Search for WIMP Inelastic Scattering Off Xenon Nuclei With Xenon100 Data

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Some nice abstract here.....

I. INTRODUCTION

Astrophysical evidence indicates that the dominant mass fraction of our Universe consists of some yet unknown form of dark matter. Well motivated models predict Dark Matter in the form of Weakly Interacting Massive Particles (WIMPs), hypothesis which is currently being tested by several direct and indirect detection experiment. some citation missing.

Most of direct detection searches focuses on elastic scattering of dark matter particles off nuclei. In this analysis instead an inelastic scattering process is explored, we consider the ^{129}Xe isotope being excited to a low-lying state with subsequent prompt de-excitation via the emission a photon. This isotope is an excellent target since its abundance in natural xenon is of 26.4% and a relatively low energy is necessary to excite its 3/2+ state above the 1/2+ spin ground state. These type of processes were previously studied in detail for liquid xenon detector in [1]. Inelastic WIMP-nucleus scattering in xenon is complementary to elastic scattering for spin-dependent interactions, the former dominates the integrated rate above $\simeq$ 10 keV of energy deposition. Furthermore, in the case of dark matter detection, this channel can be employed to asses whether the nature of the fundamental interaction is spin-dependent or not.

II. XENON100 DETECTOR

The Xenon100 experiment is a dual phase liquid xenon TPC. For a given interaction in the liquid target this type of detector produces two separated signals, one proportional to the prompt scintillation (S1) the other to ionization (S2).

To add: describe and explain cS1 and cS2 definitions, some sentences about detector stability, maybe science run data used and calibration campaign goes here, maybe Ly and Y measurements used goes here.

III. DATA ANALYSIS

This analysis is performed using XENON100 Run-II science data, which corresponds to an exposure of 224.6 live days. The detector response to electronic re-

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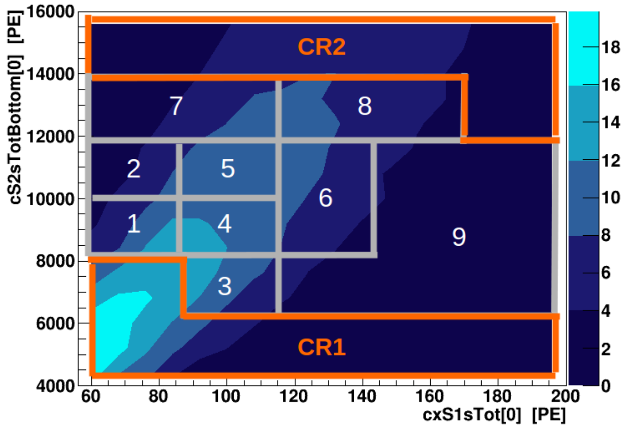

FIG. 1. Signal region and control region.

coil (ER) has been characterized using ^{60}Co and ^{232}Th radioactive sources, while response to inelastic nuclear recoil (NR) scattering was calibrated using an ^{241}AmBe source.

The inelastic scattering of a WIMP with the nucleus of ^{129}Xe produces an energy deposit via nuclear recoil with subsequent emission of a 39.6 keV de-excitation photon. The largest fraction of the energy released in the event is via electronic recoil due to the emitted photon, this represents an unusual signature for this kind of detector and brings the possible signal to overlay a phase space region with large backgrounds. The choosen region of interest for this analysis surrounds the 39.6 keV xenon line in the cS1-cS2 plane which is further divided into sub-regions, as shown in Figure 1.

Events are asked, other than falling in the defined region of interest, to fullfill several selection criteria which can be sumarized as: selection aimed to reduce noise impact including energy (S1) and S2 thresholds, events must be of single scatter nature and fall into a predefined fiducial volume. This analysis follows the selection criteria described in detail in [2] for Run-II, with only few exceptions. In particular, the selection on S2 width as a function of drift time has been optimized on a sample of events selected from the 39.6 keV line and set to a 95% acceptance on these. Events are required to be single scatter by applying a threshold on the second largest S2 peak size, for this analysis this threshold has been optimized to 160 PE and set constant as function of S2 signal size. Finally the chosen fiducial volume corresponds to 34 Kg of liquid xenon.

A. Signal Simulation

The detector response to inelastic scattering of WIMPs off ^{129}Xe nucleus was simulated using an empirical model. The total deposited energy is divided into two independent contributions: the one related to the 39.6 keV de-exitation photon and the one relative to the simultaneous nuclear recoil of the xenon atom, the number of photons and charge yield detected is simulated separatedly for each contribution and then added togheter.

The ER induced by the de-exitation photon is simulated assuming a two dimensional normal distribution as its pdf in the cS1-cS2 plane, $f(cS1, cS2)$, described (except a normalization factor) in equation 1:

$$f(cS1, cS2) = exp\Big(- \frac{1}{2(1-\rho^2)}\Big[\frac{(cS1-\mu_{cS1})^2}{\sigma_{cs1}^2} + \frac{(cS2-\mu_{cS2})^2}{\sigma_{cs2}^2} - \frac{2\rho(cS1-\mu_{cs1})(cS2-\mu_{cs2})}{\sigma_{cs1}\sigma_{cs2}}\Big]\Big) \quad (1)$$

where μ_{cS1} and μ_{cS2} represents the average observed cS1 and cS2 given a 39.6 keVee , σ_{cs1} and σ_{cs2} are the standard deviation in cS1 and cS2 respectively, while ρ stands for the correlation between cS1 and cS2. The detector related light yield L_y measured at 39.6 keV, necessary to evaluate the average number of photon detected (μ_{cS1}), is obtained as the result of a NEST model [3–5] fit to data collected with several lines. The same model is used to predict the charge yield at 39.6 keV which is then scaled according to the detector's secondary scintillation gain Y, determined from detector response to single electrons [6]. Note that the corrected S2 observed by the bottom PMT array is used in this analysis. The detector resolution at 39.6 keV in cS1 and cS2 has been measured to be respectively 15.8% and 14.7% and used to extract the standard deviations σ_{cs1}, σ_{cs2}. The correlation parameter is assumed to be independent of energy (at least in the considered range) and measured using the 164 keV xenon activated line by ^{124}AmBe calibration data, this line is choosen since allows to disentangle efficiently contribution from nuclear recoil. The measured correlation is $\rho = -0.45 \pm 0.10$.

The cS1 and cS2 distributions from NR contribution are predicted starting from the nuclear recoil energy spectrum for WIMPs inelastic interaction [1]. The average cS1 and cS2 are given by equations 2 and 3 respectively, where $\mathcal{L}_{eff}$ is the liquid xenon NR relative scintillation efficiency while $S_{ee} = 0.58$ and $S_{nr} = 0.95$ describe the scintillation quenching due to the electric field [7]. The parameterization and uncertainties of $\mathcal{L}_{eff}$ as a function of E_{nr} are based on existing direct measurements [8]. The light yield at 122 keVee originate from the same NEST model fit as described above. For the cS2 the parameterization of $Q_Y(E_{nr})$ is taken from [9]. Finally all detector related resolution effects are introduced following the prescriptions described in [2].

$$cS1_{nr} = E_{nr}\,\mathcal{L}_{eff}(E_{nr})\,L_y\,\frac{S_{nr}}{S_{ee}} \quad (2)$$

$$cS2_{nr} = E_{nr}\,Q_Y(E_{nr})\,Y \quad (3)$$

The pdf of the ER and NR contributions are then convoluted toghether to obtain the overall pdf of the signal.

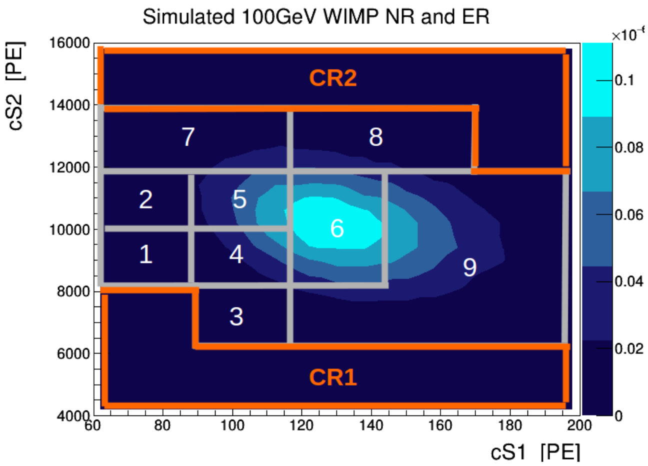

FIG. 2. Signal region and control region, for WIMP of mass 100 GeV.

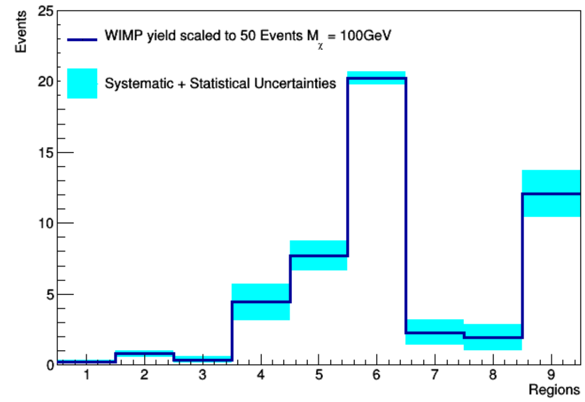

FIG. 3. Signal region, uncertainties for WIMP of mass 100 GeV.

A 2D (cS1 versus cS2) acceptance map is applied to the signal pdf to reproduce data selection effects. Acceptances are computed separately for each selection criteria using ^{124}AmBe calibration sample, selections as the outer volume veto and the single scatter interaction represent an exception and a detailed computation has been performed in these cases. The acceptance average in the region of interest to about 0.80 ± 0.05. Figure 1 shows an example of full simulated signal model for a WIMP of 100 GeV mass.

The signal simulation procedure has been validated reproducing the 39.6 keV xenon line from interaction due to ^{124}AmBe source and has been compared to data. For the comparison the proper ^{124}AmBe nuclear recoil and acceptances were simulated. The simulated events were found in agreement with calibration data within statistical uncertainties.

B. Background Model

The main expected background contribution in the region of interest is due material radioactivity, composed mainly by photons interacting via compton scattering. Background contribution due to the activation of the xenon 39.6 keV line from radiogenic neutrons is expected to be negligible. The background is modeled using data from ^{60}Co calibration campaign, which are assumed to well represent the background density distribution in the cS1-cS2 plane.

The calibration sample yields about 22'000 events in the ROI, these are then scaled to data according to a measured background scale factor τ_{bkg}. The scale factor is measured in the two control regions shown in Figure 1 and labelled CR1 and CR2. The two control regions give compatible results and the computed average is $\tau_{bkg} = 0.034 \pm 0.002$, where the reported uncertainty is of statistical nature only.

The distribution of the calibration sample has been compared to the data of the sience run in the two control regions, agreement is found within statistical uncertainties. ^{60}Co calibration data have been compared in the region of interest to data from ^{232}Th calibration campaign, the largest deviation between the two shapes is within 4%. An additional systematic uncertainty of 4% has been applied to the expected background yield of each sub-region of the ROI.

C. Systematic Uncertainties

Uncertainties on the total prediction of background events arise from the uncertainty on the measure of the normalization factor, τ_{bkg}, and amount to 6%, contribution of radiogenic neutrons are neglected. Systematic uncretainty on the shape of the predicted bakground distribution are assesed by the maximal discrepancy in the ROI between the ^{60}Co and ^{232}Th calibration samples, a 4% systematic additional to statistical uncertainty is assigned to the expected yield of each sub-region, note that uncertainties belonging to different sub-regions are considered independent from each other.

Uncertainty on the total yield of the signal arising from uncertainties on the selection acceptance are found to be very weakly dependent on the WIMP mass, an overall 6% acceptance uncertainty is then applied to all WIMP hypotesis.

Uncertainties on the energy scale and, more generally, related to detector response are parametrized using the respective uncertainties on the measure of L_y, $\mathcal{L}_{eff}$, Y, Q_Y and ρ. The simulation shows that these type of uncertainties mainly affect the pdf of the signal model in the ROI, and very weakly the total signal yield. They are taken into account by simulating several signal pseudo-sample for each WIMP mass, the pseudo-sampleis are produced varying the model parameters respectively of ± 1 standard deviation. For each sub-region is then computed an overall uncertainty by adding in quadrature the variations of each pseudo-sample with respect to nominal. Figure 3 is an example of such a systematic uncertainty computation for WIMP mass of 100 GeV.

All the uncertainties discussed here are parametrized within a binned profiled likelihood function using the framework [10, 11]. All parameters related to systematic uncertainties are assumed to be normally distributed.

IV. RESULTS

In an exposure of 34 kg of liquid xenon and 224.6 live days of data a yield of 764 events are found in the region of interest, this is compatible with the expectation of $756 \pm 5^{(stat.)} \pm 55^{(syst.)}$ events from the background only hypothesis. Figure 4 shows how these events are distributed in the region of interest, the bottom panel shows the ratio between data and expected background, where the gray and orange shaded areas represent respectively statistical and systematic uncertainty on the background expectation. This result is interpreted via a binned profiled likelihood approach by means of the test statistic $\tilde{q}$ and its asymptotic distributions described in [12].

Assuming an isothermal WIMP halo with a local density of $\rho_\chi = 0.3\ GeV/cm^3$, a local circular veloc- ity of $v_0 = 220$ km/s, and a galactic escape velocity of $v_{esc} = 544$ km/s, other assumptions..., a 90% CL$_s$ [13] confidence level limit is computed on the spin dependent inelastic WIMP-nucleon cross section, σ_{ine}, as a function of the WIMP mass, m_χ, and shown in Figure 5. The expecetd median sensitivity is reported with its relative one (green area) and two (yellow area) standard deviation uncertainty. A limit is set on σ_{ine} to $3.3 \times 10^{-38}\ cm^2$ for a WIMP of mass 100 GeV. This limit is compared with decide which other experiment to plot.

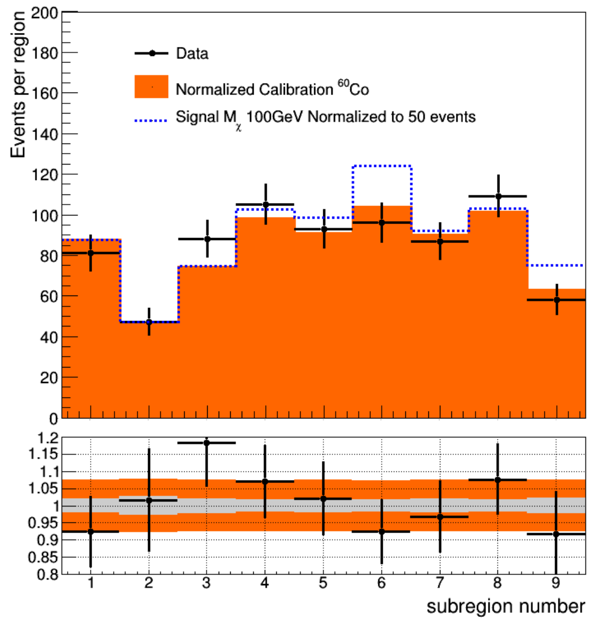

FIG. 4. Results, comparison between data and expected background.

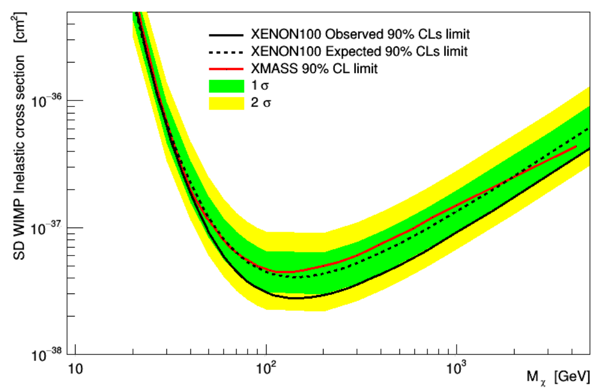

FIG. 5. Observed and expected limits.

[1] L. Baudis, G. Kessler, P. Klos, R. F. Lang, J. Menndez, S. Reichard, and A. Schwenk. Signatures of Dark Matter Scattering Inelastically Off Nuclei. *Phys. Rev.*, D88(11):115014, 2013.

[2] E. Aprile et al. XENON100 Dark Matter Results from a Combination of 477 Live Days. *Phys. Rev.*, D94(12):122001, 2016.

[3] M Szydagis, A Fyhrie, D Thorngren, and M Tripathi. Enhancement of nest capabilities for simulating low-energy recoils in liquid xenon. *Journal of Instrumentation*, 8(10):C10003, 2013.

[4] John Allison et al. Geant4 developments and applications. *IEEE Trans. Nucl. Sci.*, 53:270, 2006.

[5] S. Agostinelli et al. GEANT4: A Simulation toolkit. *Nucl. Instrum. Meth.*, A506:250–303, 2003.

[6] E Aprile et al. Observation and applications of single-electron charge signals in the xenon100 experiment. *Journal of Physics G: Nuclear and Particle Physics*, 41(3):035201, 2014.

[7] E. Aprile, C. E. Dahl, L. DeViveiros, R. Gaitskell, K. L. Giboni, J. Kwong, P. Majewski, Kaixuan Ni, T. Shutt, and M. Yamashita. Simultaneous measurement of ionization and scintillation from nuclear recoils in liquid xenon as target for a dark matter experiment. *Phys. Rev. Lett.*, 97:081302, 2006.

[8] E. Aprile et al. Dark Matter Results from 100 Live Days of XENON100 Data. *Phys. Rev. Lett.*, 107:131302, 2011.

[9] E. Aprile et al. Response of the XENON100 Dark Matter Detector to Nuclear Recoils. *Phys. Rev.*, D88:012006, 2013.

[10] Lorenzo Moneta, Kevin Belasco, Kyle S. Cranmer, S. Kreiss, Alfio Lazzaro, Danilo Piparo, Gregory Schott, Wouter Verkerke, and Matthias Wolf. The RooStats Project. *PoS*, ACAT2010:057, 2010.

[11] Wouter Verkerke and David P. Kirkby. The RooFit toolkit for data modeling. *eConf*, C0303241:MOLT007, 2003. [,186(2003)].

[12] Glen Cowan, Kyle Cranmer, Eilam Gross, and Ofer Vitells. Asymptotic formulae for likelihood-based tests of new physics. *Eur. Phys. J.*, C71:1554, 2011. [Erratum: Eur. Phys. J.C73,2501(2013)].

[13] Alexander L. Read. Modified frequentist analysis of search results (The CL(s) method). In *Workshop on confidence limits, CERN, Geneva, Switzerland, 17-18 Jan 2000: Proceedings*, pages 81–101, 2000.