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Anticipation of the discovery potential sensitivity of next-generation neutrinoless double beta decay experiments

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The upcoming wave of neutrinoless double beta decay experiments is geared towards probing the inverted mass ordering and transitioning into the normal ordering domains. We undertake a quantitative assessment of the projected experimental sensitivities, with a specific emphasis on the discovery potentials anticipated prior to the execution of experiments. We assess the sensitivity of the counting analysis using full Poisson statistics and compared with its continuous approximation. The inclusion of additional measurable signatures such as energy can enhance sensitivity, and this is accounted for through a maximum likelihood analysis. This study serves as an example to the generic problem of making sensitivity projections to proposed projects with predicted background prior to the experiments are performed.

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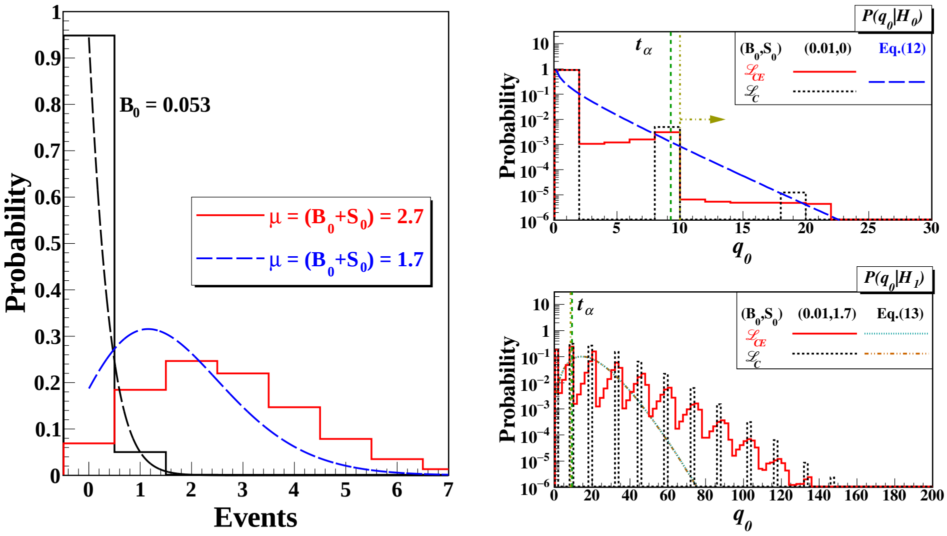
1. Introduction

Experimental efforts to detect neutrinoless double beta decay ($0\nu\beta\beta$) are at the forefront of nuclear and particle physics research. The pursuit for $0\nu\beta\beta$ is considered the most sensitive experimental avenue to confirm if neutrinos are Majorana particles, providing critical insights on the absolute scale of neutrino mass and the underlying mass generation mechanism. In experimental searches for $0\nu\beta\beta$ and other rare processes, prior knowledge of the background is typically available before the experiments are conducted. Subsequently, a fundamental aspect at the design stage is to make sensitivity projections according to statistical criteria chosen by experimenters, before the experiments are performed. In this work, we quantitatively evaluate the projected sensitivities in terms of discovery potential, which is crucial for optimizing experimental specifications and ensuring cost-effectiveness across different investments [1].



(a) (b)

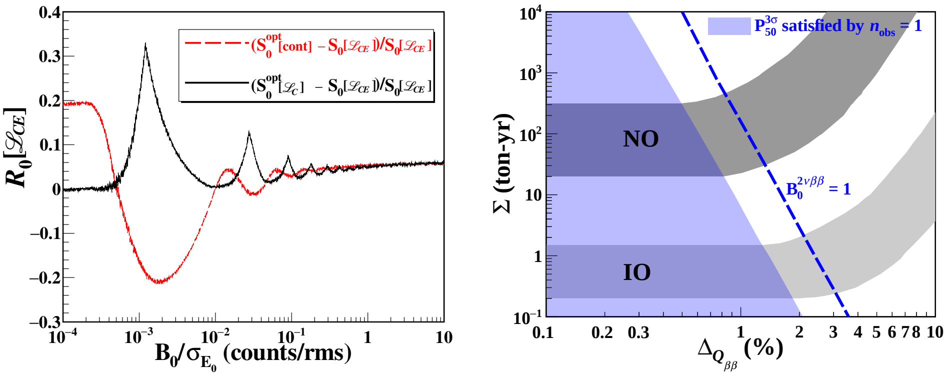
Figure 1: (a) The differences between the full Poisson distribution and its continuous approximation are highlighted for B_0=0.053, with μ=(B_0+S_0), where S_0 represents the minimal signal strength at $P_{50}^{3\sigma}$. The complete distribution yields μ=2.7, contrasting with 1.7 in the continuous approximation. (b) The test statistic q_0 distributions for simulated datasets under the null $[P(q_0|H_0)]$ and alternative $[P(q_0|H_1)]$ hypotheses are depicted for the low-B_0 scenario with $(B_0, S_0)=(0.01, 0)$ and $(0.01, 1.7)$, along with the acceptance threshold t_α. Superimposing the approximations from Eqs. (12) and (13) as per Ref. [1] demonstrates their consistency with $[P(q_0|H_0)]$ and $[P(q_0|H_1)]$ at larger scales, but diverge at low (B_0,S_0).

2. Statistical analysis

Utilizing Poisson distributions in statistical analysis is fundamental for addressing rare signals and low-background scenarios. Given a positive expected background B_0, a Poisson distribution with mean μ=B_0 is constructed, illustrated in Fig. 1(a) for both the complete [1] and continuous approximations [2]. However, when experimental measurements encompass multiple variables such as energy, the Poisson counting approach alone is inadequate for extracting all the information from signal and background. Thus, an alternative and more comprehensive formulation of the test statistic (q_0) using the maximum likelihood ratio method is required, as illustrated in Fig. 1(b) with the distributions of q_0 for simulated data under the null $[P(q_0|H_0)]$ and alternative $[P(q_0|H_1)]$ hypotheses. Readers are referred to Ref. [1] for a comprehensive investigation of our methodology.

3. Discovery potential sensitivity assessment – ^{136}Xe isotope

Sensitivity targets in experiments are generally articulated as: "Discovery potential at 3σ with 50% probability" ($P_{50}^{3\sigma}$) and "upper limits at 90% confidence level", which characterize both potential positive and negative outcomes. At $P_{50}^{3\sigma}$, the deviation in S_0 yields of complete $S_0^{opt}[\mathscr{L}_C]$ and continuous S_0^{opt}[cont] Poisson in the optimal region of interest (RoI) is exhibited in Fig. 2(a) relative to maximum likelihood ratio method $S_0[\mathscr{L}_{CE}]$, which shows that S_0^{opt}[cont] can underestimate the strength of $S_0[\mathscr{L}_{CE}]$ by up to 20%, and $S_0^{opt}[\mathscr{L}_C]$, on the other hand, can overestimate by as much as 30%. The present work focuses on sensitivity projections for upcoming ^{136}Xe-based $0\nu\beta\beta$ experiments, utilizing the profile likelihood method within the $P_{50}^{3\sigma}$ framework.



(a) (b)

Figure 2: (a) Sensitivity differences of $S_0^{opt}[\mathscr{L}_C]$ and S_0^{opt}[cont] relative to $S_0[\mathscr{L}_{CE}]$ are investigated as a function of (B_0/σ_{E_0}) using the $P_{50}^{3\sigma}$ approach. (b) Irreducible $2\nu\beta\beta$ background effects on $0\nu\beta\beta$ sensitivity for ^{136}Xe are highlighted in the exposure (Σ) versus FWHM energy resolution ($\Delta_{Q_{\beta\beta}}$) space. Reference bands for inverted (IO) and normal neutrino mass orderings (NO) are also shown.

To improve sensitivity, all planned $0\nu\beta\beta$ experiments are focused on achieving a nearly background-free regime. The blue shaded region in Fig. 2(b) represents a background-free zone (from both ambient and $2\nu\beta\beta$ sources), where detecting a single event in the RoI would indicate a positive signal under the $P_{50}^{3\sigma}$ framework. To operate within this regime, the necessary experimental requirements are $\Delta Q_{\beta\beta} < 1.3\%$ and $\Sigma > 1.5$ ton-year for IO, and $\Delta Q_{\beta\beta} < 0.5\%$ and $\Sigma > 315$ ton-year for NO. The white region illustrates where $2\nu\beta\beta$ background limits $0\nu\beta\beta$ sensitivity, with the dotted line indicates the point at which an average of one $2\nu\beta\beta$ background event begins to contaminate the RoI.

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