Directional Detection of Dark Matter with MIMAC

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Abstract. Directional detection is a promising search strategy to discover galactic Dark Matter. We present a Bayesian analysis framework dedicated to Dark Matter phenomenology using directional detection. The interest of directional detection as a powerful tool to set exclusion limits, to authenticate a Dark Matter detection or to constrain the Dark Matter properties, both from particle physics and galactic halo physics, will be demonstrated. However, such results need highly accurate track reconstruction which should be reachable by the MIMAC detector using a dedicated readout combined with a likelihood analysis of recoiling nuclei.

1. Introduction
Taking advantage of the astrophysical framework, directional detection of Dark Matter is an interesting strategy to distinguish WIMP events from background ones [1]. Indeed, like most spiral galaxies, the Milky Way is supposed to be immersed in a halo of WIMPs which outweighs the luminous component by at least one order of magnitude. As the Solar System rotates around the galactic center through this Dark Matter halo, WIMP events should mainly come from the direction to which points the Sun velocity vector and which happens to be roughly in the direction of the constellation Cygnus ($\ell_\odot = 90^\circ, b_\odot = 0^\circ$). Hence, we argue that a clear and unambiguous signature of a Dark Matter detection could be achieved by showing the correlation of the measured signal with the direction of the solar motion.
However, the simultaneous measurement of the recoil energy and the recoil direction of a nucleus target of the detector material is a major experimental challenge. In the case of a Fluorine target at 50 mbar, the mean track length of a 10 keV recoil is of the order of 300 $\mu$m and about 3 mm at 100 keV. Then, directional detection of Dark Matter requires very sensitive experiment combined with highly performant technology. In this context, the MIMAC project has been proposed [2] and the track reconstruction strategy and some expected resolutions will presented hereafter.

2. Directional Detection Phenomenology
The first step when analysing directional data should be to look for a signal pointing toward the constellation Cygnus with a sufficiently high significance [3]. If no evidence in favor of a Galactic origin of the signal is deduced from the previous analysis, then an exclusion limit should be derived [4]. On the left panel of figure 1 we present the projected discovery regions and exclusion limits for a forthcoming directional detector proposed by the MIMAC collaboration. We consider a 10 kg CF$_4$ detector operated during $\sim$ 3 years, allowing 3D track reconstruction, with a 10$^\circ$
angular resolution, a recoil energy range of 5-50 keV and with a conservative background rate of 10 evts/kg/year. From the left panel of figure 1, two different scenarios may be distinguished:

- The dark and light-grey shaded areas represent the contours where a directional detection of Dark Matter would have an expected significance greater than 3σ and 5σ. These contours are deduced from the map-based likelihood method presented in [3]. As an illustration, if the WIMP-nucleon cross-section is about $10^{-4}$ pb with a WIMP mass of 100 GeV $c^2$, the detector would have a Dark Matter detection with a significance greater than 3σ.
- If the WIMP-nucleon cross-section is lower than $10^{-5}$ pb, then an exclusion limit is deduced using the extended likelihood method (black dashed line) presented in [4]. As a benchmark and to illustrate the effect of background on exclusion limits, the detector sensitivity (no event) is presented (black solid line).

Left panel of figure 1 also presents exclusion limits from direct detection experiments, KIMS [5] and Picasso [6] as well as the theoretical region, obtained within the framework of the constrained minimal supersymmetric model taken from [7]. We can conclude that a directional detector like MIMAC will cover an important region of interest worth being investigated.

As shown in [8], it is possible to go further by exploiting all the information from a directional detector, i.e. the energy and the direction of each event. We will then consider the most optimistic scenario where the WIMP nucleon cross-section is sufficiently large ($\sigma_p = 10^{-3}$ pb) to get a high significance Dark Matter detection. In such case, we have shown the possibility to constrain the WIMP properties, both from particle physics ($m_\chi, \sigma_n$) and galactic Dark Matter halo physics (velocity dispersions) [8] with a single directional experiment. To do so,
we used a Markov Chain Monte Carlo algorithm dedicated to the sampling of the likelihood function characterized by 8 free parameters which are \( \{ m_\chi, \log_{10}(\sigma_n), l_\odot, b_\odot, \sigma_x, \sigma_y, \sigma_z, R_b \} \), where the direction \((l_\odot, b_\odot)\) refers to the main direction of the recorded events, \( \sigma_p \) is the WIMP-nucleon cross section, \( m_\chi \) the WIMP mass, \( \sigma_{x,y,z} \) the velocity dispersions of the WIMP velocity distribution and \( R_b \) is the background event rate. As a result, one can see from the right panel of figure 1 that strong and consistent constraints on the \((m_\chi, \log_{10}(\sigma_n))\) plane can be obtained within the framework of a multivariate Gaussian WIMP velocity distribution, where the dispersions, and hence the anisotropy, are set as free parameters. Indeed, even in the case of an extremely anisotropic halo model, the WIMP mass and cross section are consistent with the input values as the velocity distribution is being constrained simultaneously. This is the first step toward a Dark Matter halo model independent analysis that could be done using data from upcoming directional experiment.

3. Track reconstruction with MIMAC

3.1. MIMAC prototype

The MIMAC prototype is the elementary chamber of a future large matrix of chambers. It allows us to perform a track measurement with the required performance to achieve directional detection of Dark Matter. The primary electron-ion pairs produced by a nuclear recoil in one chamber of the matrix are detected by drifting the electrons to the grid of a bulk micromegas [9] and by producing the avalanche in a very thin gap (128 or 256 \( \mu \)m). The electrons move towards the grid in the drift space and are projected on the anode thus allowing to get information on X and Y coordinates. To access the X and Y dimensions, a bulk micromegas with a 10 by 10 cm\(^2\) active area segmented in pixels with a pitch of 424 \( \mu \)m is used as a 2D readout. In order to reconstruct the third dimension Z of the recoil, a self-triggered electronics has been developed. It allows to perform the anode sampling at a frequency of 50 MHz, leading to time slices of 20 ns width along the Z dimension. This electronic also includes a dedicated 16 channels ASIC [10] associated to a DAQ [11]. The total recoil energy is deduced from the measured ionization quenching factor (IQF) [2].

3.2. Likelihood approach for track reconstruction

A straightforward track reconstruction algorithm consists in using a three dimensional linear fit of the center of gravity of each time slice. However, we found that this method failed at recovering the correct \( \theta \) angle due to the longitudinal diffusion of the electrons. In order to recover correctly the track properties, two strategies can be used:

- If one is able to get the Z position of the track in the detector, e.g. by using a PMT sensitive to the primary scintillation, the electron diffusion can be correctly estimated and substracted
- If no additional readout is used, the only way to recover without bias the track properties, is to fit all the parameters at the same time using a likelihood approach. This is the strategy that we have developed and which is presented hereafter.

To perform this likelihood approach dedicated to track reconstruction within the MIMAC experiment, we combined the use of three different softwares: SRIM [12] for the track simulation, MagBoltz [13] for the estimation of the electron drift properties (velocity and diffusion), and the MIMAC DAQ simulation software. This way, we are able to simulate tracks as measured by the detector. Of course, this highlights the need for the detector commissioning as any discrepancy between the simulation and the measurement will result in bias in the track reconstruction.
In order to estimate the expected performance of the detector, in terms of spatial and angular resolution, systematical studies have been done. To do so, we have simulated about one thousand tracks generated isotropically in the lower half sphere (going downward) at a fixed Z coordinate and energy. In the case of a Fluorine recoil in our gas mixture (70% CF\(_4\) + 30% CHF\(_3\)), we found that \(\sigma_{x,y}\) is about 1 mm at 20 keV and 0.4 mm at 100 keV and that it is independent from the Z coordinate. About \(\sigma_z\), we found a resolution of about 1.5 mm at 40 keV and 1 mm at 100 keV, with a weak dependence with the Z coordinate. The fact that the spatial resolutions are of the order of a millimeter will allow us to perform an accurate three dimensional fiducialization of the detector volume to prevent from surface events. The expected angular resolution \(\sigma_{\gamma}\) depends strongly on the energy of the recoiling nucleus. Indeed, the angular resolution is about 55° at 20 keV while it is about 30° at 100 keV. However, it does not depend on the Z coordinate of the track in the 3 cm to 7 cm range.

We used a Boosted Decision Tree [14] as a sense recognition discriminant by first finding the maximum Likelihood according to the two hypothesis: Up and Down. Then, we generate a large sample of tracks (around 10,000) corresponding to the best fits of the two hypothesis. If the track is going upward or downward, the BDT value should be positive or negative respectively. As a working example, we have simulated 1000 tracks generated at 100 keV, in the direction \((\theta = 45^\circ, \phi = 0^\circ)\), going downward and at 1.3 cm of the anode. We found that 77% of the tracks have a negative BDT value, thus corresponding to a 77% sense recognition efficiency for this given set of parameters (position, direction and energy).

4. Conclusion
In this paper, we have shown that directional detection of Dark Matter could be sensitive to very low cross-sections \(\sim 10^{-8}\) pb, in the case of a 10 kg CF\(_4\) detector running during three years, and could hence be very competitive with existing experiments. Moreover, using this unique kind of direct search of Dark Matter could lead to unambiguous arguments in favor of a positive detection of Dark Matter. Also, we have shown that a directional detection of Dark Matter will allow to constrain the Dark Matter properties both from particle physics and galactic halo physics. However, directional detection represents a major experimental challenge. In this context, the MIMAC experiment has been proposed and combined with a dedicated likelihood analysis, we have shown that MIMAC should be able to perform a highly performant directional detection of Dark Matter.

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