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Something Something Something
bla bla for Super Kamioknade

by

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ABSTRACT

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List of Abbreviations

ADC Analog to Digital Converter

Chapter 1

Introduction

1.1 A Brief History of the Neutrino

While neutrinos have been around for about 13.8 billion years [1, 2], and humans for a slightly shorter but still respectable about 200,000 years, humans have only been aware of the neutrino for the relatively short period of about 90 years. The existence neutrino was first proposed by Wolfgang Pauli in a letter to a meeting in Tübingen, Germany, in 1930, as a possible explanation for the observed continuous beta decay spectrum [3]. In this letter Pauli wrote

...there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light. The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass.—The continuous β -spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and

electron is constant. [3]

This first proposal was tentative, and it is interesting to note that Pauli first used the name "neutron," the particle we today know as the neutron having not yet been discovered. In 1932, the heavy neutron we know today was discovered by James Chadwick, and so the light neutral particle first proposed by Pauli was renamed the "neutrino" by Enrico Fermi. In 1934, Fermi published a quantitative theory of β -decay which included neutrinos as an assumed component [4], and predicted the continuous beta-decay spectrum.

Continued measurements of the beta-decay spectrum and observations of new meson decays using nuclear track emulsion strengthened the evidence in the existence of the neutrino. However, it was not until the early 1950's that the neutrino was explicitly observed. Fred Reines and Clyde Cowan placed a large liquid scintillator detector near a nuclear reactor in Hanford, Washington. They hoped to observe neutrinos produced by the reactor interacting with the protons of the liquid scintillator through inverse beta decay, $p + \bar{\nu} \rightarrow n + e^+$. They searched for events with a delayed coincidence between the scintillation light due to the positron and the γ produced by the capture of the neutron on Cadmium with which the liquid scintillator had been loaded. They noted a change in the measured event rate when the reactor was on versus when it was off, which agreed well with the predicted neutrino event rate [5]. They soon confirmed the result with an upgraded experiment as Savannah River [6, 7].

Chapter 2

Neutrino Theory

Chapter 3

Boosted Dark Matter

3.1 Introduction

There is ample evidence for the existence of dark matter [8–11], and its abundance has been well measured to account for about 25% of the energy density of the universe [1, 2]. However, beyond its existence and abundance, little else is known about the properties of dark matter. A promising possible dark matter particle is the Weakly Interacting Dark Matter Particle (WIMP), but thus far attempts at its direct detection have left such a particle undiscovered [12–14]. Indirect detection of dark matter through the detection of its standard model annihilation products and detection of dark matter produced at particle accelerators have thus far similarly produced null results [15–20]. Boosted dark matter has been recently proposed in [21] and discussed as an alternative to the standard WIMP paradigm [22–26]. As opposed to WIMP models where the dominant dark matter particle couples directly to standard matter, in Boosted dark matter models the dominant dark matter particle instead couples to a lighter dark matter particle which in turn couples to standard matter. The lighter dark matter particle could be produced through annihilation, semi-annihilation, or

decay of the heavier dark matter particle, and if the mass difference between the dominant heavy dark matter and lighter sub-dominant dark matter is large enough these light dark matter particles will be relativistic. Reference [21] introduces an example model where the heavy dark matter particle annihilates into the lighter dark matter particle, which couples to standard model particles through the exchange of a dark photon. Such dark matter scenarios can be searched for by looking for the interaction of the boosted dark matter particle with standard matter. These interactions could be either with electrons, or nucleons. This technote reports a search for interactions of boosted dark matter particles with electrons in Super Kamiokande (SK), with the boosted dark matter originating either from the Galactic Center or the sun. In SK these interactions appear as elastically scattered electrons pointing back to either the Galactic Center or the sun. This search is performed on 2,628.1 days of SK-IV data, which corresponds to 161.9 kT-years.

3.2 Galactic Halo Models

Since the boosted dark matter being searched for comes from some interaction of the heavy non-interacting dark matter, it's directional distribution around the galactic center is dependent on the density profile of the dark matter halo around the galactic center. A general form for the density profile (assumed to be spherically symmetric) from cold dark matter simulations is [27]

$$\rho(r) = \frac{\rho_0}{(r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{(\beta - \gamma)/\alpha}} \quad (3.1)$$

Parameters of Equation ?? for the NFW [28], Moore [29], and Kravtsov [30] halo

models are shown in Table 3.1.

	α	β	γ	r_s	ρ_0	$\rho(R_{sc})$
Moore	1.5	3	1.5	28	0.0527	0.27
NFW	1	3	1	20	0.259	0.3
Kravtsov	2	3	0.4	10	0.703	0.37

Table 3.1: Halo parameters for NFW, Moore, and Kravtsov models. The scale radius r_s is in units of [kpc] while the two densities ρ_0 and $\rho(R_{sc})$ are in units of [GeV/cm³]. R_{sc} is the solar circle radius, 8.5 kpc [27].

The rate of boosted dark matter events coming from the annihilation or decay of dark matter from a particular direction in the sky is proportional to the so called “J-factor”, which is the line of sight integral of dark matter density for decay, or density squared for annihilation, and is a function of the angle between the event direction and the direction to the galactic center:

$$\mathcal{J}_{ann}(\theta_{GC}) = \frac{1}{R_N \rho_N^2} \int_0^{l_{\max}} \rho^2 \left(\sqrt{R_{sc}^2 - 2lR_{sc} \cos \theta_{GC} + l^2} \right) dl \quad (3.2)$$

$$\mathcal{J}_{decay}(\theta_{GC}) = \frac{1}{R_N \rho_N} \int_0^{l_{\max}} \rho \left(\sqrt{R_{sc}^2 - 2lR_{sc} \cos \theta_{GC} + l^2} \right) dl \quad (3.3)$$

where θ_{GC} is the angle to the Galactic Center and R_{sc} is the solar circle radius (8.5 kpc). The upper limit of integration l_{\max} is defined by the adopted halo size R_{MW} :

$$l_{\max} = \sqrt{R_{MW}^2 - R_{sc}^2 \sin^2 \theta_{GC}} + R_{sc} \cos \theta_{GC}. \quad (3.4)$$

While the halo size R_{MW} appears to be an additional important parameter, ρ drops off sharply past 20-30 kpc, as shown in Fig. 3.2(a), so that the calculation of \mathcal{J} is insensitive to the chosen value of R_{MW} as long as it is above this range. The prefactors $\frac{1}{R_N \rho_N^2}$ and $\frac{1}{R_N \rho_N}$ in Equations ?? and ?? are arbitrary scaling factors used to make \mathcal{J}

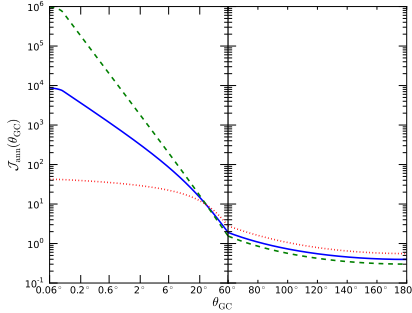


Figure 3.1: stuff

dimensionless. Figure 3.2 shows the dark matter halo density J factors for the Moore, NFW, and Kravstov models. The J factors in 3.2(b) and 3.2(c) are calculated with $R_{\text{MW}} = 40$ kpc and the standard scaling choice of $R_N = R_{sc} = 8.5$ kpc, $\rho_N = 0.3$ GeV/cm³. The J factor is taken to be flat at the innermost 0.1° to avoid divergence of \mathcal{J} due to cuspy profiles, which may be an artifact of simulation [27].

3.3 Event Selection

A cut based selection is used to select electron elastic-scatter-like events. The selection begins with the FCFV sample, which consists of all events which pass the Fully-Contained event reduction, plus four additional cuts: wall > 200 cm, which defines the fiducial volume, nhitac < 16, evis > 30 MeV, and if the event is 1-ring like, the final cut amome > 100 MeV. From this FCFV sample, 4 analysis cuts are applied:

1. 1-ring
2. e-like
3. 0 decay electrons
4. 0 tagged neutrons

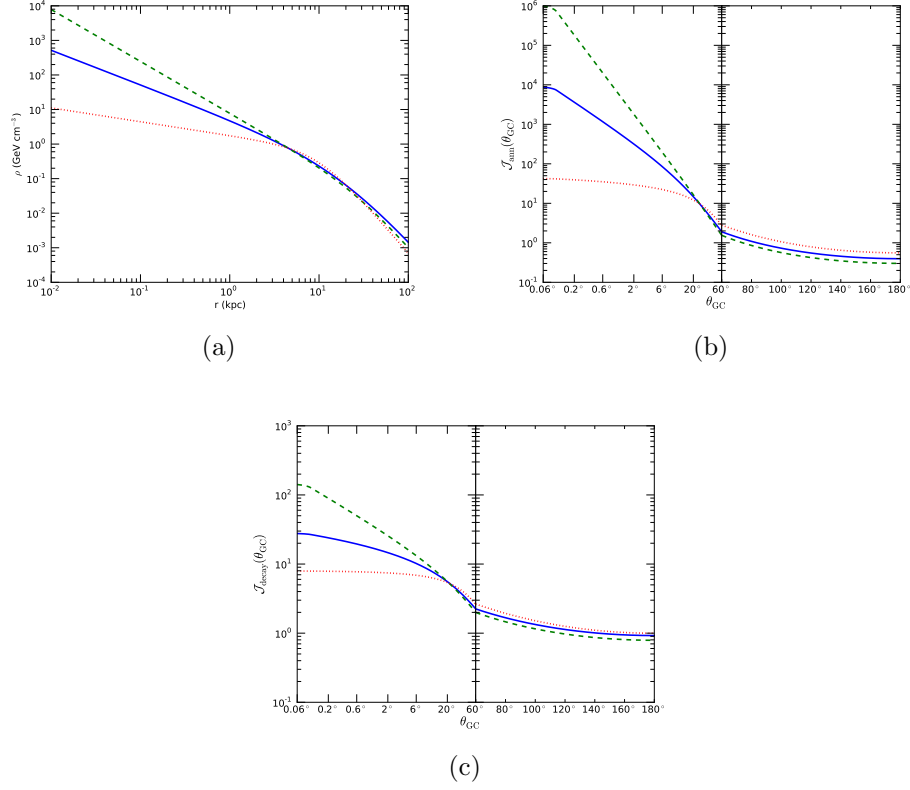


Figure 3.2: Moore (dashed green), NFW (solid blue) and Kravstov (dotted red) dark matter halo models. 3.2(a) shows the dark matter density as a function of distance from the galactic center. 3.2(b) and 3.2(c) show the J factors for the product of annihilating and decaying dark matter as a function of angle from the galactic center. Note that the x-axis is logarithmic on the left and linear on the right of 3.2(b) and 3.2(c).

The first two cuts search for the single relativistic scatter from an electron elastic scatter, while the final two cuts remove events with any indication of a nuclear interaction. The number of events found in all SK-IV after each cut is shown for three different energy ranges in 3.2 The neutron tagging cut plays an important role in background reduction, particularly in the high energy sample, as can be seen in ???. Its inclusion limits the current analysis to SK-IV only, since neutron tagging is not possible on SK-I-III data.

	Evis<1.33 GeV	1.33 GeV<Evis<20 GeV	20 GeV< Evis
FCFV	15206	4908	97
and single ring	11367	2868	53
and e-like	5655	1514	53
and 0 decay-e	5176	1134	17
and 0 tagged neutrons	4132	683	4

Table 3.2: Number of events in SK4 data passing each cut for 3 energy ranges.

3.4 Signal MC

In order to study the efficiency of the event selection and the optimal opening angle for a Galactic center search, a signal monte carlo of 200,000 electromagnetic shower events was produced, with electron energies ranging from 30 MeV to 1 TeV. The MC was split into 4 energy ranges: 30 MeV-1 GeV, 1 GeV-10 GeV, 10 GeV-100 GeV, and 100 GeV to 1 TeV. Fifty thousand events were produced in each energy range, with a flat linear energy spectrum in each range. Event positions within the detector were randomly selected uniformly within a cylinder 1 meter inside the wall of the inner detector, in order to account for migration of events in the fiducial volume, which is 2 meters inside the wall of the inner detector.

The direction of the electromagnetic showers was chosen assuming the NFW annihilation model. For each event, a random direction in equatorial coordinates was chosen so that the probability of an event's source being placed at an angle θ_{GC} from the galactic center is proportional to $\mathcal{J}_{ann}(\theta_{GC}) \sin \theta_{GC}$. The $\sin \theta_{GC}$ factor is a geometrical affect. Note that we are simulating a case where the scattered electrons direction is exactly parallel to the direction of the boosted dark matter. While there would be expected to be some model dependent smearing of the boosted dark matter direction to the electron direction, the scattering is expected to be strongly peaked in the forward direction [21]. Thus, since it both has a minimal effect and is model dependent, the effect of this scattering directional smearing is ignored in the pro-

duction of the signal MC. In order to transform from equatorial coordinates to the horizontal coordinates of the detector, a random time is chosen for each event. These times are randomly distributed at times during Super-K good data runs which are used in the analysis. The time chosen for an event is then used to transform from equatorial to horizontal coordinates. While the simulation is created assuming the NFW annihilation model, other models can be studied by reweighting each event by the ratio of the new models J-factor to the NFW annihilation J-factor:

$$w_{\text{Model X}} = \frac{\mathcal{J}_{\text{Model X}}(\theta_{\text{GC}})}{\mathcal{J}_{\text{NFW ann}}(\theta_{\text{GC}})} \quad (3.5)$$

The Model dependent smearing mentioned above can similarly be added back into the simulation by event reweighting.

The signal MC was run through the most of the full SK MC production process: Simulation (SKDETSIM), FC reduction (FCCOMB), reconstruction (APFIT), and ntuple creation (FILLNT,ROOT2ZBS). The only portions of the full SK MC production process excluded were PC and UPMU reduction (since this is an FC only analysis), fitQun reconstruction (since this analysis uses only APFIT variables), and neutron tagging. Although neutron tagging is an extremely important part of this analysis, there are no simulated neutrons in the signal MC, so we can safely assume that the background rate of false positive neutron tags in the signal MC is the same as the background rate found in the atmospheric MC (1.8%).

The angular and energy resolutions for events passing all selection and analysis cuts are shown in Figures 3.3 and 3.4. As can be seen in Figure 3.3, the angular resolution for these events is better than 3° for all energy ranges. The bias towards understating the energy in the high energy range (Figure 3.4(c)) and long tail on the negative side is due to the detector becoming saturated for very high energy events.

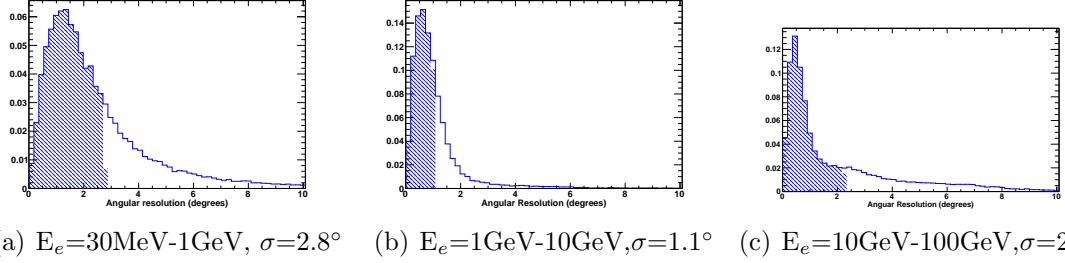


Figure 3.3: Angular resolution for events passing all selection and analysis cuts, from signal MC in 3 energy ranges.

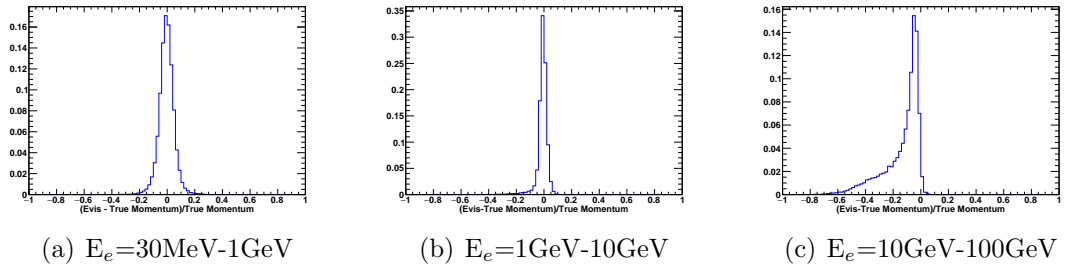


Figure 3.4: Energy resolution for events passing all selection and analysis cuts, from signal MC in 3 energy ranges.

The efficiency of the selection and analysis cuts is shown in Figure 3.5. Efficiency is defined as the number of events passing a set of cuts divided by the number of events simulated in the fiducial volume. This is not exactly equivalent to the fraction of events produced in the fiducial volume which pass all cuts, as some events will migrate into the fiducial volume to offset events migrating out of the fiducial volume. The total efficiency of the analysis turns on around 100 MeV and stays above 90% until around 5-10 GeV, and then remains above 80% until around 50 GeV. The main cause of the reduction of efficiency with energy is the loss of containment at high energies; many higher energy electromagnetic showers are able to penetrate from the FV into the OD, and so do not pass fully-contained cuts.

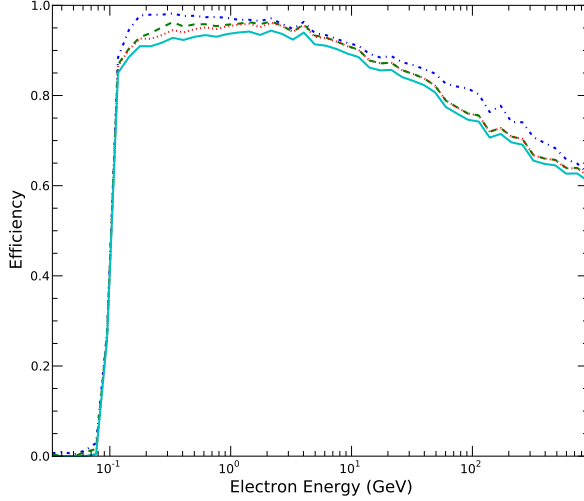


Figure 3.5: Efficiency of the selection and analysis cuts as a function of energy. Beginning with the FCFV reduction (dashed-dotted blue), the addition of the 1-ring (dashed green), e-like (dotted red) and finally 0 decay electrons and 0 tagged neutrons cuts to arrive at the final efficiency (solid cyan) are shown. Note that the efficiency of the 0 decay electrons cut is $> 99.99\%$, so that the drop from the dotted red line to solid cyan line is due solely to the background rate of the neutron tagging algorithm.

3.5 Ring Counting

The ring counting algorithms in APFIT have never been tuned for high energy events. As it turns out, APFIT finds phantom rings in many high energy electromagnetic showers, as in Figure 3.6. Because of this, the efficiency of the 1-ring cut for this analysis drops off very sharply around 10 GeV if no adjustment is made, as shown in Figure 3.7.

These phantom rings are caused by fluctuations in the light patterns of high energy events. Because there is a large amount of light in a high energy event, these statistical fluctuations can trick APFIT into thinking it sees a low energy ring in addition. To fix this pathology, a test variable is constructed to merge rings which

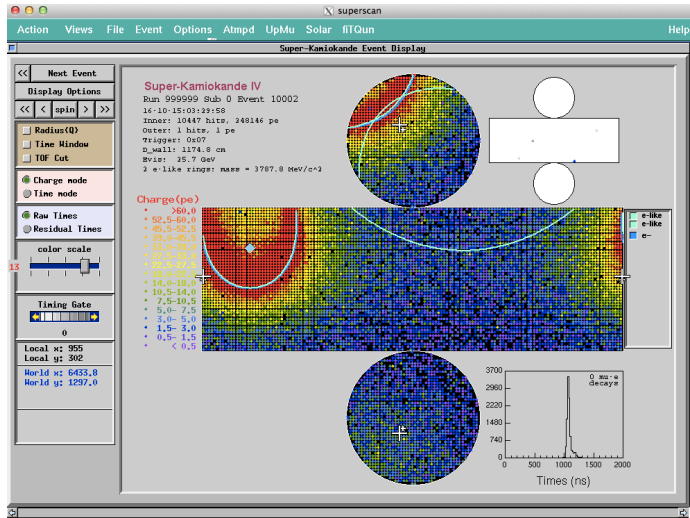


Figure 3.6: Example of a phantom ring found by APFIT. This is a single electron at 28 GeV. APFIT correctly finds the ring corresponding to the electron, but also finds an additional phantom ring

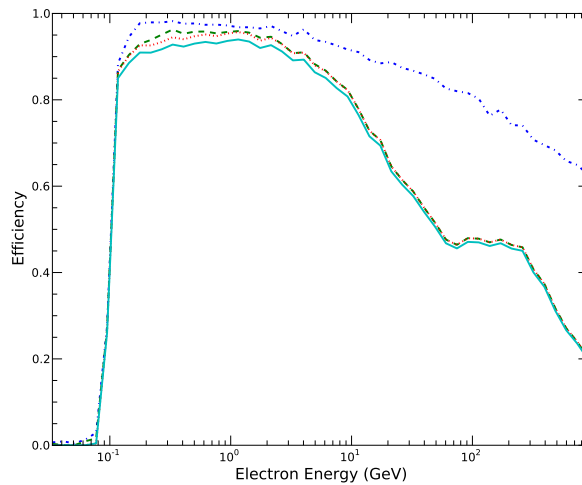


Figure 3.7: Efficiency of the selection and analysis cuts as a function of energy, with no ring counting adjustment. Color scheme is the same as in Figure 3.5. Note the sharp drop in the efficiency of the 1-ring cut (dashed green).

could reasonably be caused by statistical fluctuations:

$$\alpha_{i_{\text{ring}}}^2 = \frac{1}{N_{\text{PMT}, \theta < 70^\circ}} \sum_{j_{\text{PMT}, \theta < 70^\circ}} \frac{Q\text{Dev}_{i_{\text{ring}}, j_{\text{PMT}}}^2}{Q\text{Dev}_{i_{\text{MER}}, j_{\text{PMT}}}} \quad (3.6)$$

where $N_{\text{PMT}, \theta < 70^\circ}$ is the number of PMT's within 70° of the direction of the ring, i_{MER} is the index of the most energetic ring, and $Q\text{Dev}_{i,j}$ is the devided charge of the j^{th} PMT assigned to the i^{th} ring, defined as:

$$Q\text{Dev}_{i,j} = Q_j^{\text{measured}} \frac{Q_{i,j}^{\text{expected}}}{\sum_k Q_{k,j}^{\text{expected}}} \quad (3.7)$$

where $Q_{i,j}^{\text{expected}}$ is the charge expected in the j^{th} PMT due to the i^{th} ring and Q_j^{measured} is the charge measured in the j^{th} PMT. $Q\text{Dev}_{i,j}$ is stored in the common block array APPEDEV in APFIT. In order to fill APPEDEV with usable values, `springsep(2,1,1,3)` is run. For rings which are not the most energetic ring, α is calculated, and the ring is merged into the most energetic ring if $\alpha < 0.6$. Figure 3.8 shows the distribution of values of α for real and fake rings in the signal electromagnetic shower and background atmospheric neutrino MC. Since, the 1-ring cut efficiency is only problematic at high energies, this merging technique is only applied to events with $E_{\text{vis}} > 1.33$ GeV. With merging, the efficiency improves from that seen in Figure 3.7 to that seen in Figure 3.5, with minimal increase of the atmospheric background.

3.6 Analysis

The analysis technique is very simple; Count the number of events in a cone drawn around the potential source, and determine if this number is consistent with the expected background of atmospheric neutrinos. In order to choose the optimal opening

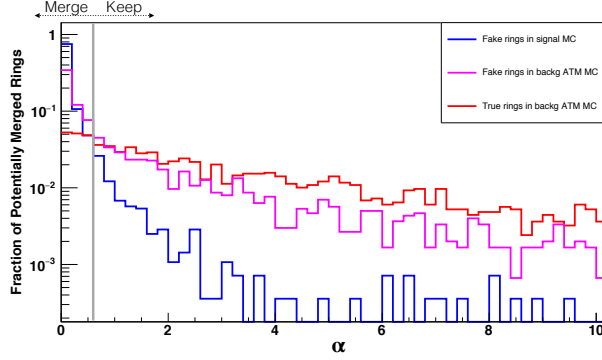


Figure 3.8: Test variable for merging rings in high energy events. If $\alpha > 0.6$, the ring is merged into the most energetic ring.

angle for a galactic center search, a figure of merit is defined as $\text{Efficiency}/\sqrt{\text{Bckg}}$ for different cone half opening angles, using the signal MC described in Section 3.4 to compute the Efficiency for each cone and the official SK atmospheric MC for the number of events expected in the cone. These figures of merit for cone half opening angles up to 40° are shown in Figure 3.9. In these figures of merit we care only about the shape not the magnitudes of the $\text{Efficiency}/\sqrt{\text{Bckg}}$, so the values for different models have been scaled by different amounts so that they can be seen together on the same plot. As can be seen, the optimal angle ranges from $< 5^\circ$ for NFW dark matter annihilation to $> 40^\circ$ for Kravtsov dark matter decay. Because of this, the analysis is performed with 8 different Galactic Center cone angles, ranging from 5° to 40° in steps of 5° . For the solar search, the search is much more localized directionally, with the sun having an angular diameter of just 0.5° . Therefore, a single cone with half opening angle of 5° is used for the solar search.

In order to quantify the agreement of the observed data with the background only or some level of excess signal hypothesis, a Poisson χ^2 statistic is used which incorporates the systematic uncertainty of the background estimate using the pull

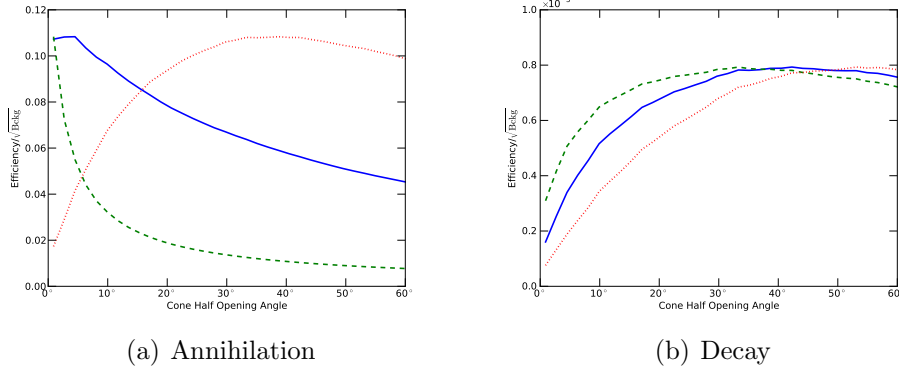


Figure 3.9: Cone opening angle optimization for boosted dark matter from annihilation and decay. In both 3.9(a) and 3.9(b) the solid blue is the NFW halo model, dotted red is the Kravtsov halo model, and dashed green is the Moore halo model. Note since the scaling is arbitrary, the efficiencies have been scaled by different amounts for each model so that they can all be seen on the same plot.

method [31, 32]:

$$\chi^2(s) = \min_{\epsilon} \left[2 \left(E - \mathcal{O} + \mathcal{O} \ln \frac{\mathcal{O}}{E} \right) + \epsilon^2 \right] \quad (3.8)$$

where,

$$E = b(1 + \epsilon\sigma) + s \quad (3.9)$$

and b is the estimated background with systematic uncertainty ϵ , s is the signal excess being tested, and \mathcal{O} is the observed number of events. The test statistic $\Delta\chi^2$ is calculated by subtracting from χ^2 for the particular value of s the minimum χ^2 for any value of s . Note that this χ_{\min}^2 is easily computed as:

$$\chi_{\min}^2 = \begin{cases} 0, & \text{if } b \leq \mathcal{O} \\ \chi^2(0), & \text{if } b > \mathcal{O} \end{cases} \quad (3.10)$$

For each tested value of s , a large number of toy MC are produced. If the fraction of toy MC produced with $\Delta\chi^2(s)$ less than the value found for the data is greater than

or equal to α , then s is excluded at α confidence [33].

The minimization of χ^2 over ϵ is done by setting

$$\frac{\partial \chi^2}{\partial \epsilon} = 2(b\sigma - \frac{\mathcal{O}b\sigma}{b(1 + \sigma\epsilon) + s}) + 2\epsilon = 0. \quad (3.11)$$

Equation ?? leads to a simple quadratic equation with solutions

$$\epsilon = \frac{-(b\sigma^2 + 1 + s/b) \pm \sqrt{(b\sigma^2 + 1 + s/b)^2 - 4\sigma(b\sigma + \sigma s - \mathcal{O}\sigma)}}{2\sigma}. \quad (3.12)$$

Both solutions to Equation ?? are tested, and the smaller of the two resulting χ^2 values is taken as the correct χ^2 . Note that if $\epsilon < -1/\sigma$, which would imply pulling the background to a negative value, then ϵ is set to $-1/\sigma$ so that the background is pulled to 0. Generally this would only happen for Data and MC which agree very poorly with a large systematic uncertainty, however it must be accounted for since it could occur a small number of times over many toy MC samples.

3.6.1 Trials Factors

The correlations between the 8 galactic center cones (the smaller cones are subsets of the larger cones) leads to complicated trials factors when trying to understand the significance of any excess. In order to understand the trials factors, 250,000 toy mc ensembles were created for both low and medium energy samples. For each energy range, 8 bins in $\cos \theta_{GC}$ of width 5° are shifted by a single shared systematic error for that energy range, chosen from a random Gaussian distribution with width given by the systematic uncertainties computed in Section 3.7. From the expected background, the number of toy mc events in each bin is then chosen as a Poisson random variable. The number of events in each of the 8 cones around the galactic

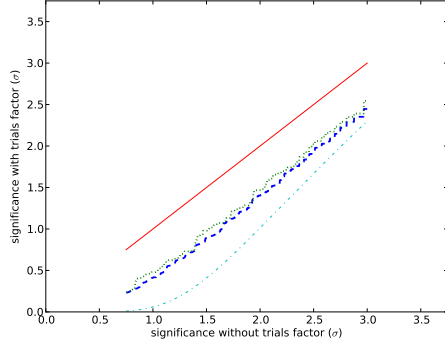


Figure 3.10: Trials factor effect. The dashed blue (dotted green) line converts the significance of an excess without the trials factor included into the significance with the trials factor included for the low (medium) energy sample, based on Toy MC. As reference, the solid red line shows $y=x$, the conversion for perfectly correlated measurements, and the dashed-dotted cyan line shows the conversion for 8 uncorrelated measurements. Note that the effect for the galactic center cones falls between the perfectly correlated and perfectly uncorrelated effects, as expected.

center is then calculated for the toy mc ensemble by adding up the events in the bins contained in each cone. The significance of any excess in each cone is computed as described above, and the largest excess out of the 8 cones is recorded. The probability that at least 1 of the 8 cones finds an excess of a particular significance α is then calculated, which allows for the adjustment of the significance to include the trials factor. The results of this study are shown in Figure 3.10. Note that the results fall between the expectations for 8 perfectly correlated or 8 completely uncorrelated measurements.

3.6.2 Limits on a simple Model

Reference [21] presents a baseline boosted dark matter model. In this model, a heavy dark matter particle A is the dominant dark matter of the universe. This particle A does not couple directly to standard matter, but instead annihilates into a

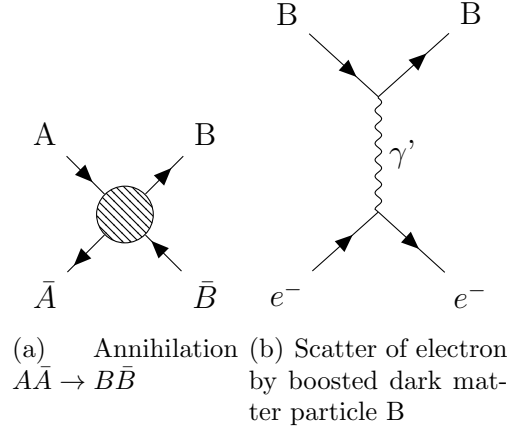


Figure 3.11: Feynman diagrams of boosted dark matter creation by annihilation of dominant heavy dark matter particles, and scatter of electron by boosted dark matter through exchange of a dark photon.

lighter dark matter particle B, which couples to standard matter through the exchange of a dark photon $m_{\gamma'}$, as in ???. The relic abundance of A is determined by an assisted freeze out scenario, and the thermal cross section is set to $\langle\sigma_{A\bar{A}\rightarrow B\bar{B}}\rangle = 5 \times 10^{-26} \text{ cm}^3/\text{s}$ in order to achieve the observed relic density $\Omega_A \approx 0.2$ [21]. The flux of boosted dark matter from the galactic center is

$$\frac{d\Phi}{d\Omega dE_B} = \frac{1}{2} \frac{r_{\text{sun}}}{4\pi} \left(\frac{\rho_{\text{local}}}{m_A} \right)^2 \mathcal{J} \langle\sigma_{A\bar{A}\rightarrow B\bar{B}}\rangle \delta(E_B - m_A). \quad (3.13)$$

Note that any adjustment to the thermal cross section simply results in a corresponding scaling of the limits on $\sigma_{Be^- \rightarrow Be^-}$ found in ???.

This model can be described by four free parameters: The mass of the dominant dark matter species m_A , the mass of the boosted dark matter m_B , the mass of the dark photon $m_{\gamma'}$, and the total cross section of the boosted dark matter on electrons σ_{tot} . Since the boosted dark matter is coming from annihilation of A, the energy of the boosted dark matter is equal to m_A . The maximum energy of the recoil electron

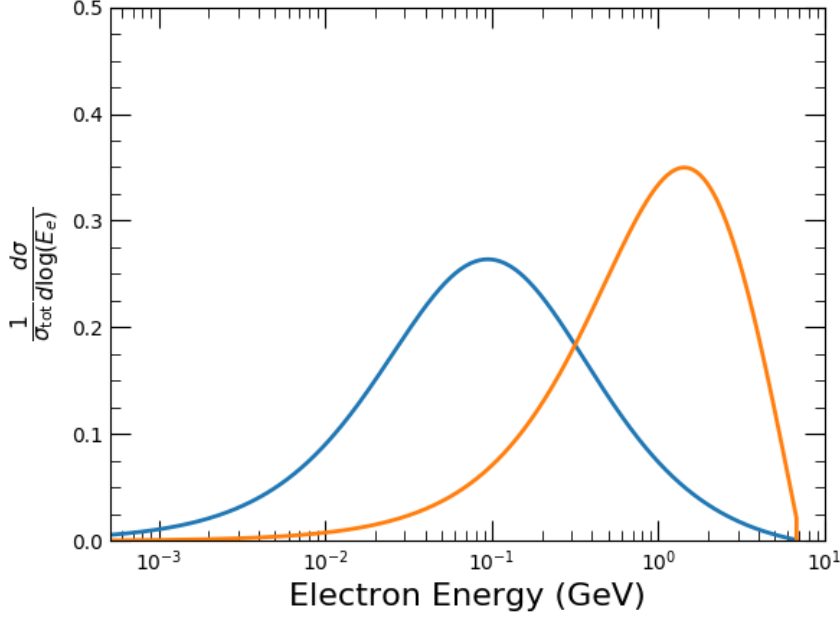


Figure 3.12: Recoil electron spectrum for simple model. The blue is for $m_{\gamma'} = 10$ MeV, while the red is for $m_{\gamma'} = 50$ MeV. Both use values of $m_A = 20$ GeV and $m_B = 200$ MeV.

scattered by the boosted dark matter is then set by kinematics:

$$E_e^{\max} = m_e \frac{(m_A + m_e)^2 + m_A^2 - m_B^2}{(m_A + m_e)^2 - m_A^2 + m_B^2}. \quad (3.14)$$

The shape of the recoil electron spectrum is largely set by the mass of the dark photon, with lower values of the dark photon mass leading to a spectrum more peaked towards smaller electron recoil energies, as shown in ???. The value σ_{tot} acts simply as a scaling factor.

A fit was performed over this four-dimensional parameter space. For each halo model, the number of expected signal events in each energy range at any particular point in parameter space is predicted by reweighting the signal MC discussed in ???. This reweighting accounts for the model dependent recoil electron energy spectrum,

a well as the model dependent smearing between the boosted dark matter direction and the recoil electron direction. A binned χ^2 statistic was then computed similar to the one described above:

$$\chi^2(m_A, m_B, m_{\gamma'}, \sigma_{\text{tot}}) = \sum_i^3 \min_{\epsilon_i} \left[2 \left(E_i - \mathcal{O}_i + \mathcal{O}_i \ln \frac{\mathcal{O}_i}{E_i} \right) + \epsilon_i^2 \right] \quad (3.15)$$

where

$$E_i = b_i(1 + \epsilon_i \sigma_i) + s_i. \quad (3.16)$$

Note that there are 3 uncorrelated systematic errors representing the systematic uncertainty on the background estimate for each energy bin and no systematic uncertainty included for the signal. A minimum χ^2 over the whole 4-D parameter space was found, and the $\Delta\chi^2$ test statistic was defined as

$$\Delta\chi^2(m_A, m_B, m_{\gamma'}, \sigma_{\text{tot}}) = \chi^2(m_A, m_B, m_{\gamma'}, \sigma_{\text{tot}}) - \chi_{\text{min}}^2. \quad (3.17)$$

Note that the χ_{min}^2 used here is different from the one found in ???. Additionally, each halo model was considered separately so that there was a different minimum used for the Moore, NFW, and Kravtsov models, respectively. For each halo model only a single search cone was considered, with the 5° cone chosen for the Moore halo, the 10° cone chosen for the NFW model, and the 40° cone chosen for the Kravtsov model. The choice of search cone for each model was made based on ???. Frequentist confidence regions could then be defined using toy MC. A point in parameter space is considered excluded at confidence level α if less than $(1-\alpha)$ of toy MC ensembles produced at the point resulted in a $\Delta\chi^2$ at the point greater than or equal to the value found from the data. In these toy MC samples both statistical fluctuations and systematic fluctuations of the background were taken into account.

In ??, confidence regions are presented for a baseline value of $m_{\gamma'} = 20$ MeV in the plane $\sigma_{\text{tot}}/m_A^2$ vs E_{max} where E_{max} has been defined in ??. The 4-D space $(m_A, m_B, m_{\gamma'}, \sigma_{\text{tot}})$ is thus profiled down to a 3-D space $(E_{\text{max}}, m_{\gamma'}, \sigma_{\text{tot}}/m_A^2)$. Since the boosted dark matter flux goes as $1/m_A^2$ (See ??), $\sigma_{\text{tot}}/m_A^2$ is proportional to the total signal event rate, and so all points in 4-D parameter space which are profiled onto the same point in 3-D parameter space will have very similar expected numbers of signal events.

The computation of confidence regions in the profiled space is performed as follows [32]. First, the set $U_{E_{\text{max}}, \sigma_{\text{tot}}/m_A^2}$ is defined as the set of all values of $(m_A, m_B, \sigma_{\text{tot}})$ which correspond to E_{max} and $\sigma_{\text{tot}}/m_A^2$. Then the profile $\hat{\chi}^2$ and profile $\Delta\hat{\chi}^2$ are defined as:

$$\hat{\chi}^2(E_{\text{max}}, m_{\gamma'}, \sigma_{\text{tot}}/m_A^2) = \min_{(m_A, m_B, \sigma_{\text{tot}}) \in U_{E_{\text{max}}, \sigma_{\text{tot}}/m_A^2}} \chi^2(m_A, m_B, m_{\gamma'}, \sigma_{\text{tot}}) \quad (3.18)$$

$$\Delta\hat{\chi}^2(E_{\text{max}}, m_{\gamma'}, \sigma_{\text{tot}}/m_A^2) = \hat{\chi}^2(E_{\text{max}}, m_{\gamma'}, \sigma_{\text{tot}}/m_A^2) - \chi_{\text{min}}^2. \quad (3.19)$$

A point $(E_{\text{max}}, m_{\gamma'}, \sigma_{\text{tot}}/m_A^2)$ is considered excluded at confidence level α if there is no point in $U_{E_{\text{max}}, \sigma_{\text{tot}}/m_A^2}$ with the given value of $m_{\gamma'}$ for which more than or equal to $(1-\alpha)$ of toy MC ensembles produced at the point result in a $\Delta\hat{\chi}^2$ greater than or equal to the one found in the data.

3.7 Background Estimation

In order to estimate the expected background in the Low Energy and Mid Energy samples, a data based technique was used which minimizes the effect of any systematic uncertainties on the background estimate. For a detector operated uniformly over a long period of time, different right ascensions at the same declination will all

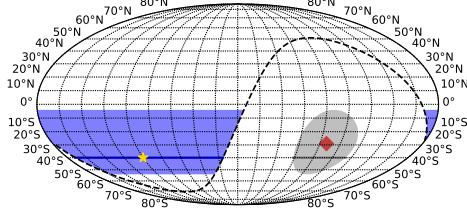


Figure 3.13: “Away From Source” (AFS) region shown in blue, and search cone shown in gray for a search cone of 25° half-opening angle around the galactic center. The red diamond is at the location of the galactic center. The dotted black line represents the 80° cone outside of which the AFS region is defined. For an event at the location of the yellow star, the weight for background estimation is the ratio of the gray arc to the blue arc.

correspond to the same set of directions in detector coordinates. This means that the expected background in a cone around the galactic center can be estimated by counting all events in the same declination band as the cone. In order to avoid contaminating the background estimate with a potential signal excess from the search cone, only events with $\theta_{GC} > 80^\circ$ are included in the background estimate. The background estimate “Away From Source” (AFS) region and search cone are shown for a 25° degree cone around the Galactic Center in ??.

Since at the same declination the AFS region and search cone span different amounts of right ascension, events found in the AFS region must be weighted according to their declination in order to find the correct background estimate for the search cone. The weight of each event in the AFS region is equal to the ratio of right ascensions spanned by the search cone to right ascensions spanned by the AFS region at that declination, which is visualized in ????. This weight can be written in terms of the variables in Figure 3.14(b) as $w = \frac{\alpha_{\text{cone}}}{\pi - \alpha_{\text{AFS}}}$. To compute α_{cone} and α_{AFS} , the points must be found where a cone of half opening angle θ centered on the direction

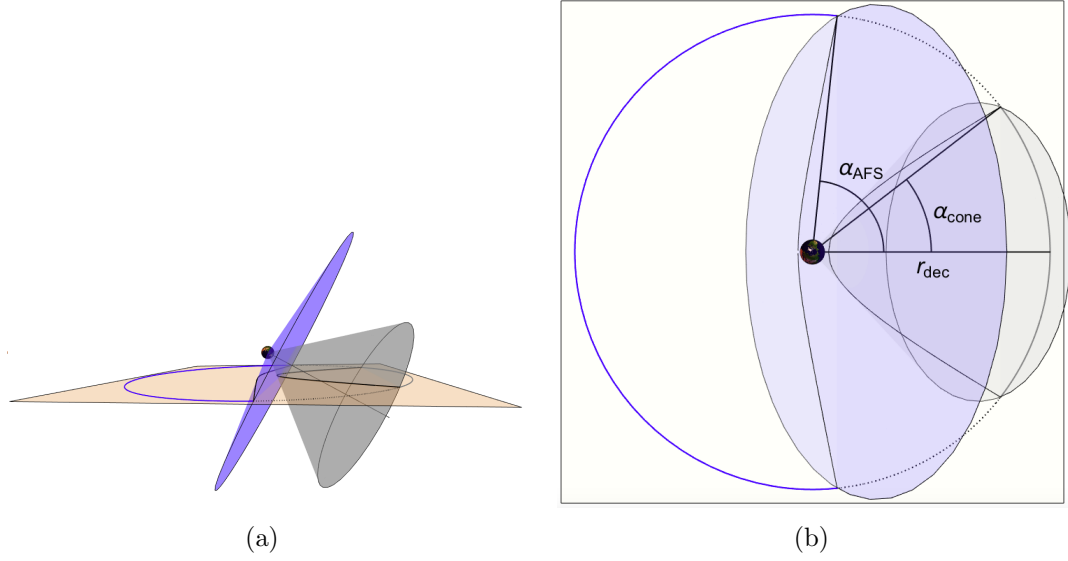


Figure 3.14: Visualization of the event weighting for background estimation. An event found in the AFS region at the declination represented by the plane is weighted by the ratio of the gray arc to the blue arc. Figure 3.14(b) shows Figure 3.14(a) as seen from directly above. The Mathematica code used to create these images can be found in ??

to the galactic center, a plane at declination ϕ_{dec} , and the unit sphere intersect. (The directions are without loss of generality assumed to be unit vectors, thus the inclusion of the unit sphere requirement). In ??, for the AFS region (GC search cone), these points are at the intersection of the blue (gray) cone, pink plane, and the circle drawn on the plane. The circle in ?? is the intersection of the plane and the unit sphere, and so $r_{\text{dec}} = \cos \phi_{\text{dec}}$. Defining the x-axis as pointing toward the right ascension of the galactic center at declination 0, the z-axis as extending from the poles of the earth so that $+\hat{z}$ correspondes with a declination of 90° and $-\hat{z}$ with a declination of -90° , and the y-axis accordingly to keep the coordinate system right handed, we can write the position of the two intersection points as:

$$\hat{v}_{\pm} = (x', \pm y', z') \quad (3.20)$$

and the Galactic Center direction as:

$$\hat{v}_{\text{GC}} = (\cos(-29^\circ), 0, \sin(-29^\circ)) \quad (3.21)$$

Since \hat{v}_\pm are on the plane at declination ϕ_{dec} we have:

$$z' = \sin \phi_{\text{dec}} \quad (3.22)$$

Additionally, since \hat{v}_\pm are on the cone of half opening angle θ around the Galactic Center we have

$$\frac{|\hat{v}_\pm - (\hat{v}_\pm \cdot \hat{v}_{\text{GC}})\hat{v}_{\text{GC}}|}{|(\hat{v}_\pm \cdot \hat{v}_{\text{GC}})\hat{v}_{\text{GC}}|} = \tan \theta \quad (3.23)$$

$$\hat{v}_\pm \cdot \hat{v}_{\text{GC}} > 0 \quad (3.24)$$

Solving Equation 3.23 under the condition of Equation 3.24, we have:

$$\frac{\sqrt{(\hat{v}_\pm - (\hat{v}_\pm \cdot \hat{v}_{\text{GC}})\hat{v}_{\text{GC}}) \cdot (\hat{v}_\pm - (\hat{v}_\pm \cdot \hat{v}_{\text{GC}})\hat{v}_{\text{GC}})}}{\sqrt{((\hat{v}_\pm \cdot \hat{v}_{\text{GC}})\hat{v}_{\text{GC}}) \cdot ((\hat{v}_\pm \cdot \hat{v}_{\text{GC}})\hat{v}_{\text{GC}})}} = \tan \theta \quad (3.25)$$

$$\frac{\sqrt{\hat{v}_\pm \cdot \hat{v}_\pm + (\hat{v}_{\text{GC}} \cdot \hat{v}_{\text{GC}} - 2)(\hat{v}_\pm \cdot \hat{v}_{\text{GC}})^2}}{\sqrt{(\hat{v}_\pm \cdot \hat{v}_{\text{GC}})^2 \hat{v}_{\text{GC}} \cdot \hat{v}_{\text{GC}}}} = \tan \theta \quad (3.26)$$

$$\frac{\sqrt{1 - (\hat{v}_\pm \cdot \hat{v}_{\text{GC}})^2}}{\hat{v}_\pm \cdot \hat{v}_{\text{GC}}} = \tan \theta \quad (3.27)$$

$$1 - (\hat{v}_\pm \cdot \hat{v}_{\text{GC}})^2 = \tan^2 \theta (\hat{v}_\pm \cdot \hat{v}_{\text{GC}})^2 \quad (3.28)$$

$$\hat{v}_\pm \cdot \hat{v}_{\text{GC}} = \sqrt{\frac{1}{1 + \tan^2 \theta}} \quad (3.29)$$

$$x' \cos(-29^\circ) + \sin \phi_{\text{dec}} \sin(-29^\circ) = \sqrt{\frac{1}{1 + \tan^2 \theta}} \quad (3.30)$$

$$x' = \frac{-\sin \phi_{\text{dec}} \sin(-29^\circ) + \sqrt{\frac{1}{1 + \tan^2 \theta}}}{\cos(-29^\circ)} \quad (3.31)$$

where we have used the fact that $(\hat{v}_{\text{GC}} \cdot \hat{v}_{\text{GC}}) = (\hat{v}_{\pm} \cdot \hat{v}_{\pm}) = 1$. The angle α is then found as

$$\cos \alpha = \frac{x'}{r_{\text{dec}}} = \frac{-\sin \phi_{\text{dec}} \sin(-29^\circ) + \sqrt{\frac{1}{1+\tan^2 \theta}}}{\cos(-29^\circ) \cos \phi_{\text{dec}}} \quad (3.32)$$

The weight for an event in the AFS region at declination ϕ_{dec} can thus be found as

$$w(\phi_{\text{dec}}) = \frac{\alpha_{\text{cone}}}{\pi - \alpha_{\text{AFS}}} \quad (3.33)$$

$$\cos \alpha_{\text{cone}} = \frac{-\sin \phi_{\text{dec}} \sin(-29^\circ) + \sqrt{\frac{1}{1+\tan^2 \theta_{\text{cone}}}}}{\cos(-29^\circ) \cos \phi_{\text{dec}}} \quad (3.34)$$

$$\cos \alpha_{\text{AFS}} = \frac{-\sin \phi_{\text{dec}} \sin(-29^\circ) + \sqrt{\frac{1}{1+\tan^2 \theta_{\text{AFS}}}}}{\cos(-29^\circ) \cos \phi_{\text{dec}}} \quad (3.35)$$

The background estimate and uncertainty on the estimate are then

$$B_{\text{est}} = \sum_i w(\phi_{\text{dec},i}) \quad (3.36)$$

$$\sigma B_{\text{est}} = \sqrt{\sum_i w^2(\phi_{\text{dec},i})}. \quad (3.37)$$

A similar technique could be applied to the search around the sun, however the declination of the sun changes with time, and so the math becomes more complicated. Instead, a slightly different approach was taken. The search cone for the solar search is a 5° cone around the sun, and everything outside of this cone is taken as the AFS region. For an event in the AFS region, the correct weight to use for background estimation is then the ratio of time that the horizontal coordinate direction of the event is within the 5° cone around the sun to the time it is outside the cone. These weights are calculated as follows. Direction in horizontal coordinates are divided into a grid of 1000 bins in azimuth by 600 bins in cosine zenith. The weight for events in each bin is then computed by stepping through a year in steps of 1 second and counting up the amount of time each bin is within 5° of the sun. The fraction of time

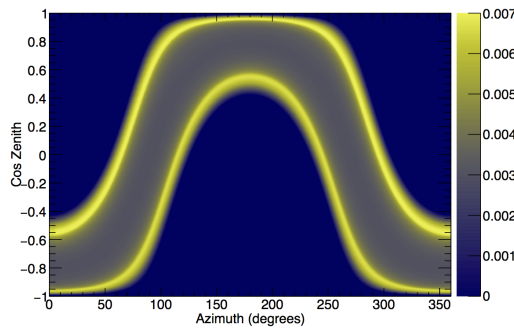


Figure 3.15: The fraction of time spent with 5° of the sun, as a function of cosine zenith and azimuth.

spent within 5° of the sun as a function of cosine zenith and azimuth is shown in ??

In both the application to the galactic center and to the sun it is implicitly assumed that the detector has been run uniformly in time. This assumption could introduce error in the background estimates if instead the detector has run much more at certain times of the day or year than at others. Therefore 500 years of atmospheric neutrino MC was used to test the validity of the AFS method. The time of each MC event was chosen from the times of real data events. The AFS method was then applied to the MC. The background estimate made by the AFS method applied to the MC was compared to the number of events found in the search cone in the MC. If these numbers were found to be very different, it would indicate non-uniformity of the time when the detector has been run is leading to a bias in the AFS background estimate. As can be seen in ??, the difference is both statistically consistent with 0, and much smaller than the uncertainty in the AFS background estimates when applied to real data. Therefore, any potential bias in the AFS method introduced by non-uniform running of the detector can be ignored.

For the High Energy event sample, there would be too few events in the AFS region for the above technique to work well. Instead, the MC estimate for the expected number of atmospheric neutrino events in the search cone was taken as the background

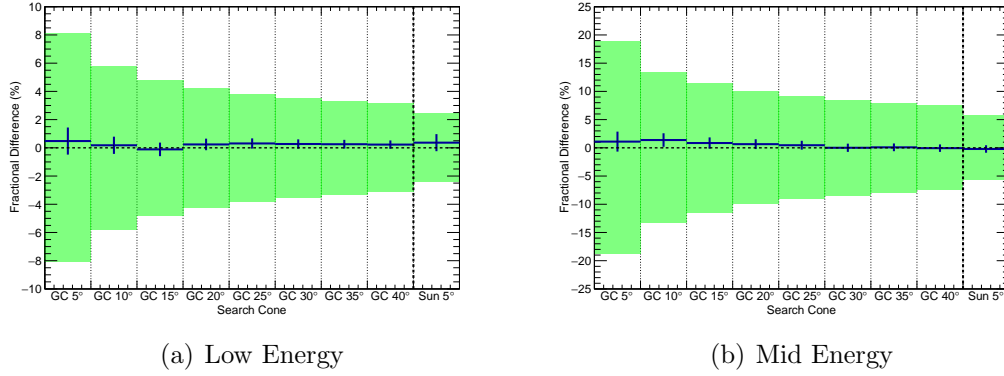


Figure 3.16: Verification of AFS method. The blue histogram shows the fractional difference between the AFS background estimate when applied to MC and the actual number of events in the search cone in MC. The green shows the AFS background estimate uncertainty when applied to data.

estimate. The MC was livetime normalized and oscillated according to 3-flavor oscillations with oscillation parameters $\Delta M_{23}^2 = 2.5 \times 10^{-3} \text{ GeV}^2$, $\Delta M_{12}^2 = 7.65 \times 10^{-5} \text{ GeV}^2$, $\sin^2 \theta_{23} = 0.5875$, $\sin^2 \theta_{13} = 0.0219$, $\sin^2 \theta_{12} = 0.309$, $\delta_{cp} = 4.19$. The systematic uncertainty on this estimate is found by summing in quadrature the effect of and 1- σ shift of all 75 official SK-IV systematics. The uncertainty of oscillation parameters were also included as systematics. Of these only 18 cause more than a 1% shift in our background estimate at 1- σ . The uncertainties which cause more than a 5% shift at 1- σ are shown in Table 3.3. As seen in Table 3.3, the systematic uncertainty of the Higher Energy sample is dominated by the systematic uncertainty of the neutron tagging cut. This uncertainty accounts for the uncertainty in the efficiency of our neutron tagging algorithm, as well as the uncertainty in the production and transport of neutrons in the detector. It was estimated by a Data-MC comparison of the fraction of events passing the first three selection cuts which also had zero tagged neutrons as a function of visible energy. Above about 10 GeV of visible energy, there are very low statistics for the data, and so a Data-MC comparison is difficult to make.

Therefor, above 3 GeV both the data and MC were fitted to logarithmic functions $A + B \log \frac{E_{\text{vis}}}{\text{GeV}}$, as shown in Figure 3.17(a). The systematic uncertainty was then taken as the difference between the Data fit and the MC fit in the region above 7.6 GeV of visible energy. The total uncertainty for the High Energy event sample is 29.8%.

The background estimate results for the 8 cone sizes around the galactic center and the 5° cone around the Sun are shown in ???. The background estimates for the low and mid energy regions are compared to MC background estimates in ??. The systematic uncertainties on the MC background estimates for the low and mid energy samples were computed in the same way as for the high energy sample, resulting in uncertainties of 18.4% and 17.7% respectively. As can be seen in ??, the two background estimation techniques agree with one another to within systematic uncertainties, and the systematic uncertainties on the AFS technique are much smaller than those on the MC based estimate.

Systematic	1- σ shift
Neutron Tagging Cut	23%
Normalization (Flux, Data reduction, FV)	11%
Energy Calibration	6%
Garczyk and Socyzk 1π axial coupling	5%

Table 3.3: Largest systematic uncertainty contributions for High Energy sample.

3.8 Results

The galactic center and solar searches were performed on 2628.1 days of SK-IV data, which corresponds to 161.9 kton-years. The results of the searches are summarized in ??????. There are no indications of excesses from the galactic center or the sun. The results are converted to event rate limits and presented in ??. The locations of all events in the sky are shown in ?????. As can be seen there is no visual

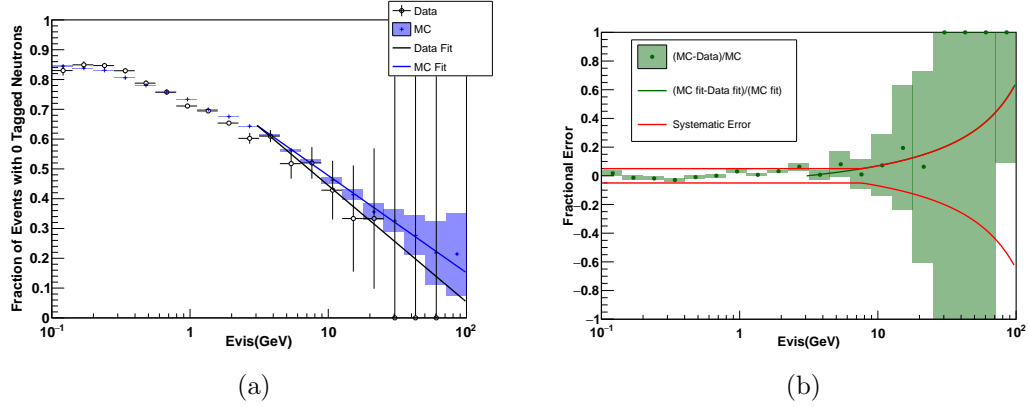


Figure 3.17: Neutron tagging cut systematic error estimation. 3.17(a) shows the fractional number of events passing the neutron tagging cut after passing all previous cuts for both Data and MC, along with logarithmic fits. The filled rectangles around the MC show statistical uncertainty in the MC. 3.17(b) shows the resulting systematic uncertainty, set to 5% below 7.6 GeV, and the difference in the two fits from 3.17(a) above 7.6 GeV.

clustering of events around the galactic center.

Limits were also calculated on a simple model, as described in ???. Since the point with σ_{tot} is allowed at 90% CI, the 90% CI contours can be interpreted as 90% CI upper limits. These upper limits are presented for $m_{\gamma'} = 20\text{MeV}$ in ???. When $E_{\text{max}} > 10\text{ GeV}$, the effect of the detector energy threshold is negligible, and the 90% CI upper limit on $\sigma_{\text{tot}}/m_A^2$ remains constant as E_{max} increases. In this region the limit for $m_{\gamma'} = 20\text{MeV}$ with the NFW halo model is found to be $1.5 \times 10^{-37}(\text{cm}^2/\text{GeV}^2)$.

3.9 Conclusion

A search for an excess of electron-elastic-scatter-like events from the galactic center or the sun was performed over 2628.1 days of SK-IV data, which corresponds to 161.9 kton-years. No excess above atmospheric neutrino background was observed around with the galactic center of the sun. Limits were computed for a simple boosted

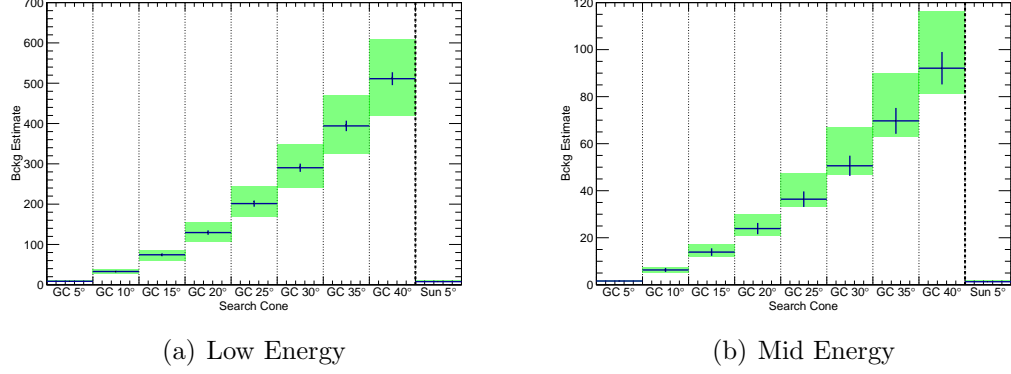


Figure 3.18: Comparison of AFS background estimates to MC background estimates for Low Energy and Mid Energy samples. The two background estimation techniques agree to within systematic uncertainties, and the AFS technique has much smaller systematic uncertainties.

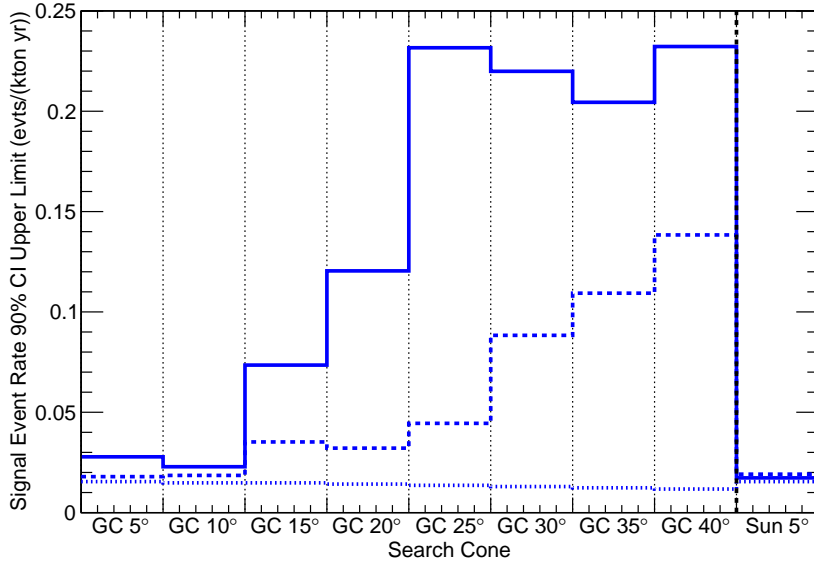


Figure 3.19: Signal event rate 90% C.I. upper limits for SubGeV (solid line), Mid Energy (dashed line), and High Energy (dotted line) samples.

	Low Energy	Mid Energy	High Energy
GC 5° cone	8.6 ± 0.7	1.6 ± 0.3	0.011 ± 0.003
GC 10° cone	32.9 ± 1.9	6.3 ± 0.84	0.041 ± 0.012
GC 15° cone	74.4 ± 3.6	13.9 ± 1.6	0.096 ± 0.029
GC 20° cone	129.9 ± 5.5	23.9 ± 2.4	0.17 ± 0.05
GC 25° cone	201.4 ± 7.7	36.4 ± 3.3	0.26 ± 0.08
GC 30° cone	290.3 ± 10.2	50.6 ± 4.3	0.37 ± 0.11
GC 35° cone	394.1 ± 13.0	69.7 ± 5.5	0.49 ± 0.15
GC 40° cone	511.2 ± 16.0	92.1 ± 6.9	0.63 ± 0.19
Sun 5° cone	7.74 ± 0.19	1.29 ± 0.08	0.011 ± 0.003

Table 3.4: Background estimates for the three energy ranges for 8 cone sizes around the galactic center and a 5° cone around the sun. Uncertainties on the background estimates are the systematic uncertainties as discussed in the text.

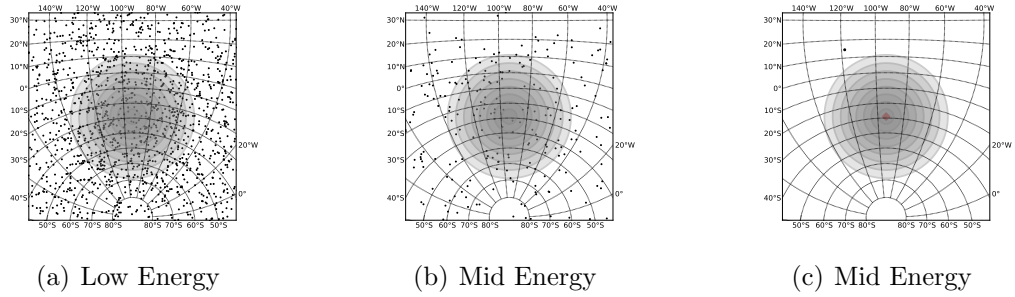


Figure 3.20: Location of all events passing analysis cuts near the galactic center. The 8 grey circles show the 8 cones around the galactic center used in the analysis.

dark matter model which would be expected to produce such events in SK, and in the region of $E_{\text{max}} > 10\text{GeV}$, the 90% CI upper limit on $\sigma_{\text{tot}}/m_A^2$ was found to be $1.5 \times 10^{-37} \text{ (cm}^2/\text{GeV}^2\text{)}$ for $m_{\gamma'} = 20 \text{ MeV}$ and the NFW galactic halo model.

	Expected Bckg	Data	Signal 90% C.I.
GC 5° cone	8.6 ± 0.7	7	0-4.5
GC 10° cone	32.9 ± 1.9	24	0-3.7
GC 15° cone	74.4 ± 3.6	70	0-11.9
GC 20° cone	129.5 ± 5.5	127	0-19.5
GC 25° cone	201.4 ± 7.7	211	0-37.5
GC 30° cone	290.3 ± 10.2	292	0-35.6
GC 35° cone	394.1 ± 13.0	387	0-33.1
GC 40° cone	511.2 ± 16.0	502	0-37.6
Sun 5° cone	7.74 ± 0.19	5	0-2.8

Table 3.5: Results for low energy events

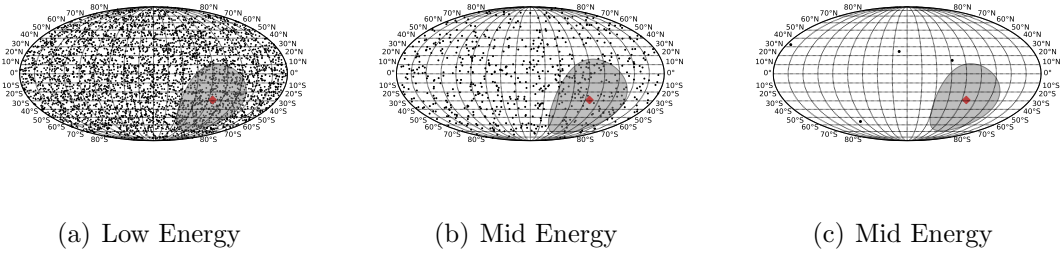


Figure 3.21: Location of all events passing analysis cuts. The grey shows a 40° cone around the galactic center, which is shown by the red diamond

	Expected Bckg	Data	Signal 90% C.I.
GC 5° cone	1.6 ± 0.3	1	0-2.9
GC 10° cone	6.3 ± 0.84	4	0-3.0
GC 15° cone	13.9 ± 1.6	12	0-5.7
GC 20° cone	23.9 ± 2.4	19	0-5.2
GC 25° cone	36.4 ± 3.3	31	0-7.2
GC 30° cone	50.6 ± 4.3	50	0-14.3
GC 35° cone	69.7 ± 5.5	70	0-17.7
GC 40° cone	92.1 ± 6.9	94	0-22.4
Sun 5° cone	1.29 ± 0.08	1	0-3.1

Table 3.6: Results for medium energy events

	Expected Bckg	Data	Signal 90% C.I.
GC 5° cone	0.011 ± 0.003	0	0-2.5
GC 10° cone	0.041 ± 0.012	0	0-2.4
GC 15° cone	0.096 ± 0.029	0	0-2.4
GC 20° cone	0.17 ± 0.05	0	0-2.3
GC 25° cone	0.26 ± 0.08	0	0-2.2
GC 30° cone	0.37 ± 0.11	0	0-2.1
GC 35° cone	0.49 ± 0.15	0	0-2.0
GC 40° cone	0.63 ± 0.19	0	0-1.9
Sun 5°	0.011 ± 0.003	0	0-2.5

Table 3.7: Results for high energy events

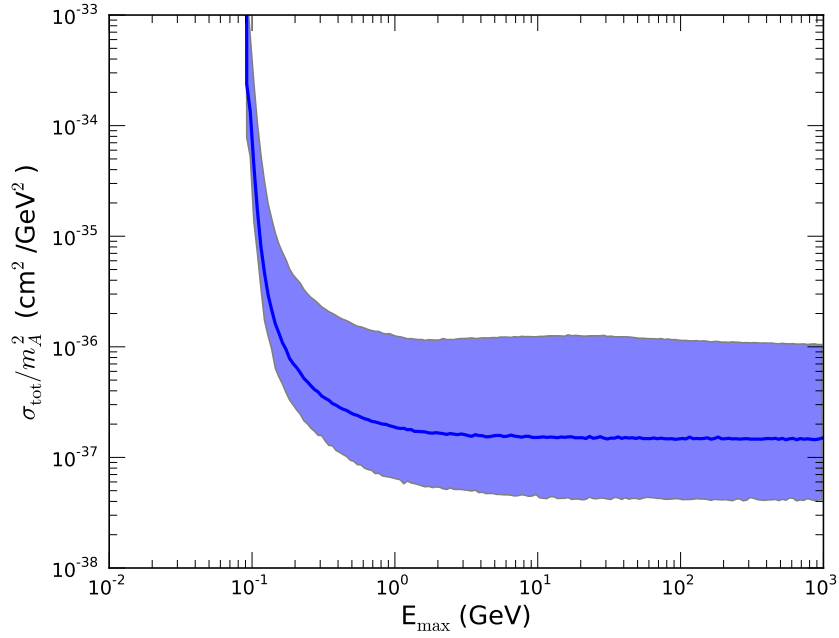


Figure 3.22: Limits on simple model, for $m_{\gamma'} = 20$ MeV. The dark blue line is for the NFW halo, and the upper and lower limits of the band are for the Kravtsov and Moore models, respectively.

Bibliography

- [1] P. A. R. Ade, *et al.* Astron. Astrophys. **594** A13 (2016)
- [2] G. Hinshaw, *et al.* Astrophys. J. Suppl. **208** 19 (2013)
- [3] L. M. Brown. Phys. Today **31N9** 23 (1978)
- [4] E. Fermi. Z. Phys. **88** 161 (1934)
- [5] F. Reines, C. L. Cowan. Phys. Rev. **92** 830 (1953)
- [6] C. L. Cowan, *et al.* Science **124** 103 (1956)
- [7] F. Reines, C. L. Cowan. Nature **178** 446 (1956)
- [8] F. Zwicky. Helv. Phys. Acta **6** 110 (1933). [Gen. Rel. Grav.41,207(2009)]
- [9] V. C. Rubin, N. Thonnard, W. K. J. Ford. The Astrophysical Journal **238** 471 (1980)
- [10] K. G. Begeman, A. H. Broeils, R. H. Sanders. Mon. Not. Roy. Astron. Soc. **249** 523 (1991)
- [11] G. R. Blumenthal, *et al.* Nature **311**, 5986 517 (1984)
- [12] L. Collaboration, *et al.* arXiv.org (2013)

- [13] The CDMS II Collaboration. *Science* **327**, 5973 1619 (2010)
- [14] E. Aprile, *et al.* *Physical Review Letters* **109**, 18 181301 (2012)
- [15] S. Desai, *et al.* *Phys. Rev.* **D70** 083523 (2004). [Erratum: *Phys. Rev.* **D70**, 109901(2004)]
- [16] M. Rameez, T. Montaruli. *PoS ICRC2015* 1209 (2016)
- [17] S. Adrian-Martinez, *et al.* *JCAP* **1311** 032 (2013)
- [18] V. Khachatryan, *et al.* *Eur. Phys. J.* **C75**, 5 235 (2015)
- [19] G. Aad, *et al.* *Eur. Phys. J.* **C75**, 7 299 (2015). [Erratum: *Eur. Phys. J.* **C75**, no.9, 408(2015)]
- [20] J. Goodman, *et al.* *Phys. Rev.* **D82** 116010 (2010)
- [21] K. Agashe, *et al.* *JCAP* **1410**, 10 062 (2014)
- [22] J. F. Cherry, M. T. Frandsen, I. M. Shoemaker. *Physical Review Letters* **114**, 23 231303 (2015)
- [23] A. Bhattacharya, R. Gandhi, A. Gupta. *JCAP* **1503**, 03 027 (2015)
- [24] J. Kopp, J. Liu, X.-P. Wang. *Journal of High Energy Physics* **2015**, 4 105 (2015)
- [25] K. Kong, G. Mohlabeng, J.-C. Park. *Physics Letters B* **743**, C 256 (2015)
- [26] J. Berger, Y. Cui, Y. Zhao. *Journal of Cosmology and Astroparticle Physics* **2014**, 10 062 (2014)
- [27] H. Yüksel, *et al.* *Physical Review D* **76**, 12 123506 (2007)

- [28] J. F. Navarro, C. S. Frenk, S. D. M. White. The Astrophysical Journal **462** 563 (1996)
- [29] B. Moore, *et al.* Monthly Notices of the Royal Astronomical Society **310**, 4 1147 (1999)
- [30] A. V. Kravtsov, *et al.* The Astrophysical Journal **502**, 1 48 (1998)
- [31] G. L. Fogli, *et al.* Physical Review D **66**, 5 053010 (2002)
- [32] C. Patrignani, *et al.* Chin. Phys. **C40**, 10 100001 (2016)
- [33] G. J. Feldman, R. D. Cousins. Physical Review D **57**, 7 3873 (1998)

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