# Snowmass2021 - Letter of Interest

## *Dual-Readout Time Projection Chamber: exploring sub-millimeter pitch for directional dark matter and tau identification in $\nu_\tau$CC interactions.*

## Topical Group(s):

☑ (NF3) Beyond the Standard Model
☑ (NF10) Neutrino detectors
☑ (CF1) Dark Matter: Particle-like
☑ (IF07) Electronics/ASICs
☑ (IF08) Noble Elements
☑ (IF09) Cross Cutting and Systems Integration

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**Abstract**

We propose the development of Dual-Readout Time Projection Chambers (TPC) capable of submillimeter tracking resolution via the readout of positive ions at the cathode. Detection at micron-scale pitches in massive detectors implies major technological challenges. However, there are several emerging technologies that may make micron-scale tracking of ions a reality during the next Snowmass period, enabling such a detector to be realized at scale. If it can be demonstrated, such a technology has the potential to push DM detection under the neutrino floor sensitivity and unlock a full exploration of nu tau interactions, two of the most burning questions in contemporary and foreseeable future particle physics.

**A tale of two questions.**

Compelling evidence for the existence of dark matter (DM) from a number of independent large-scale phenomena [1,2,3,4] has driven the last 20 years of experimental and theoretical effort to search for a DM particle candidate. No suitable candidate has been found and DM remains a key unsolved mystery in fundamental physics. Direct detection experiments have pushed the limits on the scattering cross sections close to the sensitivity floor imposed by solar neutrinos, which would hinder the DM signal for traditional detectors. A well studied solution to surpass the neutrino floor is the use of detection techniques with directional reconstruction capabilities [5]: the DM signal is expected to point preferentially in the direction of the constellation Cygnus, unlike solar and radioactive backgrounds. Tracking the increasingly short nuclear recoil from DM interaction, as well as discriminating between electron and nuclear recoils via the direct measurement of dE/dx, would provide a powerful background rejection technique.

The tau neutrino, on the other hand, has been experimentally well established. The value of studying tau neutrinos is clear: precise measurement of neutrino oscillations in the nu tau appearance and disappearance channels would directly test the unitarity of the neutrino mixing matrix [6,7]. Any deviation from unitarity would suggest a portal into physics beyond the Standard Model. Yet, with a global sum of 21 identified nutau candidates [8, 9, 18], tau neutrinos remain the least experimentally probed particles in Standard Model. The Super-Kamiokande and IceCube experiments have developed statistical methods to separate the tau neutrino component in the atmospheric flux; upcoming experiments such as DeepCore or DUNE plan to use similar techniques [10,11,12]. Yet, the only technology deployed to select nu tau CC interaction via the tau identification at accelerator neutrino energies is nuclear emulsion. This guarantees excellent tracking (1 μm in the active volume), but the long timescales and awkward data acquisition methods involved in emulsion readout makes scalability of such techniques impractical.

Experiments addressing DM searches with directional techniques and experiments aiming to detect taus in nutau CC interactions face some similar challenges. In order to overpower the small cross section for neutrinos interactions or to compete with the current stringent limits on DM scattering, they must utilize a large target mass, requiring a detection medium with the highest possible density. Additionally, this large mass needs to be instrumented with an extremely fine-granularity tracking capability of order of tens of microns, to reconstruct directions of very low energy recoils or to identify the short-lived tau particle. This capability must, furthermore, be employed in such a way that the extreme channel density does not become a prohibitive technological hurdle for a large detector.

**Dual-readout TPCs:** Here we express interest in the concept of dual-readout TPCs: a high pressure gaseous TPC collecting charge from both the ionization electrons at the anode and the positive ions at the cathode. Noble element TPCs have long been used in both DM and neutrino experiments, and provide a number of desirable properties, such as full homogenous calorimetry in dense media and 4pi tracking, among others. The intrinsic spatial limitation of this technology is driven by the transverse diffusion of the electrons during drift. Unlike electrons, ions remain thermal during their drift, and so their diffusion is much reduced. The use of positive ions collected at the cathode would push the intrinsic physical resolution of such a chamber in the 10-100 micron region. The challenge associated with this scheme is the development of a sensor that can reliably detect slow positive ions with the required granularity.

In a dual-readout TPC, the anode sensors would allow a “coarse” (mm to cm) event reconstruction using conventional electron detection methods, while the cathode would push the scale of tracking in the tens of micron region via detection of ions. If the anode readout is pixelated, it would be possible to identify the 3D region of interest (ROI) for the interaction, map it to a cathode equivalent ROI, and trigger the fine cathode readout online. Using the disparate timescales of electron (microseconds) and ion (seconds) drift this way not only evades problems associated with what may be an unmanageable data rate from a finely granular cathode, but also allows for solutions where readout is triggered in a locally defined region, based on coarse reconstruction of electron positions. For readout of the ion signal, there are at least two distinct but promising technological solutions.

**TopMetal:** The recently developed Topmetal-II -- a CMOS pixel sensitive to direct charge -- has demonstrated functionality when embedded in a standard 0.35 μm CMOS Integrated Circuit process. The corresponding sensor made of 72 x 72 pixel array for charge collection with 83 μm pitch has been successfully read out through time-shared multiplexing. Tests showed that the sensor achieved a < 15 e− analog noise and a 200 e= minimum threshold for digital readout per pixel, and capability for the detection of both electrons and ions drifting in gas, demonstrating readout device in future TPCs without low background and low rate-density experiments [15].

**Ion Microscopy:** Techniques for ion sensing and microscopy in gas are under development for neutrinoless double beta decay (0νββ) searches (barium tagging), spearheaded by the University of Texas at Arlington group within the NEXT collaboration. In those systems the target ion is a doubly charged metal dication. However, for noble TPCs with admixtures of certain gases, such as CF4, the positive ions are expected to be sufficiently chemically reactive that novel fluorescent chemosensors could be deployed that exhibit turn-on fluorescence upon reaction with them at the cathode. A system with a fluorescent ion-sensing layer probed by a mobile laser excitation source and EMCCD camera could resolve projected ion tracks with micron precision, seconds to minutes after the original interaction. Positioning of the camera could be realized using similar systems to those being considered for barium tagging in liquid or gaseous xenon, in schemes where the sensor moves to the ion rather than vice versa. Groundwork has demonstrated single ion detection at scanning surfaces with 2 nm spatial resolution [16], and developed bespoke fluorophores with dry fluorescent response to target metal dications [17]. The development of chemosensors for positive ion detection within its host gas, as opposed to metal dications, has been explored conceptually and appears plausible, with several promising chemoreceptors already identified.

**Conclusion:** Direct dark matter detection below the neutrino floor and a full exploration of nu tau interactions are two of the most pressing questions in contemporary particle physics. Both have been explored, though recent technological progress appears to have saturated due to the difficulty of realizing suitable instrumentation at scale. During the next Snowmass process, investment in technologies that can realistically address these questions is vital, and it is likely that creative solutions will be required. We advocate that development of Dual-Readout TPCs for submillimeter tracking, especially given new solutions to moderate channel count at the cathode, has the potential for enabling major and transformative advances.

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