Charge Readout Prototyping and Beam Tests for ND-GAr

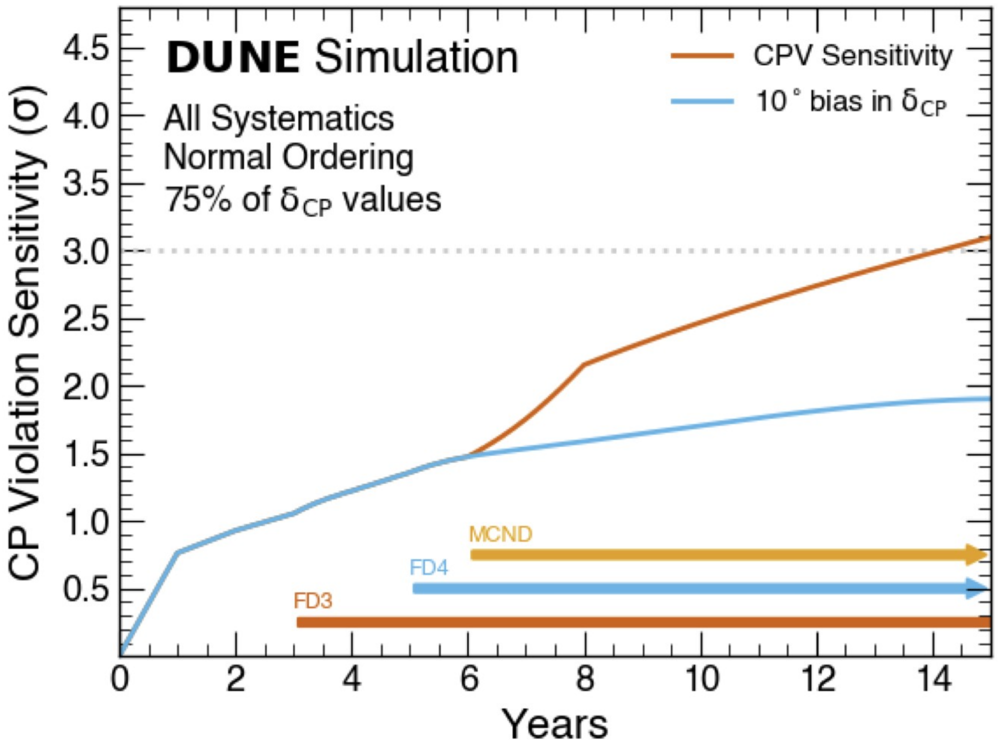
Tanaz A. Mohayai, Indiana University,
on Behalf of DUNE

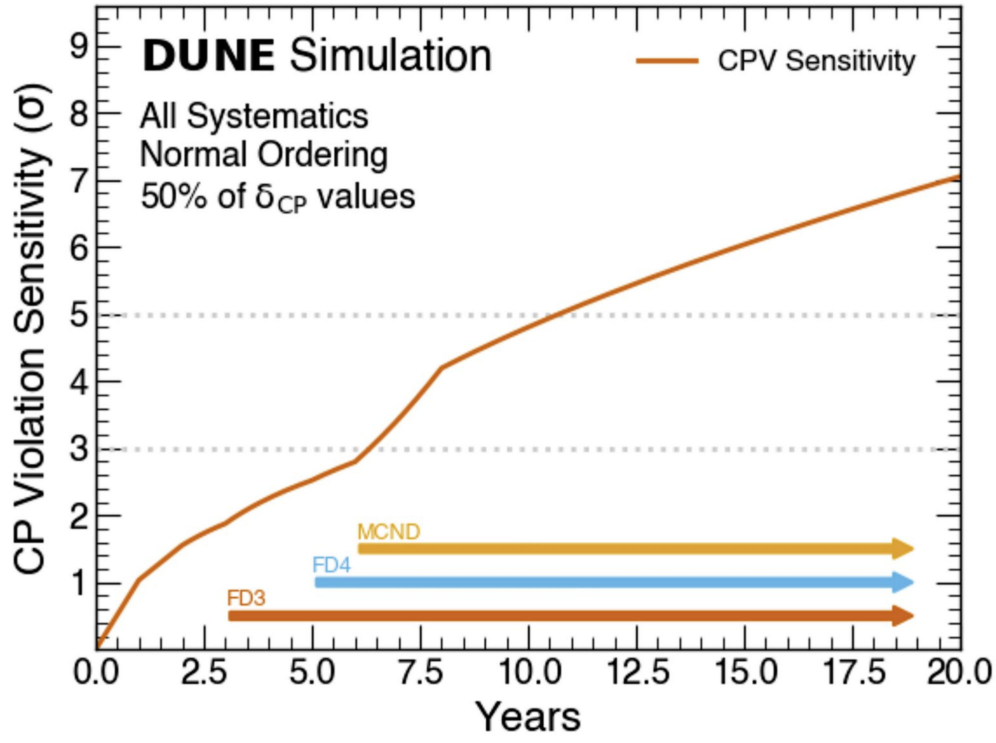
Neutrinos@CERN Workshop
January 24, 2025

DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE Phase II

- Critical to achieve DUNE's full scope – includes upgrades to **ND**, FD, and beam for higher statistics
  - Only the ND upgrade to ND-GAr (**MCND** in the plot), which leverages a gas argon TPC design, addresses neutrino interaction and detector acceptance systematics



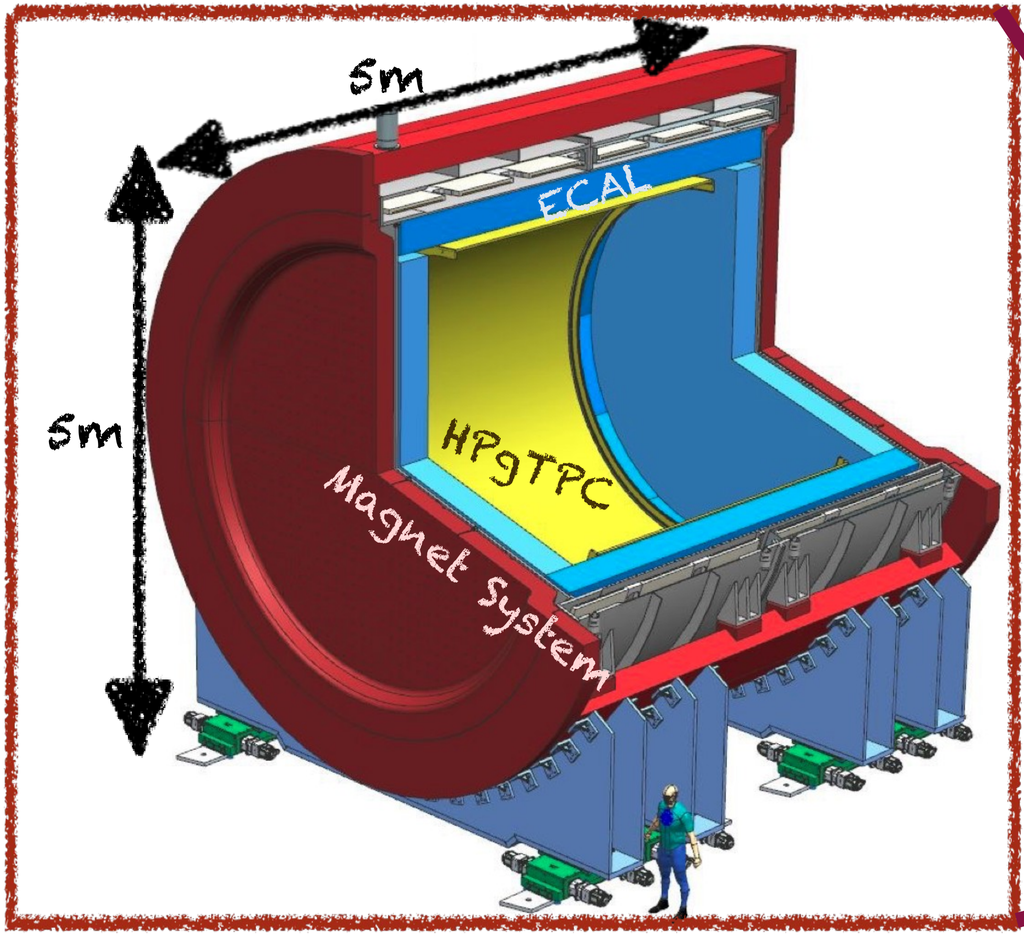


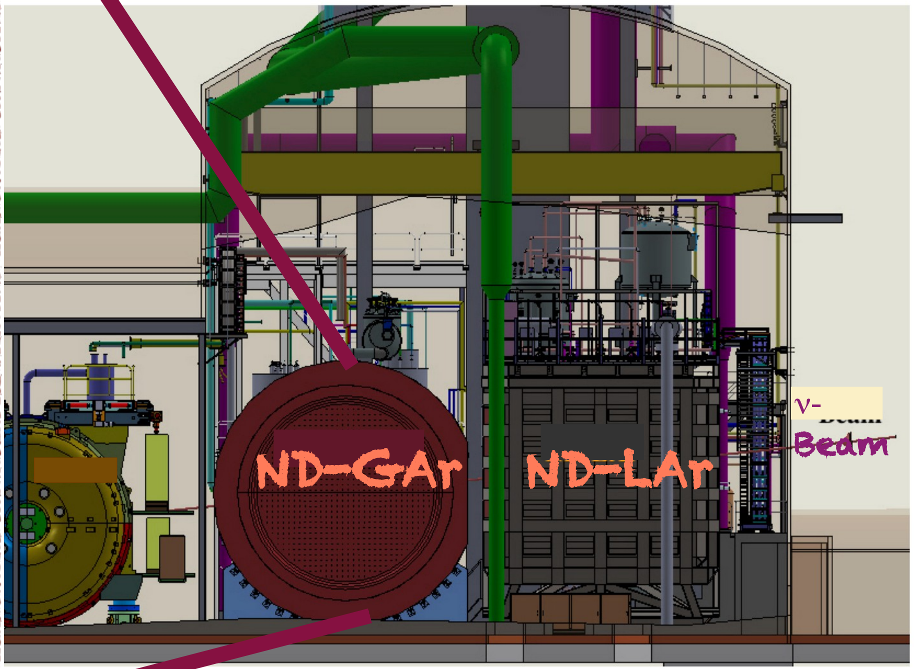
Phase II ND Upgrade: when phase I muon spectrometer will is replaced by ND-GAr

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

ND-GAr

- Key design features recommended by P5 include a **high-pressure gaseous argon detector (HPgTPC)**, **ECAL**, and **magnetized volume**
  - Also includes evolving design features (e.g. pixelization, amplification, and granularity) – requires R&D and test beam to meet physics goals

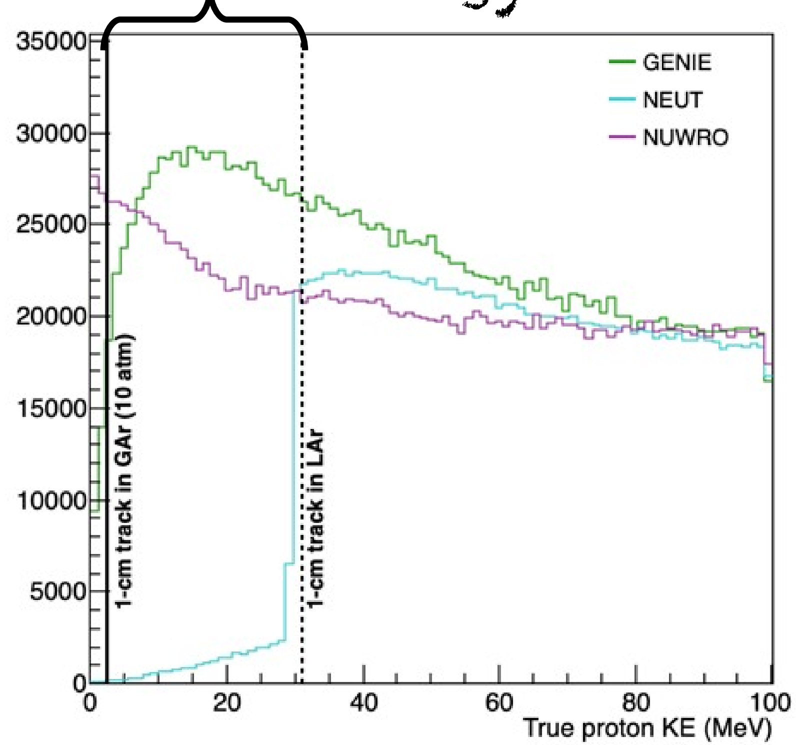




Role in Reducing ν-Interaction Systematics

- 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

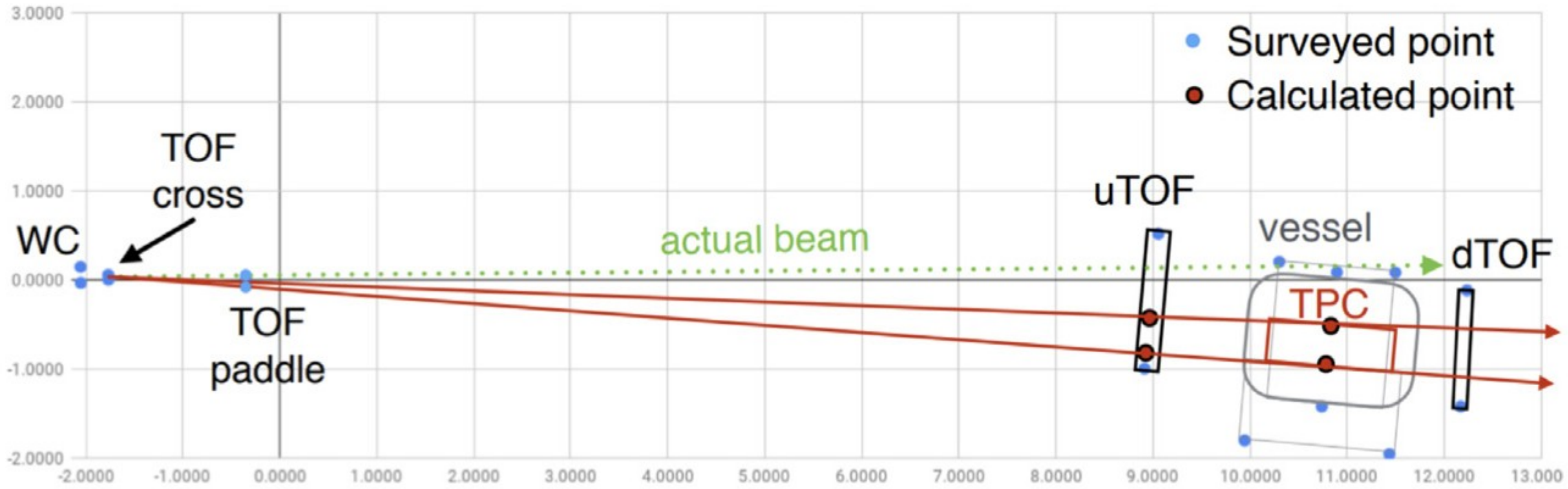
HPgTPC gives access to inaccessible regions of proton energy thanks to its low energy threshold



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

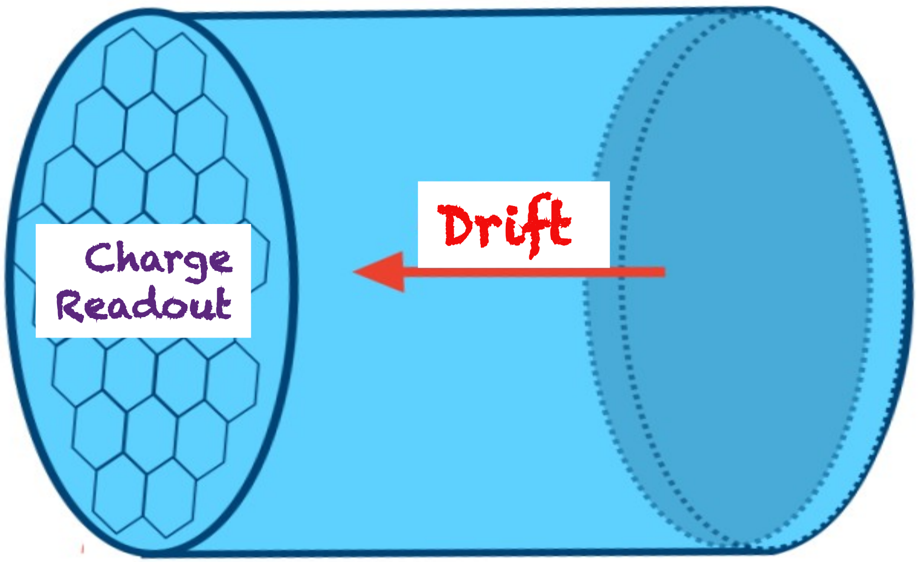
Bridging Physics and Design

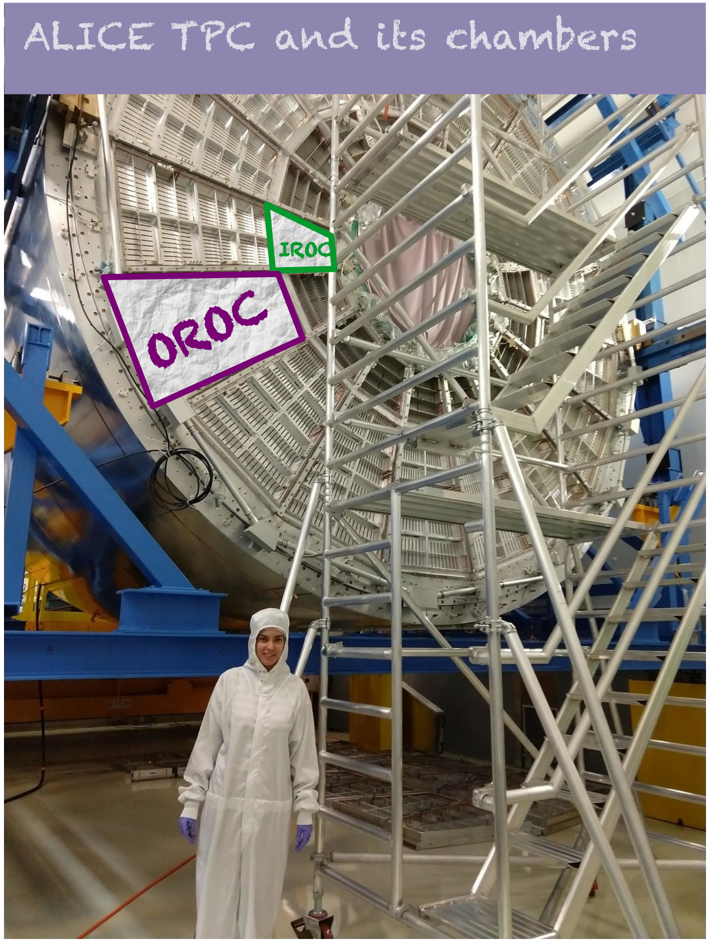
- **Test beams** → a platform to validate design concepts and physics performance under controlled conditions
- First neutrino-TPC prototype was out at CERN's T10 beamline– focus was on the low-momentum proton beam (≤ 0.5 GeV), provided important lessons learned



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



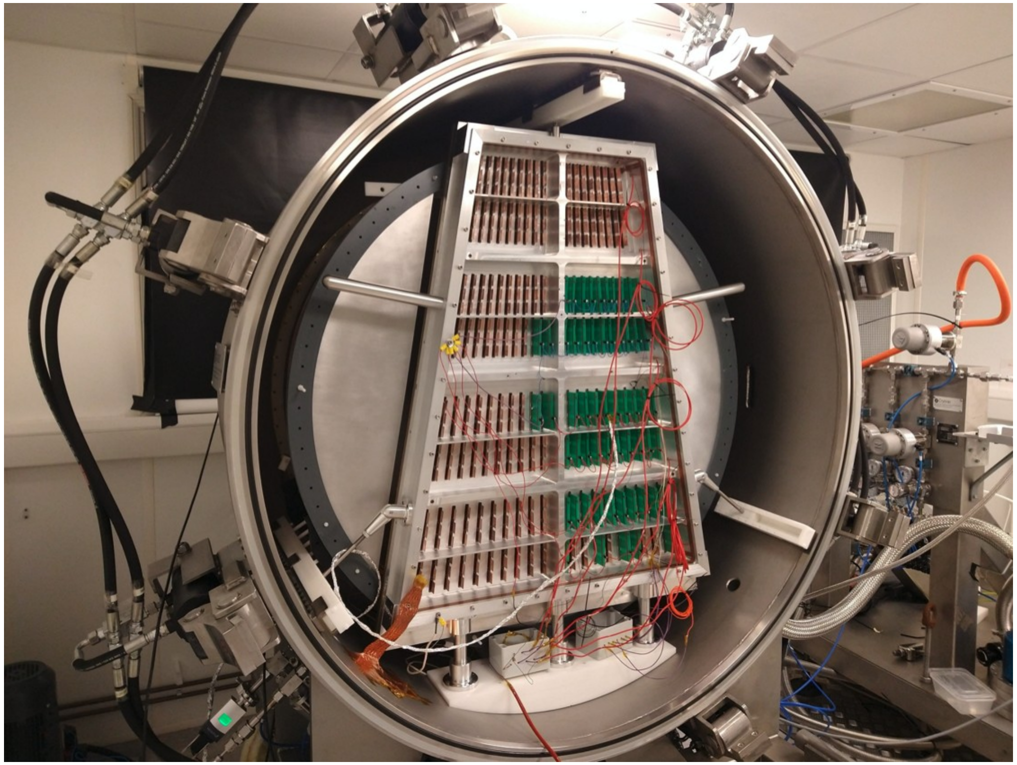


- On-going R&D thrusts towards the next beam tests:
  - TPC amplification: focused initially on the acquired **ALICE MWPCs,** the current focus is on **MPGDs such as GEMs**
  - TPC readout electronics: test of the SAMPA-based electronics

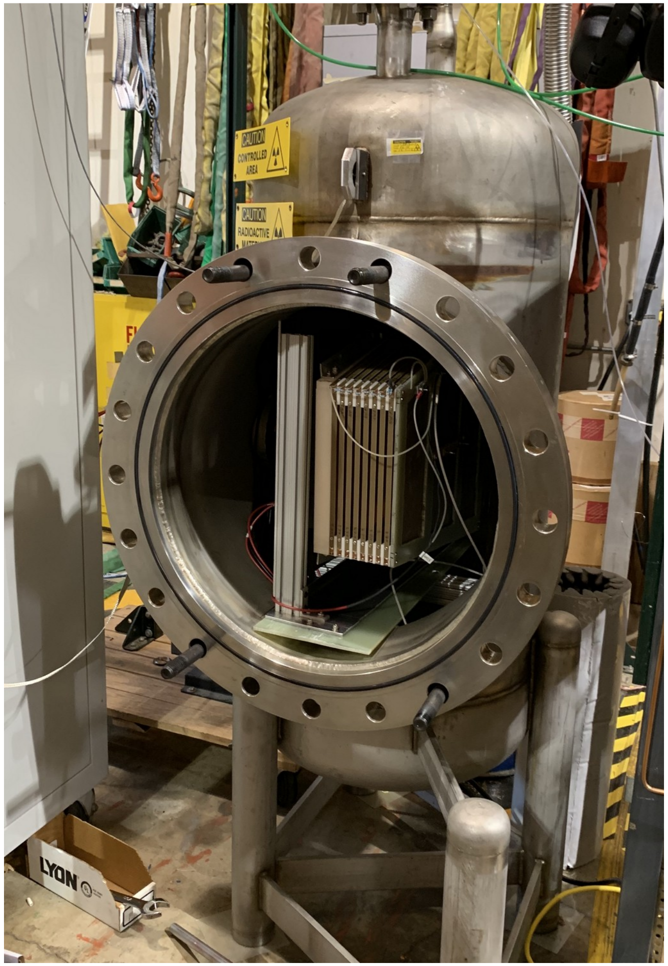
TPC Amplification R&D – MWPC

- Initial efforts focused on MWPCs acquired from ALICE
  - Two efforts in US (GOAT) and UK (TOAD, same pressure vessel as the CERN test beam) completed a pressure scan of the chambers

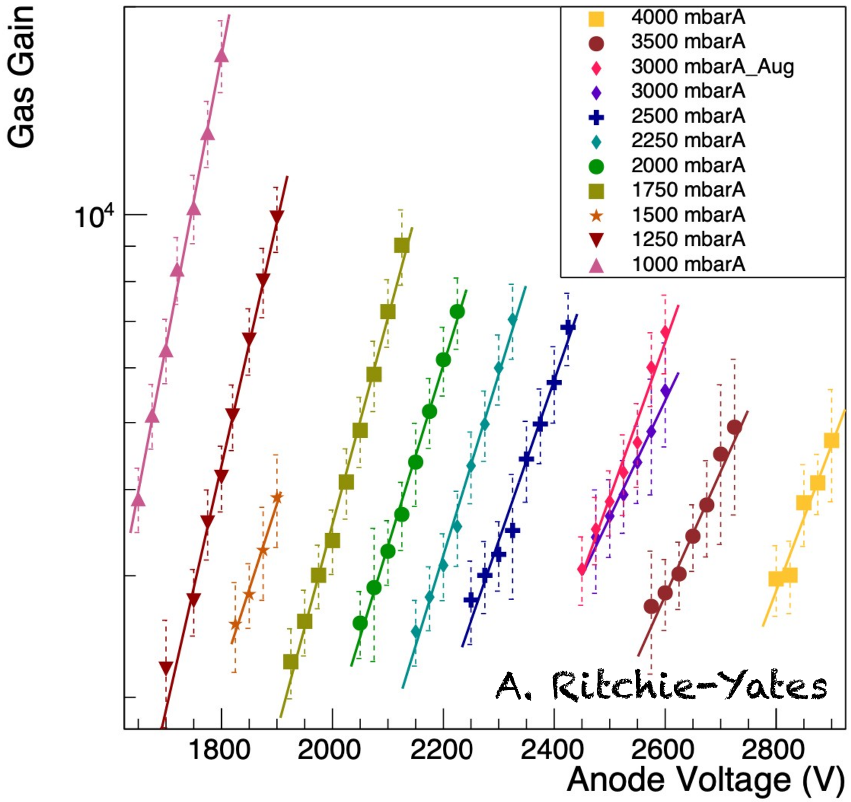
Royal Holloway Prototype which was used at CERN T10 beamline, recently moved to Fermilab Test Beam, now named TOAD

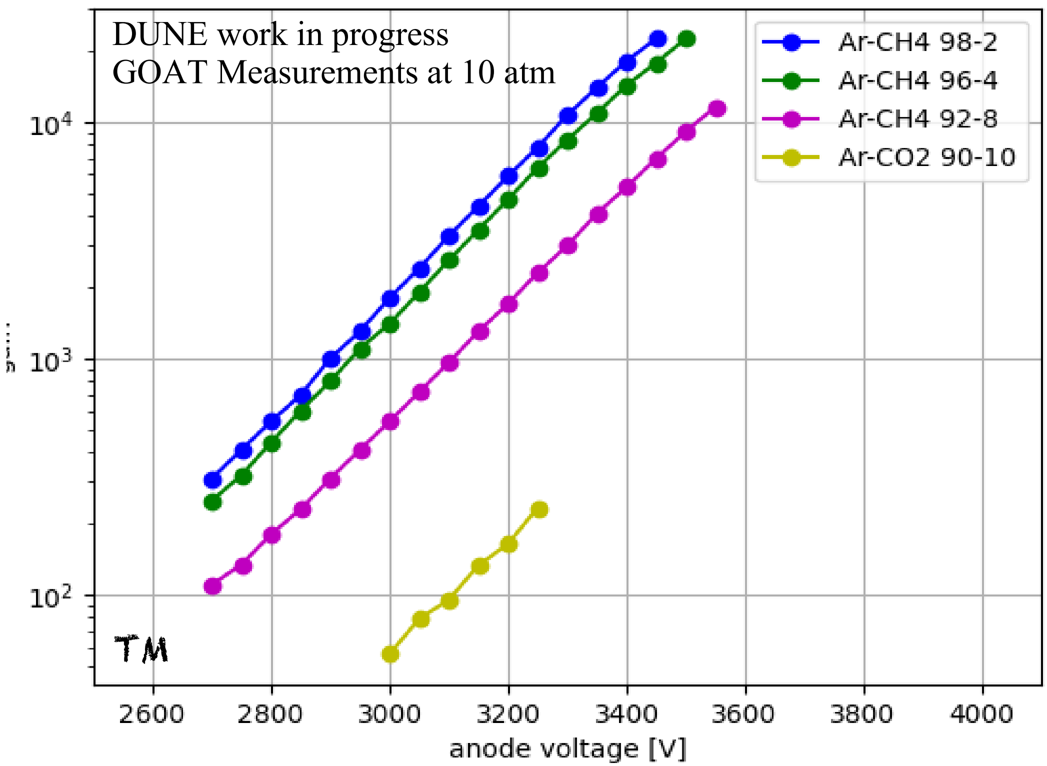


Fermilab Test Stand, housing an IROC, also named GOAT



- Chambers able to maintain the same gain at higher pressures with appropriately scaled voltages:
  - Using an Ar-CH_4 mixture, a gain of 1k possible with ~3kV (deemed the safe operational limit by ALICE)



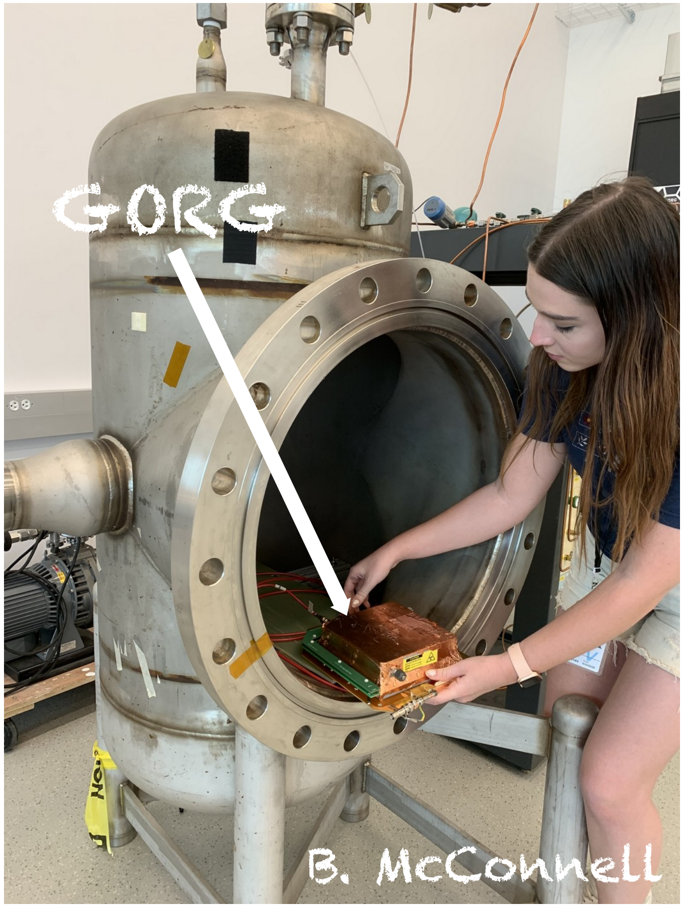


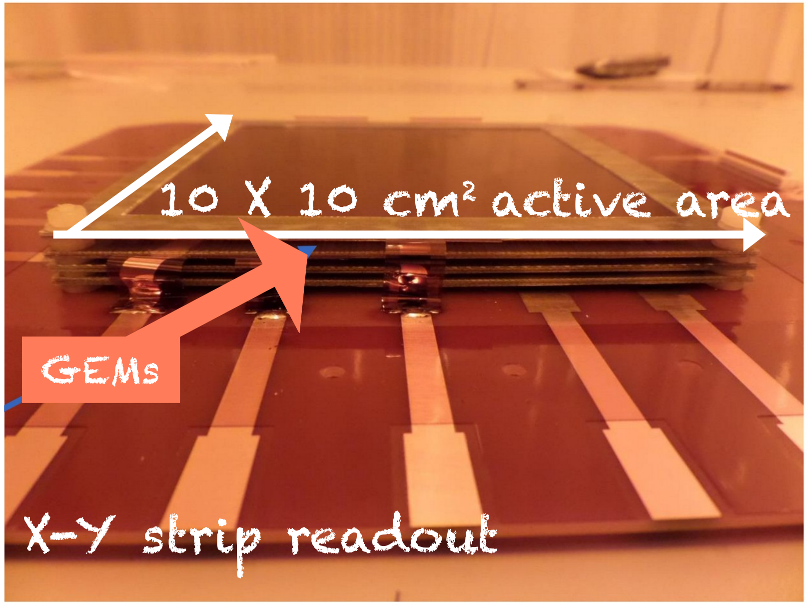
https://doi.org/10.48550/arXiv.2305.08822

TPC Amplification R&D – GEMs

- The next phase of R&D is centered on GEM-based systems
  - On-going efforts include GORG setup (GEM Over-pressured with Reference Gases), building on TM's New Initiatives, with a future test beam planned post-R&D in the coming years

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



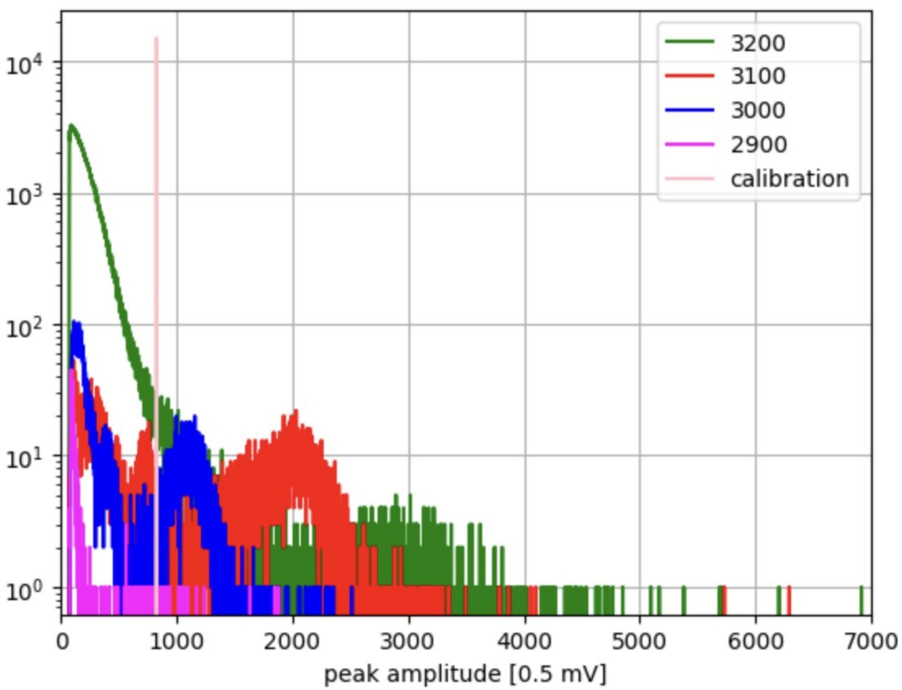


TPC Amplification R&D - GEMs

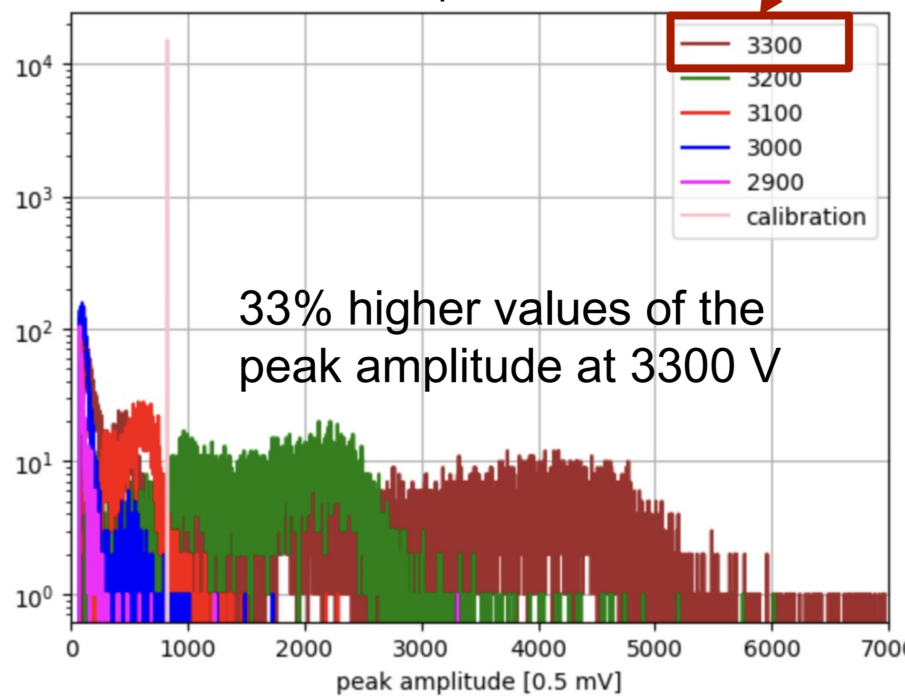
- 1 atm bench tests indicate the expected trend with the Fe-55 pulse height distribution
  - ★ GOAT pressure vessel being prepared for the upcoming pressure scans

improved voltage stability enables higher voltage supply to the GEMs

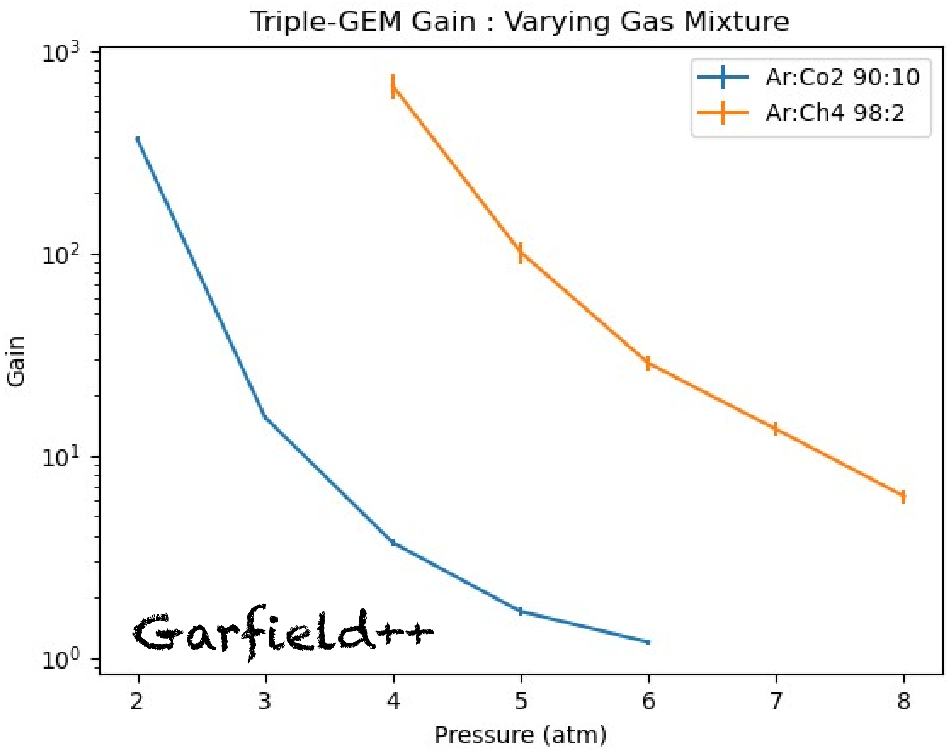
Ar:CO_2 90:10

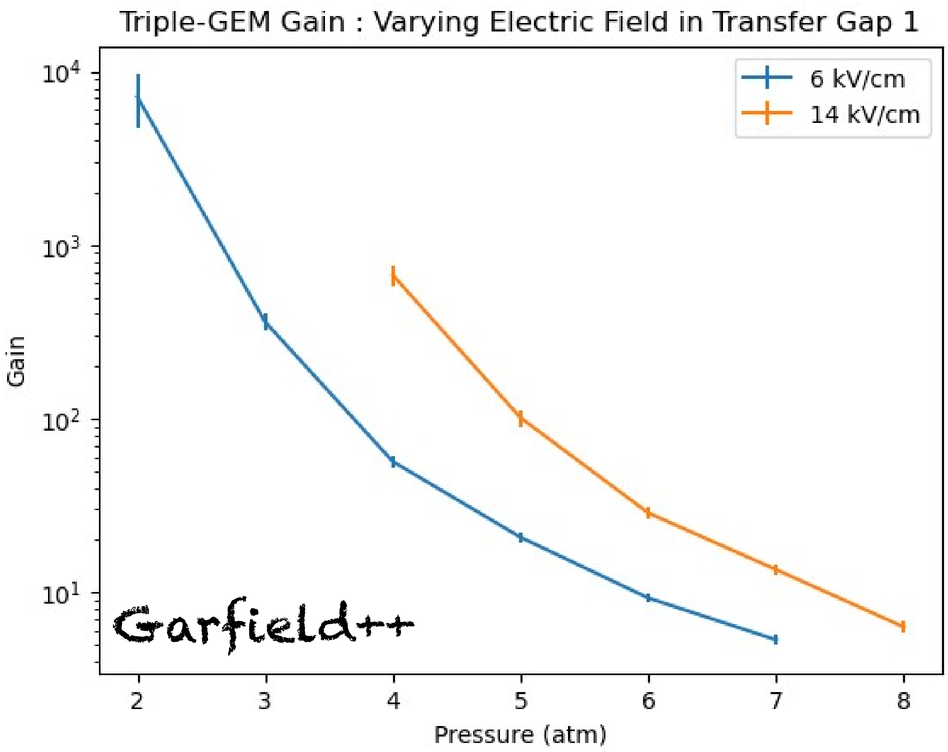


Ar:CH_4 98:2



- Prior to pressure scans, simulation studies are guiding the optimization of triple-GEM parameters
  - Some parameters, such as **gas mixture and transfer fields,** can be easily adjusted to maintain high gain at higher pressures for a given voltage

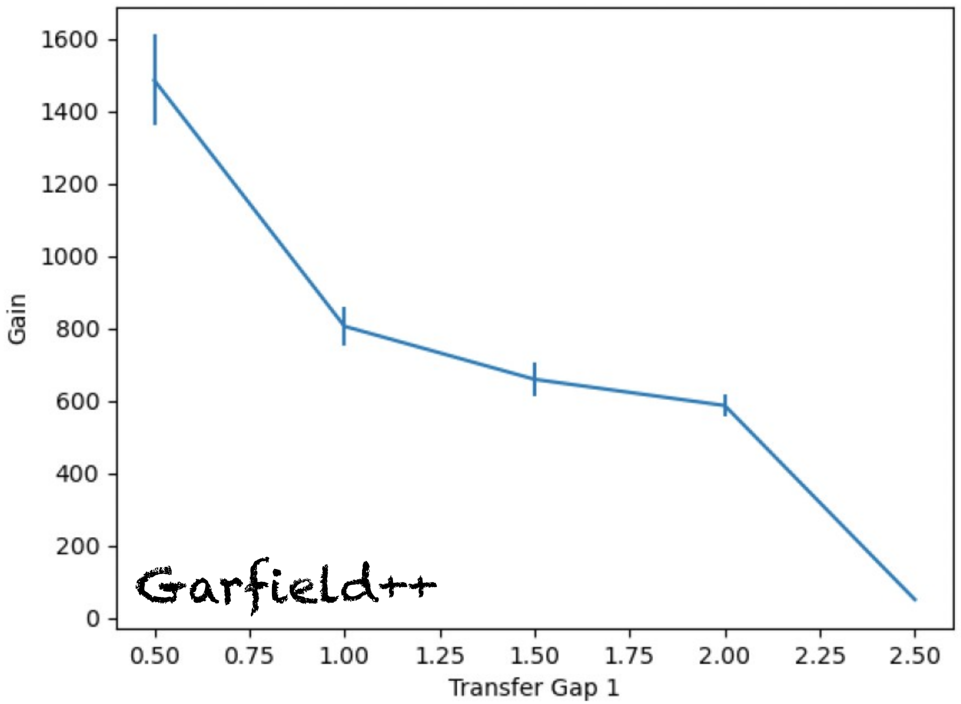


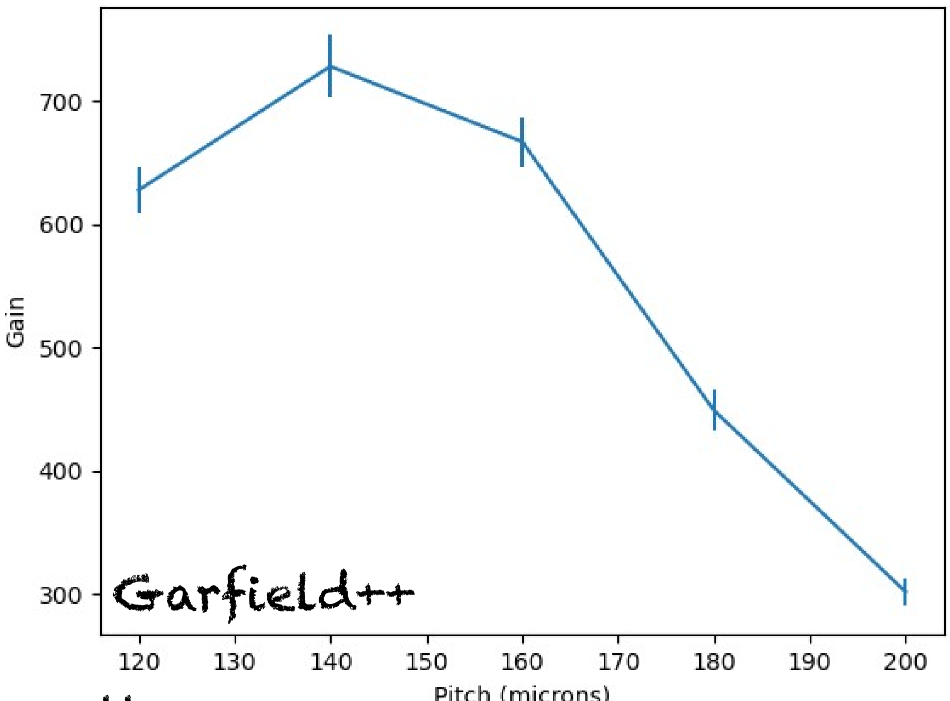


B. McConnell

TPC Amplification R&D – GEMs

- Prior to pressure scans, simulation studies are guiding the optimization of triple-GEM parameters
  - Other parameters such as transfer or induction **gap configurations and GEM hole pitch** when modified are design-level modifications and require a re-engineered triple-GEM stack



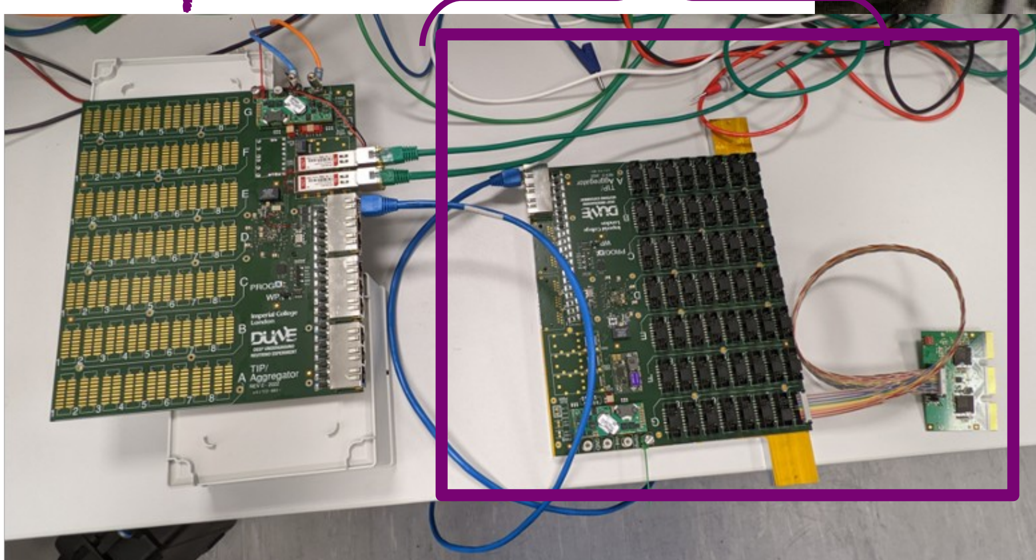


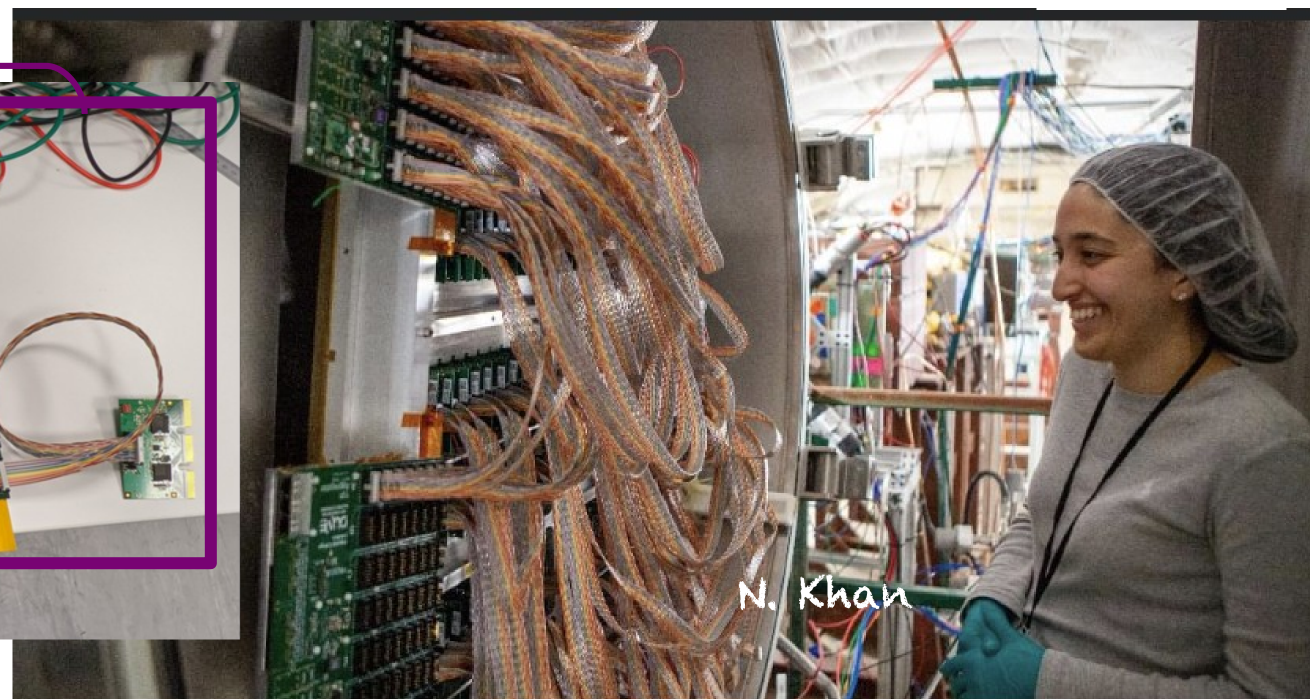
B. McConnell

Readout Electronics R&D – Latest Test Beam

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

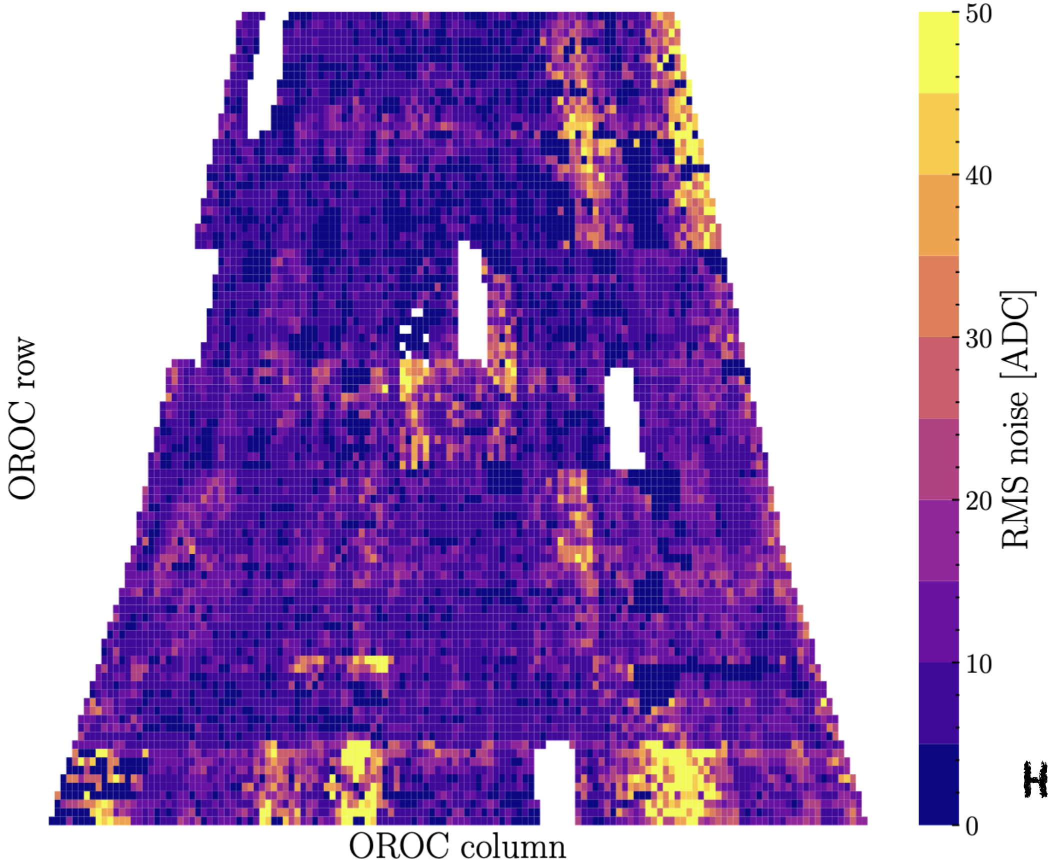
placed inside the pressure vessel

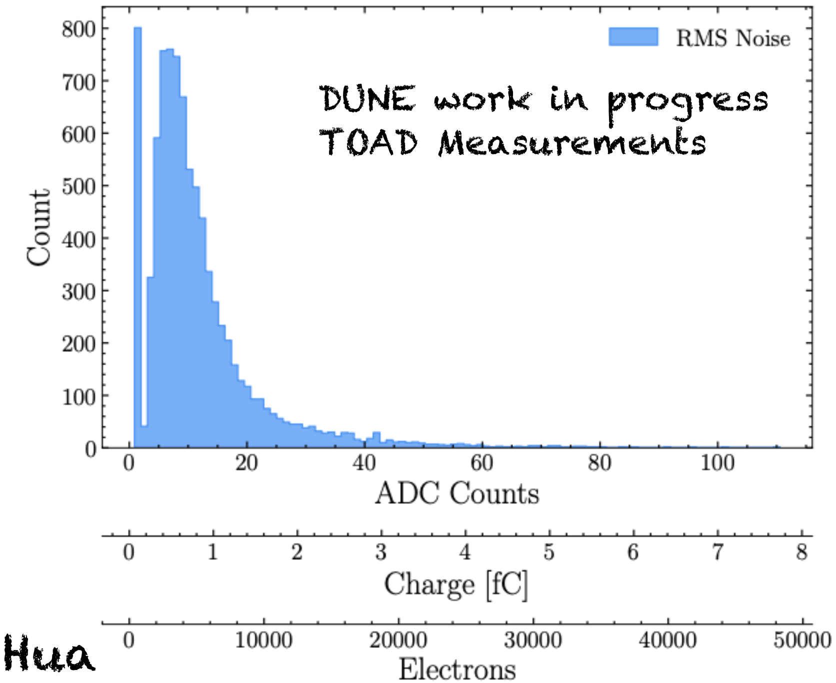




Readout Electronics R&D – Latest Test Beam

- Additional important measurements were electronics noise at 4.5 bar Ar-CH4 (96:4) – demonstrated that electronics can operate under this pressure for the first time
- Detailed pressure, volume, temperature studies also 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:
  - The focus would be on low-energy beams, specifically T9-T11 beams with energies that match our requirements
- Existing pressure vessel, TOAD, tested at CERN and Fermilab, a viable platform:
  - Requires upgrades, such as active cooling, temperature monitoring, sensors

Integration in a Future Test Beam

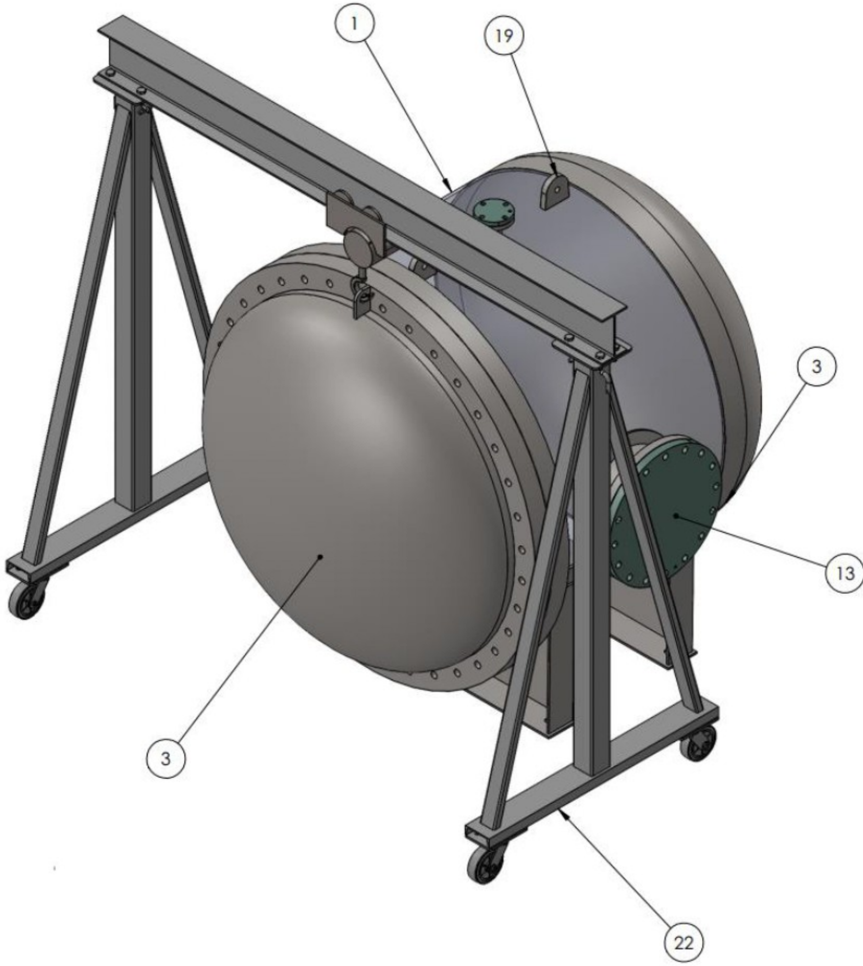
- The primary objectives:
  - Demonstrate long-term operation of the GEMs with SAMPA readout electronics at high pressure
  - Demonstrate reconstruction of low energy tracks
  - Probe the low-momentum region where models are in disagreement
- CERN Neutrino Platform a potential site for this:
  - The focus would be on low-energy beams, specifically T9-T11 beams with energies that match our requirements
- Existing pressure vessel, TOAD, tested at CERN and Fermilab, a viable platform:

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

Neutron Test Beam Campaign

- CERN test beam program could also include neutron beams:
  - n_TOF as a potential site
- Indiana University is 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 < 500 MeV unlikely to go through vessel walls → protons from neutron scatters on argon provide the means to validate low-energy hadron reconstruction
  - Insights from these tests also 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
  - Begin simulation studies for GEM optimizations
  - Initiate pressure scans and prepare for SAMPA integration

- 2026-2028
  - Develop and test medium and larger-scale GEM prototypes
  - Carry out phase I of neutron beam studies at Indiana University and optimize GEM prototype from initial results

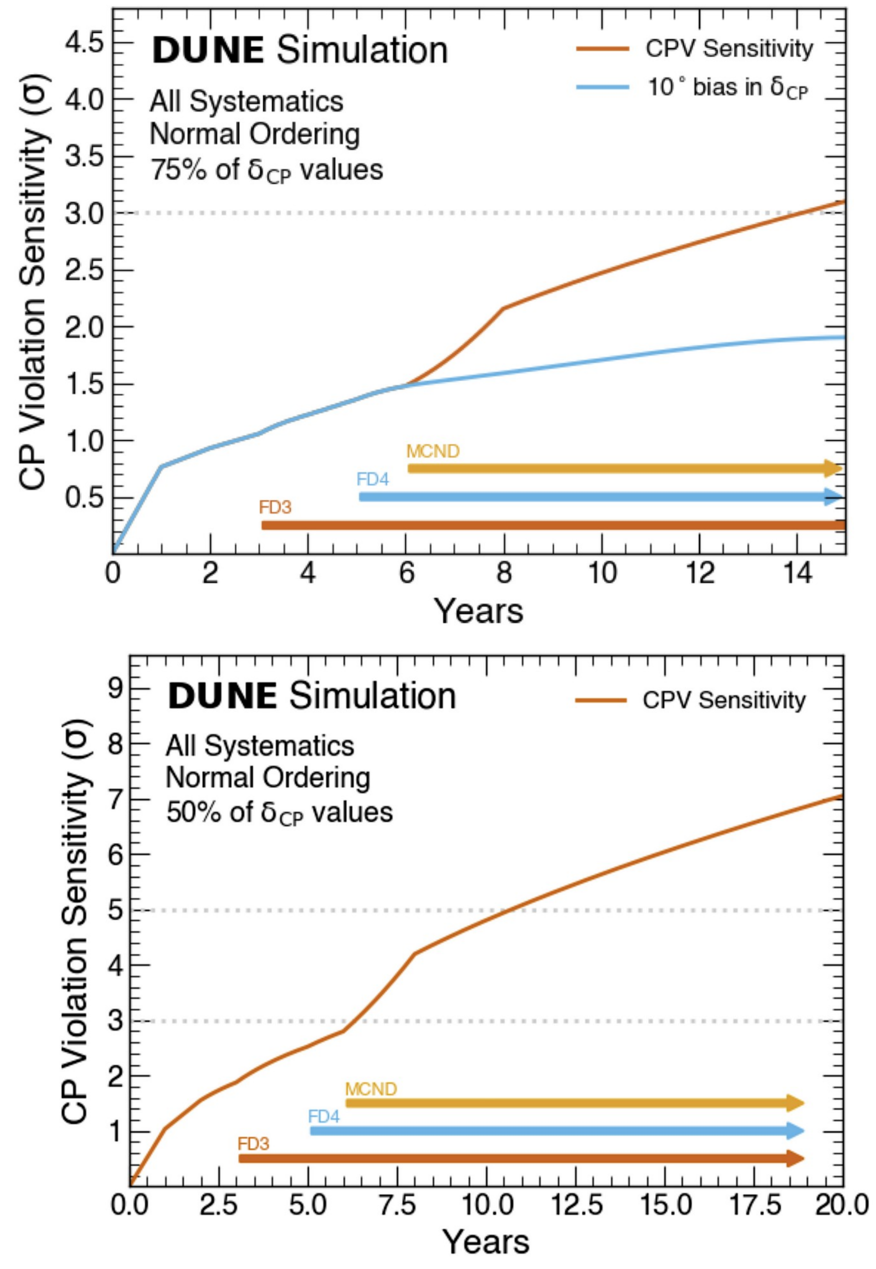
- 2029–2030
  - Prepare for CERN beam tests, including finalizing GEM and electronics designs

- 2029–2033
  - Carry out test beam campaigns with maturing hardware prototypes and perform full slice tests

Summary

- ND-GAr is essential for DUNE to:
  - Reach a 5σ sensitivity to CP violation
  - Examine 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:
  - Lessons learned from R&D with salvaged MWPCs, focus shifting to GEMs as primary candidate for charge readout
  - Several beam tests have been completed, providing important lessons learned, with further beam tests planned – a potential site could be CERN!



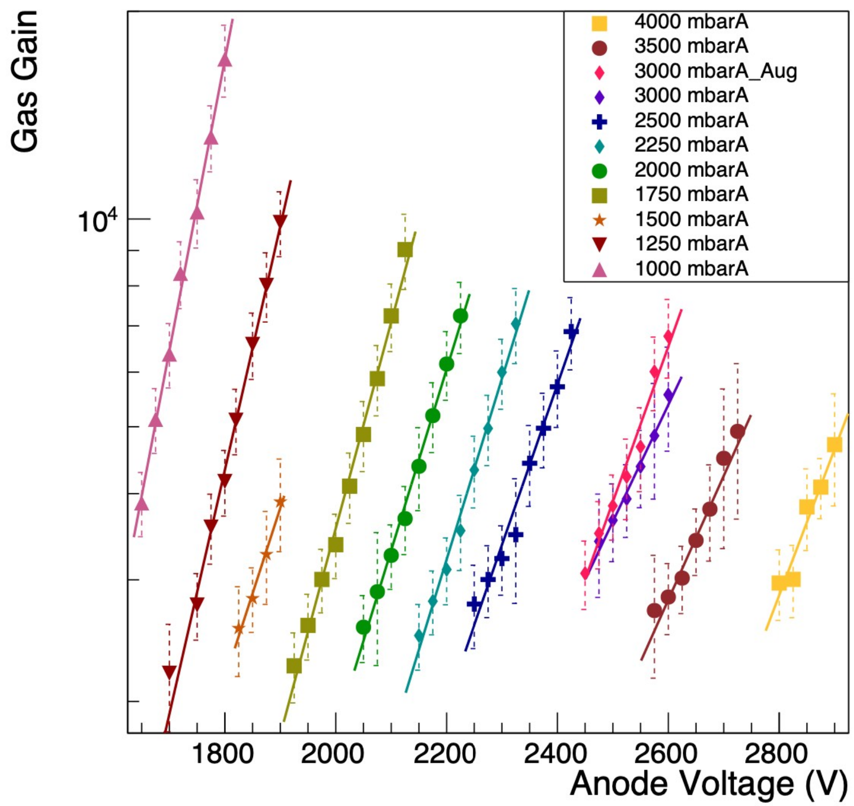
Additional Slides

Bridging Physics and Design

- 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

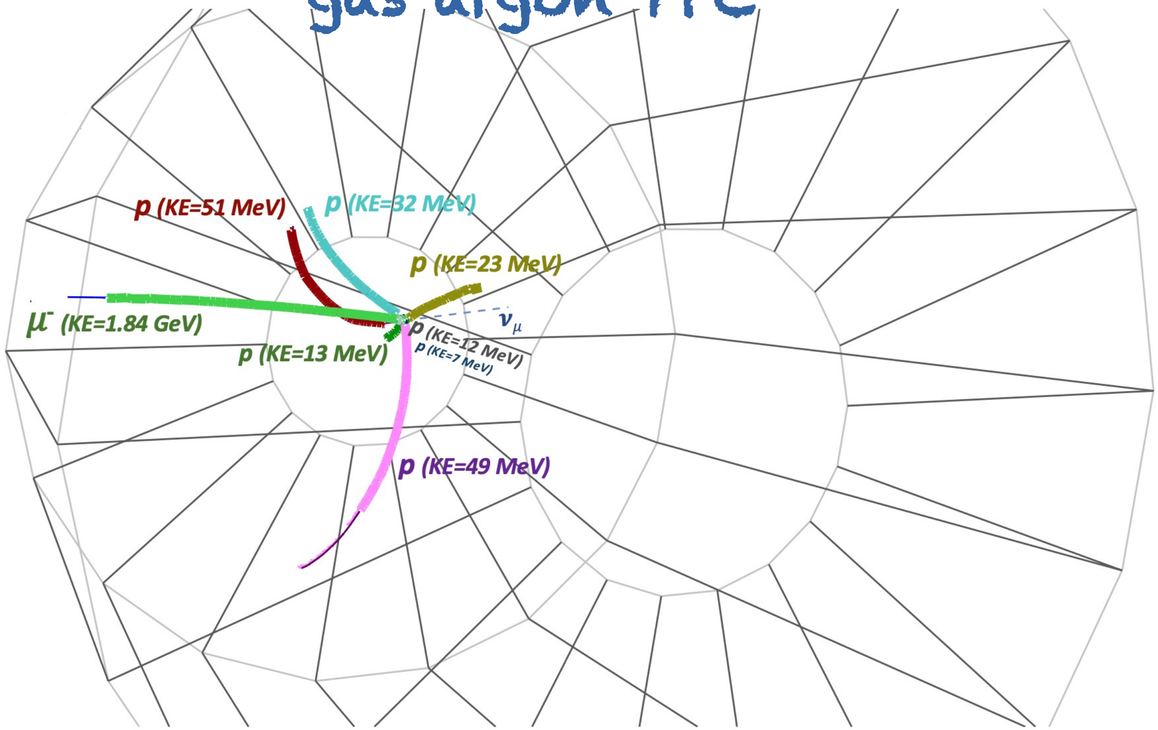
1-ton fiducial mass in 1-year ν-mode (5×5 m TPC with Ar mixture at 10 atm) using 1.2 MW beam power

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 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

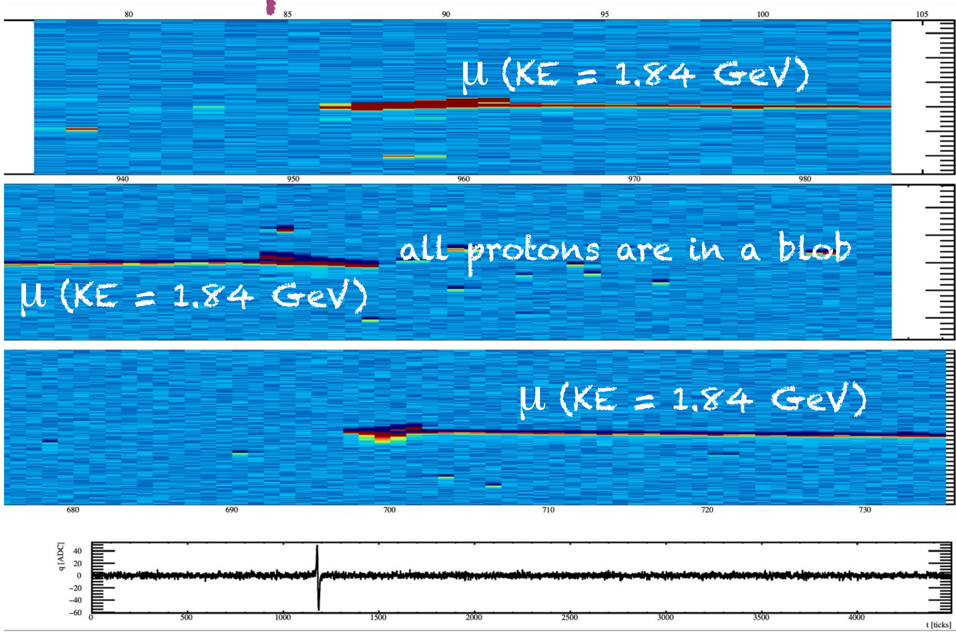


https://doi.org/10.48550/arXiv.2305.08822

ND-GAr's high pressure gas argon TPC



same simulated neutrino event with 7 protons in a LArTPC

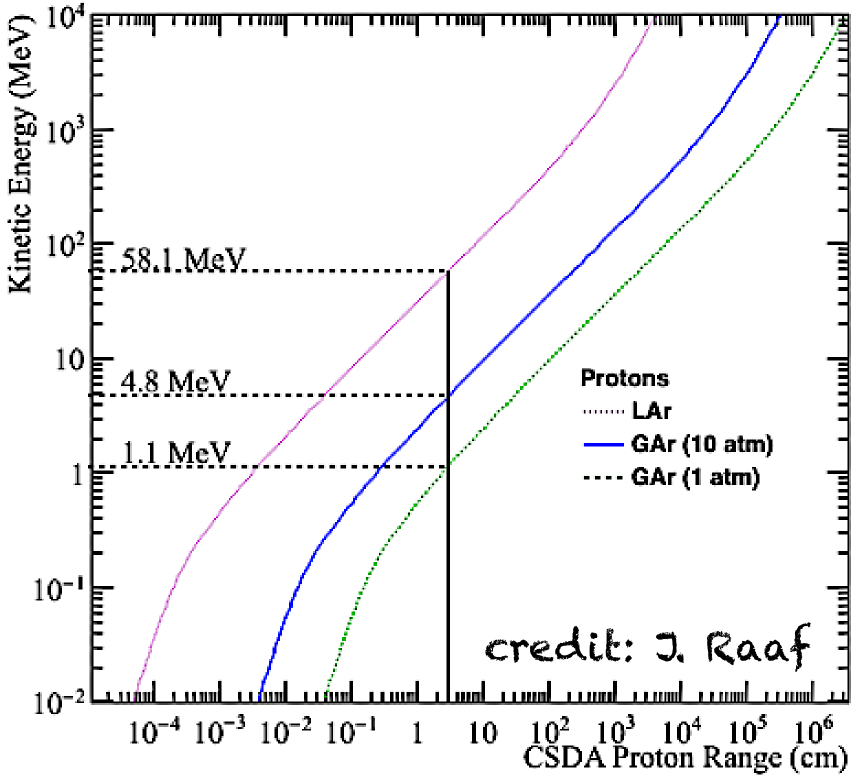


Instruments 2021, 5(4), 31; https://doi.org/10.3390/instruments5040031

ND-GAr's Low Energy Threshold Capability

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

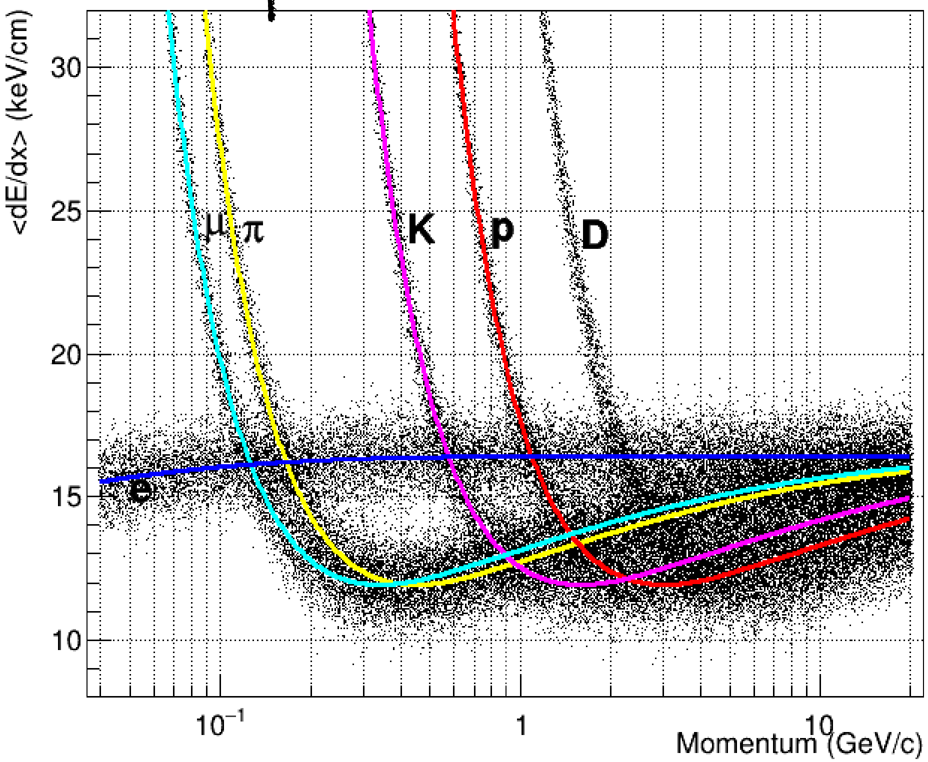
A GAr-based detector sees lower KE protons than a LArTPC



ND-GAr's PID Capability

- 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

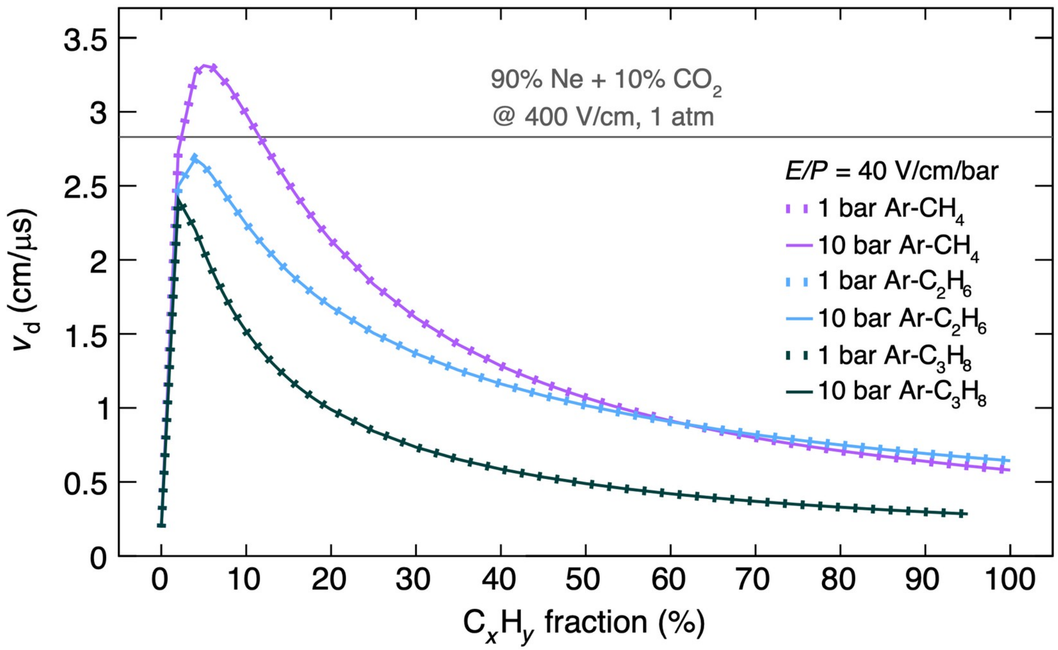
dE/dx-based PID will be comparable to PEP-4's

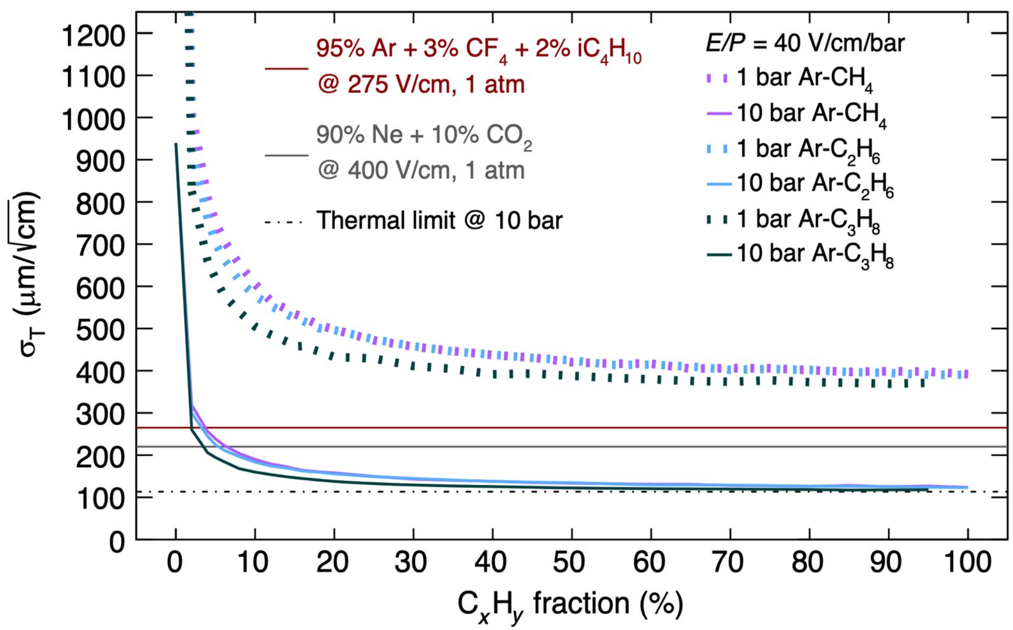


DUNE Collaboration, A. Abed Abud et al. Instruments 5 no. 4, (2021) 31, arXiv:2103.13910 [physics.ins-det].

Additional 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)

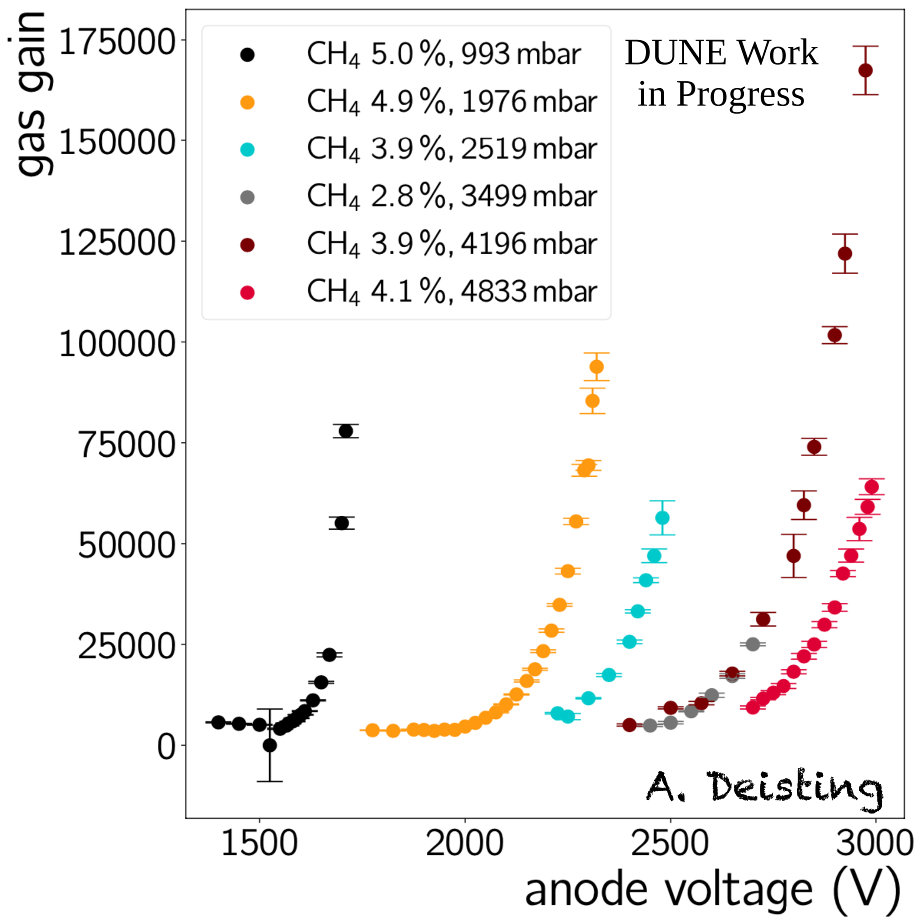




P. Hamacher-Baumann et al., Phys. Rev. D 102, 033005 (2020)

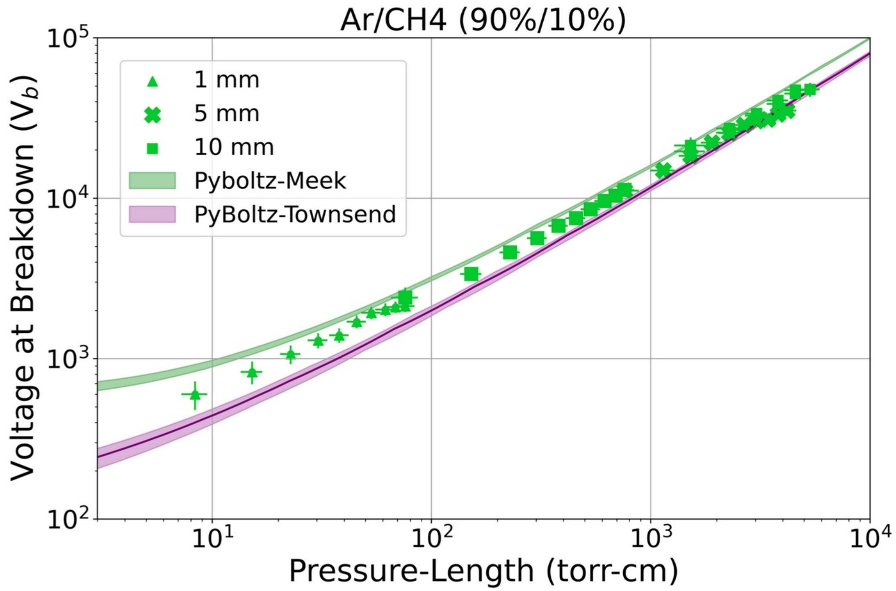
Additional R&D Efforts

- 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



Additional 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

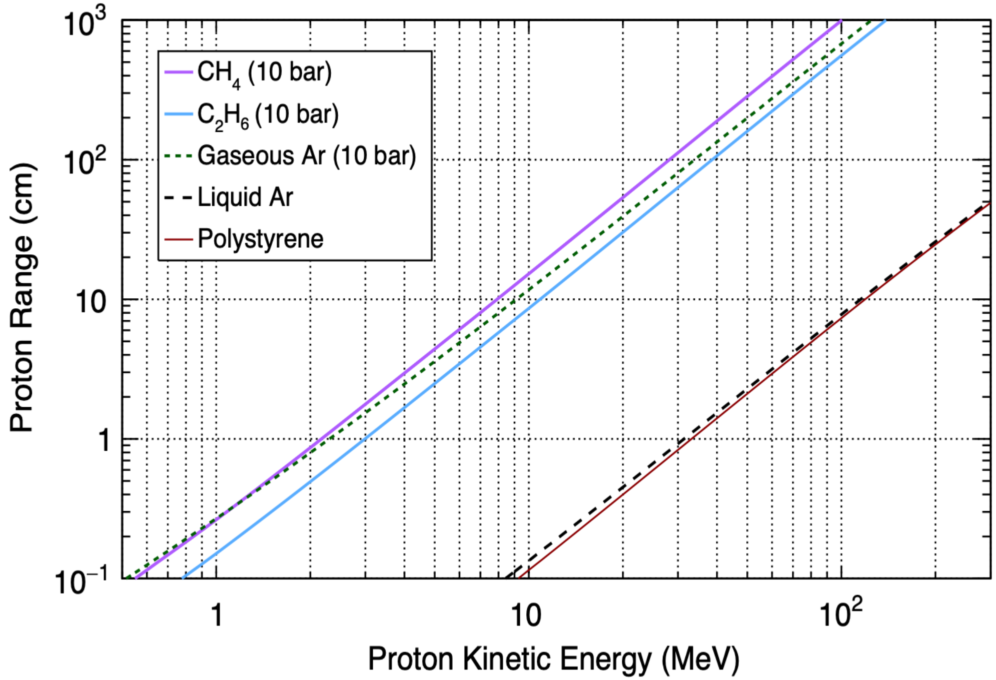


Norman, L. *et al.* Dielectric strength of noble and quenched gases for high pressure time projection chambers. *Eur. Phys. J. C* **82**, 52 (2022)

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**

Additional R&D Efforts

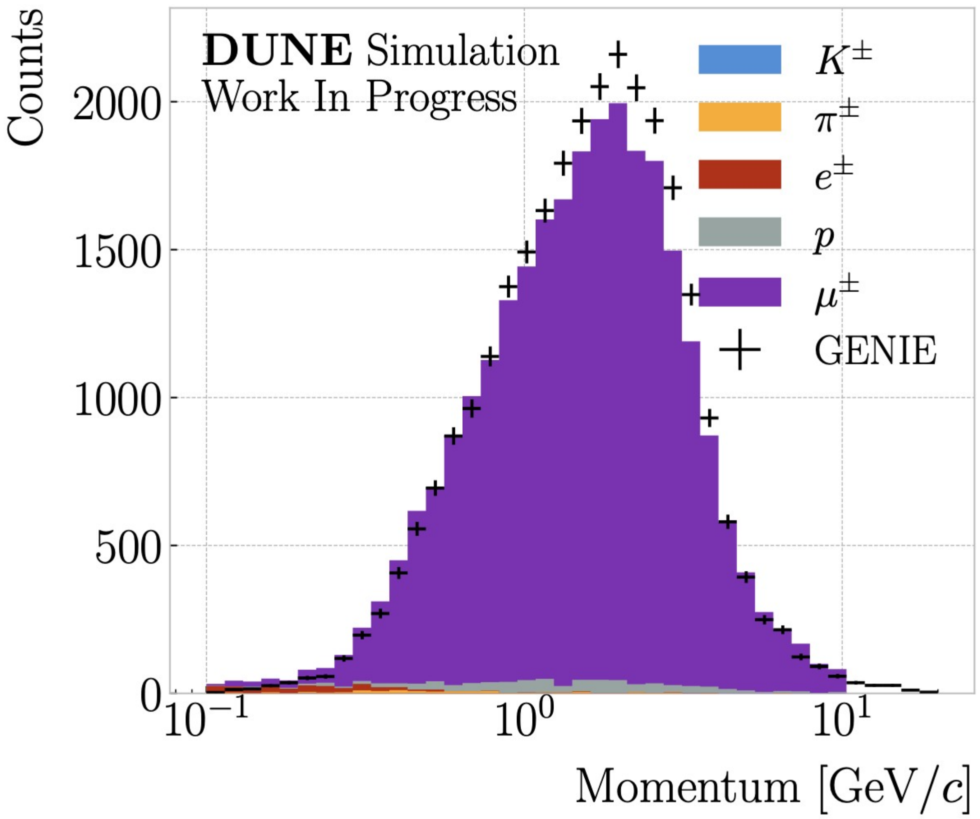
- What is involved in the charge readout optimization studies:
  - Testing the chambers @ various pressures up to 10 atm (e.g. ALICE chambers previously operated at 1 atm)
  - Defining a base gas mixture – reference is argon-based gas with 10% CH_4 admixture (97% of interactions on Ar) but can be optimized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

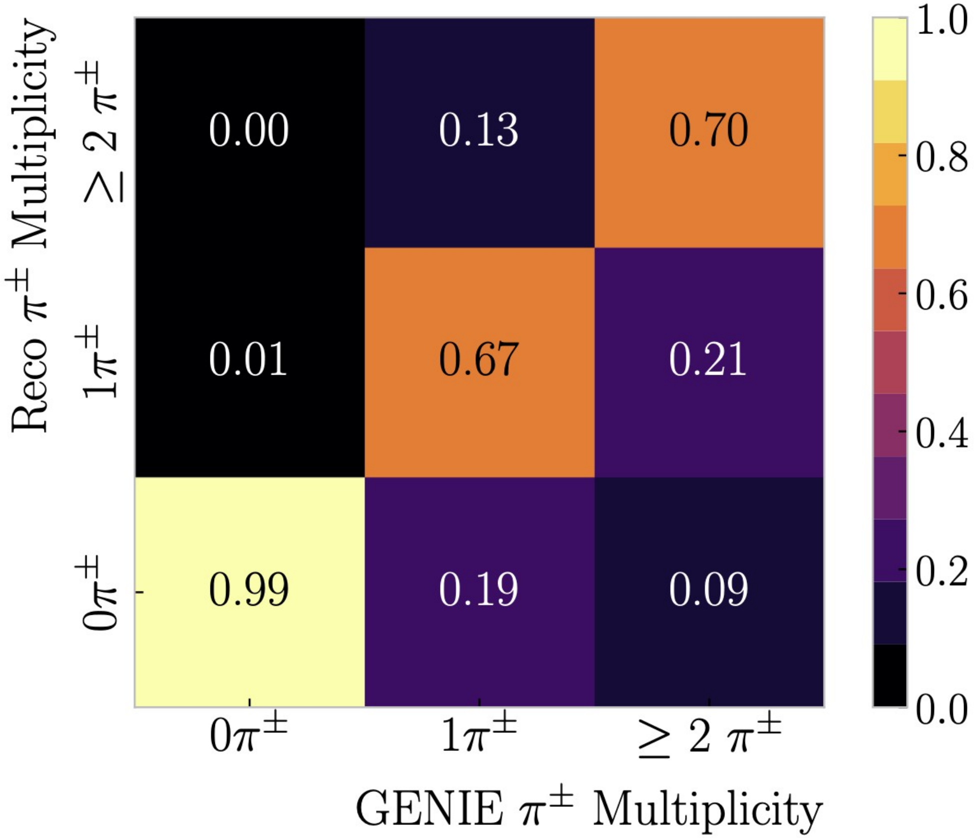


P. Hamacher-Baumann et al., Phys. Rev. D 102, 033005 (2020)

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