Neutrino-hydrogen interactions with a high-pressure TPC

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We investigate the idea of detecting pure neutrino-hydrogen interactions in a multinuclear target using the transverse kinematic imbalance (TKI) technique [Lu, et al., Phys. Rev. D92, 051302 (2015)] in a high-pressure Time Projection Chamber (HPTPC). With full-solid-angle acceptance, MeV-level-energy detection threshold, state-of-the-art tracking resolution, and an $O(100\,\text{m}^3)$ gas volume at 10 bar, a HPTPC could provide an opportunity to realize this technique. We propose the use of hydrogen-rich gases in the TPC to achieve high detection purity with large hydrogen mass. With the projected neutrino beam exposure at the DUNE experiment, neutrino-hydrogen events of the order of $10^4$ per year with purity above 90% could be achieved with such a HPTPC using methane gas. In this paper, we present a systematic study of the event rate and purity for a variety of argon-alkane mixtures, and examine these gas candidates for the TPC tracking-related properties.

I. INTRODUCTION

Neutrino-oscillation measurements rely on our understanding of neutrino interactions in the GeV regime to infer the neutrino energy and flux. To achieve the required interaction rates, neutrino detectors use materials that can be practically scaled up, like water, plastics or liquid argon, at the cost of dealing with complex neutrino-nucleus interactions that result in a major source of systematic uncertainties [1, 2]. Understanding neutrino interactions has become crucial for T2K [3] and NOvA [4], and so will be for DUNE [5] and Hyper-Kamiokande [6].

As intranuclear effects can only be inferred from final-state particles, detectors in future experiments are being designed for lower detection thresholds and larger acceptance. One such detector concept is the high-pressure Time Projection Chamber (HPTPC), which is one of the near detector components at DUNE [5]. The DUNE HPTPC, in its current design, consists of a barrel with a volume of about 100 m$^3$ (active dimension of 5.2 m in diameter and 5 m in length) that holds a pressurized gas at 10 bar at room temperature. To provide constraints on neutrino interactions at the DUNE far detectors that use liquid argon, the default gas mixture of the HPTPC is P-10 (90% Ar + 10% CH$_4$), providing argon mass of about 1.5 t. Housed in a magnet with a field strength of 0.5 T, this HPTPC provides tracking and charge separation for particles originating from the neutrino-gas interactions. In addition to the full ($4\pi$ solid angle) acceptance, its proton detection threshold is 3 MeV of kinetic energy [5], over an order of magnitude smaller than in solid or liquid detectors (Fig. 1).

For neutrino-oscillation measurements, while heavy ($Z \geq 6$) nuclei are commonly used for neutrino interactions, hydrogen instead would be the ideal target material due to the lack of nuclear effects, if it could be used in large masses and free of background from other nuclei. Hydrogen bubble chambers were used to detect neutrinos before the 1990s; neutrino-hydrogen interactions measured in recent experiments, all using plastic scintillators, mineral oil, or water as the targets, are inseparable from background mostly coming from carbon and oxygen (cf. Ref. [8] for a review). Recently, it has been proposed [9] that neutrino-hydrogen interactions from a neutrino beam could be selected event by event from a compound target that contains hydrogen if sufficient momentum resolution is achieved. The idea was to use the transverse kinematic imbalance (TKI) of the final-state particles with respect to the neutrino beam direction: with perfect tracking, interactions on hydrogen would have balanced final-state transverse momenta—that is, zero TKI—while the TKI on heavy nuclei is irreducibly

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wide due to nuclear effects such as Fermi motion and final-state interactions (FSIs).

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 the DUNE 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—the target material that neutrinos interact on. In this work, we discuss the feasibility of hydrogen-rich gas mixtures in a HPTPC, with a focus on the perspective of measuring neutrino-hydrogen interactions given the state-of-the-art tracking performance, an $O(100 m^3)$ gas volume at 10 bar, and a neutrino rate as expected at DUNE.

This paper is organized as follows: In Section II we introduce the HPTPC gas mixture candidates after reviewing the TKI technique that allows the use of hydrogen-containing chemical compounds for pure neutrino-hydrogen interactions. In Section III we analyze the gas mixtures in terms of the hydrogen mass and purity. Because the TKI technique relies on the TPC tracking, we discuss the gas mixture properties in terms of drift velocity, diffusion, and gas gain in Section IV. In Section V we summarize this study and discuss the outlook towards a full realization of measuring neutrino-hydrogen interactions with a HPTPC.

II. GAS MIXTURE CANDIDATES

A. The Method of TKI

In neutrino interactions on nuclei other than hydrogen, the nuclear remnant carries away energy and momentum. The kinematics between the incoming neutrino and the outgoing particles are therefore imbalanced. If the neutrino energy is unknown, only the imbalance among the momenta transverse to the neutrino direction is experimentally accessible; the method of TKI is to use the details of this imbalance to precisely identify inuonuclear dynamics and the absence thereof [9–23]. In order to observe the balanced transverse momenta on hydrogen, all final-state particles need to be measured. While a gaseous TPC has the optimal acceptance and detection threshold for interactions on its gas, it is only sensitive to charged particles. Therefore, the particular neutrino-hydrogen interaction channels to consider are the ones with only charged final states, which dominantly are the following three-track events [9] (for similar ideas cf. Refs. [15, 18]: for antineutrino-hydrogen quasielastic interactions with a neutron in the final neutrino, cf. Ref. [22]):

$$\nu + p \rightarrow \mu^- + p + \pi^+, \text{ and (1)}$$
$$\bar{\nu} + p \rightarrow \mu^+ + p + \pi^-, \text{ (2)}$$

where $\nu$ ($\bar{\nu}$) is the (anti)neutrino and $\mu$, $p$, and $\pi$ are a muon, proton, and pion, respectively. The $p\pi^+$ channel takes place primarily through the Delta resonance $\Delta^{++}(1232)$ production, while for $p\pi^-$, in addition to the Delta resonance $\Delta^0(1232)$, charge-neutral nucleon resonances with higher mass also contribute significantly (see discussions below).

Without loss of generality, consider neutrino interactions on a CH model “molecule” which has the same hydrogen-carbon ratio as polystyrene [(C$_8$H$_8$)$_n$],

$$\nu + CH \rightarrow \mu^- + p + \pi^+ + X, \text{ and (3)}$$
$$\bar{\nu} + CH \rightarrow \mu^+ + p + \pi^- + X, \text{ (4)}$$

where $\mu$, $p$, and $\pi$ are required to have kinetic energy greater than 3 MeV, and X stands for the molecular remnant. Flux-averaged differential cross sections in the polar angle $\theta$ with respect to the neutrino direction, as well as in the particle momentum $p$, are calculated using the event generator GiBUU [24] with the DUNE fluxes [5].

As can be seen in Figs. 2 and 3, the 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, as opposed to the forward angular acceptance imposed by an external target to the TPC, for example, in the T2K near detector [25]. With the full acceptance and the low threshold, a HPTPC could detect the large majority of the final-state particles. If instead with the thresholds of 100 MeV and 75 MeV for protons and pions, respectively, as in a polystyrene tracker [14, 26], 26% (18%) of the (anti)neutrino events would be below threshold—in the antineutrino channel, the additional high-mass resonances \( N(1440), N(1535), \) and \( N(1650) \)] enhance the high-momentum parts of the spectra and therefore reduce the impact by the thresholds.

Across the whole \( \theta-p \) phase space, the hydrogen signal and carbon background are indistinguishable. To identify the hydrogen, a three-track TKI corresponding to Eqs. (1) and (2), the so-called double-transverse momentum imbalance, was introduced [9]:

\[
\delta p_{TT} \equiv \hat{p}_\nu \times \hat{p}_\mu \cdot (\vec{p}_p + \vec{p}_\pi),
\]

where \( \hat{p}_\kappa \) and \( \vec{p}_\kappa \) denote the unit and full momentum vectors of the particle \( \kappa \), respectively (Fig. 4).

While the intrinsic \( \delta p_{TT} \) on hydrogen is zero, the one on heavy nuclei is dominated by Fermi motion and has a width of \( \sim 200 \text{MeV}/c \). The reconstruction resolution of \( \delta p_{TT} \) by the T2K TPC is estimated to be \( \sim 20 \text{MeV}/c \) [9]. The T2K TPC transverse (to the magnetic field) momentum \( (p_T) \) resolution is \( \mathcal{O}(1\%) \) at \( p_T = 1 \text{GeV}/c \) [28]. With state-of-the-art TPC tracking performance, like that achieved with the ALICE TPC, whose \( p_T \)–resolution is \( \mathcal{O}(1\%) \) at 1 GeV/c \([29, 30]\), one would expect that a \( \delta p_{TT} \)–resolution of \( \mathcal{O}(1 \text{MeV}/c) \) could be obtained. The measured \( \delta p_{TT} \) distribution from hydrogen could be further narrowed with an improving detector resolution, in contrast to the one from heavy nuclei which has an irreducible width of \( \sim 200 \text{MeV}/c \) due to intranuclear dynamics. This is the essence of the TKI technique for an event-by-event selection of neutrino-hydrogen interactions.

To illustrate this idea, the same GiBUU calculation as above is used and a smeared \( \delta p_{TT} \) is introduced by adding to the true \( \delta p_{TT} \) a random variable \( \epsilon \):

\[
\delta p_{TT}^{\text{smeared}} = \delta p_{TT} + \epsilon,
\]

where \( \epsilon \) follows a Cauchy-Lorentz p.d.f. \( \sim 1/(\epsilon^2 + \Gamma^2) \) to emulate the reconstruction resolution. The width parameter \( \Gamma \) takes three values: 20 MeV/c (as is for the T2K TPC), 10 MeV/c, and 5 MeV/c, for different tracking performance. In practice, momentum resolution is commonly fit by two Gaussian functions, where the second one is needed to describe the relatively small amount of events that have large reconstruction bias; instead, the Cauchy-Lorentz p.d.f. is chosen to provide a unified description [9]. The differential cross sections in the smeared \( \delta p_{TT} \) (Fig. 5) show that, while the hydrogen \( \delta p_{TT} \) changes its Lorentzian shape with the width, the background varies insignificantly.

To select the neutrino-hydrogen interactions, one could cut on \( \delta p_{TT}^{\text{smeared}} \). To quantify the performance of
Such a selection, the signal and background integrated cross section, $S$ and $B$ respectively, within the region $|\delta_{pTT}^{\text{smeared}}| < 3\Gamma$ are calculated in Table I. In both neutrino and antineutrino channels, at $\Gamma = 20 \text{MeV}/c$, the signal and background are of a similar size, yielding a $S/B$-ratio about 1. At a four-fold reduction of $\Gamma$, the calculated $S/B$-ratio reaches 3.2, the corresponding purity $[S/(S+B)]$ being 76%. On the one hand, it is important to point out that these numbers depend on the modeled nuclear effects. More generally speaking, the departure of hydrogen-carbon ratio from the impulse approximation expectation—1/6 for the whole phase space—is a measure of the nuclear medium effects [9]. As the $S/B$-ratio is affected by FSI on top of the Fermi motion of the initial bound proton, mismodeled FSI such as the elastic component of GENIE $hA$ [10, 12, 14, 19, 21] could cause significant bias [31]. In the current GiBUU calculation, because $\pi^+$ and $\pi^-$ experience very similar FSI inside the carbon remnant, even though both the signal and background size are different between the neutrino and antineutrino channels, the $S/B$-ratio is shown to be very similar between the two. On the other hand, regardless of the underlying nuclear effects, for the same size of signal, the background size decreases with $\Gamma$. As the relative size of the background is reduced—via an improvement of the tracking resolution and an increase in the hydrogen content as discussed in the following sections—the relative background uncertainty will decrease and become insignificant.
Gas mixtures for TPCs have long been studied in field regions suitable for drift and gas amplification (cf. Refs. [32–34] for review). Their typical composition is a noble gas with one or more admixtures of other gases to engineer drift properties, like drift velocity and diffusion, for the intended detector geometry and event characteristics. Organic molecules like alkane in the admixture stabilize the gas amplification by absorbing UV photons in the avalanche gas amplification process, hence the name quenchers. In case of Ar-alkane mixtures, the quencher reduces diffusion and can increase the drift velocity (see Section IV for detail). Given satisfactory properties, quenchers alone could also act as counter gases in TPCs. This turns out to be advantageous for the measurement of neutrino-hydrogen interactions. For example, 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. The calculated differential and integrated cross sections are shown in Fig. 6 and Table II, respectively. An S/B-ratio of 13 and a selection purity of 93% are achieved thanks to the four-fold increase in the signal size.

P-10 as a TPC gas has been used widely (cf., for example, Ref. [35]). Other gases have been used in, for example, the ALICE TPC and the T2K near detector TPCs. The former chose 90% Ne + 10% CO$_2$ to cope with the high multiplicity environment at very high event rates in heavy-ion collisions [29], while the latter uses 95% Ar + 3% CF$_4$ + 2% iC$_4$H$_{10}$ to measure the final-state particles from neutrino interactions on polystyrene in upstream detectors [28]. Both examples have been operating at atmospheric pressure.

In DUNE, in order to provide constraints on neutrino interactions on argon in the far detectors, P-10 is the default gas mixture of the near detector HPTPC. Therefore, we focus on argon-based, in particular Ar-alkane, mixtures as an extrapolation of the default gas. Depending on the argon mass fraction (that is, the argon purity in terms of mass), one could choose a certain argon concentration for the desired argon mass. For example, as is shown in Fig. 7, both P-50 (50% Ar + 50% CH$_4$) and 50% Ar + 50% C$_3$H$_8$ have the same argon mass, but the argon mass fraction in P-50 is higher by a relative 50%.

In the following, we discuss a range of Ar-alkane mixtures as HPTPC gas candidates by examining their hydrogen content and tracking-related properties. Unless otherwise specified, we fix the temperature at 25°C throughout the discussions.

### III. HYDROGEN CONTENT

In the previous calculation for a CH target, a 5 MeV/c $\delta p_{\text{TT}}$-resolution leads to a selection S/B-ratio of 3.2, corresponding to a purity of 76%. In a HTPPC, as one can choose a variety of gas mixtures, the selection purity, which depends on the ratio between the number of free protons and that of the bound ones, can be optimized alongside with the hydrogen mass as follows.

A CH target has a proton free-to-bound ratio of 1/6, the same as in P-50 (Fig. 8). This ratio increases with the methane concentration and reaches 1/2 for P-90 (10% Ar + 90% CH$_4$), and 2/3 for pure CH$_4$. 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 $(2/3)/(1/6) = 4$ (Table II).

One mole of P-50 has the same amount of hydrogen as one mole of H$_2$. In addition, as is shown in Fig. 8 at 10 bar in a volume of 106.19 m$^3$, the P-50 gas contains the same hydrogen mass as $\sim 1$ t of polystyrene. This amounts to $\sim 10\%$ of the proposed DUNE 3DST detector that is a polystyrene tracker with dimensions $2.4 \times 2.4 \times 2$ m$^3$ [5]. With the projected DUNE beam exposure, $10^{21}$ protons on target (POT) per year and $10^{-3}$ neutrinos/m$^2$/m$^{-2}$/POT [5], this hydrogen mass gives $\sim 5000$ three-track events [Eqs. (1) and (2)] per year assuming a typical cross section of $10^{-43}$ m$^2$ (Table I, cf. also Ref. [8]). It follows immediately that pure CH$_4$ improves the hydrogen event rate by a factor of 2, to $\sim 10^4$
ionize the gas (this process is referred to as primary ionization) where electrons are liberated and driven towards the readout plane under the influence of electromagnetic fields. The spatial and time information of the amplified and collected drift electron signals is used to reconstruct the primary ionization coordinates. In the presence of a magnetic field, charges and momenta of the primary particles can be measured.

During their propagation, the drift electrons collide with the gas molecules at energy and time scales different from those in the primary ionization. The rate of these collision depends on the gas density that is sensitive to the temperature and pressure; running detectors are regularly calibrated towards a certain operational point via temperature \((T)\) and pressure \((P)\) scaling (see, for example, Ref. [28]). Such density corrections for the drift field \((E)\) and the gas parameters that we will discuss in this Section are given in Table III [32, 33, 37].

As alkanes \((C_xH_{2y}, y = 2x + 2)\) are acyclic saturated hydrocarbons, it follows that \(CH_4\) with \(x = 1\) provides the highest proton free-to-bound ratio among all hydrocarbons. For a given concentration, other members in the alkane series like ethane \((C_2H_6)\) and propane \((C_3H_8)\) can provide larger hydrogen mass with a different proton free-to-bound ratio (Fig. 8). For example, 50% \(Ar + 50% C_3H_8\) has twice the hydrogen mass as \(P-50\). However, this 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 93% and for isobutane \((iC_4H_{10})\) it is 34% [36]—higher than these they liquefy. Therefore, 7% \(Ar + 93% C_3H_8\) provides the maximal hydrogen mass among all Ar-alkane candidates.

IV. TRACKING-RELATED GAS PROPERTIES

The measurement of neutrino-hydrogen interactions [Eqs. (1) and (2)] from an Ar-alkane gas mixture via the TKI technique relies on the reconstruction of the primary charged particle \((\mu^+, p, \pi^\pm)\) trajectories in the TPC. When these particles traverse the detector volume, they ionize the gas (this process is referred to as primary ionization) where electrons are liberated and driven towards the readout plane under the influence of electromagnetic fields. The spatial and time information of the amplified and collected drift electron signals is used to reconstruct the primary ionization coordinates. In the presence of a magnetic field, charges and momenta of the primary particles can be measured.

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The discussion of the Ar-alkane properties, including drift and gas gain, will be focused on their impact on the TPC performance. All calculations were performed using MagBoltz version 11.7 [39] interfaced to Garfield++ [40]. While the temperature was set to 298 K, results with var-

![Figure 8](image_url)

**FIG. 8.** Proton free-to-bound ratio vs. hydrogen mass for different Ar-alkane mixtures. As a comparison, the ratio for polystyrene \((CH)\) is indicated by a horizontal line regardless of the hydrogen mass. The hydrogen mass is converted to the hydrogen-equivalent polystyrene mass, as well as to the neutrino-hydrogen event rate per year, assuming a cross section of \(10^{-43}\) m\(^2\) which is typical for the signal channels [Eqs. (1) and (2)], and an exposure of 10\(^{21}\) protons on target \((POT)\) per year with a flux of 10\(^{-3}\) neutrinos/m\(^2\)/POT that gives the projected neutrino rate at DUNE [5].

![Figure 9](image_url)

**FIG. 9.** Measured drift velocity of P-10 at three pressures, from close to atmospheric up to ~ 6 bar at 296–297 K [38]. The data closely follow the pressure scaling law (Table III) over a span of 5 bar. For comparison, the calculated drift velocity at 10 bar by MagBoltz [39] (interfaced to Garfield++) is also shown. The error bars are statistical only and smaller than the marker size.
ious electric field strengths at 1 bar or 10 bar are compared. The C$_2$H$_6$ fraction in the Ar-alkane mixture is scanned from 0 % to 100 %, with the exception of propane (C$_3$H$_8$) that liquefies above 93 % at 10 bar. The effect of a magnetic field parallel to the electric field is explicitly discussed only when relevant.

As a validation, the calculated drift velocity (more detail in Section IV A) for P-10 is compared to the measurements by the High Pressure Gas Monitoring Chamber [38]. Figure 9 shows the experimental data in three pressure settings up to ~ 6 bar. After correcting for the temperature and pressure, the data show the expected scaling behavior over the full measurement range. The MagBoltz calculation reproduced the measurement satisfactorily, except that at fields below 40 V/cm $E$/p scaling (Table III), to maintain the same drift velocity in the same gas at 10 bar, a field strength of 4 kV/cm is required, which means a cathode voltage of 1 MV across a 2.5 m drift length. However, as commercial power supplies are not readily available above 500 kV, we consider $E$/p $\sim$ 40–200 V/cm/bar a practical operational region in an ALICE-sized TPC at 10 bar. In comparison, the T2K TPC has a drift velocity of 7.8 cm/$\mu$s at 275 V/cm in one atmospheric pressure of 95% Ar + 3% CF$_4$ + 2% iC$_4$H$_{10}$ [28].

The calculated drift velocity at 40 V/cm/bar is shown in Fig. 10. At a few % alkane concentration, the drift velocity dramatically increases from the pure-argon value 0.2 cm/$\mu$s by an order of magnitude. This is due to the so-called Ramsauer minimum of argon [42]: the low excitation energy of alkanes effectively reduces the energy of the drifting electrons such that the collisional cross section of electrons on argon reaches a minimum, making the gas as a whole more transparent to the drifting electrons. The drift velocity then falls back as the concentration increases, approaching 0.5 cm/$\mu$s for pure methane and ethane, and even lower for propane-rich mixtures (still higher than for pure argon). This level of drift velocity corresponds to sub-millisecond drift time across a 2.5 m drift length, which would allow for an O(1 kHz) event rate, much higher than the ones foreseen in future accelerator neutrino experiments [5].

While the magnitude of the drift velocity is not critical here, an optimal tracking performance relies on a uniform and stable drift velocity in the large gas volume, which in turn poses a constraint on the gas system [43]. The drift velocity varies with the alkane concentration. Figure 11 shows the fractional change of the drift velocity for every percentage increase of the alkane concentration. At 40 V/cm/bar for any C$_x$H$_y$ concentration above 5 %, the change of the drift velocity is greater than 1 %, which indicates that a per-mil-level stability of the drift velocity requires a control on the concentration at the per-mil level.

In the practical operational region 40–200 V/cm/bar, the drift velocity generally increases with $E$. Figure 12 shows the drift velocity as a function of the pressure-scaled $E$ for the alkane concentrations 10%, 50%, and 100% (90% for C$_3$H$_8$). In particular, at $E$/p $< 50$ V/cm/bar, $v_d \propto E^2$, where $a \sim 1.0–1.2$. In this quasilinear region, the electron

A. Drift Velocity

In a TPC, the electron drift velocity ($v_d$) is used to convert the signal arrival time to the coordinate in the drift direction, enabling the reconstruction of the primary ionization spatial coordinate along the drift direction. The ALICE TPC has a drift velocity of 2.83 cm/$\mu$s with an electric field strength $E = 400$ V/cm across a drift length of 2.5 m in one atmospheric pressure of 90% Ne + 10% CO$_2$ [29]. Due to the $E$/p-scaling (Table III), to maintain the same drift velocity in the same gas at 10 bar, a field strength of 4 kV/cm is required, which means a cathode voltage of 1 MV across a 2.5 m drift length. However, as commercial power supplies are not readily available above 500 kV, we consider $E$/p $\sim$ 40–200 V/cm/bar a practical operational region in an ALICE-sized TPC at 10 bar. In comparison, the

FIG. 10. MagBoltz [39] (interfaced to Garfield++ [40]) calculation of the drift velocity at 40 V/cm/bar as a function of the alkane concentration. Ar-alkane mixtures at 1 bar and 10 bar are compared. The ALICE (90% Ne + 10% CO$_2$) value [29] is indicated by a horizontal line. Note the $E$/p-scaling (see also Table III).

FIG. 11. Fractional change of drift velocity (in %) for every percentage increase of the alkane concentration.
FIG. 12. Drift velocity as a function of the scaled electric field strength for different gas mixtures with alkane concentrations (a) 10%, (b) 50%, and (c) 100% (90% for C<sub>3</sub>H<sub>8</sub>). The reference value from T2K (95% Ar + 3% CF<sub>4</sub> + 2% C<sub>4</sub>H<sub>10</sub>) is also shown.

is largely field-independent. For pure alkane at 10 bar [Fig. 12 (c)], the typical mobility is \( \mu \approx 0.001 \text{ cm}^2/\text{V}\cdot\text{sec} \). Furthermore, the drift velocity variation is \( O(\%) \) for every \( 1 \text{ V/cm/bar} \) change, as can be seen in Fig. 12. Compared to TPCs operating at atmospheric pressure, the pressure variation in a high-pressure TPC is relatively better under control as the pressurized vessel is not connected to the atmosphere.

B. Diffusion

Once liberated, the primary ionization electrons start to diffuse in all directions through scattering on gas molecules. The size of the spread grows with time \( t \) as \( \sim \sqrt{t} \). Under the influence of an electric field, the diffusing electron clouds drift and the spread in the transverse and longitudinal direction to the field are characterized by \( \sigma_T, \sigma_L \), respectively, and \( L \) is the drift length. Diffusion limits the TPC point resolution and track separation threshold. For its momentum reconstruction in a high-multiplicity environment, ALICe chose \( \sigma_T = 220 \text{ mm/}\sqrt{\text{cm}} \) [29]. In T2K, the near detector TPC has \( \sigma_T = 265 \text{ mm/}\sqrt{\text{cm}} \) [28, 44].

The calculated \( \sigma_T \) for various Ar-alkane mixtures at \( 40 \text{ V/cm/bar} \) is shown in Fig. 13. Because of the \( 1/\sqrt{P} \)-suppression at the same \( E/P \) (Table III), the diffusion in 10 bar for most of the mixtures is smaller than in ALICe—nearly by half for concentrations above 20%. It slowly decreases with the alkane concentration and approaches the thermal limit \( 113 \text{ mm/}\sqrt{\text{cm}} \) at \( E/P = 40 \text{ V/cm/bar} \) [33]. In Fig. 14, the transverse diffusion is shown to decrease with \( E \) in the practical region 40–200 V/cm/bar except for P-10 which becomes stable. In addition, at higher concentration as it approaches the thermal limit, the dependence on \( E \) of different alkane becomes similar.

FIG. 13. Transverse diffusion coefficient calculated at \( 40 \text{ V/cm/bar} \) as a function of the alkane concentration. The thermal limit for 10 bar is also shown.

The longitudinal diffusion was also calculated and shows similar size and trends as the transverse diffusion. A comparison between the two at 10 bar and \( 40 \text{ V/cm/bar} \) is shown in Table IV.

With an additional magnetic field parallel to the electric field, \( B \parallel E \), the transverse diffusion is sup-
affected by the parallel magnetic field.

C. Gas Gain

After propagation through the drift region, electrons are amplified in strong electric fields that start ionization avalanches. Electrodes pick up the amplified signal which can then be more easily digitized by a number of electronics. In an amplification region with a spatial coordinate $s (s_0 < s < s_1)$, the gas gain $G$ depends on the path of the electrons [33]:

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

where $\alpha$ is the first Townsend coefficient and $\eta$ the attachment coefficient, both being functions of the electric field strength $E(s)$. In our calculation, there is no impurity in the Ar-alkane mixtures, so attachment only proceeds via dissociation of the alkane molecules [33]. Generally, the attachment is a small correction to the amplification; however, at amplification onset the drifting electrons reach energies sufficient for dissociation—the resulting attachment cannot be neglected and the effective Townsend coefficient $(\alpha - \eta)$ is considered.

Following the density correction in Table III, gas amplification is enhanced by the pressure but delayed in onset field due to a shortened electron mean free path—a larger field strength is needed to provide enough energy to trigger the avalanche.

The calculations in this work assumed no Penning transfer contribution to $\alpha$. Penning transfers are ionizing energy transfers between two different gas species and can be summarized by a single transfer probability $\mathcal{R}$ that enhances $\alpha$ [45], in which case $\alpha$ in Eq. (9) is replaced by $(1 + \mathcal{R})\alpha$. Values for $\mathcal{R}$ have been calculated from gas gain measurements for common argon-based drift gases, but not for quencher fractions above 10% [45]. For an Ar-alkane mixture (not for pure alkane), the systematic deviation can be very large. However, when neglecting Penning transfers, the onset of gas amplification, i.e. the minimal field that makes $\alpha(E) > 0$, remains unchanged [45, 46].

### Table IV. Longitudinal and transverse diffusion coefficients for Ar-alkane mixtures calculated at 10 bar and 40 V/cm/bar.

| Concentration (%) | $\sigma_L$ (cm$^2$/m$^2$) | $\sigma_T$ (cm$^2$/m$^2$) |
|-------------------|--------------------------|--------------------------|
| CH$_4$            | 10                       | 224                      | 190                      |
|                   | 50                       | 174                      | 133                      |
|                   | 100                      | 151                      | 124                      |
| C$_2$H$_6$        | 10                       | 189                      | 183                      |
|                   | 50                       | 150                      | 134                      |
|                   | 100                      | 133                      | 123                      |
| C$_3$H$_8$        | 10                       | 174                      | 160                      |
|                   | 50                       | 130                      | 122                      |
|                   | 90                       | 122                      | 118                      |

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**FIG. 14.** Scaled transverse diffusion coefficient as a function of the scaled electric field strength. Note the $\sqrt{P}\sigma_T(E/P)$-scaling (see also Table III).
The calculated effective Townsend coefficients for different Ar-alkane mixtures at 10 bar are shown in Fig. 15. Due to the $E/p$-scaling, the onset field strength at 10 bar is a factor of 10 larger than at 1 bar, and it is shown to increase with the alkane concentration, from 50-100 kV/cm for 10% to 150-250 kV/cm for pure alkanes. High concentrations of propane require significantly larger amplification fields to reach $\alpha - \eta$ values comparable to methane and ethane. In comparison, the gain onset for the ALICE TPC gas (90% Ne + 10% CO$_2$, 1 bar) is at around 4 kV/cm [29, 47].

The need for such high voltages poses a challenge to currently existing gas amplification structures. Wire chambers [29] and MicroMegas [48] are typically operated at about 10 – 100 kV/cm/bar. The biasing voltage needed to achieve these fields varies between $\mathcal{O}(100 – 1000)$ V. At 10 bar, the bias voltage would be up to $\mathcal{O}(10$ kV$)$; a challenge for high voltage safety from spark protection to electrostatic distortion of wires. The significantly higher voltages needed for high fractions of C$_3$H$_8$ 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 close to 80 kV/cm and 1 bar [49].

V. SUMMARY AND DISCUSSIONS

In this paper, we study the feasibility of measuring neutrino-hydrogen interactions in a HPTPC using argon-alkane gas mixtures. The charged-particle sensitivity of the TPC and its full acceptance and low threshold make it ideal for an exclusive measurement of the (anti)neutrino $\mu^+\pi^\pm$ production [Eqs. (1) and (2)] that could be used to identify interactions on the hydrogen component out of other nuclear target backgrounds [9]. With event-generator calculations, we confirm the efficient phase-space coverage of the detector. By modeling the detector response to the $\delta p_{TT}$ observable [Eqs. (5) and (6)], we demonstrate that by improving the resolution the signal-background ratio could be efficiently enhanced. A hydrogen-enriched TPC gas in an $\mathcal{O}(100$m$^3$) volume at 10 bar could not only further increase the signal-background ratio but also deliver a significant event rate. The highest purity is provided by pure CH$_4$ with a purity above 90% (assuming a $\delta p_{TT}$ resolution of $\Gamma = 5$ MeV/c), and an expected rate of $\sim 10^4$ event per year at the projected DUNE exposure. Such an event rate is twice of that by pure hydrogen. The highest hydrogen mass is provided by 7% Ar+93% C$_3$H$_8$ that nearly doubles the pure CH$_4$ signal yield with a twice-better signal-background ratio than by polystyrene.

We also examine the gas mixture properties that are related to TPC tracking. At high pressure, the effective drift field is reduced. Due to the limitation on megavolt ultra high power supplies, the electric field strength across several meters of drift length will not be strong enough to saturate the drift velocity to reach the stable maximum. In the practical operational region ($E/p \sim 40–200$ V/cm/bar) we consider, the drift velocity is (quasi)linear to the field strength with electron mobility $\sim 0.001$ cm$^2$/V·s at 10 bar. The resulting drift time could comfortably cope with the highest event rates foreseen in future accelerator-neutrino experiments. The sensitive drift velocity poses a constraint on the gas system: a per-mil-level stability requires a per-mil-level control on the gas composition, the drift field strength, as well as the temperature and the pressure.

The high pressure also reduces both transverse and longitudinal diffusion to significantly below the ALICE...
values. At $E/p = 40 \text{V/cm/bar}$ and high alkane concentration, the diffusion coefficients approach the thermal limit $\sim 100 \text{cm}^2/\text{cm} \cdot \text{bar}$ and become almost independent of the alkane type. The impact on the diffusion by a parallel magnetic field is shown to be negligible due to the small electron mobility.

One further impact on the gas properties by the high pressure is the much stronger amplification field required for gas gain to set in. For pure alkane the onset field strength is $150-250 \text{kV/cm}$, about 50 times of the ALICE value.

In this work, we used the GiBUU neutrino-event generator for the calculation of the signal and background rates. The underlying nuclear effects belong to a currently very active research area and the resulting uncertainties on our estimation need to be addressed both theoretically and most importantly by dedicated experiments. We modeled the detector response to the TKI observable by a one-parameter smearing function. For the next order accuracy, a detailed tracking model (and eventually a full detector simulation taking into account the detector geometry) could be applied to the particle-by-particle momentum vectors given by an event generator. Having these potential future improvements in mind, we emphasize in this paper the scaling behavior of the signal and background with the tracking resolution and the hydrogen content of the gas. We argue that with the state-of-the-art tracking performance foreseen in a future HPTPC (see Appendix A for further discussions) and the existing hydrogen-rich gas mixtures, the impact by the nuclear effects would be insignificant. It would be crucial at this early stage to estimate a more realistic $\Gamma$ value that a near-future HPTPC could achieve so that further discussions could proceed on the physics opportunities provided by a high-purity neutrino-hydrogen sample.

In the search of hydrogen-rich gas, we start with argon-hydrocarbon mixtures. The main purpose of the argon component is to provide early-stage synergy with the DUNE argon program. For example, the first-stage hydrogen program could proceed with P-50 to establish the baseline performance while still providing high-statistics neutrino-argon events (the carbon background might need to be constrained or statistically subtracted with the help of auxiliary measurements). Except for this practical concern, the argon component could be replaced by helium, for example, to study neutrino interactions on light nuclei. The carbon base, on the other hand, is motivated by its small number of (bound) protons. In addition, hydrocarbon, in particular alkane, is a well-studied TPC gas. As is shown in this work, the drift and gas gain properties with high-concentration alkane do not raise serious concerns in the TPC design. Yet, as it has been mentioned in this paper, the existing calculation of the gas properties could be further improved. In addition to developing better models for higher order accuracy, dedicated measurements of the gas properties are valuable. It is important to point out that, it might be very interesting to search for other hydrogen-rich gas mixtures, including nonbinary ones, that have additional merits like UV transparency [50]. In addition, the use of flammable gas such as CH$_4$ in underground laboratories requires extra precautions: a successful search for alternative hydrogen-rich nonflammable gas mixtures would ease this practical concern.

Finally, we would like to mention possible physics opportunities beyond the neutrino oscillation program with such a hydrogen-rich HPTPC, as it revives the possibility of neutrino-hydrogen interaction measurements after 30 years. The exclusive processes $\nu p \rightarrow \mu^\mp p + 2\pi^\pm$ which the hydrogen-extraction technique relies on are the ideal channels to study neutrino deeply virtual meson production ($\nu$DVMP) where Generalized Parton Distributions (GPDs) could be extracted [51, 52]. Because (anti)neutrons probe different quark flavors and spins, $\nu$DVMP unfolds the nucleon structure in a complementary way to the GPD program in the proposed Electron-Ion Collider [53]. In addition, because the TKI technique can also be applied to electron and muon beams—the corresponding leading exclusive channel being $e p \rightarrow e p$, where $e$ is the electron or muon—electron/muon-hydrogen interactions [54, 55] could be studied by a HPTPC. Furthermore, because of the common detector technology, the extraction technique for $\nu/\ell$-hydrogen interactions could be tested with a small-scale prototype detector at electron/muon beam lines at, for example, Mainz Microtron (MAMI) [56] or CERN.

Appendix A: Multiple Scattering

The ultimate TPC tracking performance is limited by multiple scattering, diffusion, the geometry of the readout unit, and the field distortion in the drift volume. The first two depend on the gas. As is shown in Section IV B, the diffusion is suppressed at high pressure and approaches the thermal limit at high alkane concentration. For completeness, in this section we estimate the size of multiple scattering in the Ar-alkane gas mixtures.

Multiple scattering is commonly quantified by the (r.m.s.) angular deflection, $\theta_{\text{MS}}$. It depends on the radiation length $X_0$ [measured in g/cm$^2$ (length×density)] [8]:

$$\theta_{\text{MS}} = \frac{13.6 \text{MeV}/c}{p} \sqrt{F} (1 + 0.038 \ln F), \quad (A1)$$

with the particle momentum $p$ and

$$F = \frac{x}{X_0^2}, \quad (A2)$$

where $x/X_0$ is the thickness of material measured in $X_0$ and $\beta$ is the particle velocity in unit of $c$. The gas-dependent part is

$$F \propto \frac{\rho}{X_0} \propto \frac{PA}{X_0}, \quad (A3)$$

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$$F \propto \frac{\rho}{X_0} \propto \frac{PA}{X_0}, \quad (A3)$$
FIG. 16. Weighted inverse radiation length, $A/X_0$, as a function of the alkane concentration. The ALICE (90% Ne + 10% CO$_2$) and T2K (95% Ar + 3% CF$_4$ + 2% iC$_4$H$_{10}$) values [29] are indicated by the horizontal lines.

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