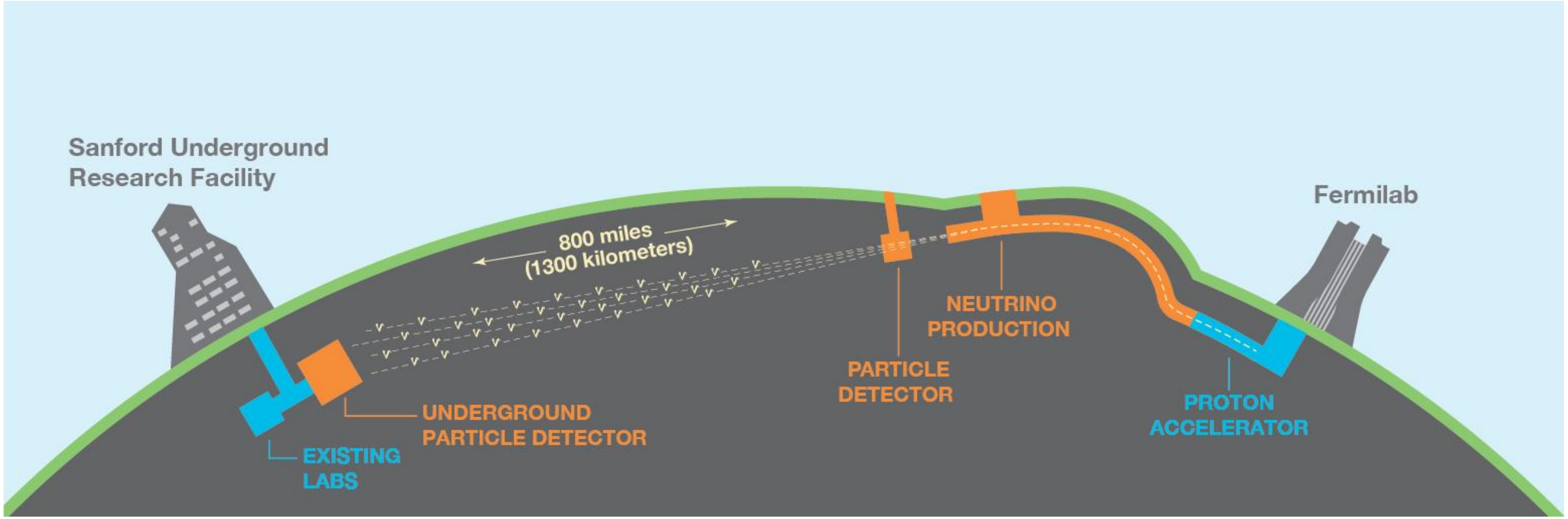
DEEP UNDERGROUND NEUTRINO EXPERIMENT

PHYSICS OPPORTUNITIES WITH ND-GAR:
TKI TECHNIQUES IN CROSS-SECTION STUDIES

UNIVERSITY OF OXFORD

Author:
Federico Battisti

DUNE: DEEP UNDERGROUND NEUTRINO EXPERIMENT



- DUNE will be a world-class, international particle physics experiment hosted by Fermilab. It consists of a FD to be located 1.5 km underground at SURF in South Dakota, 1300 km from a ND that will be located on the Fermilab site in Illinois

- Main objectives:
  1. Conduct a comprehensive program of neutrino oscillation measurements using the intense LBNF (anti)neutrino beam;
  2. Search for proton decay in several decay modes;
  3. Detect and measure the ν_e flux from a core-collapse supernova within our galaxy, should one happen during the lifetime of the experiment.

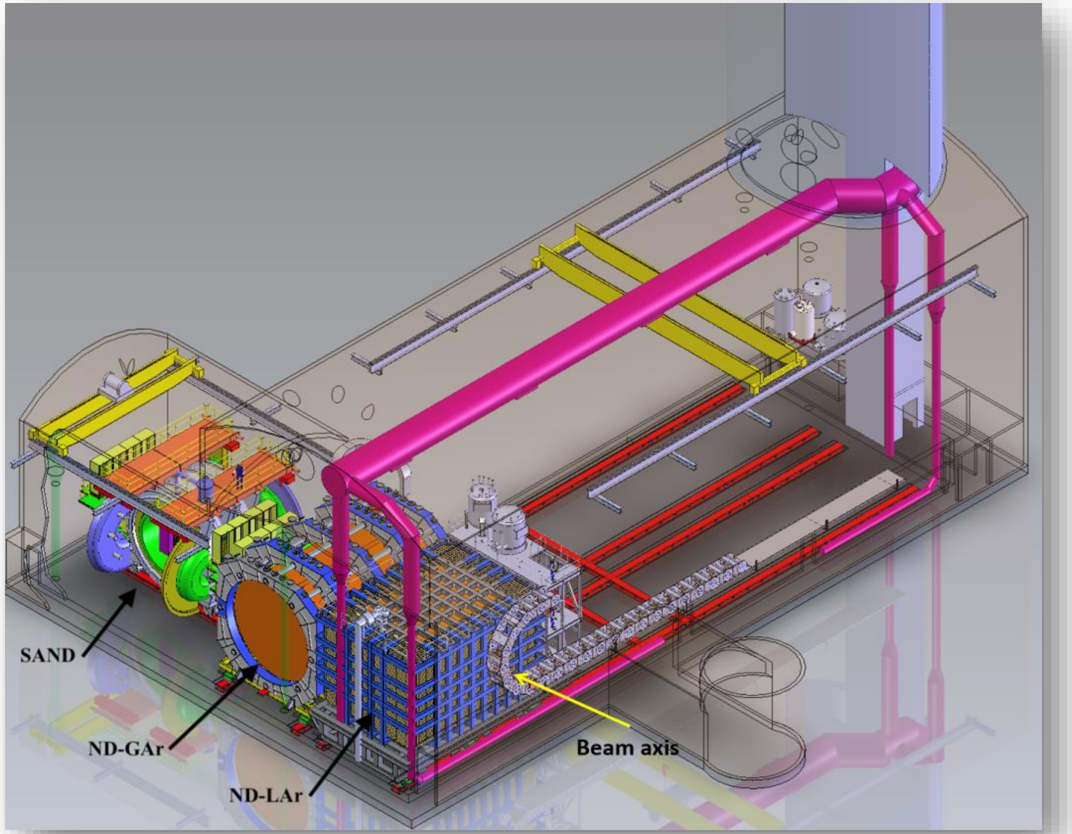
ND: MAIN GOALS

- Key aim of the DUNE experiment is to measure neutrino interaction rates from which can be extracted the oscillation probabilities for $\nu_\mu/\bar{\nu}_\mu$: determining these probabilities as a function of the neutrino energy will allow for precision measurements of the free parameters of the PMNS matrix (especially δ_{CP})

- The ND located near the neutrino source at Fermilab will measure the un-oscillated neutrino interaction rate. The FD will measure the neutrino interaction rate after oscillations: a comparison of the measurements at the far and near detectors allows for the extraction of oscillation probabilities

- The role of the ND is to serve as the experiment's control:
  1. Establishes the null hypothesis (i.e., no oscillations) under the assumption of the three neutrino paradigm
  2. Measures and monitors the beam
  3. Constrains systematic uncertainties
  4. Provides essential input for the neutrino interaction model

ND: MAIN COMPONENTS AND DESIGN

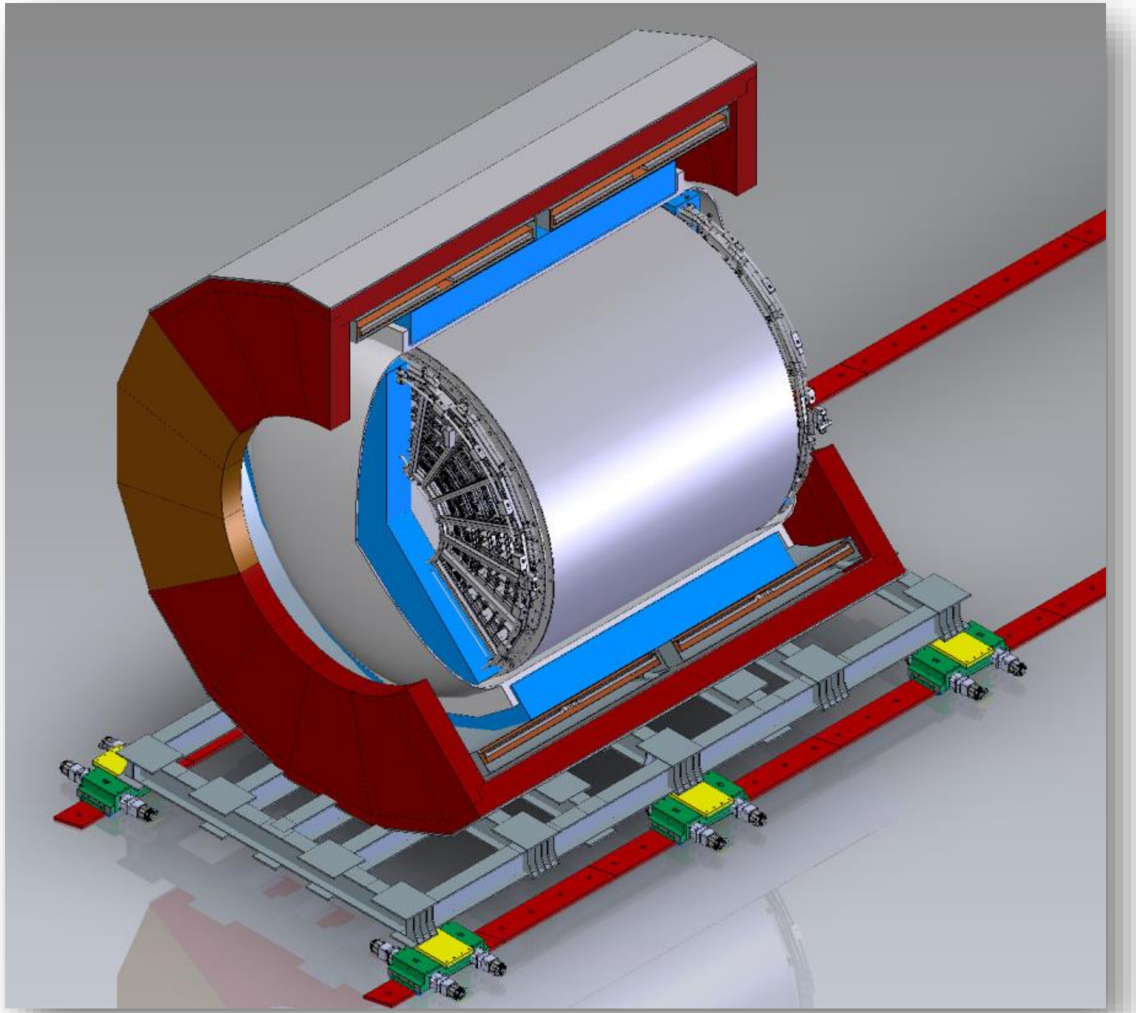


- DUNE ND has three primary detector components:

  1. ND-LAr: LArTPC using ArgonCube technology. Has same target nucleus and uses same fundamental detection principles as the FD to reduce sensitivity to nuclear effects and detector-driven systematics. Differences needed due to intensity of the beam at the ND
  2. SAND: on-axis magnetized beam monitor. Inner tracker surrounded by an ECAL inside a large solenoidal magnet
  3. ND-GAr: high pressure gaseous argon TPC surrounded by an electromagnetic calorimeter (ECAL) in a 0.5 T magnetic field with a muon system

- DUNE-PRISM: ND-LAr and ND-GAr can move to take data in positions off the beam axisto allow for deconvolution of the neutrino flux and interaction cross section, mapping mapping of the reconstructed versus true energy response

ND-GAR: PURPOSE AND MOTIVATION

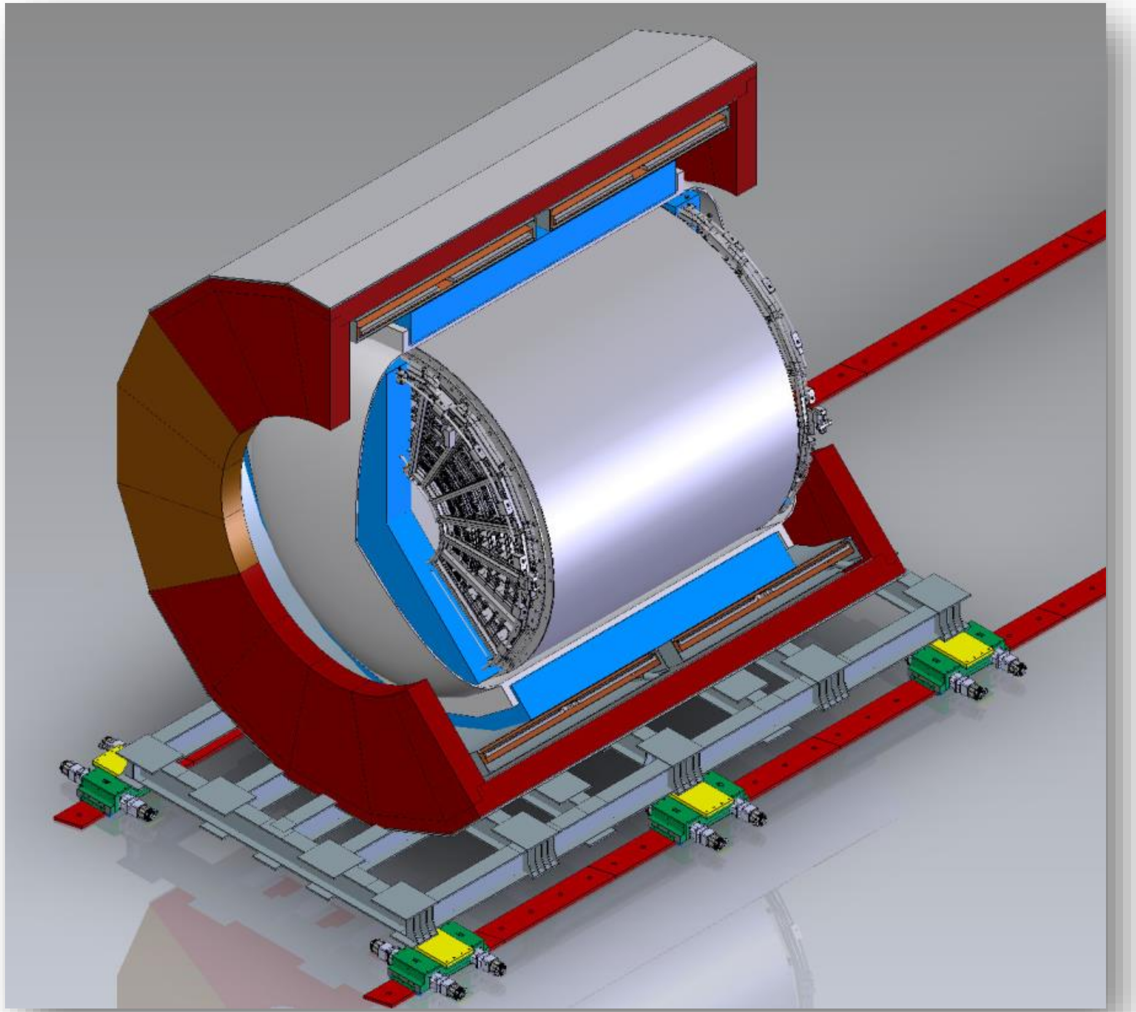


- ND-GAr : high pressure gaseous argon TPC surrounded by an electromagnetic calorimeter (ECAL) in a 0.5 T magnetic field with a muon system

- Provides a lower-density medium with excellent tracking resolution to momentum analyze the muons from ND-LAr

- Constitutes large, independent sample of ν-Ar interactions that can be studied with a very low momentum threshold for charged particle tracking, excellent tracking resolution, nearly uniform angular coverage, and with systematic uncertainties that differ from the ND-LAr

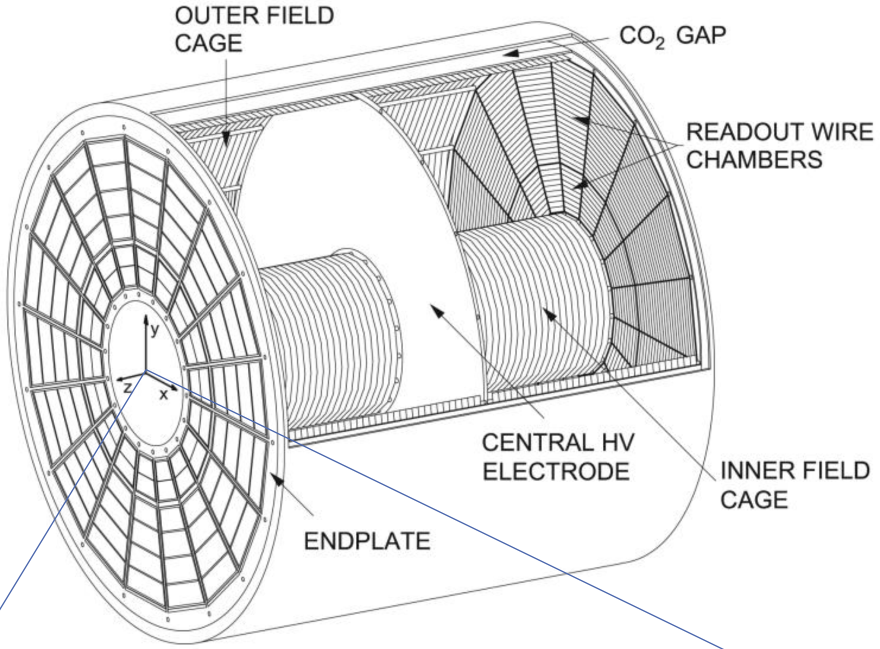
ND-GAR: PURPOSE AND MOTIVATION

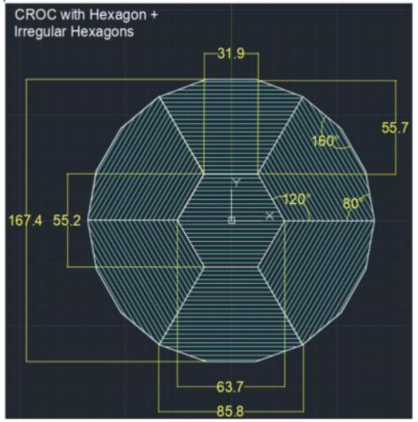


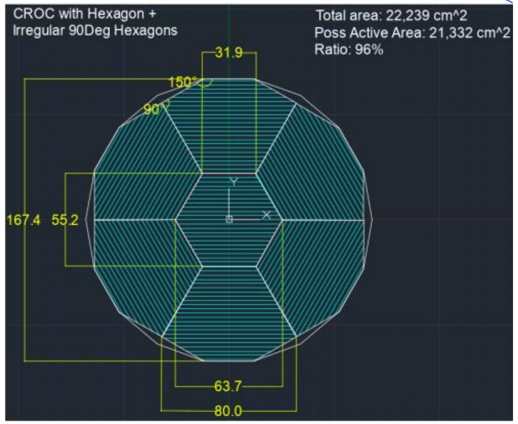
- Has access to lower-momentum protons and has better particle identification of charged pions which allow for the study charged particle activity near the interaction vertex

- Gas samples will have low level of secondary interactions: helpful for identifying the particles produced in the primary interaction and modeling secondary interactions in denser detectors

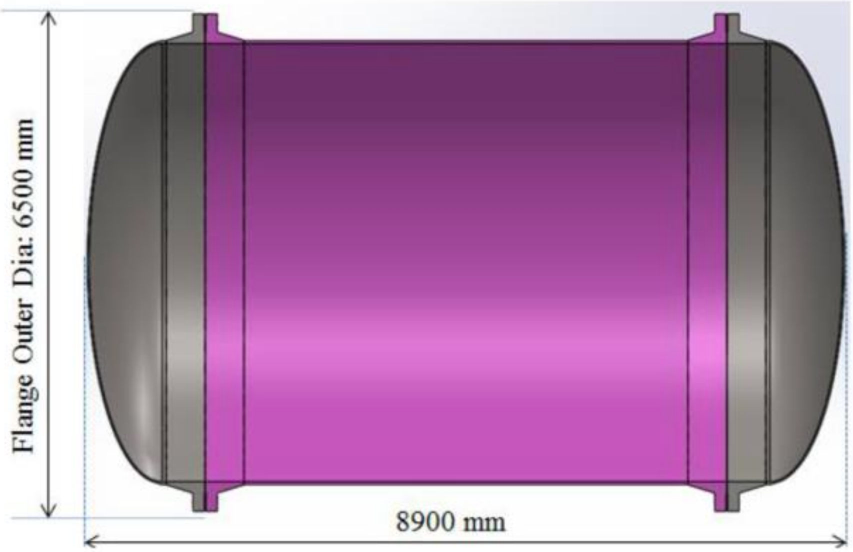
ND-GAR DESIGN: HIGH PRESSURE GAS TPC



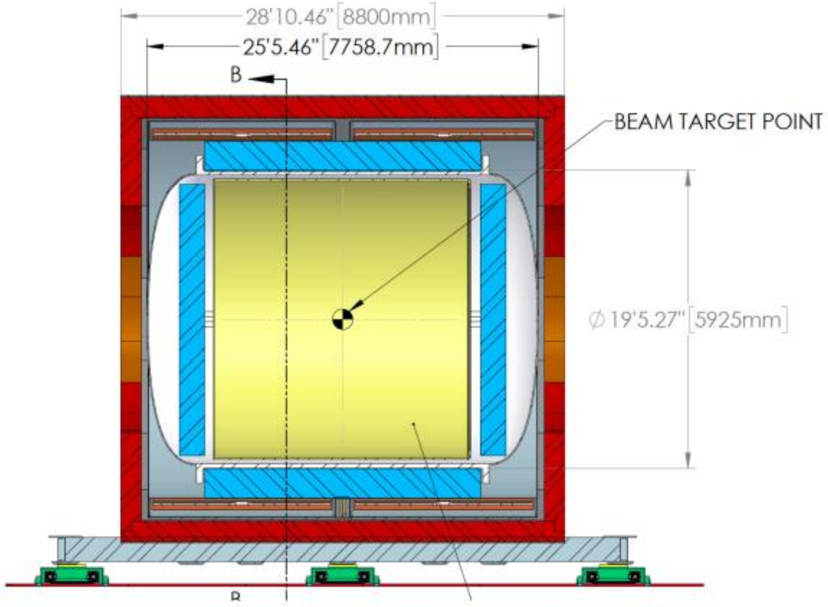


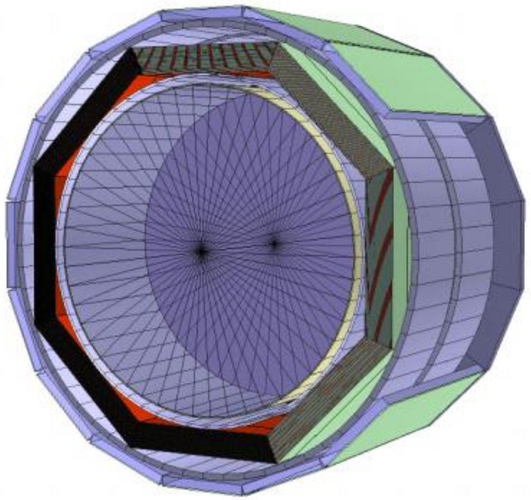


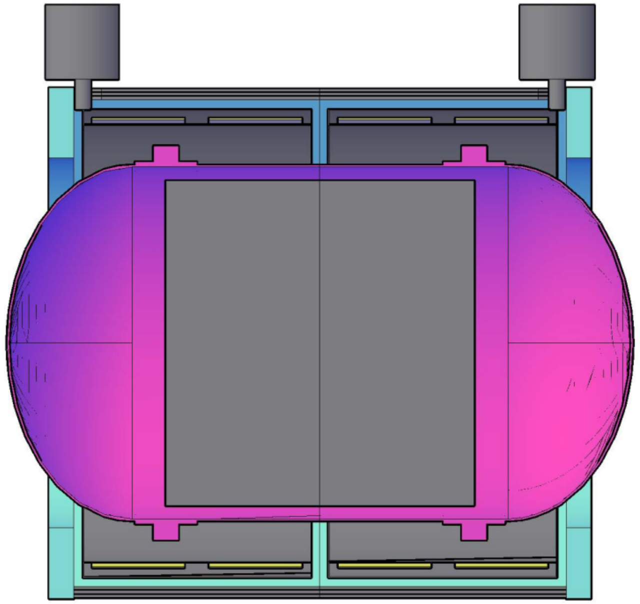
- HPTPC Based on ALICE TPC with two main differences:
  1. No inner field cage of silicon tracker, substituted by Central Read-Out Chambers (CROC)
  2. Pressure vessel to contain high density gas
- Standard gas used is an argon-CH4 mixture 90%-10%, at 10 bar



ND-GAR DESIGN: ECAL AND MAGNET







- ECAL design inspired by ALICE's AHCAL
- Octagonal shape barrel, each octant composed of several trapezoidal modules (layers of polystyrene scintillator as active material read out by SiPMs sandwiched between absorber sheets)
- Arrangement of the modules with respect to the pressure vessel is under study and optimization

- Solenoid designed as thin as possible
- Axis perpendicular to the neutrino beam
- Iron distribution in the return yoke that minimises the material between the ND-LAr and the active elements of ND-GAr

HYDROGEN INTERACTIONS IN ND-GAR AND TKI

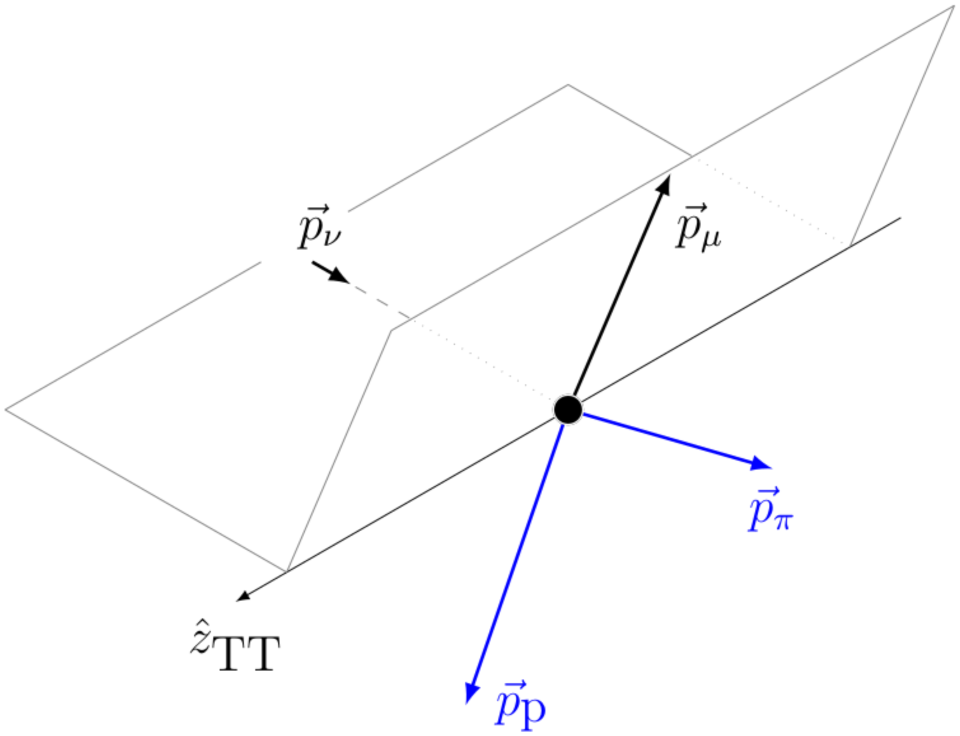
- Due to the absence of nuclear effects in neutrino hydrogen interactions, hydrogen would be the ideal target or a neutrino oscillation experiment, if it were possible to use it in large quantities without the presence of other nuclides

- Neutrino-hydrogen interactions from neutrino beam could be selected in an event-by-event basis from a compound target that contains hydrogen using transverse kinematic imbalance (TKI) of the final-state particles: with perfect tracking, interactions on hydrogen would have balanced final-state transverse momenta while the TKI on heavy nuclei is irreducibly wide due to nuclear effects

- A large HPTPC, with hydrogen in its gas mixture, could be the ideal detector to realize this technique and provide high quality data on neutrino-hydrogen interactions.

- The default P-10 gas of ND-Gar's HPTPC contains only very limited hydrogen mass, and the background from both carbon and argon is overwhelming. However, a TPC has the unique advantage of being flexible in switching the gas.

HYDROGEN INTERACTIONS IN ND-GAR AND TKI



- To observe the balanced transverse momenta on hydrogen, all final-state particles need to be measured. Consider interactions with charged particles in final state:

$$\nu + p \rightarrow \mu^- + p + \pi^+$$
$$\bar{\nu} + p \rightarrow \mu^+ + p + \pi^-$$

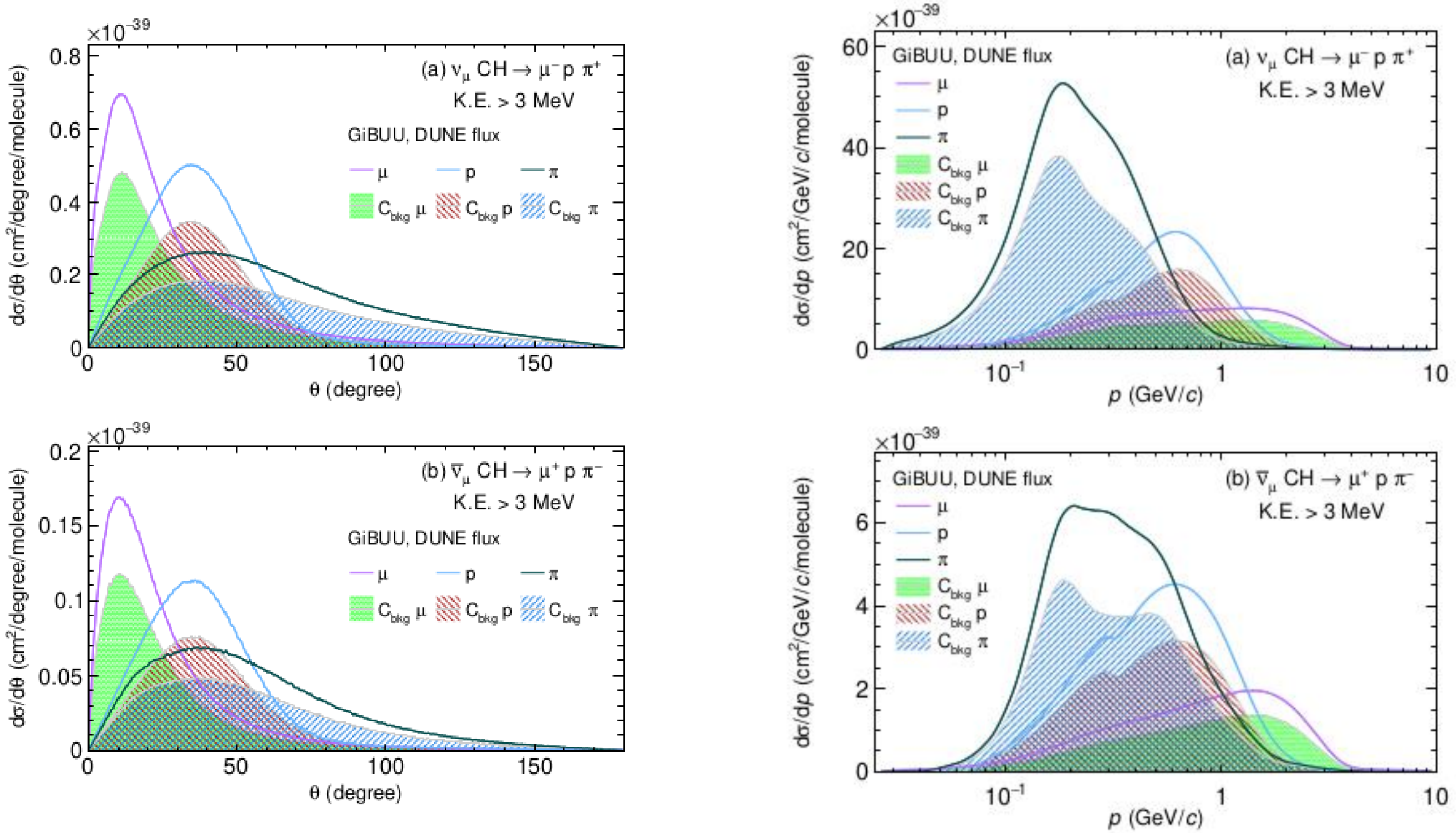
- To quantify the transverse kinematic imbalance we introduce double-transverse momentum imbalance:

$$\delta p_{TT} = (\vec{p}_\pi + \vec{p}_p) \cdot \hat{z}_{TT}$$

- Where $\hat{z}_{TT}$ is the unit vector along $\vec{p}_\nu \times \vec{p}_\mu$, and $\vec{p}_\mathrm{K}$ denotes the momentum vector of particle κ

- Intrinsic δp_{TT} on hydrogen is zero, on heavy nuclei it is dominated by Fermi motion and has a typical width of ~ 200 MeV/c

GIBUU SIMULATION: HP-TPC ADVANTAGES FOR TKI



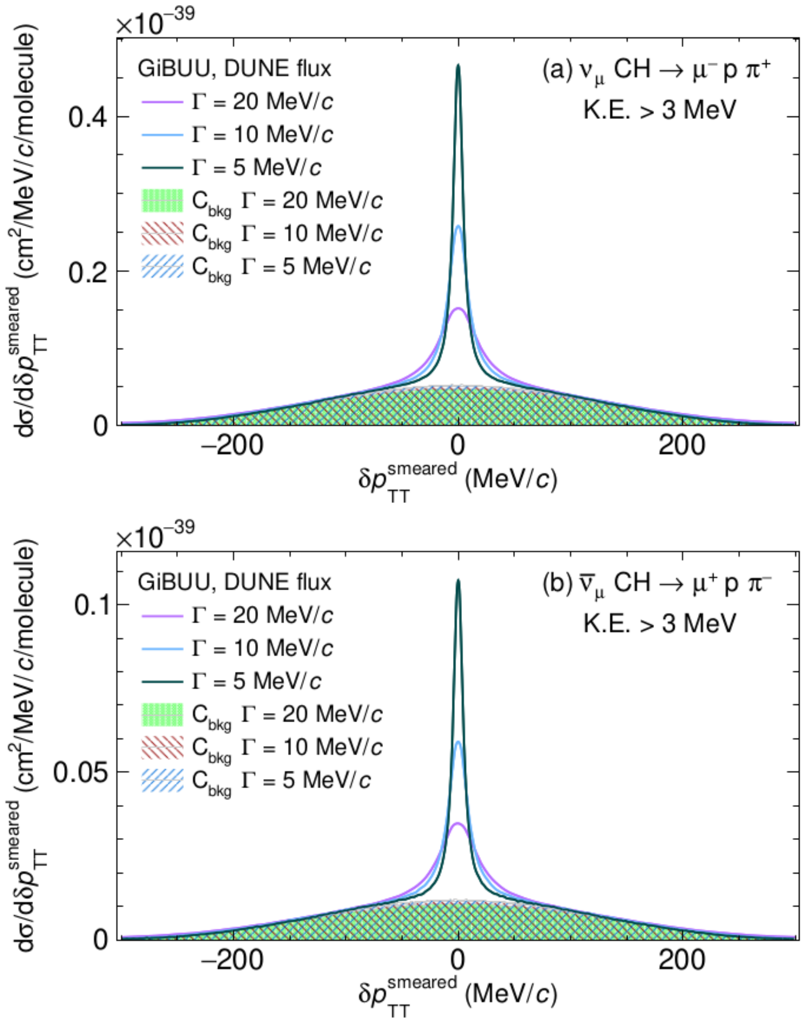
- With the full acceptance and the low threshold (3MeV in ND-GAr), a HPTPC could detect the large majority of the final-state particles

- Considering instead thresholds of 100 MeV and 75 MeV for protons and pions, respectively, as in a polystyrene tracker only 26% of the neutrino and 18% of the antineutrino events would be below threshold

GIBUU simulated flux-averaged differential cross section as a function of the final-state particle momentum p and angle for (a) ν and (b) $\bar{\nu}$ interactions on CH

- Muons are mostly at low angle and high momentum, the pions are at high angle and low momentum, and the protons, between them.
- As neutrinos interact with the gas inside the TPC, high-angle events could be detected: advantageous compared to the forward angular acceptance imposed by an external target to the TPC (T2K)

CUTS ON δp_{TT}

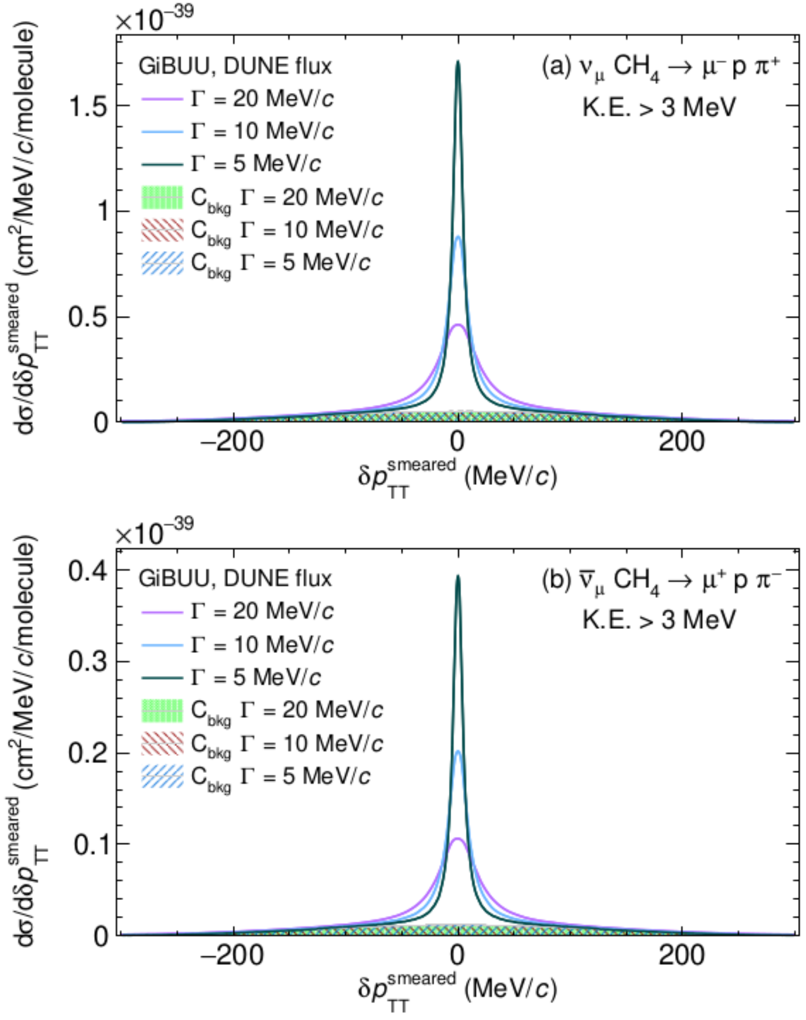


- δp_{TT} distribution on heavy nuclei has an irreducible width due to intranuclear dynamics ~ 200 MeV/c
- Intrinsic δp_{TT} on hydrogen is zero: its measured distribution is a function of detector resolution

- Use same GiBUU calculation to produce a smeared $\delta p_{TT}^{smeared} = \delta p_{TT} + \epsilon$ where ϵ Cauchy-Lorentz ($\sim 1/(\epsilon^2 + \Gamma^2)$ with $\Gamma = 20{,}10{,}5\ MeV/c$) random variable to mimic reconstruction resolution
- To select the neutrino-hydrogen interactions cut on δp_{TT}. To quantify the performance, calculate the signal S and background B integrated cross section, within the region $\delta p_{PP}^{smeared}$

$\lvert\delta p_{\mathrm{TT}}^{\mathrm{smeared}}\rvert < 3\Gamma$	Γ (MeV/c)	σ (10^{-39} cm^2) S	B	S/B	purity (%)
	20	5.4	5.9	0.92	48
ν CH	10	5.4	3.2	1.7	63
	5	5.4	1.7	3.2	76
	20	1.2	1.3	0.93	48
$\bar{\nu}$ CH	10	1.2	0.73	1.7	63
	5	1.2	0.38	3.3	77

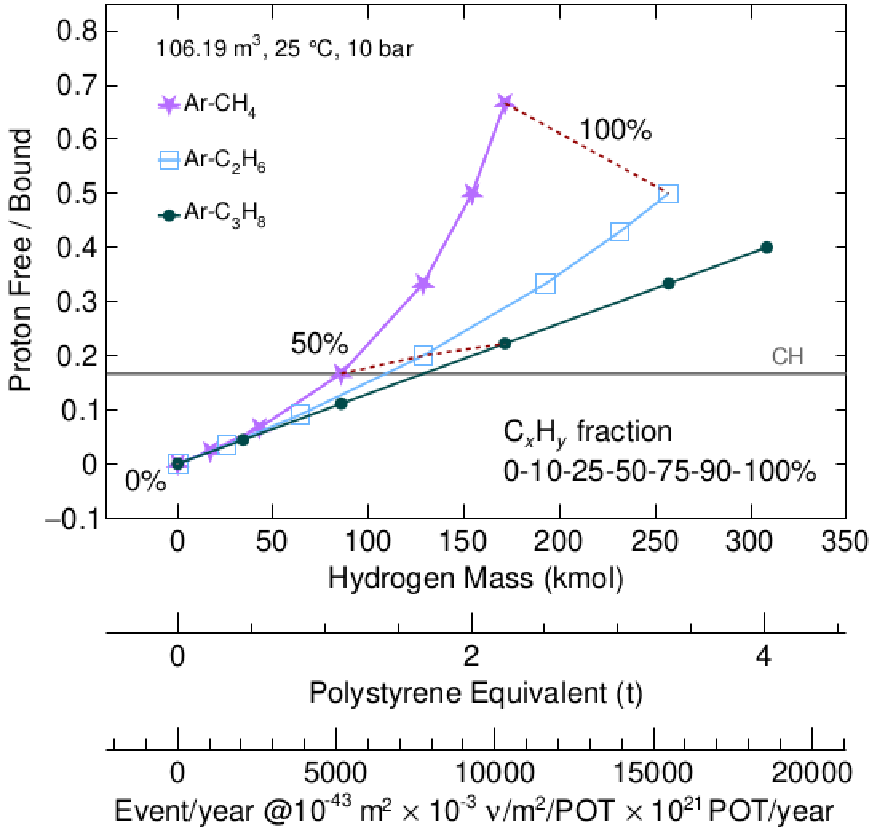
CHANGING THE C-H RATIO: CH_4



- With a pure CH_4 target in comparison to CH, the hydrogen mass is increased by a factor of four for the same amount of carbon background
- An S/B-ratio of 13 and a selection purity of 93% are achieved thanks to the four-fold increase in the signal size
- By replacing CH (or P-50) with pure CH_4 as the interaction target, the S/B ratio is shown to be improved by a factor of (2 / 3)/(1 / 6) = 4

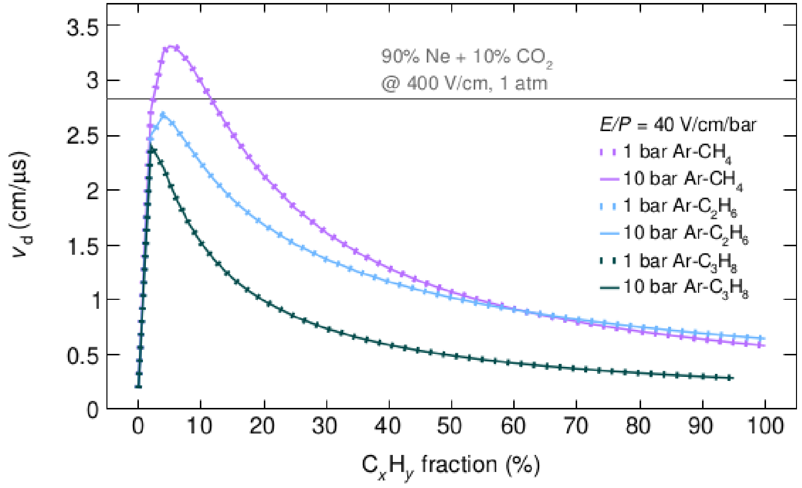
$\Gamma = 5\,\mathrm{MeV}/c$		$\sigma\ (10^{-39}\,\mathrm{cm}^2)$			
$\lvert\delta p_{TT}^{smeared}\rvert < 3\Gamma$		S	B	S/B	purity (%)
ν	CH	5.4	1.7	3.2	76
	CH_4	22	1.7	13	93
$\bar{\nu}$	CH	1.2	0.38	3.3	77
	CH_4	5.0	0.38	13	93

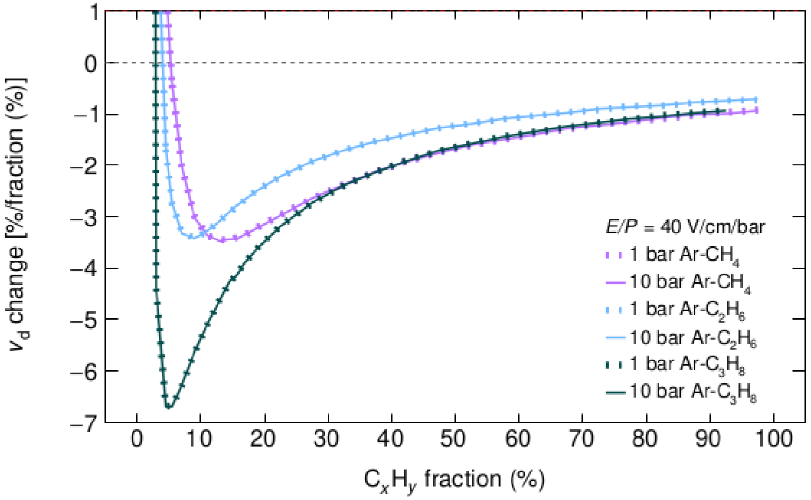
HYDROGEN CONTENT IN ALKALINE MIXTURES



- Alkanes (C_xH_y, y = 2x + 2) are acyclic saturated Hydrocarbons: CH_4 with x = 1 provides the highest proton free-to-bound ratio among all hydrocarbons
- For a given concentration, other alkenes like ethane (C_2H_6) and propane (C_3H_8) can provide larger hydrogen mass
- Progress along the series is limited by the phase boundaries of the gas candidates. At 25 ◦ C and 10 bar, the maximal concentration of C_3H_8 is 95 % and for isobutane (C_4H_{10}) it is 35 %
- 5% Ar + 95% C_3H_8 provides maximal hydrogen mass among all Ar-alkane candidates.

GAS MIXTURE PROPERTIES: DRIFT VELOCITY



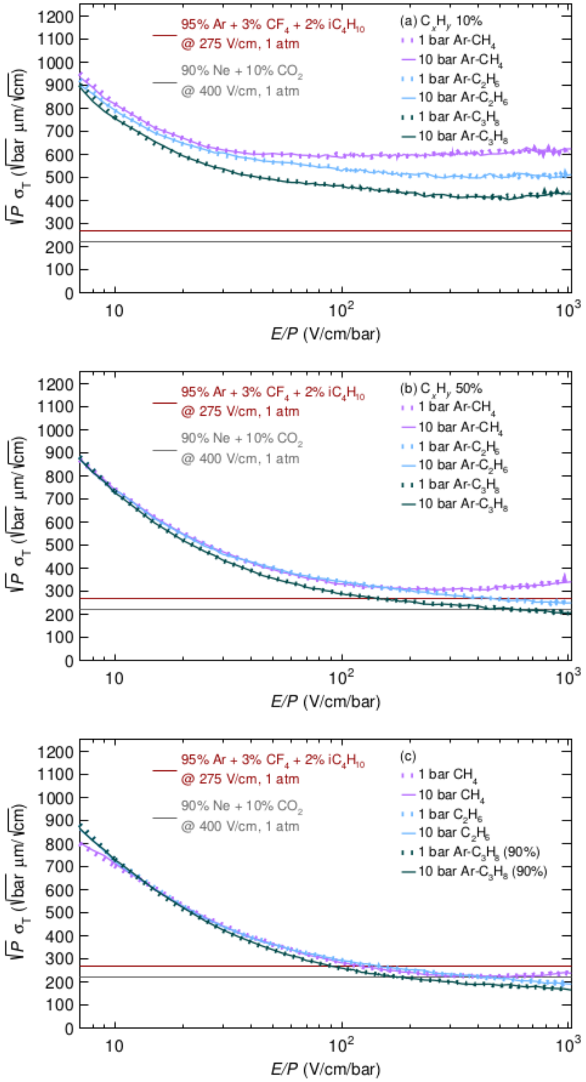


- In a TPC, the electron drift velocity (v_d) is used to convert the signal arrival time to a position along the drift direction, enabling the three-dimensional reconstruction of the primary ionization spatial coordinates

- Calculated drift velocity at 40 V/cm/bar: at a few percentage of alkane concentration, the drift velocity dramatically increases from the pure-argon value 0.2 cm / μs by an order of magnitude (Ramsauer minimum of argon) then falls back approaching 0.5 cm / μs for pure methane and ethane
- This level of drift velocity corresponds to sub-millisecond drift time across a 2.5 m drift length, which would allow for a pile-up-free event rate of O(1 kHz)

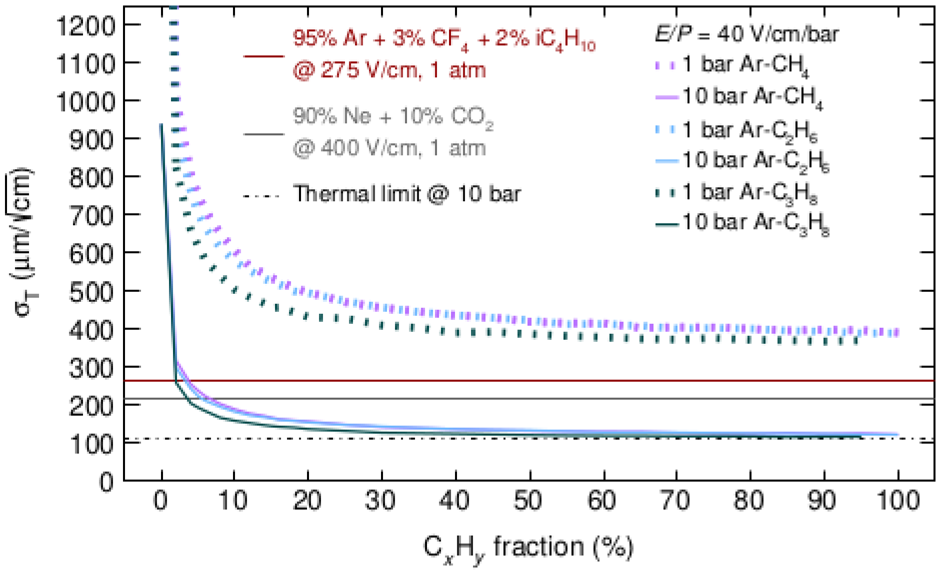
- Optimal tracking performance relies on a uniform and stable drift velocity in the large gas volume: fractional change of the drift velocity for every percentage increase of the alkane concentration
- At 40 V/cm/bar for any C_xH_y a per-mil-level stability of the drift velocity requires a control on the quencher concentration at the per-mil level

GAS MIXTURE PROPERTIES: DIFFUSION

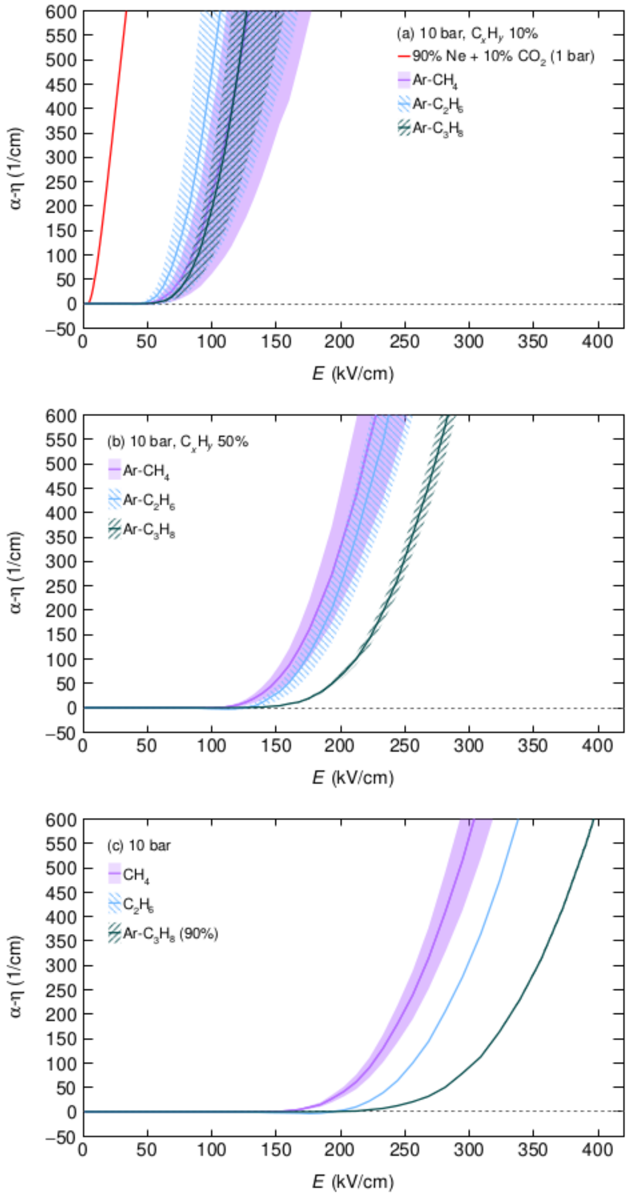


- Primary ionization electrons diffuse in all directions through scattering, the size of the spread growing as square root of time
- Diffusion limits the TPC point resolution and track separation threshold

- Transverse diffusion is shown to decrease with E in the practical region 40–200 V/cm/bar (except for P-10, where it becomes stable)
- Calculated transverse diffusion coefficient for various Ar-alkane mixtures at 40 V/cm/bar : because of the 1/ P suppression at the same E / P the diffusion in 10 bar for most of the mixtures is smaller than in ALICE



GAS MIXTURE PROPERTIES: GAS GAIN



- In an amplification the gas gain G depends on the path of the electrons

$$G = exp\left[\int_{s_0}^{s_1}(\alpha - \eta)ds\right]$$

where α is the first Townsend coefficient and η the attachment coefficient

- The calculated effective Townsend coefficients for different Ar-alkane mixtures at 10 bar are shown:
    - Due to E/P -scaling, the onset field strength at 10 bar is a factor of 10 larger than at 1 bar. The onset is also increases with the alkane concentration
    - High concentrations of propane require significantly larger amplification fields to reach $\alpha - \eta$ values comparable to methane and ethane

- The significantly higher voltages needed for high fractions of C_3H_8 might prove prohibitive in order to reach sufficient gas gain. A new technology, the resistive MicroMegas, has proven to be operational under such high fields

SUMMARY AND CONCLUSIONS

- The charged-particle sensitivity of ND-Gar’s TPC and its full acceptance and low threshold make it ideal for a measurement of the neutrino exclusive μpπ via TKI techniques: this could be used to identify interactions on the hydrogen component out of other nuclear target backgrounds

- Modeling the detector response to the δp_{TT} it can be seen that the signal-background ratio could be efficiently enhanced by improving the tracking resolution and choosing alkanes with higher hydrogen content (the highest being provided by the mixture 5% Ar + 95% C_3H_8)

- We’ve also considered the gas-mixture properties related to TPC tracking:
  - Drift velocity: (quasi)linear to the field strength in the operational region considered; drift time compatible with the highest event rates foreseen in future accelerator-neutrino experiments; per-mil-level drift velocity stability requires a per-mil-level control on the gas composition
  - Diffusion: high pressure reduces both transverse and longitudinal diffusion to significantly below the ALICE value
  - Gas Gain: much stronger amplification field required for gas gain to set in