FERMILAB-SLIDES-19-025-ND

High-Pressure Gas TPC (HPgTPC) for DUNE Near Detector

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Physics Opportunities in the Near DUNE Detector Hall

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Fermilab

Outline

- Purpose
- Conceptual Design
- Expected Physics Performance
- ν Channels of Interest
- Summary & Discussion

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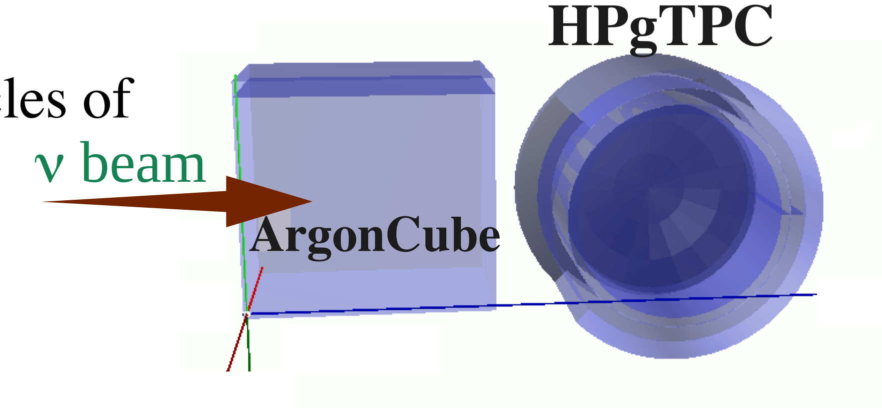
Purpose

Primary role is controlling the systematic uncertainties present in oscillation measurements – those dominated by cross-section, flux, & ν-energy
Other important roles:

- **As a component of the DUNE near detector**:
  - Tag muons originating in ArgonCube
  - Tag sign of charged particles exiting ArgonCube
- **As a stand-alone magnetized spectrometer**:
  - In ν-interactions in the gas, detect charged particles of very low energies
  - Has superb:
    - Tracking efficiency, PID
    - Momentum & angular resolution
  - Magnetic field helps HPgTPC to:
    - Determine charge sign on an event-by-event basis & discriminate between $\nu/\bar{\nu}$
    - A background-free sample of ν_e CC events via sign tagging in b-field
- **As a tracker surrounded by the ECAL calorimeter:**
  - Detect neutrons & tag exiting particles



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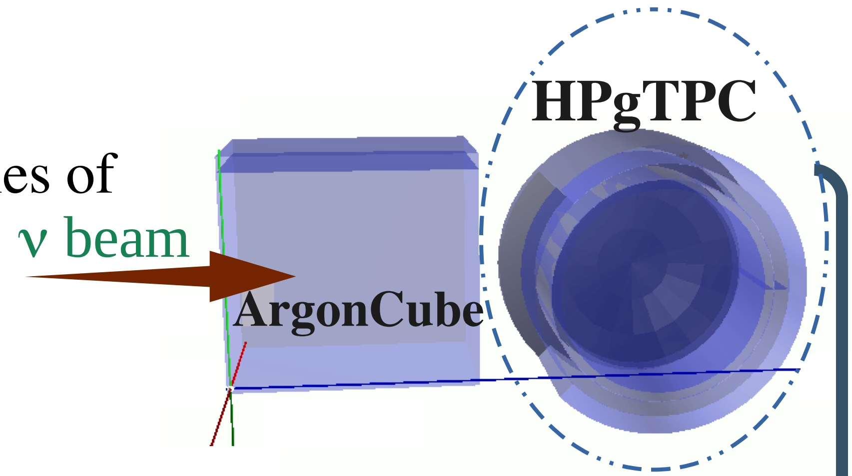

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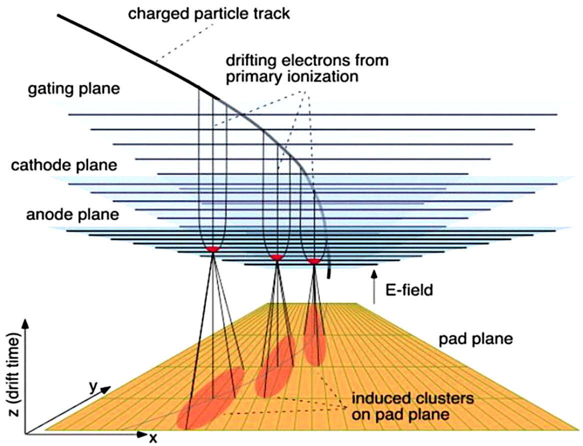
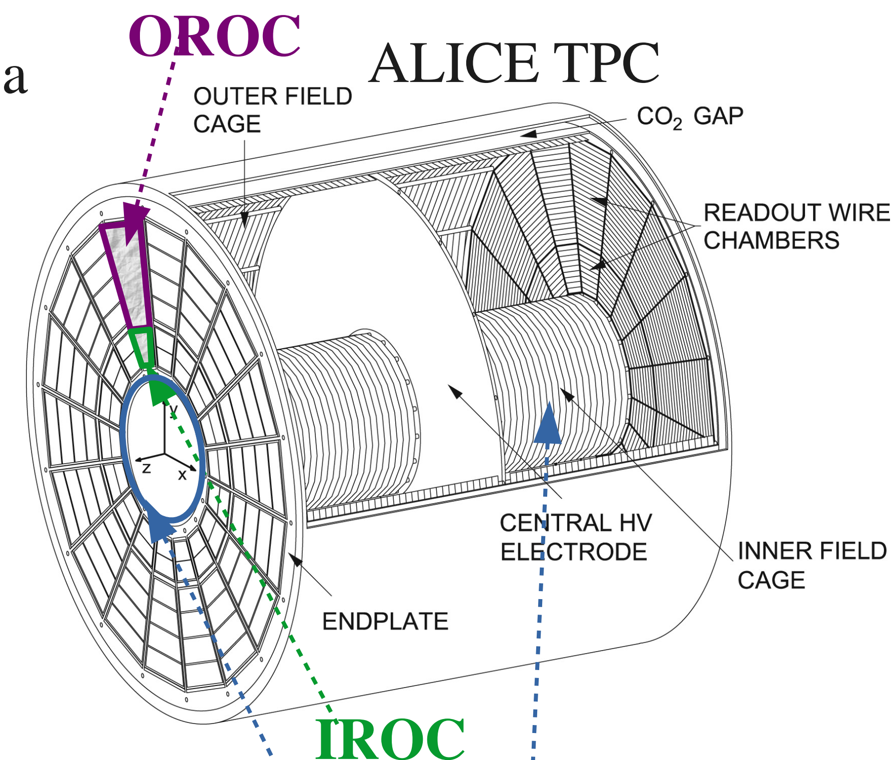
HPgTPC Conceptual Design

- Copy of the ALICE TPC:
  - Will reuse 72 ALICE **Inner** and **Outer** Readout Chambers (**IROC** and **OROC**):
    - Available because of planned ALICE upgrade, a significant cost reduction for DUNE



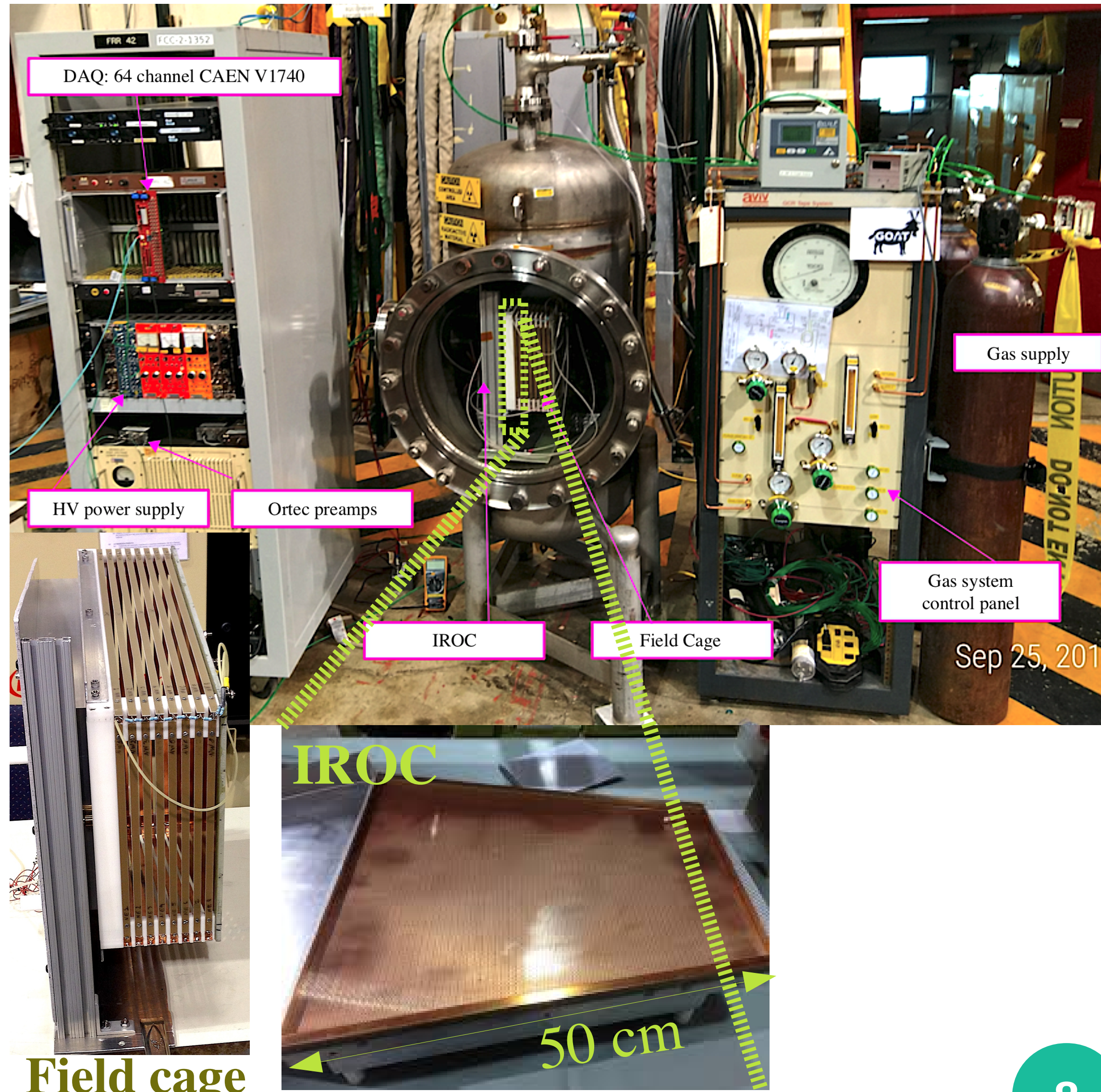
    - Operated @ 1 atm pressure in ALICE. Will operate @ 10 atm pressure in DUNE HPgTPC
- Primary gas mixture in DUNE HPgTPC will be Ar-CH_4 (P10 with 97% of interactions on Ar):
- Possible to study other nuclei such as H_2 (safety concern but not impossible!), D_2, Ne, CF_4, Xe



Not provided by ALICE: **central readout chambers** (do not exist in ALICE), **field cages,** front-end electronics

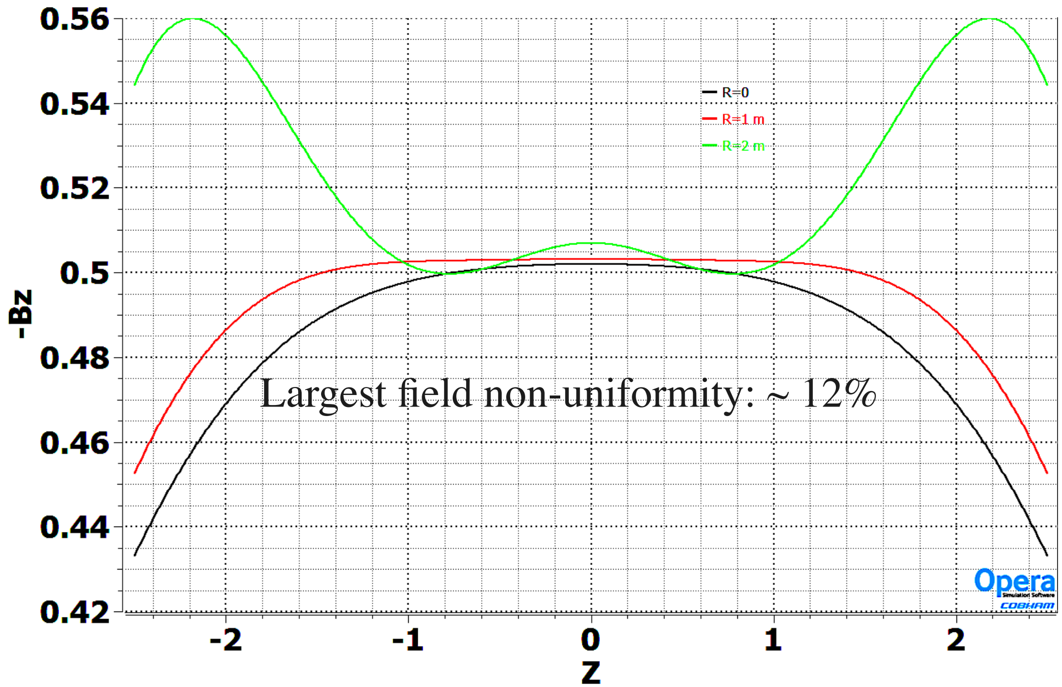
HPgTPC Test Stand @ FNAL

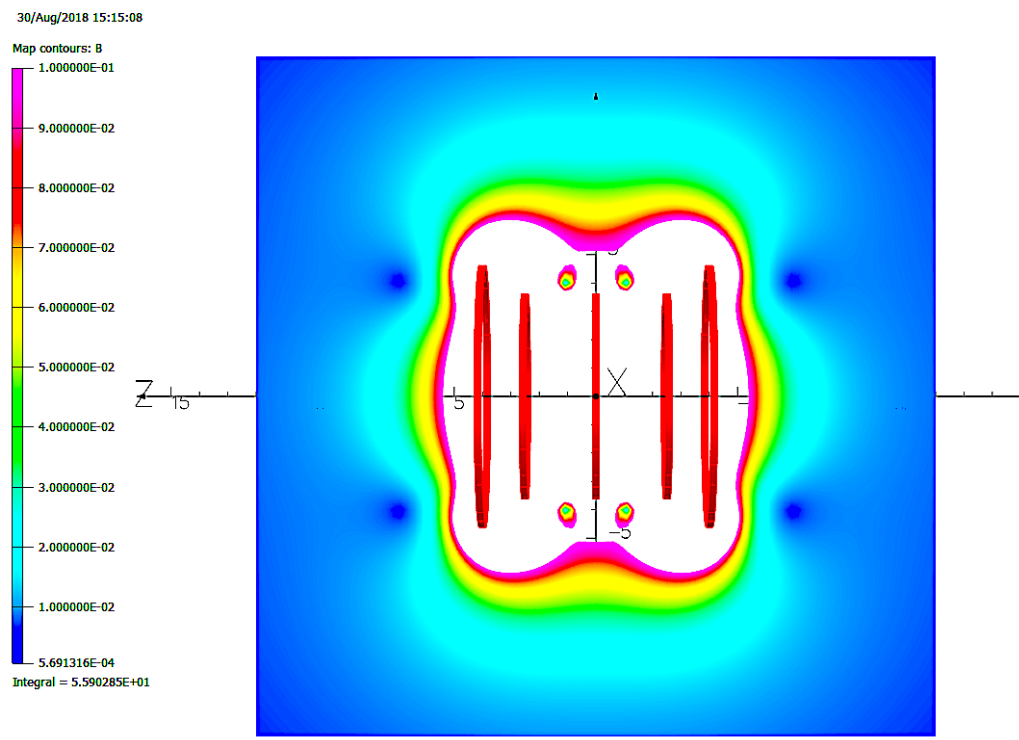
- **G**aseous-Argon **O**peration of the **A**LICE **T**PC, **GOAT**
  - Test ALICE readout chambers at 10 atm and in various gas mixture (currently 90-10 Ar-CO_2)
  - Develop full front-end electronics chain
- Various components in **GOAT**:
  - Signal readout with ALICE **IROC**
  - **Field cage**
  - Front-end with preamps and CAEN digitizers
- Upgrades to components underway; stay tuned!



Conceptual Design – HPgTPC Magnet

- One of the proposed designs:
  - 3 superconducting Helmholtz & a pair of trim (added for field uniformity) coils
- Parameters affecting its design:
  - Uniformity in central field + fringe field (should be minimized)

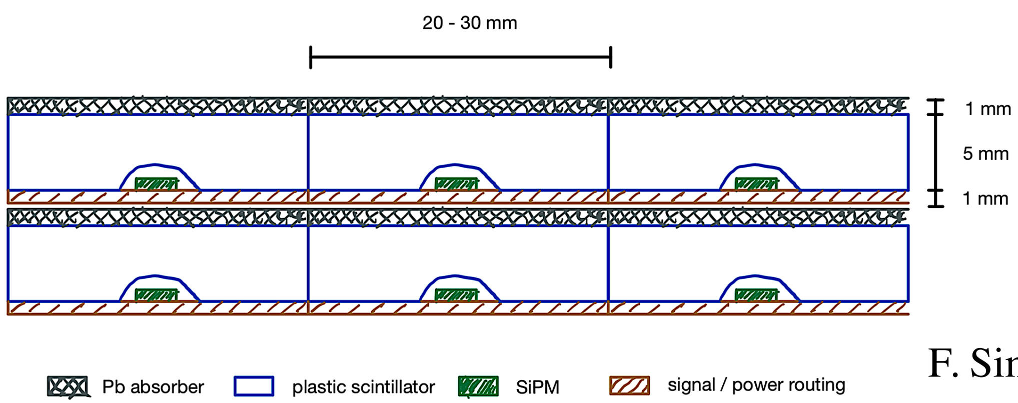


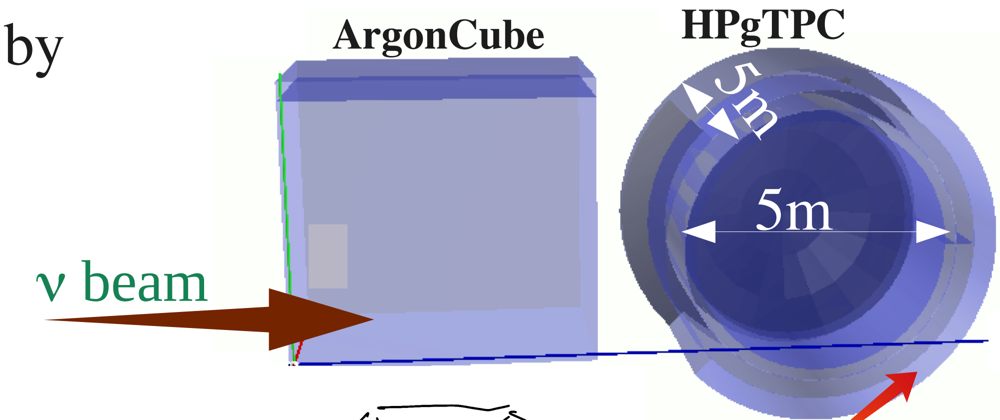


A. Bross, V. Kashikhin, T. Strauss, G. Velev

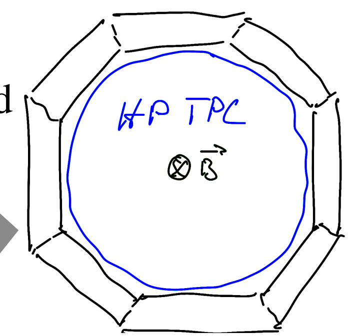
Conceptual Design – HPgTPC ECAL

- An electromagnetic calorimeter, inspired by the CALICE calorimeter design:
  - Made of plastic scintillators (readout by silicon photomultipliers) sandwiched between lead absorber sheets





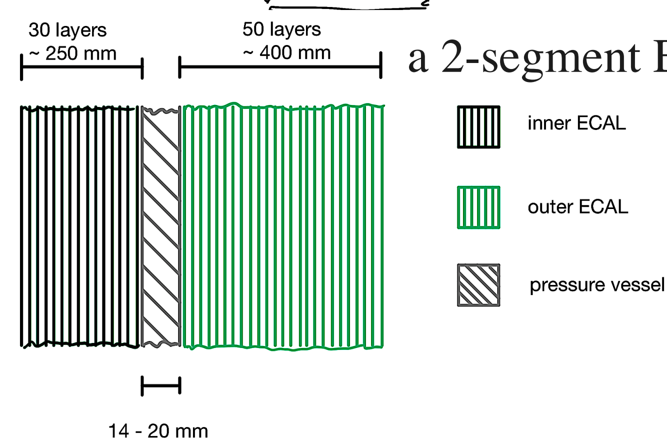
ECAL placed in HPgTPC



F. Simon, E. Brianne

- Factors affecting its design:
  - Limited space inside the pressure vessel → possibly needs a 2-segment design
  - Good directional resolution → high granular with a high sampling frequency

a 2-segment ECAL design



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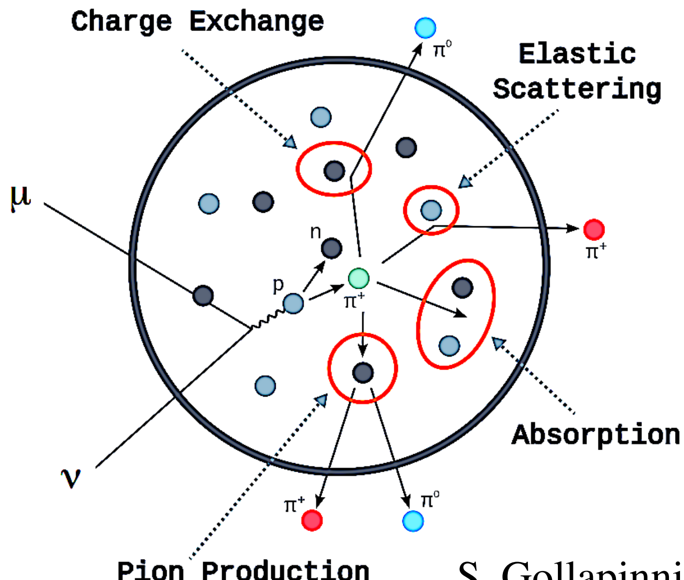
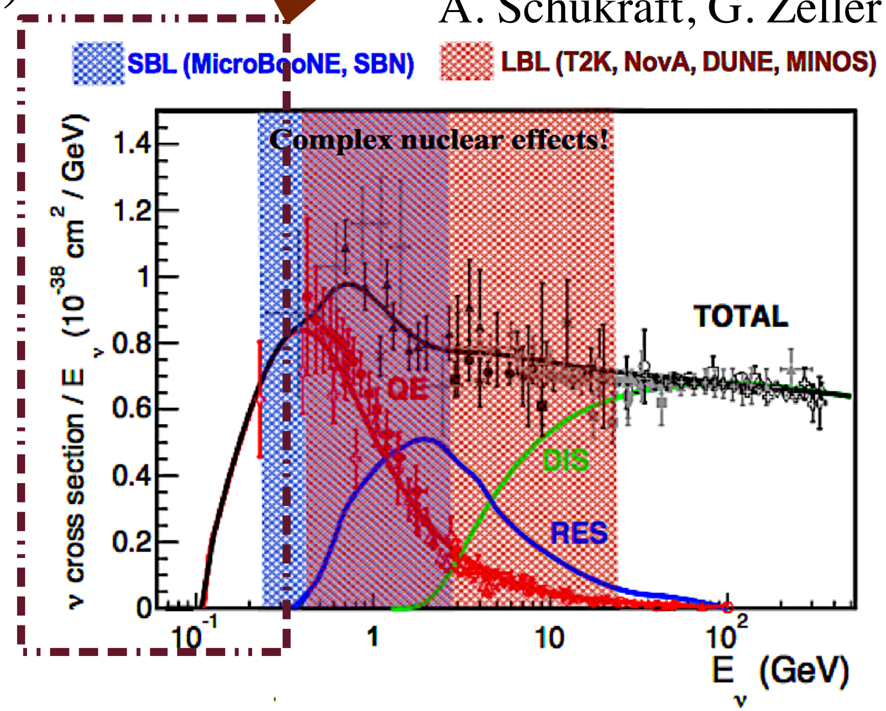
HPgTPC Physics Role

- Crucial to understand ν-N interactions to accurately reconstruct **ν-energy** & cross-section
- Nucleus is a complicated environment:
  - Experimental data limited in nuclear targets & no data in **low ν-energy**
- HPgTPC helps:
  - Lower density ($\rho_{LAr}/\rho_{GAr} \approx 85$ for 10 atm GAr) → lower detection threshold → higher sensitivity to charged particles at lower energies



A. Schukraft, G. Zeller

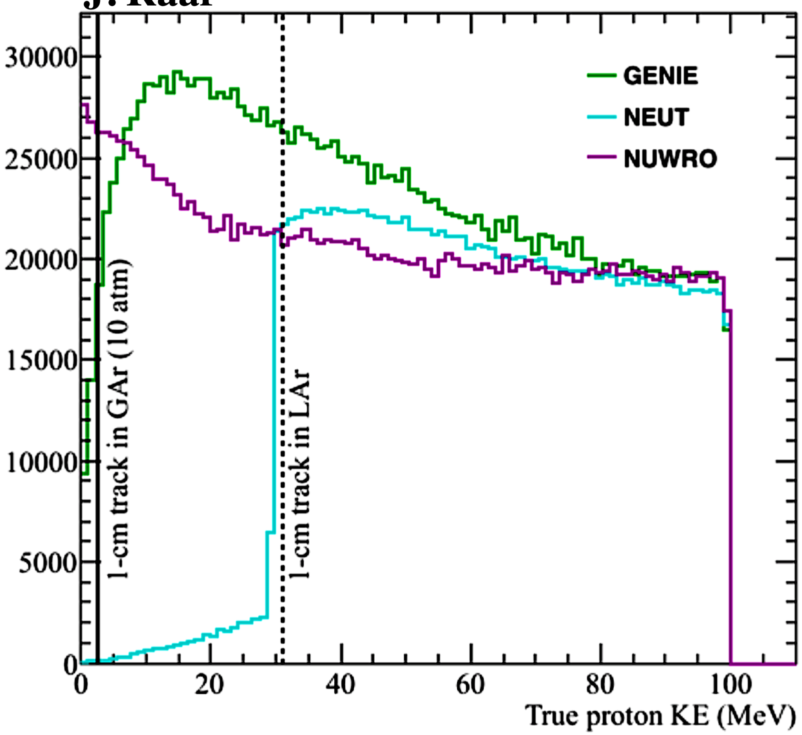


S. Gollapinni, "Neutrino Cross section Future," Proc. NuPhys2015

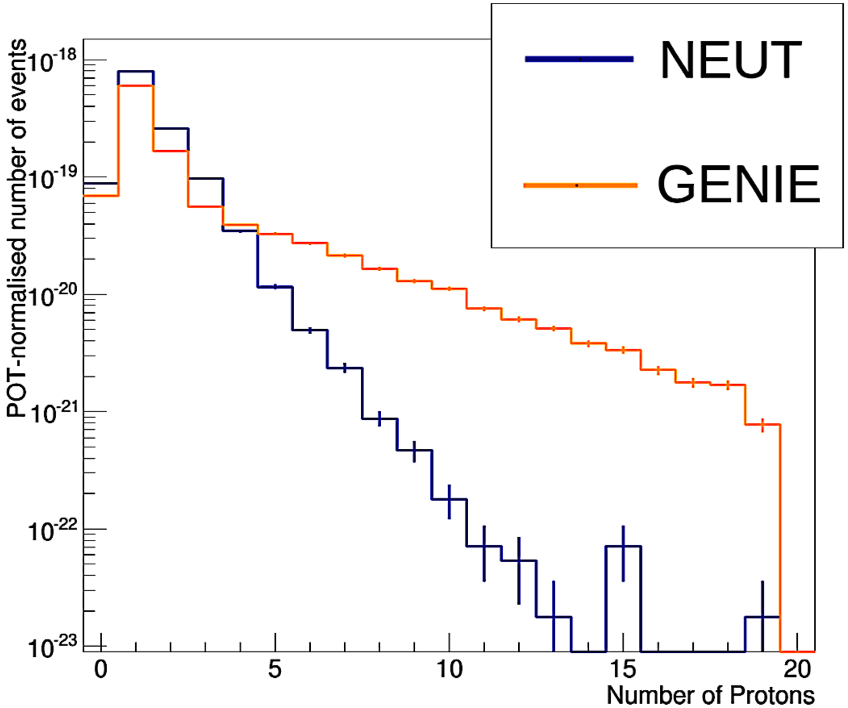
HPgTPC Physics Role

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

J. Raaf

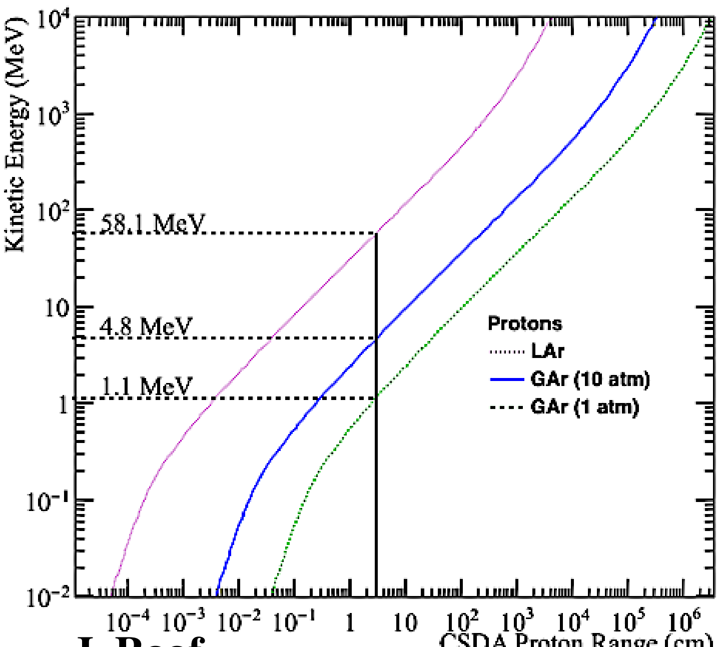


P. Hamilton T2K-Thesis-062

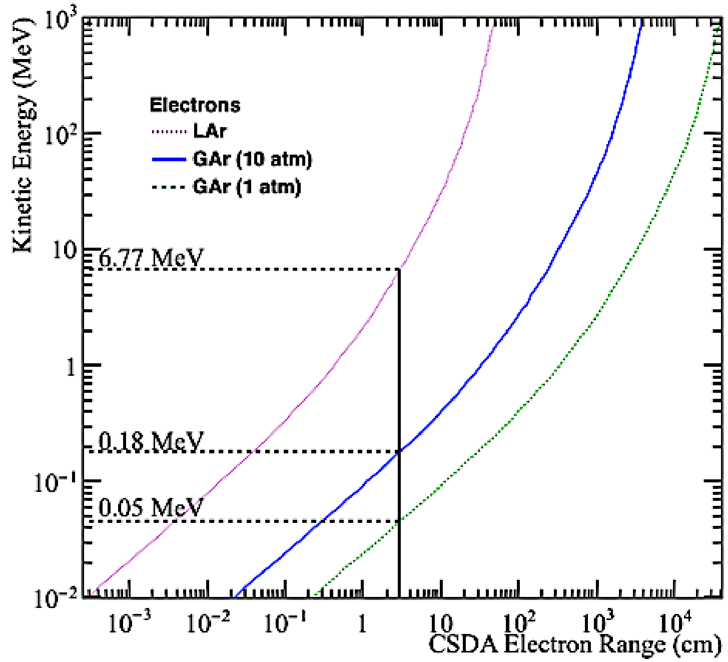


Expected Physics Performance

- 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



J. Raaf



5 MeV K.E. particles

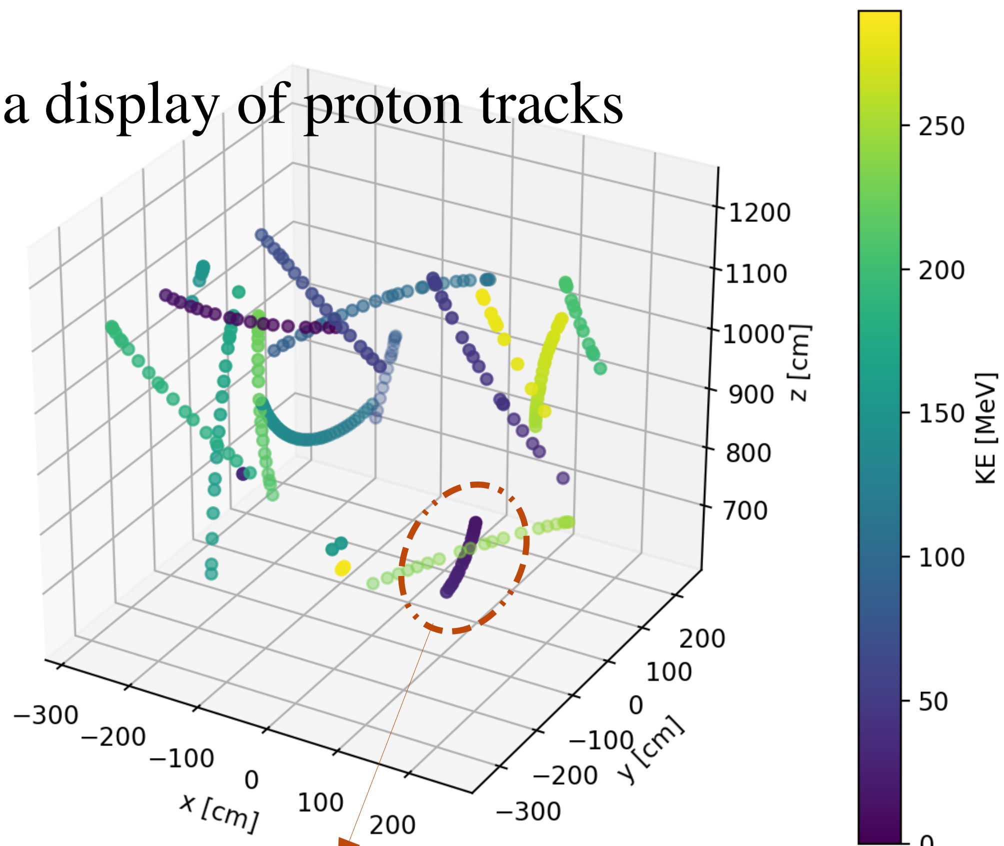
Species	Length (cm)
Protons	3
π^+	10
π^-	10
μ^+	15

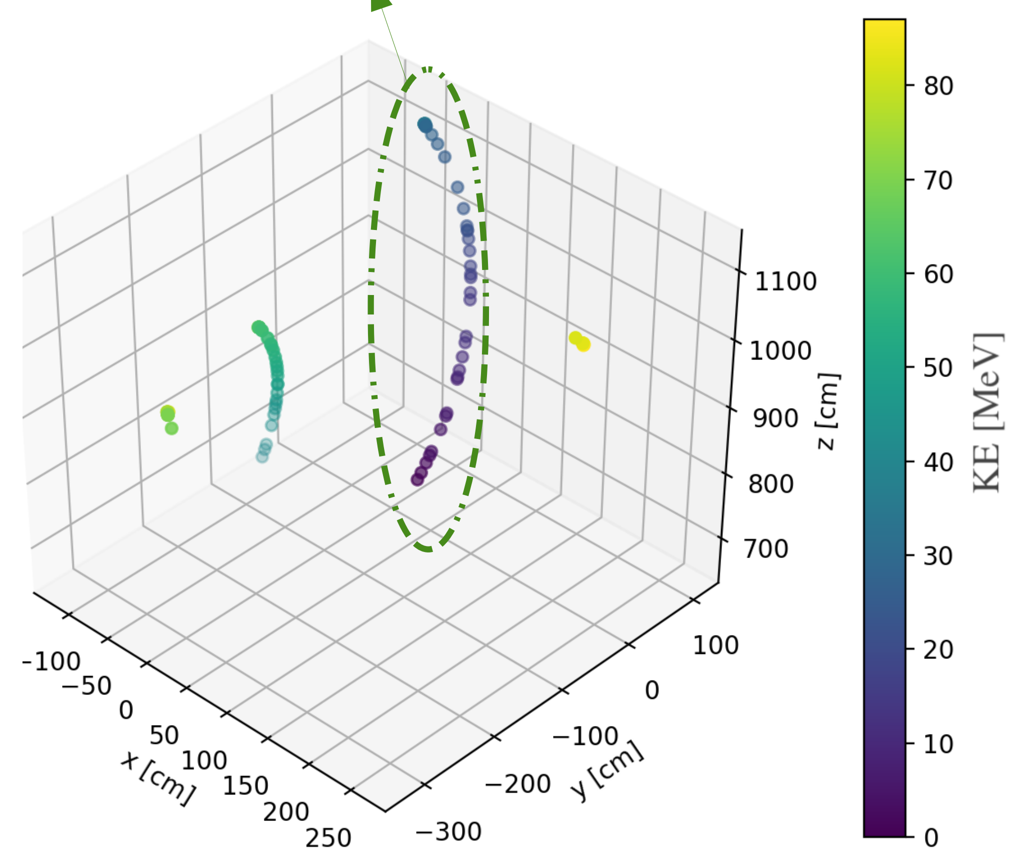
Expected Physics Performance

- 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



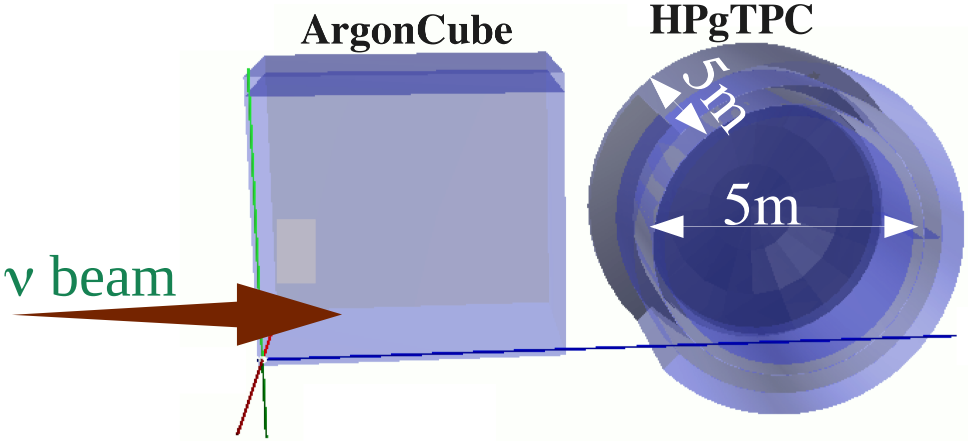


40 MeV proton with range of ~ 1 m

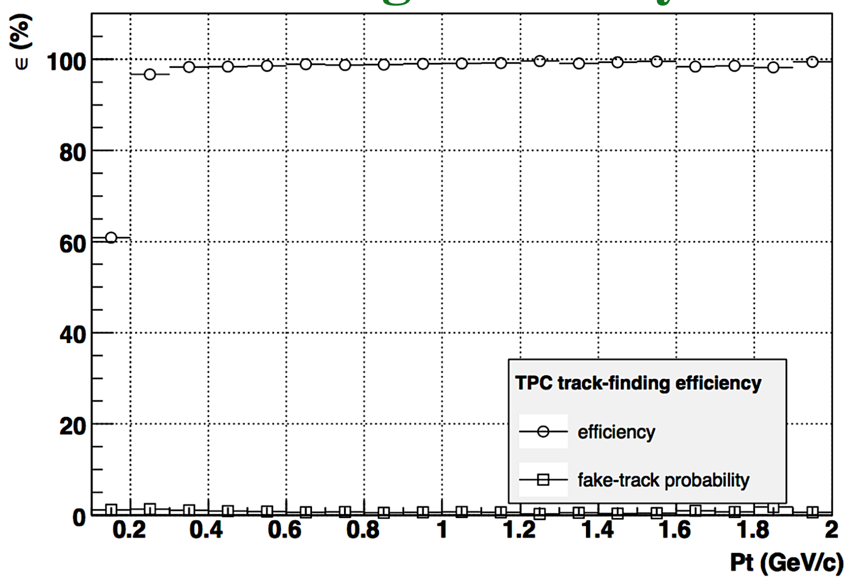
a display of electron tracks

Expected Physics Performance

- A 4π coverage & excellent **tracking efficiency** (based on ALICE performance)
- High multiplicity in HPgTPC will not be an issue – hint: take a look at the ALICE events



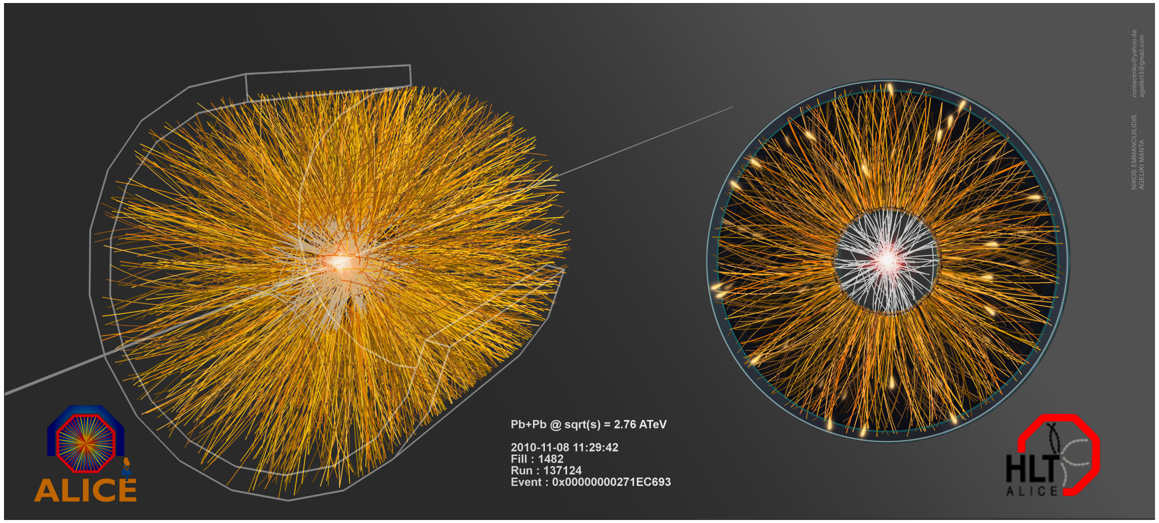
Tracking Efficiency



C. W. Fabjan et al. (ALICE), J. Phys. G32, 1295 (2006)

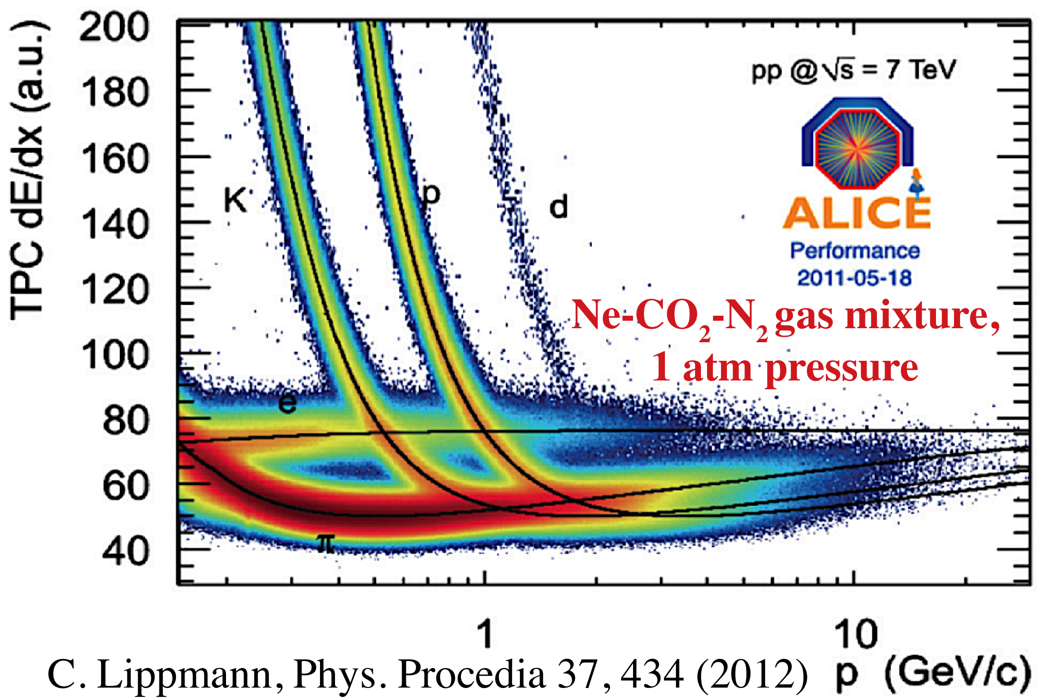
Credit: aliceinfo.cern.ch

ALICE TPC Events

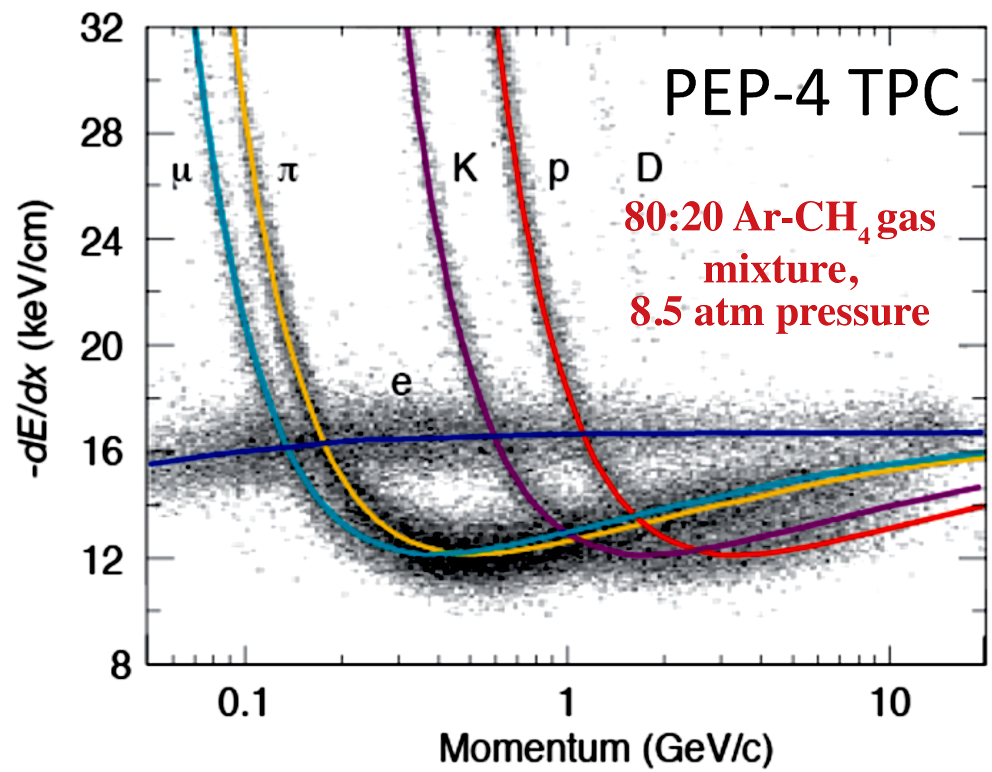


Expected Physics Performance

- Excellent PID based on ALICE & PEP-4 results – HPgTPC will operate at even higher pressure (10 atm pressure) than PEP-4 (8.5 atm pressure) → even better PID
- Clear distinction between particles, in particular at lower momenta



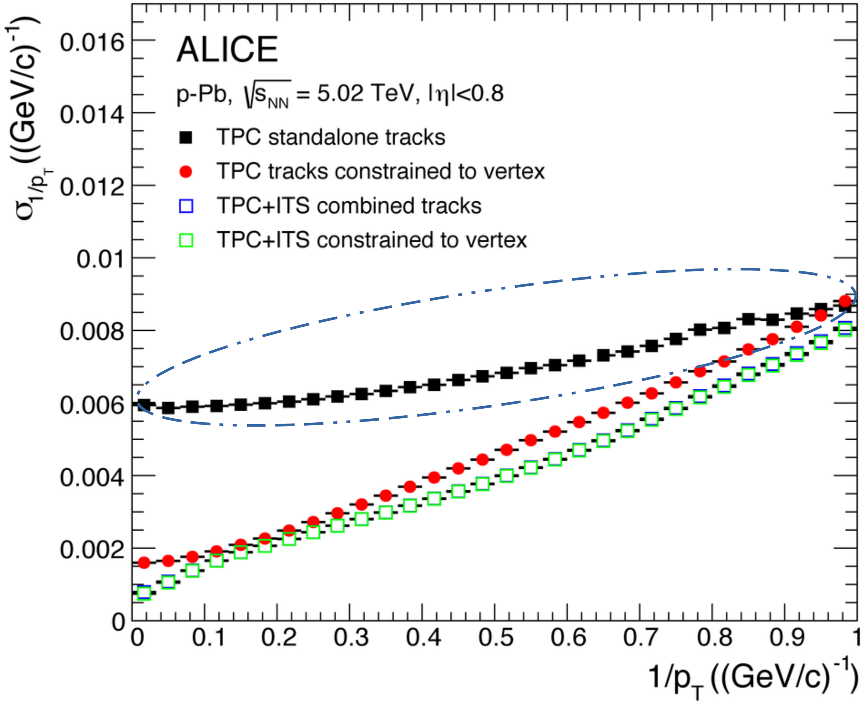
C. Lippmann, Phys. Procedia 37, 434 (2012)



Expected Physics Performance

- Performance parameters based on ALICE & PEP-4:
  - Less multiple scattering in gas (a limiting factor in momentum resolution) → great momentum (black squares in momentum resolution plot) & angular resolutions

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
σ(dE/dx)	5	%
σ_{p_T}/p_T	0.7	% (10-1 GeV/c)
σ_{p_T}/p_T	1-2	% (1-0.1 GeV/c)
Energy scale uncertainty	$\lessapprox 1$	% (dominated by δ_p/p)
Charge particle detection thresh.	5	MeV (K.E.)
ECAL resolution	5-7/$\sqrt{E/\mathrm{GeV}}$	%
ECAL pointing resolution	$\simeq$ 6 at 500 MeV	degree

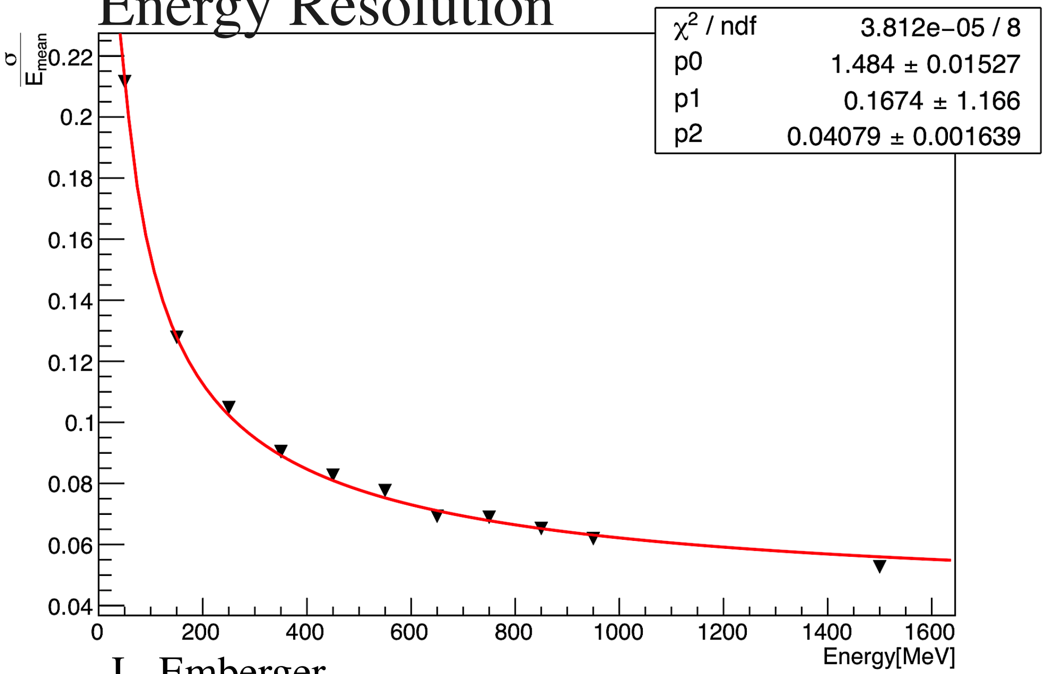


B. B. Abelev et al. (ALICE), Int. J. Mod. Phys. A29, 1430044 (2014), 1402.4476

Expected Physics Performance

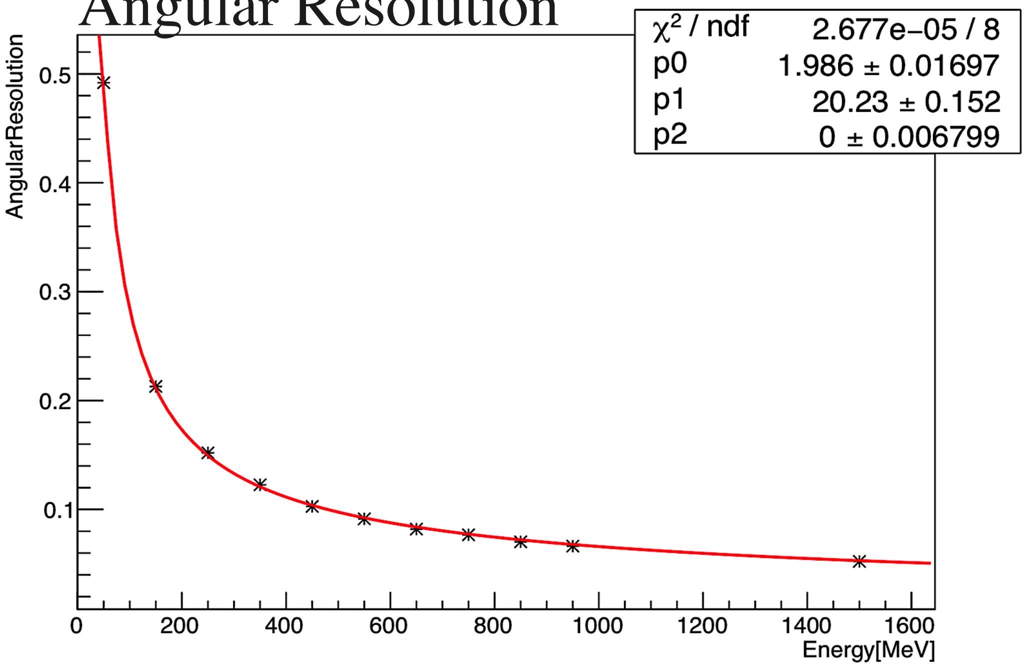
- Parameters used in determining ECAL performance:
  - Energy & angular resolution – obtained using:
    - GEANT-4 based simulation, simplified detector model, simplified reconstruction & single photon energies
    - A 2-segmented ECAL design

Energy Resolution



L. Emberger

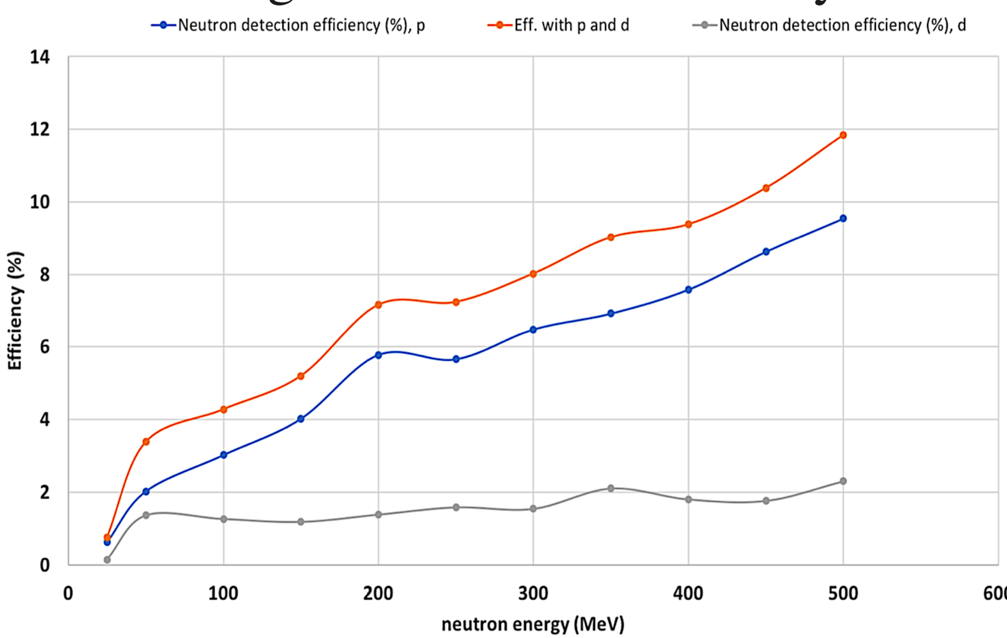
Angular Resolution



Expected Physics Performance

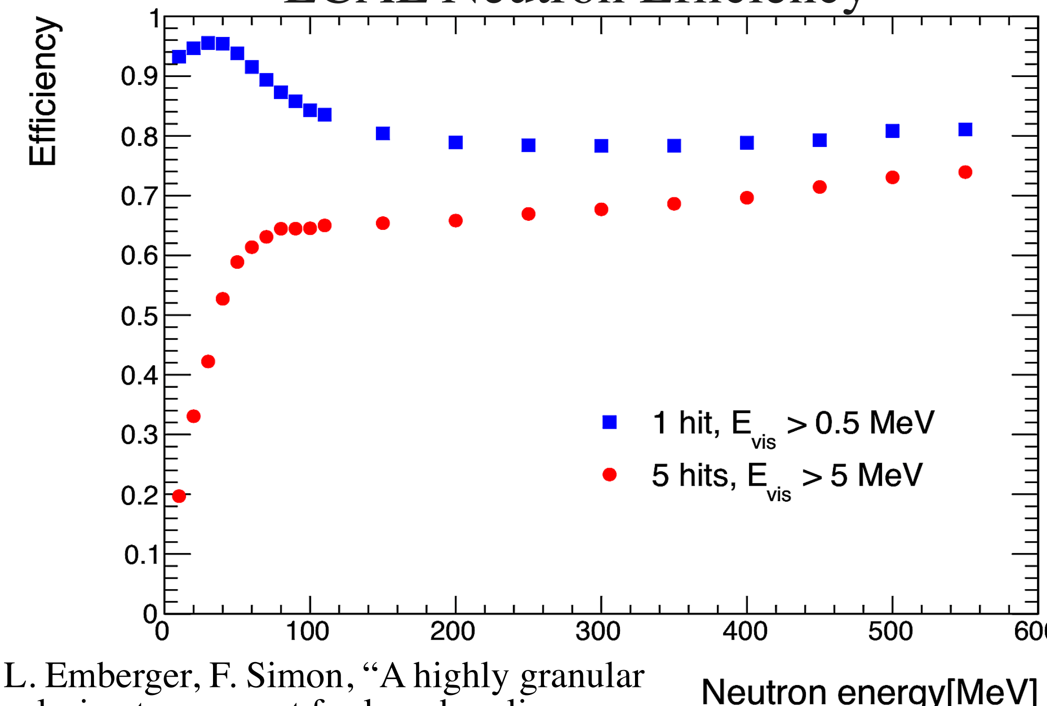
- Primary use of ECAL:
  - Mark timing of interaction, for interactions with particles exiting gas (70%)
  - Tagging neutrons
- Neutron tagging efficiency in HPgTPC not enough – ECAL can help

HPgTPC Neutron Efficiency



A. Bross

ECAL Neutron Efficiency



L. Emberger, F. Simon, “A highly granular calorimeter concept for long baseline near detectors,” Proc. CALOR 2018

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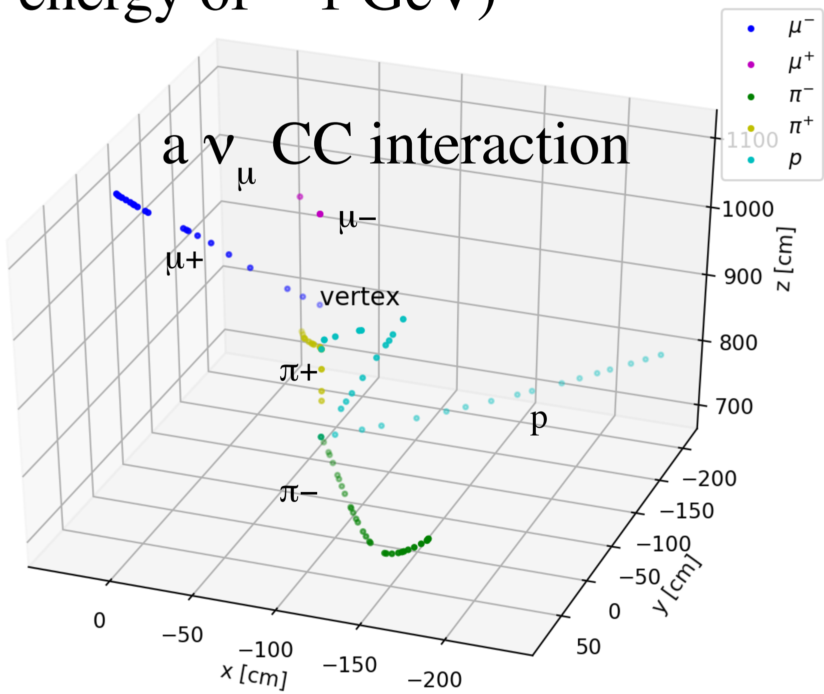
Key ν channels

- Some standard ν channels & their stats
- Event display from ν_μ CC interaction:
  - GENIE event generator to generate the ν-interactions + GEANT4-based simulation to reconstruct the energy (ν-energy of ~ 1 GeV)



Event class	Number of events per ton-year
ν_μ CC Total	1.64×10^6
ν_μ NC Total	5.17×10^5
ν_μ CC Coherent	8.35×10^3
ν_μ NC Coherent	4.8×10^3
ν_μ - electron elastic	135
ν_μ CC π^0 inclusive	4.47×10^5
ν_μ NC π^0 inclusive	1.96×10^5
ν_μ Low ν (250 MeV)	2.16×10^5
ν_μ Low ν (100 MeV)	7.93×10^4
$\bar{\nu}_\mu$ CC Coherent ($\bar{\nu}$ mode)	6.90×10^3
ν_e CC Total	1.89×10^4
ν_e NC Total	5.98×10^3
ν_e CC Coherent	93
ν_e NC Coherent	52

Key ν channels

- As a magnetized tracker, HPgTPC can:
  - Obtain a background-free sample of ν_e CC events via wrong-sign tagging in b-fied
- In LArTPC:
  - ν_μ NC π^0s are misidentified as ν_e CCs
- In HPgTPC, not an issue:
  - No π^0s conversion in gas
  - Most NC π^0 events easily tagged by oppositely-bending e^+ and e^- tracks

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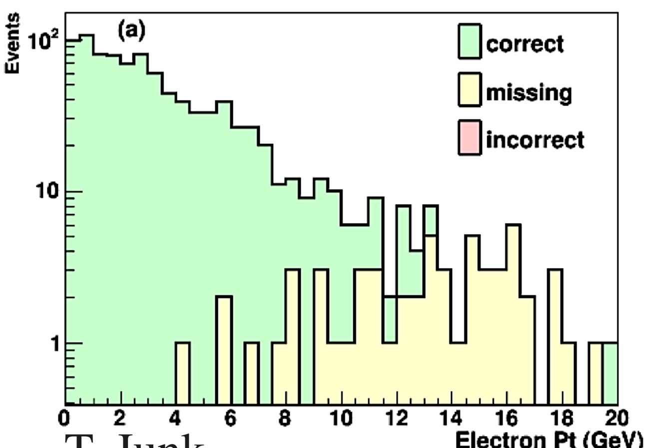


T. Junk

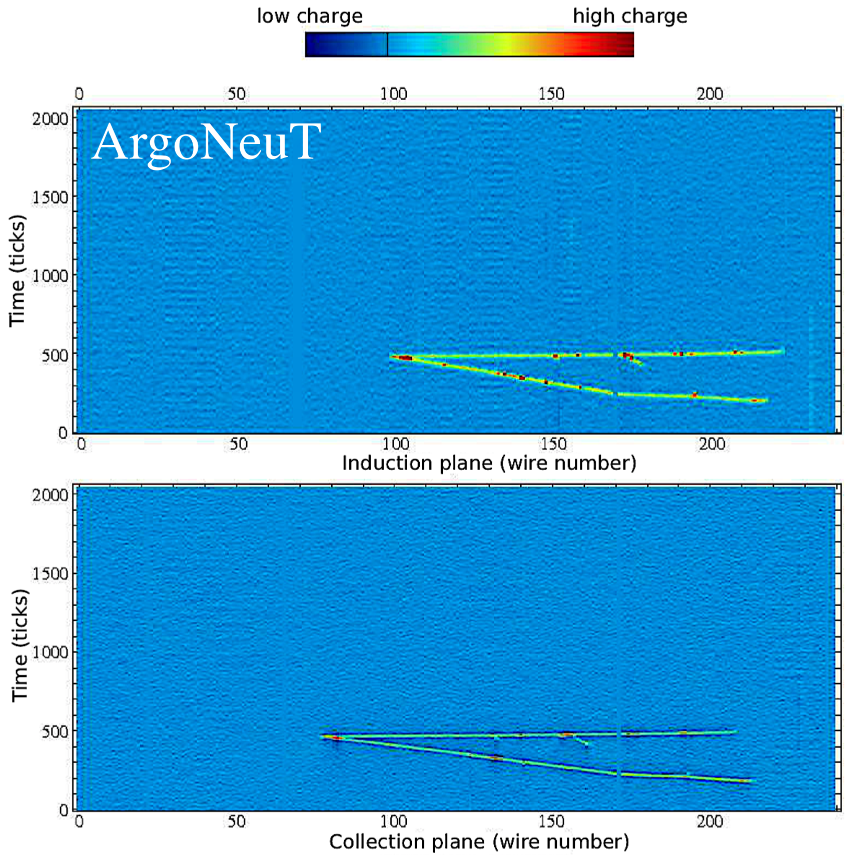
Key ν channels

- CC $\pi^{+/-}$ coherent scattering is a channel of interest:
  - Same cross-section for ν and $\bar{\nu}$ → can check for any biases in the two running modes
  - Almost no energy transfer to nucleus → estimate true ν–energy for both ν & $\bar{\nu}$

	Coherent-like Events (Fraction passing cuts)
All non-coherent CC events (no cuts)	745720 (1.0)
LArTPC (E_{thresh} = 40 MeV)	407 (0.0005)
HPgTPC (E_{thresh} = 5 MeV)	8 (1×10^{-5})
HPgTPC (E_{thresh} = 2.5 MeV)	1 (1×10^{-6})

- A cleaner sample can be selected with HPgTPC (thanks to its the low threshold) than LArTPC

Tingjun Yang et al. (ArgoNeuT collaboration) "First Measurement of Neutrino and Antineutrino Coherent Charged Pion Production on Argon," Phys. Rev. Lett. 113, 261801 (2014)



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Summary & Discussion

- The aim of the full near detector suite is to reduce the systematic uncertainties in the oscillation measurement to a few % level:
  - Main sources of uncertainty are measurements of cross-section, flux, and ν-energy
- The HPgTPC is a crucial component of the near detector suite:
  - Augment upstream detector by tracking and sign-tagging particles exiting LArTPC
  - Collect independent sample of neutrino interactions on argon
  - Extend neutrino cross section measurements to lower energies in region where data are sparse
  - Background-free samples of CC coherent and intrinsic beam ν_e
  - Test & tune generator models at lower energies
  - Capable of operating with other nuclear target materials (H_2, D_2,…)
- The HPgTPC may also provide opportunities to search for exotic physics
  - Milli-charged particles? Dark matter?… let's discuss!

On behalf of the HPgTPC team: L. Bellantoni, E. Brianne, A. Bross, K. Duffy, G. Fernandez Moroni, T. Junk, J. Martin-Albo, T. Mohayai, J. Raaf

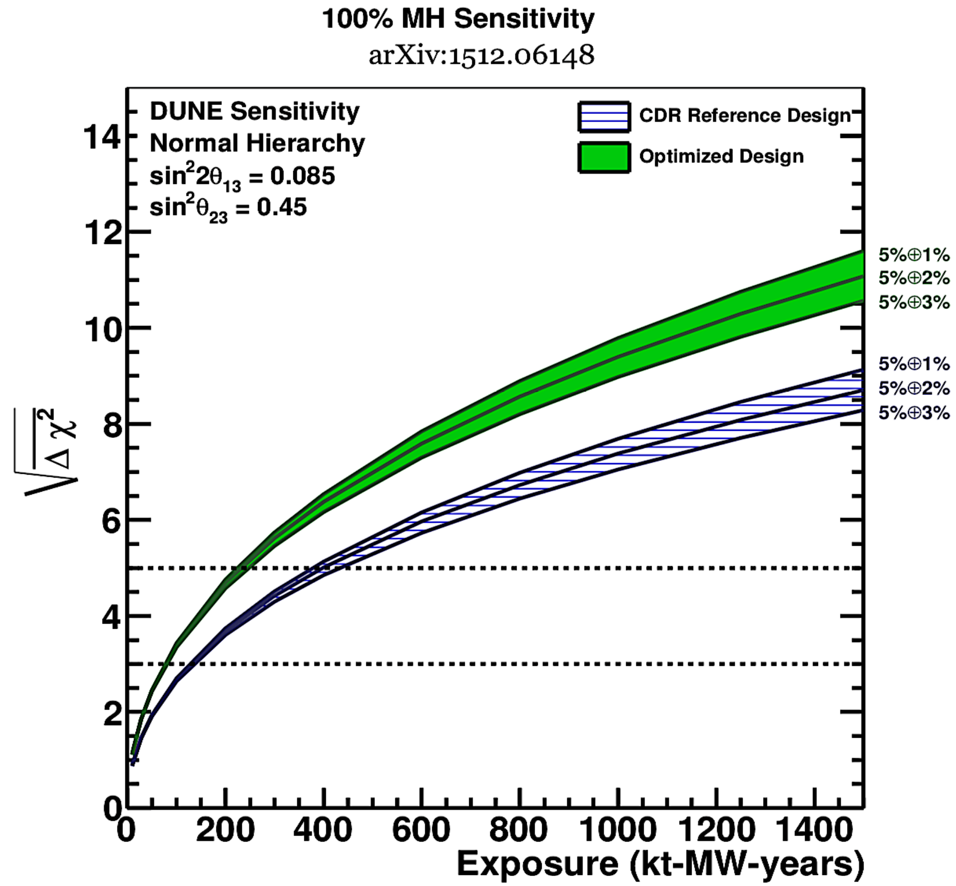
Thank You!

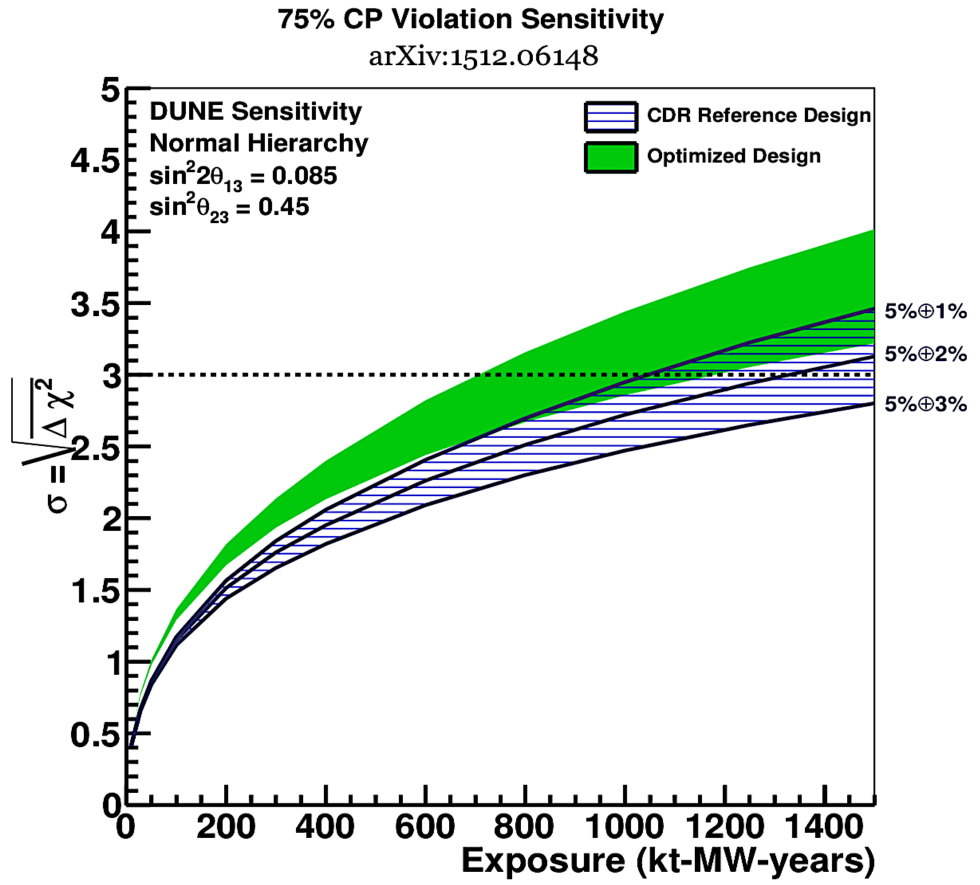
More collaborators are welcome!
Contact us if interested!

Additional Slides

Near Detector Physics Motivation

- Reducing the systematic uncertainties in the oscillation measurement to a few % level:
  - Main sources of uncertainties are measurements of **cross-section**, **flux**, & **ν-energy**





Near Detector Physics Motivation

- Reducing the systematic uncertainties in the oscillation measurement to a few % level:
  - Main sources of uncertainties are measurements of **cross-section**, **flux**, & **ν-energy**
- Observable is **disappearance/appearance events** vs. the **ν-energy**

a simplified oscillation measurement, from an experimental point of view:

$$P_{\nu_\alpha \to \nu_{\alpha'}} \approx \frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} \times \frac{\epsilon^{ND}(E_\nu)}{\epsilon^{FD}(E_\nu)}$$

where

$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} = \frac{\int \Phi_{\nu_{\alpha'}}(E_\nu)\sigma_{\nu_{\alpha'}}(E_\nu)dE_\nu}{\int \Phi_{\nu_\alpha}(E_\nu)\sigma_{\nu_\alpha}(E_\nu)dE_\nu}$$

Near Detector Physics Motivation

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where

ν-energy

$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} = \frac{\int \Phi_{\nu_{\alpha'}}(E_\nu)\sigma_{\nu_{\alpha'}}(E_\nu)dE_\nu}{\int \Phi_{\nu_\alpha}(E_\nu)\sigma_{\nu_\alpha}(E_\nu)dE_\nu}$$

flux **cross-section**

Near Detector Physics Motivation

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arXiv:1512.06148 arXiv:1512.06148