A Gaseous Argon-Based Near Detector to Enhance the Physics Capabilities of DUNE

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Snowmass Community Summer Study Workshop

DUNE and Neutrino Interactions Session

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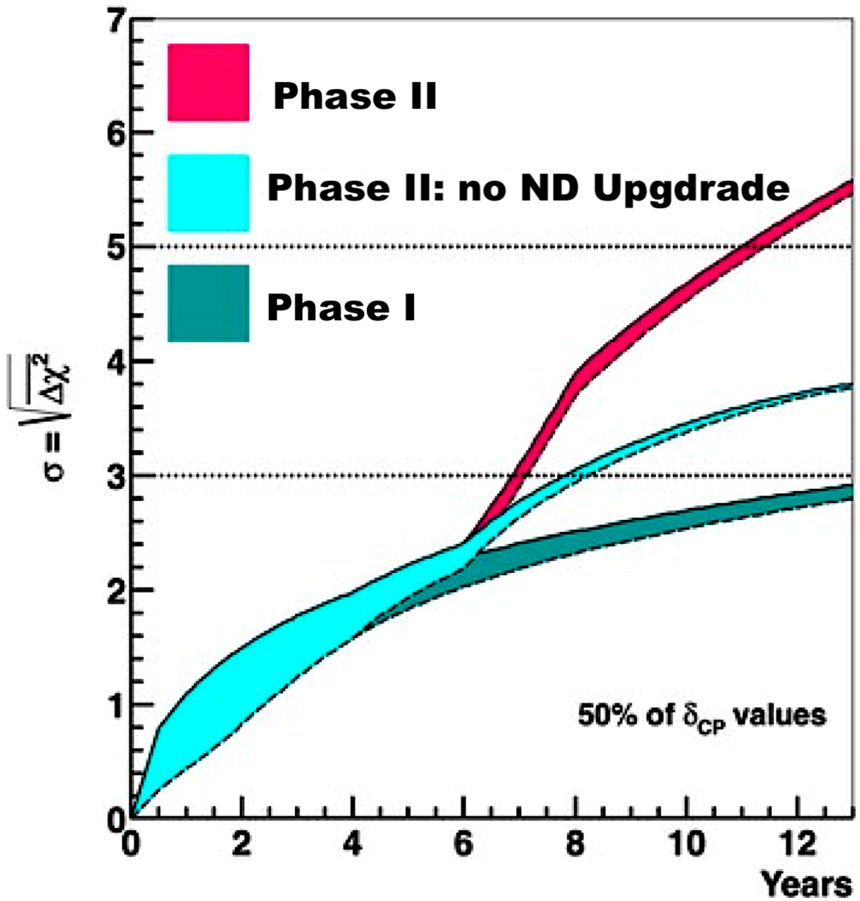
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Fermilab

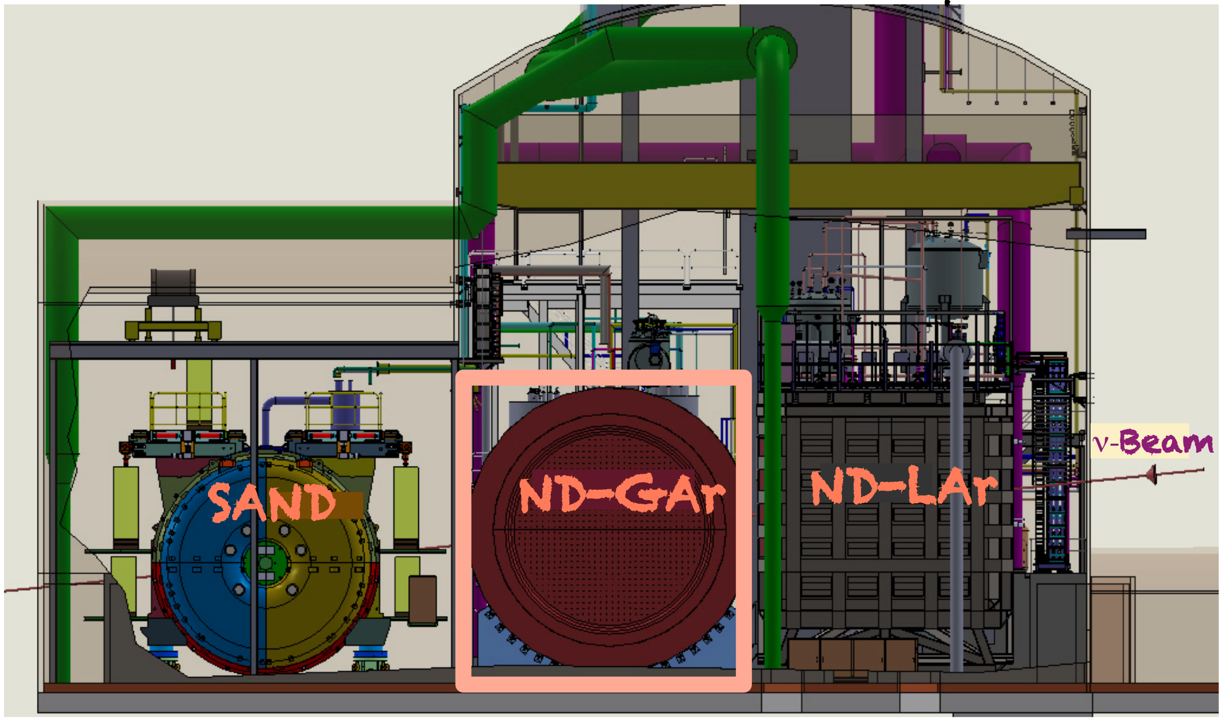
Why a Gaseous-argon Based ND

- **DUNE's gaseous-argon based ND, ND-GAr (Phase II, ND Upgrade)** measures ν-Ar interactions with low threshold and high resolution to enable **5σ sensitivity to CP violation** and provides the basis for a comprehensive and a strong BSM program in DUNE



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

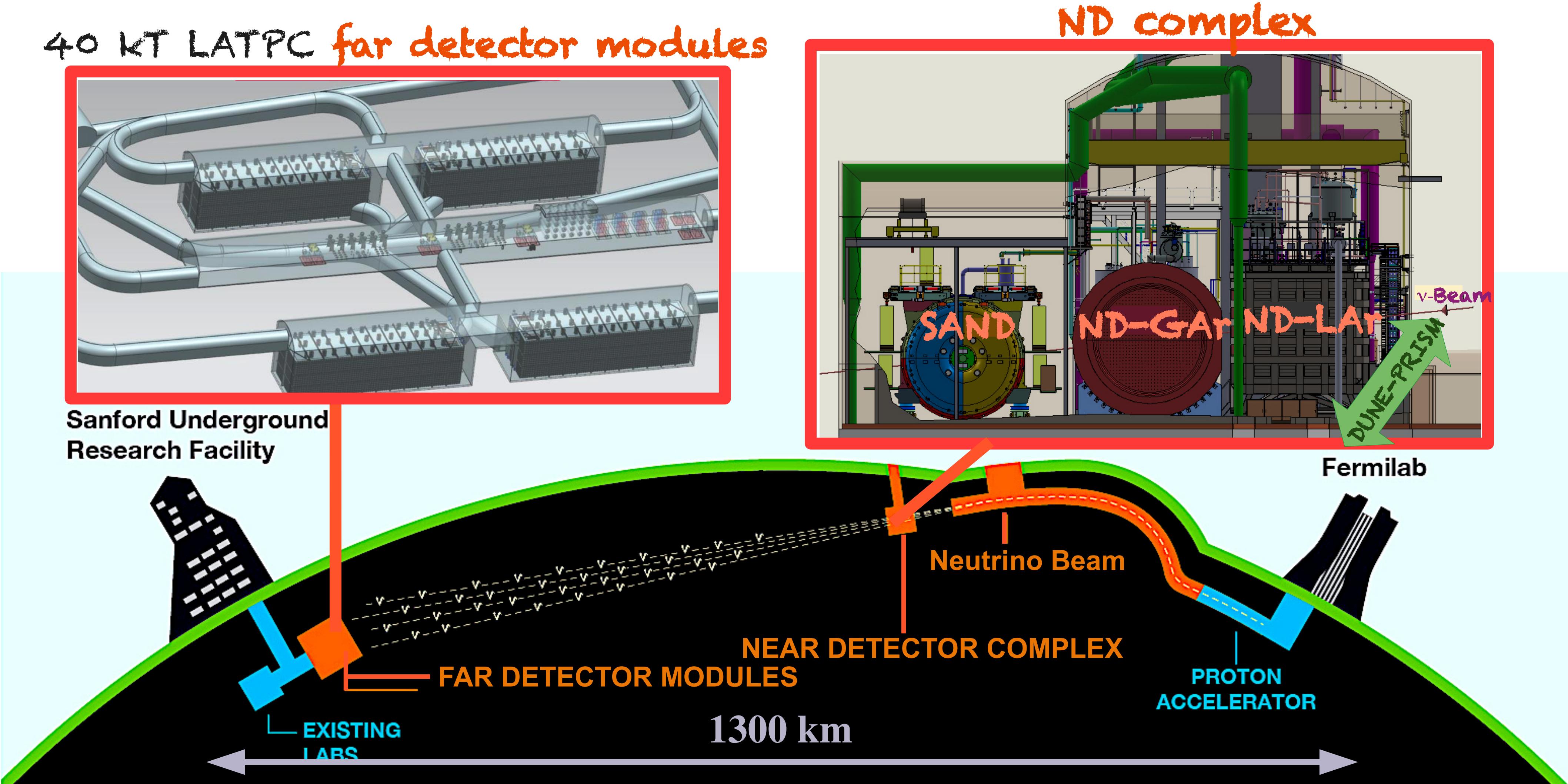
DUNE Near Detector, ND Complex



in the early running, a simpler downstream detector can reconstruct muon tracks exiting ND-LAr (Phase I)

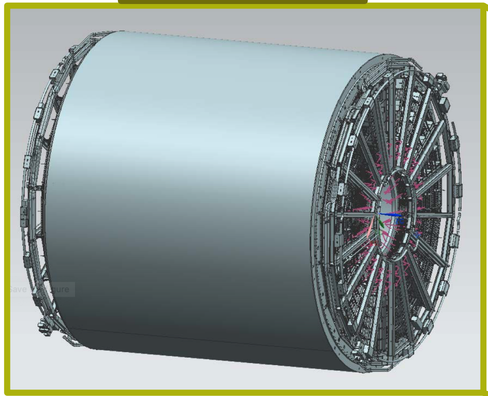
ND-GAr in DUNE

- DUNE's highly capable **ND complex** includes **ND-LAr** (see Z. Vallari's talk *here*), **ND-GAr**, **SAND** (see Z. Ghorbanimoghaddam's talk *here*), & **DUNE-PRISM**:
  - Precisely measure the ν-energy spectrum and ν-flavor composition of the 1.2 MW (upgradable to 2.4 MW) high-intensity, wide-band ν-beam
  - Precisely measure ν-Argon cross-sections (see K. Mahn's talk *here*)

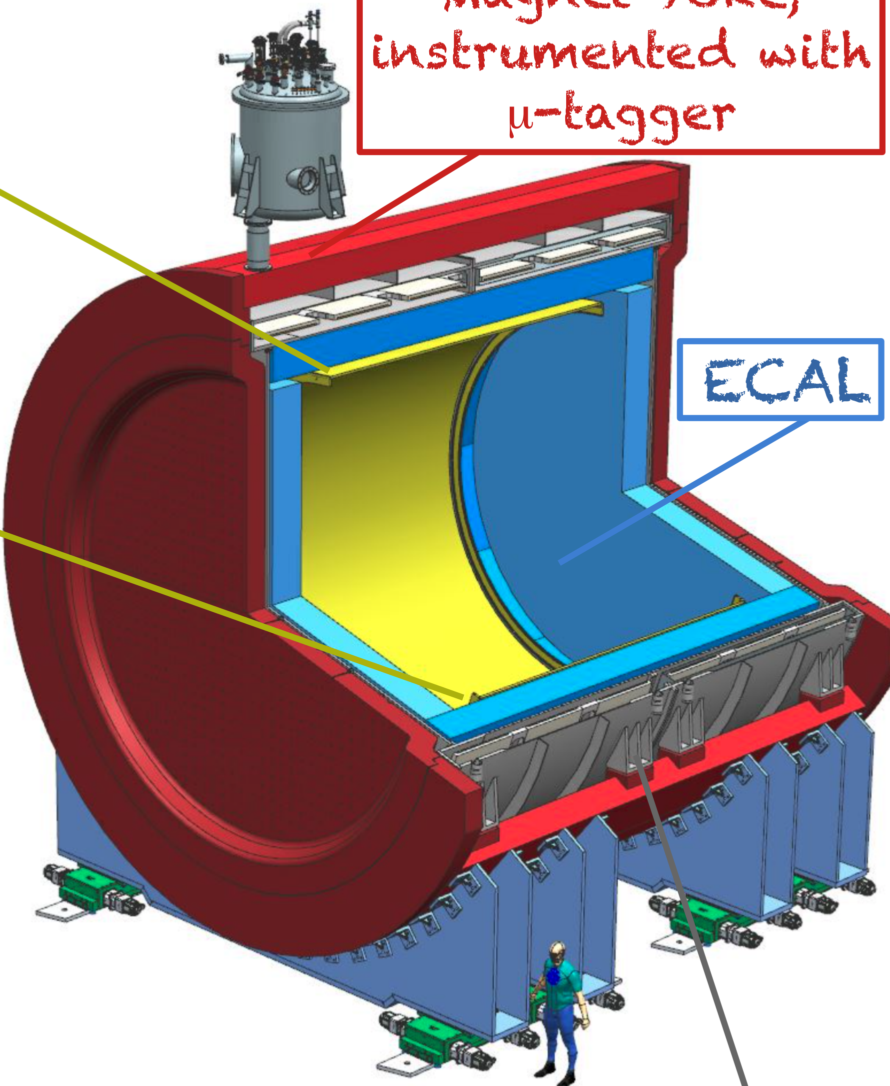


ND-GAr Concept

HPgTPC



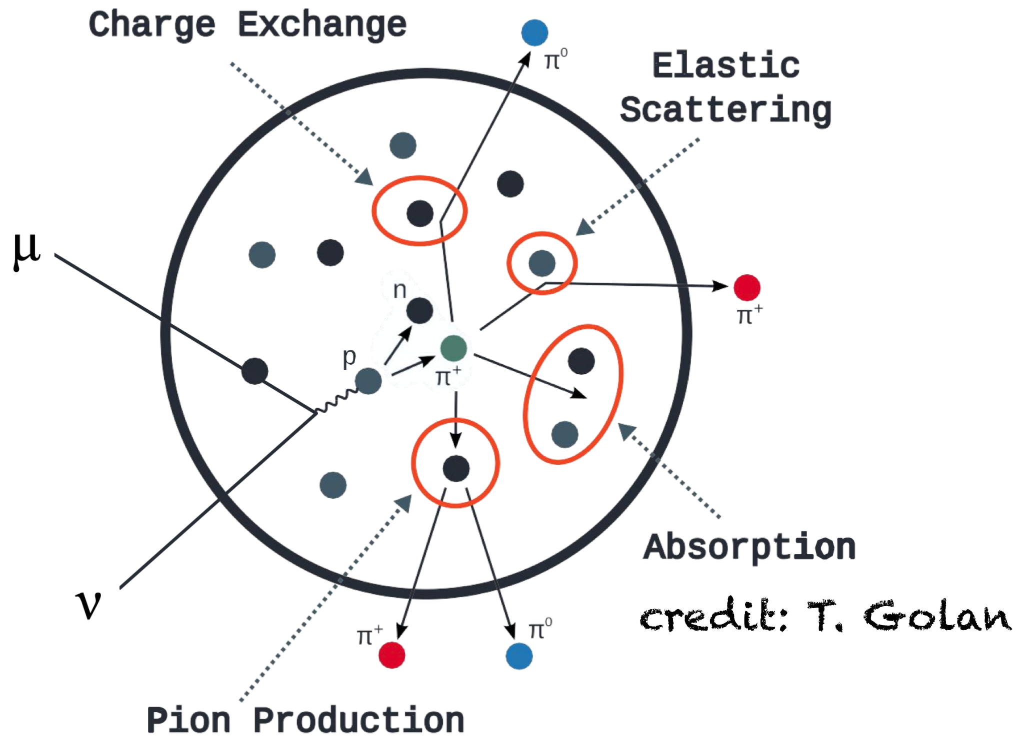
ALICE engineering drawing



- 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
- Main design capabilities:
  - Low threshold
  - Excellent PID, tracking efficiency, momentum resolution
  - 4π coverage
  - Minimal secondary interactions

The Need for the 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
  - Introduces uncertainties in neutrino energy reconstruction and neutrino event rate estimation which need to be constrained



Examples from Existing Experiments

- **Cross sections/neutrino interaction model uncertainties** from existing experiments (all using high threshold detectors) are too large for DUNE
- We need to do better – low threshold ND-GAr can help

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

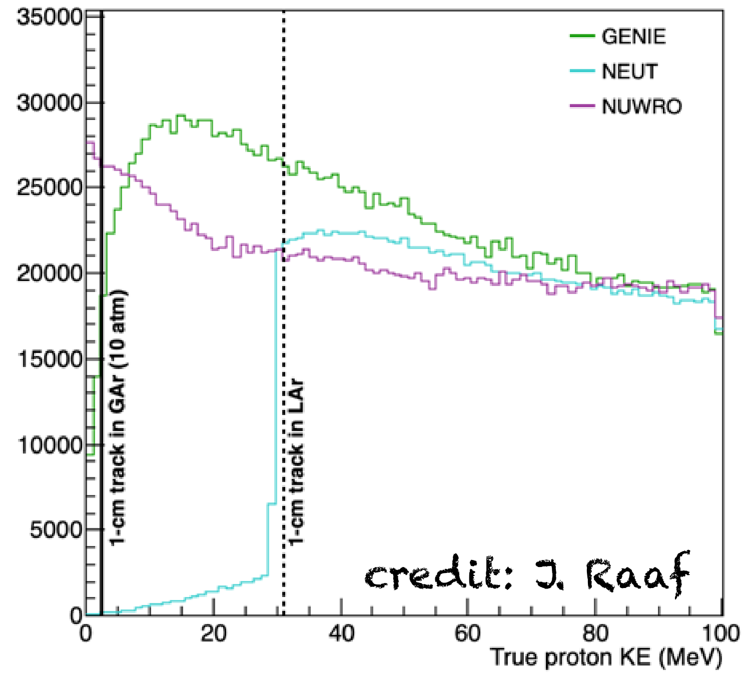
NOvA https://doi.org/10.1103/PhysRevLett.123.151803

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

The Need for the Low Threshold ND-GAr

- Lower threshold of **ND-GAr's HPgTPC** than **ND-LAr**:
  - Leads to high sensitivity to low energy protons or pions:
  - Reveals discrepancies between neutrino event generators, getting us closer to choosing more accurate neutrino-nucleus interaction models and constraining uncertainties in neutrino oscillation measurements

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



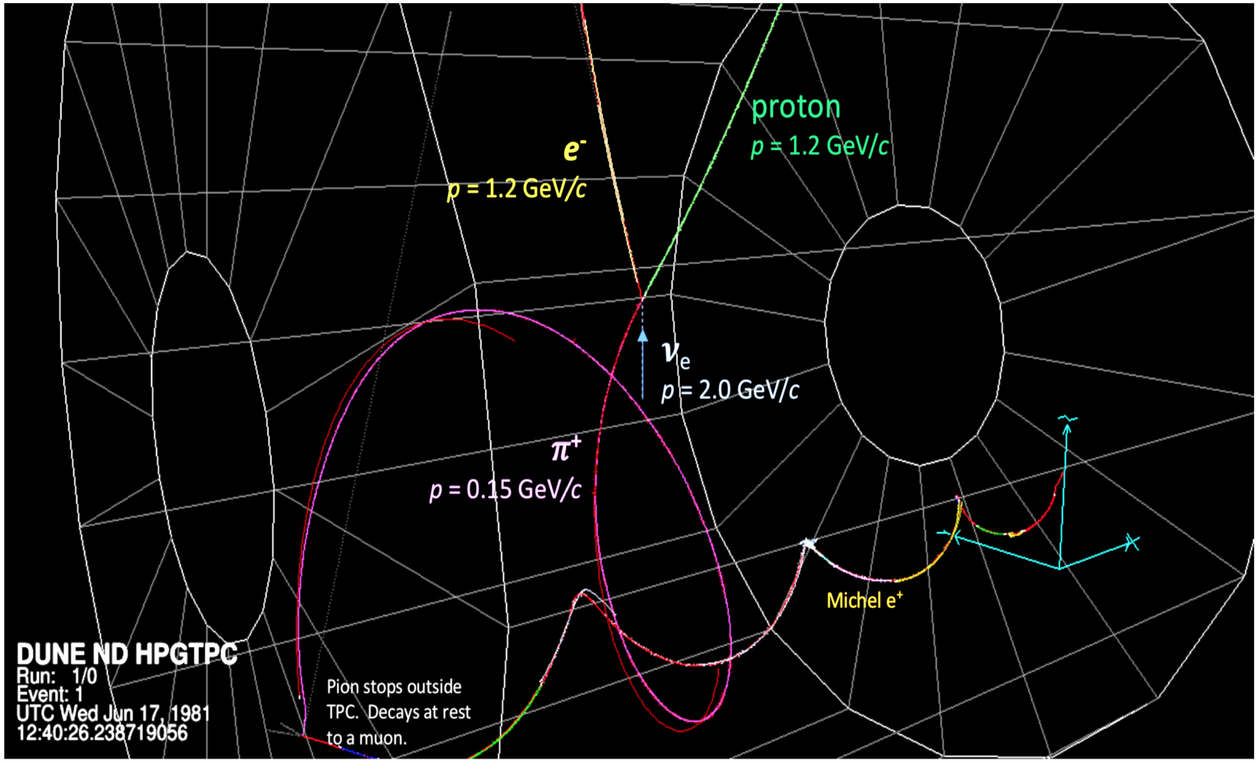
A Wealth of ν-Argon Interaction Data

- 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

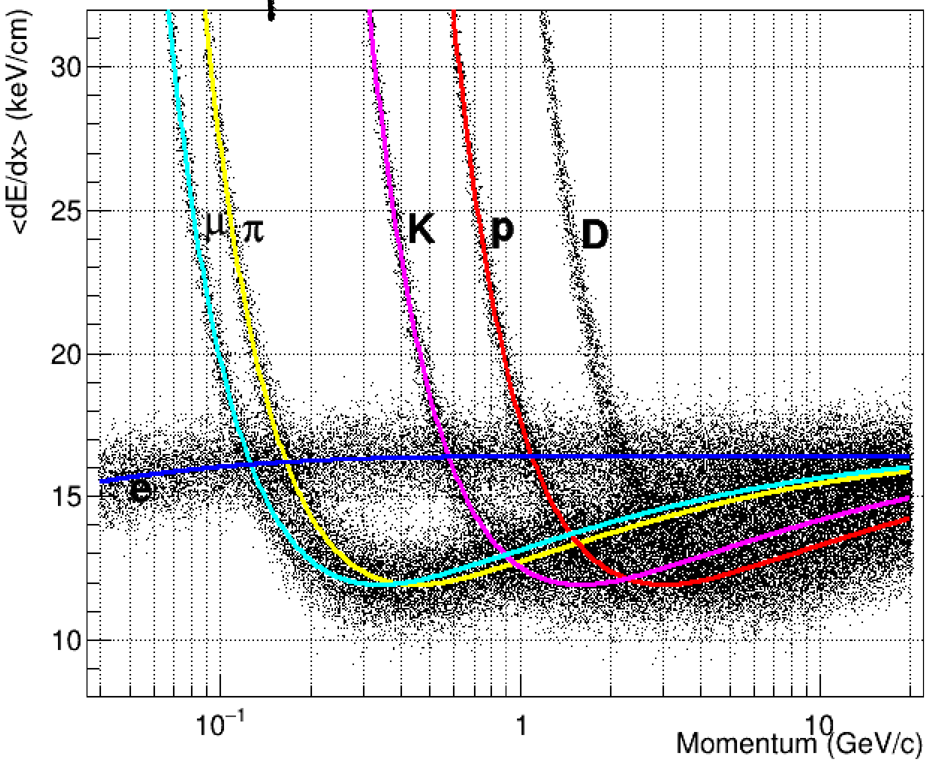
A detailed view of the ν-interaction vertex

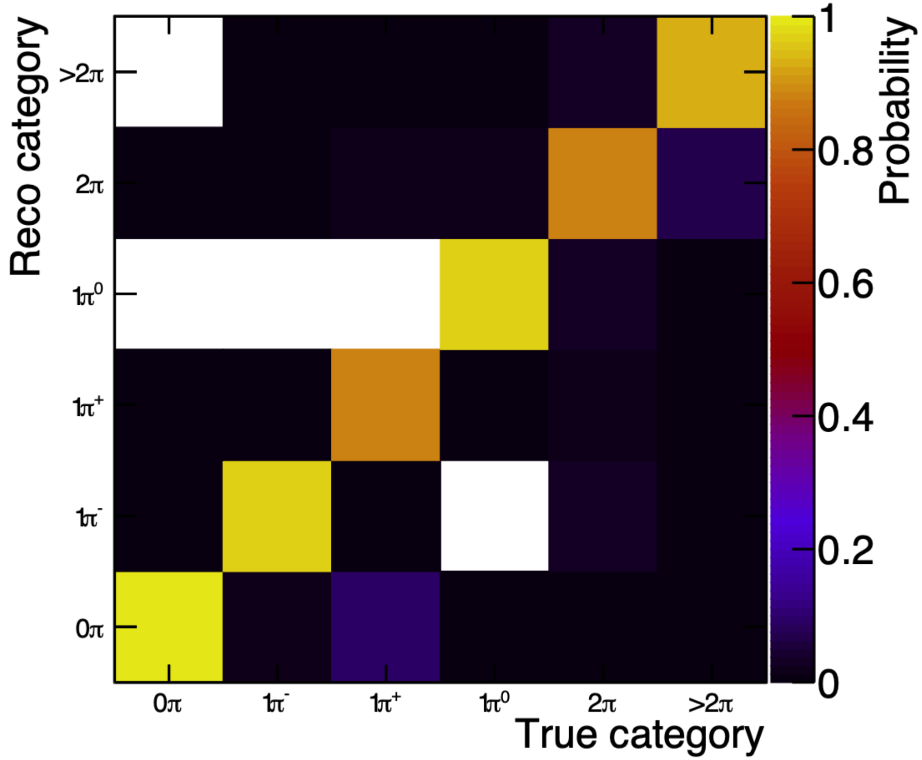


Superb PID for ν-Ar Interaction Measurements

- 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

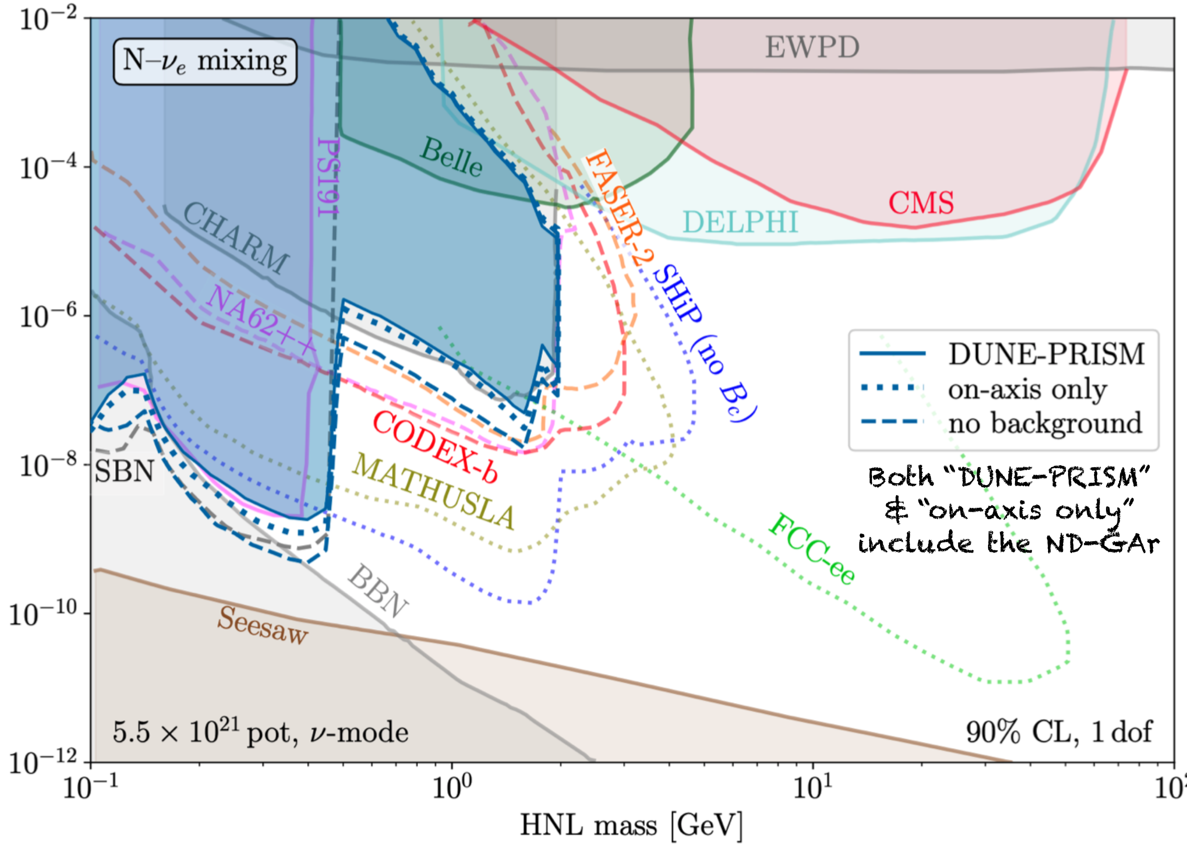




DUNE Collaboration, A. Abed Abud et al. Instruments 5 no. 4, (2021) 31, arXiv:2103.13910 [physics.ins-det].

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

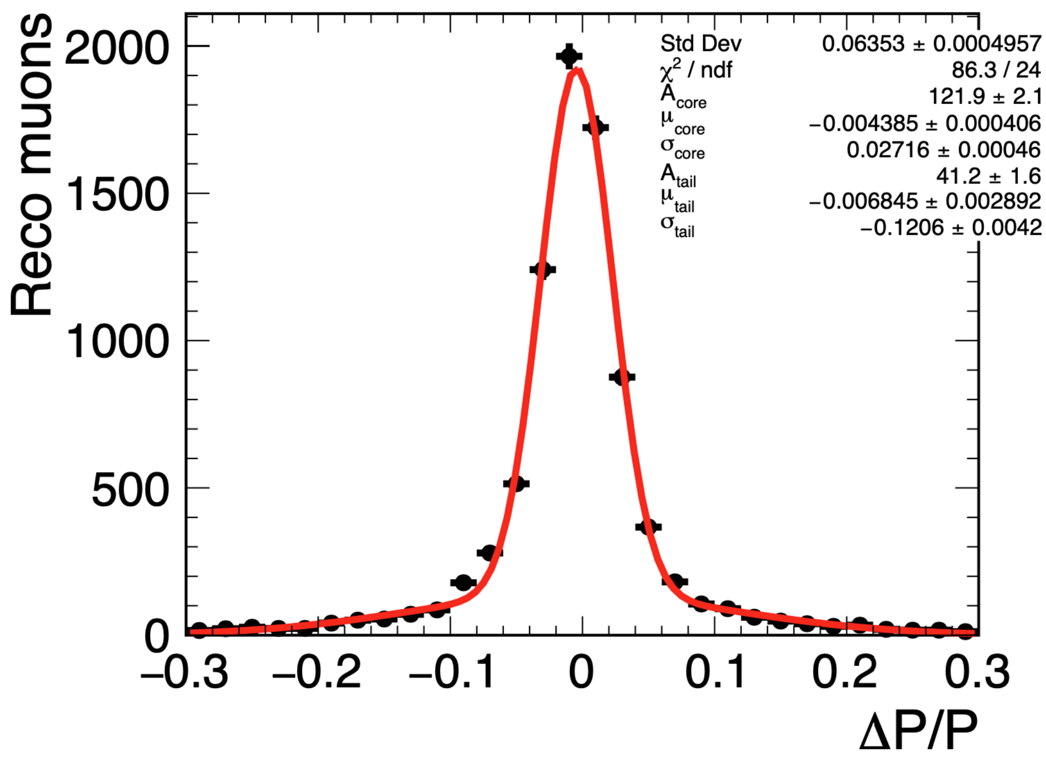


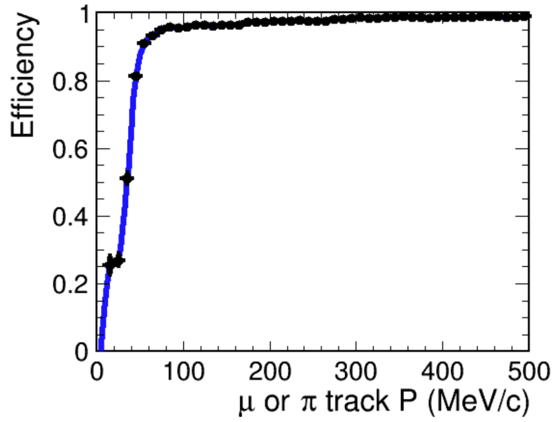
Both "DUNE-PRISM" & "on-axis only" include the ND-GAr

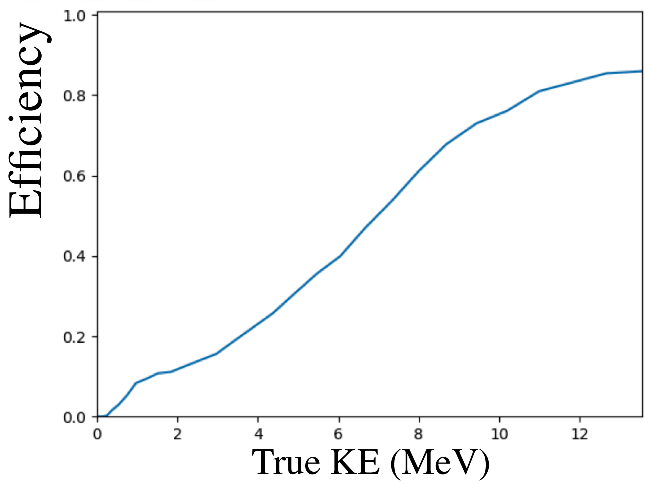
M. Breitbach, L. Buonocore, C. Frugiuele, J. Kopp and L. Mittnacht, Searching for physics beyond the standard model in an off-axis dune near detector, 2102.03383

Projected Performance

- A full end-to-end simulation and reconstruction already exists (GArSoft)!
  - Momentum resolution and tracking efficiency from a sample of muon neutrino events: **2.7%** & **>90% for tracks with >40 MeV/c momenta**, respectively
  - Proton tracking efficiency from a sample of isotropic protons at the vertex: **>80% for proton tracks with >10 MeV energies**







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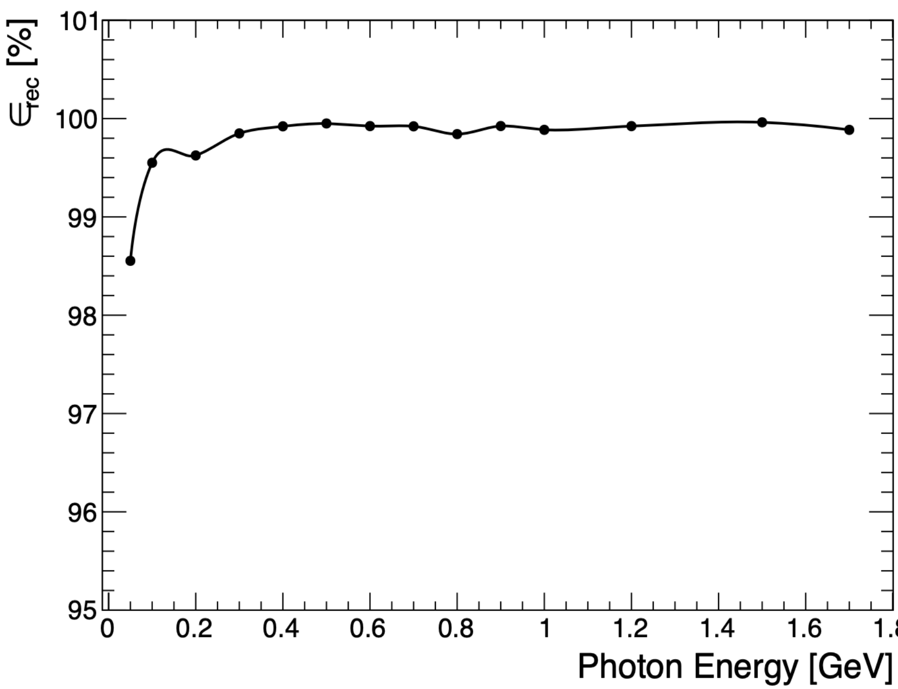
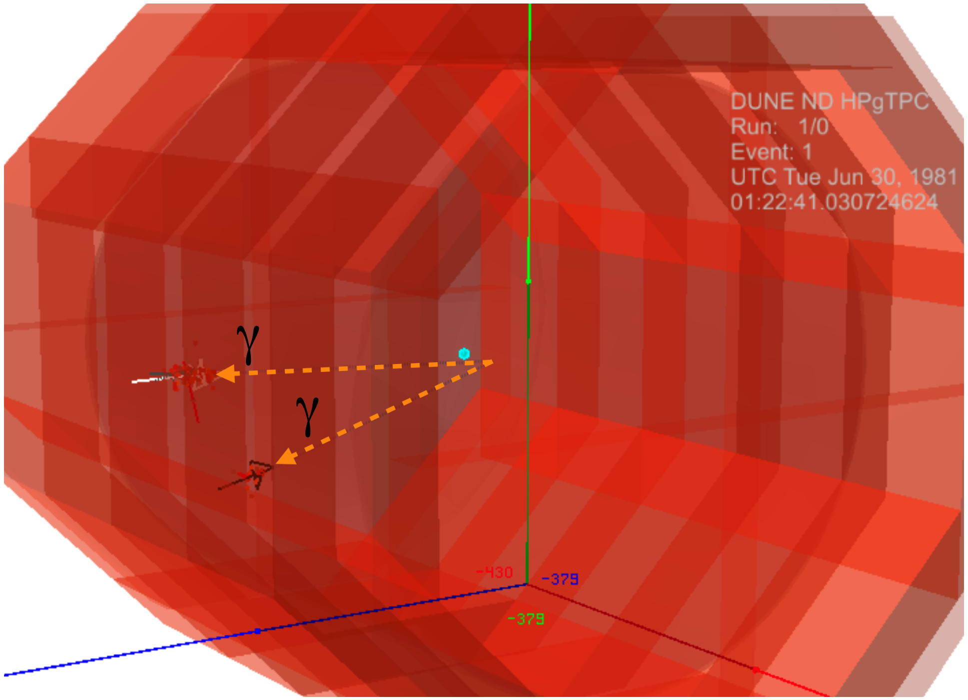
Projected Performance

- ECAL can efficiently tag/reject π^0s, γs (background to electron-neutrinos), neutrons – without ECAL, sensitivity to neutral particles is almost non-existent
- Can also tag/reject outside of fiducial volume backgrounds using timing





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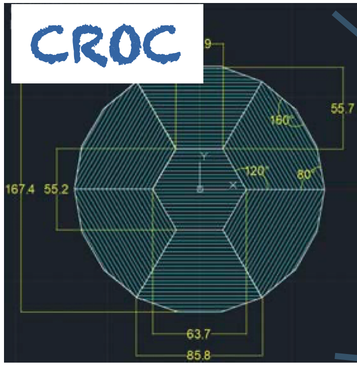
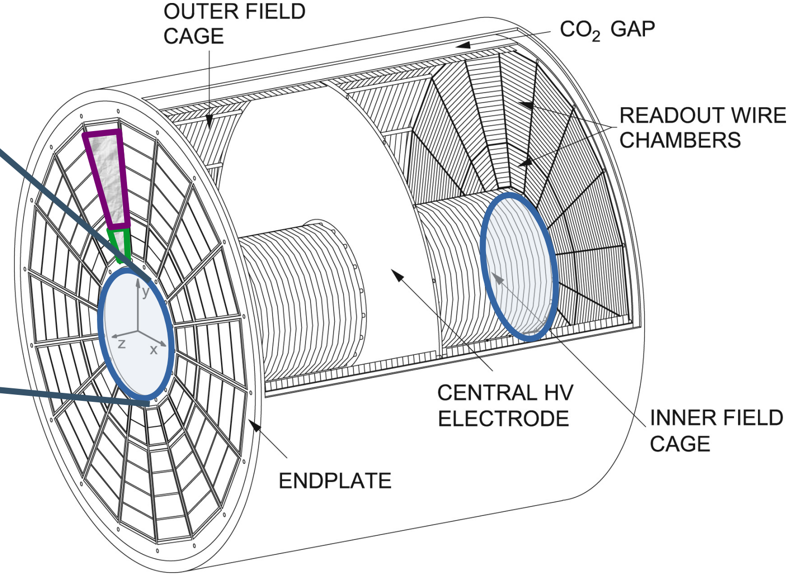
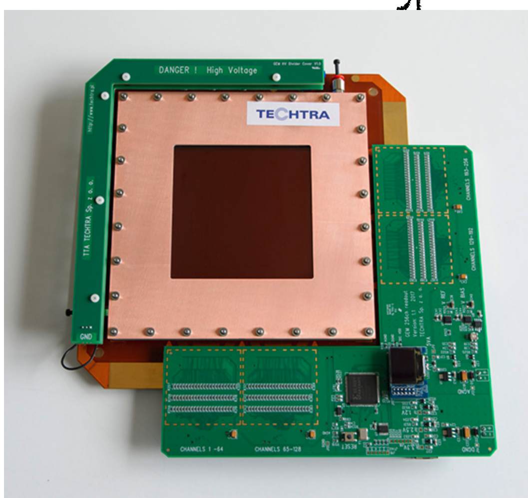
R&D Efforts





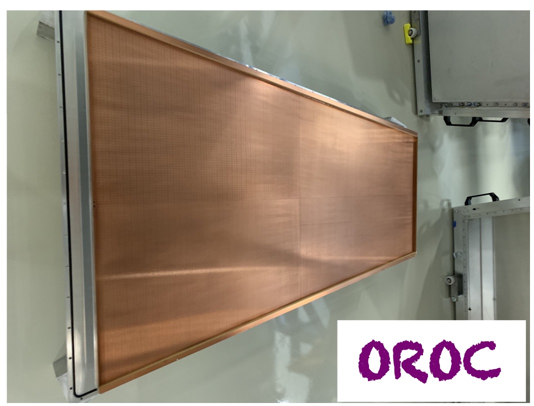
ALICE multi-wire proportional chambers

Example of a Fully-assembled GEM TPC Prototype



Techtra TTA

http://techtra.pl/en/technology/gem-based-detector/

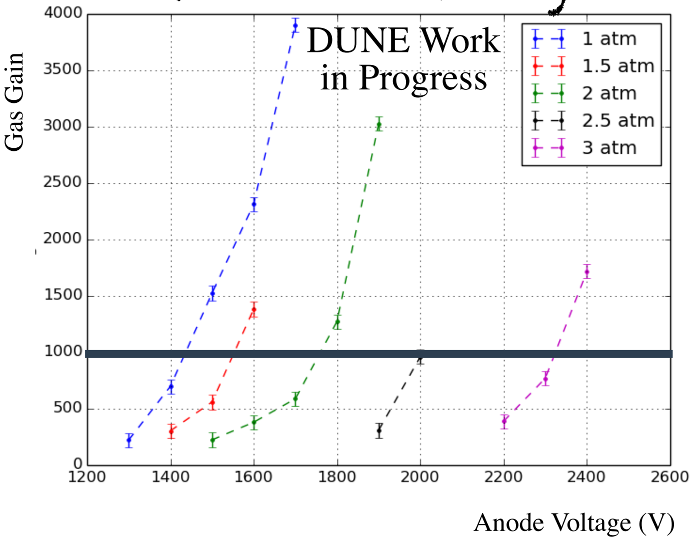


- Bulk of the charge readout R&D focused on optimizing the ALICE **inner (IROC)** and **outer (OROC)** multiwire chambers, **CROC**s need to be built
- But there are opportunities for exploring alternate designs, e.g. **Gas-electron multipliers, GEMs (T. Mohayai FNAL New Initiatives R&D award)**

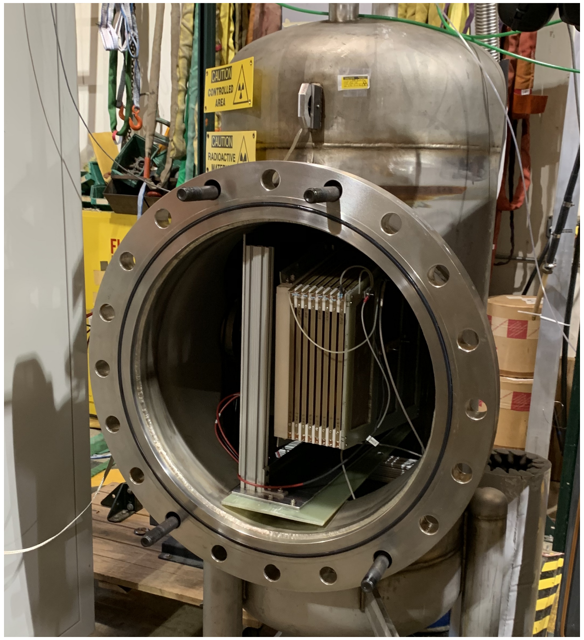
R&D Efforts

- 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)

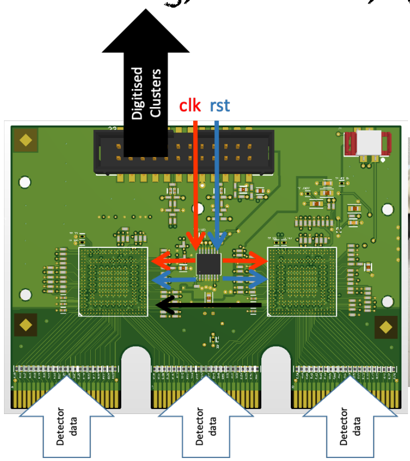
IROC Gain T. Mohayai

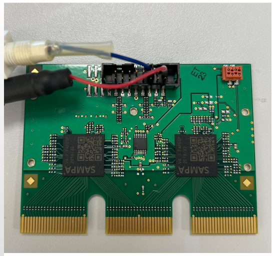


Fermilab Test Stand, housing an IROC

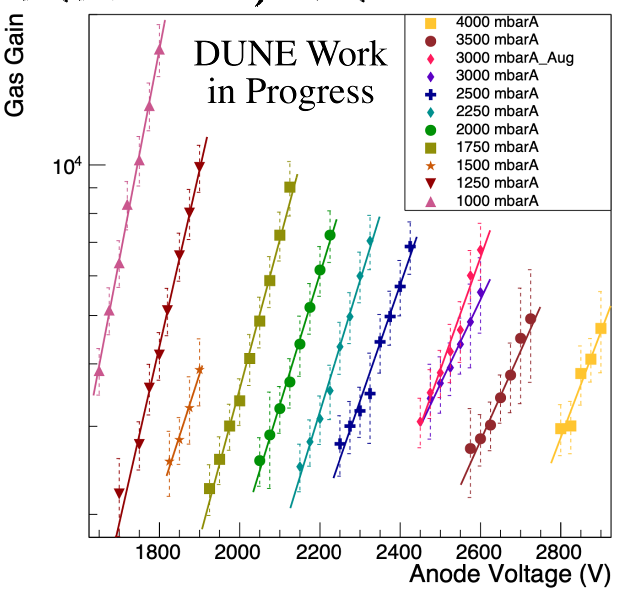


Electronics under development by Pittsburg, Fermilab, & Imperial

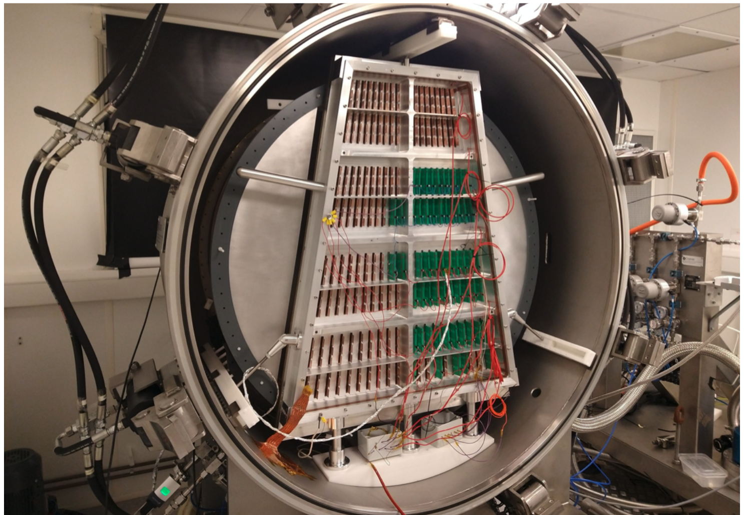


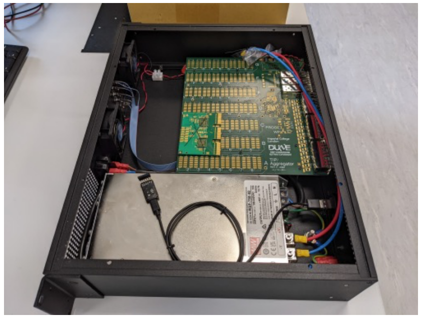


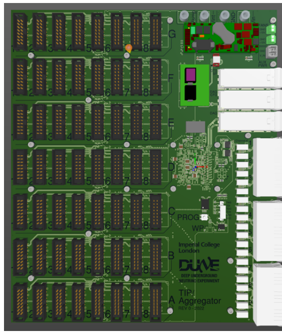
OROC Gain, A. Ritchie-Yates



Royal Holloway Test Stand, housing an OROC, moving to Fermilab Test Beam

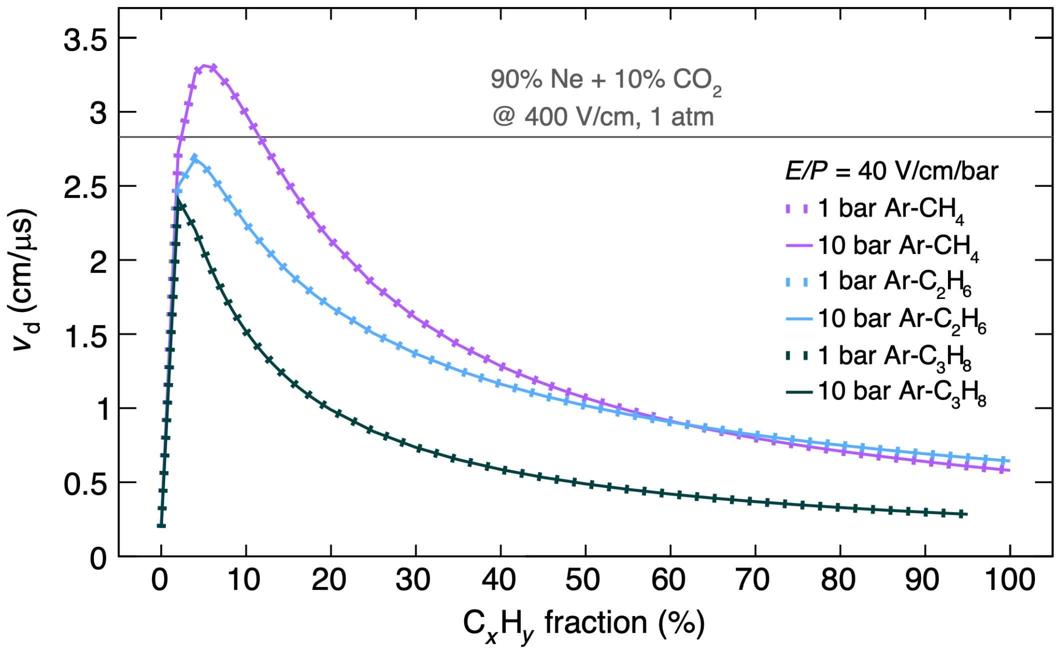


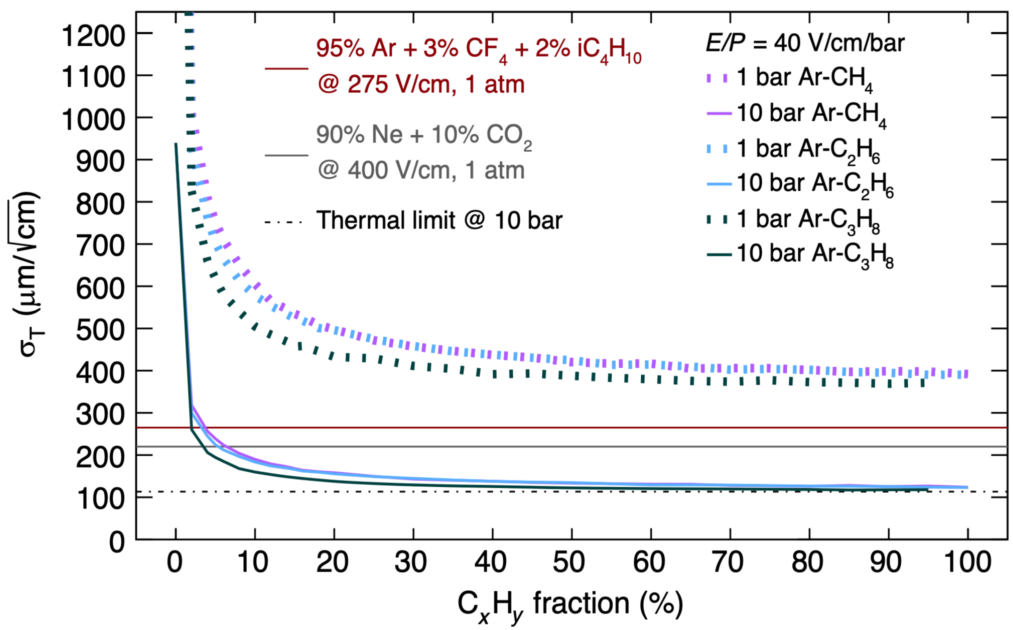




R&D Efforts

- 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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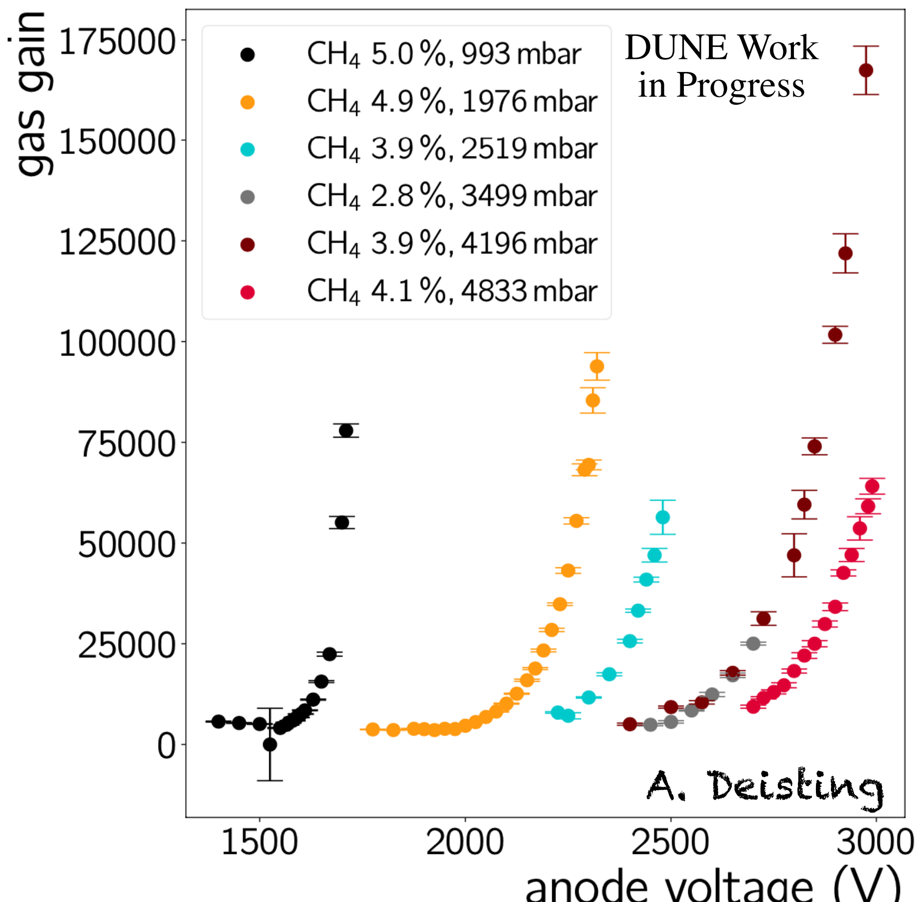
    - Maximize gas gain



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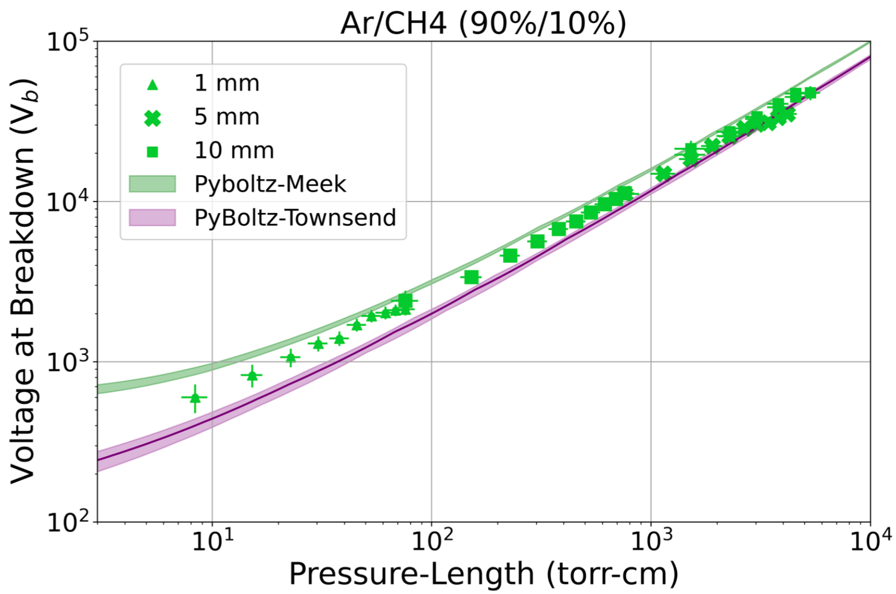
    - Maximize gas gain, while minimizing gas electrical breakdown



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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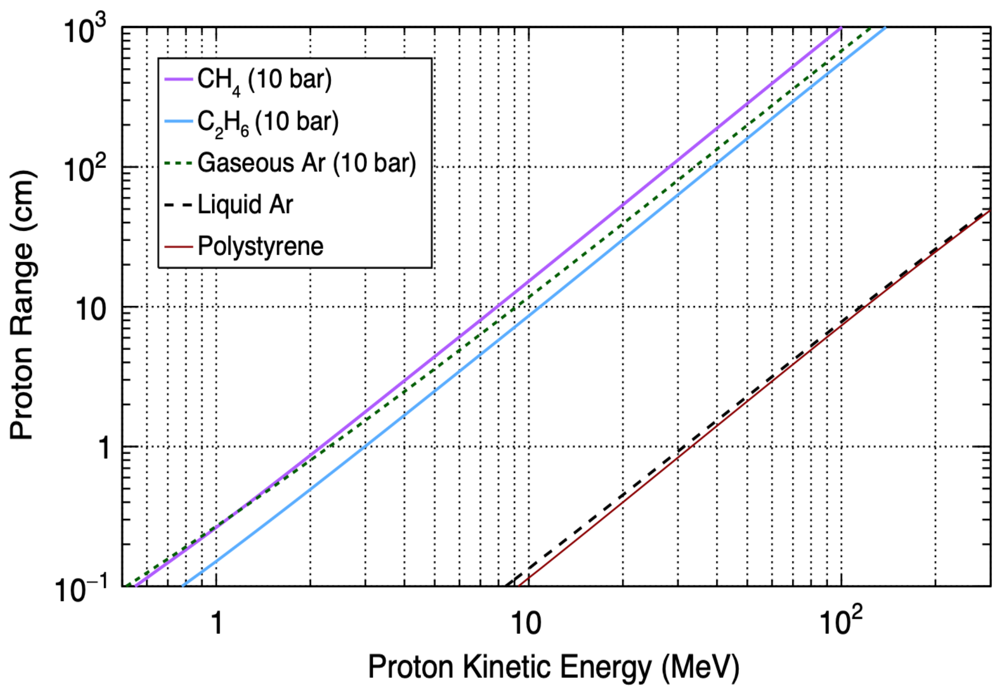
    - Ability to operate with a hydrogen-rich gas mixture to probe more fundamental neutrino-hydrogen interactions



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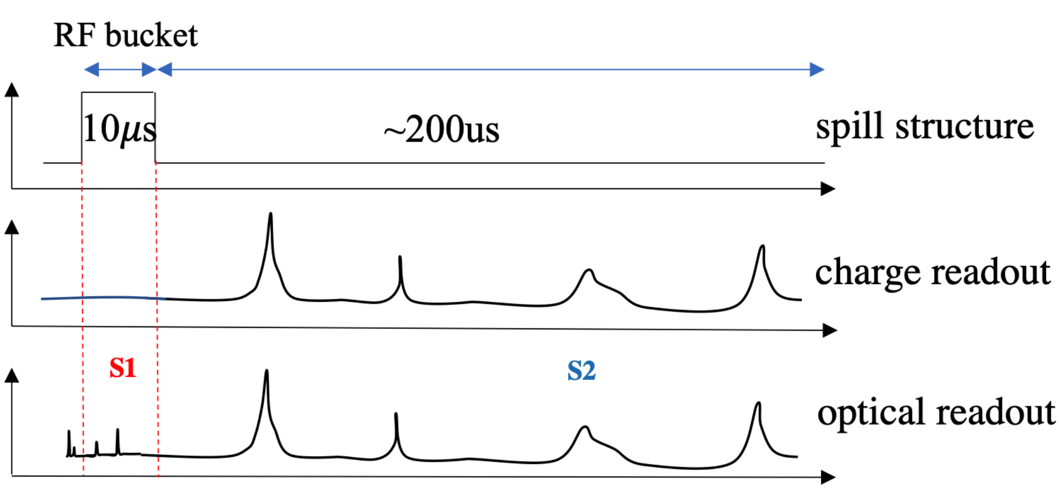
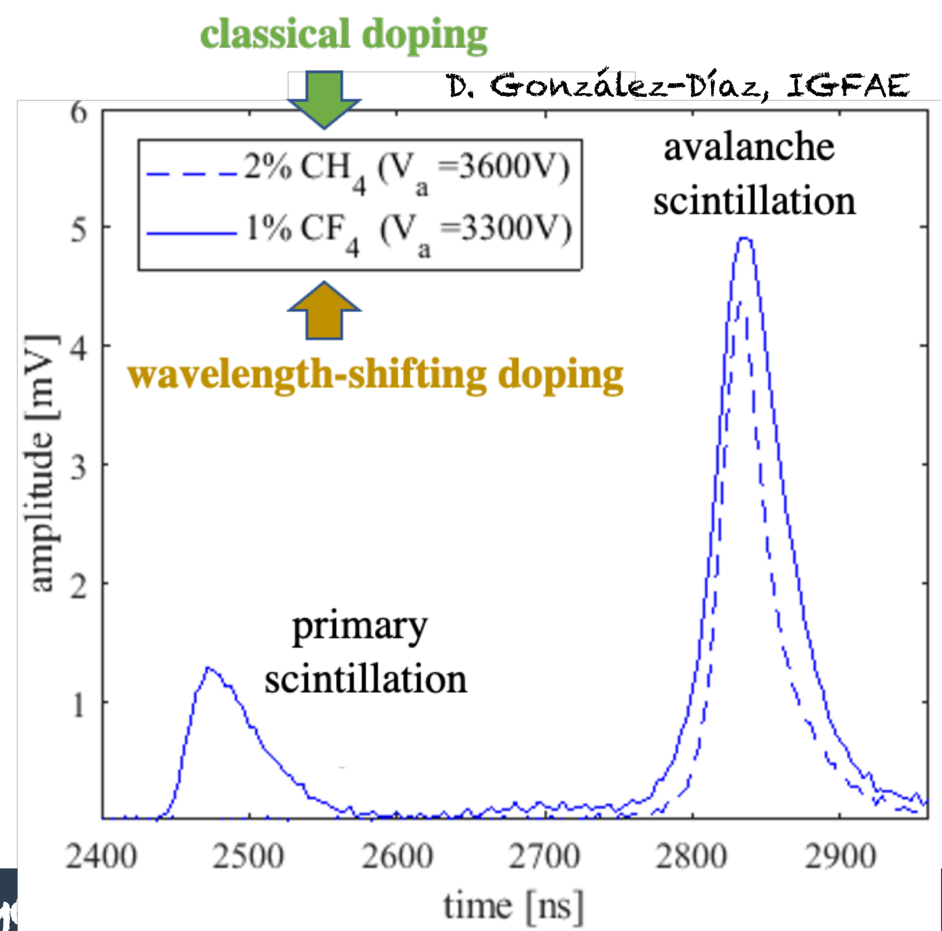
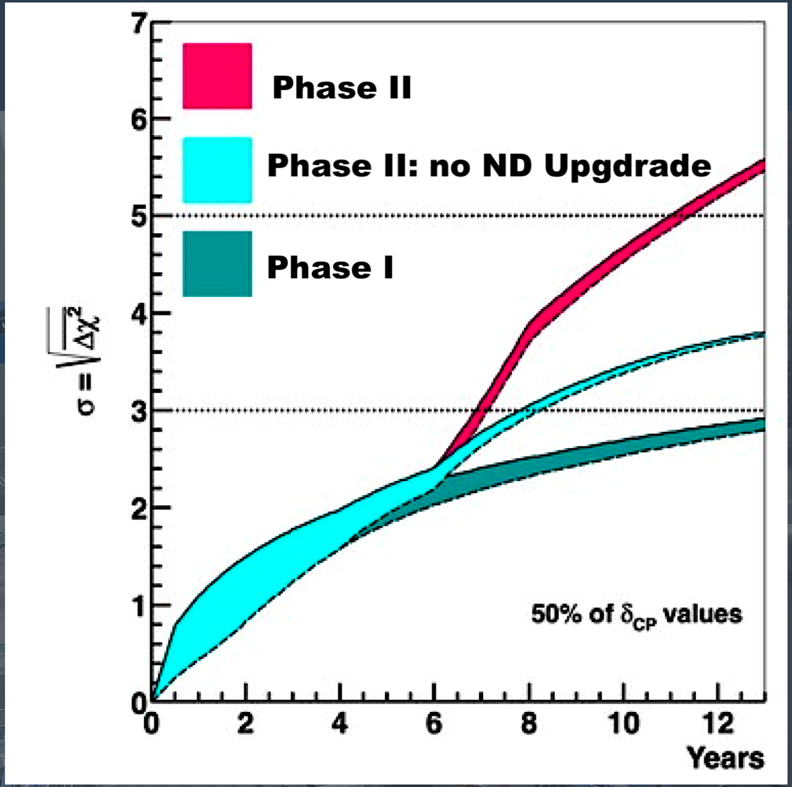
    - Control pile up (drift velocity) and improve spatial resolution (diffusion)
    - Maximize gas gain, while minimizing gas electrical breakdown
    - Ability to operate with a hydrogen-rich gas mixture to probe more fundamental neutrino-hydrogen interactions
- Optical readout & light collection:
  - Choose an admixture/dopant that will not quench the scintillation signal
  - Benefits: t_0 time-tag, BSM searches, improved track matching with ND-LAr, neutral particle reconstruction via time-of-flight, NC interaction





Summary

- The DUNE ND-GAr unique design includes components that enable:
  - DUNE to reach 5σ sensitivity to CP violation
  - A close-up view of ν-Ar interactions to more precisely identify and resolve the discrepancies in neutrino-nucleus interaction models
  - A comprehensive search for rare decays and symmetries beyond the standard model
- A wide range of detector R&D efforts are underway to build a highly capable ND-GAr:
  - Besides R&D on the acquired ALICE multiwire readout chambers, we are exploring various new detector R&D areas, including GEM development & optical readout



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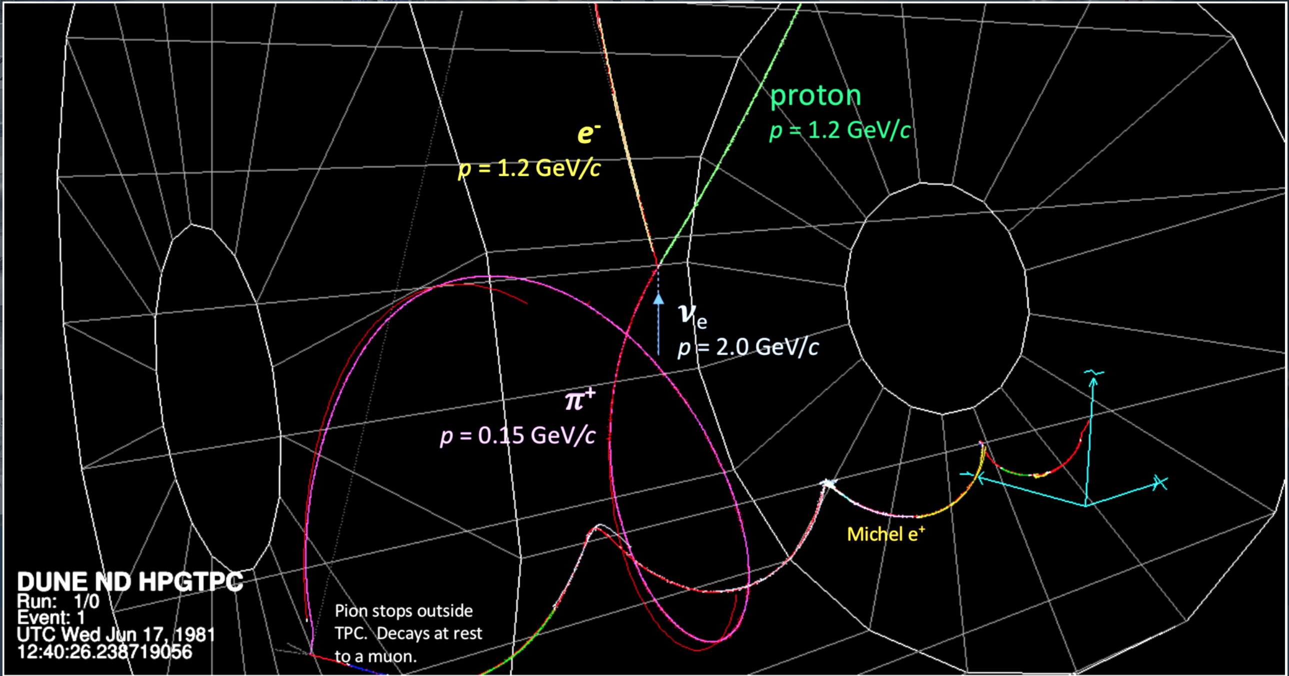
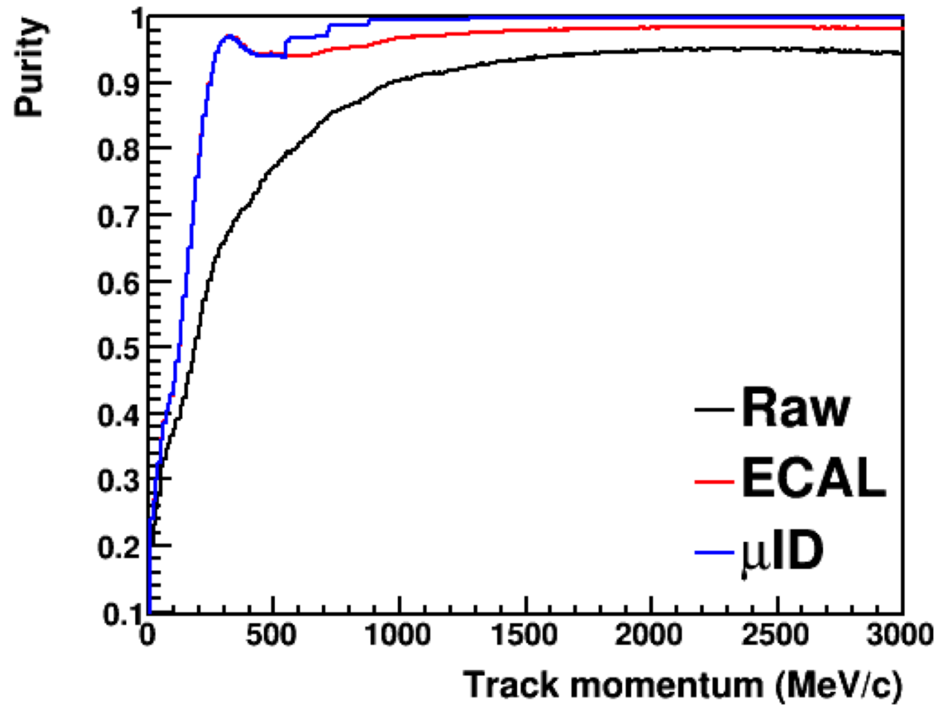


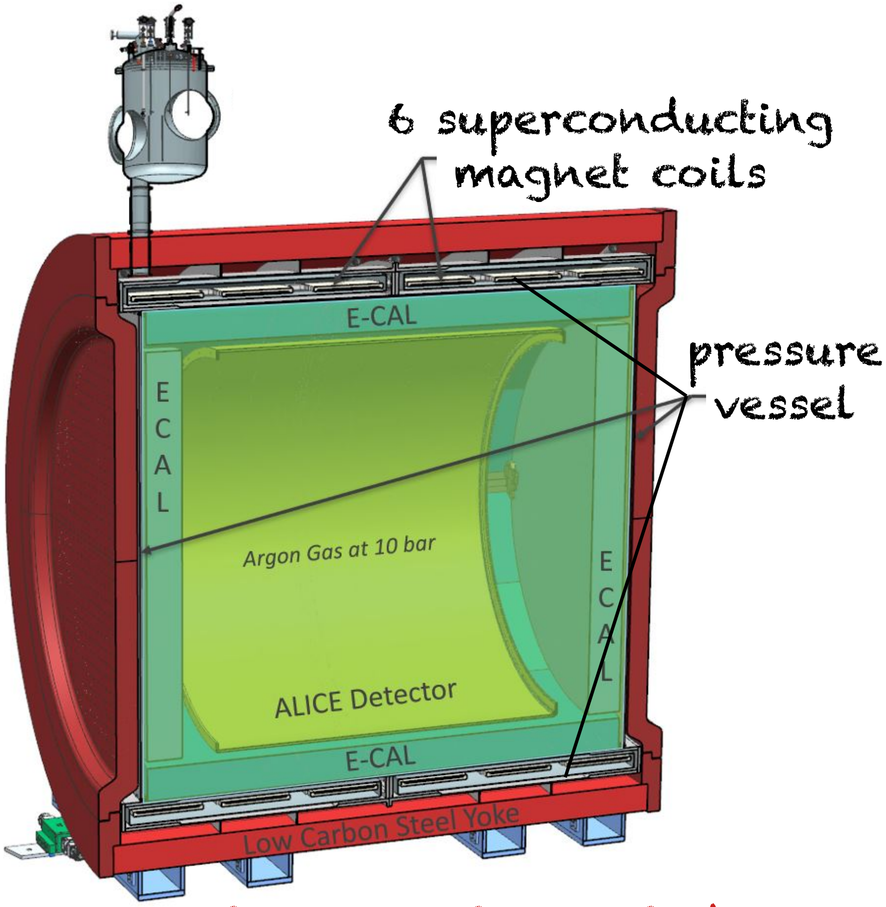
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Additional Slides

Projected Performance

- High-momentum muons and pions will range out of ECAL
- A muon tagger can achieve a purity of 100% above 1 GeV/c





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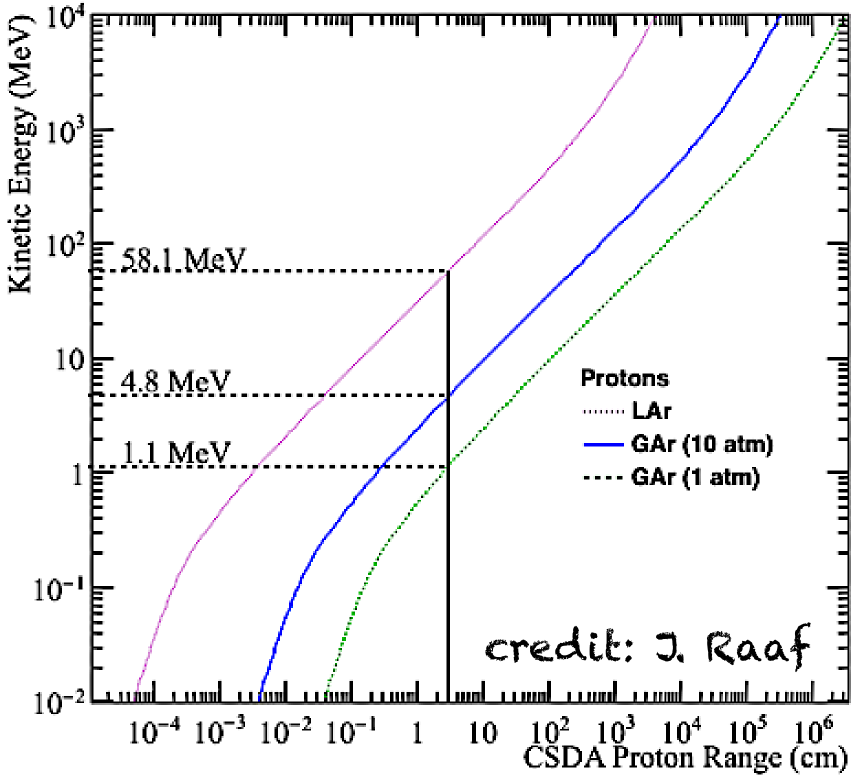
Low Threshold ND-GAr

- 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



Gas Multiplication Gain Concept