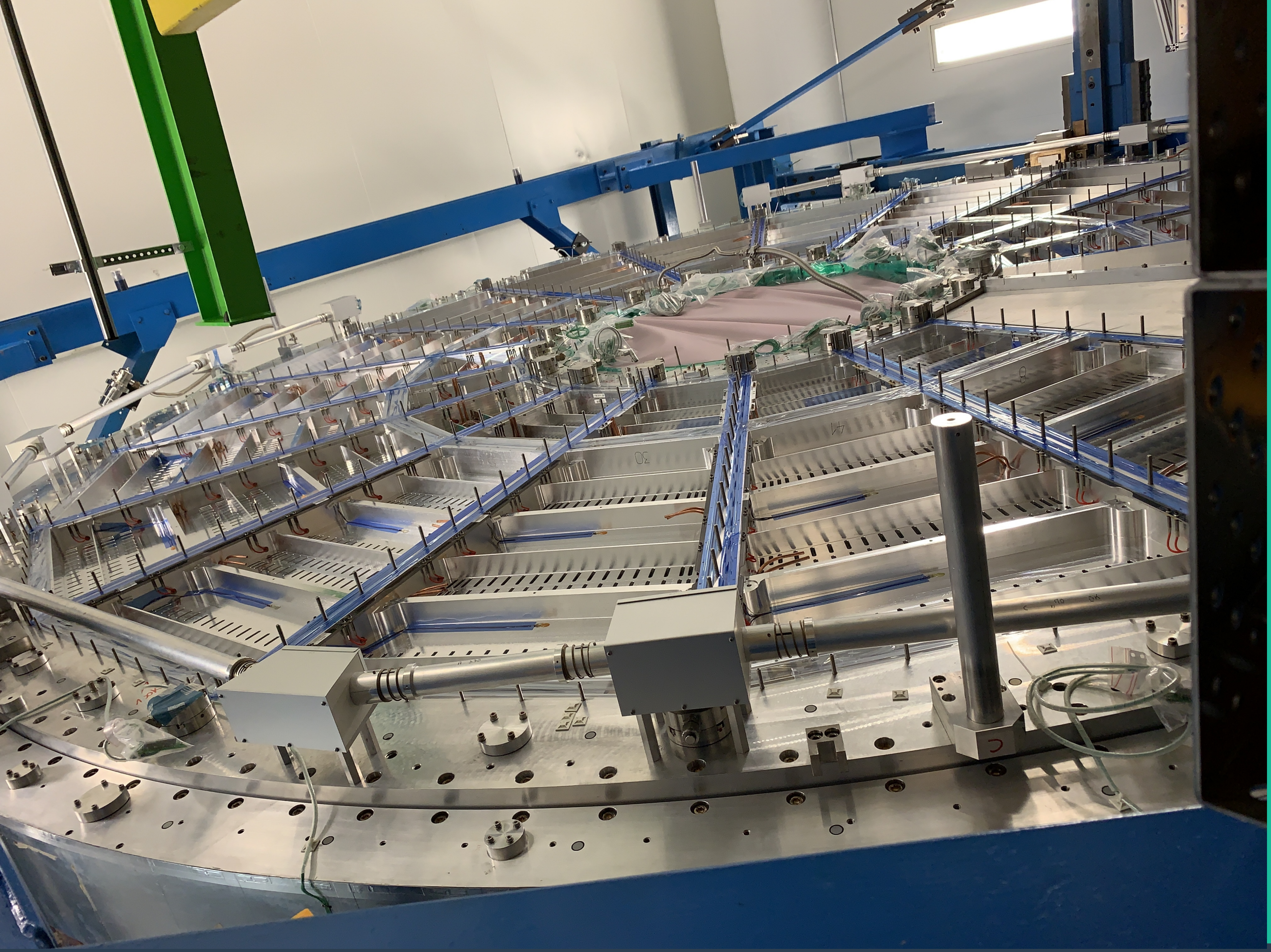


A Gaseous Argon-Based Near Detector for DUNE

Tanaz Angelina Mohayai, for the DUNE Collaboration

CPAD Workshop, Stony Brook University

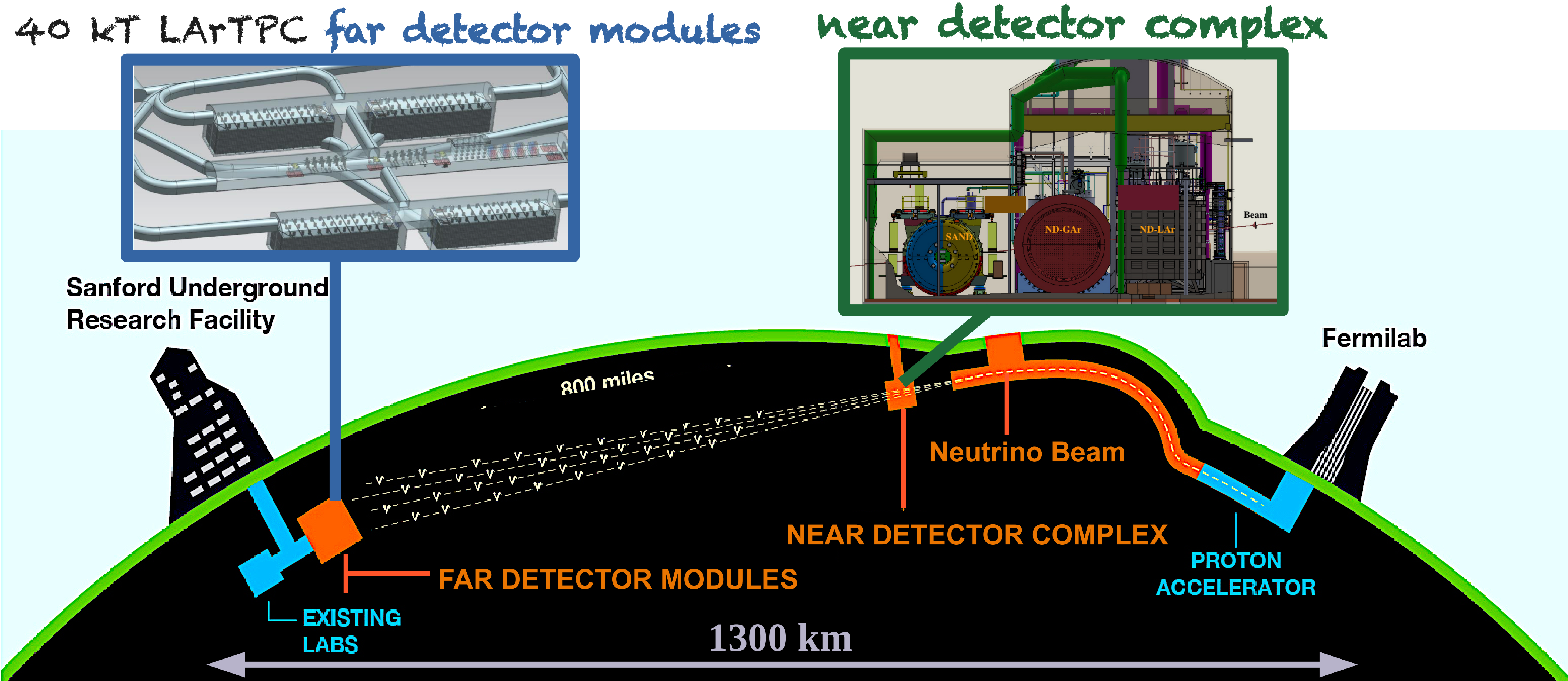
Nov. 30, 2022

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Fermilab

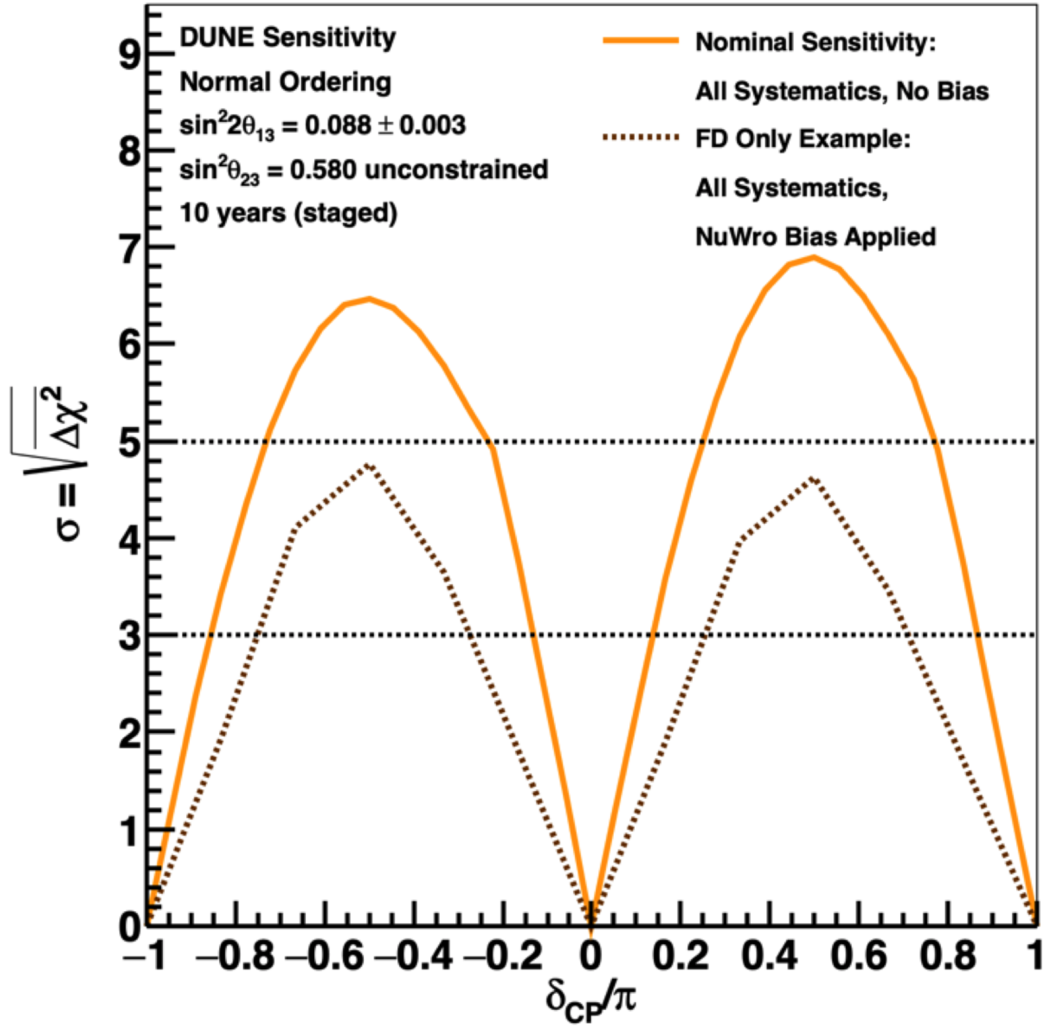
Deep Underground Neutrino Experiment

- A comprehensive physics program:
  - Search for the leptonic CP violation, determine mass ordering, precise measurements of neutrino mixing parameters, BSM searches, baryon number violation, and supernova neutrino observation
- Key components:
  - 1.2 MW, upgradable to 2.4 MW high-intensity, wide-band **neutrino beam**
  - 40 kT liquid Argon time projection chamber **far detector**
  - Highly capable **near detector complex**



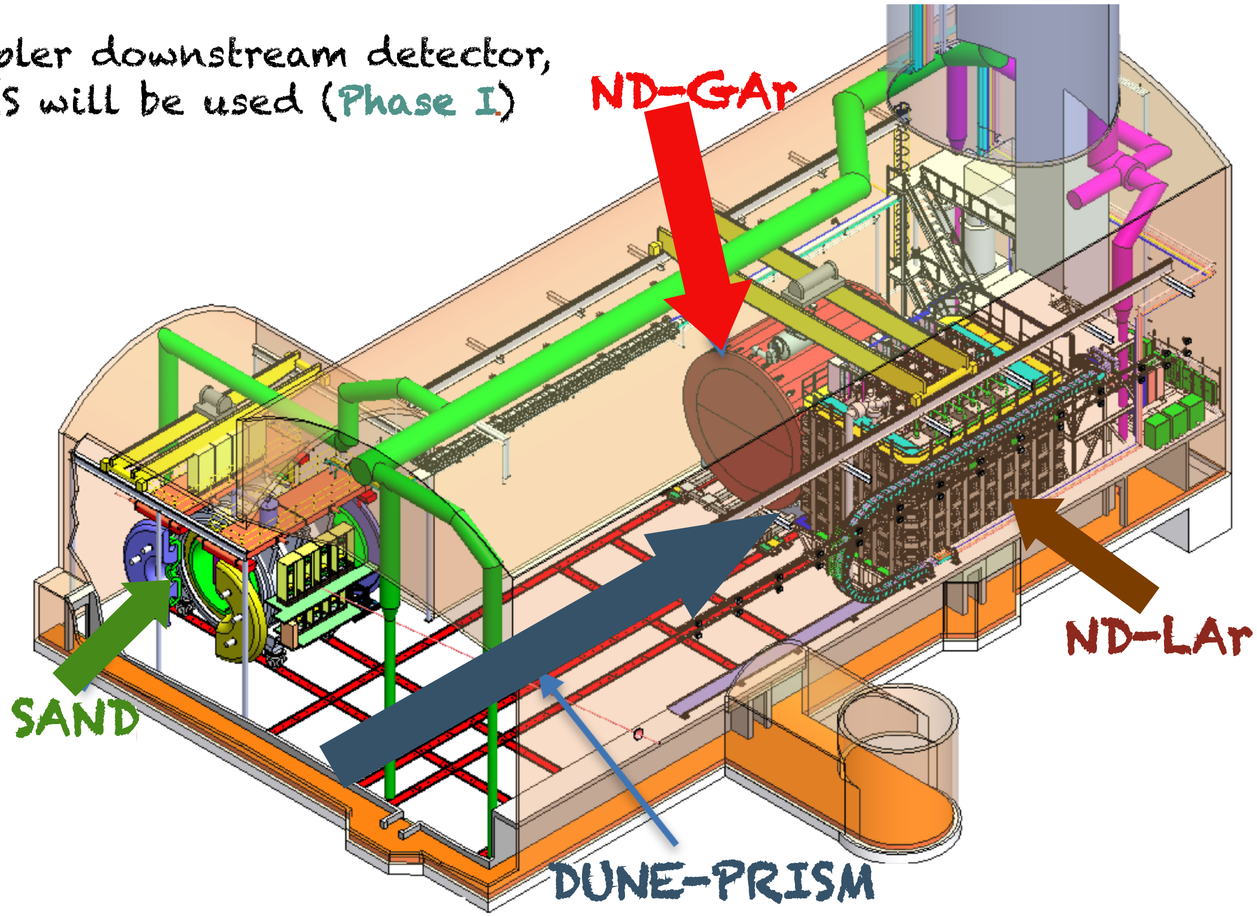
The Role of Near Detectors

- **Near Detectors, ND** reduce uncertainties by precisely characterizing the **energy spectrum and flavor composition** of the neutrino beam before neutrinos oscillate at **far detectors, FD**



DUNE Near Detectors

in the early running, a simpler downstream detector, the muon spectrometer, TMS will be used (Phase I)

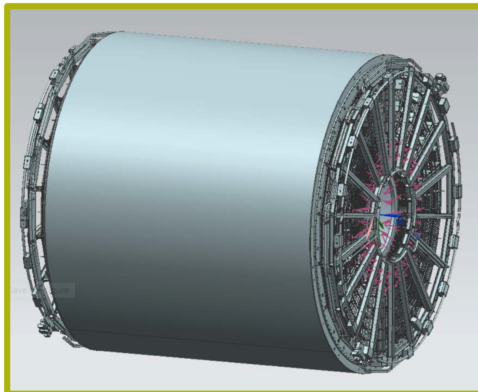


- An elaborate near detector complex:
  - ★ **ND-LAr** a liquid Argon time projection chamber, LArTPC
  - ★ **ND-GAr**, a gaseous argon-based time projection chamber
  - ★ **SAND**, system for on-axis neutrino detection

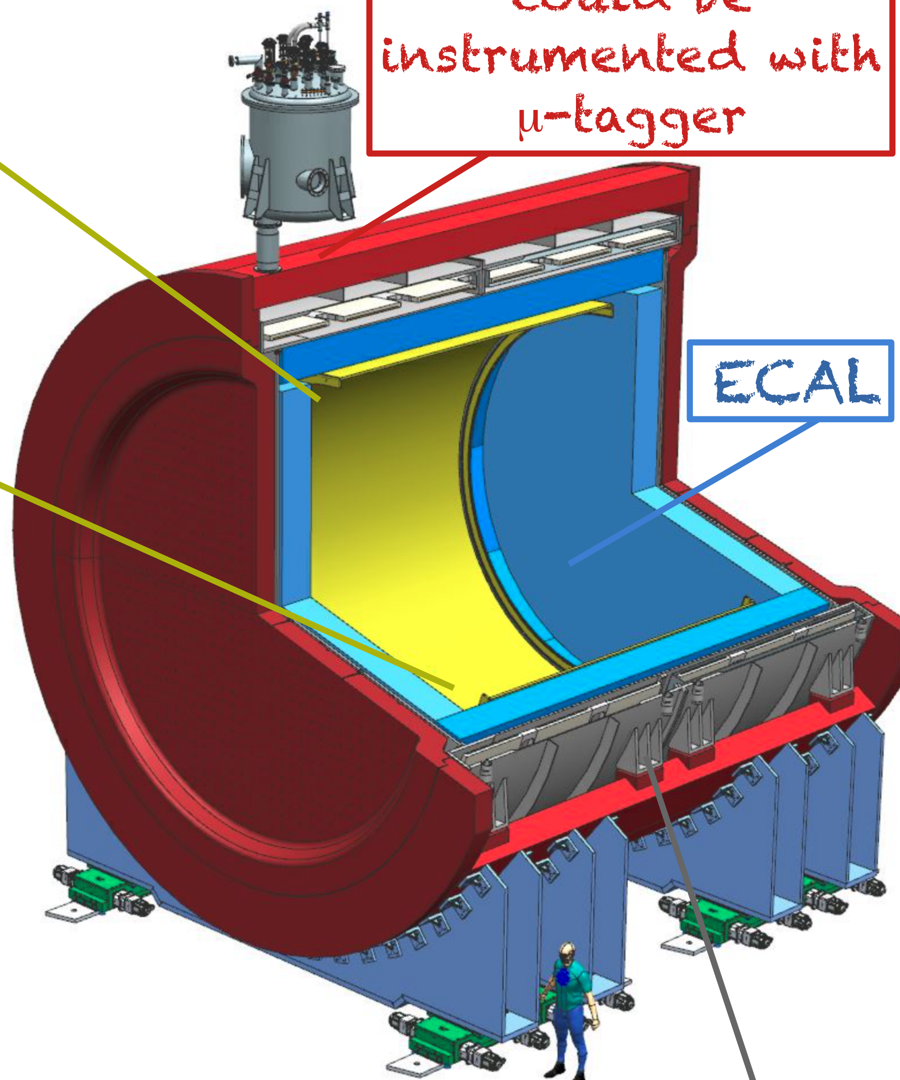
movable system, enables the DUNE-PRISM program

ND-GAr Near Detector Concept

HPgTPC



ALICE engineering drawing

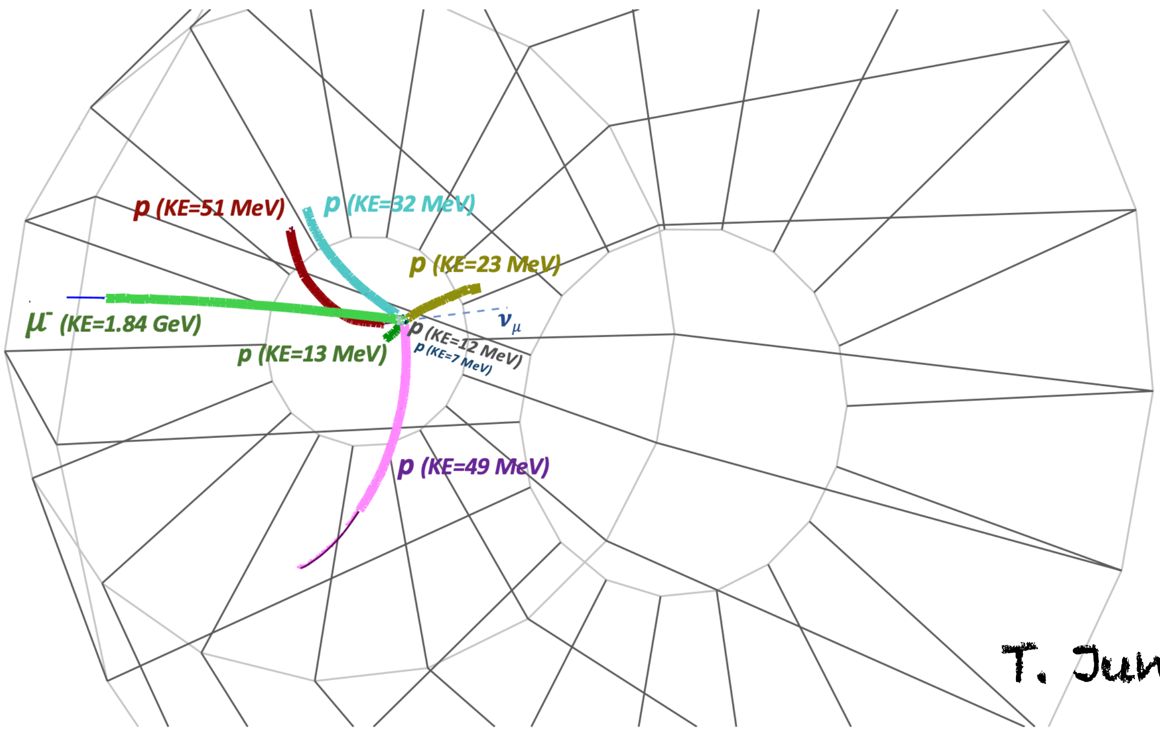


- A **magnetized High Pressure Gas Argon TPC (HPgTPC)** surrounded by **ECAL** and **μ-tagger**:
  - Reference design repurposes ALICE multi-wire chambers
  - Other designs under consideration, e.g. GEMs
- Key design capabilities:
  - Excellent PID, tracking efficiency, momentum resolution
  - 4π coverage
  - Low threshold

The importance of a low-threshold near detector

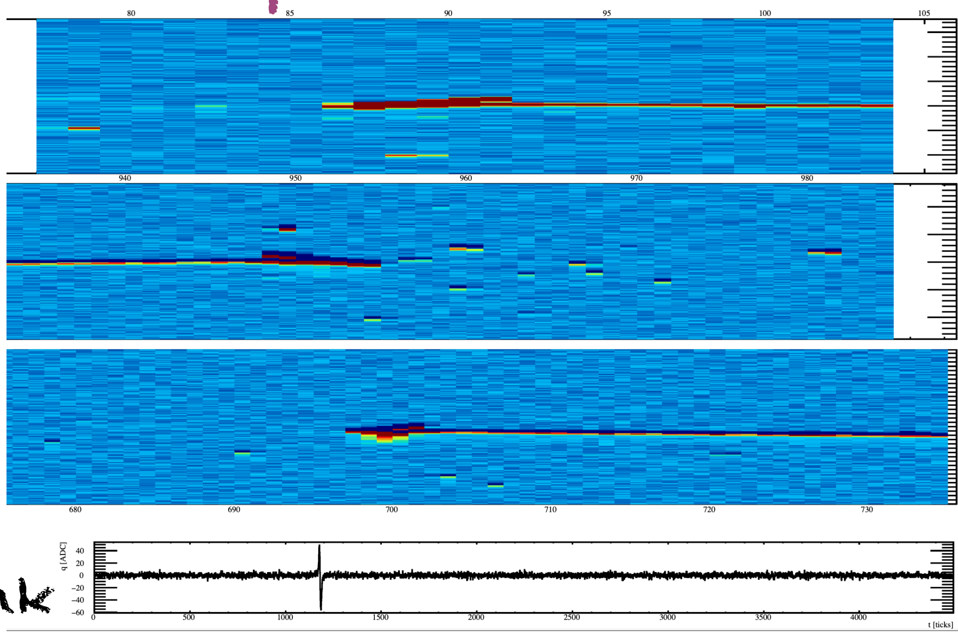
- **ND-GAr's HPgTPC** has lower threshold than a **LArTPC**:
  - Leads to high sensitivity to low energy protons or pions and a data-driven constraint on uncertainties in neutrino energy estimation and neutrino interaction cross sections

ND-GAr's HPgTPC



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

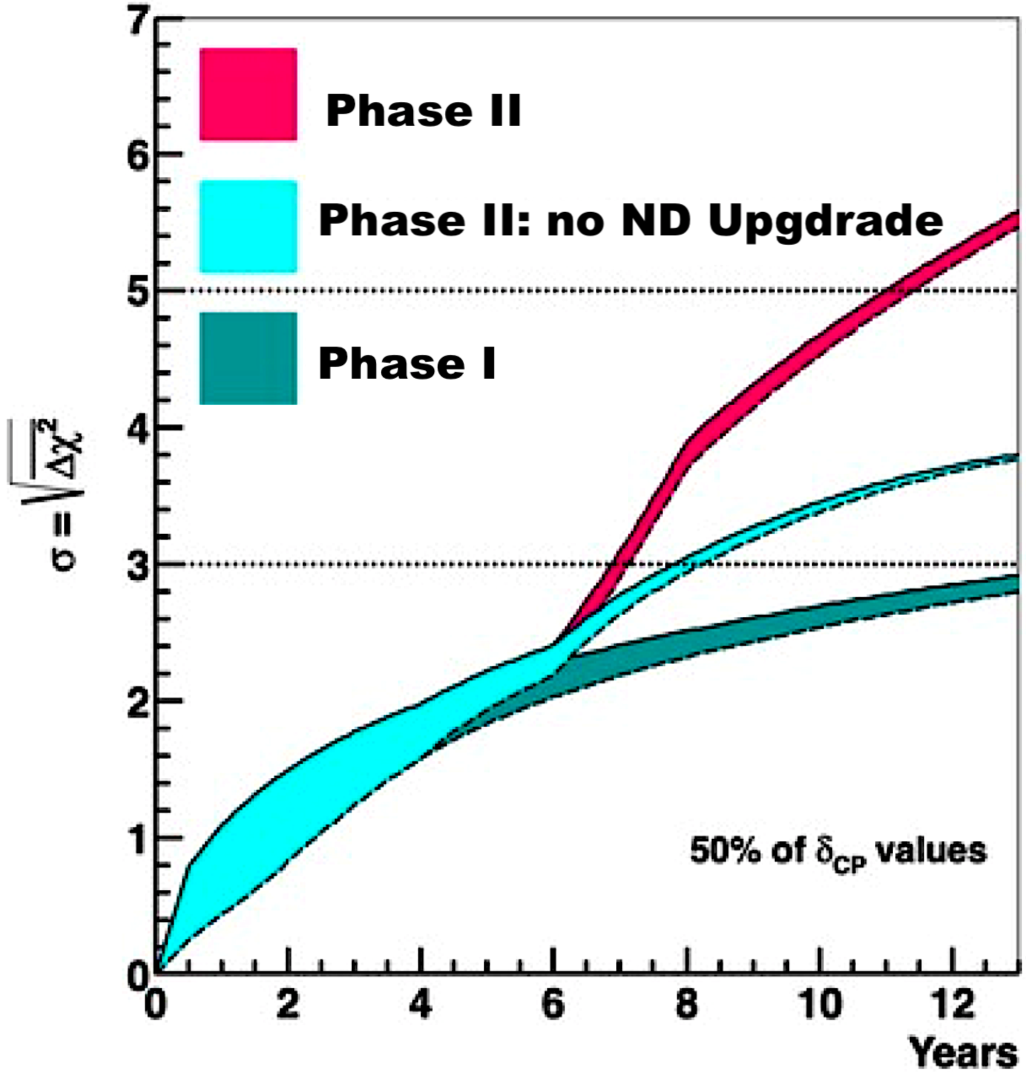
same simulated neutrino event with 7 protons in a LArTPC



T. Junk

The Impact on Oscillation Analysis

- DUNE's gaseous argon-based ND-GAr in **phase II ND Upgrade*** enables **5 σ sensitivity to CP violation** especially after ~5 years exposure

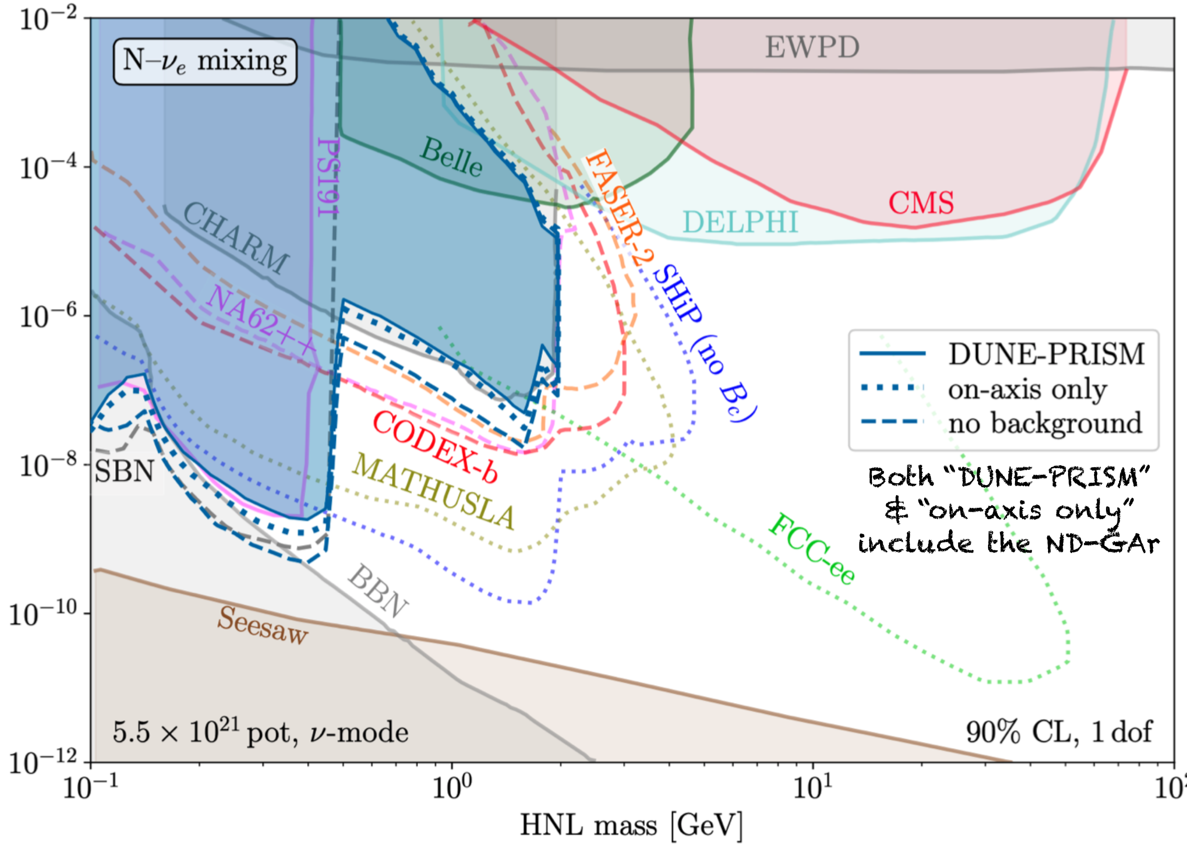


*DUNE Phase II includes upgrades to the Fermilab accelerator complex, ND (which includes replacing TMS with a gas-based detector) and FD

DUNE Collaboration, A. A. Abud et al. arXiv:2203.06100

The Impact on BSM Searches

- The **large volume** and **low density** of ND-GAr enables a rich BSM physics program in DUNE:
  - ★ Neutrino tridents
  - ★ **Heavy neutral leptons, HNL**
  - ★ Anomalous Tau neutrinos
  - ★ Light dark matter
  - ★ Heavy axions

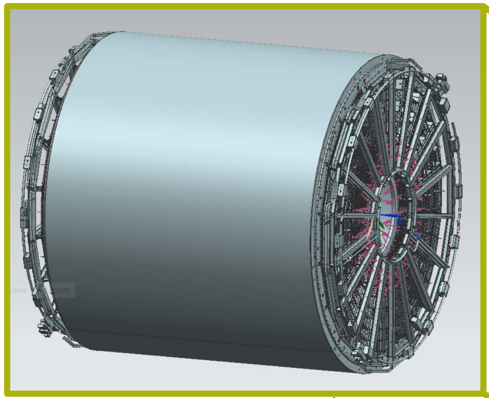


Both "DUNE-PRISM" & "on-axis only" include the ND-GAr

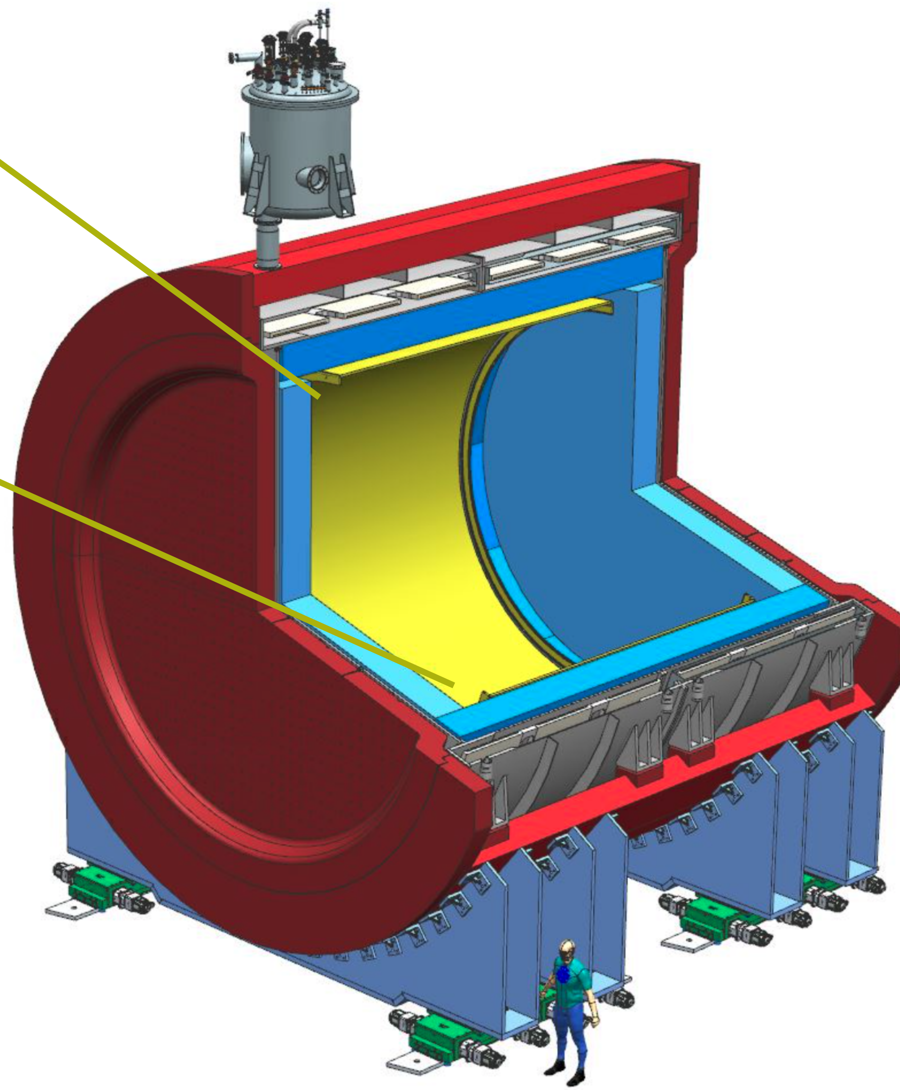
M. Breitbach, L. Buonocore, C. Frugiuele, J. Kopp and L. Mittnacht, Searching for physics beyond the standard model in an off-axis dune near detector, 2102.03383

ND-GAr R&D, with a Focus on HPgTPC

HPgTPC



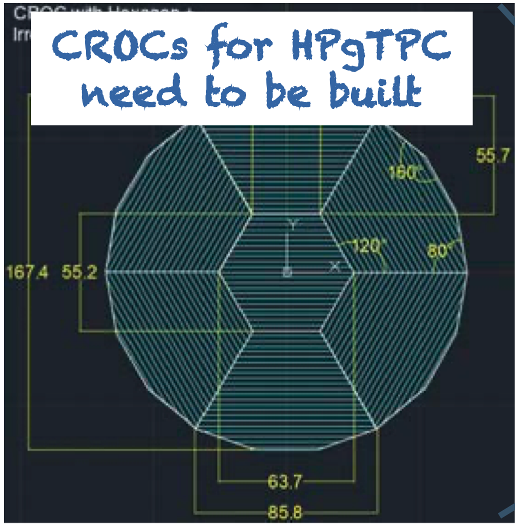
ALICE engineering drawing

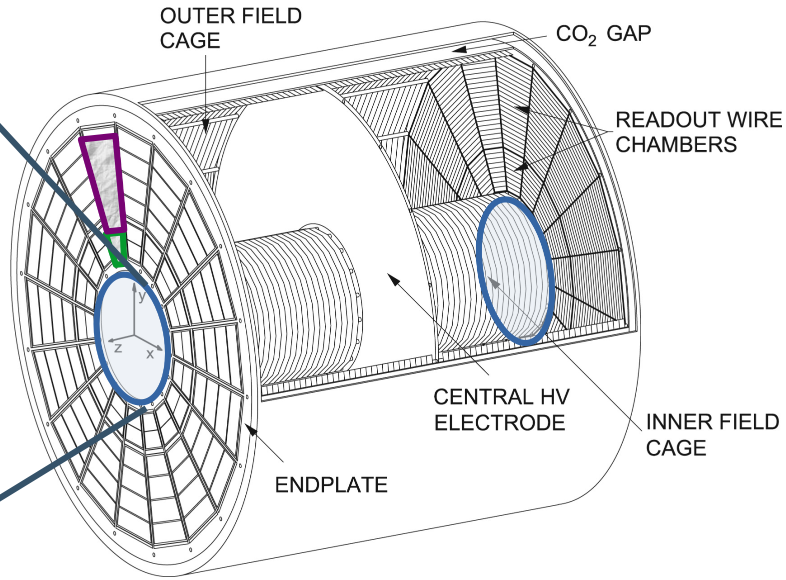


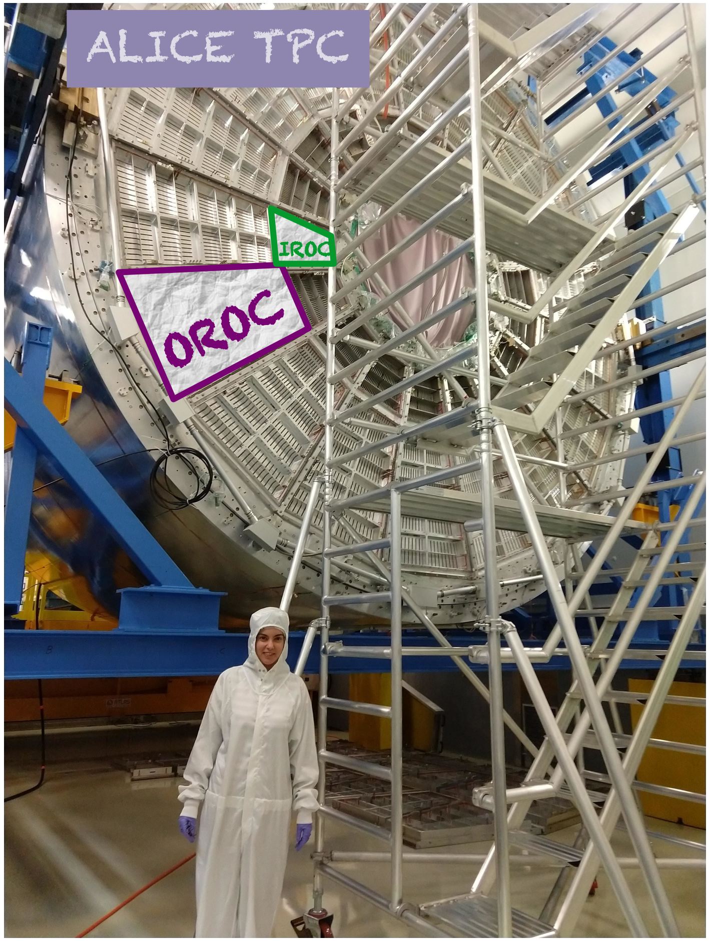
- A magnetized High Pressure Gas Argon TPC (HPgTPC) surrounded by ECAL and μ-tagger:
  - ★ Reference design repurposes ALICE multi-
  - ★ Other design under consideration, e.g. GEMs
- Main design capabilities:
  - ★ Low threshold
  - ★ Excellent PID, tracking efficiency, momentum resolution
  - ★ 4π coverage
  - ★ Minimal secondary interactions

primary focus of this talk: HPgTPC R&D

Charge Readout in HPgTPC

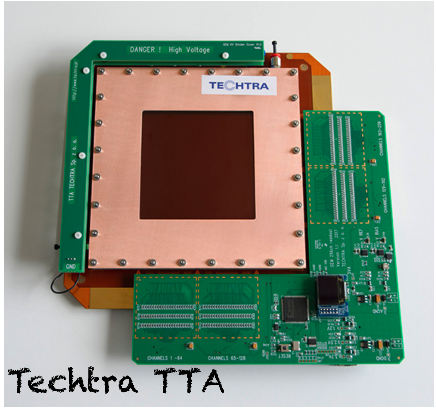


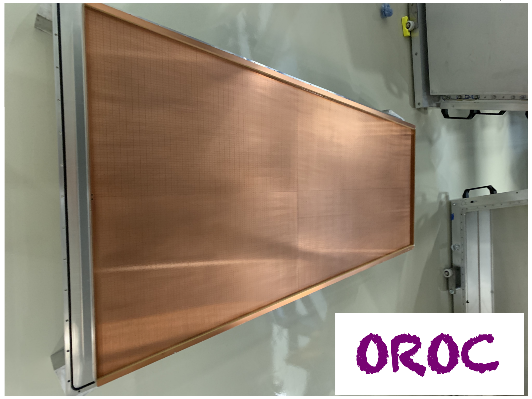


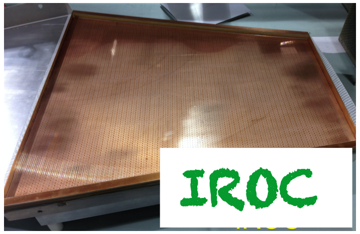


All ALICE multi-wire proportional chambers are acquired for DUNE!

GEM Readout Example



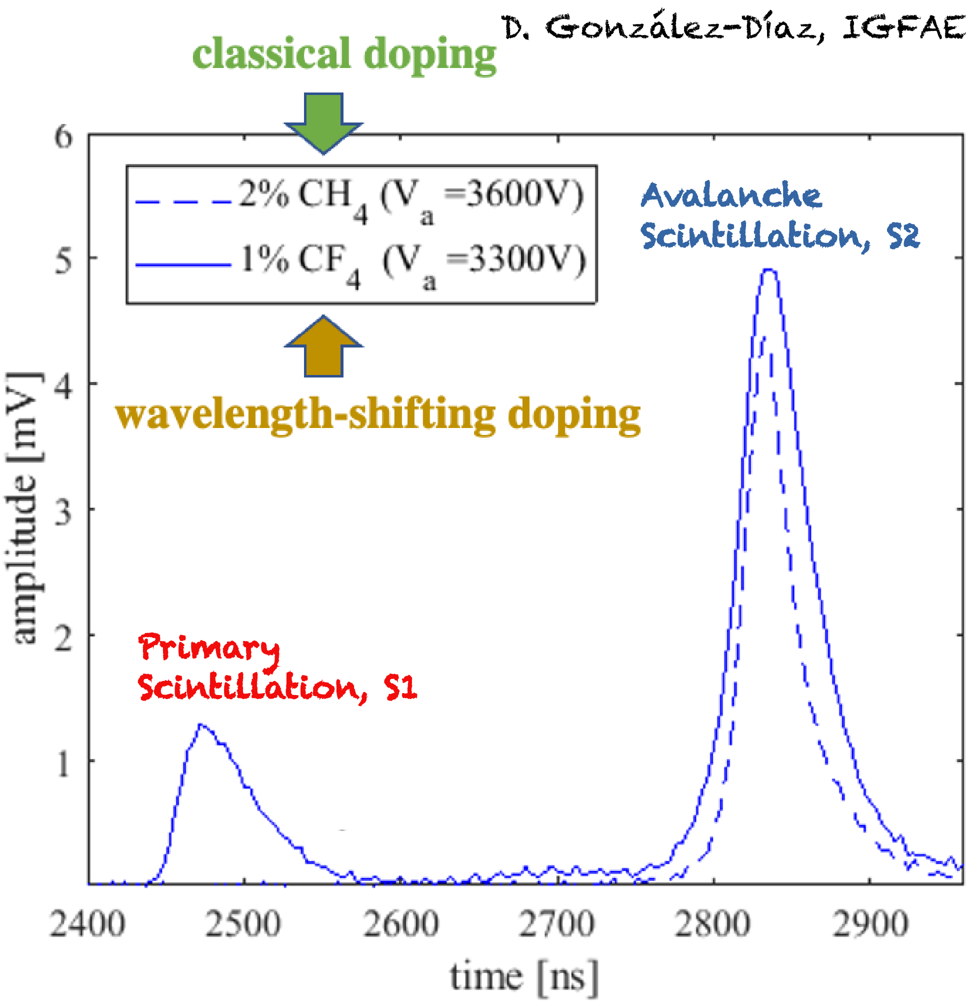


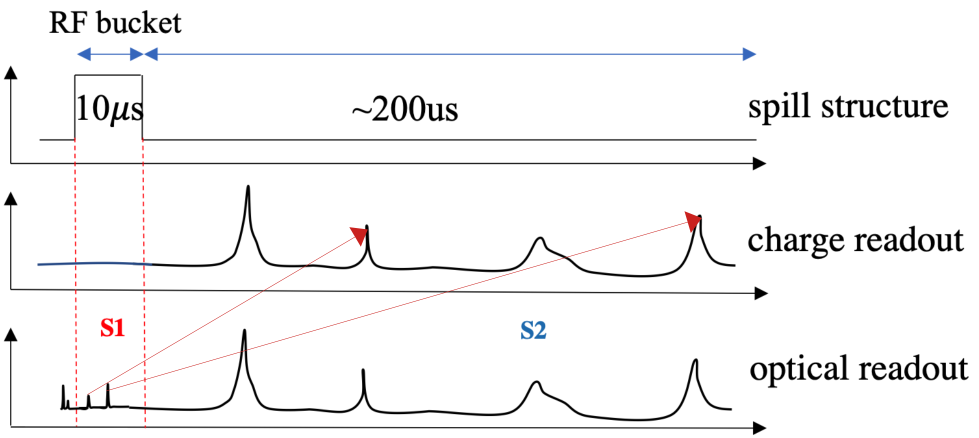


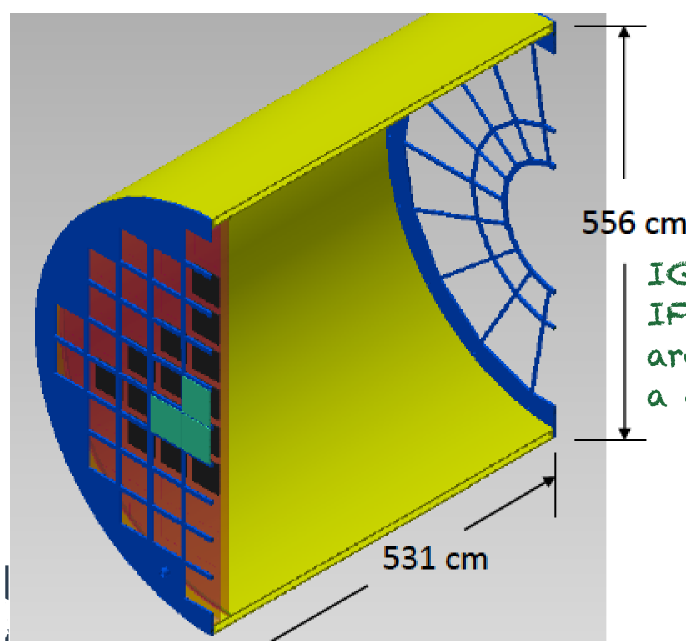
- Reference design option repurposes **the acquired** ALICE **inner (IROC)** and **outer (OROC)** multi-wire chambers and needs new readout for the center, **CROC**s
- We could also consider an alternate design (to ALICE MWPCs) where we instrument all of the endcap/s with e.g. GEMs or MicroMegas

Light Readout in HPgTPC

- Choose an admixture/dopant that will not quench the scintillation signal
  - Initial studies carried out at IGFAE focuses on **CF4**
  - Instrumental for background suppression & triggering
- Assuming a single sided drift option (reference design based on ALICE is a 2-sided drift), consider instrumenting one of the HPgTPC end caps with an array of **SiPM tiles** (other possibilities: LAPPDs…)

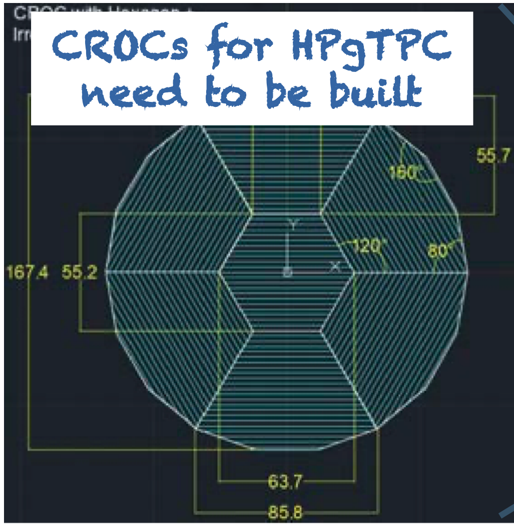


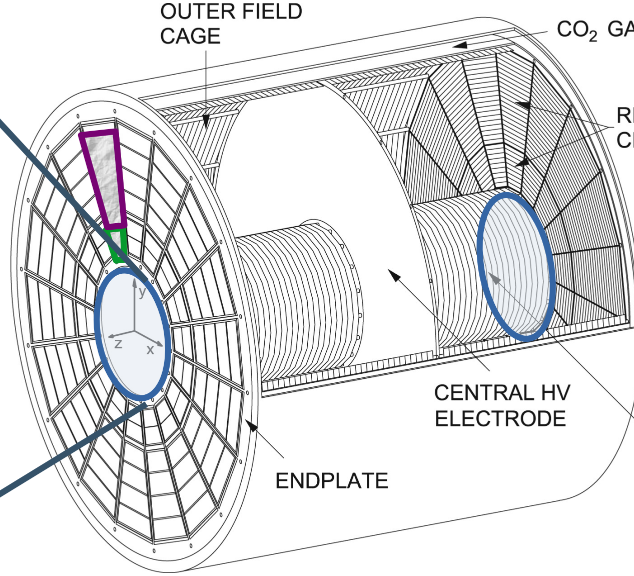


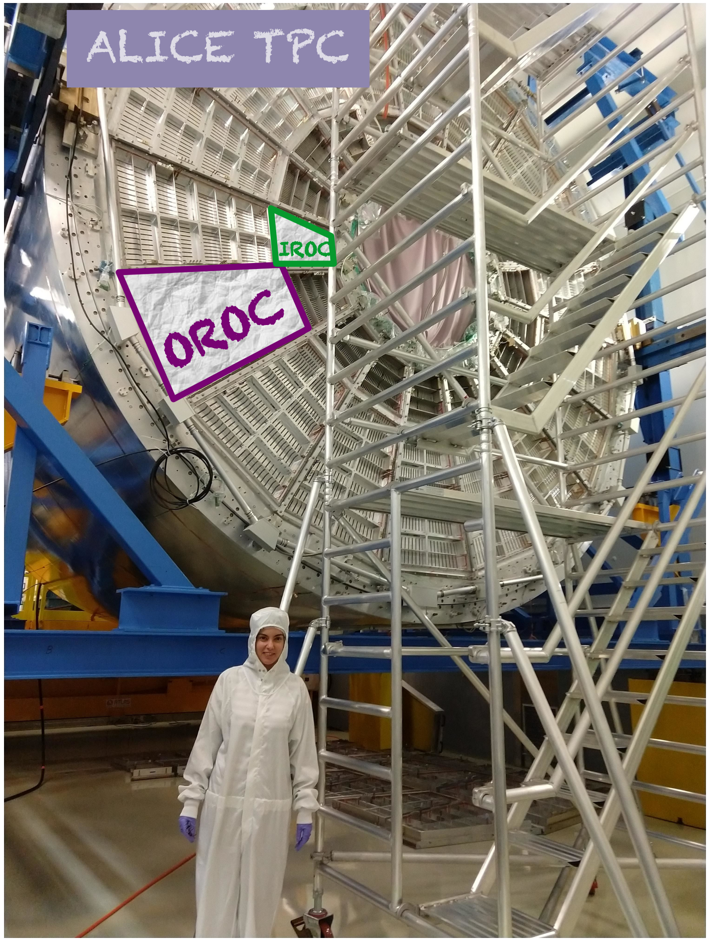


IGFAE and IFIC in Spain are working on a demonstrator

Charge Readout in HPgTPC







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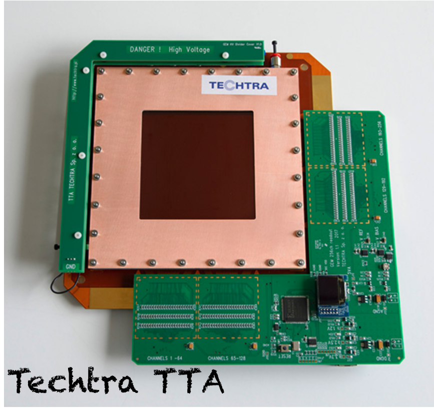
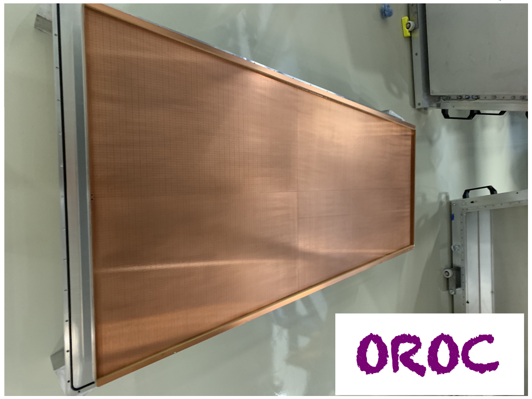
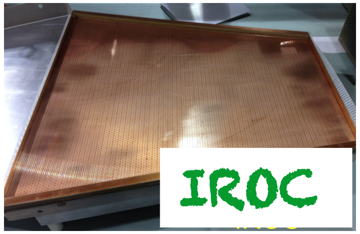
GEM Readout Example







Next few slides:
Charge readout demonstrators/test stands at Fermilab

Charge Readout Test Stand – MWPC

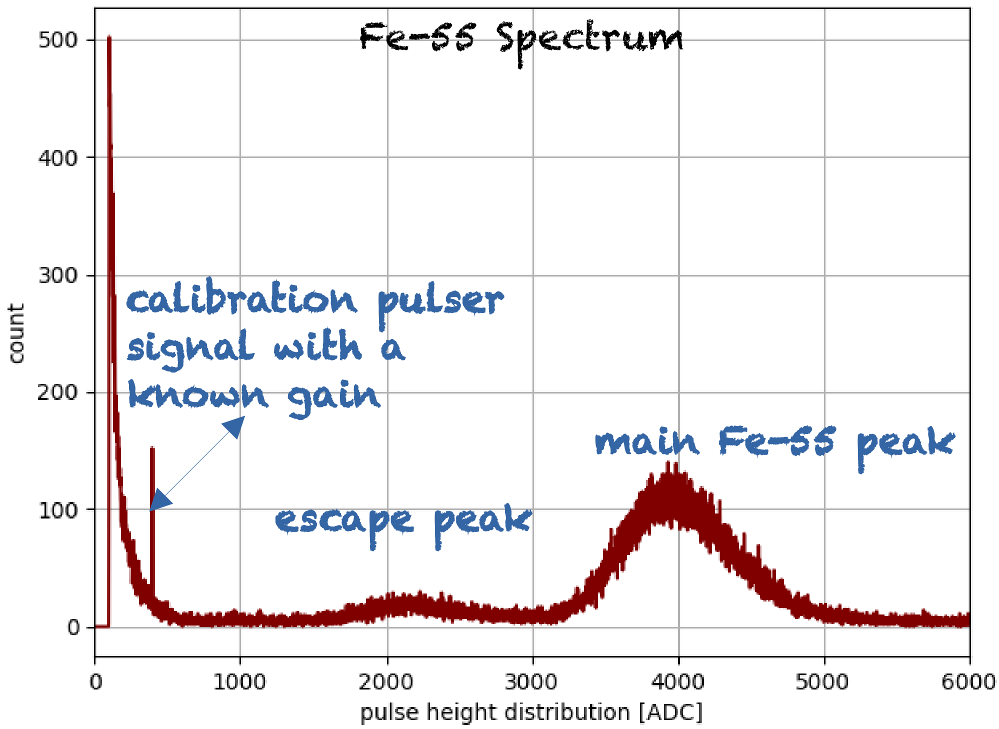
- **Pressure vessel** housing an **IROC**, aimed at calibrating the gain at various pressure set-points and amplification (anode) wire HV values

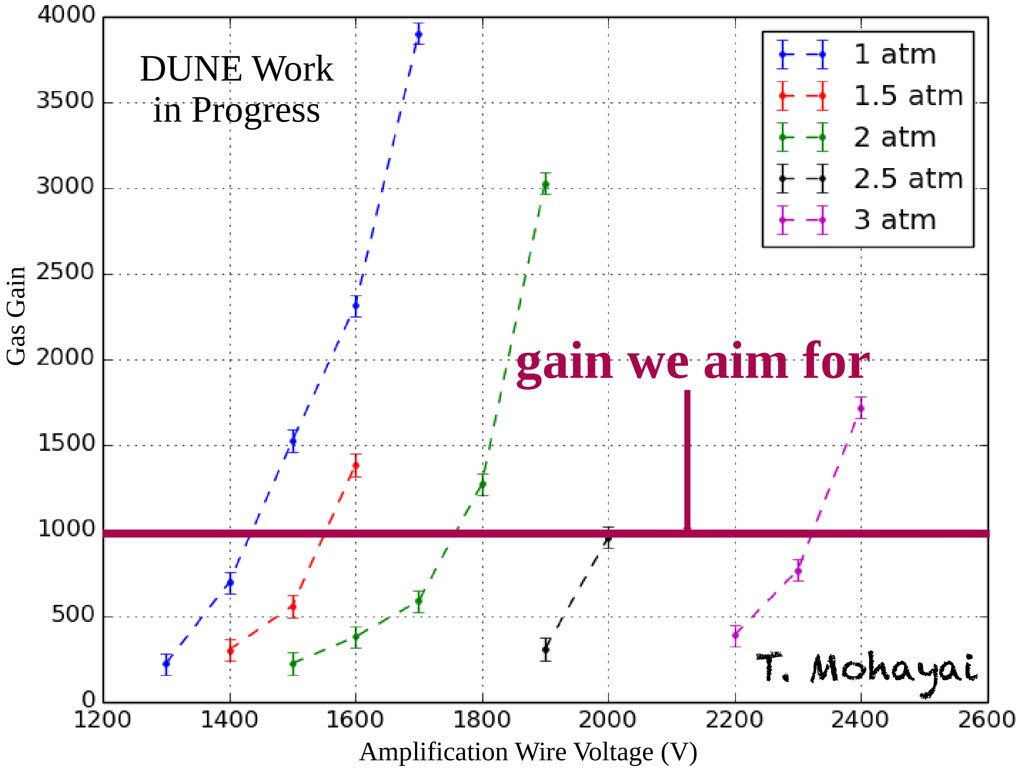
GOAT

Fermilab, Colorado Boulder, Pittsburg

Charge Readout Test Stand – MWPC

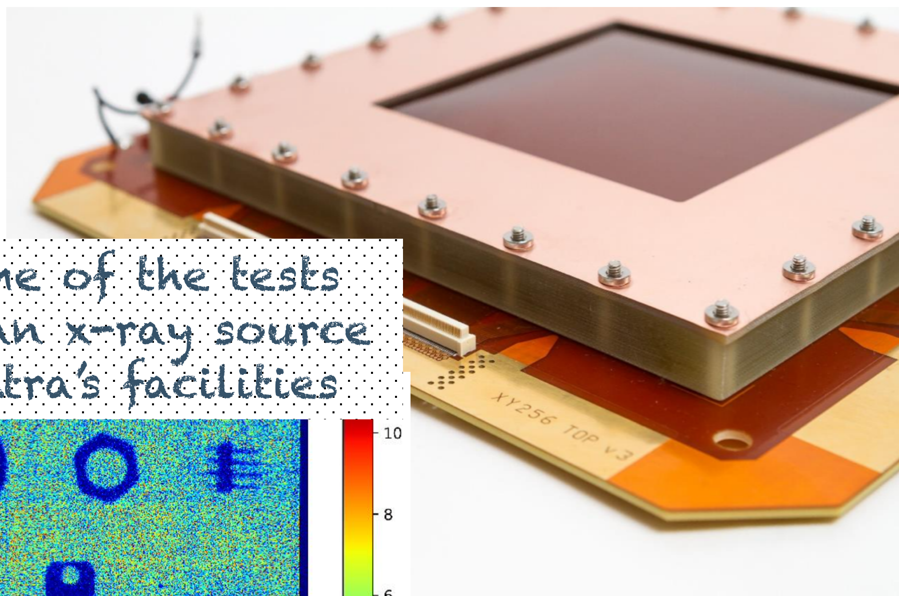
- Initial tests with an Fe-55 source and a pressurized Ar-based gas mixture demonstrates:
  - Increase in **gain** with increasing amplification wire voltage
  - Ability to maintain **gain** with increasing pressure
- More data underway – provides a pressure scan of gain up to 10 atm so stay tuned!



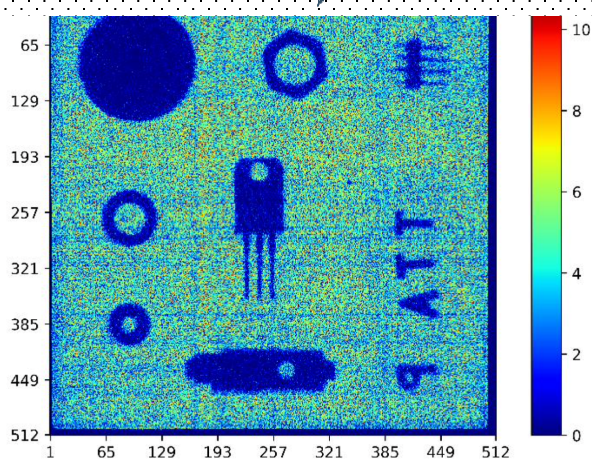


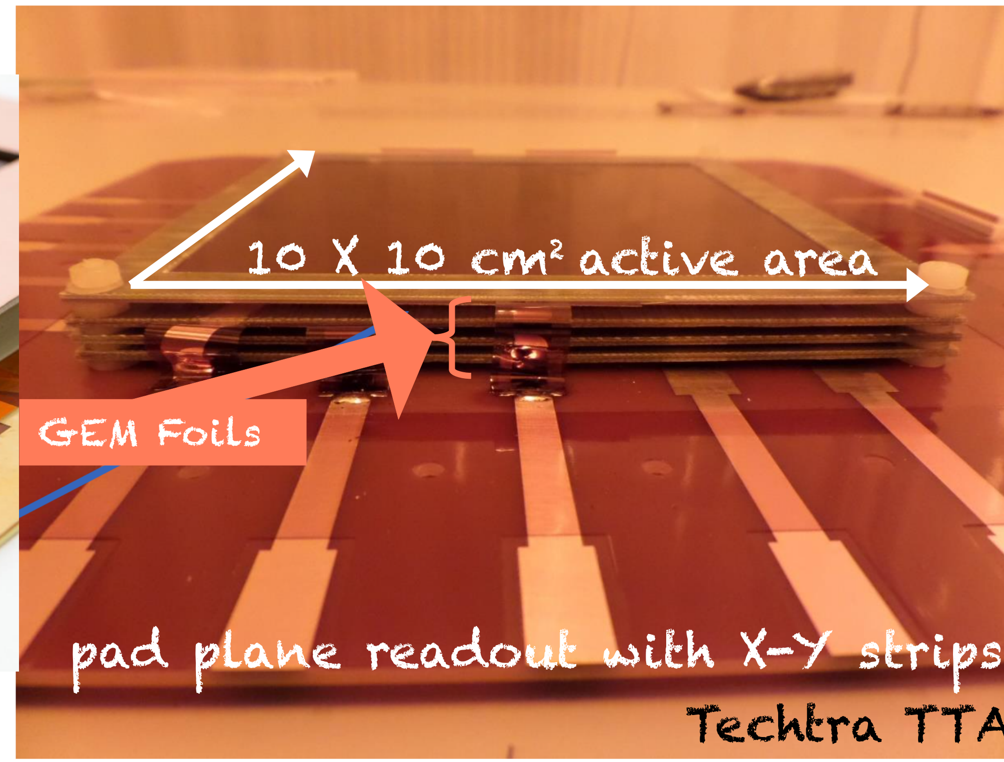
Charge Readout Test Stand – GEM

- Place a **GEM-TPC in the GOAT pressure vessel** (T. Mohayai's Fermilab New Initiatives R&D award)
  - Calibrate the GEM performance at high pressures using Fe-55 calibration source and an Ar-based gas mixture & compare with ALICE **IROC** MWPC
- The GEM TPC, built and tested by Techtra TTA, is on its way to Fermilab – stay tuned!



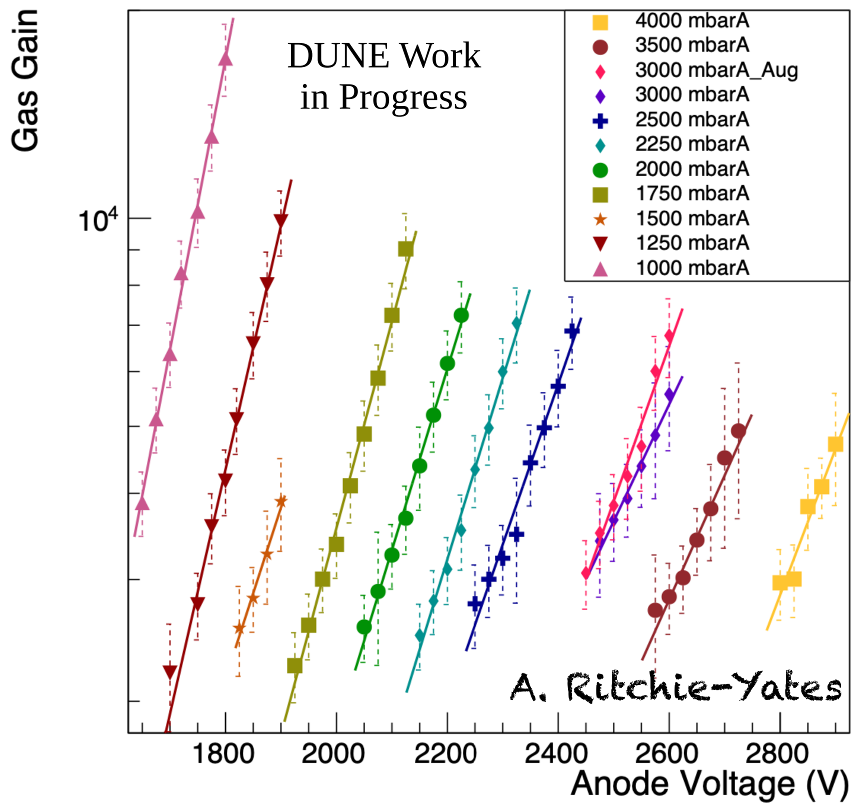
outcome of the tests using an x-ray source at Techtra's facilities



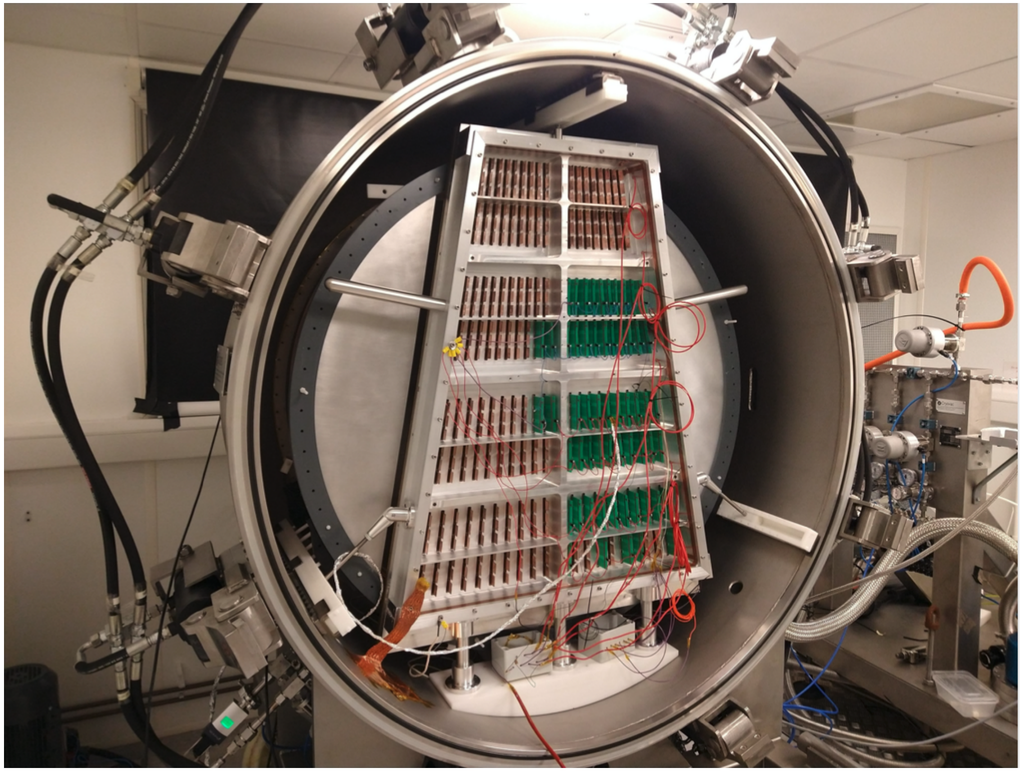


Charge Readout Test Stand – MWPC

- Hybrid charge and optical readout pressure vessel housing an ALICE **OROC** MWPC (see Deisting, Waldron et al., Instruments 2021, 5(2), 22)
- Gain calibration previously done at Royal Holloway using Fe-55 calibration source and an Ar-based gas mixture
- Currently being re-commissioned at Fermilab for its test beam run

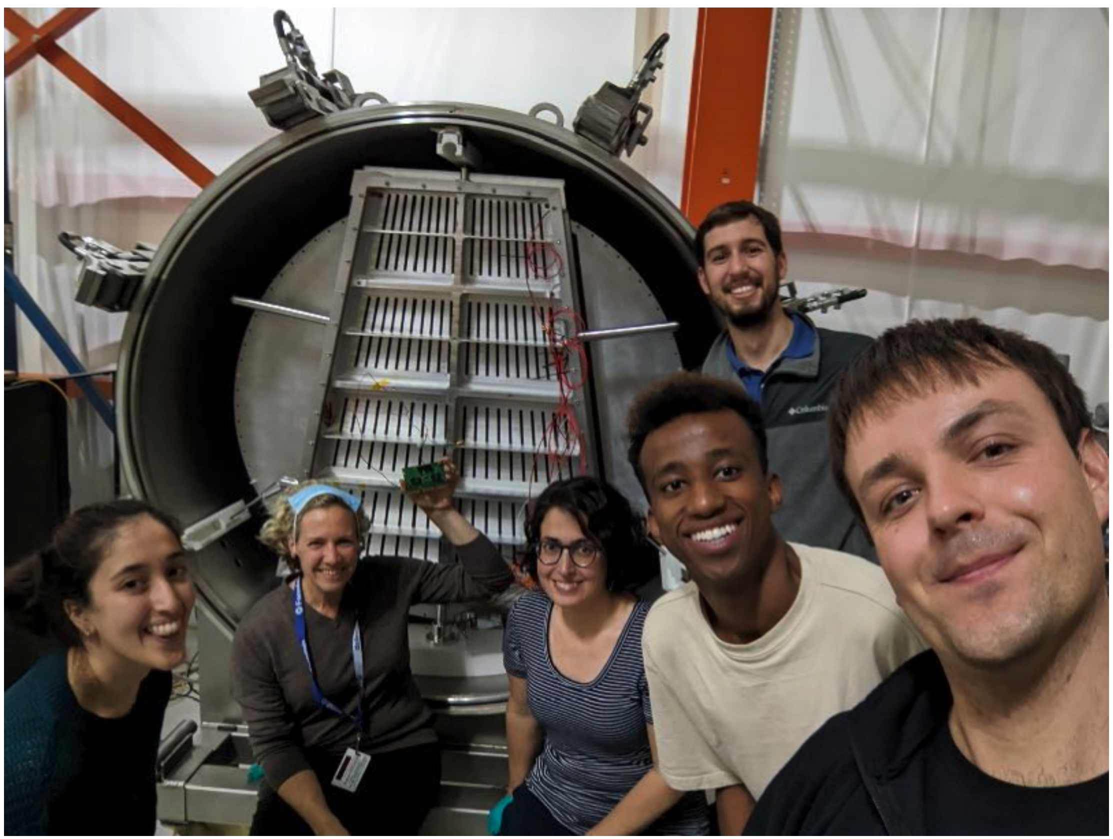


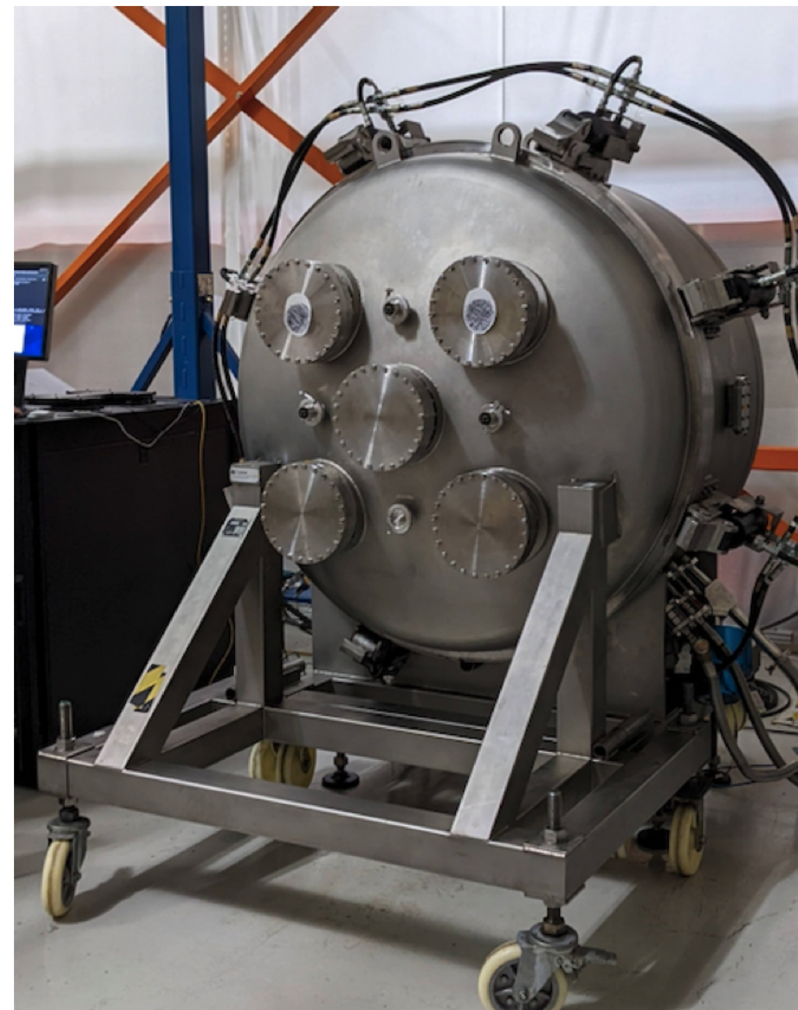
Imperial, Royal Holloway UL, Queen Mary UL, Fermilab, Pittsburgh, Oxford, Warwick, U College London, Colorado Boulder, Minnesota Duluth



Charge Readout Test Stand – MWPC

- Test beam run goals (led by N. Khan, P. Dunne at Imperial):
  - ★ Demonstrate **long-term operation of readout chamber and electronics**
  - ★ Reconstruct tracks with **full electronics and readout software**
  - ★ Collect **hadronic interactions on argon**
  - ★ Measure **proton and pion scattering on argon**
  - ★ And many more...
- Stay tuned!



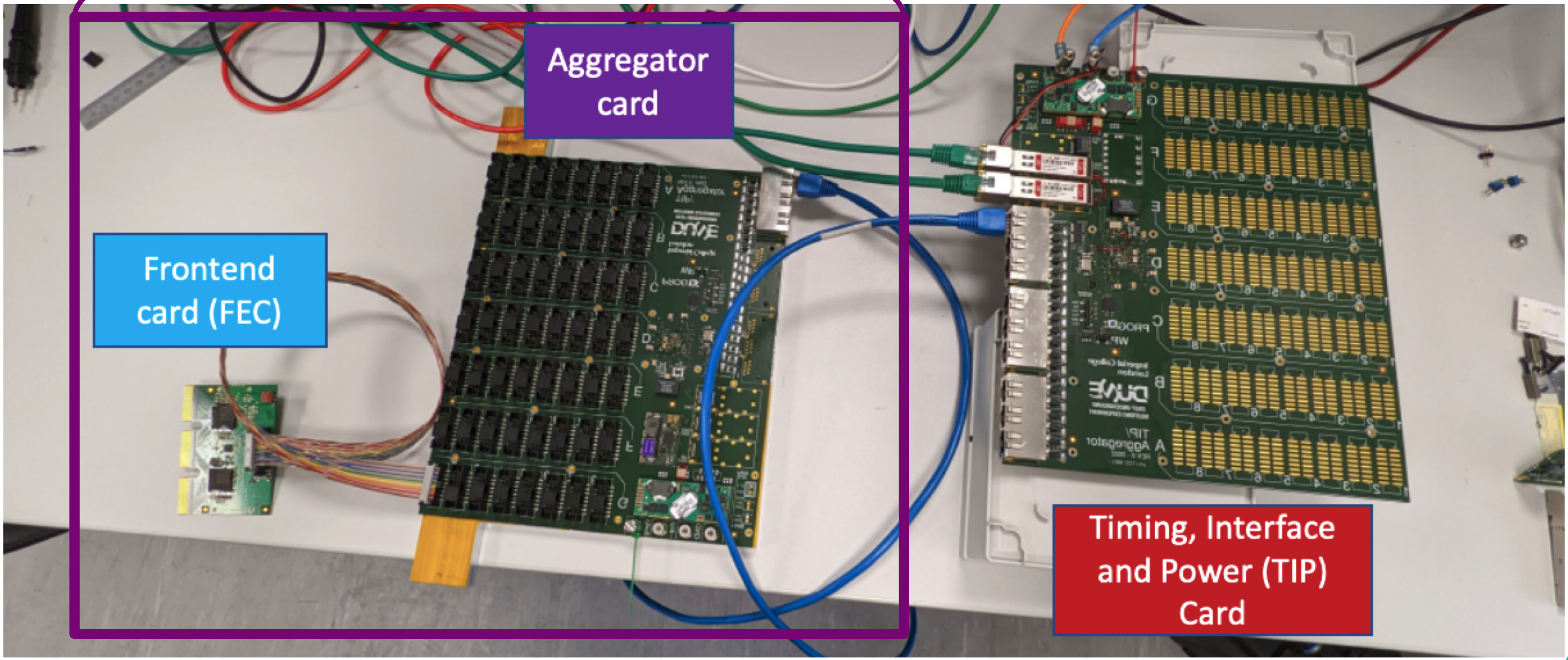


Electronics and DAQ

- TOAD is also performing a full slice test of electronics and DAQ
  - ASIC-based **ALICE SAMPA cards** digitize the readout system (can be used for both ALICE MWPCs and GEMs)
  - An **FPGA-based aggregator** board is connected to cards, minimizing the number of feedthroughs
  - The **TIP cards** provide timing, control, and power

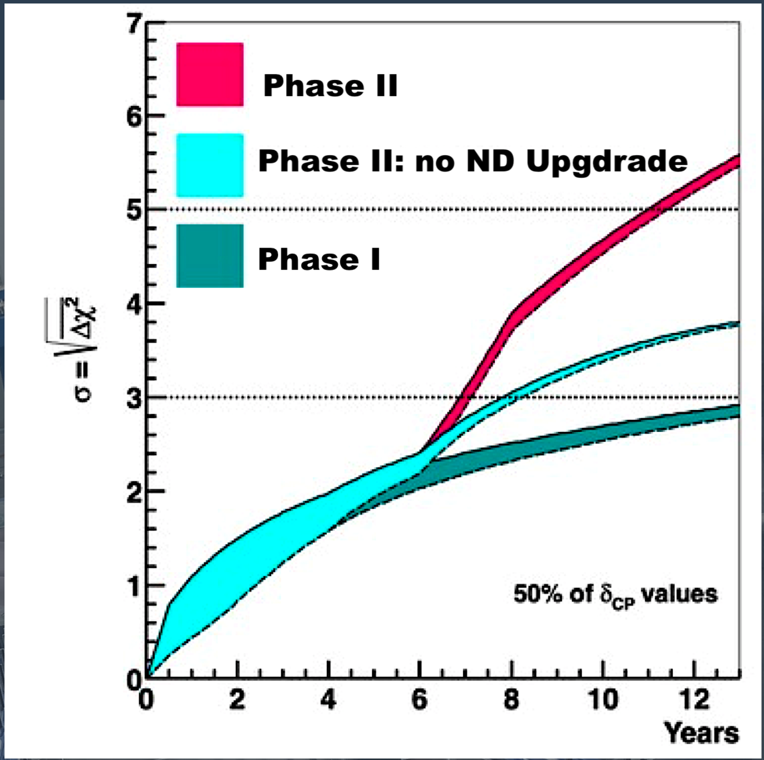
placed inside the pressure vessel

Imperial, Fermilab, Pittsburg



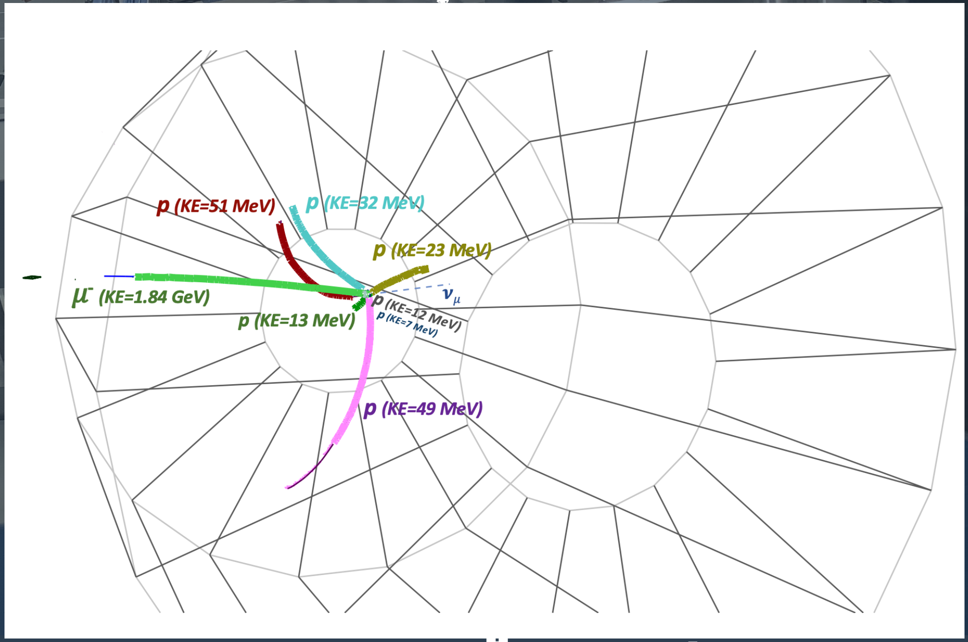
Summary

- 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
  - A close-up view of ν-Ar interactions to more accurately estimate neutrino energy in neutrino oscillation analysis
  - A comprehensive search for rare decays and symmetries beyond the standard model



DUNE Collaboration, A. A. Abud et al. in 2022 Snowmass Summer Study. 3, 2022. arXiv:2203.06100

- A wide range of detector R&D efforts are underway to build a highly capable HPgTPC, the TPC that sits at the core of ND-GAr:
  - Besides R&D on the acquired ALICE MWPCs, we are exploring various new detector R&D areas, including GEM readout

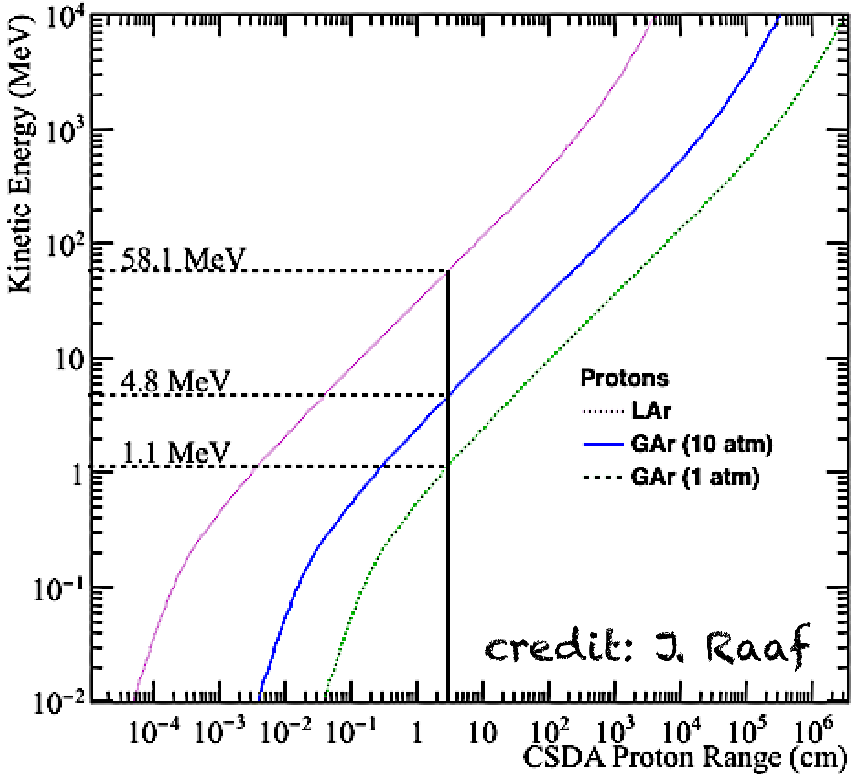


Additional Slides

Low Threshold ND-GAr

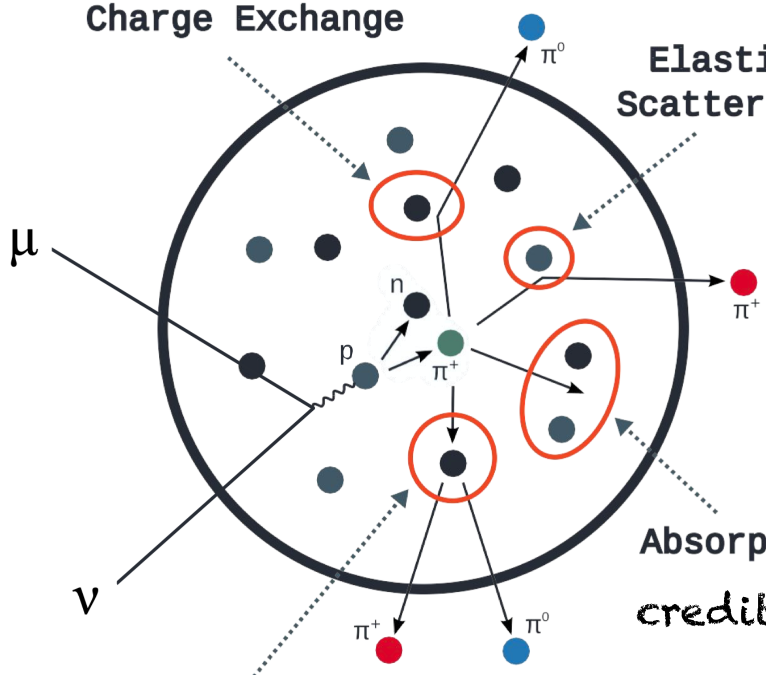
- Lower threshold of **ND-GAr's HPgTPC** than **ND-LAr**:
  - ★ Leads to a high sensitivity to low energy protons or pions:

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



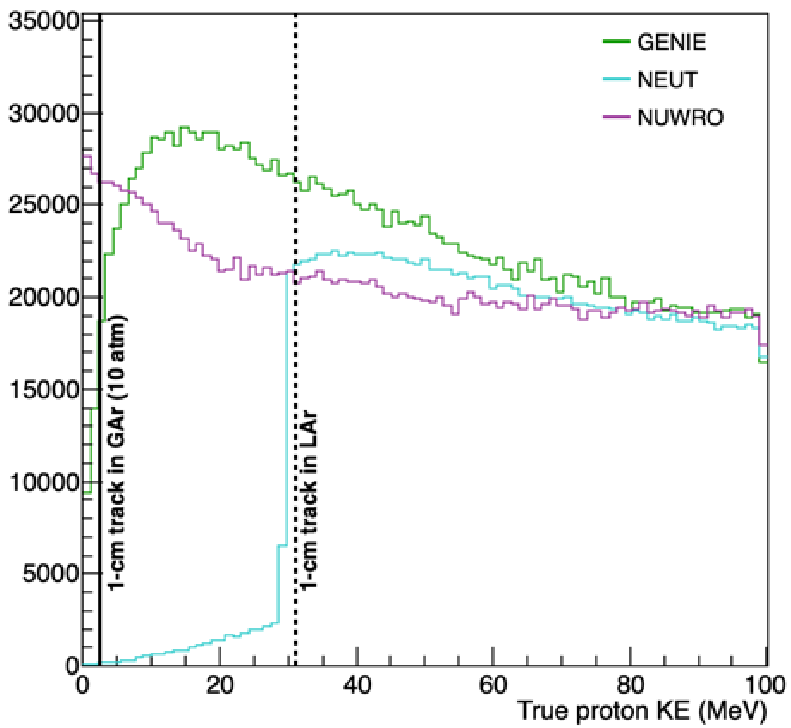
Low Threshold ND-GAr

- 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



From Existing Neutrino Experiments

- **Cross sections/neutrino interaction model uncertainties** from existing experiments (all using near detectors that have thresholds higher than HPgTPC) are too large for DUNE. We need to do better – a low threshold HPgTPC helps

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

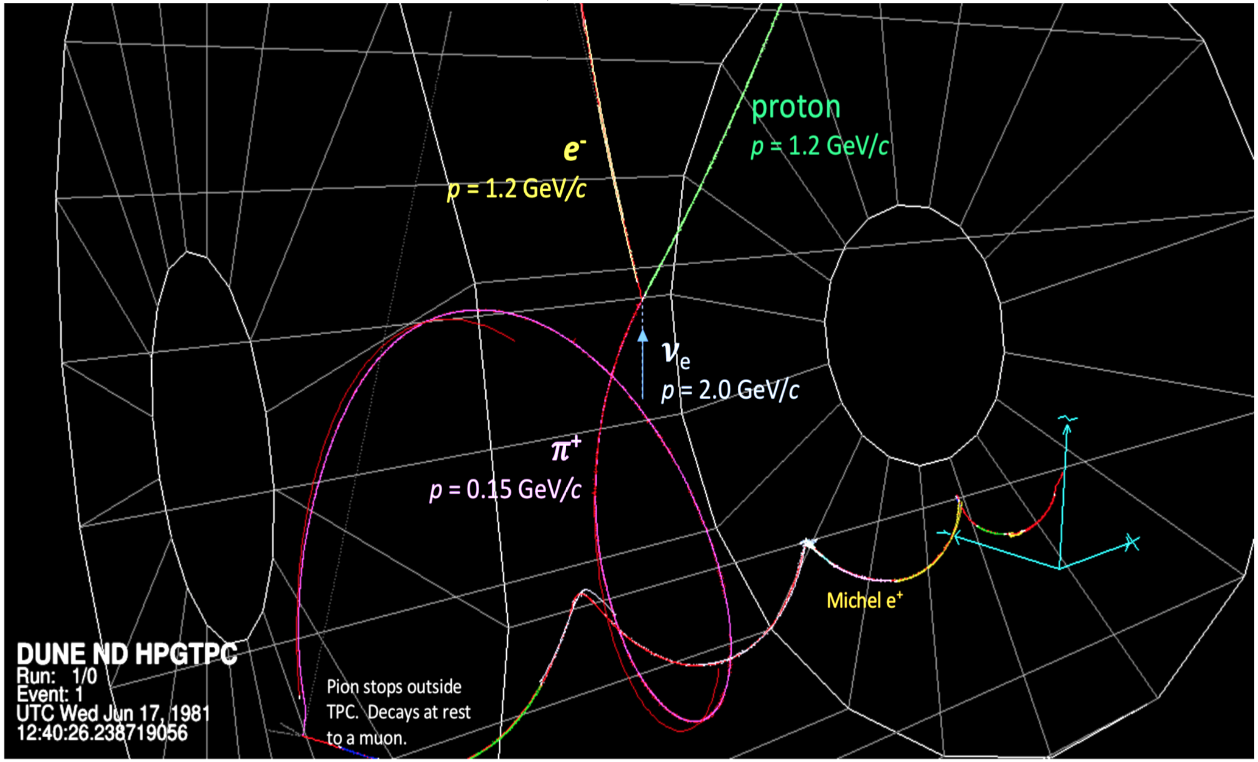
A Wealth of ν-Argon Interaction Data

- 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

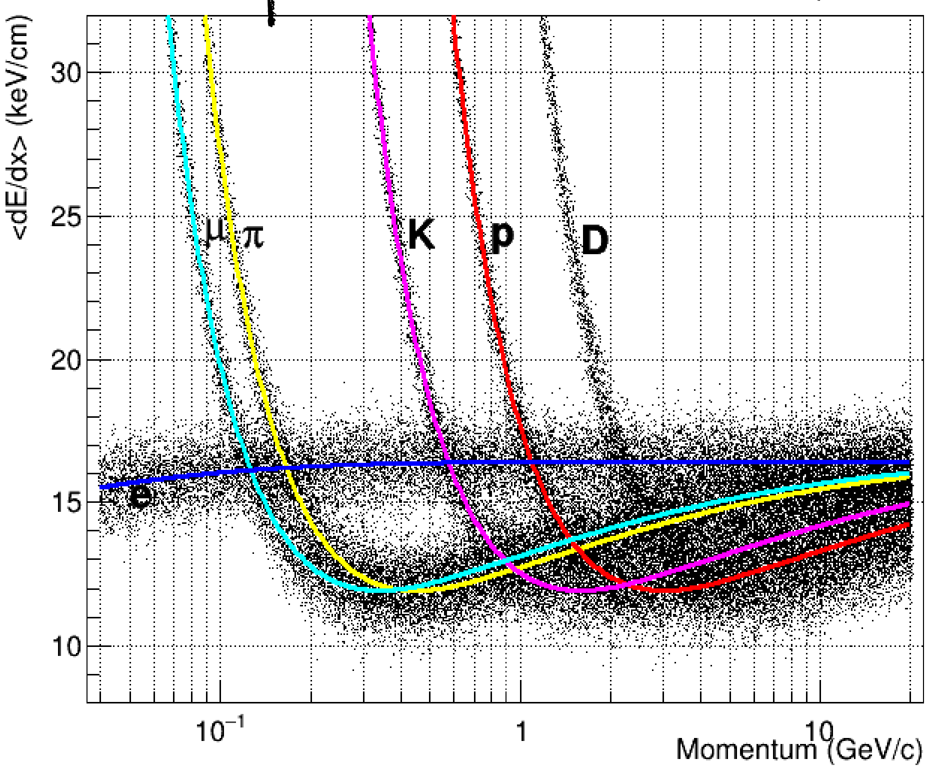
A detailed view of the ν-interaction vertex

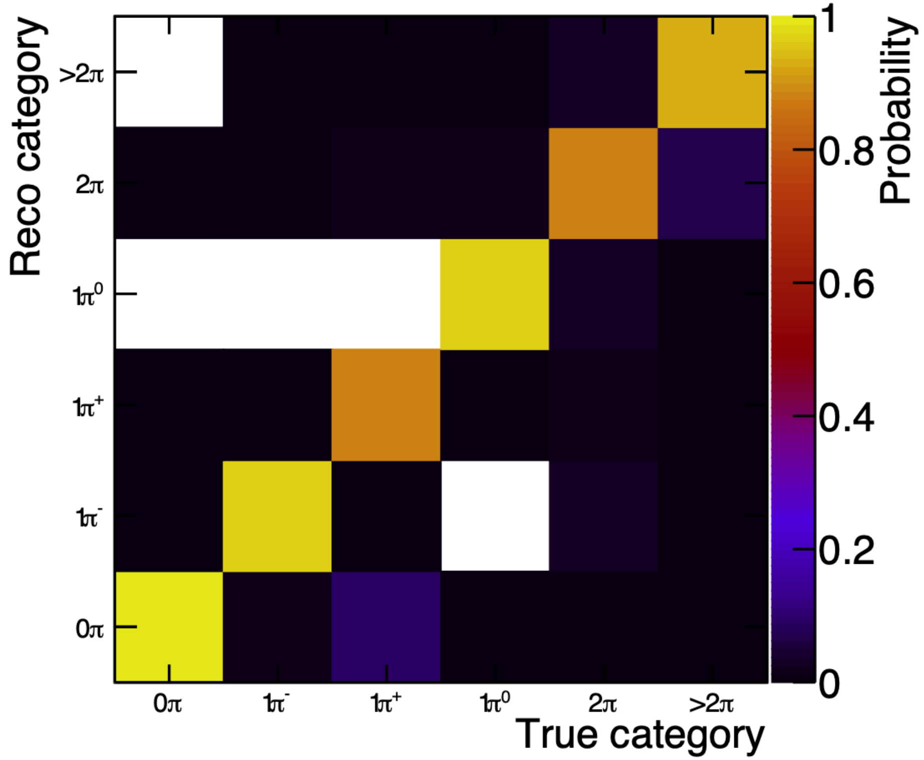


Superb PID for ν-Ar Interaction Measurements

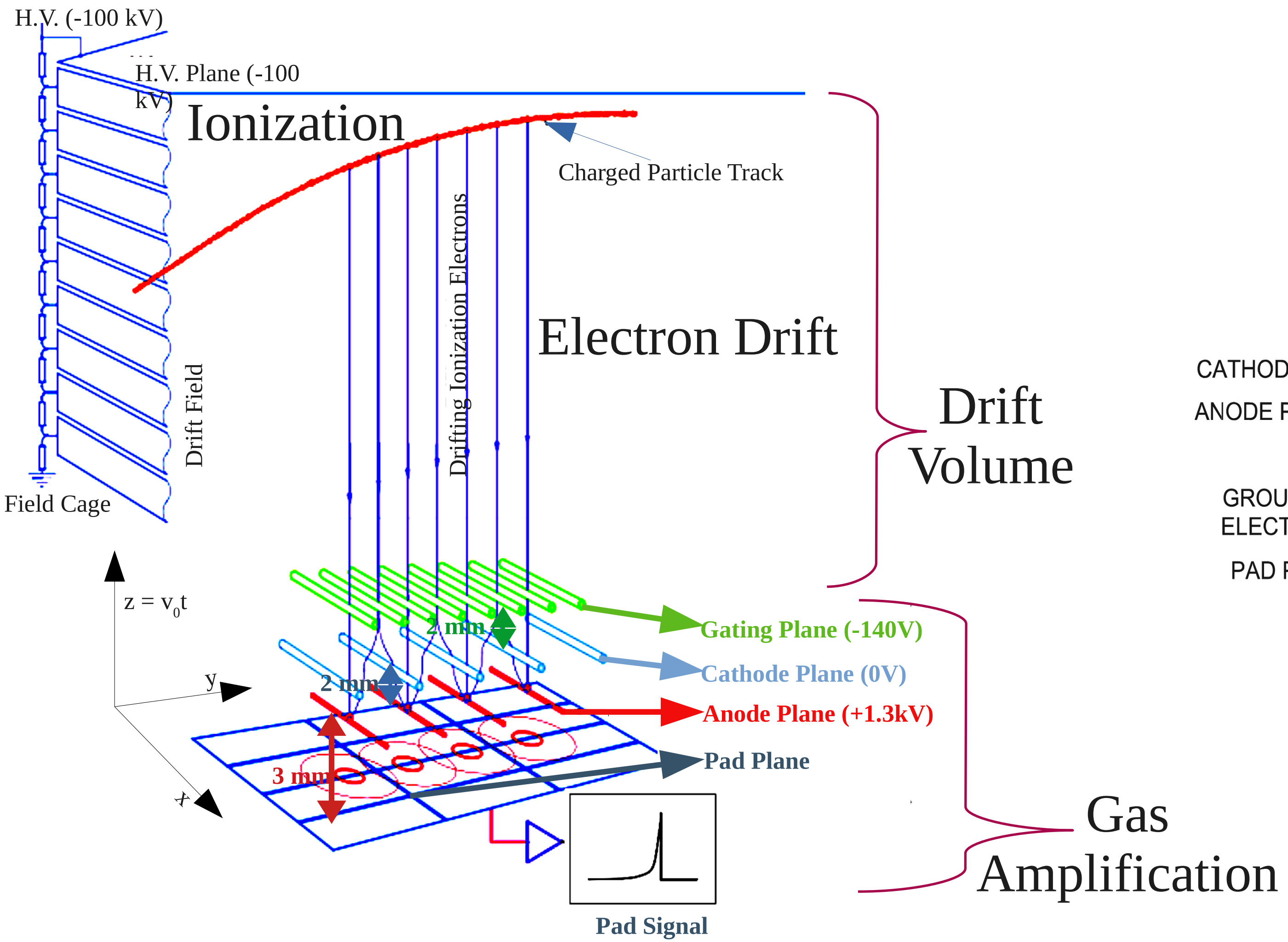
- dE/dx resolution: 0.8 keV/cm
- Excellent PID combined with low threshold feature allows ND-GAr to help with correctly identifying the **different final state topologies e.g. pion multiplicities** very well

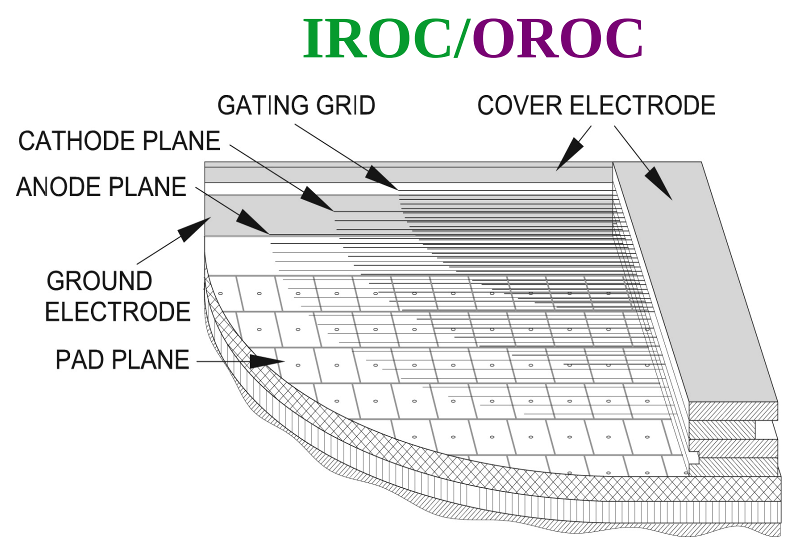
dE/dx-based PID will be comparable to PEP-4's





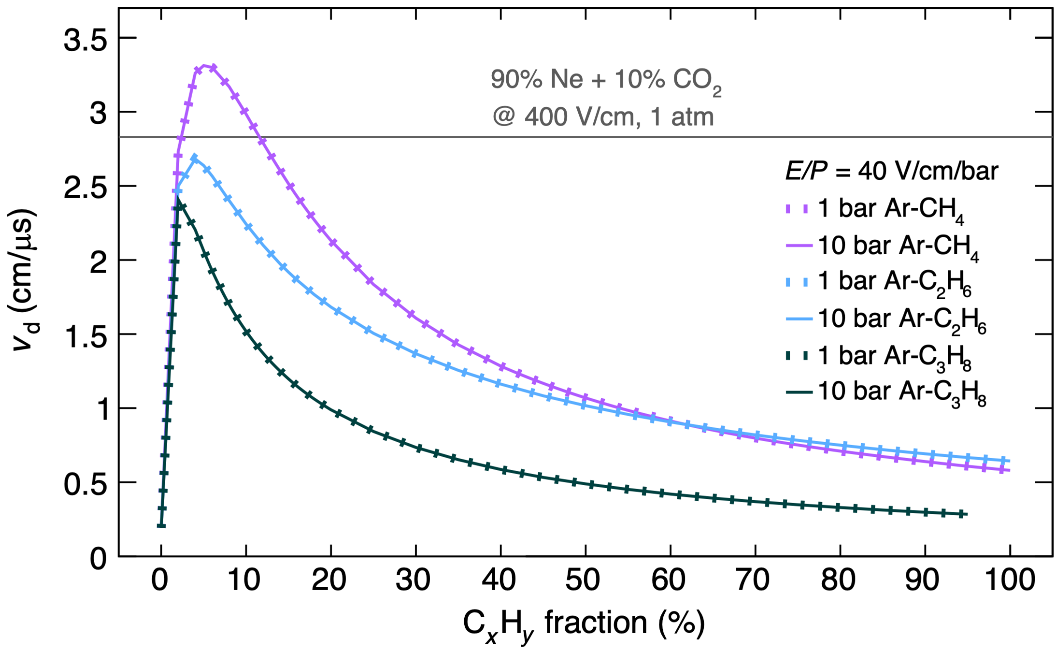
DUNE Collaboration, A. Abed Abud et al. Instruments 5 no. 4, (2021) 31, arXiv:2103.13910 [physics.ins-det].

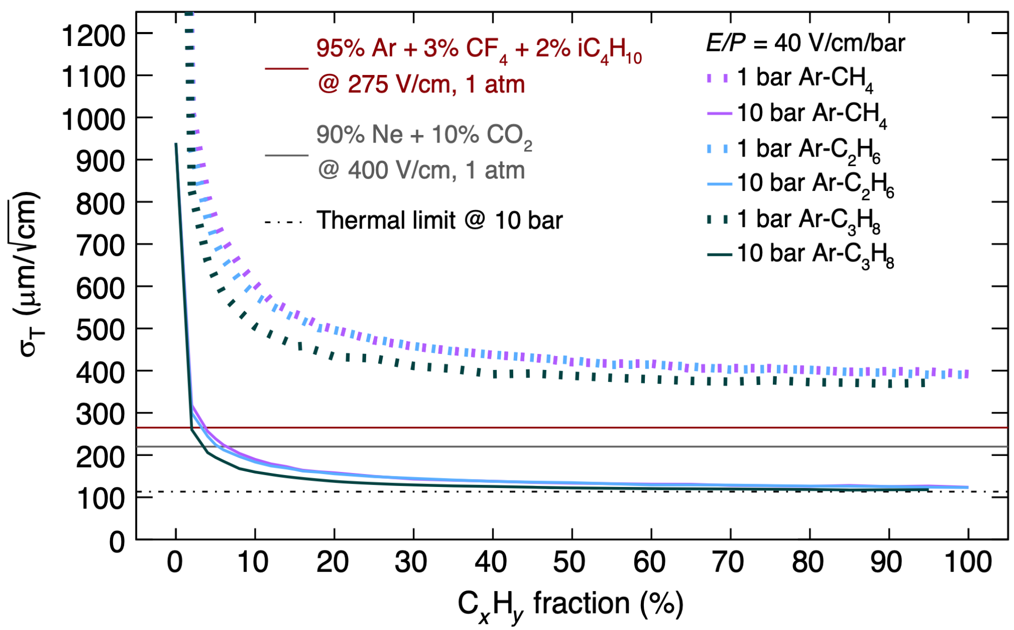

H.V. (-100 kV)
H.V. Plane (-100 kV)
Ionization
Charged Particle Track
Drifting Ionization Electrons
Electron Drift
Drift Field
Field Cage
Drift Volume
z = v0t
y
x
2 mm
2 mm
3 mm
Gating Plane (-140V)
Cathode Plane (0V)
Anode Plane (+1.3kV)
Pad Plane
Pad Signal
Gas Amplification


IROC/OROC
GATING GRID
COVER ELECTRODE
CATHODE PLANE
ANODE PLANE
GROUND ELECTRODE
PAD PLANE

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

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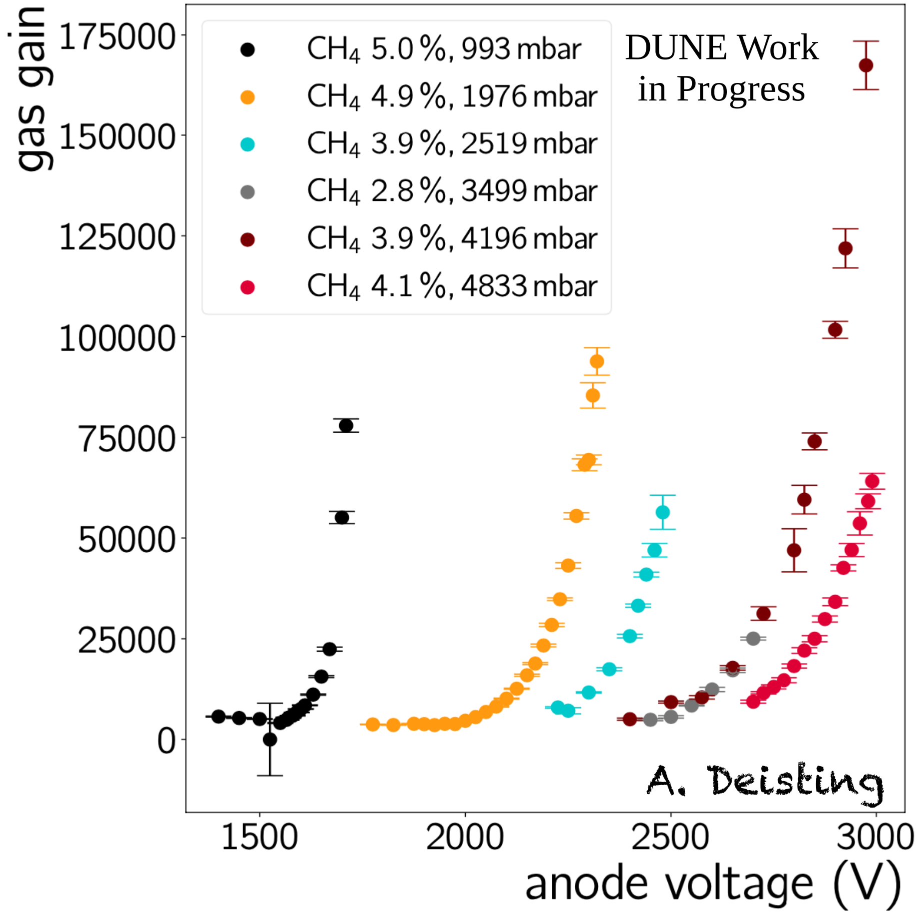
    - Maximize gas gain



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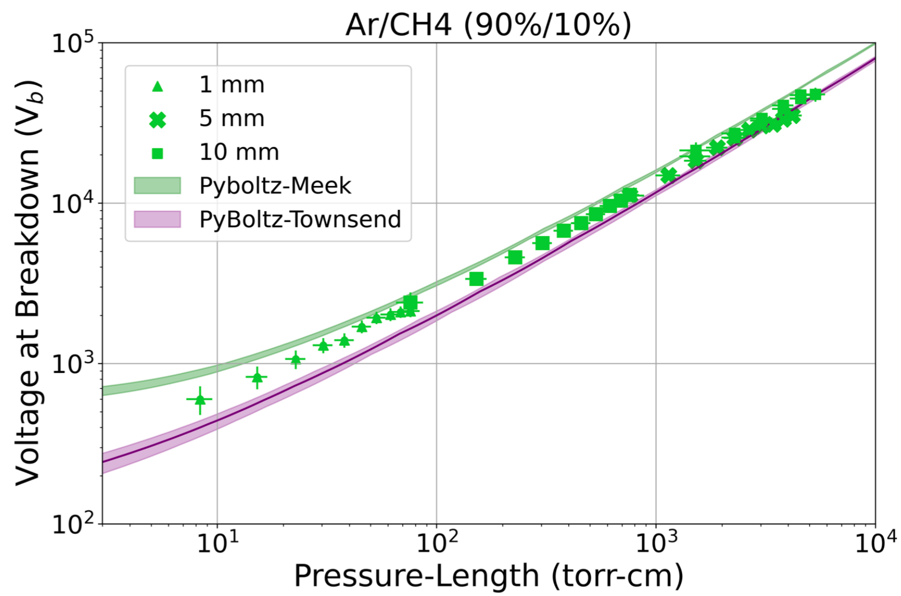
    - Control pile up (drift velocity) and improve spatial resolution (diffusion)
    - Maximize gas gain, while minimizing gas electrical breakdown



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**

R&D Efforts

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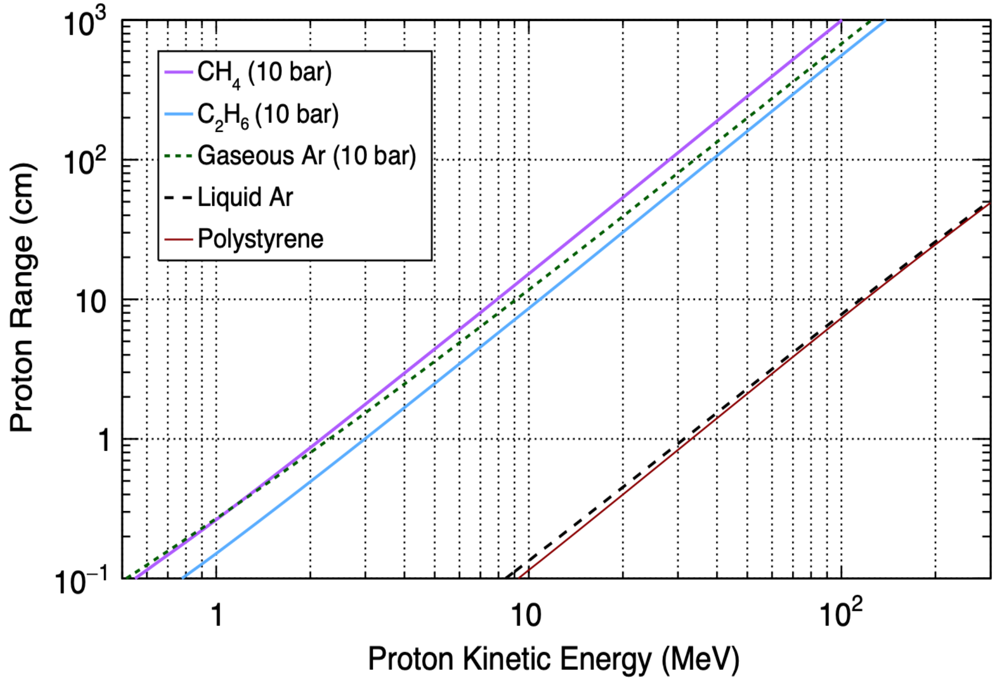
    - Control pile up (drift velocity) and improve spatial resolution (diffusion)
    - Maximize gas gain, while minimizing gas electrical breakdown
    - Ability to operate with a hydrogen-rich gas mixture to probe more fundamental neutrino-hydrogen interactions



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