R&D for a Gaseous-Ar Based Near Detector for DUNE Phase II

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for the DUNE Collaboration

2023 CYGNUS Workshop
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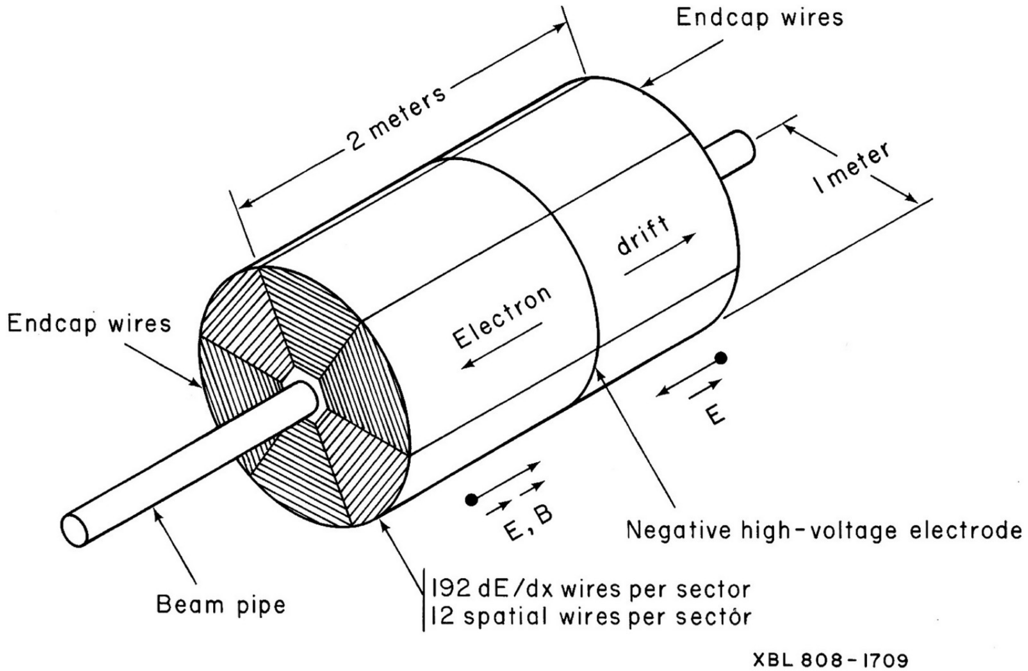
DEEP UNDERGROUND NEUTRINO EXPERIMENT

GasTPCs Exploring a Wide Range of Physics

- What you have heard about so far:
  - Rare event searches, dark matter
  - Coherent elastic neutrino-nucleus scattering (CEvNS)
- What you will hear in this talk:
  - A high-pressure gas-argon time projection chamber, a first of its kind for precision studies of neutrino oscillations!

First large-scale realization of TPCs was in Positron Electron Project, PEP-4 TPC at SLAC, a high pressure TPC in a collider



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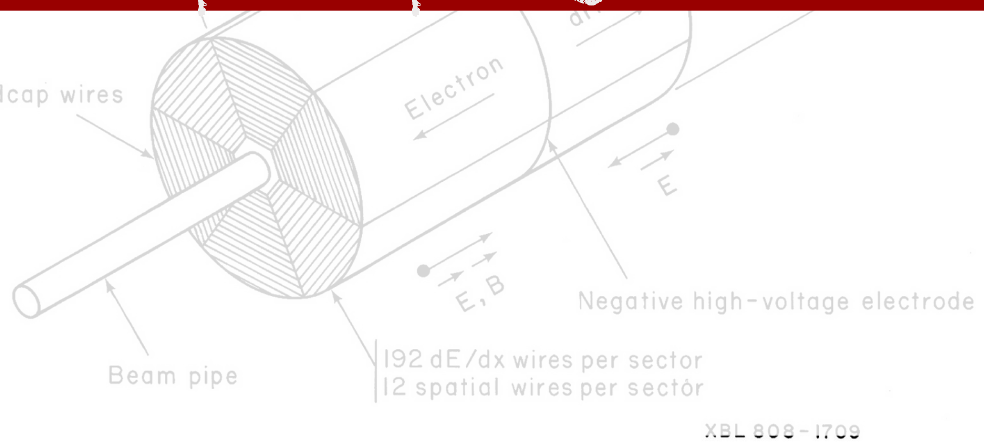
our R&D endeavors offer synergies across diverse communities, including a lot of the communities participating in this workshop



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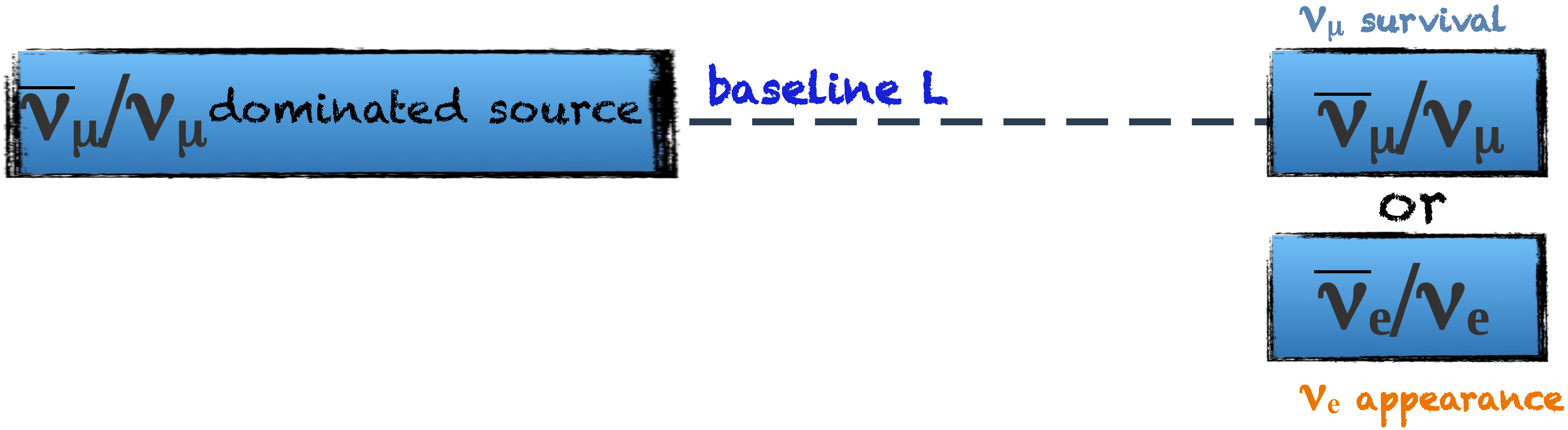
Neutrino Oscillations



- **Neutrino oscillations considered one of the strongest pieces of evidence of BSM physics**
  - Modeled with various parameters, **mixing angle, θ_{ij},** **mass splitting squared term, Δm^2_{ij}**, **CP violating term, δ_{CP}**, **baseline, L**, and **neutrino energy, E_ν**

simplified 2 flavor probability, e.g. ν_e appearance probability, $P(\nu_\mu \rightarrow \nu_e)$

$$\sin^2(2\theta)\ \sin^2(1.27\Delta m^2_{21} L/E)$$

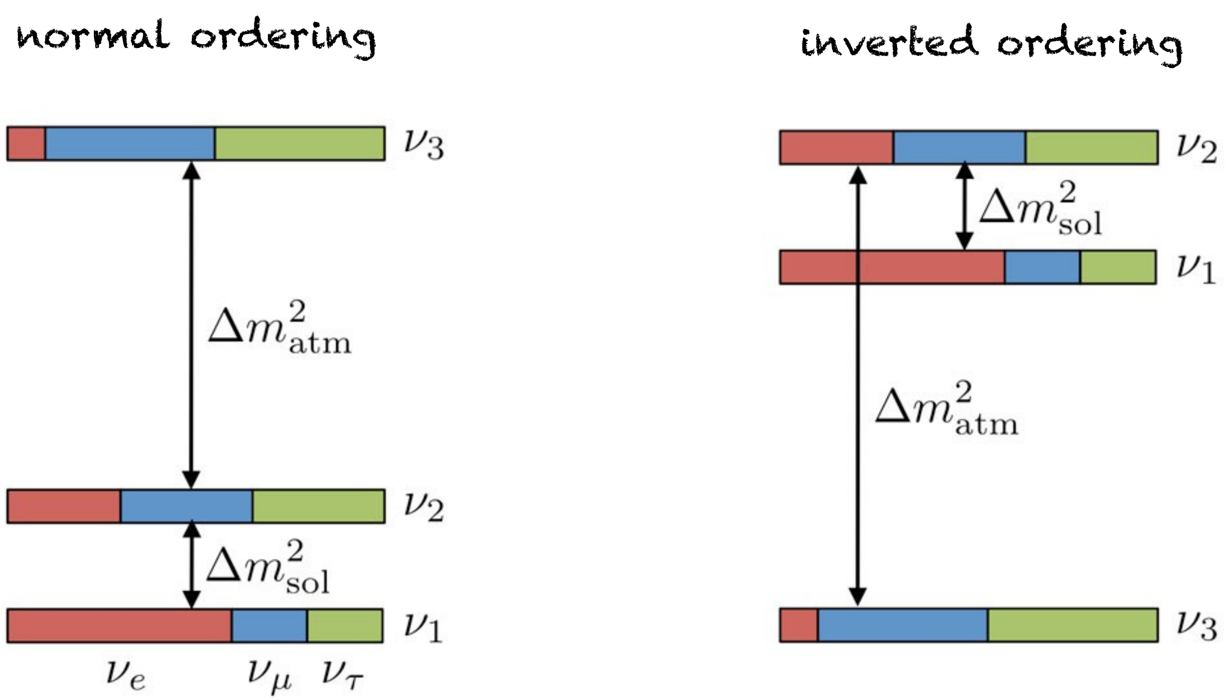
Neutrino Oscillation Parameters

NuFIT 5.2 (2022)

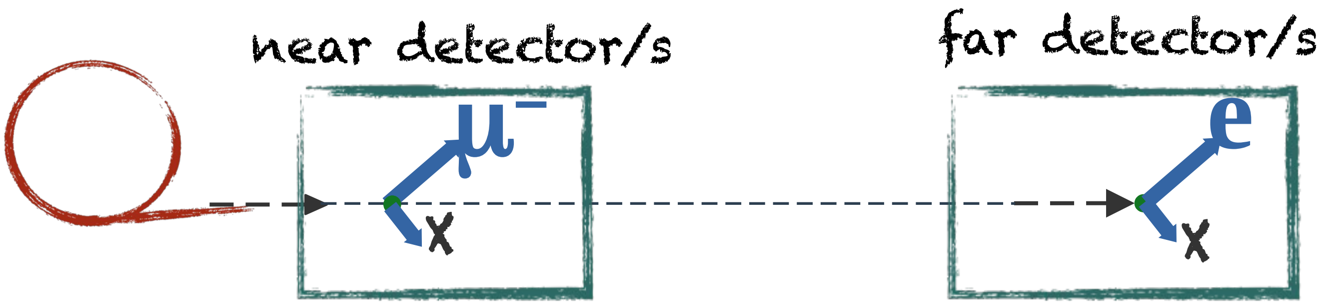
	Normal Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$
$\delta_{\rm CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$

Remaining Unknowns

- Do neutrinos violate CP symmetry, $\delta_{CP} \neq 0$?
- Three independent mixing angles θ_{23}, θ_{13}, θ_{12} measured to ~3%
- Is $\theta_{23} = 45^o$? Implies new symmetry, $\nu_\mu = \nu_\tau$ in ν_3
- Δm^2_{21}, Δm^2_{31} known to ~1-3%
- Mass ordering/sign of Δm^2_{32} is unknown



- Oscillation probabilities cannot be directly extracted by comparing near and far observables:
  - Combination of detector effects with flux & ν interaction cross sections



$$N_{\nu_e}(E_{reco}) \propto \Phi(E_\nu)\, \sigma(E_\nu)\, \epsilon\, P(\nu_\mu \rightarrow \nu_e)$$

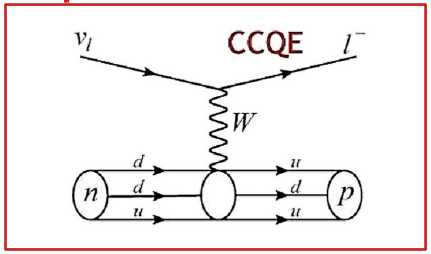
$$N_{\nu_\mu}(E_{reco}) \propto \Phi(E_\nu)\, \sigma(E_\nu)\, \epsilon$$

precisely determine neutrino flux, neutrino interaction cross section, detector efficiencies

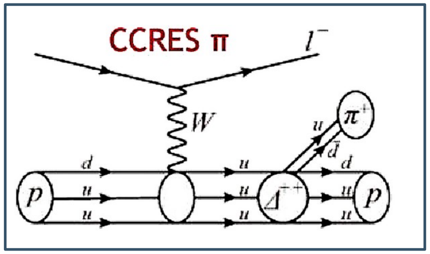
use high-performance detectors, complete theoretical models, and external data

Neutrino Interaction Cross-sections

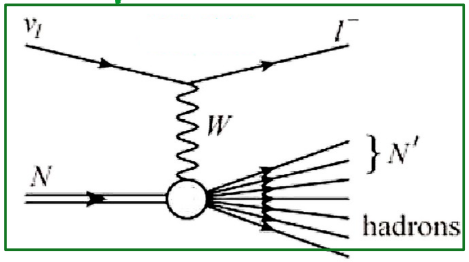
quasi elastic, QE

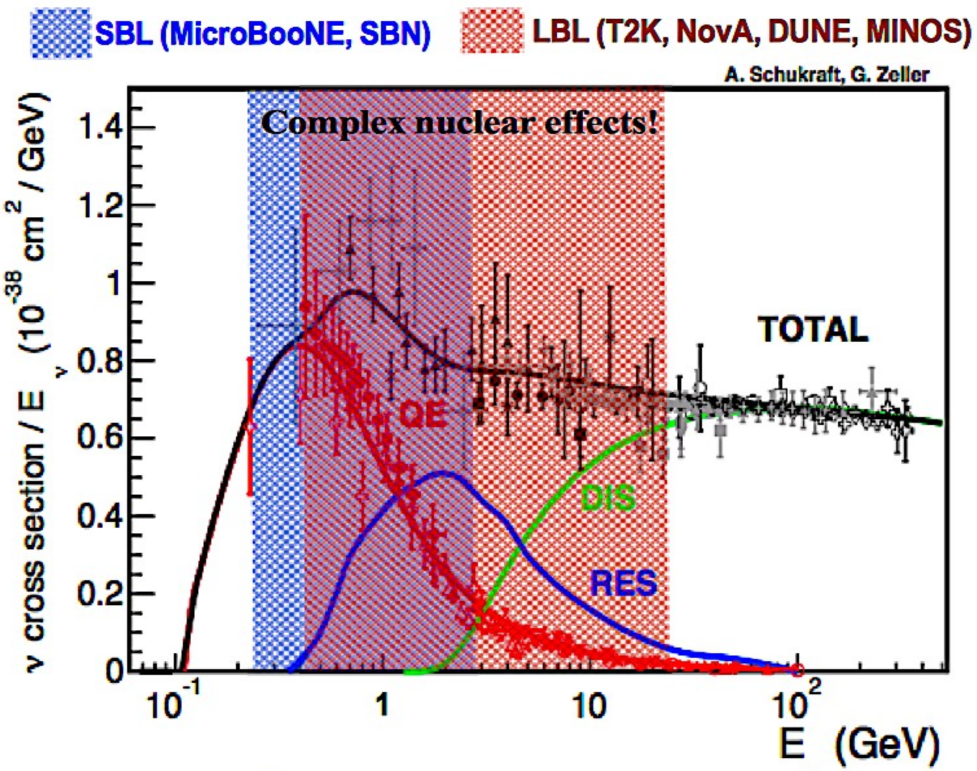


resonance, RES



deep inelastic, DIS

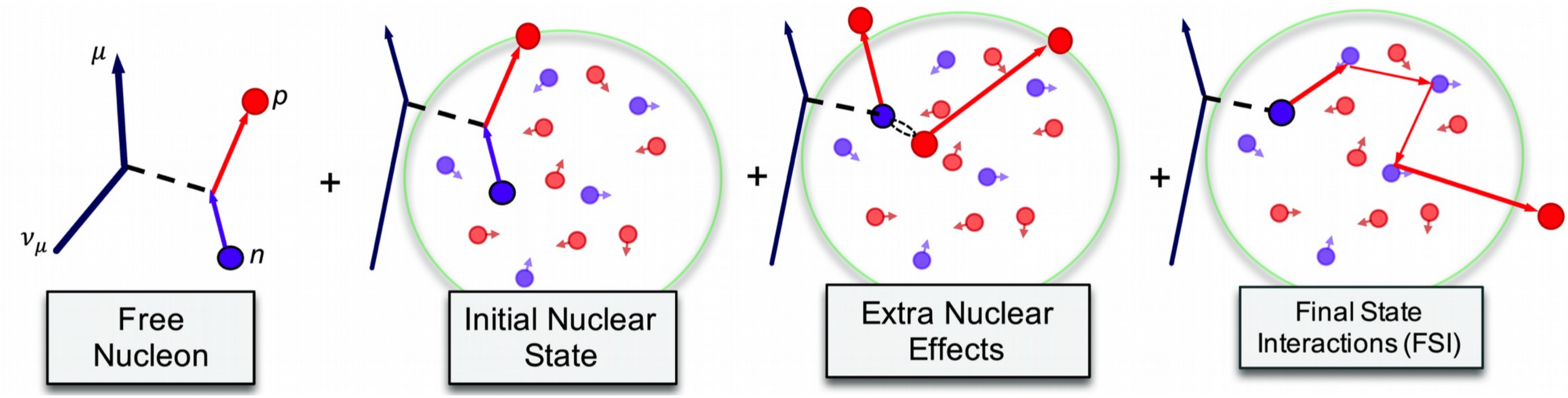




A. Schukraft, G. Zeller

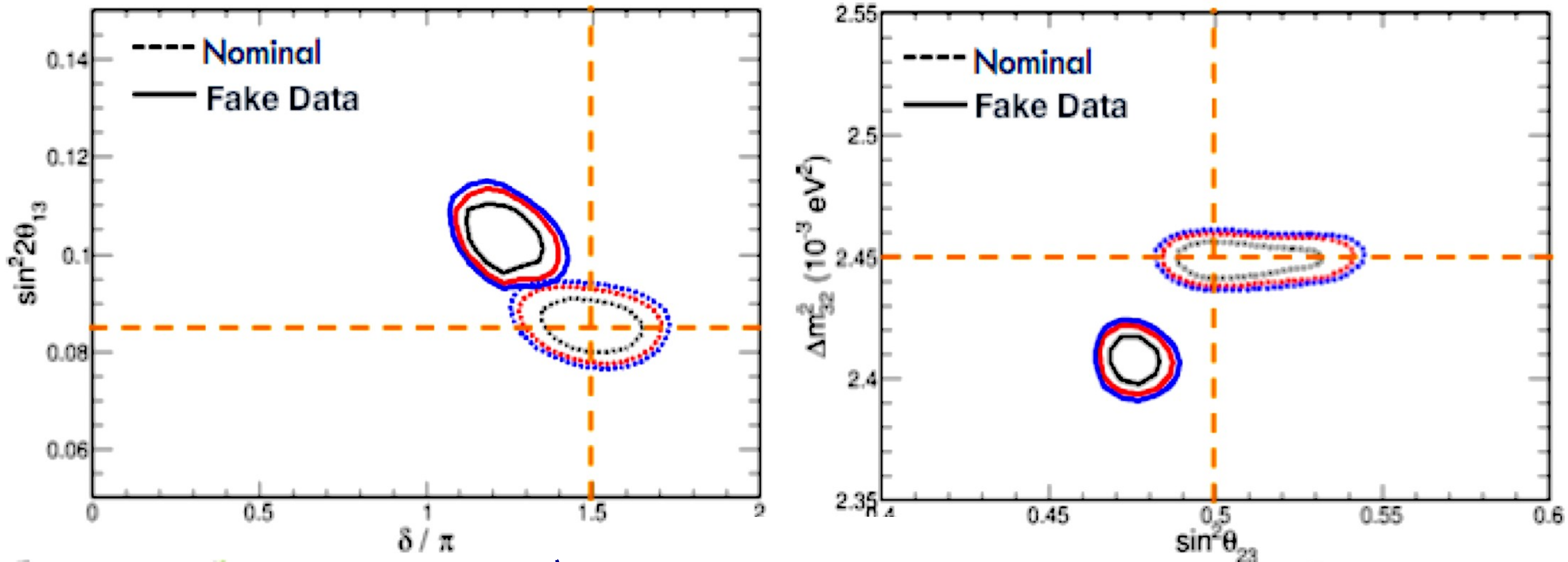
Neutrino Interaction Cross-sections

- **Neutrino interactions** (e.g. in heavy nuclear targets) are complicated:
  - Particles may re-interact before exiting the nucleus & the visible particles may not fully represent the initial kinematics of the incoming neutrino
- Neutrino event generators contain many models to describe neutrino interactions but are not yet complete, detector thresholds can also be limited
  - Introduces uncertainties in neutrino energy reconstruction and neutrino event rate estimation which need to be constrained



Effect on Oscillation Parameters

- Getting the **hadron count and energy correctly** is critical for a future oscillation experiment like DUNE



B. Abi et al 2020 JINST 15 T08008

- Case study: an illustration of the effect of getting only 20% of the proton energy wrong

Uncertainties from Existing Oscillation Experiments

- **Cross sections/neutrino interaction model uncertainties** from existing experiments are dominant
- A future precision neutrino oscillation experiment needs to do better!

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

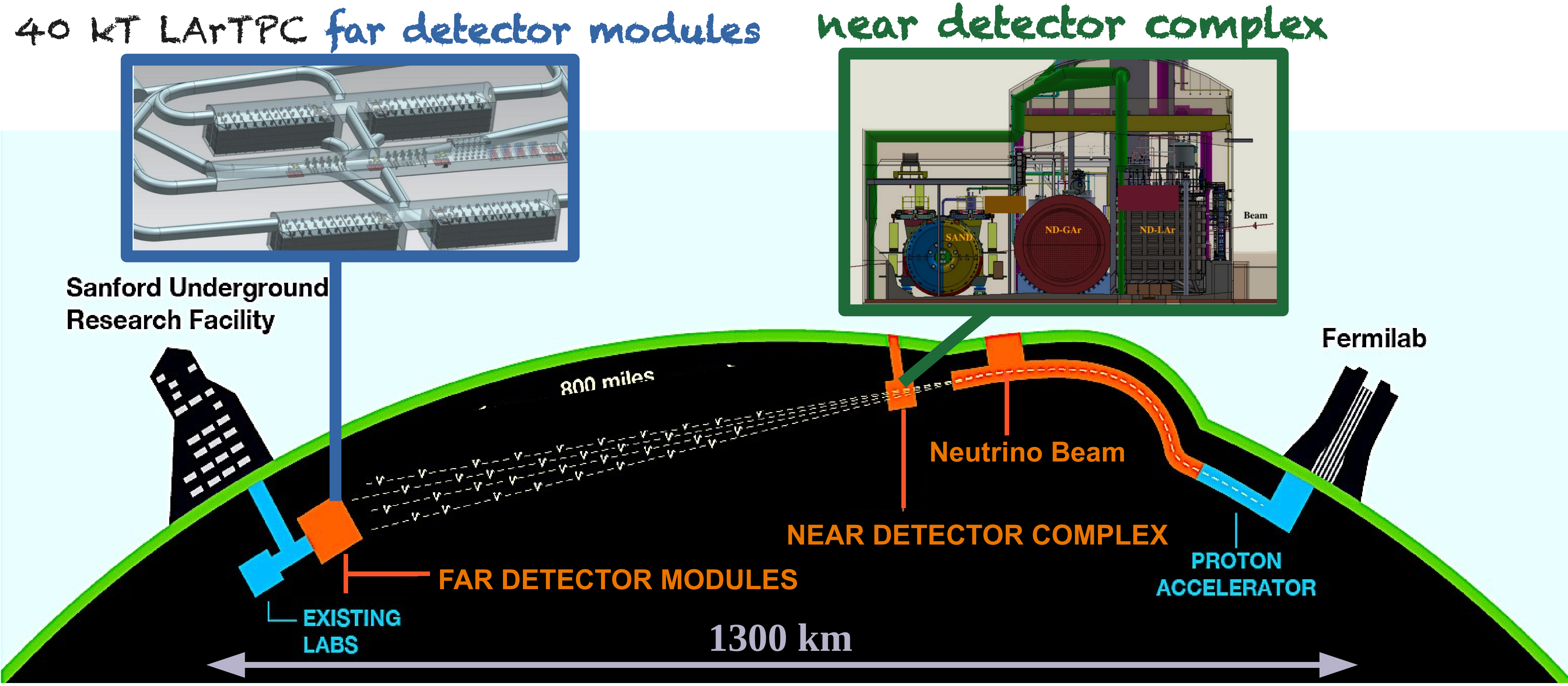
Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal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

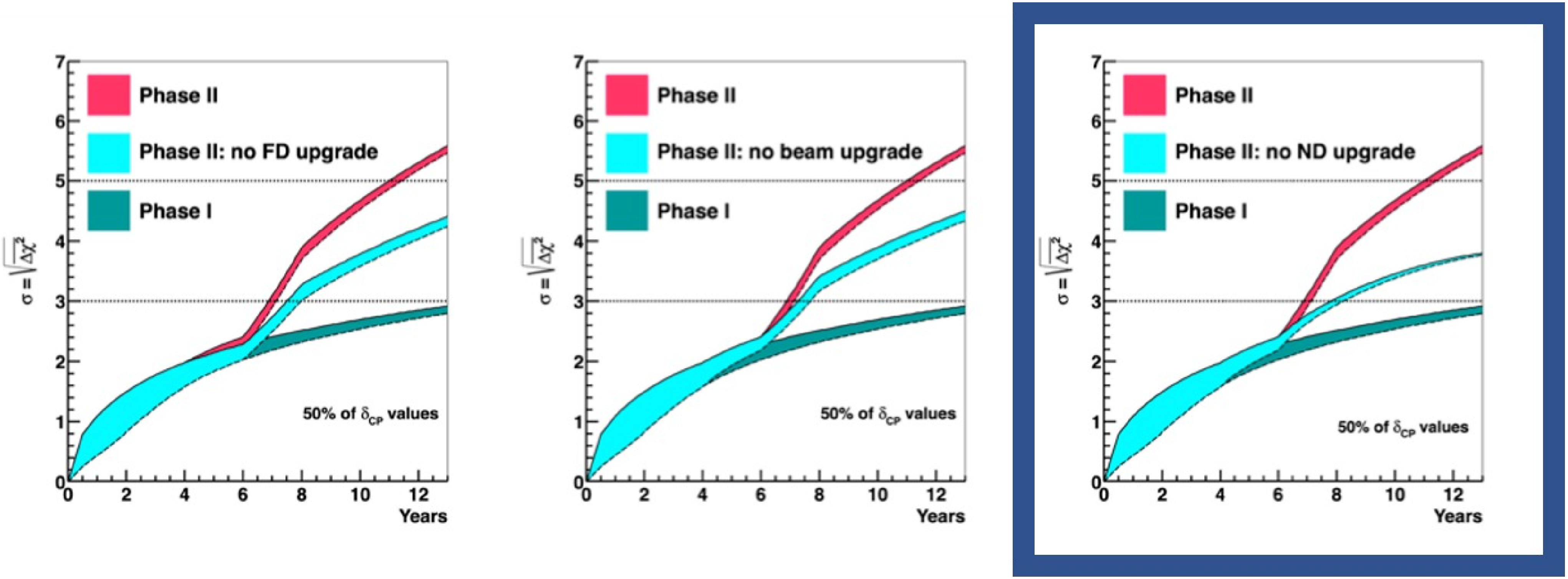
DUNE, a Future Precision Neutrino Oscillation Experiment

- 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, includes a LArTPC, and for Phase II of DUNE a Gaseous-argon based TPC**



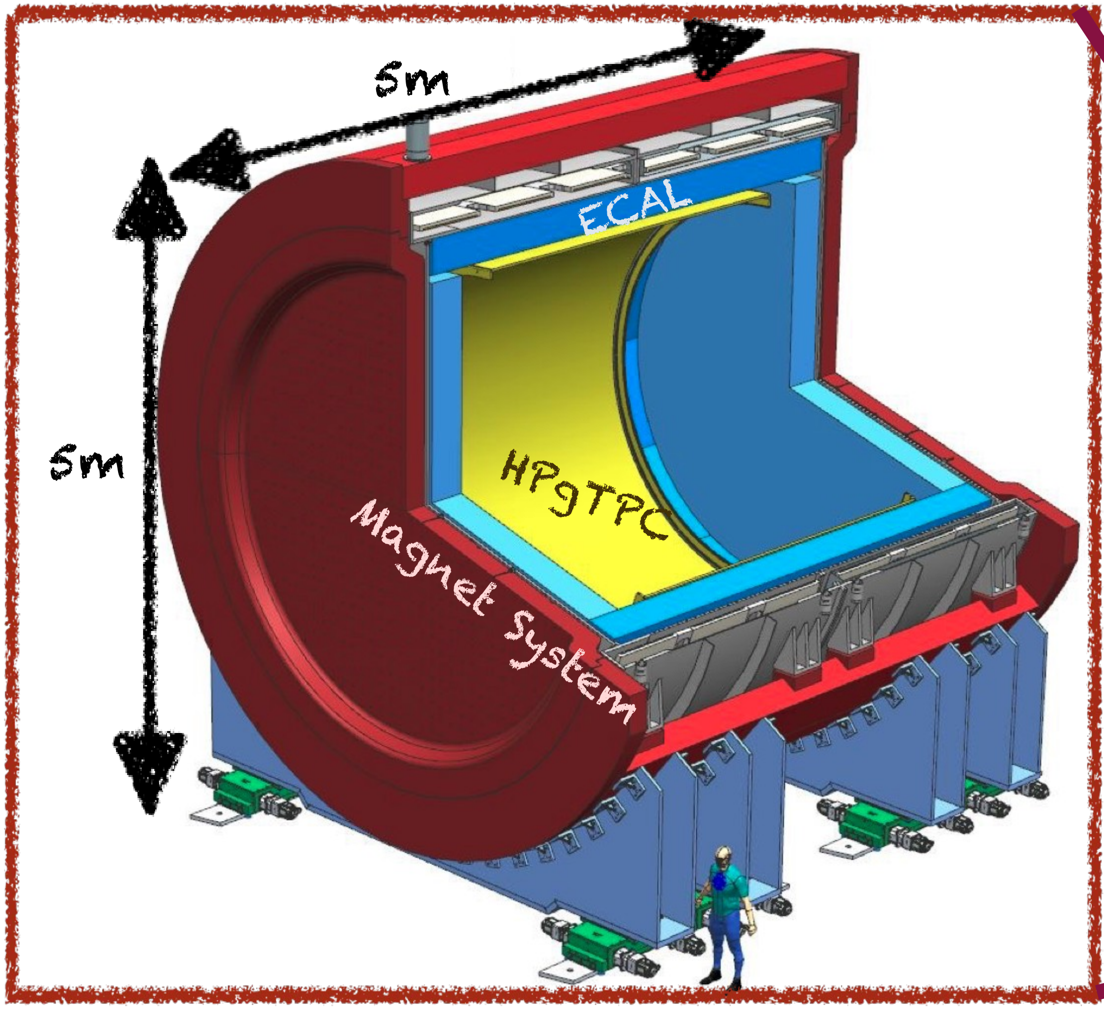
DUNE Phase II

- **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**

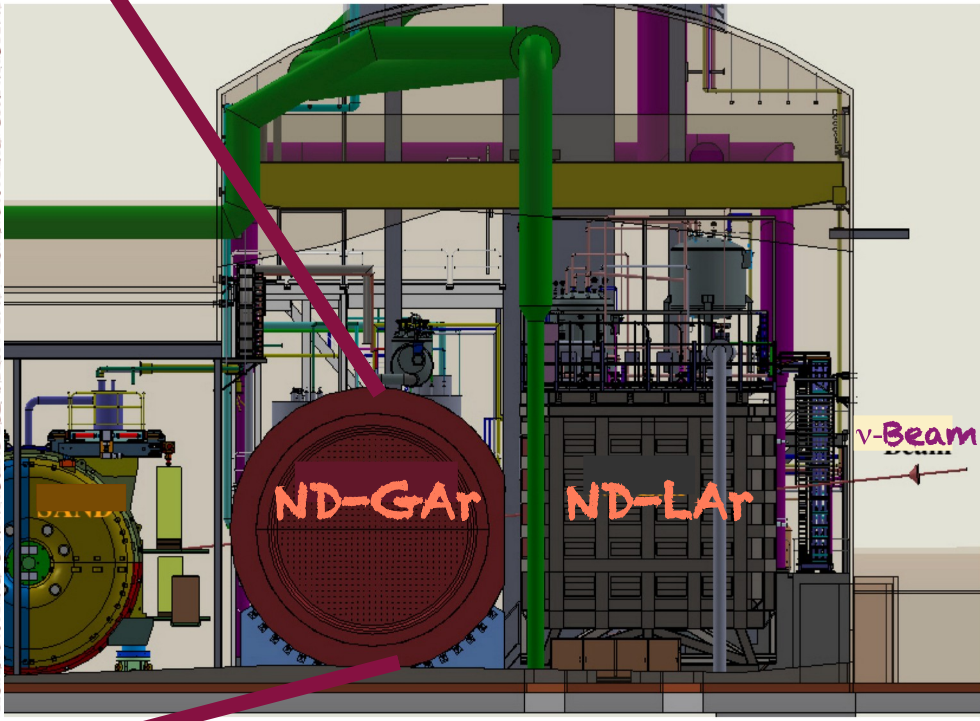


DUNE Collaboration, A. A. Abud et al. in 2022 Snowmass Summer Study. 3, 2022. arXiv:2203.06100 [hep-ex]

Near Detector Upgrade for DUNE Phase II



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

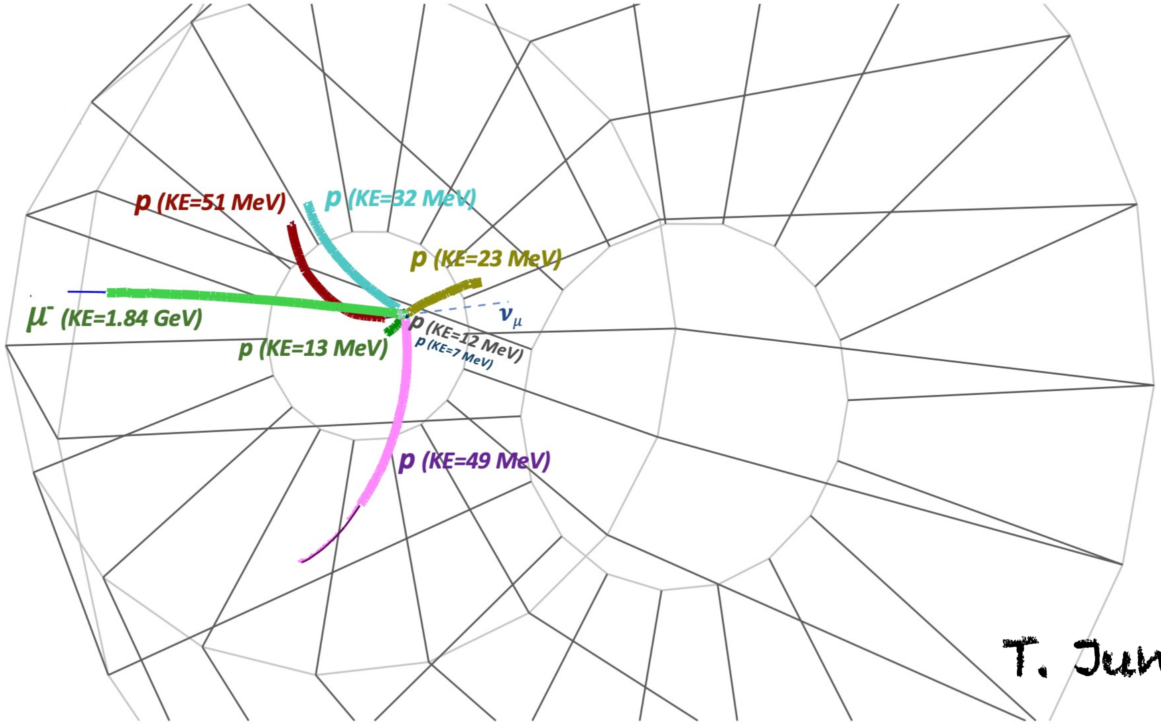


- ND-GAr, a **magnetized** **High Pressure <u>(10 atm)</u> Gas Argon TPC (HPgTPC)** surrounded by **ECAL** will be the DUNE ND Phase II upgrade
  - ★ **Energy threshold detector lower than a LArTPC**

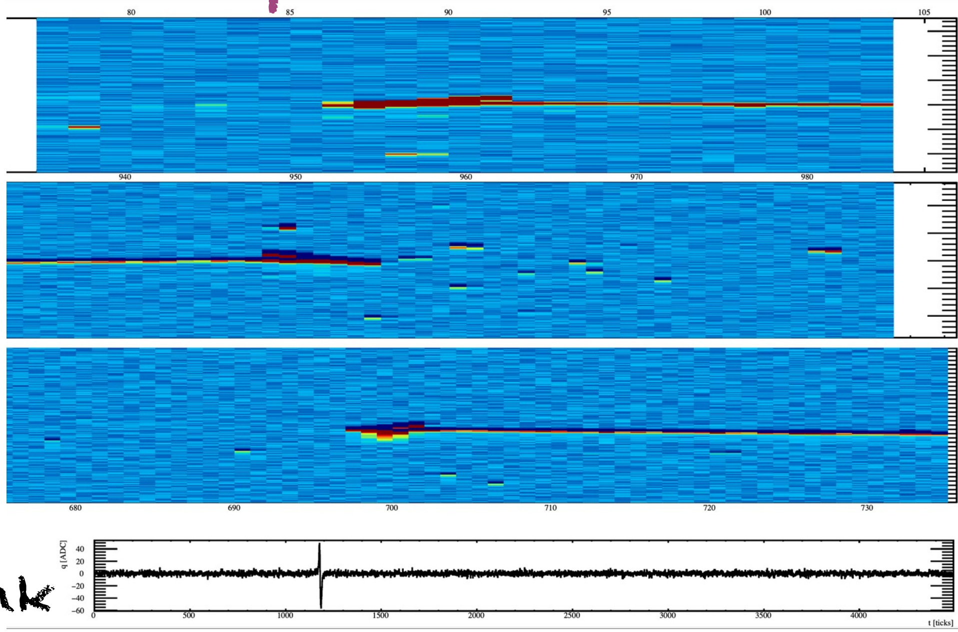
Impact of a Low Threshold Detector

- **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



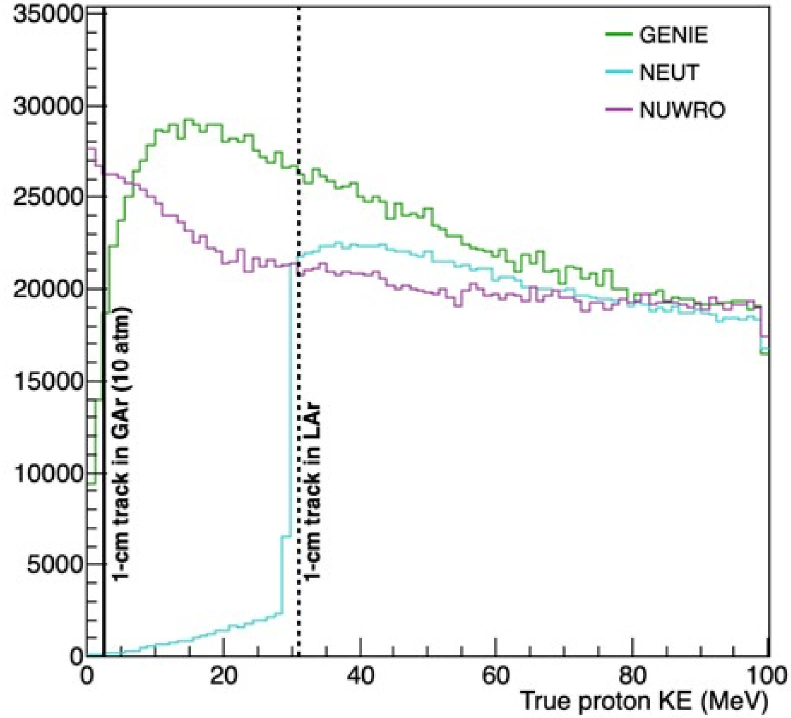
T. Junk

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



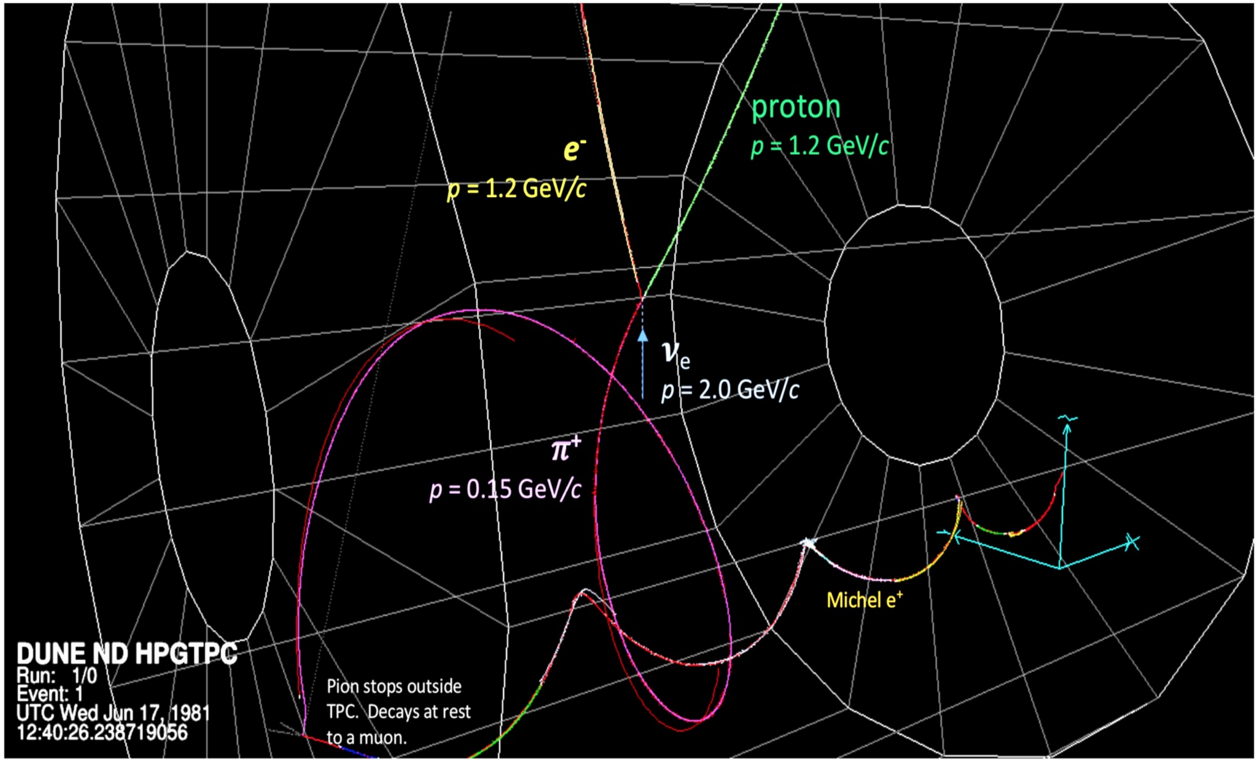
A Wealth of Neutrino Interaction Data

- 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

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

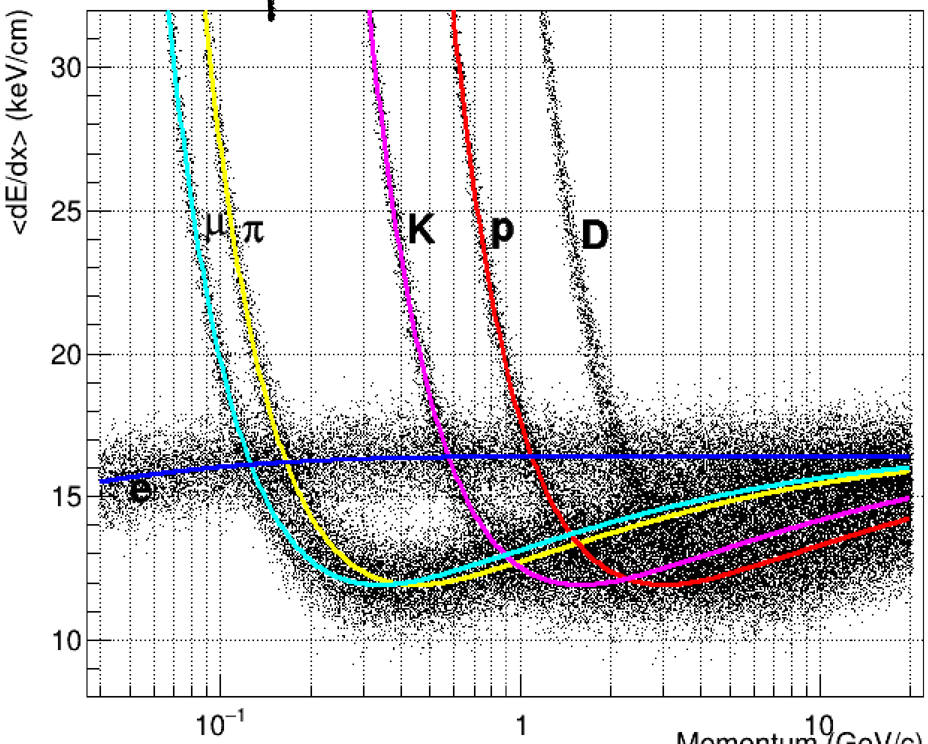
A detailed view of the ν-interaction vertex

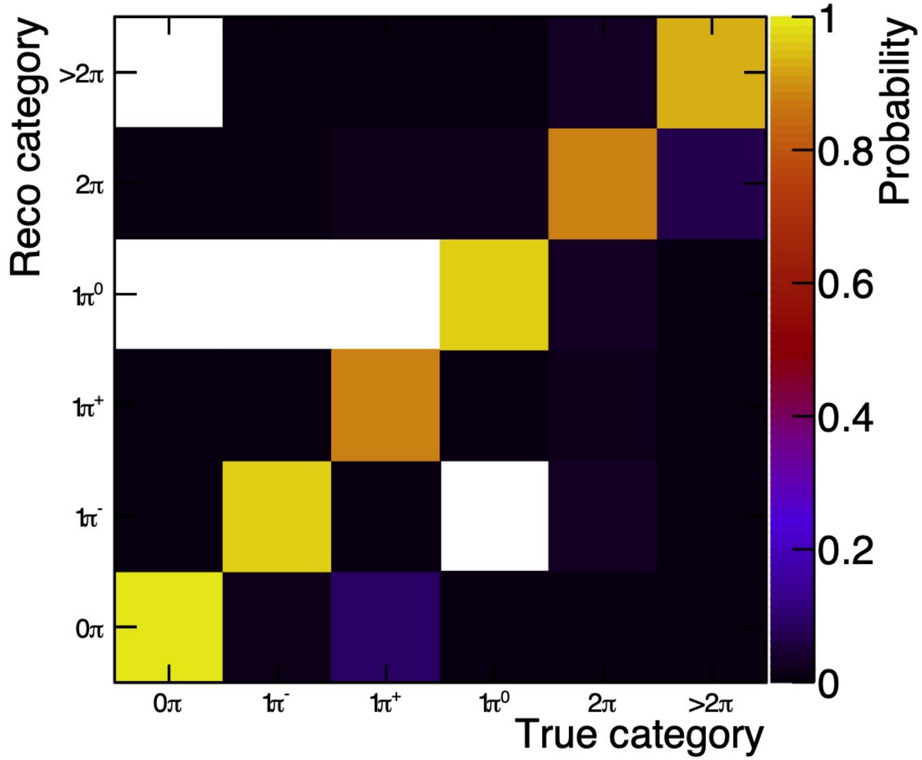


Superb PID for Neutrino Interaction Measurements

- dE/dx resolution: 0.8 keV/cm
- Excellent PID combined with low threshold feature allows ND-GAr to help with correctly identifying neutrino interactions that have pions in the final state of the neutrino interaction

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

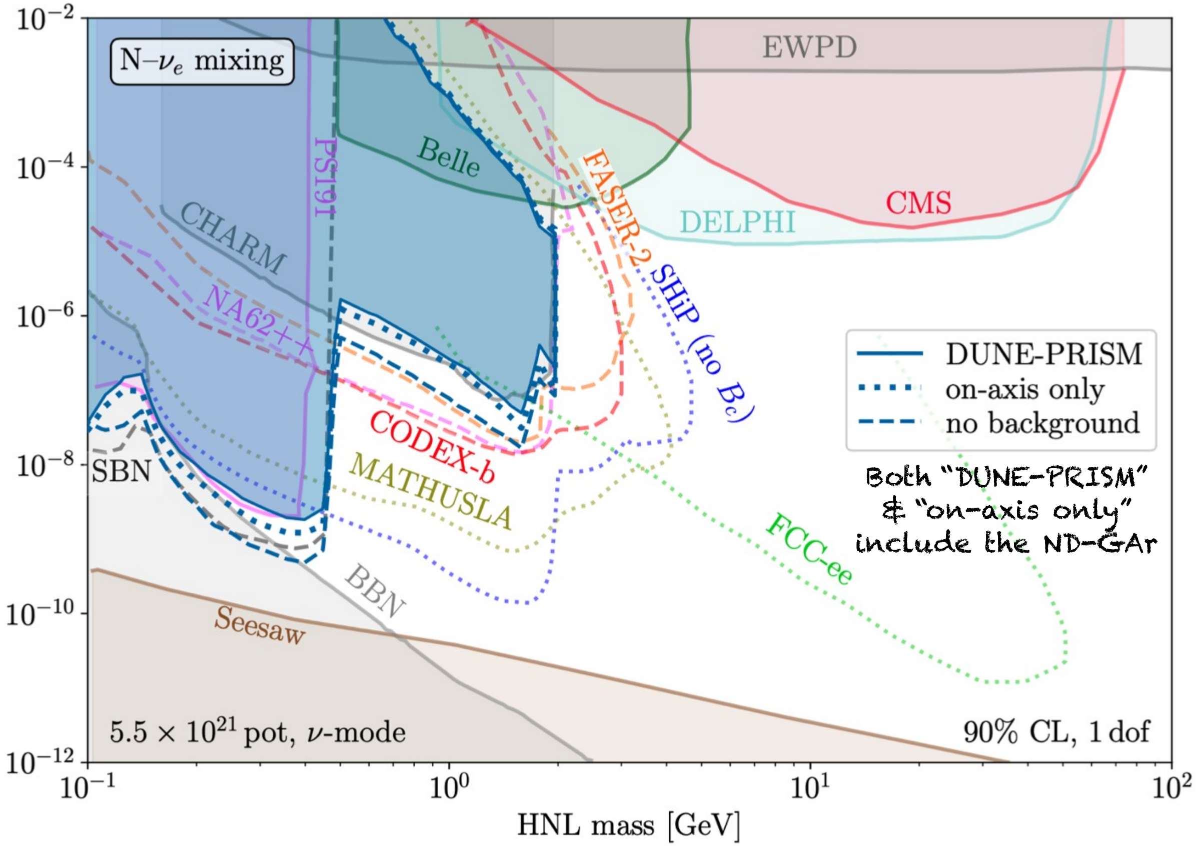




DUNE Collaboration, A. Abed Abud et al. Instruments 5 no. 4, (2021) 31, arXiv:2103.13910 [physics.ins-det].

BSM Reach

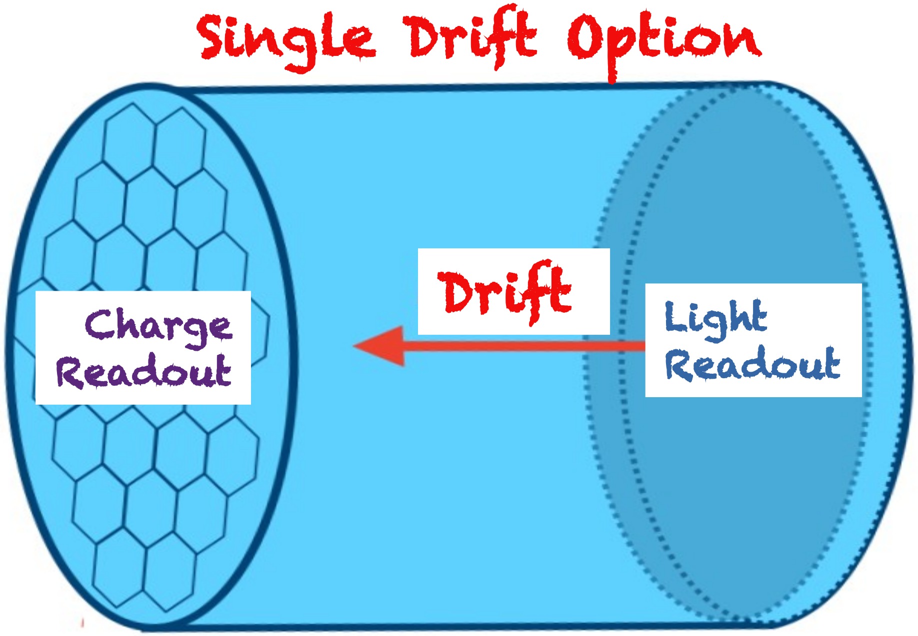
- In addition to precise measurements of neutrino-argon cross sections, ND-GAr also enables a rich BSM physics program in DUNE, e.g. rare events such as:
  - Neutrino tridents
  - Heavy neutral leptons, HNL
  - Anomalous Tau neutrinos
  - Light dark matter
  - Heavy axions



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

R&D Efforts

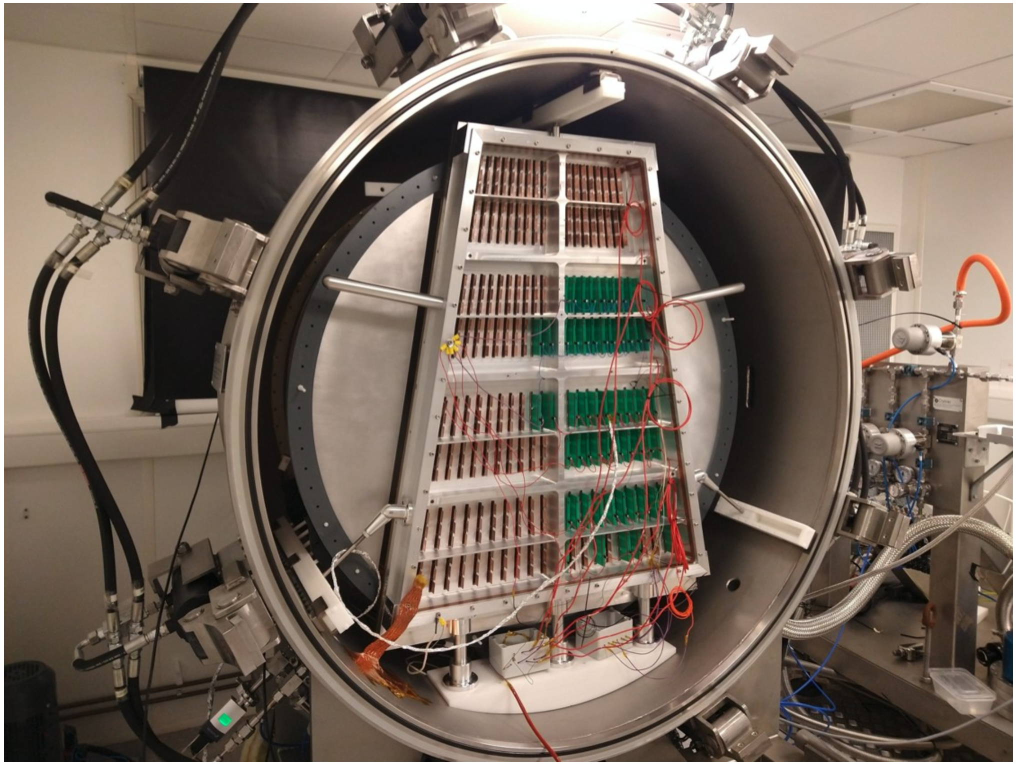


- On-going R&D thrusts of HPgTPC:
  - TPC amplification, options include acquired ALICE MWPC, GEMs
  - TPC readout, options include SAMPA, LArPix, SiPMs, LAPPDs
  - Gas mixture optimizations

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

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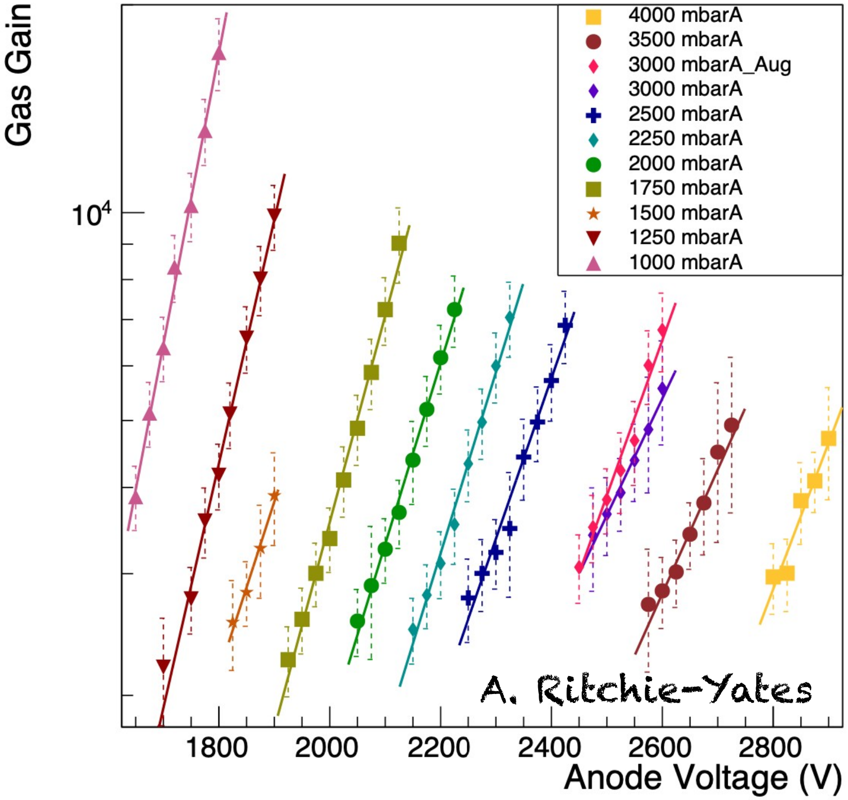
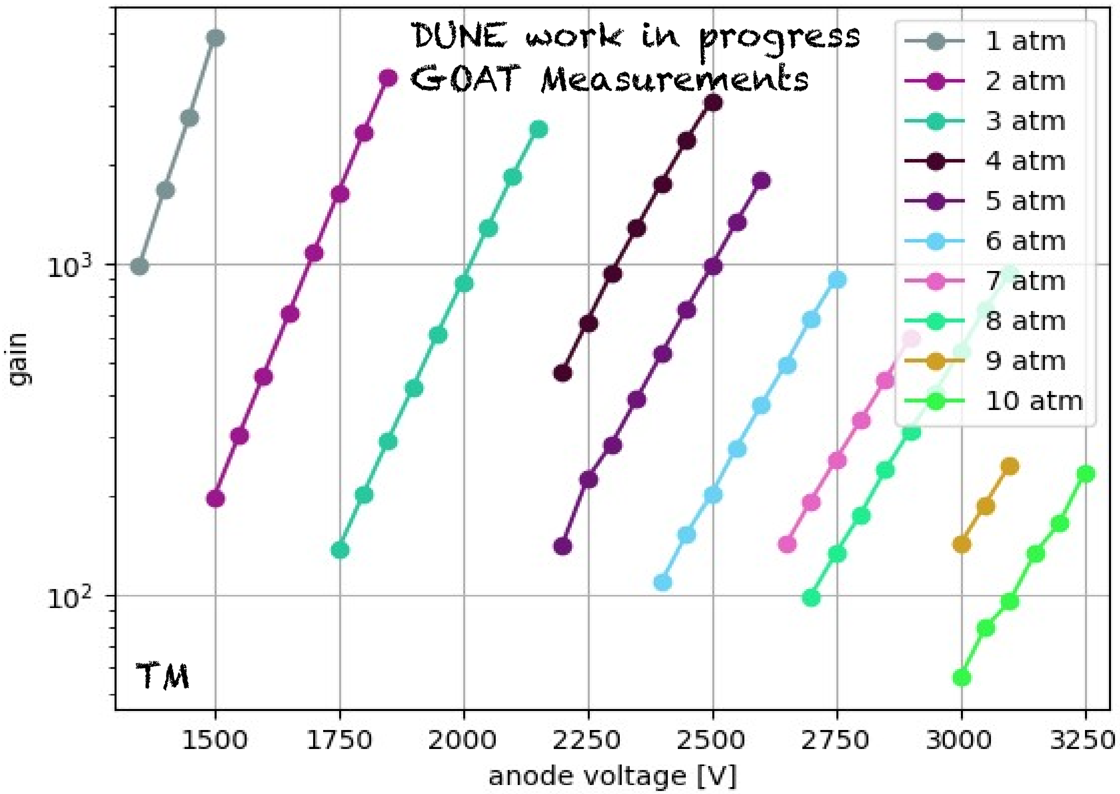
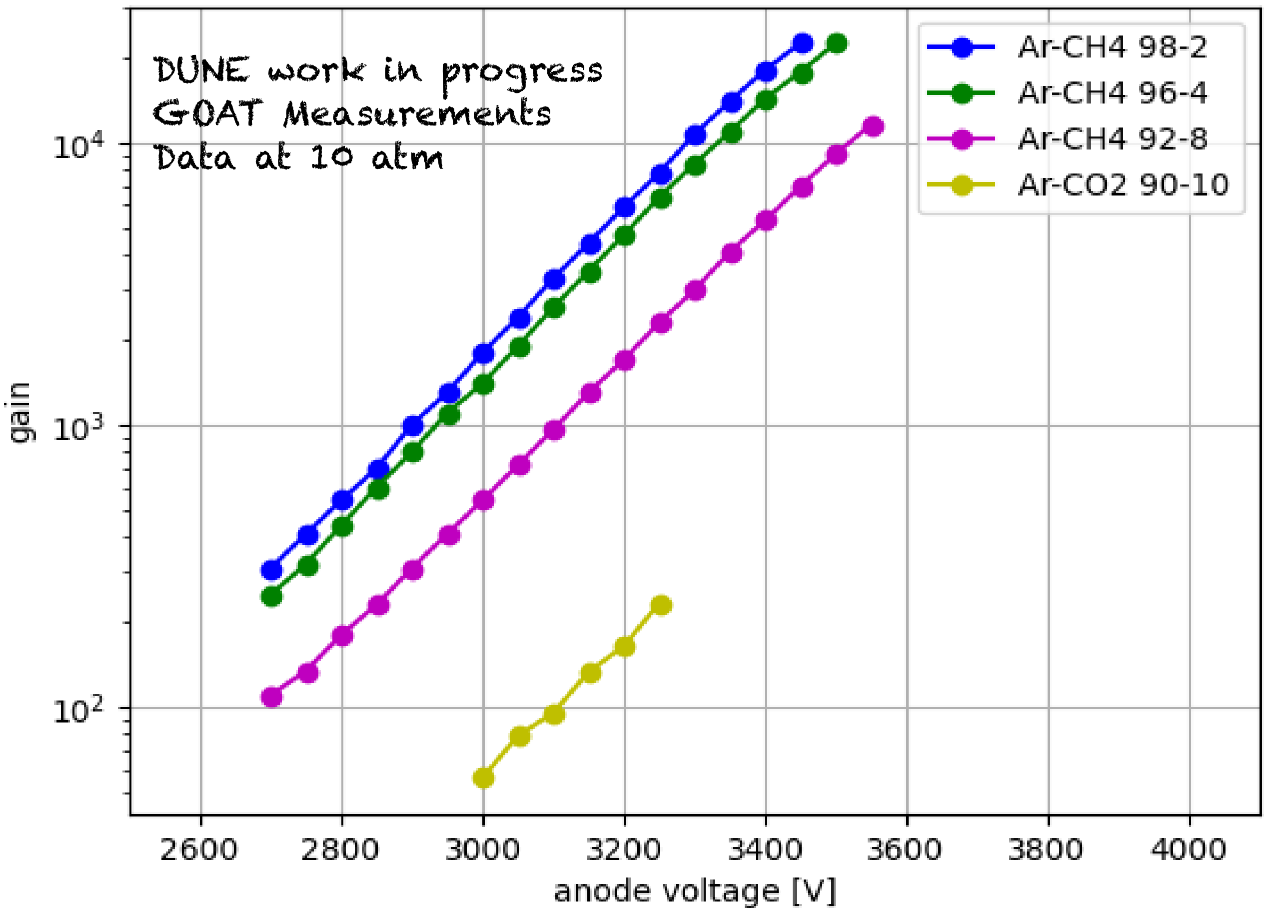
  - Two efforts in US and UK completed a pressure scan of the chambers
  - Chambers able to maintain their **gain** with increasing pressure



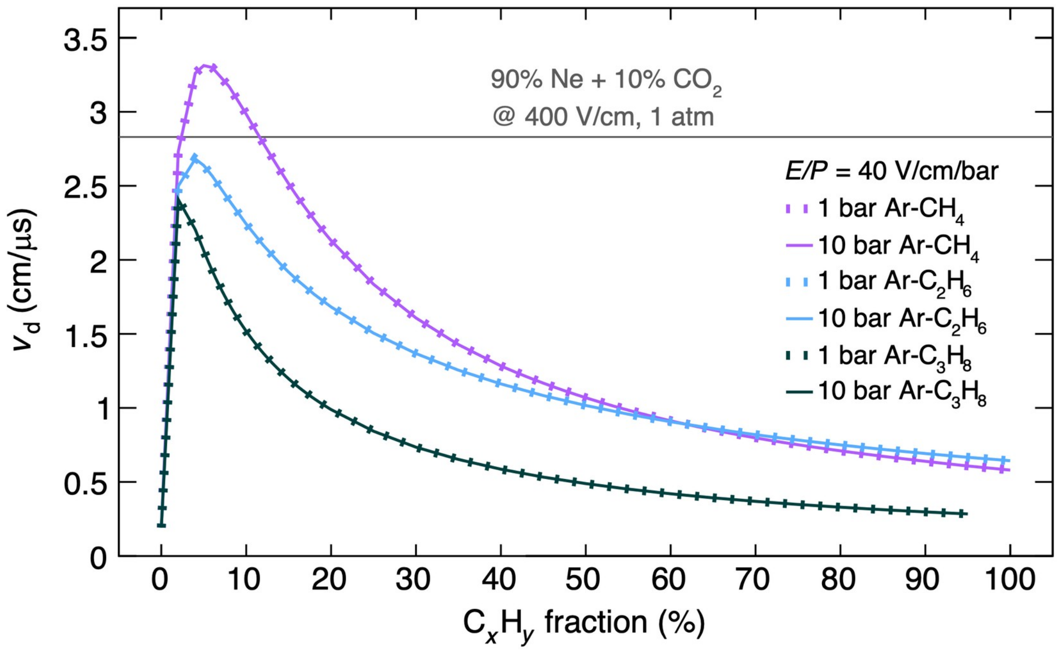


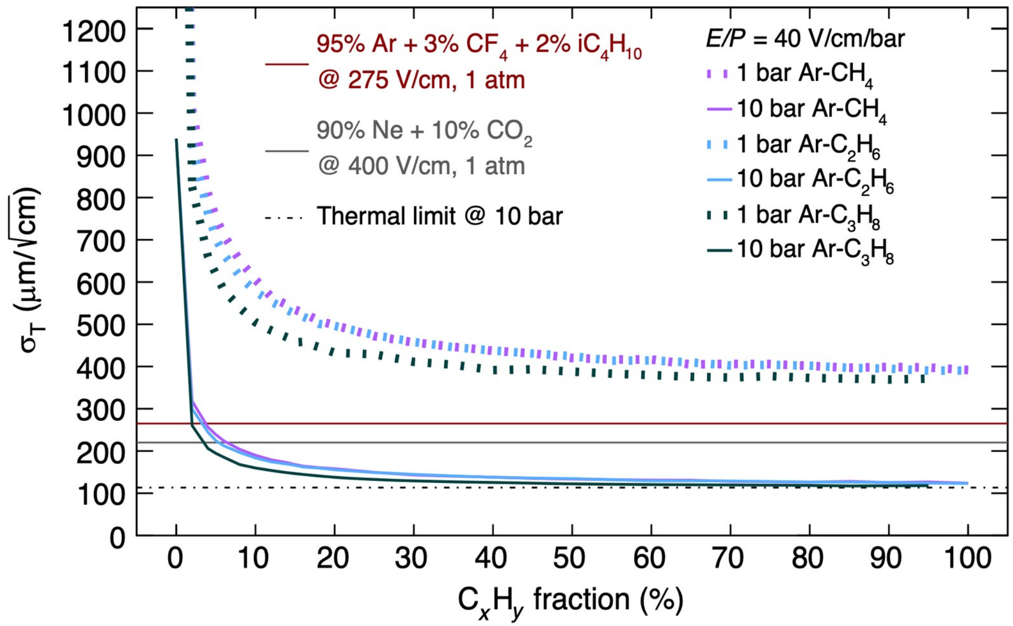
https://doi.org/10.48550/arXiv.2305.08822

- 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



- Reference gas is argon-based with 10% CH_4 admixture (97% of interactions on Ar) but can be optimized:
  - Choice of admixture to optimize the drift velocity and improve spatial resolution (diffusion)

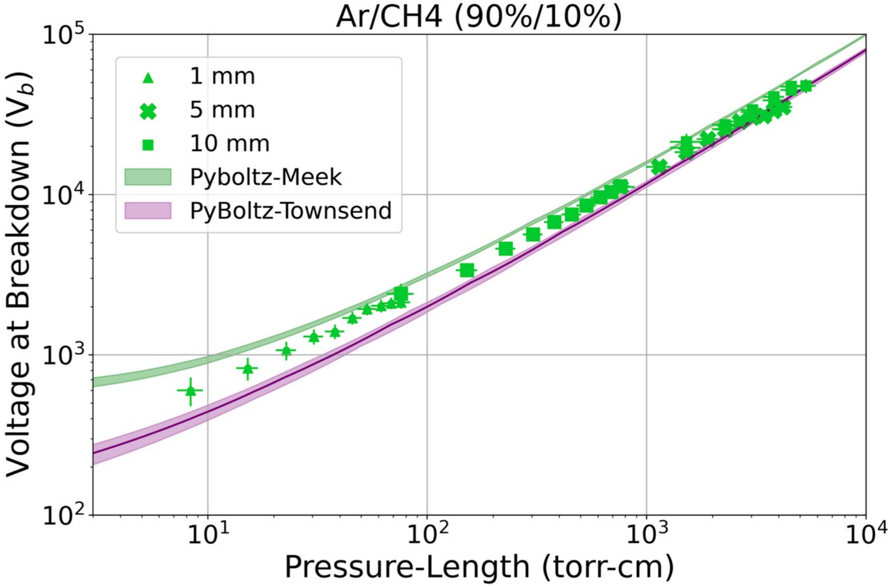




P. Hamacher-Baumann et al., Phys. Rev. D 102, 033005 (2020)

R&D Efforts – Gas Mixture Choices

- Reference gas is argon-based with 10% CH_4 admixture (97% of interactions on Ar) but can be optimized:
  - Choice of admixture to optimize the 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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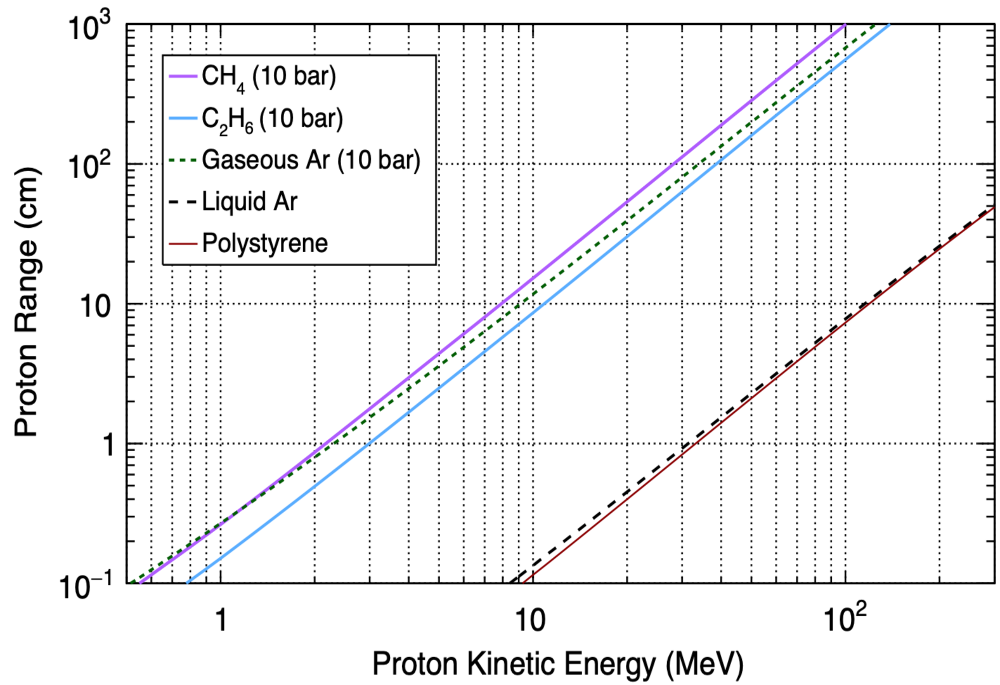
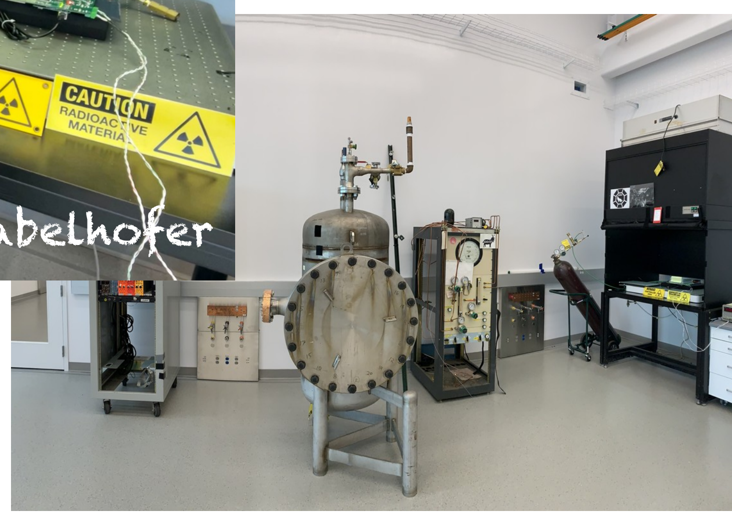
  - Choice of admixture to optimize the drift velocity and improve spatial resolution (diffusion)
  - Maximize gas gain, while minimizing gas electrical breakdown
  - Ability to operate with a hydrogen-rich gas mixture to probe more fundamental neutrino interactions on hydrogen



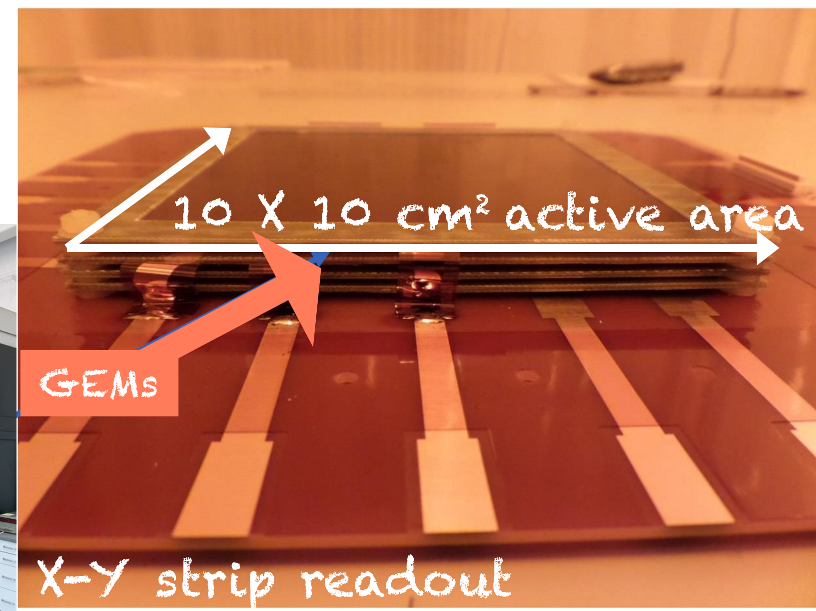
P. Hamacher-Baumann et al., Phys. Rev. D 102, 033005 (2020)

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 at Indiana University, aimed at scanning gain at various pressure set points



Led by Indiana



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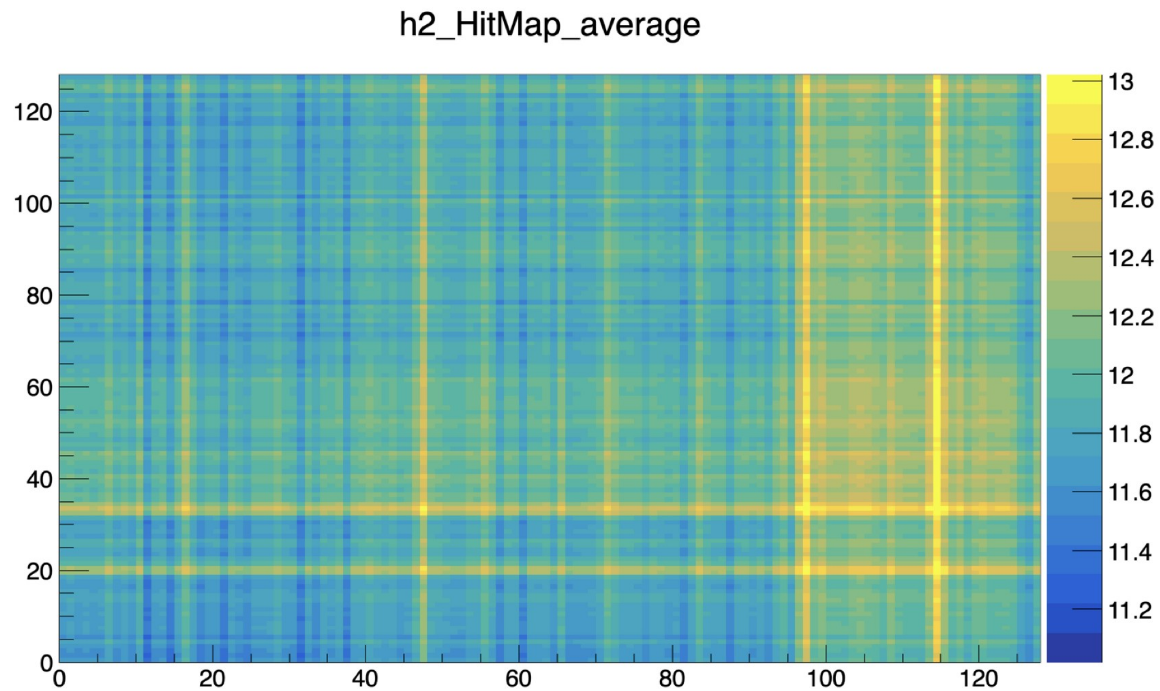

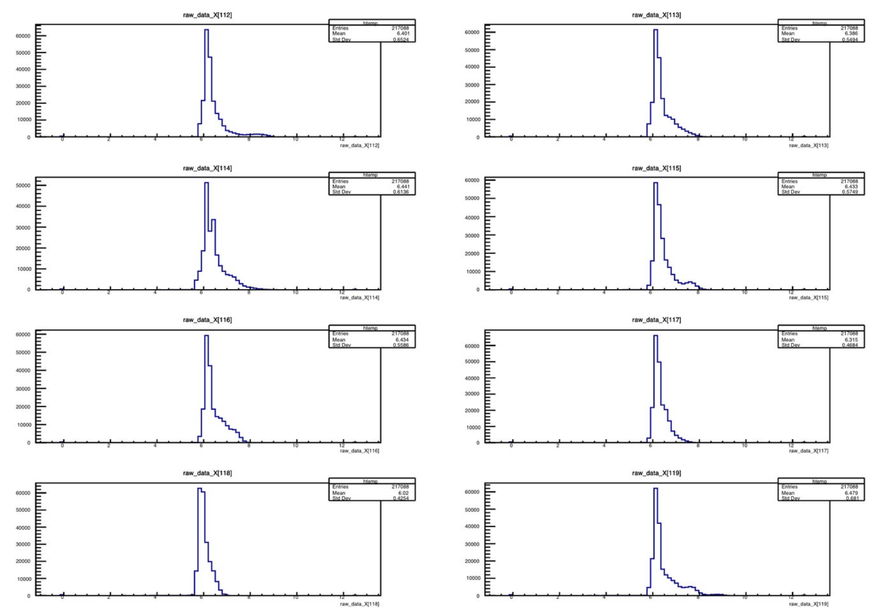

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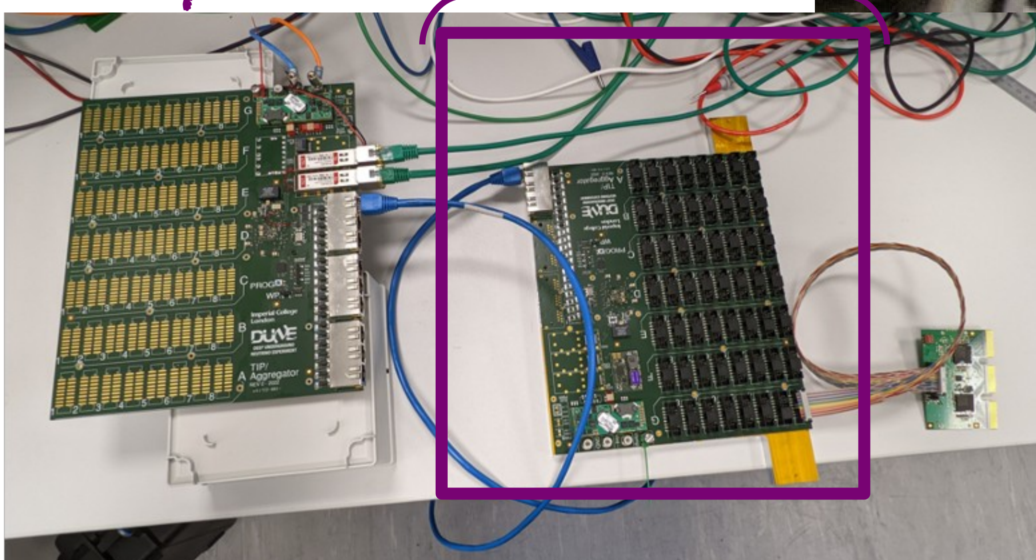
- ThickGEMs are also being considered, led by Liverpool

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



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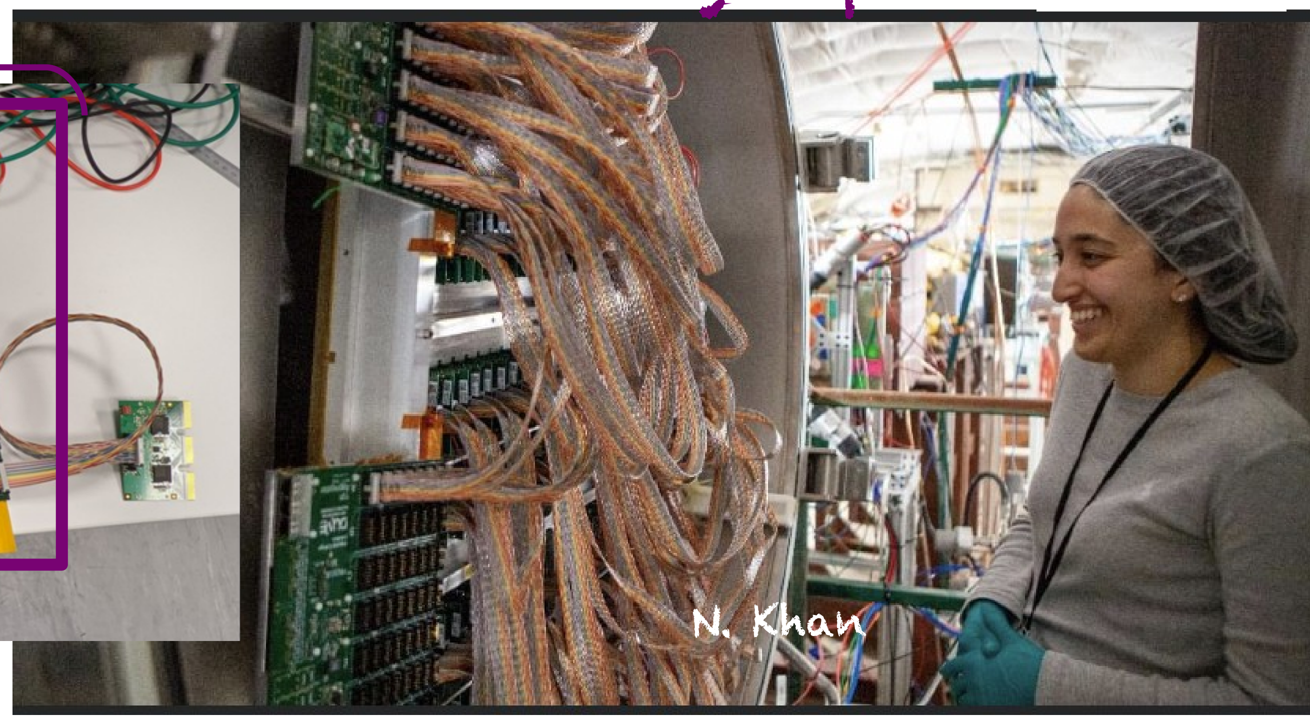
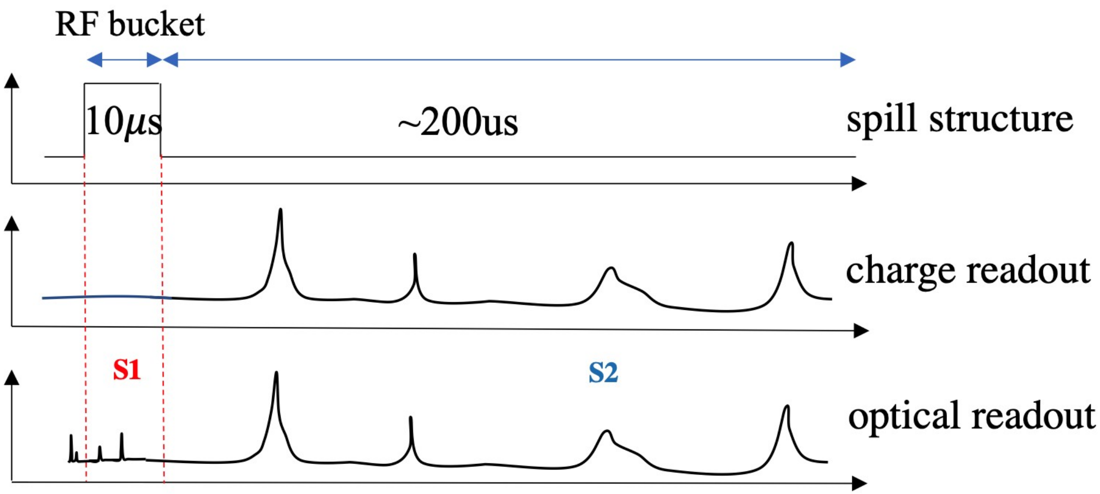
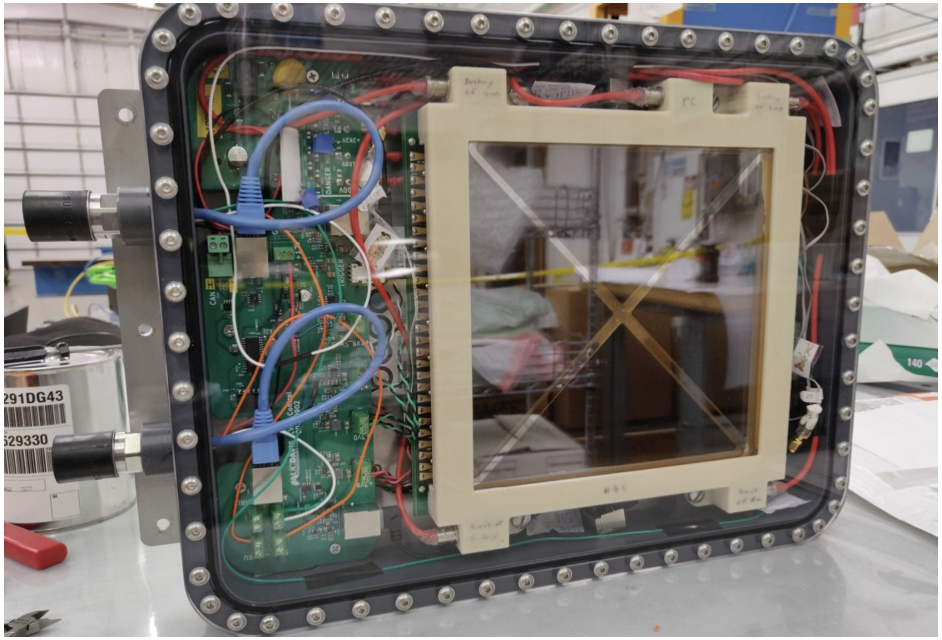


R&D Efforts – TPC Readout & Gas Mixture Choices

- 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 **CF_4**





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!