

Resolving the Mass Hierarchy with Atmospheric Neutrinos using a Liquid Argon Detector

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Abstract

We explore the potential offered by large-mass Liquid Argon detectors for determination of the sign of Δm_{31}^2 , or the neutrino mass hierarchy, through interactions of atmospheric neutrinos. We give results for a 100 kT sized magnetized detector which provides separate sensitivity to ν_μ , $\bar{\nu}_\mu$ and, over a limited energy range, to ν_e , $\bar{\nu}_e$. We also discuss the sensitivity for the unmagnetized version of such a detector. After including the effect of smearing in neutrino energy and direction and incorporating the relevant statistical, theoretical and systematic errors, we perform a binned χ^2 analysis of simulated data. The χ^2 is marginalized over the presently allowed ranges of neutrino parameters and determined as a function of θ_{13} . We find that such a detector offers superior capabilities for hierarchy resolution, allowing a $> 4\sigma$ determination for a 100 kT detector over a 10 year running period for values of $\sin^2 2\theta_{13} \geq 0.05$. For an unmagnetized detector, a 2.5σ hierarchy sensitivity is possible for $\sin^2 2\theta_{13} = 0.04$.

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1 Introduction

Parameters related to neutrino masses and mixings play a fundamental role in efforts to construct a viable theory beyond the Standard Model. Over the last decade, our knowledge of these parameters has increased at an unprecedented pace, due to crucial results from solar, atmospheric, reactor and accelerator based neutrino oscillation experiments. (For a recent review, we refer the reader to [1] and references therein.)

Among the important but as yet unanswered questions, one of the foremost is the determination of $\text{sign}(\Delta m_{31}^2)$ or the hierarchy of neutrino masses¹, presently unconstrained by available data. If $\text{sign}(\Delta m_{31}^2) > 0$, then we have the mass pattern, $m_3 \gg m_2 \gg m_1$, which is similar to that of the charged leptons. This is called the normal hierarchy (NH). If $\text{sign}(\Delta m_{31}^2) < 0$, then the mass pattern is $m_2 \geq m_1 \gg m_3$. This is called the inverted hierarchy (IH). In recent papers, the prospects for progress towards a resolution of this question offered by atmospheric neutrinos have been explored [2–10]. With most of their flux below 10 GeV, these neutrinos traverse distances up to ~ 12000 km in the earth’s matter enroute to a detector. This exposes them to appreciable resonant matter effects which occur (primarily) for energies between 2–10 GeV and distances between 4000–12500 km inside the earth [5,11,12]. Until very long baseline experiments using β -beams or neutrino factories [13] are built, atmospheric neutrinos permit us to exploit these effects, albeit in a slower and less spectacular fashion which calls for a careful analysis of accumulated effects over many bins in energy and angle. Such an approach was recently pursued in [6,10] for megaton water Čerenkov detectors (*e.g.* HK [14,15], UNO [16] or MEMPHYS [17]) and magnetized iron detectors (*e.g.* INO [18]). The salient features emerging out of the above analyses are

- Both muon and electron events arising from atmospheric neutrinos have sensitivity to sign of Δm_{31}^2 for sufficiently large values of $\sin^2 2\theta_{13}$.
- One of the major factors responsible for a reduced sensitivity is the finite energy and angular smearing of a detector.
- The muon events are more sensitive to smearing than electron events.
- Magnetized iron calorimeter detectors have the advantage of having charge identification capability but they are sensitive only to muon events
- Water Čerenkov detectors have the advantage that they are sensitive to both muon and electron events. On the other hand they do not have charge sensitivity.

The above features indicate that a detector which is sensitive both to muon and electron events as well as their charges will be ideal for probing hierarchy of neutrino masses. An important class of future detectors using Liquid Argon as their active medium, may provide this kind of set up specially if there can be magnetized versions of these. In this paper we study the hierarchy sensitivity of Liquid Argon detectors for cases with and without charge sensitivity.

¹We use the convention $\Delta m_{ji}^2 \equiv m_j^2 - m_i^2$.

2 Basic Characteristics of Liquid Argon Detectors

Liquid Argon detectors are time projection chambers with fine-grained tracking and total absorption calorimetry. Ionization electrons resulting from the passage of an energetic particle through the medium are detected by drifting their paths over several meters to wire planes. The orientation of these planes is designed to reconstruct the time, length and position of each path by recording multiple snapshots of the electrons, from which a bubble-chamber like image is constructed. The viability of this technology for a small detector has been convincingly demonstrated by [19], and intensive efforts are underway for the upgraded development of large mass detectors [20–22] to fully exploit the promise of this technique.

Essentially, the technique allows us to detect charged particles with good resolution over the range of MeV to multi GeV. It uses well studied dE/dx measurements in the medium to separate electrons, muons, pions, kaons and protons from each other. It is also possible to separate the light from electrons vs that from neutral pions with high efficiency. Magnetization over a 100 kT volume has been deemed possible [23, 24]. As mentioned earlier, we present results for both the magnetized and unmagnetized case.

We assume the following energy resolutions over the ranges that will be relevant to our calculations [21]:

For the GeV electrons that we will be interested in,

$$\sigma_e/E_e = 3\%/\sqrt{E_e} \quad (1)$$

where E_e is the electron energy and σ_e is the energy resolution of the electron. All values of energy are expressed in GeV. For the muon neutrino we take the energy resolution in terms of the muon energy to be

$$\sigma_\mu/E_\mu = 15\% \quad (2)$$

Additionally, for hadronic showers, which account for a significant fraction of the uncertainty in the determination of the primary neutrino energy, we assume

$$\sigma_{had}/E_{had} = 30\%/\sqrt{E_{had}} \quad (3)$$

where E_{had} is the hadron energy and σ_{had} is the energy resolution of the hadron.

Our procedure for inferring the neutrino energy from the measured charged lepton and hadronic energies incorporates a knowledge of the average rapidity for charged current cross-sections in this energy region. The energy resolution in terms of the neutrino energy is related to the leptonic and hadronic energy resolutions as follows:

$$\sigma_\nu/E_\nu = \sqrt{(1-y)^2(\sigma_{lep}/E_{lep})^2 + y^2(\sigma_{had}/E_{had})^2} \quad (4)$$

The rapidity is defined as $y = E_{had}/E_\nu$, where $E_\nu = E_{lep} + E_{had}$ is the energy of the neutrino. Therefore, the energy resolution in terms of the neutrino energy is given by

$$\sigma_{\nu_e}/E_{\nu_e} = \sqrt{(1-y)(0.03)^2/E_{\nu_e} + y(0.3)^2/E_{\nu_e}} \quad (5)$$

and

$$\sigma_{\nu_\mu}/E_{\nu_\mu} = \sqrt{(1-y)^2(0.15)^2 + y(0.3)^2}/E_{\nu_\mu} \quad (6)$$

for electron and muon neutrinos respectively.

In our computation, we take the average rapidity in the energy region of our interest (i.e. in the GeV range) to be 0.45 for neutrinos and 0.3 for antineutrinos [25]. The angular resolution of the detector is taken to be $\sigma_\theta = 10^\circ$. The energy threshold and ranges in which charge identification is feasible are $E_{threshold} = 800$ MeV for charge identification of muons with high efficiency and $E_{electron} = 1 - 5$ GeV for charge identification of electrons with high efficiency. Charged lepton detection and separation (e vs μ) without charge identification is possible for $E_{lepton} > \text{few MeV}$. Also, for electron events, it is expected to have a 20% probability of $\sim 100\%$ charge identification in the energy range 1 - 5 GeV.

The next section provides a brief description of our calculational and numerical procedure, prior to our discussion of the results.

3 Calculational and Numerical Procedure

We follow the procedure described in [10], and refer the reader to the description provided there for any details that may be omitted here.

Our calculation of the atmospheric electron and muon event rates uses the neutrino oscillation probabilities corresponding to the disappearance channels $P_{\mu\mu}$ and P_{ee} and appearance channels $P_{\mu e}$ and $P_{e\mu}$ for both neutrinos and antineutrinos². We have modeled the density profile of the earth by the Preliminary Reference Earth Model (PREM) [26] in order to numerically solve the full three flavour neutrino propagation equation through the earth. The total CC cross section used here is the sum of quasi-elastic, single meson production and deep inelastic cross sections [27–30]. For the incident atmospheric neutrino fluxes we use the tables from [31].

For our analysis in Liquid Argon detectors, we consider an exposure of 1 Mt yr (100 kT \times 10 years). We look at the neutrino energy range of 1 - 10 GeV and the cosine of the zenith angle (θ) range of -1.0 to -0.1. These ranges are divided into 9 bins in energy and 18 bins in zenith angle. The μ^- event rate in a specific energy bin with width dE and the solid angle bin with width $d\Omega$ is expressed as :

$$\frac{d^2N_\mu}{d\Omega dE} = \frac{1}{2\pi} \left[\left(\frac{d^2\Phi_\mu}{d \cos \theta dE} \right) P_{\mu\mu} + \left(\frac{d^2\Phi_e}{d \cos \theta dE} \right) P_{e\mu} \right] \sigma_{CC} D_{\text{eff}} \quad (7)$$

Here $\Phi_{\mu,e}$ are the atmospheric fluxes (ν_μ and ν_e), σ_{CC} is the total muon-nucleon charged current cross-section and D_{eff} is the detector efficiency. The μ^+ event rate is similar to the above expression with the fluxes, probabilities and cross sections replaced by those for anti-muons. Similarly, the e^- event rate in a specific energy and zenith angle bin is expressed as follows:

$$\frac{d^2N_e}{d\Omega dE} = \frac{1}{2\pi} \left[\left(\frac{d^2\Phi_\mu}{d \cos \theta dE} \right) P_{\mu e} + \left(\frac{d^2\Phi_e}{d \cos \theta dE} \right) P_{ee} \right] \sigma_{CC} D_{\text{eff}} \quad (8)$$

² $P_{\alpha\beta}$ denotes the probability for transition from $\nu_\alpha \rightarrow \nu_\beta$.

with the e^+ event rate being expressed in terms of anti-neutrino fluxes, probabilities and cross sections. E and θ in the above equations are true values of neutrino energy and zenith angle. We convert the above double differential event rates into those with respect to the measured neutrino energy E_m and the measured zenith angle θ_m . This is done using Gaussian resolution functions in energy and zenith angle, as explained in [10].

In the limit when only statistical errors are taken into account, the standard Gaussian definition of binned χ^2 is:

$$\chi_{\text{stat}}^2 = \sum_{i=E_m \text{ bins}} \sum_{j=\cos \theta_m \text{ bins}} \frac{[N_{ij}^{\text{ex}} - N_{ij}^{\text{th}}]^2}{N_{ij}^{\text{ex}}} \quad (9)$$

Here, N_{ij}^{ex} is the experimental and N_{ij}^{th} is theoretical number of events in the ij^{th} bin.

However, in addition to the statistical uncertainties, one also needs to take into account various theoretical and systematic uncertainties. In particular, our analysis includes a flux normalization error of 20%, a tilt factor [32] which takes into account the deviation of the atmospheric fluxes from a power law, a zenith angle dependence uncertainty of 5 %, an overall cross section uncertainty of 10 %, and an overall systematic uncertainty of 5 % [10]. These uncertainties are included using the method of pulls described in [32–34].

In this method, the uncertainty in fluxes and cross sections and the systematic uncertainties are taken into account by allowing these inputs to deviate from their standard values in the computation of N_{ij}^{th} . Let the k^{th} input deviate from its standard value by $\sigma_k \xi_k$, where σ_k is its uncertainty. Then the value of N_{ij}^{th} with the changed inputs is given by

$$N_{ij}^{\text{th}} = N_{ij}^{\text{th}}(\text{std}) + \sum_{k=1}^{\text{npull}} c_{ij}^k \xi_k \quad (10)$$

where $N_{ij}^{\text{th}}(\text{std})$ is the theoretical rate for bin ij , calculated with the standard values of the inputs and npull is the number of sources of uncertainty, which in our case is 5. The ξ_k 's are called the “pull” variables and they determine the number of σ 's by which the k^{th} input deviates from its standard value. In Eq. (10), c_{ij}^k is the change in N_{ij}^{th} when the k^{th} input is changed by σ_k (*i.e.* by 1 standard deviation). The uncertainties in the inputs are not very large. Therefore, in Eq. (10) we only considered the changes in N_{ij}^{th} which are linear in ξ_k . Thus we have a modified χ^2 defined by

$$\chi^2(\xi_k) = \sum_{i,j} \frac{[N_{ij}^{\text{th}}(\text{std}) + \sum_{k=1}^{\text{npull}} c_{ij}^k \xi_k - N_{ij}^{\text{ex}}]^2}{N_{ij}^{\text{ex}}} + \sum_{k=1}^{\text{npull}} \xi_k^2 \quad (11)$$

where the additional term ξ_k^2 is the penalty imposed for moving k^{th} input away from its standard value by $\sigma_k \xi_k$. The χ^2 with pulls, which includes the effects of all theoretical and systematic uncertainties, is obtained by minimizing $\chi^2(\xi_k)$, given in Eq. (11), with respect to all the pulls ξ_k :

$$\chi_{\text{pull}}^2 = \text{Min}_{\xi_k} [\chi^2(\xi_k)] \quad (12)$$

However, in general, the values of the mass-squared differences $|\Delta m_{31}^2|$ and Δm_{21}^2 and the mixing angles θ_{12} , θ_{23} and θ_{13} can vary over a range that reflects the uncertainty in our knowledge. To take into account the uncertainties in these parameters, we define the **marginalized** χ^2 for hierarchy sensitivity as,

$$\chi_{\min}^2 = \text{Min} \left[\chi^2(\xi_k) + \left(\frac{|\Delta m_{31}^2|^{\text{true}} - |\Delta m_{31}^2|}{\sigma (|\Delta m_{31}^2|)} \right)^2 + \left(\frac{\sin^2 2\theta_{13}^{\text{true}} - \sin^2 2\theta_{13}}{\sigma (\sin^2 2\theta_{13})} \right)^2 \right] \quad (13)$$

$\chi^2(\xi_k)$ in the above equation, is computed according to the definition given in Eq. (11). The following values for the errors are chosen

- $\sigma (\sin^2 2\theta_{13}) = 0.02$,
- $\sigma (|\Delta m_{31}^2|) = 10\% \text{ of } |\Delta m_{31}^2| = 0.25 \times 10^{-3} \text{ eV}^2$

In computing χ_{\min}^2 , we varied the values of the neutrino parameters from their true values over $\pm 3\sigma$ ranges. Note that we have not done the marginalization over the mixing angle θ_{23} . In this work, we have considered only one value of $\theta_{23}^{\text{true}} = \pi/4$. For this value of $\theta_{23}^{\text{true}}$, it is found that the χ_{\min}^2 always occurs at the true value itself. We do not marginalize over the solar parameters θ_{12} and Δm_{21}^2 in our computation, since they are known with very good precision [35].

We have computed the values of the χ^2 sensitivity to the mass hierarchy, choosing the true hierarchy to be normal. The true values of the neutrino parameters are taken to be $\theta_{23} = 45^\circ$, $\theta_{12} = 33.8^\circ$, $|\Delta m_{31}^2| = 2.5 \times 10^{-3} \text{ eV}^2$, and $\Delta m_{21}^2 = 8.0 \times 10^{-5} \text{ eV}^2$ from the current 3σ allowed ranges [35–38].

4 Results and Discussion

We give our results for an exposure of 1 Mt yr (unless otherwise stated) for two input values of θ_{13} and for detectors both with and without charge identification capability. When the detector has no charge identification capacity the χ^2 is defined as,

$$(\chi_m^2)_{noID} = \chi_{\mu+\bar{\mu}}^2 \quad (14)$$

and

$$(\chi_{el}^2)_{noID} = \chi_{e+\bar{e}}^2. \quad (15)$$

That is, we sum over the particle and antiparticle events and then compute the χ^2 . The total χ_{tot}^2 is the sum of χ_m^2 and χ_{el}^2 .

When the charge identification capability is there, the χ^2 values for muon events are computed as

$$\chi_m^2 = \chi_{\mu}^2 + \chi_{\bar{\mu}}^2 \quad (16)$$

where the individual χ^2 for muon neutrino and muon antineutrino events are evaluated and then summed. We assumed that there is 100% charge identification for muons throughout the energy range 1 - 10 GeV. That, however, is not true for electrons. In fact, there is no charge identification capability for electrons in the energy range 5 - 10 GeV and only a partial charge identification capability for lower energy electrons. Therefore the χ^2 for electron events is defined as

$$\chi_{el}^2 = n(\chi_e^2 + \chi_{\bar{e}}^2)_{1-5\text{GeV}} + (1 - n)(\chi_{e+\bar{e}}^2)_{1-5\text{GeV}} + (\chi_{e+\bar{e}}^2)_{5-10\text{GeV}}. \quad (17)$$

Here, n is the fraction of electron events in the energy range 1 - 5 GeV which are assumed to have exact charge identification capability. As mentioned earlier, we expect a $\sim 20\%$ probability of exact charge identification in the energy range 1 - 5 GeV. Hence we take $n = 0.2$ in our computation unless otherwise mentioned. In other words, 20% of the electron events in this energy range are assumed to have 100% charge sensitivity, while for the remaining 80%, the electron neutrino and antineutrino events are assumed to be indistinguishable. Realistically one expects a non-zero charge identification efficiency for the remaining 80% electron events in this range, which would give a better sensitivity to the hierarchy. Hence we have given a conservative estimate in our computation of the hierarchy sensitivity of a Liquid Argon detector. We also give an estimate of how the sensitivity would vary if n is varied from 0 to 1. The third term in the above expression is the χ^2 contribution from the electron events in the 5 energy bins in the range 5 - 10 GeV, for which charge identification is not possible. Hence this χ^2 value is calculated using the sum of electron neutrino and antineutrino events in these energy bins. χ_{el}^2 represents the sum of all χ^2 contributions from electron events.

In Table 1 we present the values of χ_m^2 and χ_{el}^2 with fixed parameters for two different values of the parameter θ_{13} . Here, $\chi_{tot}^2 = \chi_m^2 + \chi_{el}^2$ is the total fixed-parameter hierarchy sensitivity of a Liquid Argon detector with charge sensitivity. In each case, $(\chi^2)^{stat}$ denotes the sensitivity with only statistical errors (Eq. (9)) and $(\chi^2)^{pull}$ denotes the sensitivity with theoretical and systematic uncertainties incorporated as pulls (Eq. (12)). The values of $(\chi_{tot}^2)^{pull}$ are plotted against the input values of $\sin^2 2\theta_{13}$ in Figure 1.

Figure 2 shows the variation of $(\chi_{tot}^2)^{pull}$ (fixed-parameter) as n varies from 0 to 1.

In Table 2 we give the total values of the χ^2 hierarchy sensitivity with pulls and priors with marginalization over the neutrino parameters θ_{13} and Δm_{31}^2 for two different values of θ_{13}^{true} . These values, denoted by $(\chi_{tot}^2)_{min}^{pull}$, are for a Liquid Argon detector with charge sensitivity and with an exposure of 1 Mt yr, and represent the principal results of this study. The same values are plotted against the input values of $\sin^2 2\theta_{13}$ in Figure 3. For comparison, Table 3 gives the marginalized results for hierarchy sensitivity for a Liquid Argon detector without charge sensitivity.

5 Summary and Conclusions

From the results described in the previous section, we note the following features:

- Table 1 and Figure 1 give the values of fixed-parameter χ^2 for muon events with charge identification capacity and electron events with partial charge identification capacity as

| $\sin^2 2\theta_{13}$ | $(\chi_m^2)^{stat}$ | $(\chi_{el}^2)^{stat}$ | $(\chi_{tot}^2)^{stat}$ | $(\chi_m^2)^{pull}$ | $(\chi_{el}^2)^{pull}$ | $(\chi_{tot}^2)^{pull}$ |
|-----------------------|---------------------|------------------------|-------------------------|---------------------|------------------------|-------------------------|
| 0.04 | 28.5 | 9.4 | 37.9 | 24.5 | 7.0 | 31.5 |
| 0.10 | 31.7 | 14.7 | 46.4 | 25.1 | 9.3 | 34.4 |

Table 1: Values of fixed parameter χ^2 without and with pull for a Liquid Argon detector (1 Mt yr) with charge sensitivity. The contributions from muon and electron events are also shown separately.

| $\sin^2 2\theta_{13}$ | $(\chi_m^2)_{min}^{pull}$ | $(\chi_{el}^2)_{min}^{pull}$ | $(\chi_{tot}^2)_{min}^{pull}$ |
|-----------------------|---------------------------|------------------------------|-------------------------------|
| 0.04 | 6.1 | 7.7 | 13.8 |
| 0.10 | 16.2 | 11.3 | 27.5 |

Table 2: Values of total marginalized χ^2 with pull and priors, for a Liquid Argon detector (1 Mt yr) with charge sensitivity. Also shown separately are the contributions of muon and electron events to the total χ^2 .

| $\sin^2 2\theta_{13}$ | $(\chi_m^2)_{min}^{pull}$ | $(\chi_{el}^2)_{min}^{pull}$ | $(\chi_{tot}^2)_{min}^{pull}$ |
|-----------------------|---------------------------|------------------------------|-------------------------------|
| 0.04 | 1.3 | 4.9 | 6.2 |
| 0.10 | 3.5 | 9.2 | 12.7 |

Table 3: Values of total marginalized χ^2 with pull and priors, for a Liquid Argon detector (1 Mt yr) without charge sensitivity. Also shown separately are the contributions of muon and electron events to the total χ^2 .

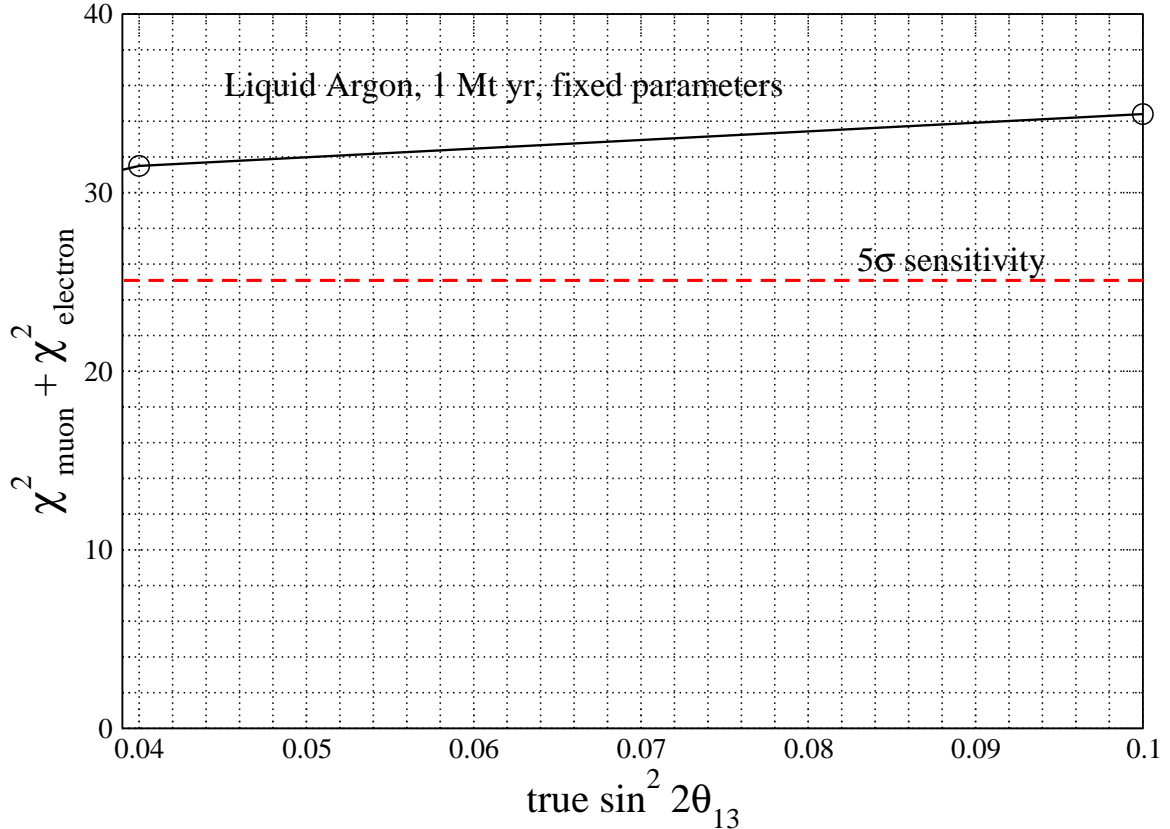


Figure 1: Values of fixed parameter χ^2 with pull versus the input (*true*) value of $\sin^2 2\theta_{13}$ for a Liquid Argon detector (1 Mt yr). Shown is $(\chi_{tot}^2)^{pull}$.

discussed in the previous section. We see that the values of fixed-parameter $(\chi_{tot}^2)^{pull}$ are uniformly high ($> 5\sigma$ for both input values of θ_{13}) for a Liquid Argon detector with 1 Mt yr exposure. Since earth matter effects are proportional to $\sin^2 2\theta_{13}$, the χ^2 is expected to vary linearly with $\sin^2 2\theta_{13}$.

- From Figure 2, we observe that the dependence of the total χ^2 on the charge identification capability for electron events is not drastic, since the contribution from the electron events in this energy range represent only about one-fifth of the total hierarchy sensitivity of a Liquid Argon detector.
- Comparing the marginalized results with and without charge sensitivity in Table 2 and Table 3, we can see that χ^2 in general increases after incorporation of charge identification power of the detector. This is expected since the hierarchy sensitivity comes mainly from the matter effect which is different for neutrinos and antineutrinos. Hence a detector with charge sensitivity is better capable of probing this. Note that the muon χ^2 shows a sharper rise with the inclusion of charge sensitivity than the electron χ^2 , since charge identification with high precision is possible over the entire energy range in the case of muons.
- From our study, a $> 4\sigma$ sensitivity to the neutrino mass hierarchy is predicted for a

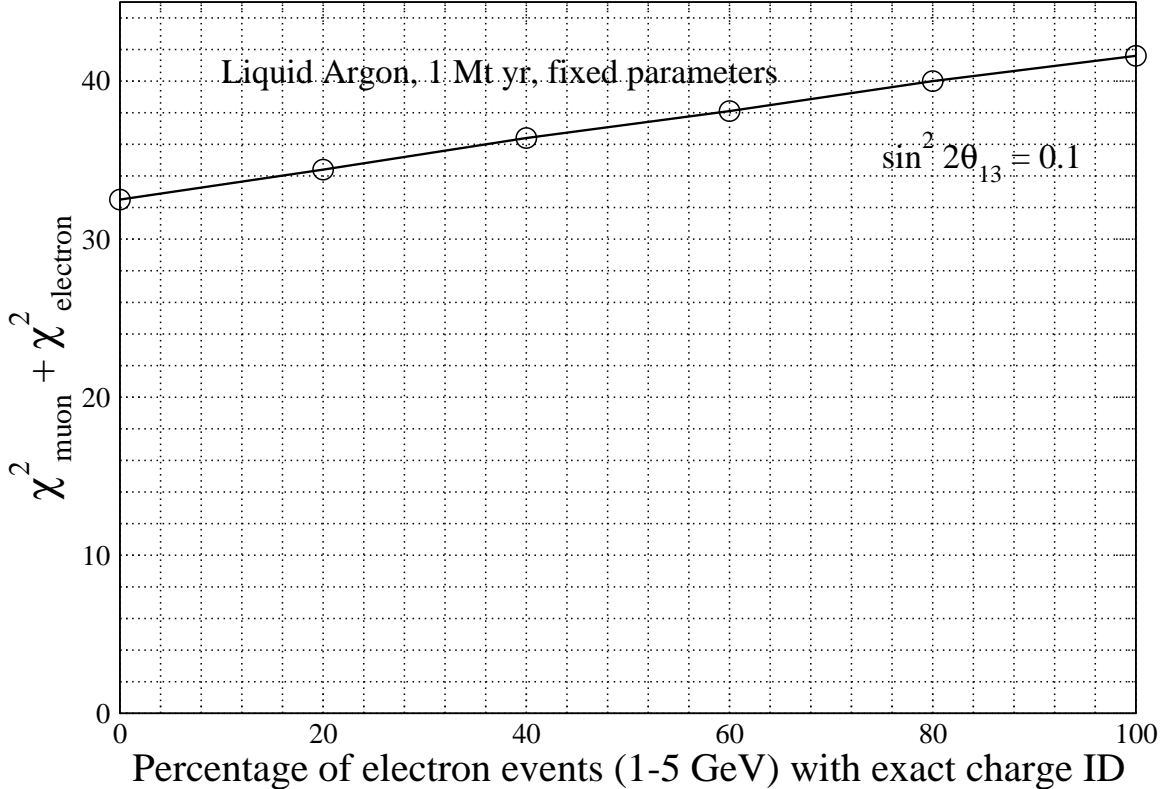


Figure 2: Values of fixed parameter χ^2 with pull versus the percentage of electron events in the range 1-5 GeV taken to be with 100 % charge ID efficiency for a Liquid Argon detector (1 Mt yr). Shown is $(\chi^2_{\text{tot}})^{\text{pull}}$. Here, $\sin^2 2\theta_{13} = 0.1$.

magnetized Liquid Argon detector with 1 Mt yr exposure for $\sin^2 2\theta_{13} > 0.05$ or $\theta_{13} > 6^\circ$. We redid our calculation for smaller exposure of 333 kT yr, which can be achieved by a smaller Liquid Argon detector (30 kT, 11 years) with charge sensitivity. In this case, we obtain the marginalized total $\chi^2 = 4.9$, which is $> 2\sigma$ hierarchy sensitivity, for $\sin^2 2\theta_{13} = 0.04$, and the marginalized total $\chi^2 = 9.8$, which is $> 3\sigma$ hierarchy sensitivity, for $\sin^2 2\theta_{13} = 0.1$.

- For a detector without charge sensitivity, a 2.5σ marginalized hierarchy sensitivity for $\sin^2 2\theta_{13} = 0.04$ is possible with 1 Mt yr exposure.

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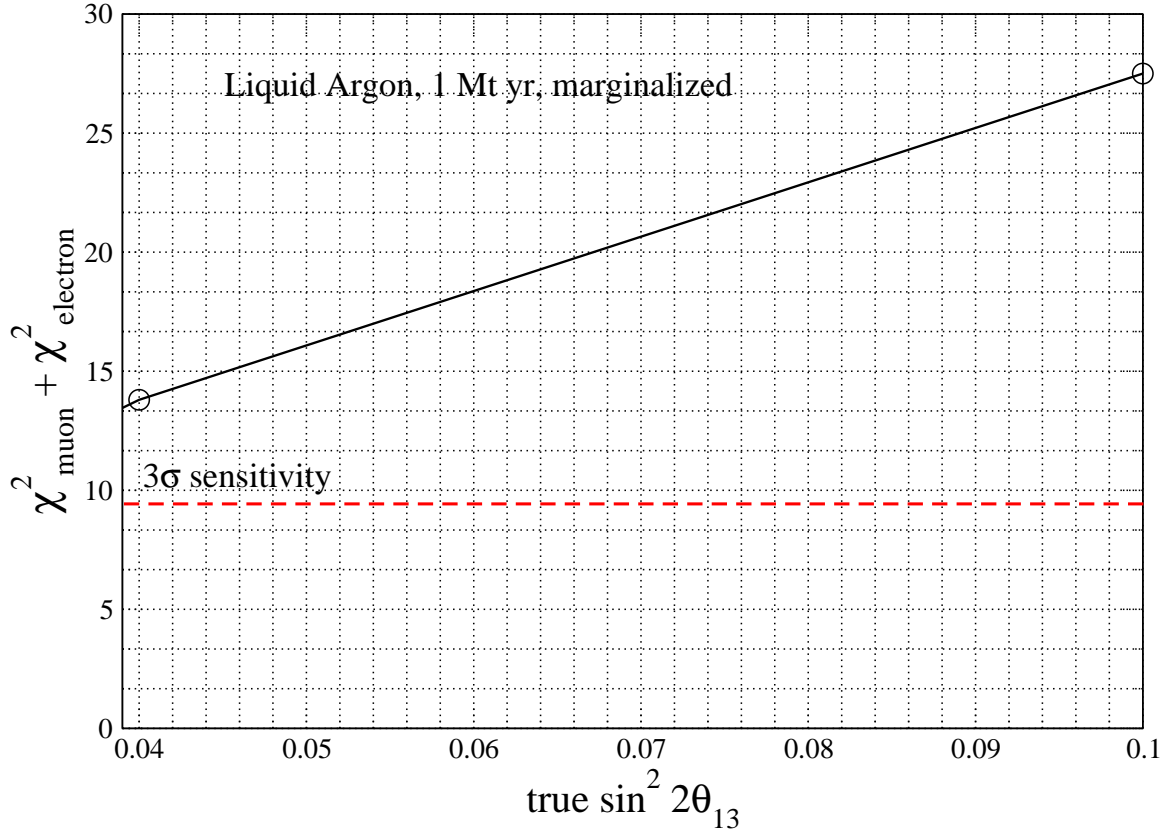


Figure 3: Values of marginalized χ^2 with pull and priors versus the input (*true*) value of $\sin^2 2\theta_{13}$ for a Liquid Argon detector (1 Mt yr). Shown is $(\chi^2_{\text{tot}})_{\text{min}}^{\text{pull}}$

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