q4 2028 Q1-Q3	Preparation for CERN Beam Tests
2028 Q4	Start of CERN Beam Test Campaign

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 for constraints on ν-interaction systematics

- A wide range of physics studies, detector R&D, and beam prototyping 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
  - Several beam tests have been completed, providing important lessons learned, with further beam tests planned – a potential site could be CERN!





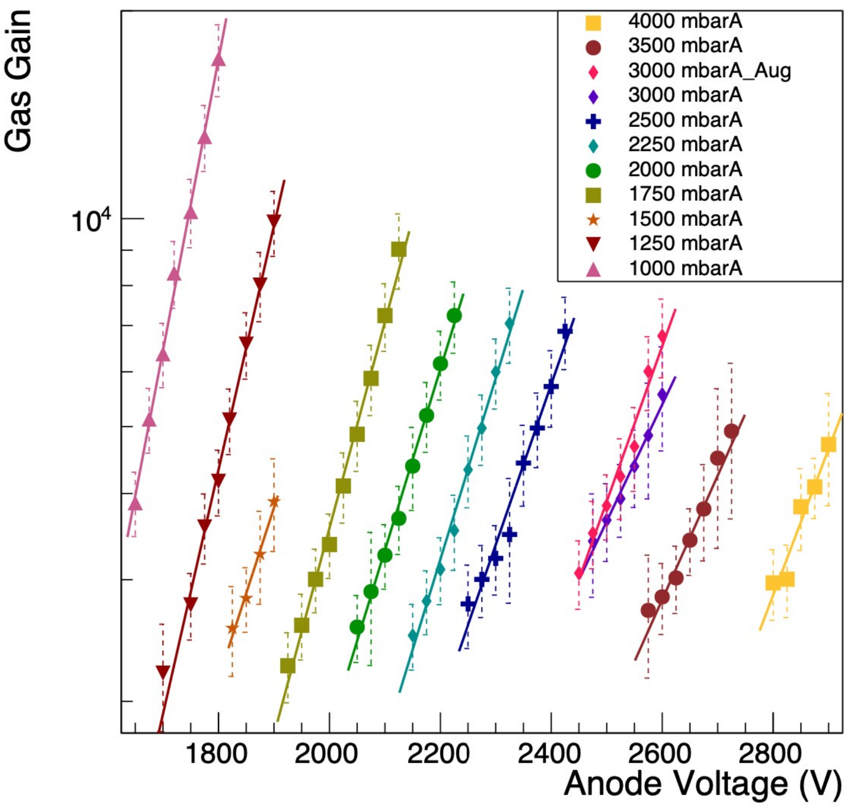
Additional Slides

Bridging Physics and Design

- Other examples:
  - Choice of gas pressure to balance increased target density with charge amplification – charge amplification (gas gain) is reduced at high pressure, affecting the achievable energy threshold

1-ton fiducial mass in 1-year ν-mode (5x5 m TPC with Ar mixture at 10 atm) using 1.2 MW 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

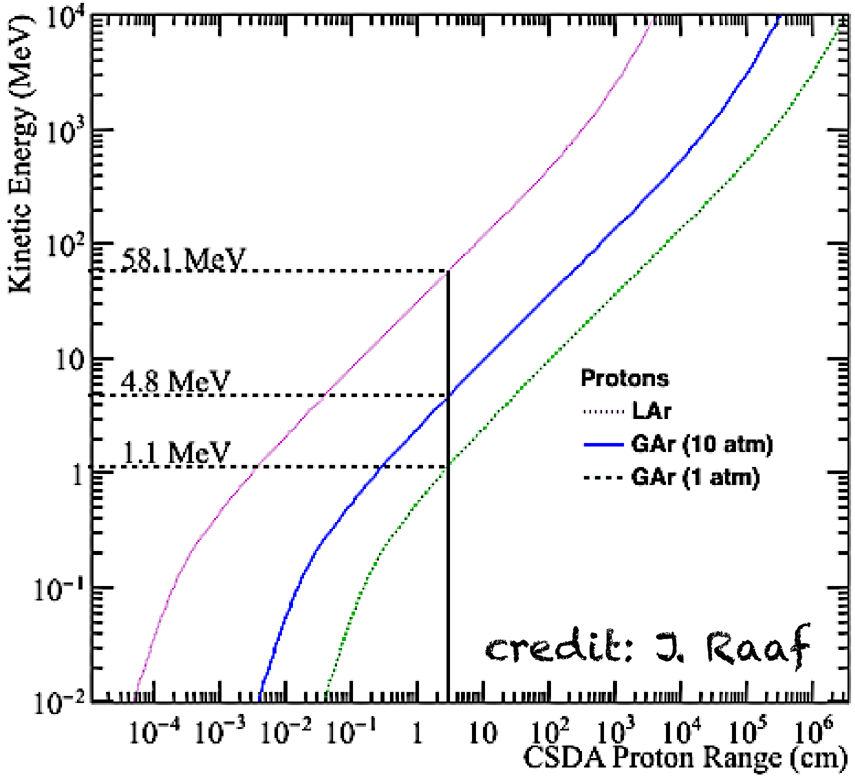


https://doi.org/10.48550/arXiv.2305.08822

Low Threshold ND-GAr

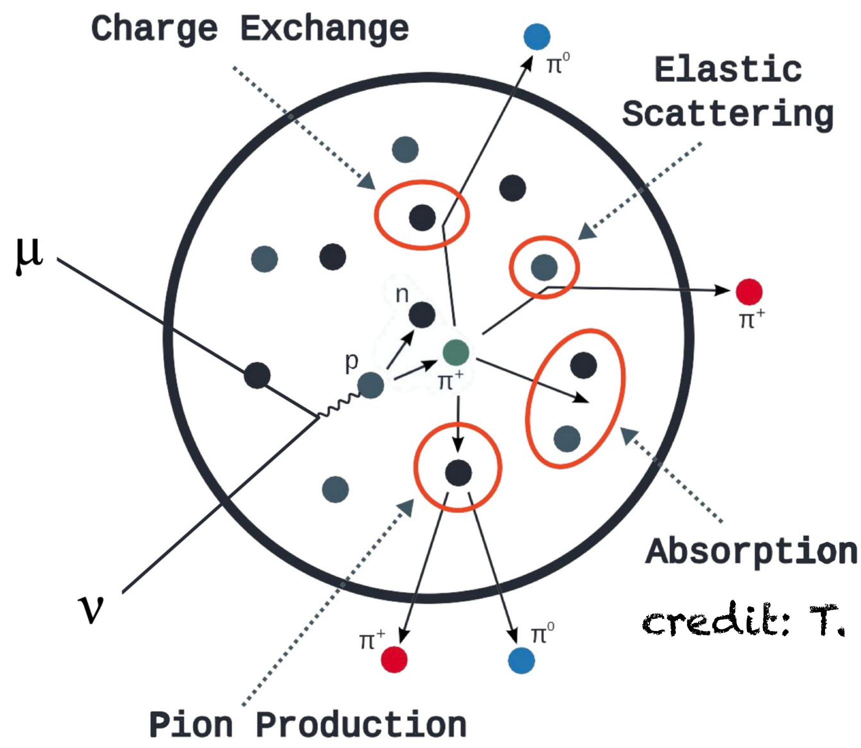
- Lower threshold of **ND-GAr's HPgTPC** than **ND-LAr**:
  - Leads to a high sensitivity to low energy protons or pions:

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



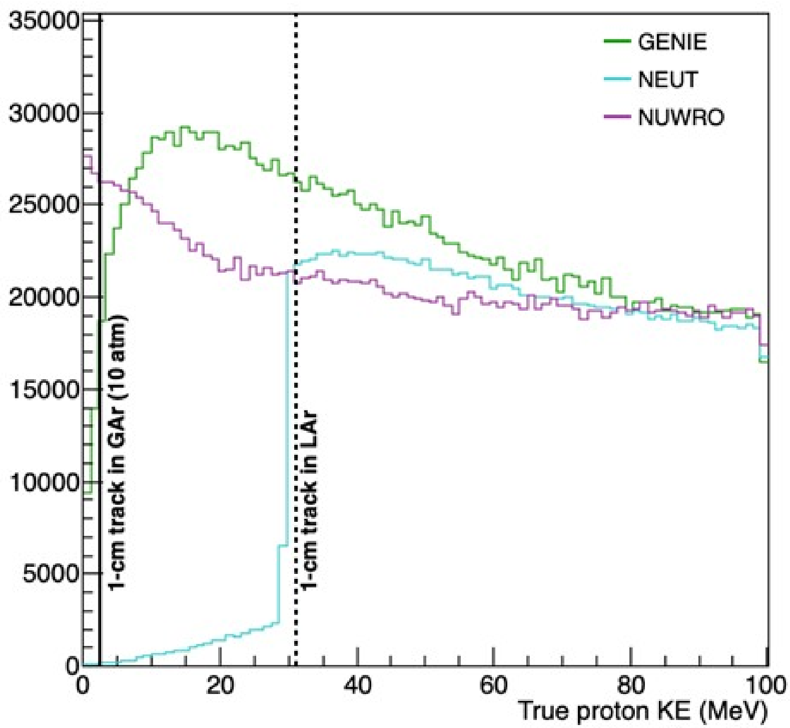
Low Threshold ND-GAr

- 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

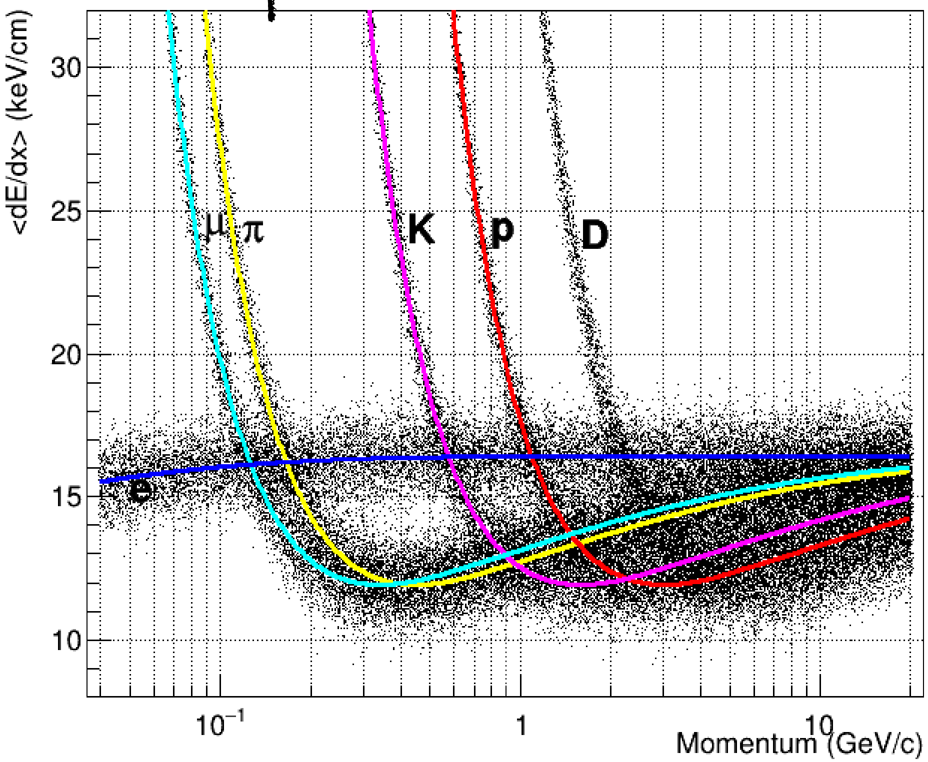
neutrino generator modeling at low proton KE, accessible with a GAr-based detector



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

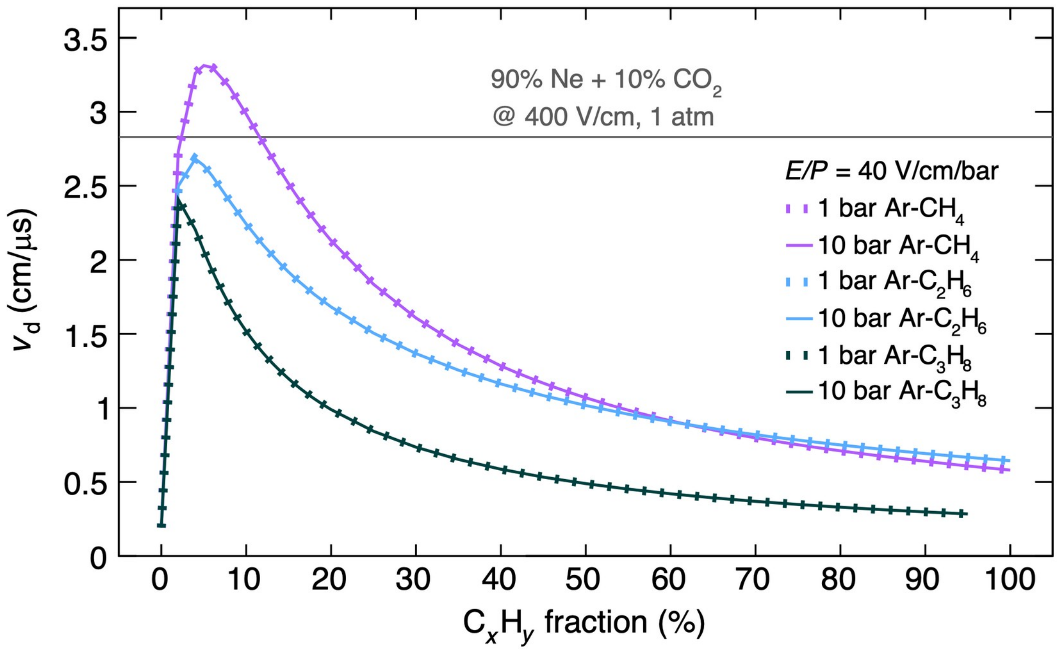
dE/dx-based PID will be comparable to PEP-4's

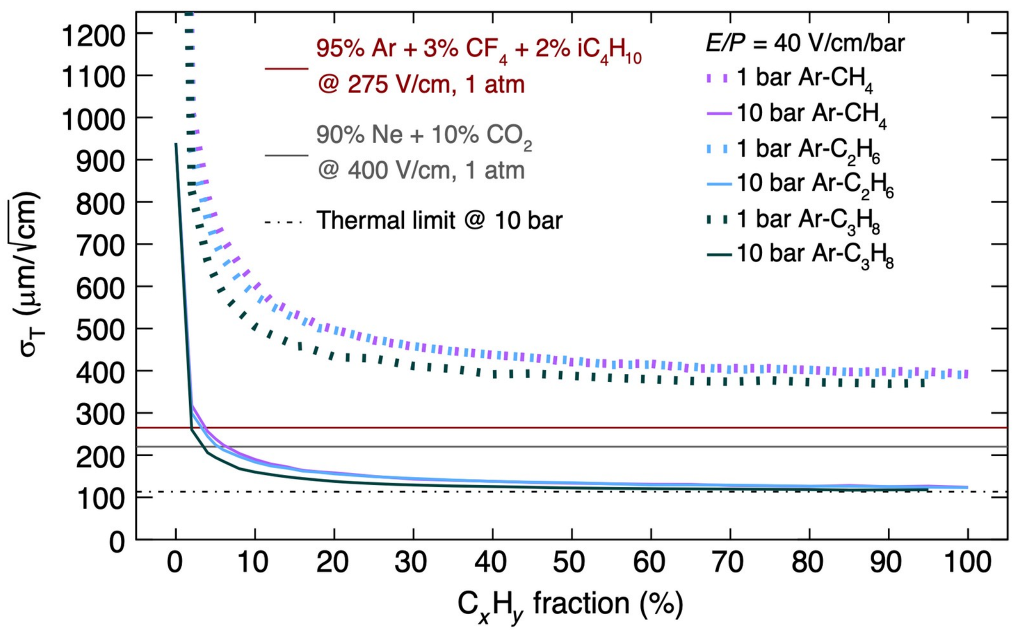


DUNE Collaboration, A. Abed Abud et al. Instruments 5 no. 4, (2021) 31, arXiv:2103.13910 [physics.ins-det].

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)

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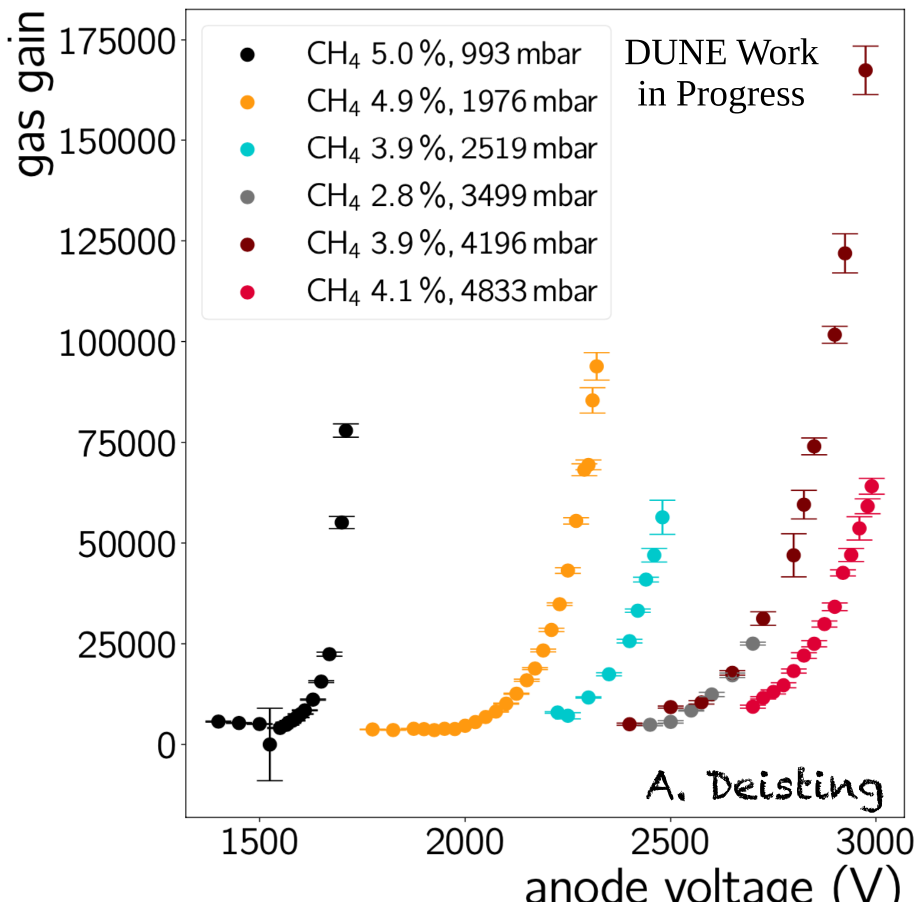
    - Maximize gas gain



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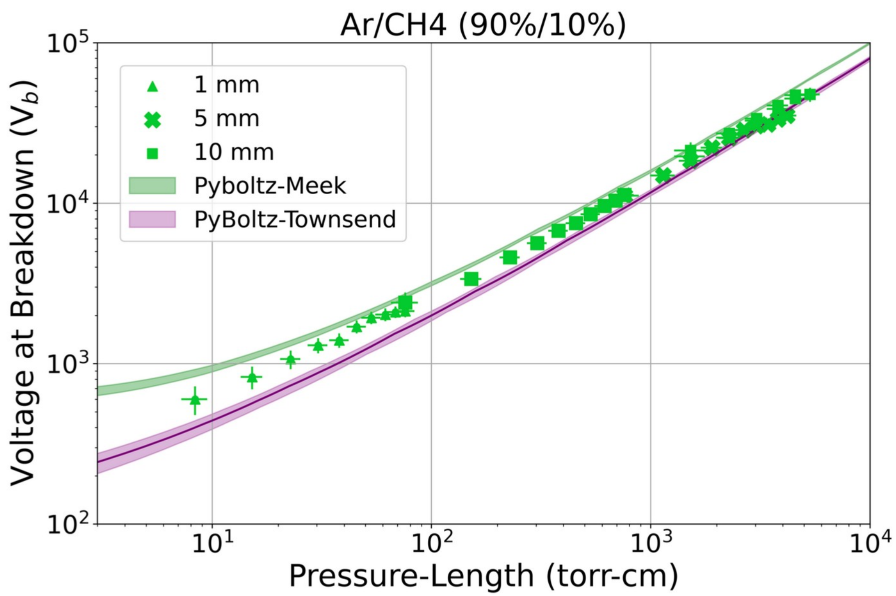
    - Control pile up (drift velocity) and improve spatial resolution (diffusion)
    - Maximize gas gain, while minimizing gas electrical breakdown



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**

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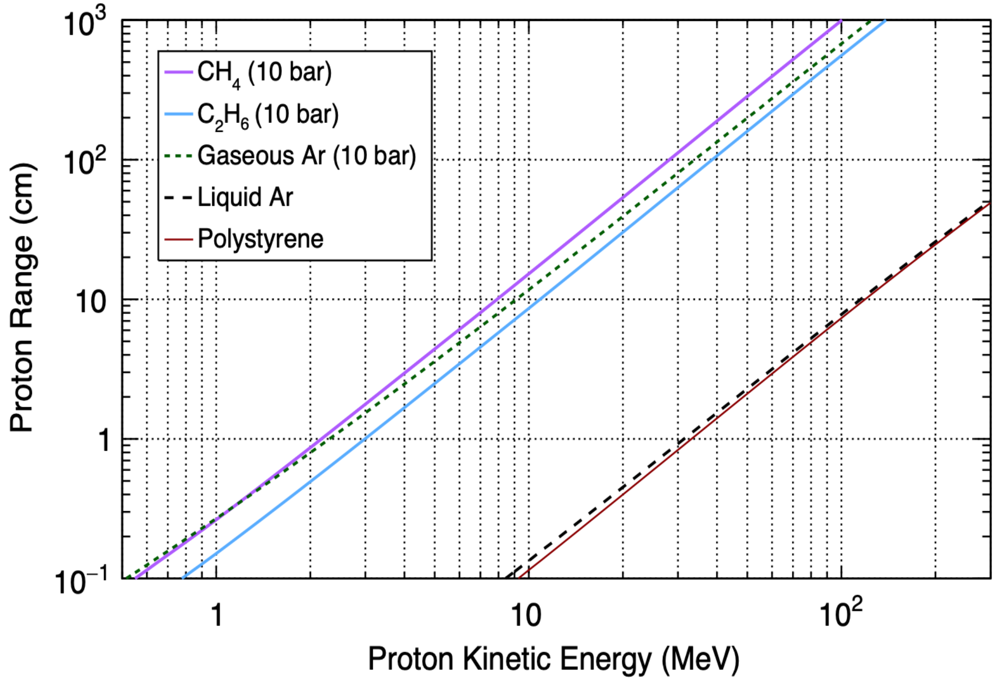
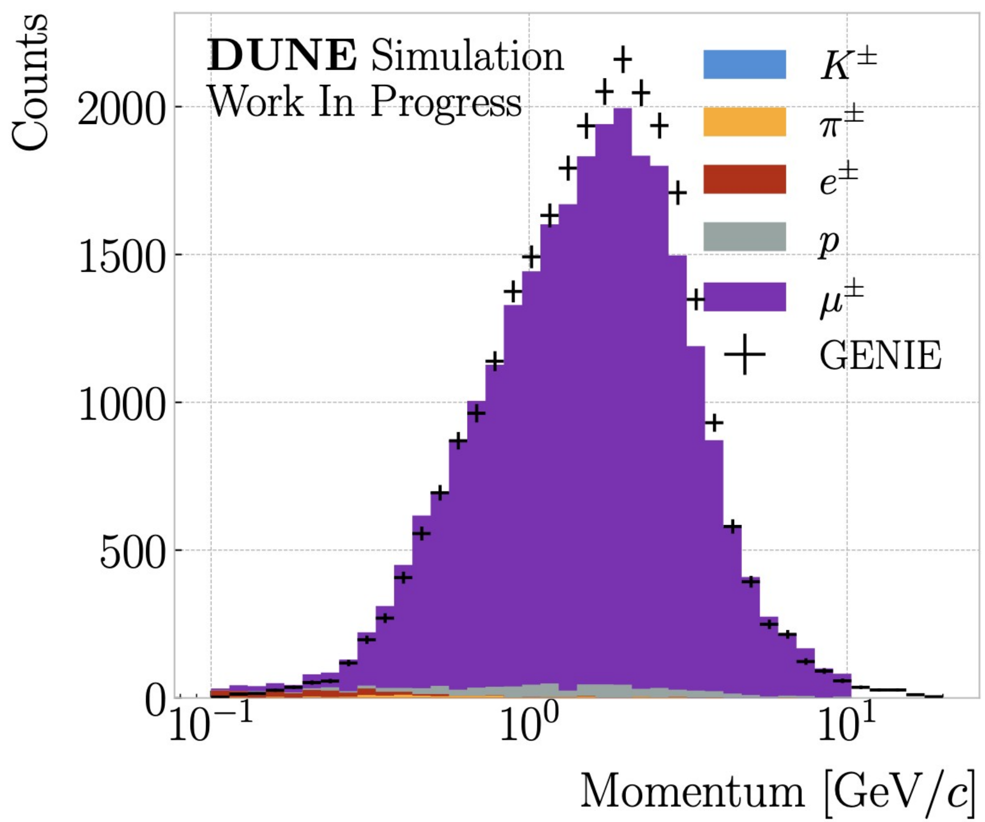
    - Control pile up (drift velocity) and improve spatial resolution (diffusion)
    - Maximize gas gain, while minimizing gas electrical breakdown
    - Ability to operate with a hydrogen-rich gas mixture to probe more fundamental neutrino-hydrogen interactions

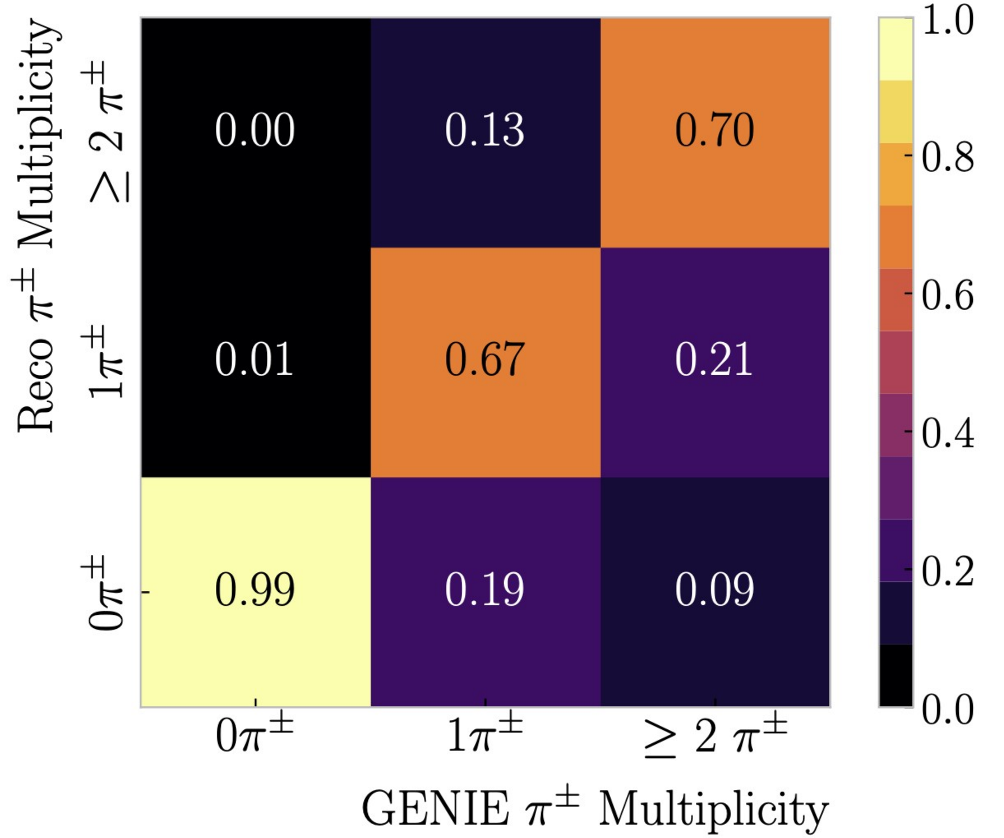


P. Hamacher-Baumann et al., Phys. Rev. D 102, 033005 (2020)

Additional Physics Reach

- High-pressure gaseous argon enables precise reconstruction of low-energy charged particle tracks, critical for studying exclusive final states, e.g. pion multiplicity





F. Martínez López

from the developing ND-GAr software, GarSoft - highlights ongoing studies, not final results