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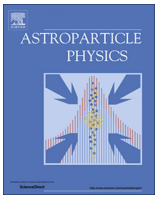

Review

Statistical issues in astrophysical searches for particle dark matter

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ABSTRACT

In this review statistical issues appearing in astrophysical searches for particle dark matter, i.e. indirect detection (dark matter annihilating into standard model particles) or direct detection (dark matter particles scattering in deep underground detectors) are discussed. One particular aspect of these searches is the presence of very large uncertainties in nuisance parameters (astrophysical factors) that are degenerate with parameters of interest (mass and annihilation/decay cross sections for the particles). The likelihood approach has become the most powerful tool, offering at least one well motivated method for incorporation of nuisance parameters and increasing the sensitivity of experiments by allowing a combination of targets superior to the more traditional data stacking. Other statistical challenges appearing in astrophysical searches are to large extent similar to any new physics search, for example at colliders, a prime example being the calculation of trial factors. Frequentist methods prevail for hypothesis testing and interval estimation, Bayesian methods are used for assessment of nuisance parameters and parameter estimation in complex parameter spaces. The basic statistical concepts will be exposed, illustrated with concrete examples from experimental searches and caveats will be pointed out.

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1. Introduction

To consult the statistician after an experiment is finished is often merely to ask him to conduct a post mortem examination. He can perhaps say what the experiment died of. R.A. Fisher.

The existence of particle dark matter is by now established beyond reasonable doubt by a variety of observational evidence, see e.g. [1] for a recent review. The nature of these particles is unknown, but one of the most popular conjectures is that it is provided by massive particles interacting roughly on the weak scale. While particle colliders attempt to produce potential dark matter candidates in collisions, astrophysical detection refers to detection of a signal of dark matter particles from astrophysical sources. This is done by either measuring the dark matter particles residing in the Galactic halo as they recoil from detector material in underground mines (termed "direct detection") or by measuring the annihilation or decay products, foremost neutrinos, charged cosmic rays and gamma-rays, from astrophysical objects (termed "indirect detection", as the particles are not measured directly but just their products). These include solar system objects (the Sun and Earth foremost for neutrino searches), as well as dwarf galaxies, galaxy clusters, the Galactic center or in extended emission, for example gamma rays from the Milky Way halo foremost for gamma-ray searches. Gamma-rays are mainly searched for by gamma-ray satellites and imaging air Cherenkov telescopes. The main approach for gamma ray telescopes on satellites is to make the gamma ray induce an electromagnetic cascade by pair conversion in a tracking detector, possibly interleaved with high-Z material to enhance the pair conversion cross-section. The direction is reconstructed with high precision in the tracking device, the energy is (mainly) measured in a dedicated calorimeter. Charged cosmic rays are very effectively rejected by scintillator based anti-coincidence detectors, as well as exploiting the cascade topology differences between gamma-ray induced and the predominantly hadronically induced cosmic ray background. The generic idea of imaging air Cherenkov telescopes is to detect the Cherenkov radiation that is produced by the charged particle cascade that is initiated by a high energy gamma ray. The Cherenkov light is reflected by large (~10 m diameter) mirrors on to cameras consisting of arrays of photomultipliers. The energy is measured by the total image signal amplitude, the direction (optimally) by combining the information from the image seen simultaneously in more than one telescope. Neutrino telescopes utilize a transparent medium (water or ice) equipped with a grid of photo-multiplier tubes to detect Cherenkov radiation emitted by neutrino induced charged particles. Background rejection relies foremost on the direction of incoming particles (mainly muons). Detectors for direct detection differ mainly in the employed detector material. Broadly, cryogenic solid state detectors, scintillating crystals or noble gas detectors are used. Background rejection relies on fiducialization, (i.e. an approach where part of the detector is not going to be used for signal detection but rather as veto for externally induced background) and/or the comparison of scintillation/ionization or phonon signal, which give different response for different types of interaction. Detectors are specially developed for low radioactive intrinsic background and situated deep underground to reduce cosmic ray background.

As for now astrophysical detection of dark matter is concerned with establishing the particle nature of dark matter and understand its nature, the primary parameters of interest are related to the properties of dark matter particles as explained before. Astrophysical properties of dark matter (as for example its density and distribution), are interesting in its own right but are nuisance parameters as far as detection of particle dark matter is concerned. An overview of the statistical tools used in searches for particle dark matter is shown in Fig. 1.

As in conventional particle physics, the main challenges for indirect and direct searches are reduction of background (reduction factors between 10^4 and 10^6) and the accurate reconstruction of physical observables (energy, charge, mass, direction or type of the incoming particle). Reduction of background is a hypothesis testing problem where detector output (such as a pattern of electrical signals in detector with several readout channels) is used to test the hypothesis that the event,[1] is either originating from a signal process or another process. In case that the detector output gives several not completely uncorrelated observables, this classification problem is often treated with multivariate machine learning algorithms. The accurate reconstruction of physical observables refers to the conversion of the detector output (for example the amplitude of an electrical signal) to a set of physical observables. The techniques used here are for example maximum likelihood estimation or multivariate regression by means of machine learning. I will in this review not discuss these techniques as they are not specific to dark matter searches, but rather generic to particle physics or experimental physics. Instead, I will focus on issues of special importance in astrophysical searches for dark matter, as for example the treatment of nuisance parameters and non-standard hypothesis testing. For an excellent and very complete text book of statistical methods in experimental physics in general, the reader is referred to [2].

In order to set the terminology for this review we will introduce the observables and parameters relevant to astrophysical searches for dark matter. In indirect detection the observable is foremost the number of dark matter induced standard model particles per unit area per unit time (i.e. the flux) and per energy interval which is related to parameters as:

$$\frac{dR}{dt\,dA\,dE} = P \cdot J(\Delta\Omega) \tag{1}$$

with R being the number of particles and P and J defined as:

$$P = \frac{\langle \sigma_{ann} v \rangle}{2m_\chi^2} \cdot \sum_i BR_i \frac{dN_\gamma^i}{dE_i} \tag{2}$$

with $(\sigma_{ann} v)$ being the annihilation cross-section averaged over the velocity distribution of dark matter particles, m_χ is the dark matter particles mass, BR_i denotes the branching fraction to different annihilation channels (e.g. quarks and anti-quarks) and $\frac{dN_\gamma^i}{dE_i}$ is the yield of particles as function of energy, determining the spectral shape of the signal. P is the particle physics factor, i.e. contains the particle properties of the dark matter particle affecting the potential signal. The other term represents the respective astrophysical part:

$$J(\Delta\Omega) = \int_{\Delta\Omega} \int_{l=0}^{\infty} dl\, d\Omega \rho_\chi^2(l) \tag{3}$$

with ρ_χ being the dark matter density, $\Delta\Omega$ the solid angle element that is integrated over in the observation. The term in Eq. (3) will in the remainder of this review be referred to as the J-factor. As astro-

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[1] The data that we are occupied with is event data, i.e. the data is a point in coordinate space, where the coordinates are detector outputs).