Overview of ND-GAr

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Neutrino Interaction Summer School
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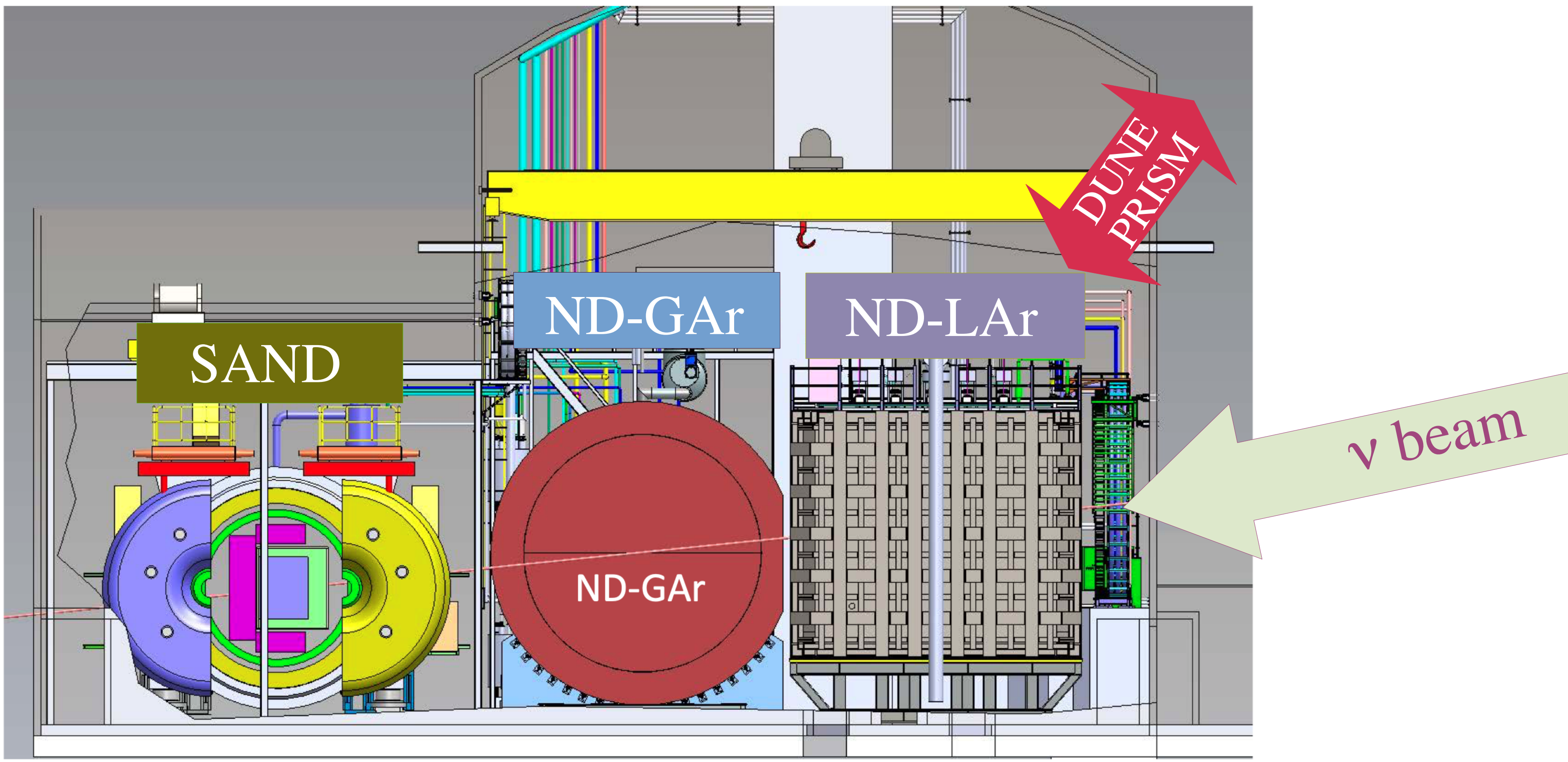
Fermilab

Outline

- ND-GAr in Near Detector Complex
- ND-GAr Capabilities
- Conceptual Design
- ND-GAr Software
- Summary

ND-GAr in the Near Detector Complex



- **Main capabilities of the near detector complex**:
  - Liquid Argon TPC, ND-LAr
  - Tracker with a gaseous Argon target, ND-GAr
  - DUNE PRISM: off-axis measurements with ND-LAr+ND-GAr
  - On-axis flux monitor System for on-Axis Neutrino Detection or SAND

Need for ND-GAr

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

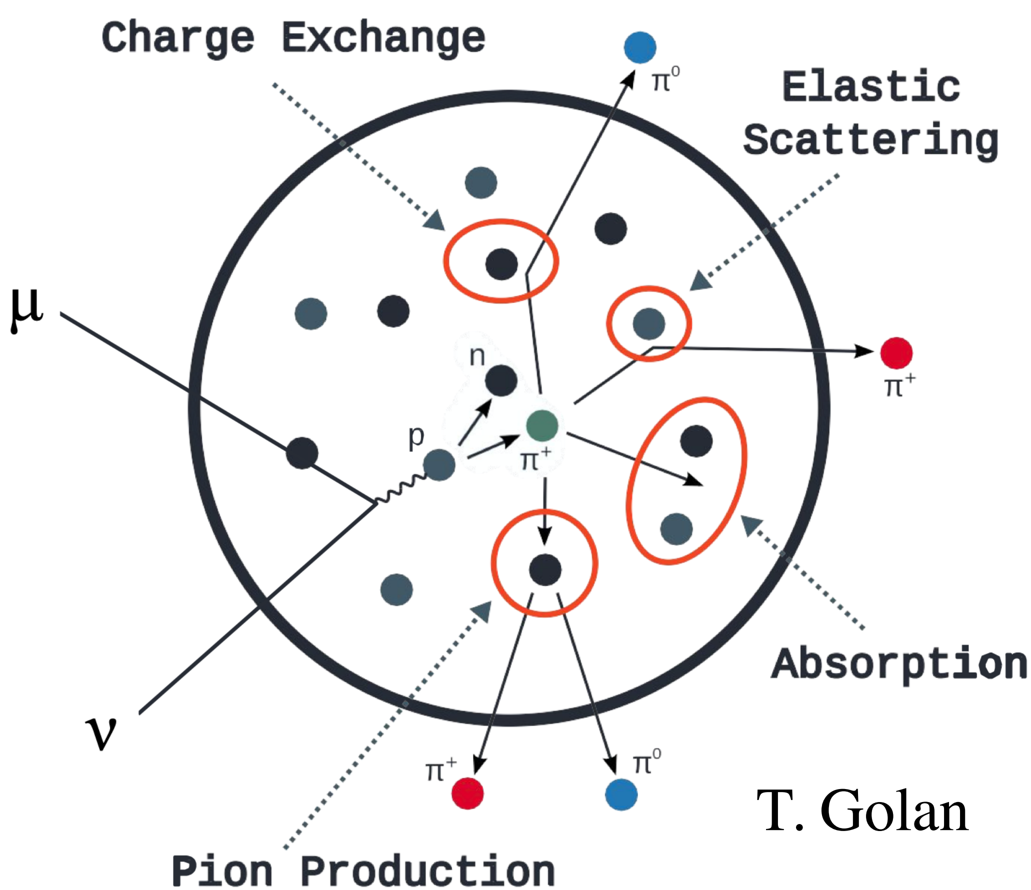
NOvA https://doi.org/10.1103/PhysRevLett.123.151803

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

Dominant sources of uncertainties in neutrino oscillation measurements are cross sections/neutrino interaction models

Need for ND-GAr

- The reason cross sections/neutrino interaction models are dominant sources of uncertainties is because nucleus is a complicated environment:
  - Difficult to infer the initial state of the interaction from final state topology, especially in heavier nuclei – initial state of nucleons, nuclear effects, and final state interactions not yet fully understood

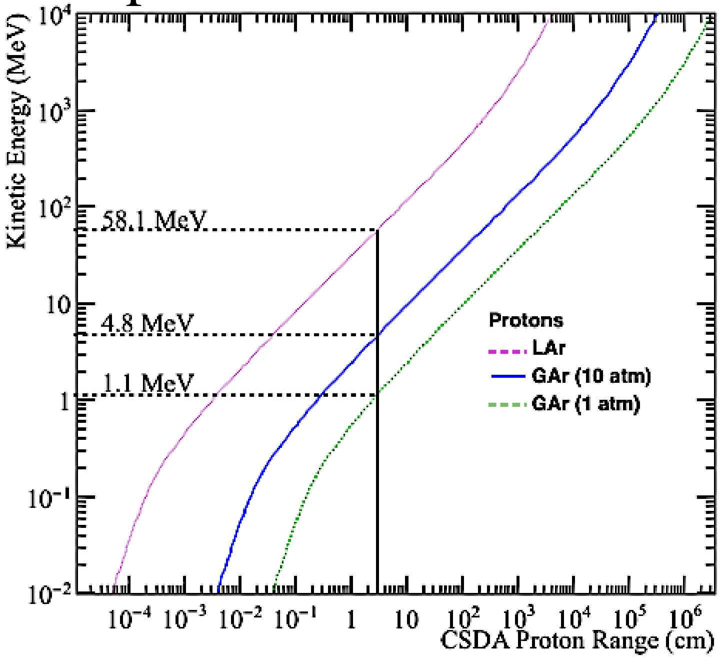


T. Golan

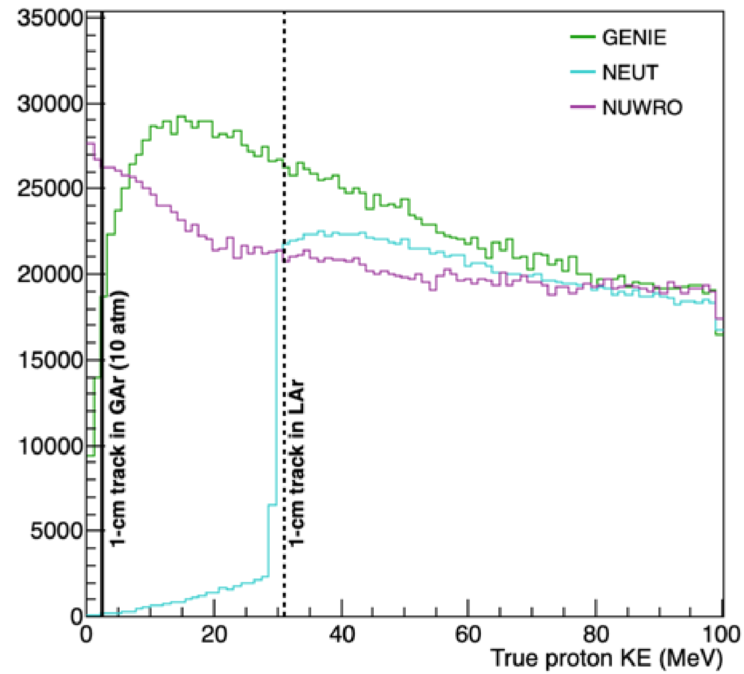
Need for ND-GAr

- The high pressure gas argon TPC component of ND-GAr can help constrain the uncertainties in cross section/neutrino interaction models:
  - ★ Lower density ($\rho_{LAr}/\rho_{GAr} \approx 85$ for 10 atm GAr) → lower detection threshold → higher sensitivity to lower energy charged particles that may not be seen in LAr
  - ★ Reveal discrepancies between different neutrino event generators & get closer at choosing a more accurate ν-N interaction model (used in event generators such as GENIE, NEUT, & NUWRO) at lower energies

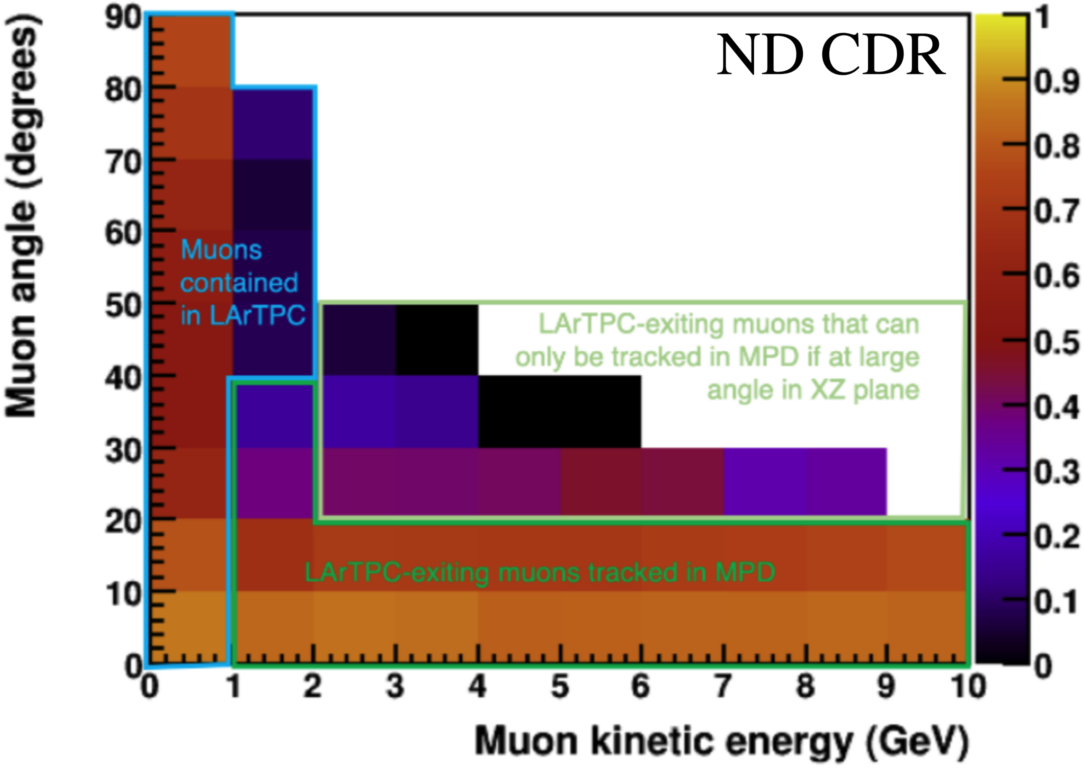
ND-GAr sees lower KE protons than ND-LAr

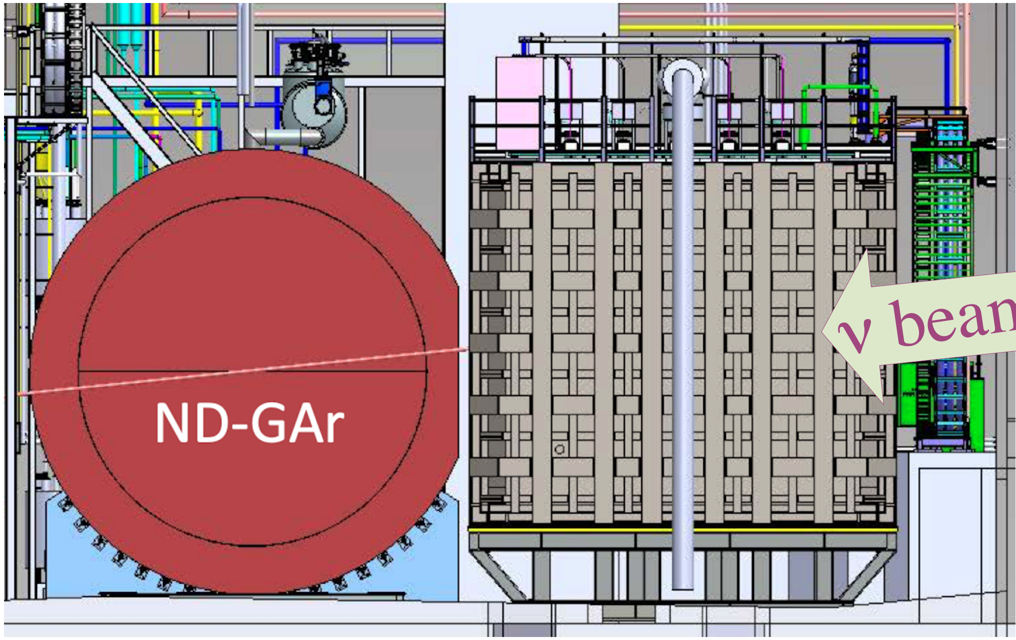


neutrino generator discrepancies at low proton KE, accessible with ND-GAr



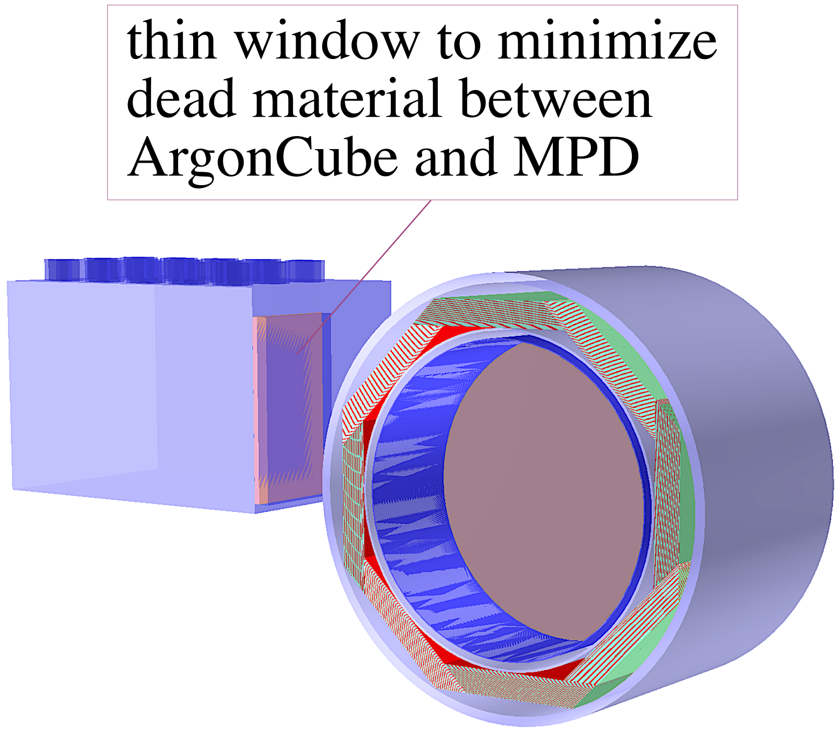
ND-GAr Capabilities

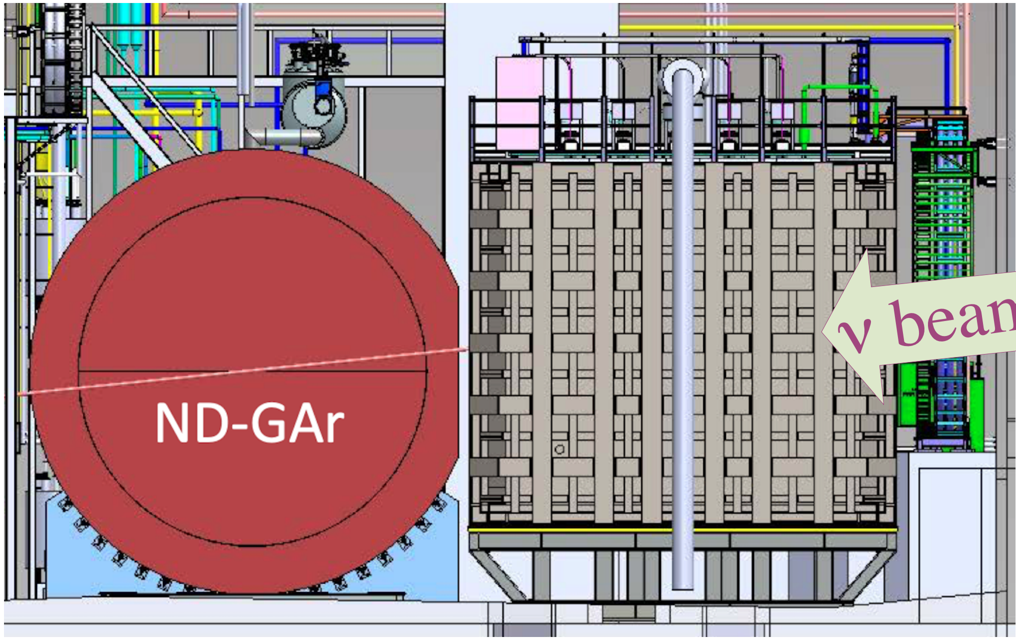




- **As a component of the DUNE near detector**:
  - Measure momenta of muons exiting ND-LAr by curvature in B-field
  - Measure sign of charged particles exiting ND-LAr

ND-GAr Capabilities





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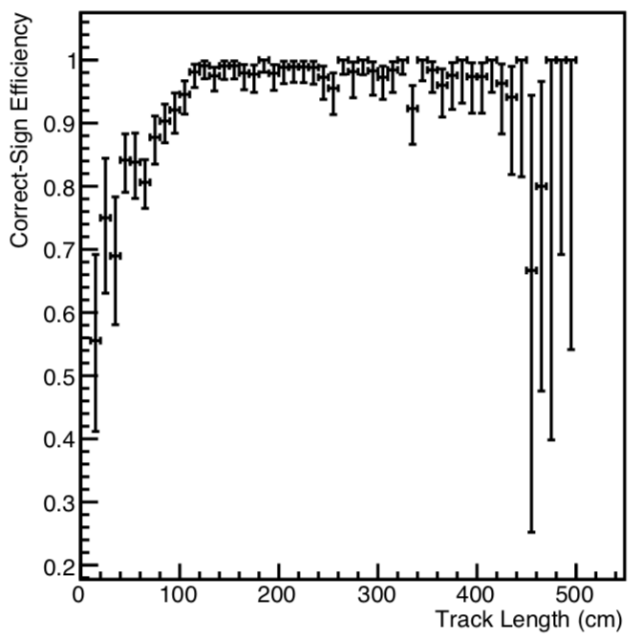
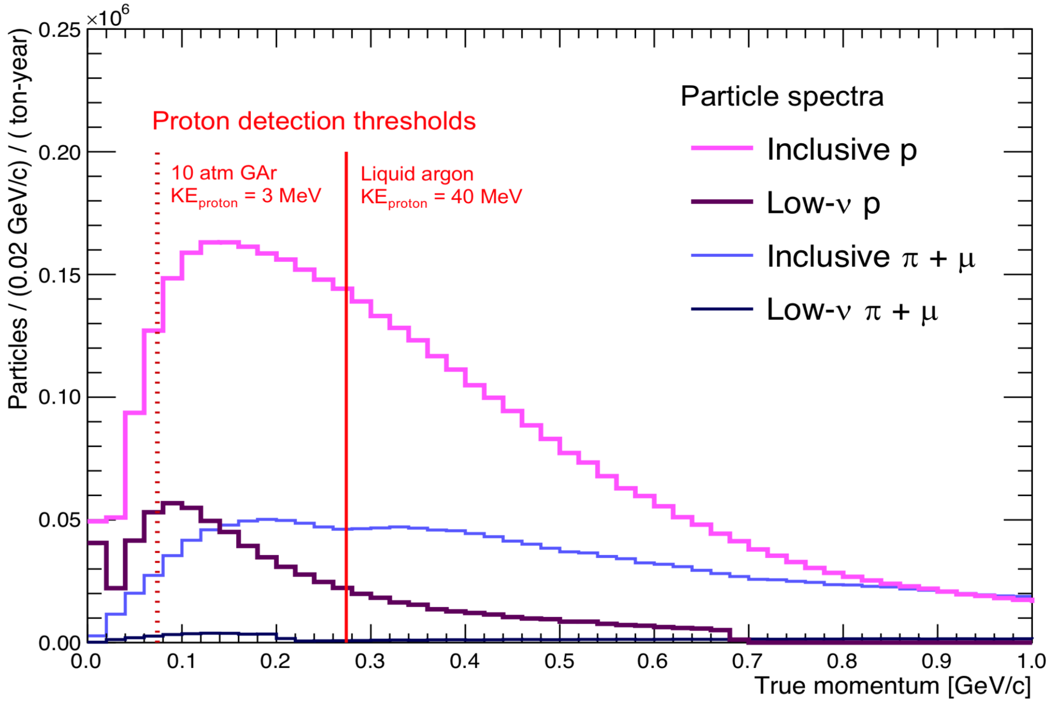
ND-GAr Capabilities



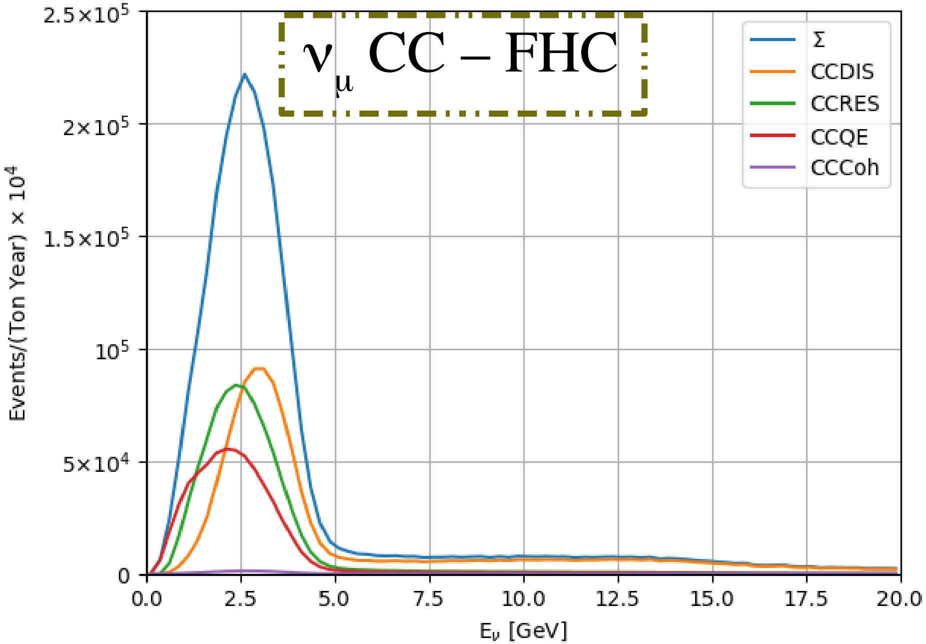


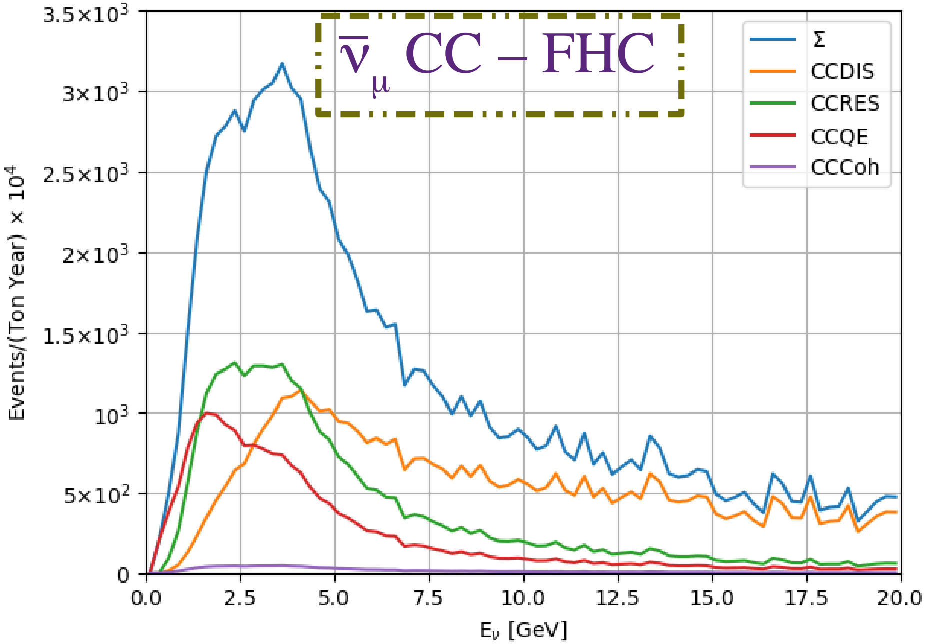
- **As an independent magnetized tracker**:
  - Sign tag charged particles exiting a neutrino interaction to reconstruct wrong-sign neutrinos
  - Lower detector threshold than LAr, achieved with ML approach
    - Places a better constraint on neutrino interaction modeling uncertainty at low energies in both ND-LAr and far detector

ND-GAr Event Rates

FHC Mode, Optimized DUNE flux (Oct 2017), GENIE v2.12.10

Event Category	Events/Ton-year	Event Category	Events/Ton-year
ν_μ CC total	2E+06	$\bar{\nu}_\mu$ CC total	9.4E+04



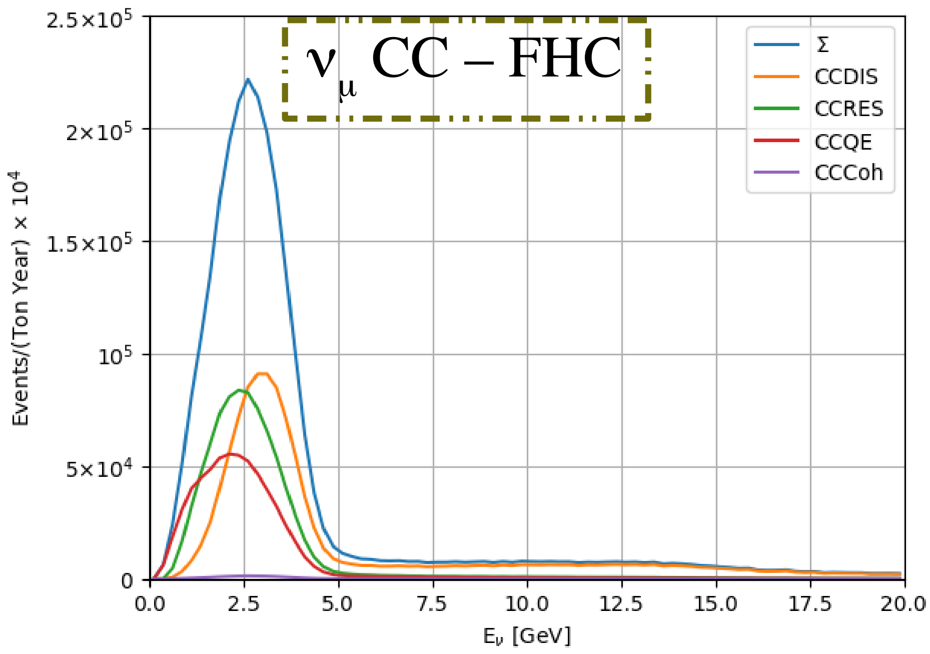


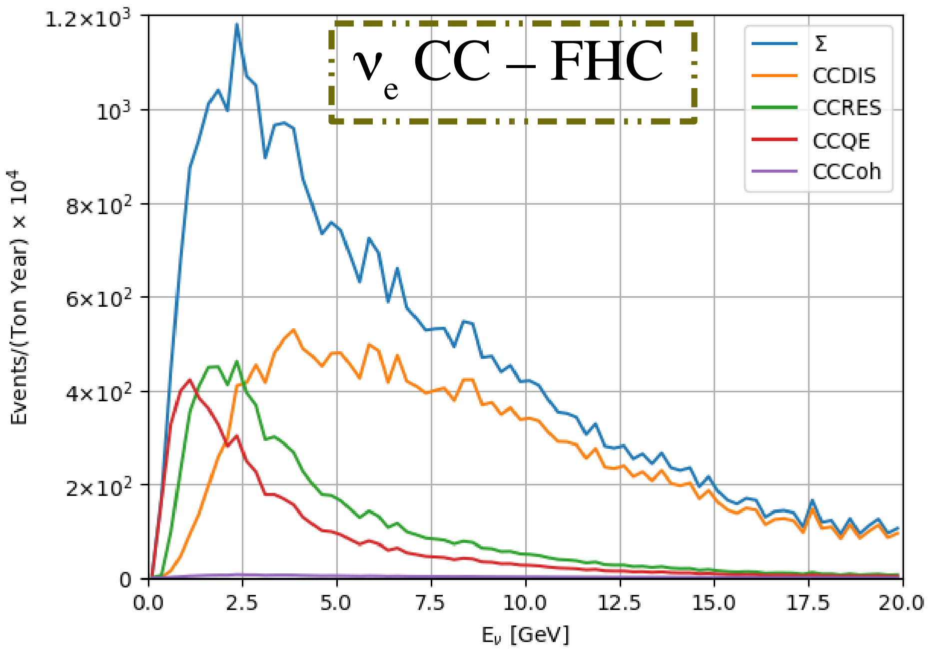
- **As a stand-alone magnetized tracker**:
  - Reconstruct wrong-sign neutrino interactions on Ar target

ND-GAr Event Rates

FHC Mode, Optimized DUNE flux (Oct 2017), GENIE v2.12.10

Event Category	Events/Ton-year	Event Category	Events/Ton-year
ν_μ CC total	2E+06	ν_e CC total	3.6E+04

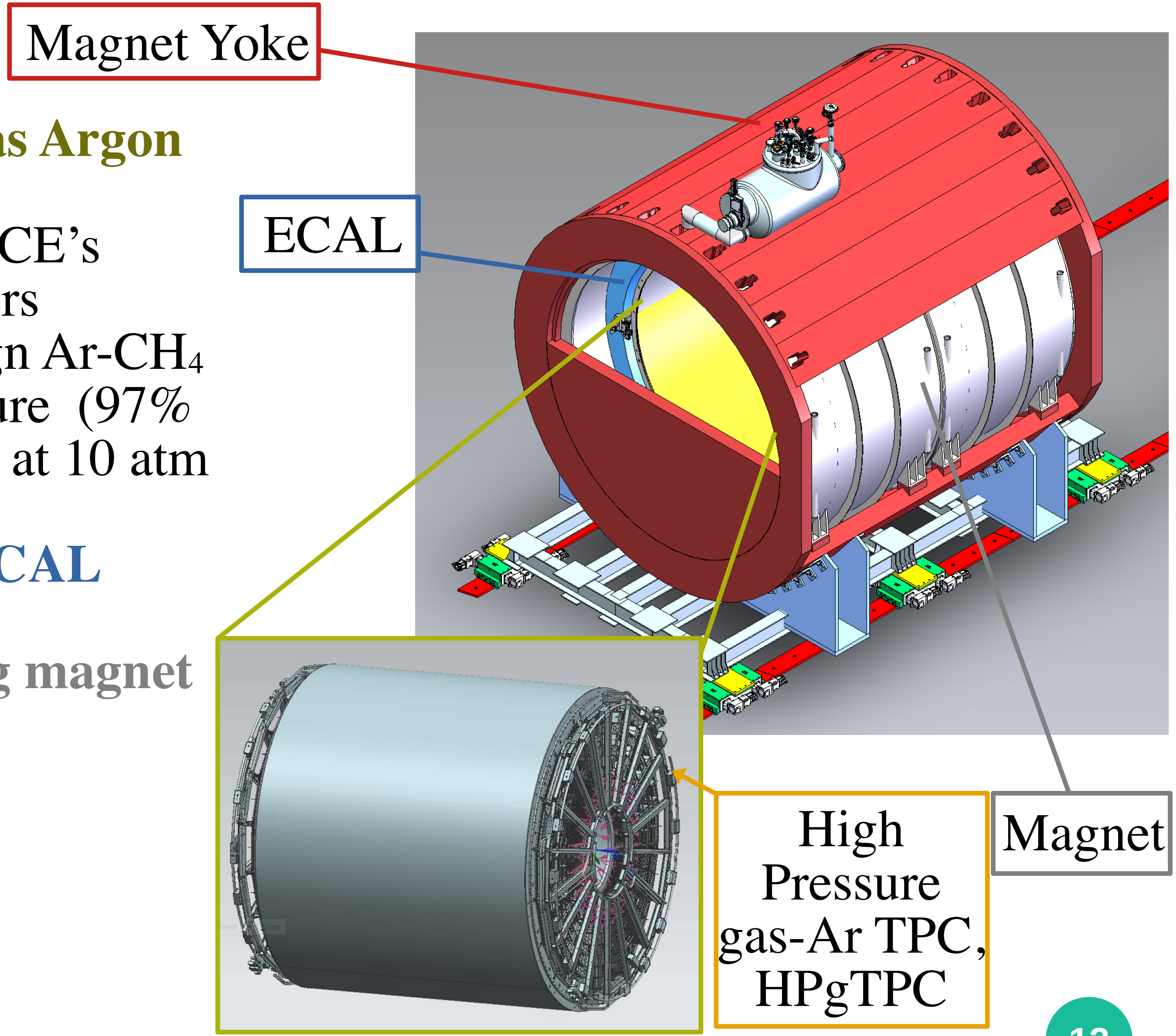




- **As a stand-alone magnetized tracker**:
  - Collect independent sample of ν-interactions on a gaseous Ar target (97% interactions on Ar)

ND-GAr Conceptual Design – HPgTPC

- **High Pressure Gas Argon TPC (HPgTPC):**
  - Will re-use ALICE's readout chambers
  - Reference design Ar-CH_4 90-10 gas mixture (97% Ar interactions) at 10 atm
- ★ **HPgTPC** will be surrounded by **ECAL calorimeter** and **superconducting magnet**



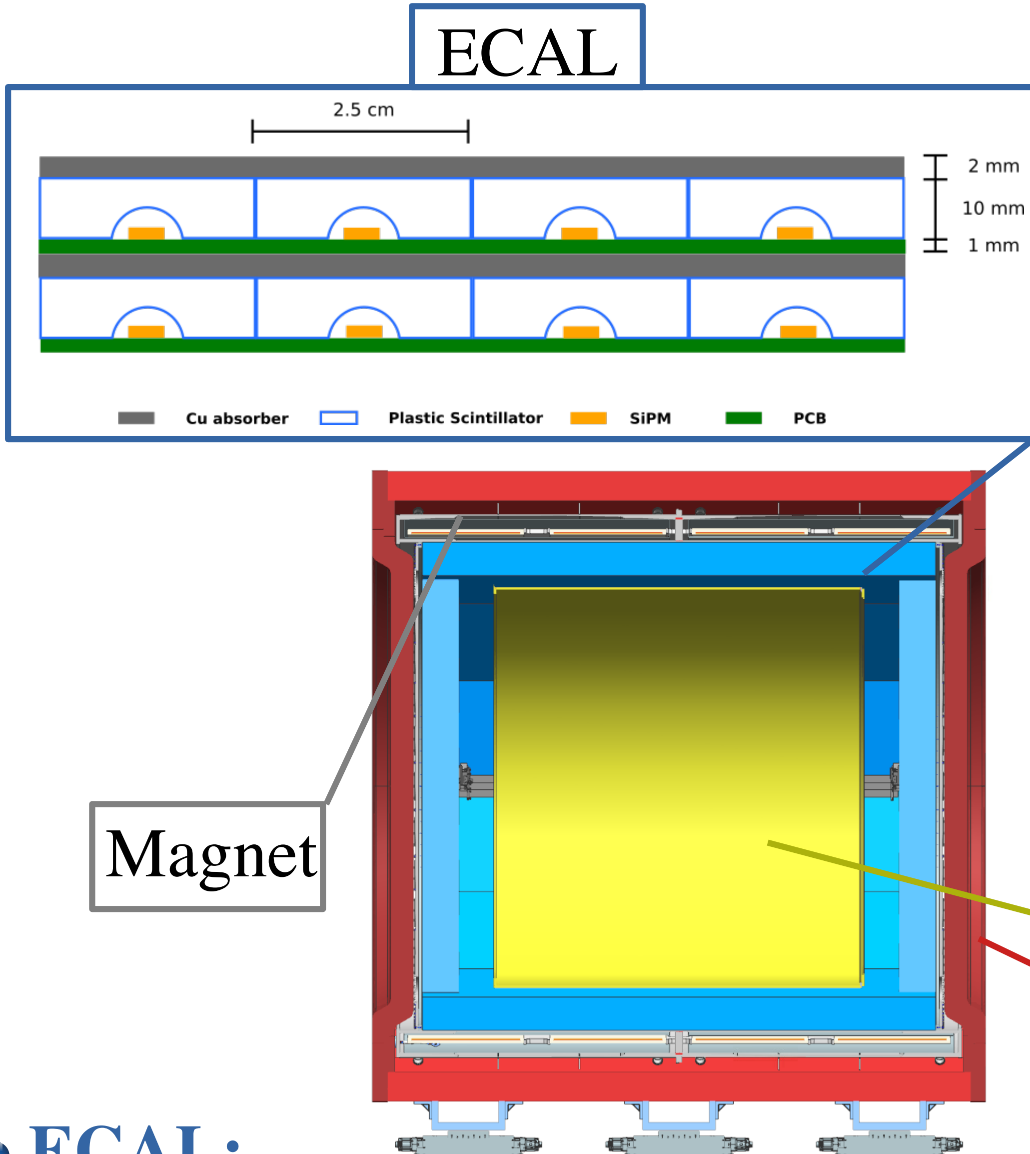
ND-GAr Conceptual Design – HPgTPC

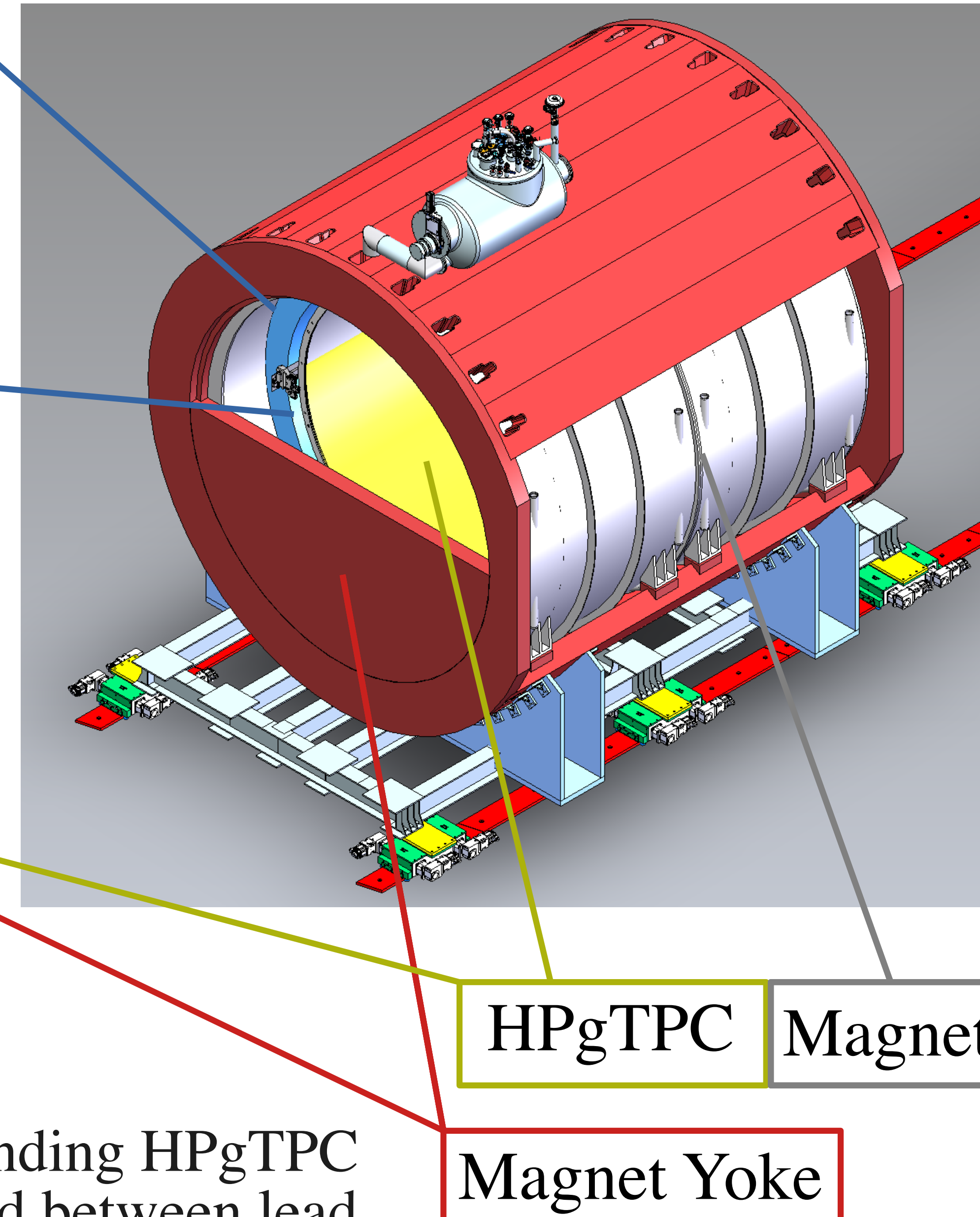
Expected MPD performance, extrapolated from ALICE and PEP-4

Parameter	Value	units
σ_x	250	μm
σ_y	250	μm
σ_z	1500	μm
$\sigma_{r\phi}$	<1000	μm
Two-track separation	1	cm
Angular resolution	2-4	mrad
$\sigma(dE/dx)$	5	%
σ_{p_T}/p_T	0.7	% (10-1 GeV/c)
σ_{p_T}/p_T	1-2	% (1 GeV/c to 0.1 GeV/c)
Energy scale uncertainty	$\lesssim 1$	% (dominated by δ_p/p)

- Need a reasonably-sized TPC for collecting 2M ν_μ CC events/ton of ^{40}Ar/year:
  - TPC the size of ALICE, if pressurized (similar to PEP-4 TPC, which was also pressurized)
    - Plan is to repurpose the recently acquired ALICE readout chambers (**Inner** and **Outer** multi-wire proportional readout chambers, **IROC** and **OROC**)
    - Superb tracking efficiency, momentum resolution, & angular resolution when extrapolating from ALICE and PEP-4

ND-GAr Conceptual Design – ECAL

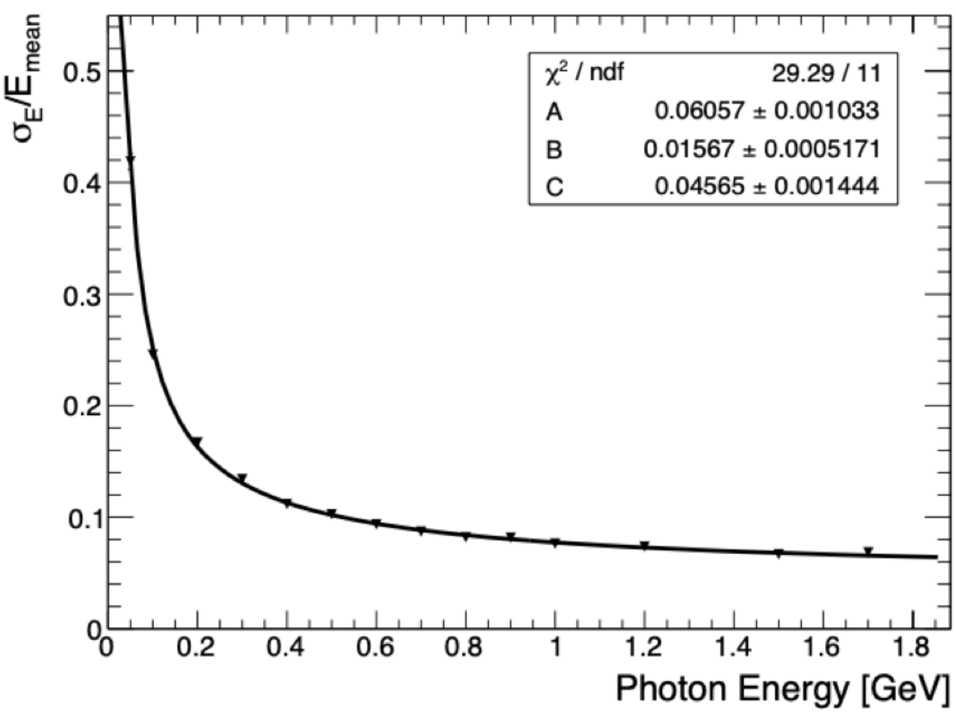


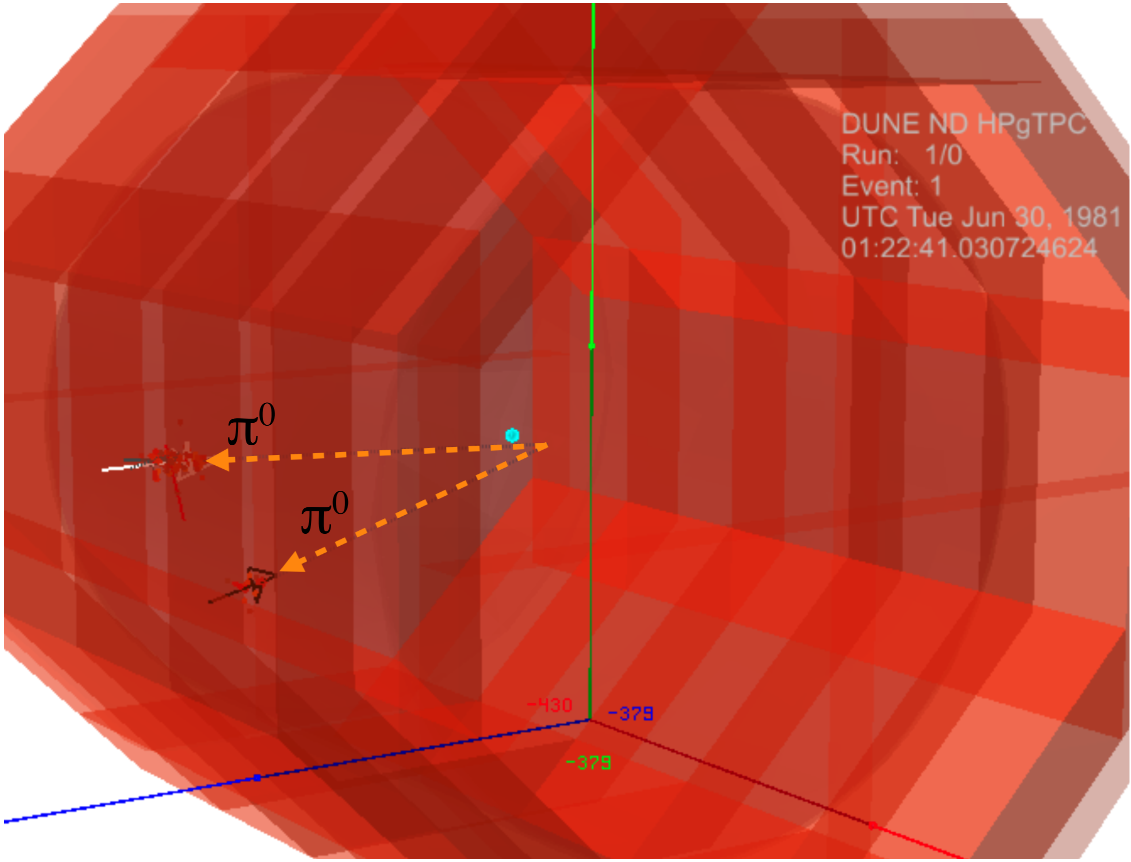


- **ECAL:**
  - An electromagnetic calorimeter surrounding HPgTPC
  - Made of plastic scintillators sandwiched between lead absorber sheets

ND-GAr Conceptual Design – ECAL

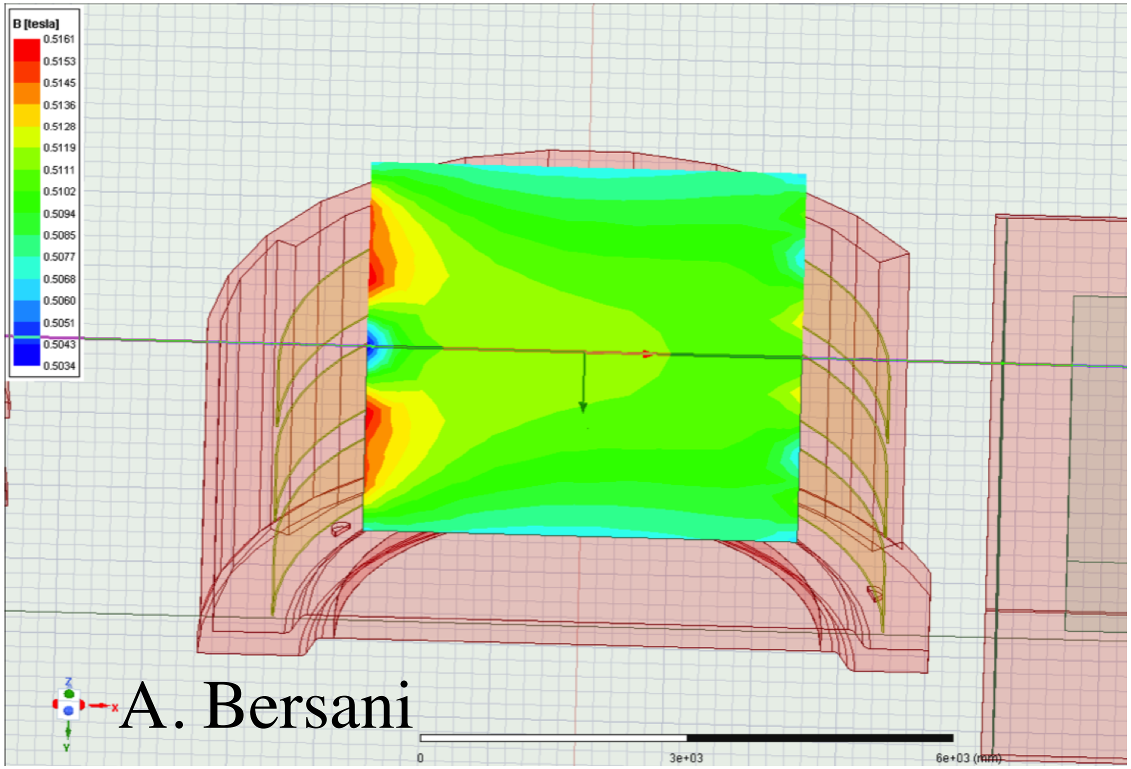
- **ECAL is used to:**
  - Tag/reject π^0 & γs that are backgrounds to ν_es
  - Tag/reject outside of fiducial volume backgrounds
  - Measure energetic neutrons

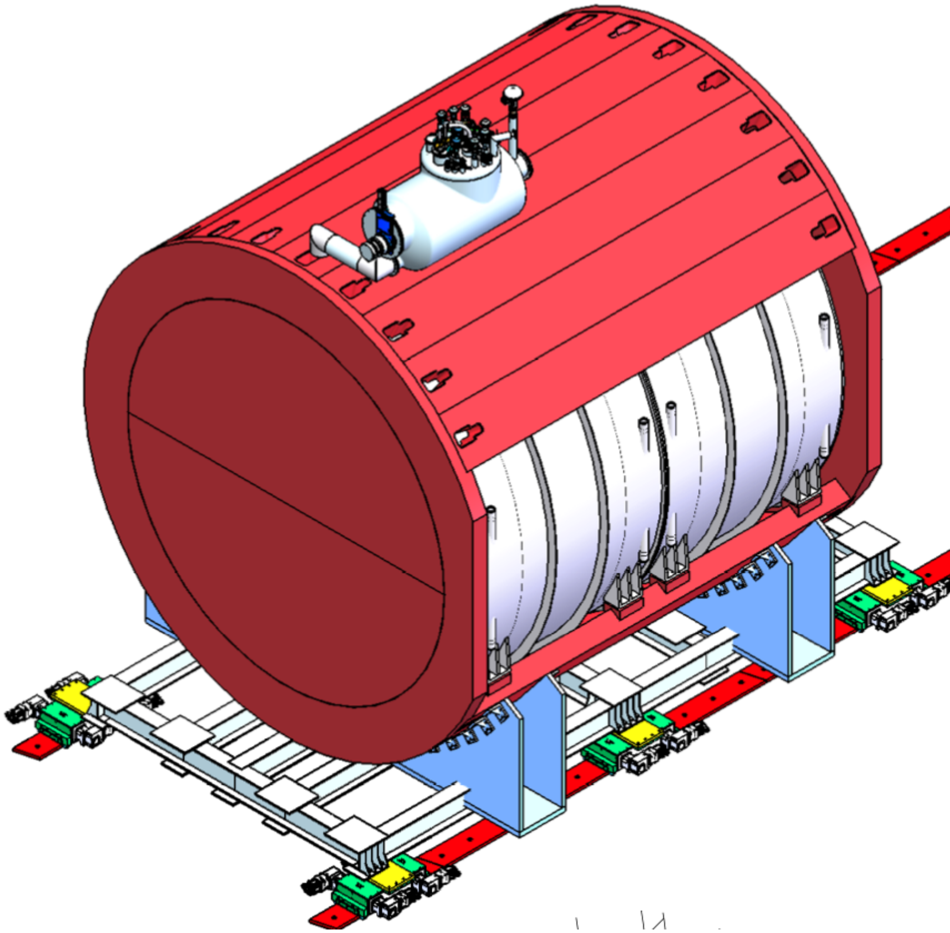




ND-GAr Conceptual Design – Magnet

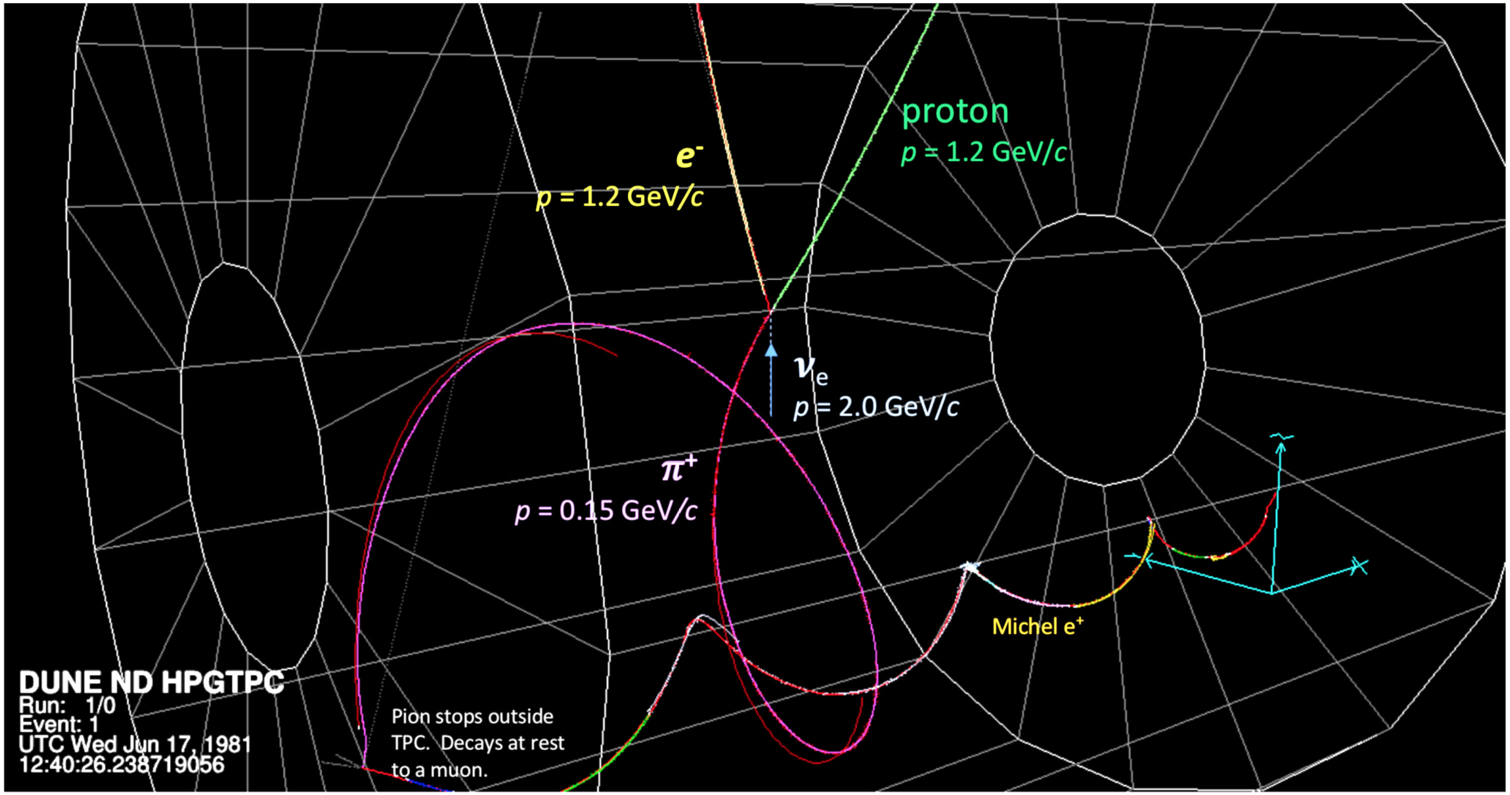
- Hosts both TPC and ECAL
- 0.5 T magnetic field in the TPC region 5 m diameter, 5 m length
- Positioned perpendicularly to the neutrino beam direction





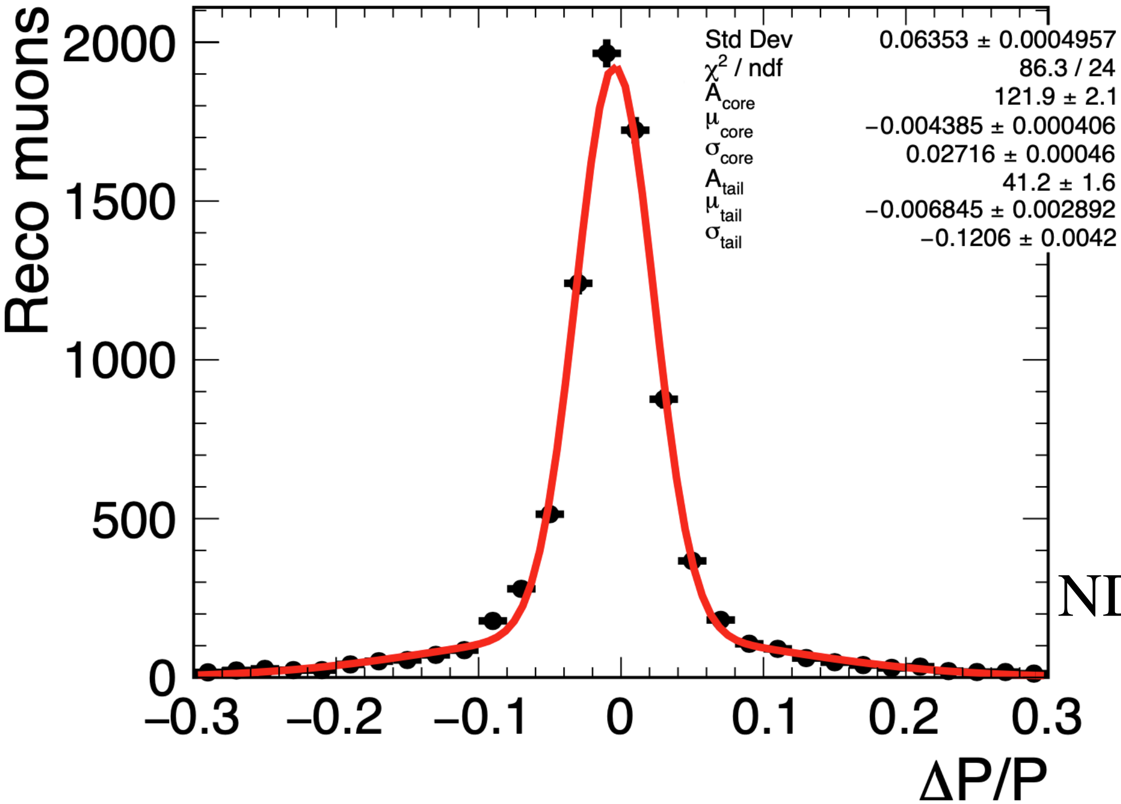
ND-GAr Software

- Called GArSoft, based on art event processing framework
- Full reconstruction chain including ECAL reconstruction:
  - ✔ Detector response
  - ✔ Electronics response
  - ✔ Digitization
  - ✔ Hit finding and clustering
  - ✔ Track reconstruction, pattern recognition, track fitting
  - ✔ Includes immediate data products as checkpoints, with a final data product in the format of an analysis tree, called garana (check out this tutorial here)

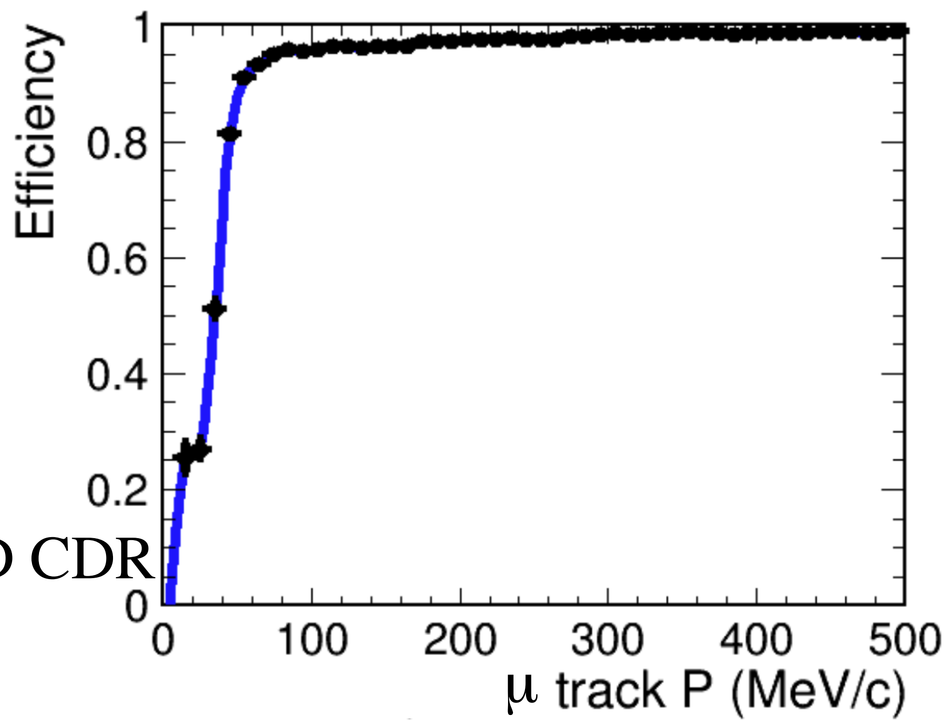


ND-GAr Software

- GArSoft's expected tracking performance, thus far:
  - Momentum resolution (left) for μs from a sample of ν_μ CC events = 2.7%
  - Tracking efficiency (right) for μs from the same sample

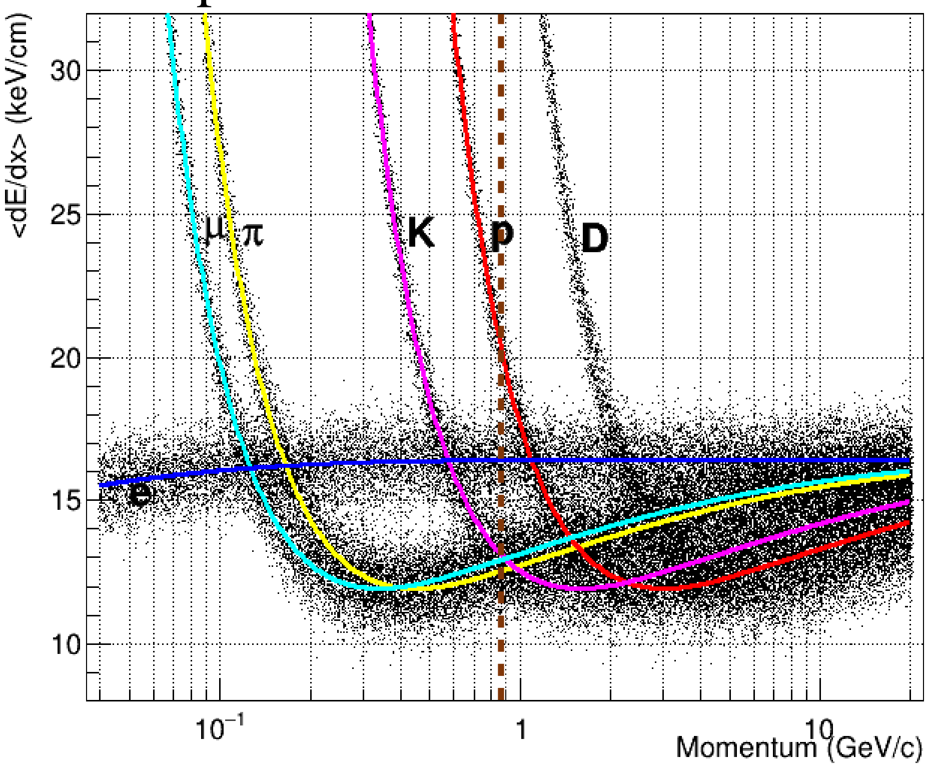


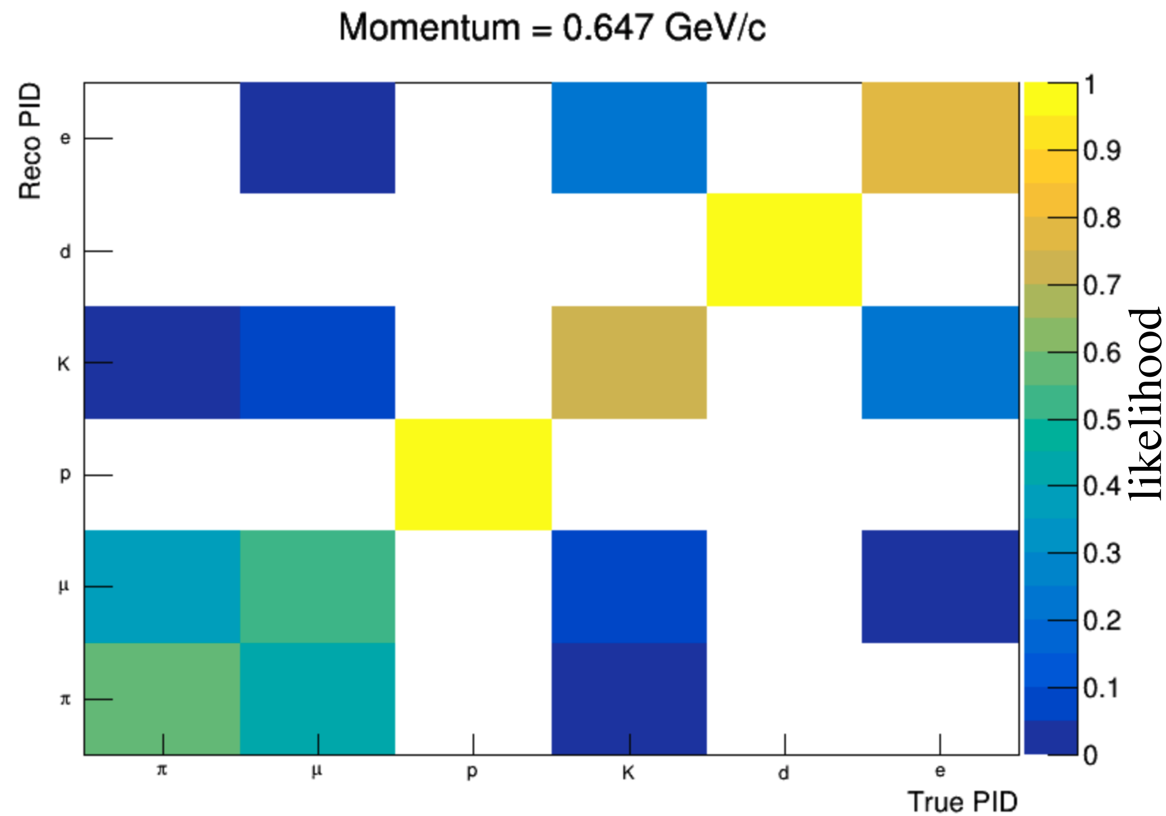
ND CDR



ND-GAr Software

dE/dx based on PEP-4, as implemented in our simulations





- Parametrized dE/dx particle ID implemented in GArSoft based on PEP-4 at 8.5 atm:
  - 0.8 keV/cm dE/dx resolution

T. A. Mohayai

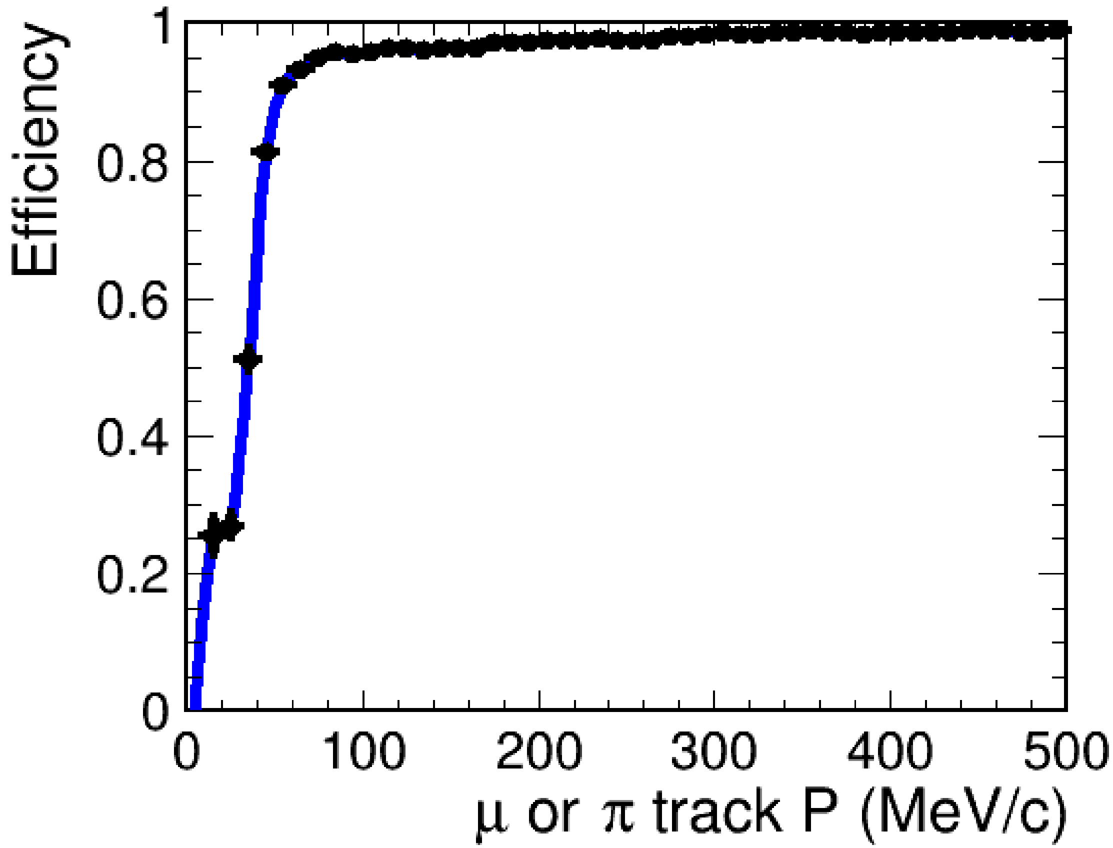
ND-GAr Summary

- The DUNE ND-GAr design includes a number of capable components to enable:
  - Tracking and sign-tagging of particles exiting ArgonCube
  - A precise view of ν-Ar interactions with low detection threshold, sign selection, and minimal secondary effects
  - Tag and analyze all components of the neutrino beam (ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$)
- ND-GAr Software includes full detector response modeling:
  - Its performance is constantly getting optimized; there is room for new collaborators to work on that
  - A number of analyses are using the GArSoft's analysis trees (garana or anatree); there is room for new collaborators to work on analysis or contribute to garana development

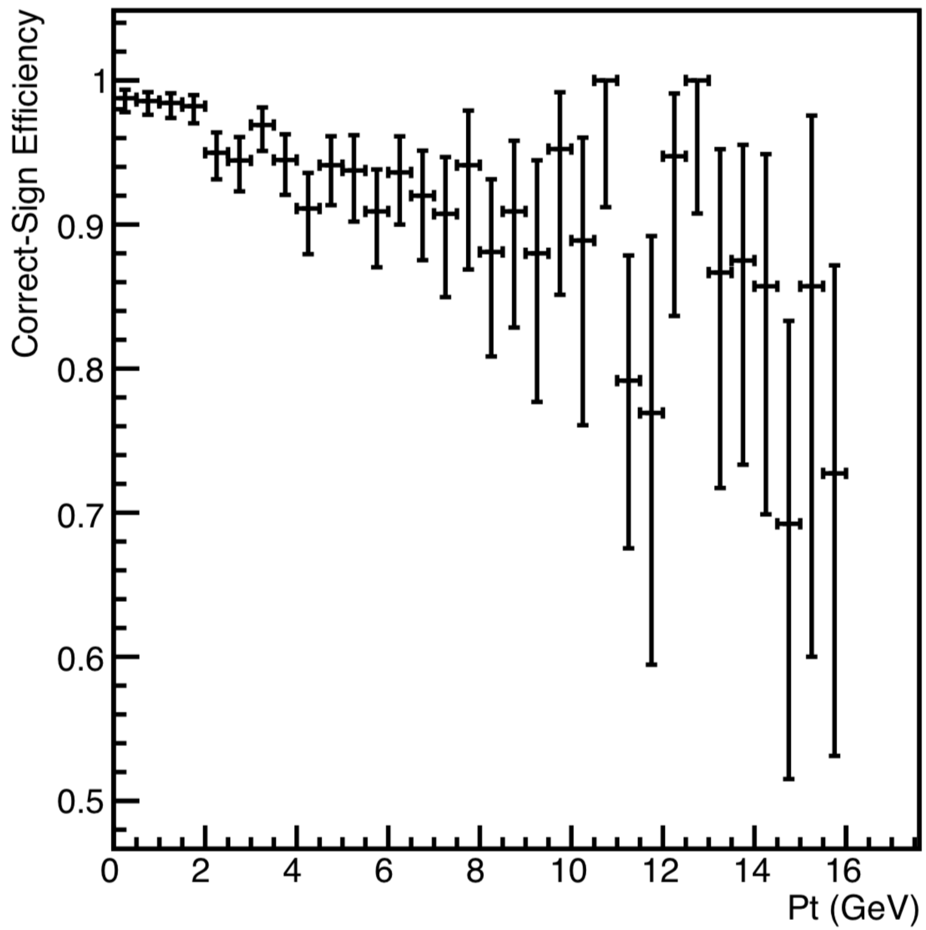
Thank You

Additional Slides

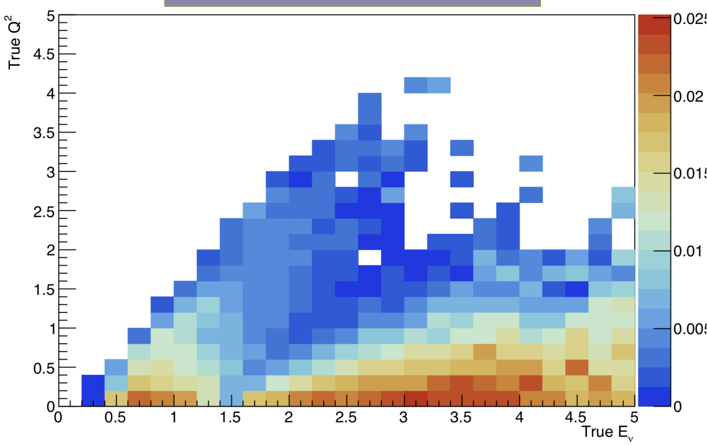
- $> 90\%$ efficiency for tracks with $p > 40$ MeV/c
- As momentum ↑ so does the efficiency



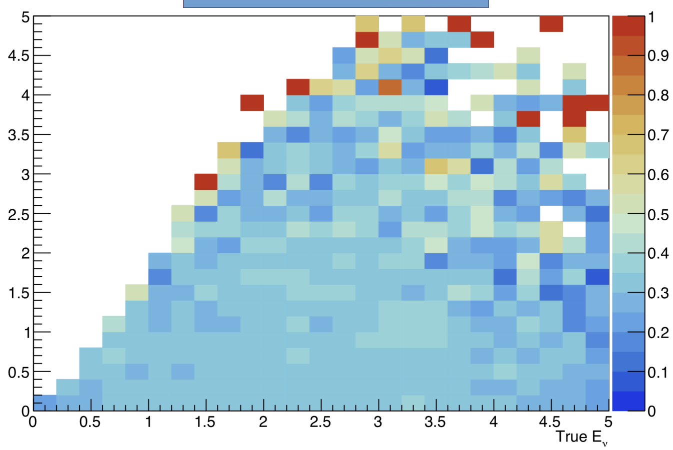
- Sign-tagging capability illustrated for e- and e+



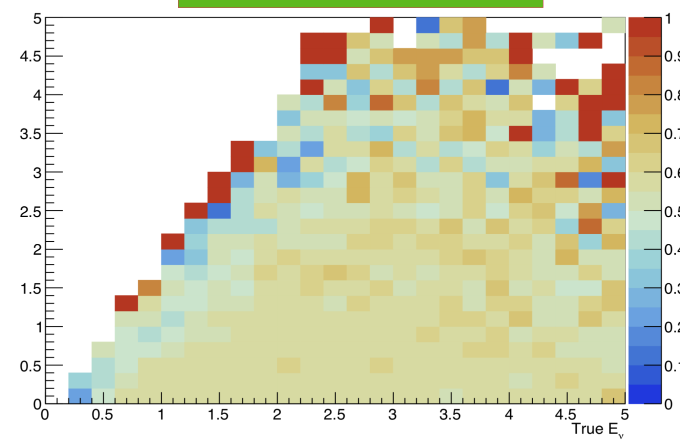
LAr TPC ND



MPD ND



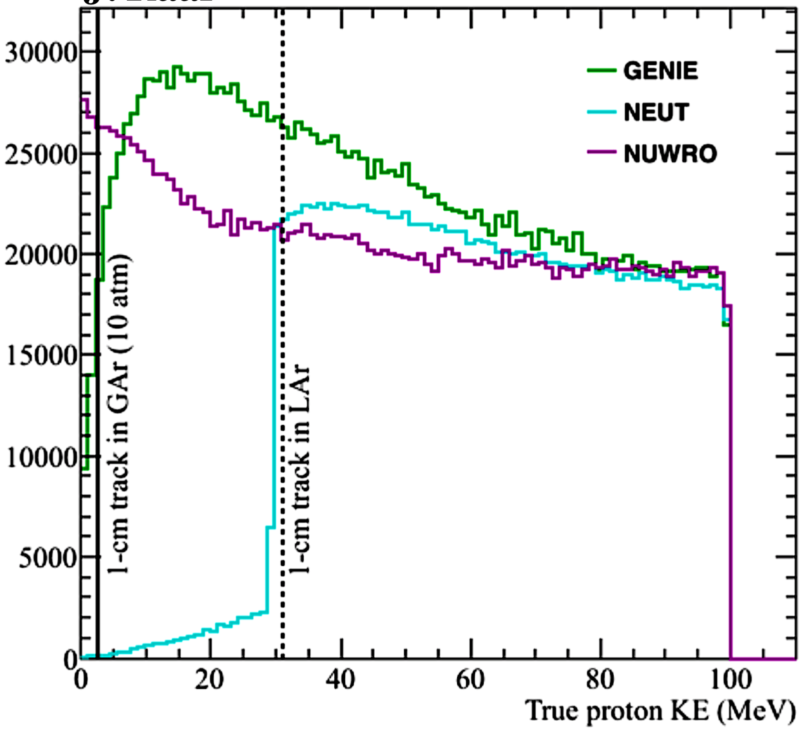
LAr TPC FD



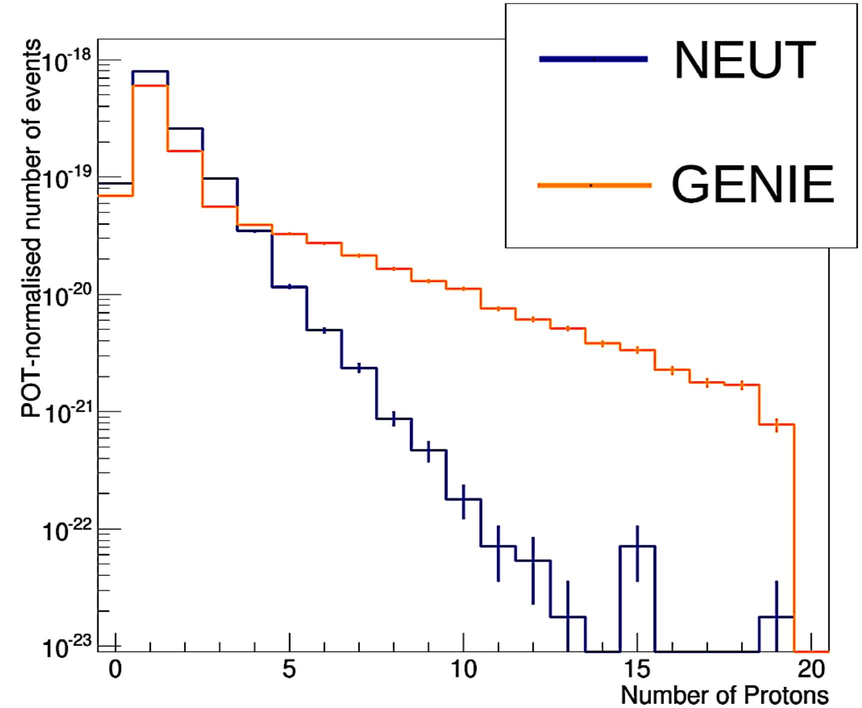
- **As an independent magnetized tracker**:
  - Full 4π coverage
    - Nearly identical acceptance as FD

- Need to understand discrepancies between event generators at lower energies
  - Lower detection threshold (than in LAr) in HPgTPC is critical for this

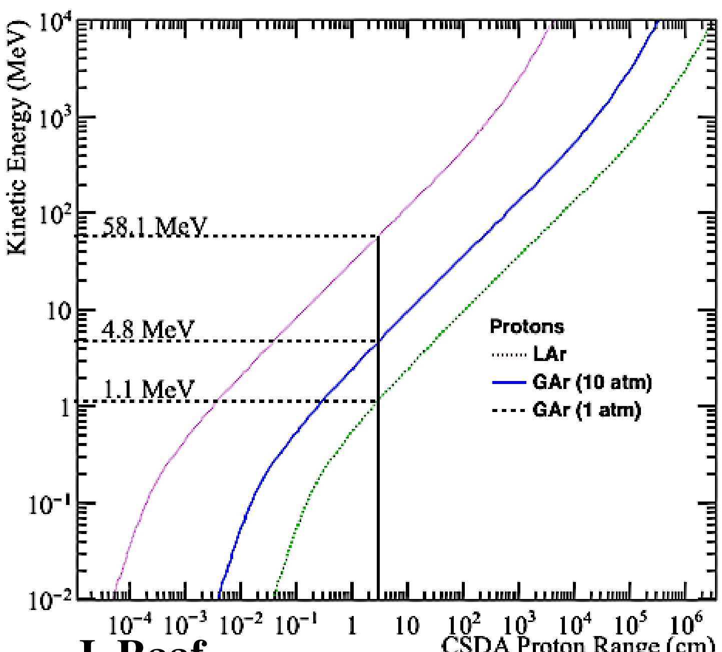
J. Raaf



P. Hamilton T2K-Thesis-062



- So, how low is the threshold for 10 atm GAr?
  - Range of a 5 MeV proton: 3 cm!
  - Ranges of less heavily ionizing particles (π, μ, e) >> proton range
- Assuming a 5 MeV detection threshold is conservative; may be able to go even lower



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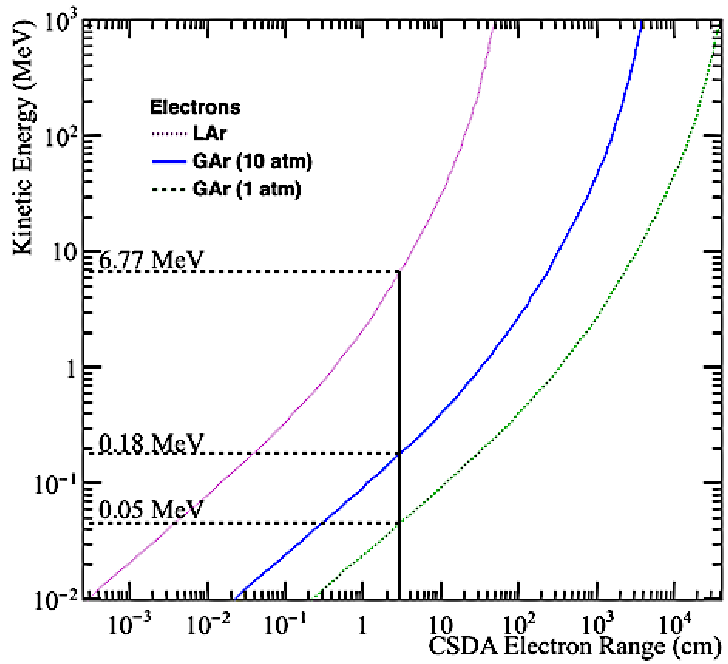


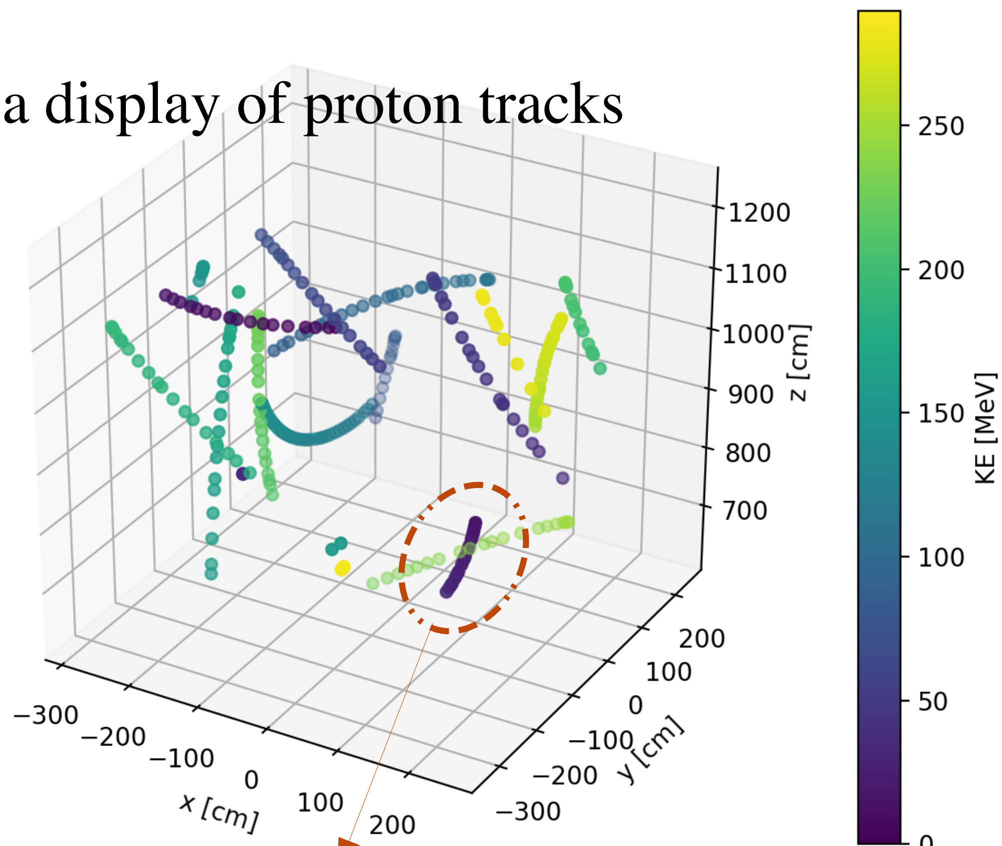
5 MeV K.E. particles

Species	Length (cm)
Protons	3
π^+	10
π^-	10
μ^+	15

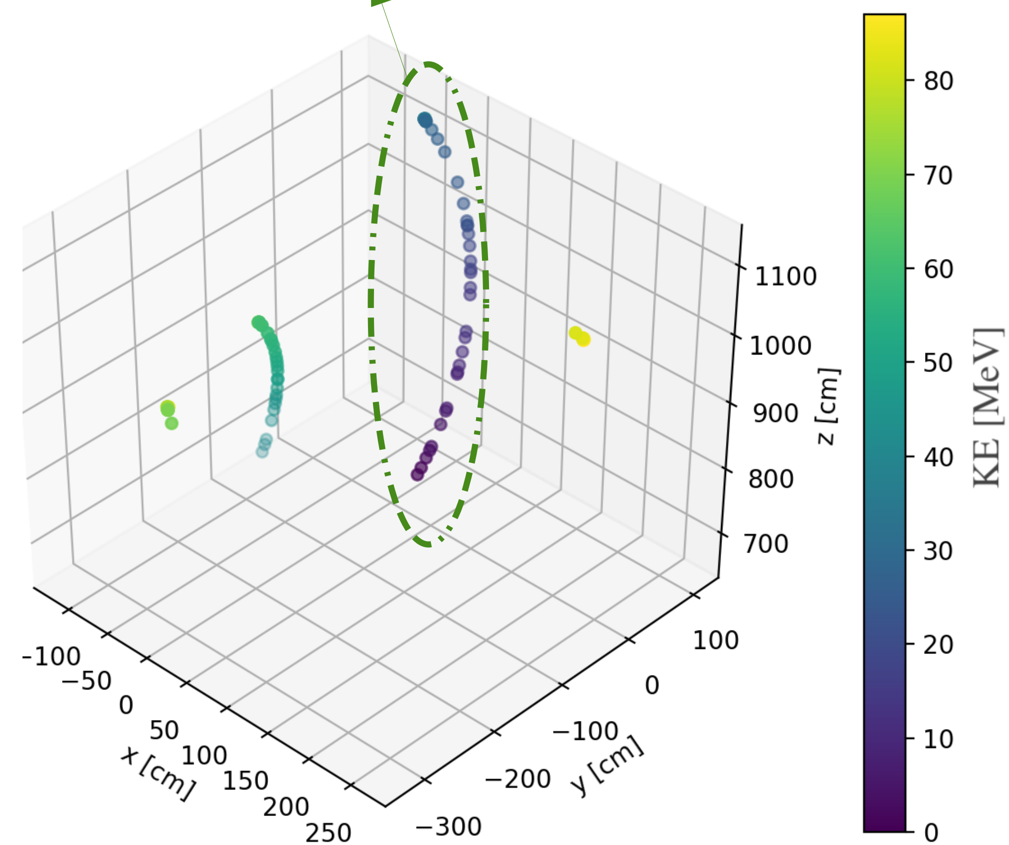
- Event displays of proton and electron tracks (some are final state particles from ν-N interactions) inside the HPgTPC

30 MeV electron traveling a distance of ~ 6 m

a display of proton tracks



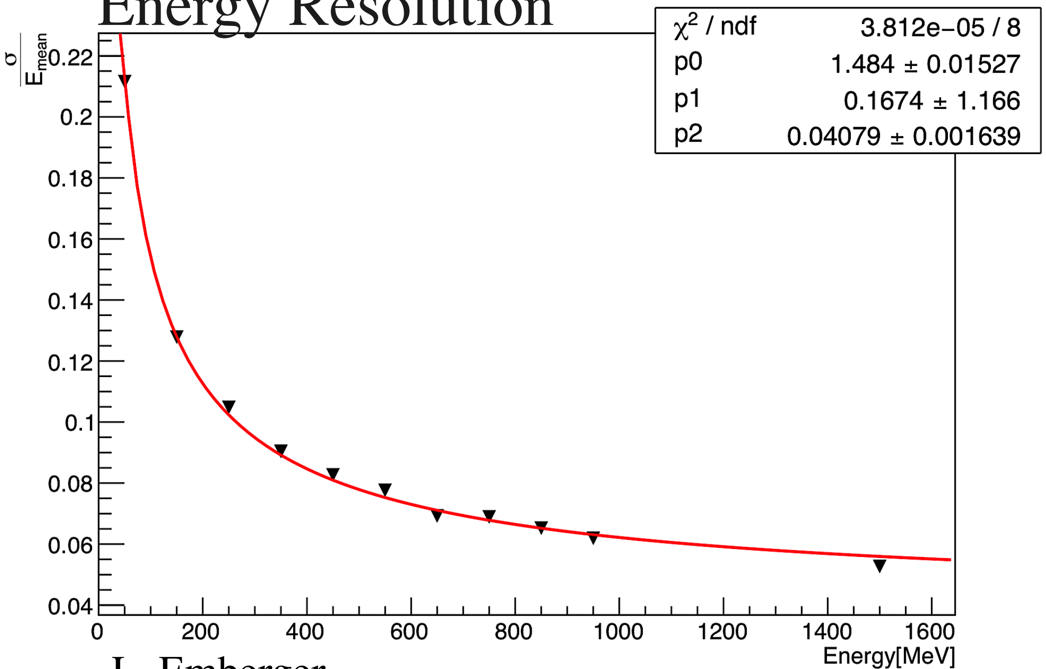
40 MeV proton with range of ~ 1 m



a display of electron tracks

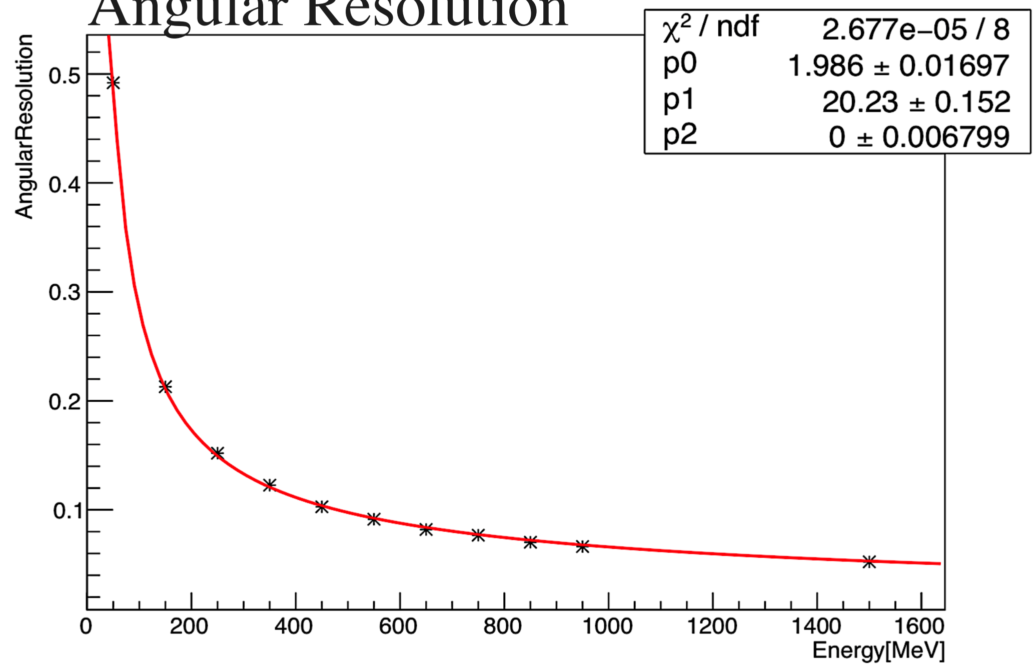
- Parameters used in determining ECAL performance:
  - Energy & angular resolution – obtained using:
    - GEANT-4 based simulation, simplified detector model, simplified reconstruction & single photon energies

Energy Resolution



L. Emberger

Angular Resolution



- Primary use of ECAL:
  - Mark timing of interaction, for interactions with particles exiting gas (70%)
  - Tagging neutrons with purity stated below