

Chapter 1

Neutrino Physics

This chapter contains a introduction to the field of neutrino physics to provide context for the main work presented in this thesis. The history of neutrino physics is an interesting story in its own right and provides the foundation for the present and future of the field. This will be briefly retold in Section 1.1 and will motivate a discussion of neutrino oscillations in Section 1.2. An overview of the current status of the field and its future is contained in Sections 1.3 and 1.4 respectively. As this thesis specifically concerns the DUNE experiment, a brief history and description of liquid argon TPCs is provided in Section 1.5 as a basis for future chapters.

1.1 Historical Context

1.1.1 Prediction of the Neutrino

The neutrino was first postulated in 1930 by Wolfgang Pauli [44] in order to account for an inconsistency in the theory of β -decay. In the apparent two-body decay

$$A \rightarrow B + e^-, \quad (1.1)$$

kinematically the electron must be emitted with an energy given by

$$E = \left(\frac{m_A^2 - m_B^2 + m_e^2}{2m_A} \right) c^2, \quad (1.2)$$

where m_α is the mass of particle α . This energy is fixed given the masses of the particles; it was observed however that the electron energy followed a distribution (Figure 1.1), with Equation 1.2 giving the maximum permitted energy. The neutrino was postulated as a third

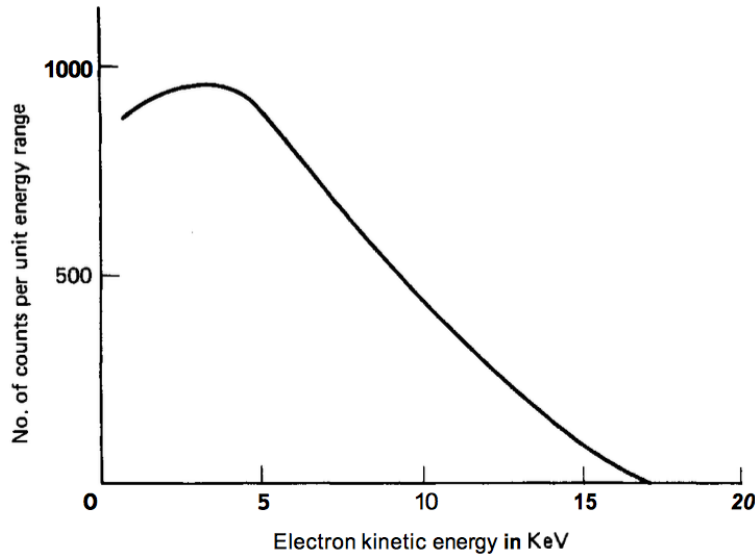


Fig. 1.1 Energy spectrum of the electron produced in beta decay [39].

final state particle in order to account for this result and retain energy conservation laws. Pauli initially called the particle a *neutron* (preempting the name Chadwick was to give his discovered particle in 1932) but his idea was met with much scepticism. It was Fermi who named the new particle *neutrino* ('little neutral one') when incorporating Pauli's hypothesis into his theory of beta decay [25, 26, 52]. With the huge success and acceptance of this theory, the field of neutrino physics was born.

Further indications of the existence of the neutrino were provided by the studies of pion and muon decay by Cecil Powell's group at Bristol [37, 38]. Topological investigations of the newly discovered π meson and its apparent decay into a lighter meson (now known to actually be the muon lepton) appear to hint at the presence of an additional, unknown, daughter particle [37]. Given the constancy of the outgoing neutrino energy, it was that a two-body decay. However, subsequent studies of the decay of this lighter 'meson' implied a three-body decay involving two final state neutrinos, analogous to the implication of the neutrino by considering the electron energy distribution [14].

1.1.2 Discovery of the Neutrino

The elegance of Fermi's theory convinced many physicists of the existence of the neutrino but until discovered experimentally it remained a hypothetical 'book-keeping' device. Given the elusive nature of neutrinos this wasn't for many years, leading to Pauli famously declaring "I have done a terrible thing. I have postulated a particle that cannot be detected". However, a series of experiments conducted between 1953 and 1956 by Clyde Cowan and Frederick

Reines confirmed the hypothesis and was later rewarded with the Nobel Prize in Physics in 1995. Using the new technology of liquid scintillator detectors [19], they designed an experiment [47] to study the (anti)neutrinos produced in inverse beta decay

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (1.3)$$

in the Hanford nuclear reactor in Washington, U.S.A. Their signal comprised of an initial release of scintillation light when the positron annihilates with an electron, followed a characteristic time later by a gamma ray corresponding to the neutron capture. The initial results from 1953 [48] hinted at an excess over predicted background but the background proved to be much larger than anticipated, mainly due to an underestimation of the effects of cosmic rays. A second experiment was conducted in 1956, this time 12 m underground and 11 m from the Savannah River reactor in South Carolina. A neutrino detection rate of 2.9 ± 0.2 per hour, greater than 20 times the accidental background rate was reported, confirming the previous indications [18]. The experimental discovery of the neutrino was confirmed. [Bit more description? – Describe detector, method for detecting positron.]

Ray Davis was also using nuclear reactors to study the interaction rates of neutrinos. Using a detector comprised of 3000 gallons of carbon tetrachloride (CCl_4) also close to the Savannah River reactor, Davis and Harmer searched for the interactions

$$\bar{\nu} + \text{Cl}^{37} \rightarrow \text{Ar}^{37} + e^- \quad (\bar{\nu} + n \rightarrow p^+ + e^-); \quad (1.4)$$

since it was known from Reines and Cowan that inverse beta decay

$$\nu + \text{Cl}^{37} \rightarrow \text{Ar}^{37} + e^- \quad (\nu + n \rightarrow p^+ + e^-) \quad (1.5)$$

occurs, this facilitates a comparison between the neutrino and the antineutrino. They found the interaction shown in Equation 1.4 occurred at a rate less than 20 times that represented in Equation 1.5, implying for the first time a difference between neutrinos and antineutrinos [22]. This gave rise to the notion of ‘lepton number’ and its conservation in physical interactions.

It was few years before the next chapter in the history of neutrinos, the discovery of the muon neutrino in 1962 at Brookhaven [21]. It was noted the apparently permitted decay

$$\mu^- \not\rightarrow e^- + \gamma \quad (1.6)$$

is never observed, inciting the possibility of two distinct neutrinos. In order to test this, Lederman, Schwarz and Steinberger used a muon neutrino beam to look for two separate

interactions:

$$\bar{\nu}_\mu + p^+ \rightarrow \mu^+ + n, \quad (1.7)$$

$$\bar{\nu}_\mu + p^+ \rightarrow e^+ + n. \quad (1.8)$$

With only one type of neutrino, each interaction would be expected to occur at around the same rate. The beam was produced by accelerating protons up to 15 GeV and using a Beryllium target to create secondary mesons, decaying to produce neutrinos with energies up to 1 GeV. 34 muon tracks were detected (with an estimated background from cosmic muons of 5) and no events consistent with electrons were observed. This remarkable result can only be rivalled by the technological advancements required; it was the first experiment to construct and use an artificial neutrino beam (common to all contemporary long-baseline experiments) and used 13.5 m thick steel from a dismantled battleship in order to ensure only neutrinos arrived at the spark chamber detector. This discovery was rewarded with the Nobel Prize in 1988.

A third generation of lepton, the τ , was discovered in 1975 by Martin Perl and his team at SLAC [45], completing the set of three charged leptons. They reported 64 events of the form

$$e^+ + e^- \rightarrow e^\pm + \mu^\mp + \geq 2 \text{ undetected particles}, \quad (1.9)$$

using the energy and angle distributions to predict at least two additional particles. They claimed ‘no conventional explanation’ could account for these events and proposed the existence of a heavier charged lepton as an intermediate stage:

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \rightarrow e^\pm + \mu^\mp + 4\nu. \quad (1.10)$$

The τ lepton was subsequently characterised by further experiments at by the Mark I detector at SLAC [24] and by the PLUTO collaboration at DESY [15]. This result heavily implied the existence of an associated neutrino to complete the symmetry observed in the first two lepton couplets.

Further evidence for a third neutrino was provided by four experiments using the Large Electron-Positron Collider (LEP) at CERN in 1989 which were studying the production of the newly discovered Z^0 boson [23, 3, 5, 1]. The width Γ_Z of the Z^0 resonance is dependent on the partial widths relating to final state charged leptons, hadrons and neutrinos;

$$\Gamma_Z = N_\nu \Gamma_\nu + 3\Gamma_{ee} + \Gamma_{\text{hadron}}, \quad (1.11)$$

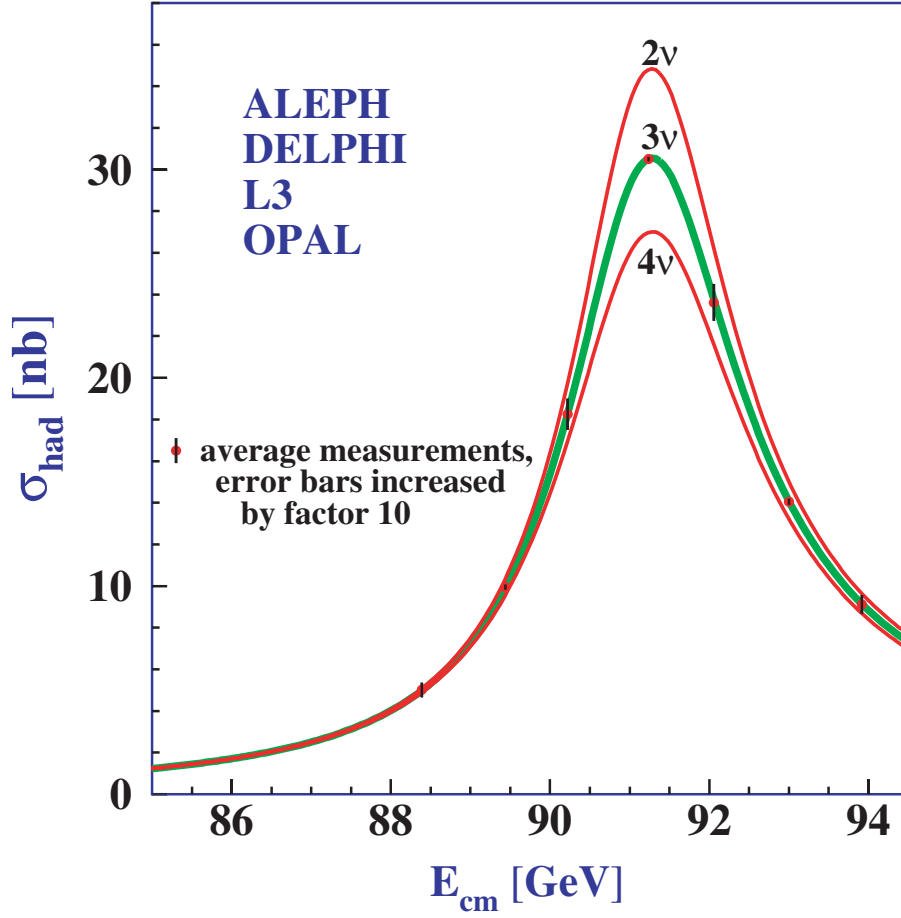


Fig. 1.2 Measurements of the hadron production cross-section around the Z resonance. The curves indicate the predicted cross-section for two, three and four neutrino species with SM couplings and negligible mass. Taken from [50].

where N_ν is the number of light ($m_\nu \leq \frac{m_Z}{2}$) active neutrinos. Figure 1.2 shows this resonance for a range of N_ν hypotheses; fitting to the data yields a value of 2.984 ± 0.008 neutrino flavours [50].

The extremely precise measurement reported by the LEP experiments was enough for a lot of physicists to claim indisputable evidence for the existence of the tau neutrino; it was partly for this reason that its experimental discovery wasn't until 25 years after the addition of the τ lepton to the Standard Model. However, in 2000 the DONUT experiment at Fermilab, IL, U.S.A. finally reported direct detection of the tau neutrino [36]. DONUT (Direct Observation of NuTau), as the name suggests, was designed specifically for the purpose of finding the third neutrino. It did this by identifying the τ as the only lepton at the interaction vertex from a ν_τ beam created by firing 800 GeV protons from the Tevatron at a tungsten beam dump. The mean energy of the ν_τ s detected at the emulsion target

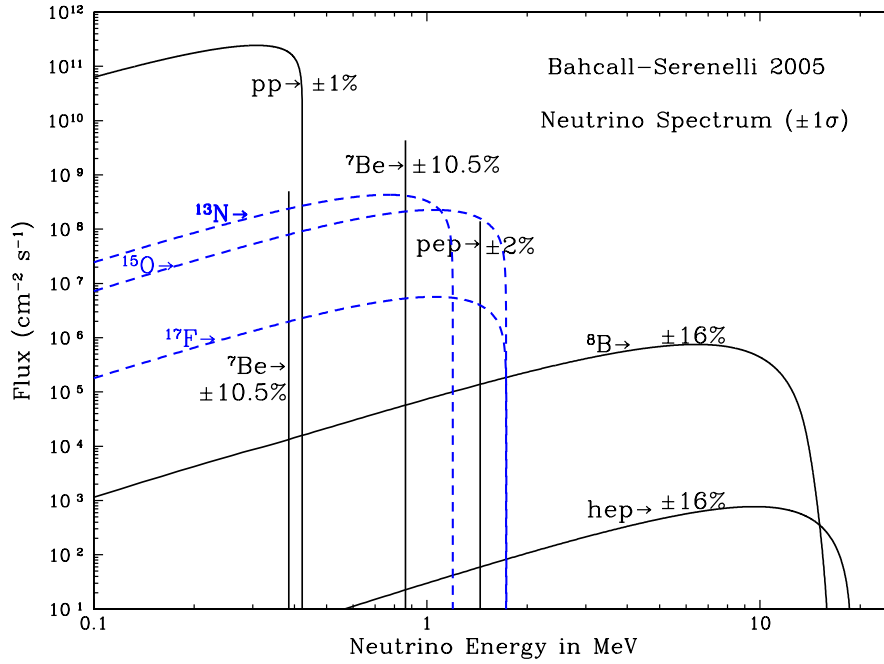


Fig. 1.3 Solar neutrino energy spectra as predicted by the Standard Solar Model [11]. The solid lines represent neutrinos produced during the p-p chain and dashed line represent neutrinos from the CNO cycle. Each spectrum illustrates a particular reaction during the process of a given chain.

36 m downstream was 111 GeV, produced by the decay of a D_S meson to a τ lepton and a $\bar{\nu}_\tau$ neutrino followed by the decay of the τ to a ν_τ . Four events were found, above a predicted background of 0.34 ± 0.05 , consistent with the Standard Model description of the tau neutrino.

1.1.3 The Solar Neutrino Problem

It has been known since the 1930s, when Hans Bethe started developing the ideas of stellar nucleosynthesis [13], that an abundance of electron neutrinos is created as byproducts of the nuclear processes powering the Sun. The Standard Solar Model (SSM), established by John Bahcall in 1968 [9], explains the nuclear fusion processes responsible for powering stars. For stars the size of the Sun, this is dominated by the *proton-proton chain*; heavier stars follow the *CNO cycle*. Figure 1.3 shows the energy spectra of neutrino released during reactions occurring during both chains.

Ray Davis, in collaboration with Bahcall, conducted the first experiment to detect these solar neutrinos in 1968. Using a similar detection technique to his previous experiments, Davis used a 380 m³ tank of tetrachloroethene (C_2Cl_4) to detect neutrinos via the inverse beta

decay reaction detailed in Equation 1.5. Given the threshold for this reaction is 0.814 MeV, the main sources of neutrinos probed by this experiment were Be^7 and B^8 . In order to eliminate backgrounds from cosmic rays, Davis constructed his experiment 4850 ft underground at the Homestake mine near Lead, SK, U.S.A. It is worth noting, in a pleasing neutrino-full-circle, this is exactly where the far detector for the DUNE experiment will be housed. The Davis Homestake experiment ran for 25 years but the results obtained [17] disagreed quite strongly with the SSM [10], consistently measuring solar electron neutrinos at a rate around a third that predicted by the model. This became known as the ‘solar neutrino problem’, and Davis was awarded the Nobel Prize for his work on this famous experiment in 2002.

The subsequent radiochemical experiments SAGE (from 1990) and GALLEX (from 1991) were sensitive to the large flux of pp neutrinos by utilising a Ga^{71} target and the lower threshold reaction

$$\nu + \text{Ga}^{71} \rightarrow \text{Ge}^{71} + e^{-}. \quad (1.12)$$

These experiments also reported ‘missing’ neutrinos, determining capture rates of $66.6^{+6.8+3.8}_{-7.1-4.0}$ SNU (SAGE) [2] and $77.5 \pm 6.2^{+4.3}_{-4.7}$ SNU (GALLEX) [7], disagreeing with the SSM prediction of 130 SNU [34]. There appeared to be a problem – either the SSM was incomplete and incorrectly over-predicted the amount of electron neutrinos or hints of new physics were beginning to appear in the experiment data.

1.1.4 The Atmospheric Neutrino Anomaly

Another abundant source of natural neutrinos come from cosmic rays interacting with the upper atmosphere and producing ‘atmospheric neutrinos’, typically via the interactions [30]

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}, \quad \mu^{-} \rightarrow e^{-} + \bar{\nu}_e + \nu_{\mu} \quad (1.13)$$

$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}, \quad \mu^{+} \rightarrow e^{+} + \nu_e + \bar{\nu}_{\mu}. \quad (1.14)$$

Since the decay lengths and kinematics are well known, the predicted ratio of muon to electron neutrinos can be calculated to a good accuracy. This ratio can be compared to an experimentally determined ratio and analysed as a measure of the efficacy of the model.

It was first noticed as early as the late 1970s by experiments designed to search for nucleon decay predicted by the then-popular Grand Unified Theories that the measured flux did not correspond to that predicted by the theory. The IMB [33] and Kamioka [35] experiments both noticed deficiencies in the ratio between muon and electron neutrinos compared to that predicted by the models. These experiments utilised large tanks of pure water surrounded by Photo-Multiplier Tubes (PMTs) to detect neutrinos via the Cherenkov

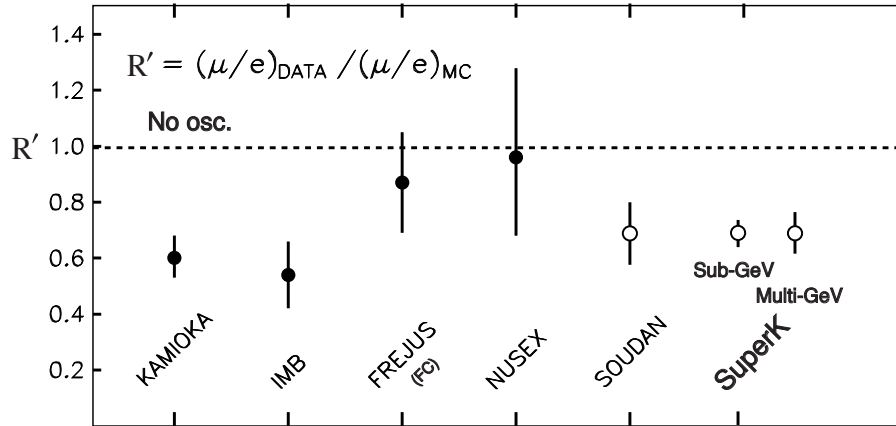


Fig. 1.4 The double ratio R of muon to electron neutrino events showing data divided by expectation [41]. Various underground atmospheric neutrino detectors are shown.

radiation created by their charged leptonic daughter particles. Using ring-imaging techniques, it is possible to distinguish between electron-like and muon-like events and therefore identify the flavour of the incoming neutrino. The problem implied by these measurements is known as the ‘atmospheric neutrino anomaly’.

Various other experiments over the following twenty years also reported similar measurements, suggesting an excess of electron neutrinos over prediction, a deficit in the number of muon neutrinos, or both. Results from numerous experiments are shown in Figure 1.4. Most experiments report a discrepancy, with its size seemingly dependent on the energy region being studied. The experiments reporting a ratio consistent with one were much smaller than the others, and with more statistics they also started observing similar effects. This anomaly, along with the issue of the solar neutrino problem, strongly hinted at a problem with our understanding of neutrino physics.

1.1.5 The Evidence for Neutrino Oscillations

The concept of neutrino oscillations is the idea that a neutrino created in a certain flavour state may not necessary be detected in the same flavour state after it has propagated over some distance and time. It was first postulated as an explanation of the Solar Neutrino Problem by Pontecorvo in 1968 [31], having initially proposed the phenomenon in 1957 as an analogy to $K^0 \rightarrow \bar{K}^0$ transition in the quark sector [46]. It offers an elegant solution to both the solar neutrino problem and the atmospheric neutrino anomaly by explaining where the ‘missing’ neutrinos had gone; it is possible they had simply ‘oscillated’ to a different flavour and therefore would not be detected as expected. Whilst there was speculation that neutrino oscillations may be the explanation behind the issues observed in the data much

sooner [16, 12], definite proof was not provided until the late 1990s. In many ways, the story of neutrino physics, from the initial observations of the Solar Neutrino Problem and the Atmospheric Neutrino Anomaly, through the speculation and theoretical developments, to the eventual proof, can be considered a triumph for the scientific method.

The Kamiokande and SuperKamiokande experiments in Japan (upgrades from the Kamioka experiment noted previously) and the SNO experiment in Sudbury, Canada produced the results which showed indisputable evidence for neutrino oscillations and provided explanations for all previous discrepancies observed. This result was monumental and the work of both collaborations was rewarded in 2015 when the Nobel Prize was awarded to T. Kajita and A. McDonald, from SuperKamiokande and SNO respectively.

1.1.5.1 SuperKamiokande and the Atmospheric Sector

In 1994, the Kamiokande experiment produced results which hinted at an angular dependence for the R -ratio deficit, implying a dependence on neutrino travel distance [29]. This result can be explained by invoking neutrino oscillations since the probability of oscillation is influenced by the propagation distance; its significantly larger successor, SuperKamiokande, was constructed in order to make precise measurements of this phenomenon. SuperKamiokande is located 1000 m underground and contains an inner detector consisting of 22.5 kton fiducial volume of pure water contained within a large stainless steel cylinder (37 m high, 34 m diameter) and surrounded by 13 142 20-inch photo-multipliers. With 40% coverage, the photocathodes extended over nearly an acre and provided ten times more pixels than any other experiment at the time. Its results in 1998 confirmed the earlier angular dependence findings of Kamiokande, Figure 1.5, and also considered the data as a function of neutrino energy and propagation distance, as shown in Figure 1.6. The observed effects disagreed with a view of non-oscillating atmospheric neutrinos but were entirely consistent with a two-flavour oscillation model, $\nu_\mu \rightarrow \nu_\tau$. This resulted in the famous published claim for the experimental discovery of neutrino oscillations [28].

1.1.5.2 SNO and the Solar Sector

After the SuperKamiokande results, it was clear that neutrino oscillations would probably also explain the deficit of electron neutrinos observed by solar neutrino experiments. It took a few years until the Sudbury Neutrino Observatory (SNO) in Canada provided some quite brilliant evidence of this in 2002 [4].

SNO was a water Cherenkov detector, like SuperKamiokande, but used heavy water, D_2O , as a detector medium. The water is contained in a 12 m acrylic spherical shell and

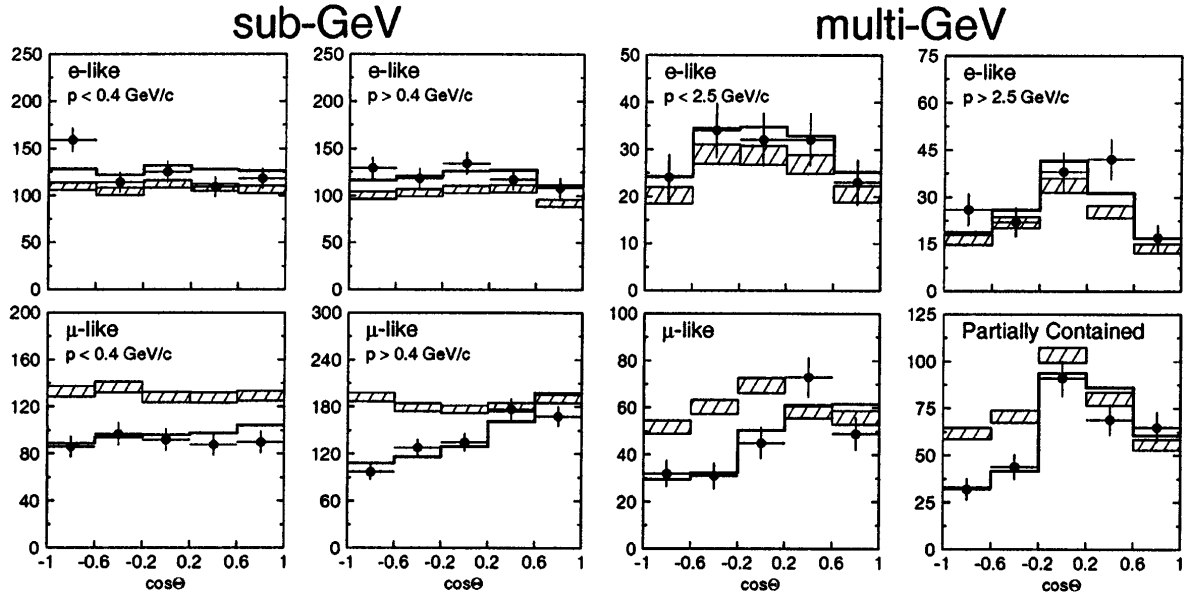


Fig. 1.5 Zenith angle distributions of μ -like and e -like events for sub-GeV and multi-GeV data sets. Upward-going particles have $\cos \Theta < 0$ and downward-going particles have $\cos \Theta > 0$. The hatched region shows the Monte Carlo expectation for no oscillations and the bold line is the best-fit expectation for $\nu_\mu \rightarrow \nu_\tau$ oscillations. Taken from [28].

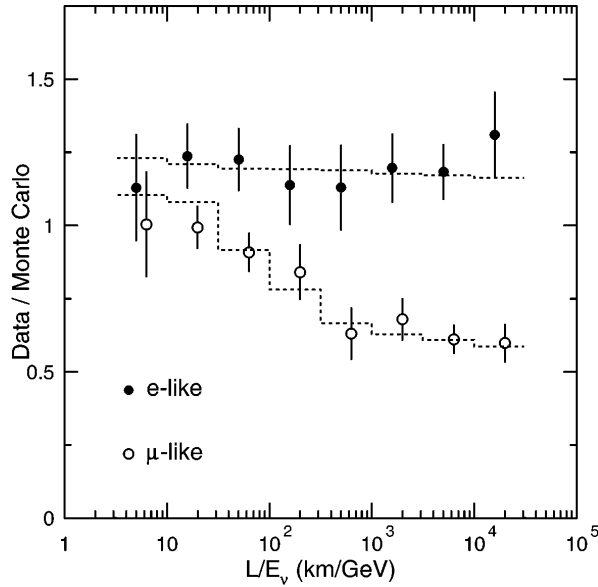


Fig. 1.6 The ratio of the number of data events to Monte Carlo events in the absence of oscillations as a function of reconstructed L/E_ν . The dashed lines show the expected shape for $\nu_\mu \rightarrow \nu_\tau$ oscillations. Taken from [28].

surrounded by 9456 photomultipliers at a depth of 6010 m water equivalent. The use of heavy water facilitated sensitivity to other neutrino interaction channels not accessible by SuperKamiokande via the charge current (CC), neutral current (NC) and elastic scattering (ES) interactions;

$$\nu_e + d \rightarrow p + p + e^- \quad (\text{CC}) \quad (1.15)$$

$$\nu_x + d \rightarrow p + n + \nu_x \quad (\text{NC}) \quad (1.16)$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (\text{ES}). \quad (1.17)$$

The CC channel is sensitive exclusively to electron neutrinos, whilst the other two are accessible by neutrinos of any flavour. This allowed for the first time a simultaneous measurement of the total neutrino interaction rate as well as the electron neutrino interaction rate. The observations of SNO were the smoking gun for neutrino oscillations; the total measured flux for all neutrinos, $\phi_{\text{NC}}^{\text{SNO}} = 6.42 \pm 1.57$ (stat.) $_{-0.58}^{+0.55}$ (sys.), agreed excellently with the electron neutrino flux predicted by the SSM, $\phi^{\text{SSM}} = 5.05_{-0.81}^{+1.01}$. However, the measured electron neutrino flux was around a third lower, $\phi_e^{\text{SNO}} = 1.76 \pm 0.05$ (stat.) ± 0.09 (sys.), consistent with previous measurements from the radiochemical experiments. The evidence seems conclusive: the solar models are correct and the neutrinos are not disappearing; there are simply changing their flavour state. A summary plot showing all solar neutrino experiments up until this point is shown in Figure 1.7 [8].

1.2 Neutrino Oscillations

The theory of neutrino oscillations is basically the quantum mechanics of mixed states and was developed on top of Pontecorvo's work by Ziro Maki, Masami Nakagawa and Shoichi Sakata [40]. If the neutrino flavour states can spontaneously convert from one to another, none can be considered as eigenfunctions of the Hamiltonian. The true stationary states are the *mass eigenstates* (ν_1, ν_2, ν_3), of which the flavour states (ν_e, ν_μ, ν_τ) can be considered linear superpositions:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}}^* \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}, \quad (1.18)$$

where U_{PMNS} is the PMNS mixing matrix which described the flavour composition of each of the mass eigenstates, and vice versa. If the PMNS matrix were diagonal, each flavour state would correspond to a single mass state and oscillations would not occur.

Total Rates: Standard Model vs. Experiment
Bahcall–Serenelli 2005 [BS05(OP)]

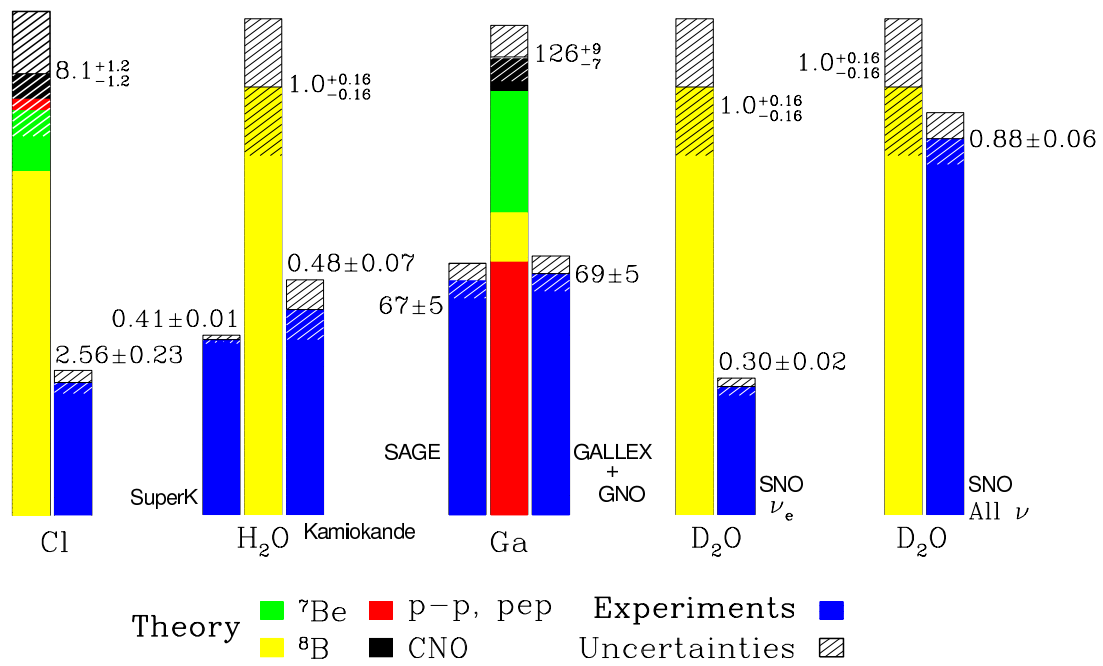


Fig. 1.7

Just as the flavour states are a superposition of mass states

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle, \quad (1.19)$$

the mass states can also be considered a superposition of flavour states

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle. \quad (1.20)$$

For the three neutrino case, the PMNS matrix, decomposed into its three axial rotations, can be expressed as

$$U_{\alpha i} \equiv \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{'Atmospheric' term}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta}s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{'Accelerator' or 'Reactor' term}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{'Solar' term}}, \quad (1.21)$$

where $c_{ij} \equiv \cos(ij)$, $s_{ij} \equiv \sin(ij)$ and δ is a CP-violating phase factor. Each axial component is often referred to by the means with which they are studied, as shown in Equation 1.21.

The weak interaction couples to the flavour eigenstates so neutrinos are always created and detected as flavour states. However, they propagate as mass states since it is these which are eigenstates of the Hamiltonian. Due to the misalignment of the flavour and mass states, oscillations can be shown to occur. A neutrino created with flavour α is a superposition of all the mass states (Equation 1.19). These states propagate as a plane wave, evolving in time and space such that

$$|\nu_i(x, t)\rangle = |\nu_i(0)\rangle e^{-i\mathbf{x}\cdot\mathbf{p}}, \quad (1.22)$$

where \mathbf{x} and \mathbf{p} are the 4-position and 4-momentum of the neutrino respectively. From Equations 1.19 and 1.22, the evolution of the flavour states over space and time is therefore

$$\begin{aligned} |\nu_\alpha(x, t)\rangle &= \sum_i U_{\alpha i}^* |\nu_i(x, t)\rangle \\ &= \sum_i U_{\alpha i}^* e^{-i\mathbf{x}\cdot\mathbf{p}} |\nu_i(0)\rangle. \end{aligned} \quad (1.23)$$

In the ultra-relativistic limit, the mass of the neutrino is negligible compared to its momentum ($m_i \ll \vec{p}$) and $\vec{x} \approx ct$;

$$E_i = \sqrt{|\vec{p}|^2 + m_i^2} = \vec{p} \sqrt{1 + \frac{m_i^2}{|\vec{p}|^2}} \approx \vec{p} + \frac{m_i^2}{2\vec{p}} \quad (1.24)$$

$$\mathbf{x} \cdot \mathbf{p} = E_i t - \vec{x} \cdot \vec{p} = \vec{p} \cdot t + \frac{m_i^2}{2\vec{p}} t - \vec{x} \cdot \vec{p} \approx \frac{m_i^2}{2\vec{p}} \vec{x} = \frac{m_i^2}{2p} x, \quad (1.25)$$

assuming the neutrino displacement is in the direction of its momentum and using natural units ($c \equiv \hbar \equiv 1$). Thus, using Equations 1.23, 1.25 and 1.20,

$$\begin{aligned} |v_\alpha(x, t)\rangle &= \sum_i U_{\alpha i}^* e^{-i \frac{m_i^2}{2p} x} |v_i(0)\rangle \\ &= \sum_i \sum_\beta U_{\alpha i}^* e^{-i \frac{m_i^2}{2p} x} U_{\beta i} |v_\beta\rangle. \end{aligned} \quad (1.26)$$

The probability of a neutrino created in flavour state α being observed in flavour β can be determined from Equation 1.26

$$P(\alpha \rightarrow \beta) = |\langle v_\alpha | v_\beta(x, t) \rangle|^2 \quad (1.27)$$

$$= \left[\sum_i U_{\alpha i} e^{i \frac{m_i^2}{2p} x} U_{\beta i}^* \right] \left[\sum_j U_{\alpha j}^* e^{-i \frac{m_j^2}{2p} x} U_{\beta j} \right] \quad (1.28)$$

$$= \sum_{i,j} U_{\alpha i} U_{\alpha j}^* U_{\beta j} U_{\beta i}^* e^{i \frac{m_i^2 - m_j^2}{2p} x}, \quad (1.29)$$

and is observed to be dependent on the neutrino momentum, the difference between the squared masses of the flavour states, the propagation distance and the relative mixing of the two flavour states encoded in the matrix elements U .

An accelerator based neutrino experiment, such as DUNE, will typically use a ν_μ -dominated beam and look for *muon neutrino disappearance* ($P(\nu_\mu \rightarrow \nu_\mu)$) and *electron neutrino appearance* ($P(\nu_\mu \rightarrow \nu_e)$). In this case, also in the relativistic limit, the relevant appearance and disappearance probabilities can be approximated, respectively, as

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(1.27 \frac{\Delta m_{13}^2 L}{E} \right) \quad (1.30)$$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \left(1.27 \frac{\Delta m_{23}^2 L}{E} \right), \quad (1.31)$$

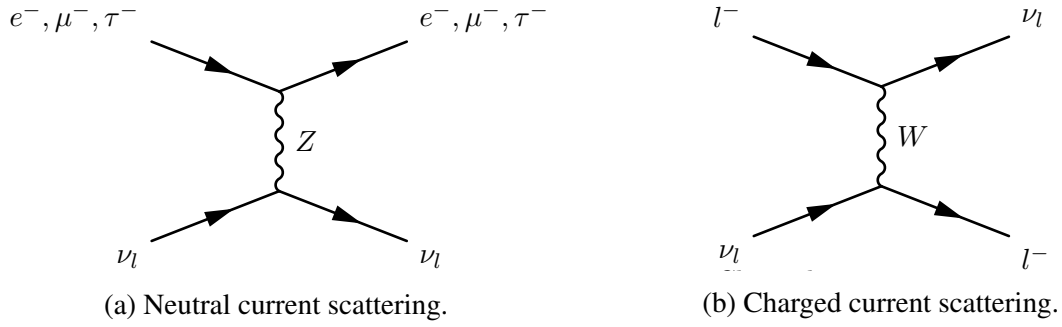


Fig. 1.8 General scattering mechanics which occur as neutrinos pass through matter. Neutral current scattering (Figure 1.8a) occurs for all neutrino flavour combinations whereas charged current scattering (Figure 1.8b) only occurs when the incoming leptons have the same flavour.

where $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ is the *mass squared splitting* in eV, L is the distance propagated in km and E is the neutrino energy in GeV.

1.2.1 Matter Effects

The oscillations considered thus far are *vacuum oscillations* which occur due to the mixing of the neutrino mass and flavour states. When neutrinos propagate through matter, an additional potential can be shown to also produce oscillations, which would occur even in the case of no vacuum oscillations.

As neutrinos pass through matter, coherent scattering (scattering in which the neutrino state is unchanged) due to neutrino interactions with matter cause neutrinos to feel a potential. As normal matter is composed of electrons, rather than their heavier counterparts muons and taus, electron neutrinos are affected more by this potential. The mechanism for this is demonstrated in Figure 1.8. This gives rise to an additional effective mass splitting between the electron neutrino and the other flavours and therefore results in the possibility of oscillations [53].

1.2.2 CP-Violation

1.2.3 Neutrino Mass

1.3 Current Understanding of Neutrino Physics

Including oscillation parameters

Mass splittings and degeneracy

SN?

1.4 Future Neutrino Experiments

1.5 The LAr TPC Concept [Lee – could be in DUNE chapter?]

The use of a liquid argon time projection chamber (LArTPC) as a high-precision fine-grained detector medium holds much promise for the successful resolution of the open questions in neutrino physics. A great amount of R&D work has taken place to advance the maturity of the technology and pioneering experiments, such as ICARUS [6], have further increased the understanding of the neutrino community of the detector techniques. Past and currently running experiments at Fermilab, such as ArgoNeuT [], LArIAT [] and MicroBooNE [], are successfully using LArTPCs to take and analyse data and it seems certain to be the future of neutrino physics in the U.S.

This section will provide a brief history of LArTPC technology and motivate its potential when used in a huge experiment such as DUNE. The basic operation of such a detector will also be described to provide background for discussion of the DUNE and 35t experiments, and of reconstruction in LArTPCs, in future chapters.

1.5.1 A Brief History of Time (Projection Chambers)

The use of a time projection chamber as a potential particle detector was put forward by David Nygren in 1974 [43]. He envisioned bubble-chamber quality data but with the possibility of digital readout of the data, facilitating extremely fine spatial resolution, good timing resolution and fast recovery after triggering. The basic concept is a drift chamber containing a noble gas placed within a field to drift ionisation electrons created by a propagating particle towards a multielectron array. This setup allows full three-dimensional reconstruction by combining information from the two-dimensional readout plane with the drift time. Nygren also included a magnetic field to assist particle identification in his design, shown in Fig. 1.9.

The extension of this concept to a liquid argon TPC and its potential as a high-precision fine-grained detector medium in neutrino physics was proposed by Carlo Rubbia in 1977 [49]. The use of a noble liquid rather than gas is necessary in neutrino experiments to provide a high enough target mass to increase the probability of a neutrino interaction. Noble liquids have high electron mobility and low diffusion, favourable properties as the detection

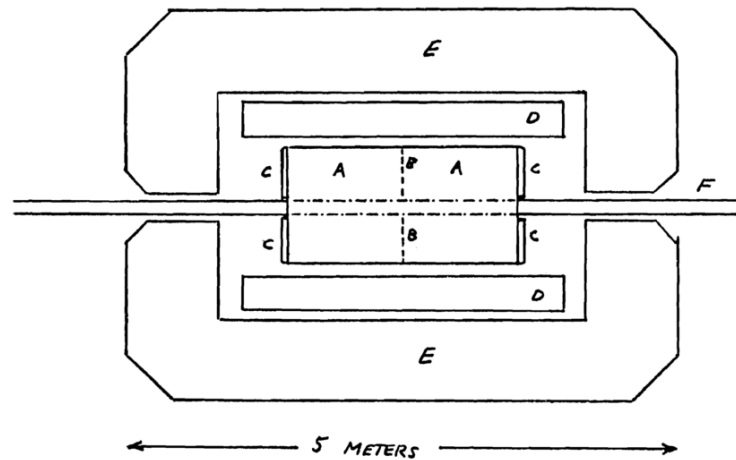


Fig. 1.9 The original concept of the time projection chamber particle detector, drawn by David Nygren in 1974 [43].

of particles is from the ionisation and scintillation light created by the particles. Given the necessity of a high electric field in order to drift these electrons to the readout places, excellent dielectric properties are also required; noble liquids possess such qualities. The properties of liquid argon which make it almost perfect for this use are demonstrated in the table in Table 1.1.

An additional advantage of this technology is the low threshold for detection; this is set by the ionisation threshold of liquid argon and is only 23.6 ± 0.5 eV [1]. Rubbia realised that a LArTPC could be the digital replacement for the high quality particle detection methods used in bubble chambers, very common in neutrino physics in the 1970s. He proposed the first LArTPC detector design, shown in Fig. 1.10, which bears a striking resemblance to the LArTPC used in experiments today.

Constructing and operating such a detector was beyond the technology of the time, and is still being understood today. The operation of a LArTPC detector and the challenges associated with this are the subject of section 1.5.2.

1.5.2 LAr TPC Operation

explain how they work

new subsubsection

[FIND OR MAKE A FIGURE TO GO WITH THE FOLLOWING DESCRIPTION...]

A LArTPC typically consists of a single, or multiple anode and cathode, at either end of an active drift region. An ionising particle passing through a LArTPC causes electrons to

Table 1.1 Properties of noble elements relevant when considering a TPC medium for a neutrino experiment.

	Water	He	Ne	Ar	Kr	Xe
Boiling point [K] @ 1 atm	373	4.2	27.1	87.3	120.0	165.0
Density [g/cm^3]	1	0.125	1.2	1.4	2.4	3.0
Radiation length [cm]	36.1	755.2	24.0	14.0	4.9	2.8
Scintillation [γ/MeV]	-	19 000	30 000	40 000	25 000	42 000
dE/dx [MeV/cm]	1.9		1.4	2.1	3.0	3.8
Scintillation λ [nm]		80	78	128	150	175
Natural abundance (Earth atm) [ppm]		5.2	18.2	9340.0	1.10	0.09
Electron mobility [cm^2/Vs]		low	low	400	1200	2200

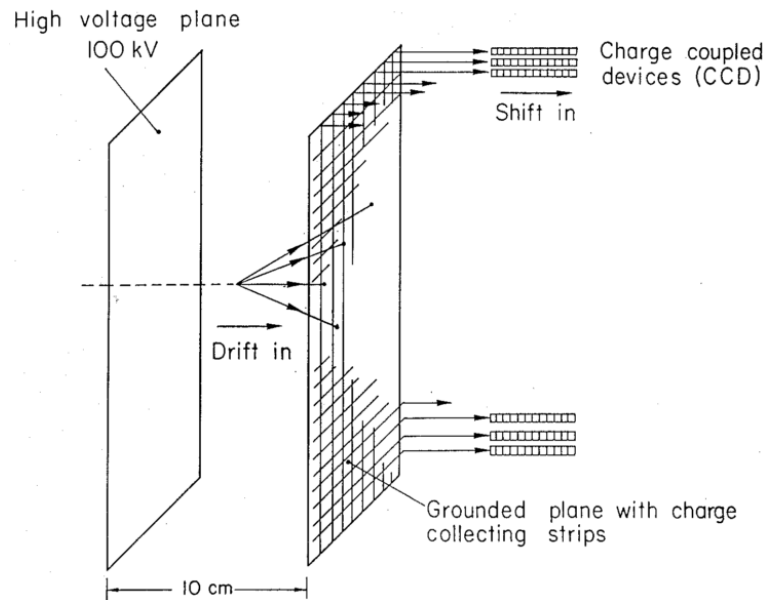


Fig. 1.10 The LArTPC detector proposed by Carlo Rubbia in 1977 [49].

become free from argon atoms and, in the presence of a field, drift towards an anode where they are read out.

The readout consists of multiple wires planes with different orientations to facilitate the reconstruction. The wires are either ‘induction’ wires, which allow the electrons to deposit charge but continue past, or ‘collection’ wires, on which the electric field lines end and all the charge on the electron is collected. Each wire plane is therefore held at a different ‘bias voltage’ to prevent any field lines ending on the induction wire, thus creating local electric fields which promote the continuing forward motion of the electrons. The signal seen is therefore dependent on the type of wire plane; a bipolar pulse on an induction plane wire and unipolar on a collection plane wire. It is also common, though not essential, to make use of a ‘grid plane’ upstream of the signal planes in order to shield them from the electron charge until they are close. Without such a plane, the bipolar pulse would be highly asymmetric, though would still have zero integral. It also makes changing the drift voltage (controlling the electric field) slightly easier as the signal planes are somewhat shielded from its effects. MicroBooNE does not operate with a grid plane and, although the 35t and the DUNE reference design make use of a grid plane, it is uncertain whether the benefit outweighs the cost for a huge LArTPC detector such as the DUNE far detector. It is worth mentioning alternative readout possibilities have been suggested but, given the scale of future LArTPCs, it is highly unlikely a viable solution which delivers superior readout at a comparable cost will be found.

Given the positive ions that are left in the medium, there is the possibility of recombination at a later time and therefore a loss of information about the initial interaction.

This is however accompanied by a flash of scintillation light which is hugely useful as a means of determining the event ‘start time’ (t_0); without this information it would be impossible to place an absolute time scale on the interaction and we would therefore not be able to resolve the coordinate along the drift direction. The magnitude of the electric field applied is the key to both processes and there is thus a compromise which must be struck in order to preserve as much information as possible. The graph in Fig. ?? demonstrates this; a field of 500 V/cm is often chosen in current LAr neutrino experiments.

A cathode is held at a high voltage

Flesh this stuff out...

U plane, V plane and collection all held at different fields. Slightly increasing in order to promote forward motion of the electrons. V held at 0V because it’s cheaper (don’t need crazy voltages, just some negative (still quite high, 100V), 0V and some positive. Grid plane (also held at potential) is to shield the APAs from the electrons until they are close. Not needed, but if not present then pulse wouldn’t be very bipolar! The charge in both portions

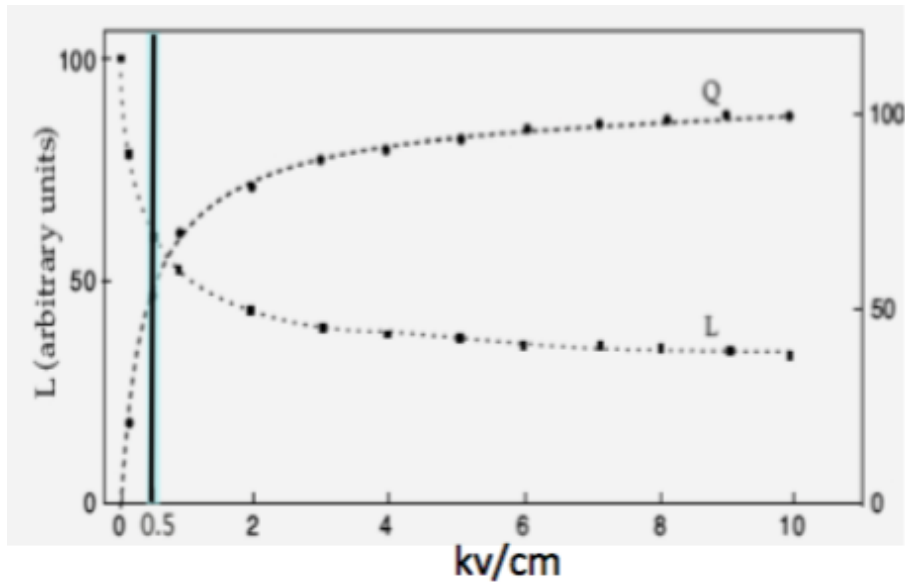


Fig. 1.11 Demonstration of the competing effect the electric field has on the luminosity of the ionisation electrons and scintillation light arriving at the detector readout. Since both are essential in reconstructing the complete interactions, a balance must be found. [PLACEHOLDER IMAGE].

will still equate but the leading end will be muchhhh longer. All electric field lines (generated from movement of electrons) end on the cathode; don't want them to end on the induction wires (hence making sure the field increases). We want them to end on the collection planes, which collects the charge. Signal shaping time (along with gain, the two front-end ASIC parameters) is to let the charge leave the wire before being hit again (or something like this!). Deconvolution I still need to understand...

In 35t, we have FE ASICs which are the very front end and apply the signal shaping and gain. Have regulators to control the power these receive (these are noisy...). Also ADC ASICs to do digitisation in the cold. MicroBooNE don't do this, this just have the front end and do everything else in the warm. FE ASICs are the problem, same for uBooNE and 35t. ADC ASIC has stuck code problem.

References

- [1] Aarnio, P., Abreu, P., Adam, W., Adrianos, P., Adye, T., Akopdzhanov, G., Alekseev, G., Allaby, J., Allen, P., Allport, P., Almed, S., Alvsvaag, S., Amaldi, U., Anassontzis, E., Antilogus, P., Apel, W., Aria, E., Asman, B., Astesan, F., Ferreres, C., Aubret, C., Augustin, J., Augustinus, A., Baillon, P., Barao, F., Barbiellini, G., Bardin, D., Barlag, S., Barlow, J., Baroncelli, A., Barranco-Luque, M., Barreira, G., Barring, O., Bartl, W., Bates, M., Baubillier, M., Becks, K., Beeston, C., Bell, W., Belokopytov, I., Beltran, P., Benedic, D., Benlloch, J., Berggren, M., Berst, J., Bertrand, D., Biagi, S., Bianchi, F., Bibby, J., Bilenky, M., Billoir, P., Bingefors, N., Bjarne, J., Bloch, D., Bogolubov, P., Bollini, D., Bolognese, T., Bonapart, M., Booth, P., Boratav, M., Borgeaud, P., Borner, H., Bosio, C., Botner, O., Bouquet, B., Bozzo, M., Braibant, S., Branchini, P., Brand, C., Brand, K., Bricman, C., Brown, R., Brummer, N., Brunet, J., Bugge, L., Buran, T., Burmeister, H., Buttar, C., Buytaert, J., Cabras, G., Caccia, M., Cairanti, S., Calvi, M., Rozas, A., Campagne, J., Campion, A., Camporesi, T., Canale, V., Cao, F., Carroll, L., Caso, C., Castelli, E., Gimenez, V. C., Cattai, A., Caoallo, F., Cerrito, L., Chadwick, G., Charpentier, P., Checchia, P., Chelkov, G., Chevalier, L., Chiccoli, C., Chiliapnikov, P., Chorowicz, V., Christophel, E., Cirio, R., Clara, M., Contreras, J., Contri, R., Couchot, F., Courty, P., Crawley, H., Crennell, D., Cresti, M., Croissiaux, M., Crosetti, G., Crosland, N., Crozon, M., Maestro, J. C., Curwen, L., Czellar, S., Dahl-Jensen, E., Dalmagne, B., Dam, M., Damgaard, G., Darbo, G., Daubie, E., Davenport, M., Angelis, A. D., Beer, M. D., Clercq, C. D., Groot, N. D., Jode, M. D., Vaissiere, C. D. L., Delikaris, D., Delpierre, P., Ciaccio, L. D., Diddens, A., Dijkstra, H., Dimitriou, N., Djama, F., Dolbeau, J., Doroba, K., Downs, R., Dracos, M., Drees, J., Dris, M., Du, S., Dulinski, W., Dzhelyadin, R., Edwards, D., Eek, L., Eerola, P., Ekelof, T., Ekspong, G., Ellila, M., Engel, J., Falaleev, V., Fenyuk, A., Alonso, M. F., Ferrer, A., Ferroni, S., Filippas, T., Firestone, A., Fischer, H., Fjeld, B., Flinn, M., Foeth, H., Fokitis, E., Folegati, P., Fontanelli, F., Forsbach, H., Fraissard, D., Franek, B., Fransson, K., Frenkiel, P., Fries, D., Froberger, J., Frodesen, A., Fruhwirth, R., Fulda-Quenzer, F., Fuster, J., Gago, J., Gaillard, M., Galeazzi, G., Gamba, D., Garat, C., Gaspar, C., Gasparini, U., Gavillet, P., Gawne, S., Gazis, E., Genat, J., Gerber, J., Glitza, K., Gokieli, R., Golovatyuk, V., Gomes, P., Cadenas, J. G. Y., Goobar, A., Gopal, G., Gorbics, M., Goret, B., Gorski, B., Goujon, G., Gracco, V., Grant, A., Grard, F., Graziani, E., Grillet, J., Gros, M., Gros, M., Grosdidier, G., Grossetete, B., Grung, B., Guglielmi, L., Gumenyuk, S., Guy, J., Hahn, F., Haider, S., Haissinski, J., Hajduk, Z., Hakansson, A., Hallgren, A., Hamacher, K., Monchenault, G. H. D., Harris, F., Heck, B., Herbst, I., Hernandez, J., Herquet, P., Herr, H., Higon, E., Hilke, H., Hofmann, H., Hofmohl, T., Holmgren, S., Hooper, J., Horisberger, R., Houlden, M., Hrisoho, A., Hrubec, J., Huitu, K., Hulth, P., Hultqvist, K., Husson, D., Hyams, B., Imbault, D., Innocente, M., Ioannou, P., Iversen, P., Jackson, J., Jalocha, P., Jarlskog, G., Jarry, P., Jean-Marie, B., Joensuu, J., Johansson, E., Johansson, H., Johansson, S., Jonker,

M., Juillot, P., Kadyrov, R., Kadyshesky, V., Kalkanis, G., Kalmus, G., Kantardjian, G., Katsanevas, S., Katsoufis, E., Keranen, R., Kesteman, J., Khomenko, B., Khovanski, N., King, B., Kisielewski, B., Klein, H., Klempt, W., Klovning, A., Kluit, P., Koene, B., Kokkinias, P., Kontaxis, I., Kopf, M., Koratzinos, M., Korcyl, K., Korytov, A., Korzen, B., Kostarakis, P., Kourkouvelis, C., Kremizis, P., Kreuzberger, T., Krolikowski, J., Krstic, J., Kucewicz, W., Kuhn, G., Kurvinen, K., Laakso, M., Lambropoulos, C., Lanceri, L., Langerveld, D., Lapin, V., Laugier, J., Lauhakangas, R., Laurikainen, P., Lavigne, B., Grand, J. L., Lebbolo, H., Lebreton, E., Leder, G., Lemonne, J., Lenzen, G., Lepeltier, V., Lidbury, J., Lieb, E., Lillestol, E., Lillethun, E., Lippi, I., Llosa, R., Loerstad, B., Loken, J., Aguera, M. L., Lorenz, P., Loukas, D., Lucock, R., Lund-Jensen, B., Lutz, P., Lyons, L., Maehlum, G., Maeland, O., Maillard, J., Makoussis, A., Maltezos, A., Mandl, F., Marco, J., Marin, J., Markou, A., Mathis, L., Matteuzzi, C., Matthiae, G., Mattsson, L., Mayet, N., Mazzucato, M., Cubbin, M. M., Kay, R. M., Menichetti, E., Meroni, C., Meyer, W., Michael, M., Michalowski, J., Mitaroff, W., Mitselmakher, G., Mjoernmark, U., Moa, T., Moeller, R., Moenig, K., Monge, R., Montalbano, G., Morettini, P., Mueller, H., Muller, H., Mur, M., Muryn, B., Myatt, G., Navarria, F., Negri, P., Nielsen, B., Nigro, M., Nikolaenko, V., Noppe, J., Nordberg, M., Nounos, S., Obraztsov, V., Orava, R., Ouraou, A., Pagot, J., Pain, R., Pakonski, K., Palka, H., Lopes, S. P., Papadopoulou, T., Pape, L., Pasini, P., Passeneau, J., Passeneau, M., Passeri, A., Pattison, J., Pegoraro, M., Perevozchikov, V., Perez, J., Pernicka, M., Perrotta, A., Petrucci, G., Pettersen, T., Pimenta, M., Pingot, O., Pinori, C., Pinsent, A., Poirer, C., Pol, M., Poliakov, B., Polok, G., Poropat, P., Privitera, P., Pullia, A., Pyyhtia, J., Quera, P., Quinton, S., Rademakers, A., Radojicic, D., Ragazzi, S., Ragazzon, R., Range, W., Raoul, J., Ratoff, P., Read, A., Redaelli, N., Regler, M., Reid, D., Reis, M., Renton, P., Resvanis, L., Richard, F., Ridky, J., Rinaudo, G., Romaya, A., Romero, A., Roncagliolo, I., Ronchese, P., Rongved, R., Rosenberg, E., Rossel, F., Rosso, E., Roudeau, P., Rovelli, T., Ruhlmann, V., Ruiz, A., Rybicki, K., Saarikko, H., Sacco, D., Sacquin, Y., Sadovsky, A., Salgado, C., Salt, J., Samarin, A., Sanchez, E., Sanchis, E., Sannino, M., Schaeffer, M., Schneider, H., Scuri, F., Sebastia, R., Segar, A., Sekulin, R., Sessa, M., Sette, G., Seufert, R., Shellard, R., Siegrist, P., Simonetti, S., Simonetto, F., Skaali, T., Skeens, J., Skjevling, G., Smadja, G., Smith, G., Sosnowski, R., Spang, K., Spassov, T., Spentzouris, P., Spiriti, E., Squarcia, S., Staack, H., Stanescu, C., Stavropoulos, G., Stichelbaut, F., Stocchi, A., Strauss, J., Strub, R., Sundell, E., Szczekowski, M., Szeptycka, M., Szymanski, P., Tavernier, S., Theodosiou, G., Tilquin, A., Timmermans, J., Tkachev, L., Toet, D., Topp-Jorgensen, S., Topphol, A., Tortora, L., Treille, D., Trevisan, U., Tristram, C., Troncon, C., Truong, T., Tsyganov, E., Turala, M., Turchetta, R., Turlot, J., Turluer, M., Tuuva, T., Tyapkin, I., Tyndel, M., Tyurin, N., Udo, F., Ueberschaer, S., Ullaland, O., Valenti, G., Apeldoorn, G. V., Dam, P. V., Doninck, W. V., Eijk, B. V., Eijndhoven, N. V., Velde, C. V., Vanuxem, J., Varela, J., Vaz, P., Vegni, G., Veitch, M., Vela, E., Velasco, J., Ventura, L., Venus, W., Verbeure, F., Vergezac, P., Vilanova, D., Melo, L. V., Vlasov, E., Vlassopoulos, S., Vodopianov, A., Vollmer, M., Volponi, S., Voulgaris, G., Voutilainen, M., Vrba, V., Wahlen, H., Walck, C., Waldner, F., Wayne, M., Weilhammer, P., Werner, J., Wetherell, A., Wickens, J., Williams, W., Winter, M., Witecki, B., Wormser, G., Woschnagg, K., Yamdagni, N., Yelton, J., Zaitsev, A., Zalewska, A., Zalewski, P., Zevgolatakos, E., Zhang, G., Zimin, N., Zinchenko, A., Zito, M., Zitoun, R., Funchal, R. Z., and Zumerle, G. (1989). Measurement of the mass and width of the Z^0 -particle from multihadronic final states produced in e^+e^- annihilations. *Physics Letters B*, 231(4):539–547.

- [2] Abdurashitov, J. N., Faizov, E. L., Gavrin, V. N., Gusev, A. O., Kalikhov, A. V., Knodel, T. V., Knyschenko, I. I., Kornoukhov, V. N., Mirmov, I. N., Pshukov, A. M., Shalagin, A. M., Shikhin, A. A., Timofeyev, P. V., Veretenkin, E. P., Vermul, V. M., Zatsepin, G. T., Bowles, T. J., Nico, J. S., Teasdale, W. A., Wark, D. L., Wilkerson, J. F., Cleveland, B. T., Daily, T., Davis, R., Lande, K., Lee, C. K., Wildenhain, P. W., Elliott, S. R., Cherry, M. L., and Kouzes, R. T. (1994). Results from SAGE (The Russian-American gallium solar neutrino experiment). *Physics Letters B*, 328(1-2):234–248.
- [3] Adeva, B., Adriani, O., Aguilar-Benitez, M., Akbari, H., Alcaraz, J., Aloisio, A., Alviggi, M. G., An, Q., Anderhub, H., Andersson, A. L., Antonov, L., Antreasyan, D., Arefiev, A., Azemoon, T., Aziz, T., Baba, P., Bagnaia, P., Bakken, J. A., Baksay, L., Ball, R. C., Banerjee, S., Bao, J., Barone, L., Bay, A., Becker, U., Beingessner, S., Bencze, G., Bencze, G., Berdugo, J., Berges, P., Bertucci, B., Betev, B. L., Biland, A., Bizzarri, R., Blaising, J. J., Blömeke, P., Bobbink, G. J., Bocciolini, M., Böhlen, W., Böhm, A., Böhringer, T., Borgia, B., Bourilkov, D., Bourquin, M., Boutigny, D., Branson, J. G., Brock, I. C., Bruyant, F., Burger, J. D., Burq, J. P., Cai, X. D., Campana, D., Camps, C., Capell, M., Carbonara, F., Cartacci, A. M., Cerrada, M., Cesaroni, F., Chang, Y. H., Chaturvedi, U. K., Chemarin, M., Chen, A., Chen, A., Chen, A., Chen, G. M., Chen, H. F., Chen, H. S., Chen, M., Chen, M. L., Chiefari, G., Chien, C. Y., Civinini, C., Clare, I., Clare, R., Coignet, G., Colino, N., Commichau, V., Conforto, G., Contin, A., Crijns, F., Cui, X. Y., Dai, T. S., D'Alessandro, R., Bouard, X. D., Degré, A., Deiters, K., Dénes, E., Denes, P., Denotaristefani, F., Dhina, M., Diemoz, M., Dimitrov, H. R., Dionisi, C., Dittus, F., Dolin, R., Drago, E., Driever, T., Duinker, P., Duran, I., Engler, A., Eppling, F. J., Erné, F. C., Extermann, P., Fabbretti, R., Faber, G., Falciano, S., Fan, S. J., Fabre, M., Fay, J., Fehlmann, J., Fenker, H., Ferguson, T., Fernandez, G., Ferroni, F., Fesefeldt, H., Field, J., Forconi, G., Foreman, T., Freudenreich, K., Friebel, W., Fukushima, M., Gailloud, M., Galaktionov, Y., Gallo, E., Ganguli, S. N., Gau, S. S., Gavrilov, G., Gentile, S., Gettner, M., Glaubman, M., Goldfarb, S., Gong, Z. F., Gonzalez, E., Gordeev, A., Göttlicher, P., Goy, C., Gratta, G., Grimes, A., Grinnell, C., Gruenewald, M., Guanziroli, M., Gurtu, A., Güsewell, D., Haan, H., Hangarter, K., Hancke, S., Harris, M., Harting, D., Hartjes, F. G., He, C. F., Heavy, A., Hebbeker, T., Hebert, M., Herten, G., Herten, U., Hervé, A., Hilgers, K., Hofer, H., Hsu, L. S., Hu, G., Hu, G. Q., Ille, B., Ilyas, M. M., Innocente, V., Isiksal, E., Jagel, E., Jin, B. N., Jones, L. W., Jongmanns, M., Jung, H., Kaaret, P., Khan, R. A., Kamyshkov, Y., Kaplan, D., Karpinski, W., Karyotakis, Y., Khoze, V., Kirkby, D., Kittel, W., Klimentov, A., Klok, P. F., Kollek, M., Koller, M., König, A. C., Kornadt, O., Koutsenko, V., Kraemer, R. W., Krastev, V. R., Krenz, W., Kuhn, A., Kumar, V., Kunin, A., Kwan, S., Landi, G., Lanius, K., Lanske, D., Lanzano, S., Lebeau, M., Lebrun, P., Lecomte, P., Lecoq, P., Coultre, P. L., Leedom, I., Goff, J. M. L., Leistam, L., Leiste, R., Lettry, J., Leytens, X., Li, C., Li, H. T., Li, J. F., Li, L., Li, P. J., Li, X. G., Liao, J. Y., Liu, R., Liu, Y., Lin, Z. Y., Linde, F. L., Lindemann, B., Linnhofer, D., Lohmann, W., Lökös, S., Longo, E., Lu, Y. S., Lubbers, J. M., Lübelmeyer, K., Luci, C., Luckey, D., Ludovici, L., Lue, X., Luminari, L., Ma, W. G., Macdermott, M., Magahiz, R., Maire, M., Malhotra, P. K., Malinin, A., Maña, C., Mao, D. N., Mao, Y. F., Maolinbay, M., Marchesini, P., Marchionni, A., Martin, J. P., Martinez, L., Martyn, H. U., Marzano, F., Massaro, G. G., Matsuda, T., Mazumdar, K., McBride, P., Meinholz, T., Merk, M., Mermoud, R., Merola, L., Meschini, M., Metzger, W. J., Mi, Y., Micke, M., Micke, U., Mills, G. B., Mir, Y., Mirabelli, G., Mnich, J., Moeller, M., Montanet, L., Monteleoni, B., Morand, G., Morand, R., Morganti, S., Morgunov, V., Mount, R., Nagy, E., Napolitano, M., Newman, H., Niessen, L., Nowak, W. D., Onvlee, J., Ossmann, J., Pandoulas, D., Paternoster, G.,

- Patricelli, S., Pei, Y. J., Peng, Y., Perret-Gallix, D., Perrier, J., Perrin, E., Pevsner, A., Pieri, M., Pieri, V., Piroué, P. A., Plyaskin, V., Pohl, M., Pojidaev, V., Pols, C. L. A., Produit, N., Prokofiev, P., Qian, J. M., Qureshi, K. N., Raghavan, R., Rahal-Callot, G., Razis, P., Read, K., Ren, D., Ren, Z., Reucroft, S., Ricker, A., Riemann, T., Rippich, C., Rodriguez, S., Roe, B. P., Röhner, M., Röhner, S., Romero, L., Rose, J., Rosier-Lees, S., Rosselet, P., Rubio, J. A., Ruckstuhl, W., Rykaczewski, H., Sachwitz, M., Salicio, J., Sassowsky, M., Sauvage, G., Savin, A., Schegelsky, V., Schetkovsky, A., Schmitt, P., Schmitz, D., Schmitz, P., Schneegans, M., Schöntag, M., Schotanus, D. J., Schreiber, H. J., Schulte, R., von Dratzig, A., Schultze, K., Schütte, J., Schwenke, J., Schwering, G., Sciacca, C., Seiler, P. G., Sens, J. C., Sheer, I., Shevchenko, V., Shevchenko, S., Shi, X. R., Shmakov, K., Shoutko, V., Shumilov, E., Siedling, R., Smirnov, N., Sopczak, A., Souvorov, V., Souyri, C., Spickermann, T., Spiess, B., Spillantini, P., Starosta, R., Steuer, M., Stickland, D. P., Stöhr, B., Stone, H., Strauch, K., Sudhakar, K., Sumner, R. L., Suter, H., Sutton, R. B., Syed, A. A., Tang, X. W., Tarkovsky, E., Tavenrath, A., Telegdi, V. L., Thenard, J. M., Thomas, E., Timmermans, C., Ting, S. C. C., Ting, S. M., Tong, Y. P., Tonutti, M., Tonwar, S. C., Töth, J., Tung, K. L., Ulbricht, J., Urbán, L., Uwer, U., Valenti, E., van de Walle, R. T., van der Graaf, H., Vetlitsky, I., Viertel, G., Vikas, P., Vivargent, M., Vogel, H., Vogt, H., Volkov, S., Vorobiev, I., Vorobyov, A., Vuilleumier, L., Walk, W., Wallraff, W., Wang, C. Y., Wang, G. H., Wang, J. H., Wang, Q. F., Wang, X. L., Wang, Y. F., Wang, Z. M., Weber, J., Weill, R., Wenaus, T. J., Wenninger, J., White, M., Wilhelm, R., Willmott, C., Wittgenstein, F., Wright, D., Wu, R. J., Wu, S. L., Wu, S. X., Wu, Y. G., Wyslouch, B., Xu, Z. Z., Xue, Z. L., Yan, D. S., Yang, B. Z., Yang, C. G., Yang, G., Yang, K. S., Yang, Q. Y., Yang, Z. Q., Ye, Q., Ye, C. H., Yeh, S. C., Yin, Z. W., You, J. M., Zabounidis, C., Zehnder, L., Zeng, M., Zeng, Y., Zhang, D., Zhang, D. H., Zhang, S. Y., Zhang, Z. P., Zhou, J. F., Zhu, R. Y., Zichichi, A., and Zoll, J. (1989). A determination of the properties of the neutral intermediate vector boson Z^0 . *Physics Letters B*, 231(4):509–518.
- [4] Ahmad, Q. R., Allen, R. C., Andersen, T. C., D'Anglin, J., Barton, J. C., Beier, E. W., Bercovitch, M., Bigu, J., Biller, S. D., Black, R. A., Blevis, I., Boardman, R. J., Boger, J., Bonvin, E., Boulay, M. G., Bowler, M. G., Bowles, T. J., Brice, S. J., Browne, M. C., Bullard, T. V., Bühler, G., Cameron, J., Chan, Y. D., Chen, H. H., Chen, M., Chen, X., Cleveland, B. T., Clifford, E. T. H., Cowan, J. H. M., Cowen, D. F., Cox, G. A., Dai, X., Dalnoki-Veress, F., Davidson, W. F., Doe, P. J., Doucas, G., Dragowsky, M. R., Duba, C. A., Duncan, F. A., Dunford, M., Dunmore, J. A., Earle, E. D., Elliott, S. R., Evans, H. C., Ewan, G. T., Farine, J., Fergani, H., Ferraris, A. P., Ford, R. J., Formaggio, J. A., Fowler, M. M., Frame, K., Frank, E. D., Frati, W., Gagnon, N., Germani, J. V., Gil, S., Graham, K., Grant, D. R., Hahn, R. L., Hallin, A. L., Hallman, E. D., Hamer, A. S., Hamian, A. A., Handler, W. B., Haq, R. U., Hargrove, C. K., Harvey, P. J., Hazama, R., Heeger, K. M., Heintzelman, W. J., Heise, J., Helmer, R. L., Hepburn, J. D., Heron, H., Hewett, J., Hime, A., Howe, M., Hykawy, J. G., Isaac, M. C. P., Jagam, P., Jelley, N. A., Jillings, C., Jonkmans, G., Kazkaz, K., Keener, P. T., Klein, J. R., Knox, A. B., Komar, R. J., Kouzes, R., Kutter, T., Kyba, C. C. M., Law, J., Lawson, I. T., Lay, M., Lee, H. W., Lesko, K. T., Leslie, J. R., Levine, I., Locke, W., Luoma, S., Lyon, J., Majerus, S., Mak, H. B., Maneira, J., Manor, J., Marino, A. D., McCauley, N., McDonald, A. B., McDonald, D. S., McFarlane, K., McGregor, G., Meijer Drees, R., Mifflin, C., Miller, G. G., Milton, G., Moffat, B. A., Moorhead, M., Nally, C. W., Neubauer, M. S., Newcomer, F. M., Ng, H. S., Noble, A. J., Norman, E. B., Novikov, V. M., O'Neill, M., Okada, C. E., Ollerhead, R. W., Omori, M., Orrell, J. L., Oser, S. M., Poon, A. W. P., Radcliffe, T. J., Roberge, A., Robertson, B. C., Robertson, R. G. H., Rosendahl, S. S. E., Rowley, J. K.,

- Rusu, V. L., Saettler, E., Schaffer, K. K., Schwendener, M. H., Schülke, A., Seifert, H., Shatkay, M., Simpson, J. J., Sims, C. J., Sinclair, D., Skensved, P., Smith, A. R., Smith, M. W. E., Spreitzer, T., Starinsky, N., Steiger, T. D., Stokstad, R. G., Stonehill, L. C., Storey, R. S., Sur, B., Tafirout, R., Tagg, N., Tanner, N. W., Taplin, R. K., Thorman, M., Thornewell, P. M., Trent, P. T., Tserkovnyak, Y. I., Van Berg, R., de Water, R. G., Virtue, C. J., Waltham, C. E., Wang, J.-X., Wark, D. L., West, N., Wilhelmy, J. B., Wilkerson, J. F., Wilson, J. R., Wittich, P., Wouters, J. M., and Yeh, M. (2002). Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory. *Phys. Rev. Lett.*, 89(1):11301.
- [5] Akrawy, M. Z., Alexander, G., Allison, J., Allport, P. P., Anderson, K. J., Armitage, J. C., Arnison, G. T. J., Ashton, P., Azuelos, G., Baines, J. T. M., Ball, A. H., Banks, J., Barker, G. J., Barlow, R. J., Batley, J. R., Bavaria, G., Beard, C., Beck, F., Bell, K. W., Bella, G., Bethke, S., Biebel, O., Bloodworth, I. J., Bock, P., Boerner, H., Breuker, H., Brown, R. M., Brun, R., Buijs, A., Burckhart, H. J., Capiluppi, P., Carnegie, R. K., Carter, A. A., Carter, J. R., Chang, C. Y., Charlton, D. G., Chrin, J. T. M., Cohen, I., Conboy, J. E., Couch, M., Coupland, M., Cuffiani, M., Dado, S., Dallavalle, G. M., Davies, O. W., Deninno, M. M., Dieckmann, A., Dittmar, M., Dixit, M. S., Duchesneau, D., Duchovni, E., Duerdoth, I. P., Dumas, D., Mamouni, H. E., Elcombe, P. A., Estabrooks, P. G., Fabbri, F., Farthouat, P., Fischer, H. M., Fong, D. G., French, M. T., Fukunaga, C., Gandois, B., Ganel, O., Gary, J. W., Geddes, N. I., Gee, C. N. P., Geich-Gimbel, C., Gensler, S. W., Gentit, F. X., Giacomelli, G., Gibson, W. R., Gillies, J. D., Goldberg, J., Goodrick, M. J., Gorn, W., Granite, D., Gross, E., Grosse-Wiesmann, P., Grunhaus, J., Hagedorn, H., Hagemann, J., Hansroul, M., Hargrove, C. K., Hart, J., Hattersley, P. M., Hatzifotiadiou, D., Hauschild, M., Hawkes, C. M., Heflin, E., Heintze, J., Hemingway, R. J., Heuer, R. D., Hill, J. C., Hillier, S. J., Hinde, P. S., Ho, C., Hobbs, J. D., Hobson, P. R., Hochman, D., Holl, B., Homer, R. J., Hou, S. R., Howarth, C. P., Hughes-Jones, R. E., Igo-Kemenes, P., Imori, M., Imrie, D. C., Jawahery, A., Jeffreys, P. W., Jeremie, H., Jimack, M., Jin, E., Jobes, M., Jones, R. W. L., Jovanovic, P., Karlen, D., Kawagoe, K., Kawamoto, T., Kellogg, R. G., Kennedy, B. W., Kleinwort, C., Klem, D. E., Knop, G., Kobayashi, T., Koepke, L., Kokott, T. P., Koshiba, M., Kowalewski, R., Kreutzmann, H., von Krogh, J., Kroll, J., Kyberd, P., Lafferty, G. D., Lamarche, F., Larson, W. J., Lasota, M. M. B., Layter, J. G., le Du, P., Leblanc, P., Lellouch, D., Lennert, P., Lessard, L., Levinson, L., Lloyd, S. L., Loebinger, F. K., Lorah, J. M., Lorazo, B., Losty, M. J., Ludwig, J., Lupu, N., Ma, J., Macbeth, A. A., Mannelli, M., Marcellini, S., Maringer, G., Martin, J. P., Mashimo, T., Mättig, P., Maur, U., McMahon, T. J., McPherson, A. C., Meijers, F., Menszner, D., Merritt, F. S., Mes, H., Michelini, A., Middleton, R. P., Mikenberg, G., Miller, D. J., Milstene, C., Minowa, M., Mohr, W., Montanari, A., Mori, T., Moss, M. W., Muller, A., Murphy, P. G., Murray, W. J., Nellen, B., Nguyen, H. H., Nozaki, M., O'Dowd, A. J. P., O'Neale, S. W., O'Neill, B., Oakham, F. G., Odorici, F., Ogg, M., Oh, H., Oreglia, M. J., Orito, S., Patrick, G. N., Pawley, S. J., Perez, A., Pilcher, J. E., Pinfold, J. L., Plane, D. E., Poli, B., Possoz, A., Pouladdej, A., Pritchard, T. W., Quast, G., Raab, J., Redmond, M. W., Rees, D. L., Regimbald, M., Riles, K., Roach, C. M., Roehner, F., Rollnik, A., Roney, J. M., Rossi, A. M., Routenburg, P., Runge, K., Runolfsson, O., Sanghera, S., Sansum, R. A., Sasaki, M., Saunders, B. J., Schaile, A. D., Schaile, O., Schappert, W., Scharff-Hansen, P., von der Schmitt, H., Schreiber, S., Schwarz, J., Shapira, A., Shen, B. C., Sherwood, P., Simon, A., Siroli, G. P., Skuja, A., Smith, A. M., Smith, T. J., Snow, G. A., Spreadbury, E. J., Springer, R. W., Sproston, M., Stephens, K., Stier, H. E., Ströhmer, R., Strom, D., Takeda, H., Takeshita, T., Tsukamoto, T., Turner, M. F., Tysarczyk, G., van den Plas,

- D., Vandalen, G. J., Virtue, C. J., Wagner, A., Wahl, C., Wang, H., Ward, C. P., Ward, D. R., Waterhouse, J., Watkins, P. M., Watson, A. T., Watson, N. K., Weber, M., Weisz, S., Wormes, N., Weymann, M., Wilson, G. W., Wilson, J. A., Wingerter, I., Winterer, V.-H., Wood, N. C., Wotton, S., Wuensch, B., Wyatt, T. R., Yaari, R., Yamashita, H., Yang, Y., Yekutieli, G., Zeuner, W., Zorn, G. T., and Zylberajch, S. (1989). Measurement of the Z0 mass and width with the opal detector at LEP. *Physics Letters B*, 231(4):530–538.
- [6] Amerio, S., Amoruso, S., Antonello, M., Aprili, P., Armenante, M., Arneodo, F., Badertscher, A., Baiboussinov, B., Baldo Ceolin, M., Battistoni, G., Bekman, B., Benetti, P., Bernardini, E., Bischofberger, M., Borio di Tigliole, A., Brunetti, R., Bruzzese, R., Bueno, A., Calligarich, E., Campanelli, M., Carbonara, F., Carpanese, C., Cavalli, D., Cavanna, F., Cennini, P., Centro, S., Cesana, A., Chen, C., Chen, D., Chen, D. B., Chen, Y., Cid, R., Cline, D. B., Cieplik, K., Cocco, A. G., Corti, D., Dai, Z., de Vecchi, C., Dabrowska, A., di Cicco, A., Dolfini, R., Ereditato, A., Felcini, M., Ferella, A., Ferrari, A., Ferri, F., Fiorillo, G., Galli, S., Garcia Gamez, D., Ge, Y., Gibin, D., Gigli Berzolari, A., Gil-Botella, I., Graczyk, K., Grandi, L., Guglielmi, A., He, K., Holeczek, J., Huang, X., Juszczak, C., Kielczewska, D., Kisiel, J., Kozlowski, T., Kuna-Ciskal, H., Laffranchi, M., Lagoda, J., Li, Z., Lisowski, B., Lu, F., Ma, J., Mangano, G., Mannocchi, G., Markiewicz, M., Martinez de la Ossa, A., Matthey, C., Mauri, F., Mazza, D., Melgarejo, A. J., Menegolli, A., Meng, G., Messina, M., Mielinski, J. W., Montanari, C., Muraro, S., Navas-Concha, S., Nicoletto, M., Nowak, J., Nurzia, G., Osuna, C., Otwinowski, S., Ouyang, Q., Palamara, O., Pascoli, D., Periale, L., Piano Mortari, G., Piazzoli, A., Picchi, P., Pietropaolo, F., Pichlopek, W., Prata, M., Rancati, T., Rappoldi, A., Raselli, G. L., Rico, J., Rondio, E., Rossella, M., Rubbia, A., Rubbia, C., Sala, P., Santorelli, R., Scannicchio, D., Segreto, E., Seo, Y., Sergiampietri, F., Sobczyk, J., Spinelli, N., Stepaniak, J., Sulej, R., Szeptycka, M., Szarska, M., Terrani, M., Trincherro, G., Velotta, R., Ventura, S., Vignoli, C., Wang, H., Wang, X., Woo, J., Xu, G., Xu, Z., Yang, X., Zalewska, A., Zalipska, J., Zhang, C., Zhang, Q., Zhen, S., and Zipper, W. (2004). Design, construction and tests of the ICARUS T600 detector. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 527(3):329–410.
- [7] Anselmann, P., Hampel, W., Heusser, G., Kiko, J., Kirsten, T., Pernicka, E., Plaga, R., Rönn, U., Sann, M., Schlosser, C., Wink, R., Wójcik, M., von Ammon, R., Ebert, K. H., Fritsch, T., Hellriegel, K., Henrich, E., Stieglitz, L., Weyrich, F., Balata, M., Bellotti, E., Ferrari, N., Lalla, H., Stolarczyk, T., Cattadori, C., Cremonesi, O., Fiorini, E., Pezzoni, S., Zanotti, L., von Feilitzsch, F., Mößbauer, R., Schanda, U., Berthomieu, G., Schatzman, E., Carmi, I., Dostrovsky, I., Bacci, C., Belli, P., Bernabei, R., D’Angelo, S., Paoluzi, L., Charbit, S., Cribier, M., Dupont, G., Gosset, L., Rich, J., Spiro, M., Tao, C., Vignaud, D., Hahn, R. L., Hartmann, F. X., Rowley, J. K., Stoenner, R. W., and Weneser, J. (1992). Solar neutrinos observed by GALLEX at Gran Sasso. *Physics Letters B*, 285(4):376–389.
- [8] Bahcall, J. N. (2005). Solar Models and Solar Neutrinos. *Physica Scripta*, 2005(T121):46.
- [9] Bahcall, J. N., Bahcall, N. A., and Shaviv, G. (1968). Present Status of the Theoretical Predictions for the ^{37}Cl Solar-Neutrino Experiment. *Phys. Rev. Lett.*, 20(21):1209–1212.
- [10] Bahcall, J. N., Pinsonneault, M. H., and Wasserburg, G. J. (1995). Solar models with helium and heavy-element diffusion. *Rev. Mod. Phys.*, 67(4):781–808.

- [11] Bahcall, J. N., Serenelli, A. M., and Basu, S. (2005). New Solar Opacities, Abundances, Helioseismology, and Neutrino Fluxes. *The Astrophysical Journal*, 621(1):L85–L88.
- [12] Becker-Szendy, R., Bratton, C. B., Casper, D., Dye, S. T., Gajewski, W., Goldhaber, M., Haines, T. J., Halverson, P. G., Kielczewska, D., Kropp, W. R., Learned, J. G., LoSecco, J. M., Matsuno, S., McGrath, G., McGrew, C., Miller, R., Price, L. R., Reines, F., Schultz, J., Sobel, H. W., Stone, J. L., Sulak, L. R., and Svoboda, R. (1992). Electron- and muon-neutrino content of the atmospheric flux. *Phys. Rev. D*, 46(9):3720–3724.
- [13] Bethe, H. A. (1939). Energy Production in Stars. *Phys. Rev.*, 55(5):434–456.
- [14] Brown, R., Camerini, U., Fowler, P. H., Muirhead, H., Powell, C. F., and Ritson, D. M. (1949). Observations With Electron Sensitive Plates Exposed to Cosmic Radiation. *Nature*, 163:82.
- [15] Burmester, J., Criegee, L., Dehne, H. C., Derikum, K., Devenish, R., Flügge, G., Fox, J. D., Franke, G., Gerke, C., Harms, P., Horlitz, G., Kahl, T., Knies, G., Rössler, M., Schmitz, R., Timm, U., Wahl, H., Waloschek, P., Winter, G. G., Wolff, S., Zimmermann, W., Blobel, V., Koppitz, B., Lohrmann, E., Lührsén, W., Bäcker, A., Bürger, J., Grupen, C., Zech, G., Meyer, H., and Wacker, K. (1977). Anomalous muon production in e^+e^- annihilations as evidence for heavy leptons. *Physics Letters B*, 68(3):297–300.
- [16] Casper, D., Becker-Szendy, R., Bratton, C. B., Cady, D. R., Claus, R., Dye, S. T., Gajewski, W., Goldhaber, M., Haines, T. J., Halverson, P. G., Jones, T. W., Kielczewska, D., Kropp, W. R., Learned, J. G., LoSecco, J. M., McGrew, C., Matsuno, S., Matthews, J., Mudan, M. S., Price, L., Reines, F., Schultz, J., Sinclair, D., Sobel, H. W., Stone, J. L., Sulak, L. R., Svoboda, R., Thornton, G., and van der Velde, J. C. (1991). Measurement of atmospheric neutrino composition with the IMB-3 detector. *Phys. Rev. Lett.*, 66(20):2561–2564.
- [17] Cleveland, B. T., Daily, T., Davis, R., Distel, J., Lande, K., Lee, C. K., Wildenhain, P., and Ullman, J. (1995). Update on the measurement of the solar neutrino flux with the Homestake chlorine detector. *Nuclear Physics B (Proceedings Supplements)*, 38(1-3):47–53.
- [18] Cowan, C. L., Reines, F., Harris, F. B., Kruse, H. W., and Mcgu, A. D. (1956). Detection of the Free Neutrino: a Confirmation. *Science*, 124(3212):103–104.
- [19] Cowan, C. L., Reines, F., Harrison, F. B., Anderson, E. C., and Hayes, F. N. (1953). Large Liquid Scintillation Detectors. *Phys. Rev.*, 90(3):493–494.
- [20] Curioni, A., Fleming, B. T., Jaskierny, W., Kendziora, C., Krider, J., Pordes, S., Soderberg, M., Spitz, J., Tope, T., and Wongjirad, T. (2009). A regenerable filter for liquid argon purification. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 605(3):306–311.
- [21] Danby, G., Gaillard, J.-M., Goulianos, K., Lederman, L. M., Mistry, N., Schwartz, M., and Steinberger, J. (1962). Observation of High-Energy Neutrino Reactions and the Existence of Two Kinds of Neutrinos. *Phys. Rev. Lett.*, 9(1):36–44.
- [22] Davis Jr., R. and Harmer, D. S. (1959). Attempt to observe the $\text{Cl}^{37}(\bar{\nu}e^-)\text{Ar}^{37}$ reaction induced by reactor antineutrinos. *Bull. Am. Phys. Soc.*, 4:217.

- [23] DeCamp, D., Deschizeaux, B., Lees, J. P., Minard, M. N., Crespo, J. M., Delfino, M., Fernandez, E., Martinez, M., Miquel, R., Mir, M. L., Orteu, S., Pacheco, A., Perlas, J. A., Tubau, E., Catanesi, M. G., de Palma, M., Farilla, A., Iaselli, G., Maggi, G., Mastrogiacono, A., Natali, S., Nuzzo, S., Ranieri, A., Raso, G., Romano, F., Ruggieri, F., Selvaggi, G., Silvestris, L., Tempesta, P., Zito, G., Chen, Y., Huang, D., Lin, J., Ruan, T., Wang, T., Wu, W., Xie, Y., Xu, D., Xu, R., Zhang, J., Zhao, W., Albrecht, H., Bird, F., Blucher, E., Charity, T., Drevermann, H., Garrido, L., Grab, C., Hagelberg, R., Haywood, S., Jost, B., Kasemann, M., Kellner, G., Knobloch, J., Lacourt, A., Lehraus, I., Lohse, T., L?ke, D., Marchioro, A., Mato, P., May, J., Mertens, V., Minten, A., Miotto, A., Palazzi, P., Pepe-Altarelli, M., Ranjard, F., Richstein, J., Roth, A., Rothberg, J., Rotscheidt, H., von R?den, W., Schlatter, D., St.Denis, R., Takashima, M., Talby, M., Taureg, H., Tejessy, W., Wachsmuth, H., Wheeler, S., Wiedenmann, W., Witzeling, W., Wotschack, J., Ajaltouni, Z., Bardadin-Otwinowska, M., Falvard, A., Gay, P., Henrard, P., Jousset, J., Michel, B., Montret, J. C., Pallin, D., Perret, P., Prat, J., Proriol, J., Prulhi?re, F., Bertelsen, H., Hansen, F., Hansen, J. R., Hansen, J. D., Hansen, P. H., Lindahl, A., Madsen, B., M?llerud, R., Nilsson, B. S., Petersen, G., Simopoulou, E., Vayaki, A., Badier, J., Bernard, D., Blondel, A., Bonneaud, G., Bourotte, J., Braems, F., Brient, J. C., Ciocchi, M. A., Fouque, G., Guirlet, R., Min?, P., Roug?, A., Rumpf, M., Videau, H., Videau, I., Zwierski, D., Candlin, D. J., Conti, A., Parrini, G., Corden, M., Georgiopoulos, C., Goldman, J. H., Ikeda, M., Levinthal, D., Lannutti, J., Mermikides, M., Sawyer, L., Antonelli, A., Baldini, R., Bencivenni, G., Bologna, G., Bossi, F., Campana, P., Capon, G., Chiarella, V., De Ninno, G., D'Ettore-Piazzoli, B., Felici, G., Laurelli, P., Mannocchi, G., Murtas, F., Murtas, G. P., Nicoletti, G., Picchi, P., Zografou, P., Altoon, B., Boyle, O., Flavell, A. J., Halley, A. W., Ten Have, I., Hearn, J. A., Hughes, I. S., Lynch, J. G., Martin, D. J., O'Neill, R., Raine, C., Scarr, J. M., Smith, K., Thompson, A. S., Brandl, B., Braun, O., Geiges, R., Geweniger, C., Hanke, P., Hepp, V., Kluge, E. E., Maumary, Y., Panter, M., Putzer, A., Rensch, B., Stahl, A., Tittel, K., Wunsch, M., Barber, G. J., Belk, A. T., Beuselinck, R., Binnie, D. M., Cameron, W., Cattaneo, M., Dornan, P. J., Dugeay, S., Forty, R. W., Gentry, D. N., Hassard, J. F., Miller, D. G., Price, D. R., Sedgbeer, J. K., Tomalin, I. R., Taylor, G., Girtler, P., Kuhn, D., Rudolph, G., Brodbeck, T. J., Bowdery, C., Finch, A. J., Foster, F., Hughes, G., Keemer, N. R., Nuttall, M., Rowlingson, B. S., Sloan, T., Snow, S. W., Barczewski, T., Bauerdick, L. A. T., Kleinknecht, K., Pollmann, D., Renk, B., Roehn, S., Sander, H. G., Schmelling, M., Steeg, F., Albanese, J. P., Aubert, J. J., Benchouk, C., Bonissent, A., Etienne, F., Nacasch, R., Payre, P., Pietrzyk, B., Qian, Z., Blum, W., Cattaneo, P., Comin, M., Dehning, B., Cowan, G., Dietl, H., Fernandez-Bosman, M., Hauff, D., Jahn, A., Lange, E., L?tjens, G., Lutz, G., M?nner, W., Moser, H. G., Pan, Y., Richter, R., Schwarz, A., Settles, R., Stiegler, U., Stierlin, U., Stimpfl, G., Thomas, J., Waltermann, G., Boucrot, J., Callot, O., Cordier, A., Davier, M., De Bouard, G., Ganis, G., Grivaz, J. F., Heusse, P., Janot, P., Journ?, V., Kim, D. W., Lefran?ois, J., Lloyd-Owen, D., Lutz, A. M., Marotte, P., Veillet, J. J., Amendolia, S. R., Bagliesi, G., Batignani, G., Bosisio, L., Bottigli, U., Bradaschia, C., Ferrante, I., Fidecaro, F., Fo?, L., Focardi, E., Forti, F., Giassi, A., Giorgi, M. A., Ligabue, F., Lusiani, A., Mannelli, E. B., Marrocchesi, P. S., Messineo, A., Palla, F., Sanguinetti, G., Scapellato, S., Steinberger, J., Tenchini, R., Tonelli, G., Triggiani, G., Carter, J. M., Green, M. G., McKemey, A. K., March, P. V., Medcalf, T., Saich, M. R., Strong, J., Thomas, R. M., Wildish, T., Botterill, D. R., Clift, R. W., Edgecock, T. R., Edwards, M., Fisher, S. M., Hill, D. L., Jones, T. J., McPherson, G., Morrissey, M., Norton, P. R., Salmon, D. P., Tappern, G. J., Thompson, J. C., Harvey, J., Bloch-Devau, B., Colas, P., Klopfenstein, C., Lan?on, E., Locci, E.,

- Loucatos, S., Mirabito, L., Monnier, E., Perez, P., Perrier, F., Pignard, B., Rander, J., Renardy, J. F., Roussarie, A., Schuller, J. P., Turlay, R., Ashman, J. G., Booth, C. N., Combley, F., Dinsdale, M., Martin, J., Parker, D., Thompson, L. F., Brandt, S., Burkhardt, H., Grupen, C., Meinhard, H., Neugebauer, E., Schöfer, U., Seywerd, H., Stupperich, K., Gobbo, B., Liello, F., Milotti, E., Ragusa, F., Rolandi, L., Bellantoni, L., Boudreau, J. F., Cinabro, D., Conway, J. S., Cowen, D. F., Feng, Z., Harton, J. L., Hilgart, J., Jared, R. C., Johnson, R. P., Leclaire, B. W., Pan, Y. B., Parker, T., Pater, J. R., Saadi, Y., Sharma, V., Wear, J. A., Weber, F. V., Sau Lan Wu, Xue, S. T., and Zobernig, G. (1989). Determination of the number of light neutrino species. *Physics Letters B*, 231(4):519–529.
- [24] Feldman, G. J., Bulos, F., Lüke, D., Abrams, G. S., Alam, M. S., Boyarski, A. M., Breidenbach, M., Dorfan, J., Friedberg, C. E., Fryberger, D., Goldhaber, G., Hanson, G., Heile, F. B., Jaros, J. A., Kadyk, J. A., Larsen, R. R., Litke, A. M., Lüth, V., Madaras, R. J., Morehouse, C. C., Nguyen, H. K., Paterson, J. M., Perl, M. L., Peruzzi, I., Piccolo, M., Pierre, F. M., Pun, T. P., Rapidis, P., Richter, B., Sadoulet, B., Schwitters, R. F., Tanenbaum, W., Trilling, G. H., Vannucci, F., Whitaker, J. S., and Wiss, J. E. (1977). Inclusive Anomalous Muon Production in e^+e^- Annihilation. *Phys. Rev. Lett.*, 38(3):117–120.
- [25] Fermi, E. (1934a). Trends to a Theory of beta Radiation. (In Italian). *Nuovo Cim.*, 11:1–19.
- [26] Fermi, E. (1934b). Versuch einer Theorie der β -Strahlen. I. *Zeitschrift für Physik*, 88(3):161–177.
- [27] Freeman, J. (2014). Courtesy of John Freeman, Fermilab.
- [28] Fukuda, Y., Hayakawa, T., Ichihara, E., Inoue, K., Ishihara, K., Ishino, H., Itow, Y., Kajita, T., Kameda, J., Kasuga, S., Kobayashi, K., Kobayashi, Y., Koshio, Y., Miura, M., Nakahata, M., Nakayama, S., Okada, A., Okumura, K., Sakurai, N., Shiozawa, M., Suzuki, Y., Takeuchi, Y., Totsuka, Y., Yamada, S., Earl, M., Habig, A., Kearns, E., Messier, M. D., Scholberg, K., Stone, J. L., Sulak, L. R., Walter, C. W., Goldhaber, M., Barszczak, T., Casper, D., Gajewski, W., Halverson, P. G., Hsu, J., Kropp, W. R., Price, L. R., Reines, F., Smy, M., Sobel, H. W., Vagins, M. R., Ganezer, K. S., Keig, W. E., Ellsworth, R. W., Tasaka, S., Flanagan, J. W., Kibayashi, A., Learned, J. G., Matsuno, S., Stenger, V. J., Takemori, D., Ishii, T., Kanzaki, J., Kobayashi, T., Mine, S., Nakamura, K., Nishikawa, K., Oyama, Y., Sakai, A., Sakuda, M., Sasaki, O., Echigo, S., Kohama, M., Suzuki, A. T., Haines, T. J., Blaufuss, E., Kim, B. K., Sanford, R., Svoboda, R., Chen, M. L., Conner, Z., Goodman, J. A., Sullivan, G. W., Hill, J., Jung, C. K., Martens, K., Mauger, C., McGrew, C., Sharkey, E., Viren, B., Yanagisawa, C., Doki, W., Miyano, K., Okazawa, H., Saji, C., Takahata, M., Nagashima, Y., Takita, M., Yamaguchi, T., Yoshida, M., Kim, S. B., Etoh, M., Fujita, K., Hasegawa, A., Hasegawa, T., Hatakeyama, S., Iwamoto, T., Koga, M., Maruyama, T., Ogawa, H., Shirai, J., Suzuki, A., Tsushima, F., Koshiba, M., Nemoto, M., Nishijima, K., Futagami, T., Hayato, Y., Kanaya, Y., Kaneyuki, K., Watanabe, Y., Kielczewska, D., Doyle, R. A., George, J. S., Stachyra, A. L., Wai, L. L., Wilkes, R. J., and Young, K. K. (1998). Evidence for Oscillation of Atmospheric Neutrinos. *Phys. Rev. Lett.*, 81(8):1562–1567.
- [29] Fukuda, Y., Hayakawa, T., Inoue, K., Ishida, T., Joukou, S., Kajita, T., Kasuga, S., Koshio, Y., Kumita, T., Matsumoto, K., Nakahata, M., Nakamura, K., Sakai, A., Shiozawa,

- M., Suzuki, J., Suzuki, Y., Totsuka, Y., Hirata, K. S., Kihara, K., Mori, M., Oyama, Y., Suzuki, A., Yamada, M., Koshiba, M., Nishijima, K., Kajimura, T., Suda, T., Suzuki, A. T., Ishizuka, T., Koga, M., Miyano, K., Miyata, H., Okazawa, H., Takei, H., Hara, T., Kishi, N., Nagashima, Y., Takita, M., Yoshimoto, A., Hayato, Y., Kaneyuki, K., Takeuchi, Y., Tanimori, T., Tasaka, S., Nishikawa, K., Beier, E. W., Frank, E. D., Frati, W., Kim, S. B., Mann, A. K., Newcomer, F. M., Berg, R. V., and Zhang, W. (1994). Atmospheric $\nu\mu$ ve ratio in the multi-GeV energy range. *Physics Letters B*, 335(2):237–245.
- [30] Gaisser, T. K. (1990). *Cosmic rays and particle physics*.
- [31] Gribov, V. and Pontecorvo, B. (1969). Neutrino astronomy and lepton charge. *Physics Letters B*, 28(7):493–496.
- [32] Hahn, A., Adamowski, M., Montanari, D., Norris, B., Reichenbacher, J., Rucinski, R., and Tope, T. (2014). The LBNE 35 Ton Prototype Cryostat. In *FERMILAB-CONF-14-420-PPD The*.
- [33] Haines, T. J., Bionta, R. M., Blewitt, G., Bratton, C. B., Casper, D., Claus, R., Cortez, B. G., Errede, S., Foster, G. W., Gajewski, W., Ganezer, K. S., Goldhaber, M., Jones, T. W., Kielczewska, D., Kropp, W. R., Learned, J. G., Lehmann, E., LoSecco, J. M., Matthews, J., Park, H. S., Price, L. R., Reines, F., Schultz, J., Seidel, S., Shumard, E., Sinclair, D., Sobel, H. W., Stone, J. L., Sulak, L., Svoboda, R., van der Velde, J. C., and Wuest, C. (1986). Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon-Decay Search. *Phys. Rev. Lett.*, 57(16):1986–1989.
- [34] Hampel, W., Heusser, G., Kiko, J., Kirsten, T., Laubenstein, M., Pernicka, E., Rau, W., Rönn, U., Schlosser, C., Wojcik, M., Zakharov, Y., Ammon, R. V., Ebert, K. H., Fritsch, T., Heidt, D., Henrich, E., Stieglitz, L., Weirich, F., Balata, M., Sann, M., Hartmann, F. X., Bellotti, E., Cattadori, C., Cremonesi, O., Ferrari, N., Fiorini, E., Zanotti, L., Altmann, M., Feilitzsch, F. V., Mößbauer, R., Berthomieu, G., Schatzman, E., Carmi, I., Dostrovsky, I., Bacci, C., Belli, P., Bernabei, R., D’Angelo, S., Paoluzi, L., Bevilacqua, A., Cribier, M., Gosset, L., Rich, J., Spiro, M., Tao, C., Vignaud, D., Boger, J., Hahn, R. L., Rowley, J. K., Stoenner, R. W., and Weneser, J. (1999). GALLEX solar neutrino observations: Results for GALLEX IV. *Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics*, 447:127–133.
- [35] Hirata, K. S., Kajita, T., Koshiba, M., Nakahata, M., Ohara, S., Oyama, Y., Sato, N., Suzuki, A., Takita, M., Totsuka, Y., Kifune, T., Suda, T., Nakamura, K., Takahashi, K., Tanimori, T., Miyano, K., Yamada, M., Beier, E. W., Feldscher, L. R., Frank, E. D., Frati, W., Kim, S. B., Mann, A. K., Newcomer, F. M., Berg, R. V., Zhang, W., and Cortez, B. G. (1988). Experimental study of the atmospheric neutrino flux. *Physics Letters B*, 205(2):416–420.
- [36] Kodama, K., Ushida, N., Andreopoulos, C., Saoulidou, N., Tzanakos, G., Yager, P., Baller, B., Boehnlein, D., Freeman, W., Lundberg, B., Morfin, J., Rameika, R., Yun, J. C., Song, J. S., Yoon, C. S., Chung, S. H., Berghaus, P., Kubantsev, M., Reay, N. W., Sidwell, R., Stanton, N., Yoshida, S., Aoki, S., Hara, T., Rhee, J. T., Ciampa, D., Erickson, C., Graham, M., Heller, K., Rusack, R., Schwienhorst, R., Sielaff, J., Trammell, J., Wilcox, J., Hoshino, K., Jiko, H., Miyanishi, M., Komatsu, M., Nakamura, M., Nakano, T., Niwa, K., Nonaka, N., Okada, K., Sato, O., Akdogan, T., Paolone, V., Rosenfeld, C., Kulik, A.,

- Kafka, T., Oliver, W., Patzak, T., and Schneps, J. (2001). Observation of tau neutrino interactions. *Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics*, 504(3):218–224.
- [37] Lattes, C. M. G., Muirhead, H., Occhialini, G. P. S., and Powell, C. F. (1947a). Processes Involving Charged Mesons. *Nature*, 159:694–697.
- [38] Lattes, C. M. G., Occhialini, G. P. S., and Powell, C. F. (1947b). Observations on the Tracks of Slow Mesons in Photographic Emulsions. 1. *Nature*, 160:453–456, 486–492.
- [39] Lewis, G. M. (1970). *Neutrinos*. Wykeham publications, London; Winchester.
- [40] Maki, Z., Nakagawa, M., and Sakata, S. (1962). Remarks on the Unified Model of Elementary Particles. *Progress of Theoretical Physics*, 28(5):870.
- [41] Mann, W. A. (2000). Atmospheric neutrinos and the oscillations bonanza. *Int. J. Mod. Phys.*, A15S1:229–256.
- [42] Montanari, D., Adamowski, M., Baller, B. R., Barger, R. K., Chi, E. C., Davis, R. P., Johnson, B. D., Kubinski, B. M., Mahoney, R., McCluskey, E. G., Najdzion, J. J., Norris, B. L., Rucinski, R. A., Schmitt, R. L., Stewart, J., Tope, T. E., and Watkins, D. J. (2014). First scientific application of the membrane cryostat technology. 1664(2014):1664–1671.
- [43] Nygren, D. R. (1974). The Time Projection Chamber - A New 4pi Detector for Charged Particles. *eConf*, C740805(PEP-0144):58–78.
- [44] Pauli, W. (1930). Open letter to the participants of the conference in Tübingen.
- [45] Perl, M. L., Abrams, G. S., Boyarski, A. M., Breidenbach, M., Briggs, D. D., Bulos, F., Chinowsky, W., Dakin, J. T., Feldman, G. J., Friedberg, C. E., Fryberger, D., Goldhaber, G., Hanson, G., Heile, F. B., Jean-Marie, B., Kadyk, J. A., Larsen, R. R., Litke, A. M., Lofgren, D., Lulu, B. A., Luthy, V., Lyon, D., Morehouse, C. C., Paterson, J. M., Pierre, F. M., Pun, T. P., Rapidis, P. A., Richter, B., Sadoulet, B., Schwitters, R. F., Tanenbaum, W., Trilling, G. H., Vannucci, F., Whitaker, J. S., Winkelmann, F. C., and Wiss, J. E. (1975). Evidence for anomalous lepton production in e^+e^- annihilation. *Physical Review Letters*, 35(22):1489–1492.
- [46] Pontecorvo, B. (1957). Mesonium and anti-mesonium. *Sov. Phys. JETP*, 6:429.
- [47] Reines, F. and Cowan, C. L. (1953a). A proposed experiment to detect the free neutrino.
- [48] Reines, F. and Cowan, C. L. (1953b). Detection of the free neutrino. *Physical Review*, 92(3):830–831.
- [49] Rubbia, C. (1977). The Liquid Argon Time Projection Chamber: A New Concept For Neutrino Detectors.pdf.
- [50] Schael, S., Barate, R., Bruneliere, R., Buskulic, D., de Bonis, I., Decamp, D., Ghez, P., Goy, C., Jézouel, S., Lees, J. P., Lucotte, A., Martin, F., Merle, E., Minard, M. N., Nief, J. Y., Odier, P., Pietrzyk, B., Trocme, B., Bravo, S., Casado, M. P., Chmeissani, M., Comas, P., Crespo, J. M., Fernandez, E., Fernandez-Bosman, M., Garrido, L., Grauges, E., Juste, A., Martinez, M., Merino, G., Miquel, R., Mir, L. M., Orteu, S., Pacheco, A.,

- Park, I. C., Perlas, J., Riu, I., Ruiz, H., Sanchez, F., Colaleo, A., Creanza, D., de Filippis, N., de Palma, M., Iaselli, G., Maggi, G., Maggi, M., Nuzzo, S., Ranieri, A., Raso, G., Ruggieri, F., Selvaggi, G., Silvestris, L., Tempesta, P., Tricomi, A., Zito, G., Huang, X., Lin, J., Ouyang, Q., Wang, T., Xie, Y., Xu, R., Xue, S., Zhang, J., Zhang, L., Zhao, W., Abbaneo, D., Bazarko, A., Becker, U., Boix, G., Bird, F., Blucher, E., Bonvicini, B., Bright-Thomas, P., Barklow, T., Buchmüller, O., Cattaneo, M., Cerutti, F., Ciulli, V., Clerbaux, B., Drevermann, H., Forty, R. W., Frank, M., Greening, T. C., Hagelberg, R., Halley, A. W., Gianotti, F., Girone, M., Hansen, J. B., Harvey, J., Jacobsen, R., Hutchcroft, D. E., Janot, P., Jost, B., Knobloch, J., Kado, M., Lehraus, I., Lazeyras, P., Maley, P., Mato, P., May, J., Moutoussi, A., Pepe-Altarelli, M., Ranjard, F., Rolandi, L., Schlatter, D., Schmitt, B., Schneider, O., Tejessy, W., Teubert, F., Tomalin, I. R., Tournefier, E., Veenhof, R., Valassi, A., Wiedenmann, W., Wright, A. E., Ajaltouni, Z., Badaud, F., Chazelle, G., Deschamps, O., Dessagne, S., Falvard, A., Ferdi, C., Fayolle, D., Gay, P., Guicheney, C., Henrard, P., Jousset, J., Michel, B., Monteil, S., Montret, J. C., Pallin, D., Pascolo, J. M., Perret, P., Podlyski, F., Bertelsen, H., Fernley, T., Hansen, J. D., Hansen, J. R., Hansen, P. H., Kraan, A. C., Lindahl, A., Mollerud, R., Nilsson, B. S., Rensch, B., Waananen, A., Daskalakis, G., Kyriakis, A., Markou, C., Simopoulou, E., Siotis, I., Vayaki, A., Zachariadou, K., Blondel, A., Bonneaud, G., Brient, J. C., Machefert, F., Roug?, A., Rumpf, M., Swynghedauw, M., Tanaka, R., Verderi, M., Videau, H., Ciulli, V., Focardi, E., Parrini, G., Zachariadou, K., Corden, M., Georgiopoulos, C., Antonelli, A., Antonelli, M., Bencivenni, G., Bologna, G., Bossi, F., Campana, P., Capon, G., Cerutti, F., Chiarella, V., Felici, G., Laurelli, P., Mannocchi, G., Murtas, G. P., Passalacqua, L., Picchi, P., Colrain, P., ten Have, I., Hughes, I. S., Kennedy, J., Knowles, I. G., Lynch, J. G., Morton, W. T., Negus, P., O'Shea, V., Raine, C., Reeves, P., Scarr, J. M., Smith, K., Thompson, A. S., Turnbull, R. M., Wasserbaech, S., Buchmüller, O., Cavanaugh, R., Dhamotharan, S., Geweniger, C., Hanke, P., Hansper, G., Hepp, V., Kluge, E. E., Putzer, A., Sommer, J., Stenzel, H., Tittel, K., Werner, W., Wunsch, M., Beuselinck, R., Binnie, D. M., Cameron, W., Davies, G., Dornan, P. J., Goodsir, S., Marinelli, N., Martin, E. B., Nash, J., Nowell, J., Rutherford, S. A., Sedgbeer, J. K., Thompson, J. C., White, R., Williams, M. D., Ghete, V. M., Girtler, P., Kneringer, E., Kuhn, D., Rudolph, G., Bouhova-Thacker, E., Bowdery, C. K., Buck, P. G., Clarke, D. P., Ellis, G., Finch, A. J., Foster, F., Hughes, G., Jones, R. W. L., Keemer, N. R., Pearson, M. R., Robertson, N. A., Sloan, T., Smizanska, M., Snow, S. W., Williams, M. I., van der Aa, O., Delaere, C., Leibenguth, G., Lemaître, V., Bauerdick, L. A. T., Blumenschein, U., van Gemmeren, P., Giehl, I., H?ldorfer, F., Jakobs, K., Kasemann, M., Kayser, F., Kleinknecht, K., M?ller, A. S., Quast, G., Renk, B., Rohne, E., Sander, H. G., Schmeling, S., Wachsmuth, H., Wanke, R., Zeitnitz, C., Ziegler, T., Aubert, J. J., Benchouk, C., Bonissent, A., Carr, J., Coyle, P., Curtil, C., Ealet, A., Etienne, F., Fouchez, D., Motsch, F., Payre, P., Rousseau, D., Tilquin, A., Talby, M., Thulasidas, M., Aleppo, M., Antonelli, M., Ragusa, F., B?scher, V., David, A., Dietl, H., Ganis, G., H?ttmann, K., L?tjens, G., Mannert, C., M?nner, W., Moser, H. G., Settles, R., Seywerd, H., Stenzel, H., Villegas, M., Wiedenmann, W., Wolf, G., Azzurri, P., Boucrot, J., Callot, O., Chen, S., Cordier, A., Davier, M., Duflot, L., Grivaz, J. F., Heusse, P., Jacholkowska, A., le Diberder, F., Lefran?ois, J., Mutz, A. M., Schune, M. H., Serin, L., Veillet, J. J., Videau, I., Zerwas, D., Azzurri, P., Bagliesi, G., Bettarini, S., Boccali, T., Bozzi, C., Calderini, G., Dell'Orso, R., Fantechi, R., Ferrante, I., Fidecaro, F., Fo?, L., Giammanco, A., Giassi, A., Gregorio, A., Ligabue, F., Lusiani, A., Marrocchesi, P. S., Messineo, A., Palla, F., Rizzo, G., Sanguinetti, G., Sciab?, A., Sguazzoni, G., Spagnolo, P., Steinberger, J., TENCHINI, R., Venturi, A., Vannini, C., Verdini, P. G., Awunor, O., Blair,

G. A., Cowan, G., Garcia-Bellido, A., Green, M. G., Medcalf, T., Misiejuk, A., Strong, J. A., Teixeira-Dias, P., Botterill, D. R., Clifft, R. W., Edgecock, T. R., Edwards, M., Haywood, S. J., Norton, P. R., Tomalin, I. R., Ward, J. J., Bloch-Devaux, B., Boumediene, D., Colas, P., Emery, S., Fabbro, B., Kozanecki, W., Lan??on, E., Lemaire, M. C., Locci, E., Perez, P., Rander, J., Renardy, J. F., Roussarie, A., Schuller, J. P., Schwindling, J., Tuchming, B., Vallage, B., Black, S. N., Dann, J. H., Kim, H. Y., Konstantinidis, N., Litke, A. M., McNeil, M. A., Taylor, G., Booth, C. N., Cartwright, S., Combley, F., Hodgson, P. N., Lehto, M., Thompson, L. F., Affholderbach, K., Barberio, E., B??hrer, A., Brandt, S., Burkhardt, H., Feigl, E., Grupen, C., Hess, J., Lutters, G., Meinhard, H., Minguet-Rodriguez, J., Mirabito, L., Misiejuk, A., Neugebauer, E., Ngac, A., Prange, G., Rivera, F., Saraiva, P., Sch??fer, U., Sieler, U., Smolik, L., Stephan, F., Trier, H., Apollonio, M., Borean, C., Bosisio, L., Della Marina, R., Giannini, G., Gobbo, B., Musolino, G., Pitis, L., He, H., Kim, H., Putz, J., Rothberg, J., Armstrong, S. R., Bellantoni, L., Berkelman, K., Cinabro, D., Conway, J. S., Cranmer, K., Elmer, P., Feng, Z., Ferguson, D. P. S., Gao, Y., Gonz??lez, S., Grahl, J., Harton, J. L., Hayes, O. J., Hu, H., Jin, S., Johnson, R. P., Kile, J., McNamara, P. A., Nielsen, J., Orejudos, W., Pan, Y. B., Saadi, Y., Scott, I. J., Sharma, V., Walsh, A. M., Walsh, J., Wear, J., von Wimmersperg-Toeller, J. H., Wiedenmann, W., Wu, J., Wu, S. L., Wu, X., Yamartino, J. M., Zobernig, G., Dissertori, G., Abdallah, J., Abreu, P., Adam, W., Adye, T., Adzic, P., Ajinenko, I., Albrecht, T., Alderweireld, T., Alekseev, G. D., Alemany-Fernandez, R., Allmendinger, T., Allport, P. P., Almeded, S., Amaldi, U., Amapane, N., Amato, S., Anashkin, E., Anassontzis, E. G., Andersson, P., Andreazza, A., Andringa, S., Anjos, N., Antilogus, P., Apel, W. D., Arnoud, Y., Ask, S., Asman, B., Augustin, J. E., Augustinus, A., Baillon, P., Ballestrero, A., Bambade, P., Barao, F., Barbiellini, G., Barbier, R., Bardin, D., Barker, G., Baroncelli, A., Battaglia, M., Baubillier, M., Becks, K. H., Begalli, M., Behrmann, A., Beilliere, P., Belokopytov, Y., Belous, K., Ben-Haim, E., Benekos, N., Benvenuti, A., Berat, C., Berggren, M., Berntzon, L., Bertini, D., Bertrand, D., Besancon, M., Besson, N., Bianchi, F., Bigi, M., Bilenky, M. S., Bizouard, M. A., Bloch, D., Blom, M., Bluj, M., Bonesini, M., Bonivento, W., Boonekamp, M., Booth, P. S. L., Borgland, A. W., Borisov, G., Bosio, C., Botner, O., Boudinov, E., Bouquet, B., Bourdarios, C., Bowcock, T. J. V., Boyko, I., Bozovic, I., Bozzo, M., Bracko, M., Branchini, P., Brenke, T., Brenner, R., Brodet, E., Bruckman, P., Brunet, J. M., Bugge, L., Buran, T., Burgsmueller, T., Buschbeck, B., Buschmann, P., Cabrera, S., Caccia, M., Calvi, M., Camacho Rozas, A. J., Camporesi, T., Canale, V., Canepa, M., Carena, F., Carroll, L., Caso, C., Castillo Gimenez, M. V., Castro, N., Cattai, A., Cavallo, F., Cerruti, C., Chabaud, V., Chapkin, M., Charpentier, P., Chaussard, L., Checchia, P., Chelkov, G. A., Chen, M., Chierici, R., Chliapnikov, P., Chochula, P., Chorowicz, V., Chudoba, J., Chung, S. U., Cieslik, K., Collins, P., Colomer, M., Contri, R., Cortina, E., Cosme, G., Cossutti, F., Costa, M. J., Cowell, J. H., Crawley, H. B., Crennell, D., Crepe, S., Crosetti, G., Cuevas, J., Czellar, S., D'Hondt, J., Dalmagne, B., Dalmau, J., Damgaard, G., Davenport, M., da Silva, T., Da Silva, W., Deghorain, A., Della Ricca, G., Delpierre, P., Demaria, N., De Angelis, A., de Boer, W., de Brabandere, S., De Clercq, C., De Lotto, B., de Maria, N., de Min, A., de Paula, L., Dijkstra, H., di Ciaccio, L., di Diodato, A., di Simone, A., Djannati, A., Dolbeau, J., Doroba, K., Dracos, M., Drees, J., Drees, K. A., Dris, M., Duperrin, A., Durand, J. D., Ehret, R., Eigen, G., Ekelof, T., Ekspong, G., Ellert, M., Elsing, M., Engel, J. P., Erzen, B., Espirito Santo, M. C., Falk, E., Fanourakis, G., Fassouliotis, D., Fayot, J., Feindt, M., Fenyuk, A., Fernandez, J., Ferrari, P., Ferrer, A., Ferrer-Ribas, E., Ferro, F., Fichet, S., Firestone, A., Fischer, P. A., Flagmeyer, U., Foeth, H., Fokitis, E., Fontanelli, F., Franek, B., Frodesen,

- A. G., Fruhwirth, R., Fulda-Quenzer, F., Fuster, J., Galloni, A., Gamba, D., Gamblin, S., Gandelman, M., Garcia, C., Garcia, J., Gaspar, C., Gaspar, M., Gasparini, U., Gavillet, P., Gazis, E., Gele, D., Gerber, J. P., Gerdyukov, L., Ghodbane, N., Gil, I., Glege, F., Gokieli, R., Golob, B., Gomez-Ceballos, G., Goncalves, P., Gonzalez Caballero, I., Gopal, G., Gorn, L., Gorski, M., Gouz, Y., Gracco, V., Grahl, J., Graziani, E., Green, C., Grefrath, A., Grimm, H. J., Gris, P., Grosdidier, G., Grzelak, K., Gunther, M., Guy, J., Haag, C., Hahn, F., Hahn, S., Haider, S., Hallgren, A., Hamacher, K., Hamilton, K., Hansen, J., Harris, F. J., Haug, S., Hauler, F., Hedberg, V., Heising, S., Hennecke, M., Henriques, R., Hernandez, J. J., Herquet, P., Herr, H., Hessing, T. L., Heuser, J. M., Higon, E., Hoffman, J., Holmgren, S. O., Holt, P. J., Holthuizen, D., Hoorelbeke, S., Houlden, M. A., Hrubec, J., Huber, M., Huet, K., Hughes, G. J., Hultqvist, K., Jackson, J. N., Jacobsson, R., Jalocha, P., Janik, R., Jarlskog, C., Jarlskog, G., Jarry, P., Jean-Marie, B., Jeans, D., Johansson, E. K., Johansson, P. D., Jonsson, P., Joram, C., Juillot, P., Jungermann, L., Kapusta, F., Karafasoulis, K., Katsanevas, S., Katsoufis, E., Keranen, R., Kernel, G., Kersevan, B. P., Kerzel, U., Khomenko, B. A., Khovanski, N. N., Kiiskinen, A., King, B. T., Kinvig, A., Kjaer, N. J., Klapp, O., Klein, H., Kluit, P., Knoblauch, D., Kokkinias, P., Konopliannikov, A., Koratzinos, M., Kostioukhine, V., Kourkoumelis, C., Kouznetsov, O., Krammer, M., Kreuter, C., Kriznic, E., Krstic, J., Krumstein, Z., Kubinec, P., Kucewicz, W., Kucharczyk, M., Kurowska, J., Kurvinen, K., Lamsa, J., Lanceri, L., Lane, D. W., Langefeld, P., Lapin, V., Laugier, J. P., Lauhakangas, R., Leder, G., Ledroit, F., Lefebure, V., Leinonen, L., Leisos, A., Leitner, R., Lemonne, J., Lenzen, G., Lepeltier, V., Lesiak, T., Lethuillier, M., Libby, J., Liebig, W., Liko, D., Lipniacka, A., Lippi, I., Loerstad, B., Lokajicek, M., Loken, J. G., Lopes, J. H., Lopez, J. M., Lopez-Fernandez, R., Loukas, D., Lutz, P., Lyons, L., MacNaughton, J., Mahon, J. R., Maio, A., Malek, A., Malmgren, T. G. M., Maltezos, S., Malychev, V., Mandl, F., Marco, J., Marco, R., Marechal, B., Margoni, M., Marin, J. C., Mariotti, C., Markou, A., Martinez-Rivero, C., Martinez-Vidal, F., Marti i Garcia, S., Masik, J., Mastroiannopoulos, N., Matorras, F., Matteuzzi, C., Matthiae, G., Mazik, J., Mazzucato, F., Mazzucato, M., Mc Cubbin, M., Mc Kay, R., Mc Nulty, R., Mc Pherson, G., Meroni, C., Meyer, W. T., Miagkov, A., Migliore, E., Mirabito, L., Mitaroff, W., Mjoernmark, U., Moa, T., Moch, M., Moeller, R., Moenig, K., Monge, R., Montenegro, J., Moraes, D., Moreau, X., Moreno, S., Morettini, P., Morton, G., Mueller, U., Muenich, K., Mulders, M., Mulet-Marquis, C., Mundim, L., Muresan, R., Murray, W., Muryn, B., Myatt, G., Myklebust, T., Naraghi, F., Nassiakou, M., Navarria, F., Navas, S., Nawrocki, K., Negri, P., Neufeld, N., Neumann, W., Neumeister, N., Nicolaidou, R., Nielsen, B. S., Nieuwenhuizen, M., Niezurawski, P., Nikolaenko, V., Nikolenko, M., Nomokonov, V., Normand, A., Nygren, A., Oblakowska-Mucha, A., Obraztsov, V., Olshevski, A., Onofre, A., Orava, R., Orazi, G., Osterberg, K., Ouraou, A., Oyanguren, A., Paganini, P., Paganoni, M., Paiano, S., Pain, R., Paiva, R., Palacios, J. P., Palka, H., Papadopoulou, T. D., Papageorgiou, K., Pape, L., Parkes, C., Parodi, F., Parzefall, U., Passeri, A., Passon, O., Pavel, T., Pegoraro, M., Peralta, L., Perepelitsa, V., Pernicka, M., Perrotta, A., Petridou, C., Petrolini, A., Phillips, H. T., Piana, G., Piedra, J., Pieri, L., Pierre, F., Pimenta, M., Piotto, E., Podobnik, T., Poireau, V., Pol, M. E., Polok, G., Polycarpo, E., Poropat, P., Pozdniakov, V., Privitera, P., Pukhaeva, N., Pullia, A., Radojicic, D., Ragazzi, S., Rahmani, H., Rakoczy, D., Rames, J., Ramler, L., Ratoff, P. N., Read, A., Rebecchi, P., Redaelli, N. G., Regler, M., Rehn, J., Reid, D., Reinhardt, R., Renton, P., Resvanis, L. K., Richard, F., Ridky, J., Rinaudo, G., Ripp-Baudot, I., Rivero, M., Rodriguez, D., Rohne, O., Romero, A., Ronchese, P., Rosenberg, E. I., Rosinsky, P., Roudeau, P., Rovelli, T., Royon, C., Ruhlmann-Kleider, V., Ruiz, A., Ryabtchikov, D., Saarikko, H., Sacquin, Y.,

Sadovsky, A., Sajot, G., Salmi, L., Salt, J., Sampsonidis, D., Sannino, M., Savoy-Navarro, A., Scheidle, T., Schneider, H., Schwemling, P., Schwering, B., Schwickerath, U., Schyns, M. A. E., Scuri, F., Seager, P., Sedykh, Y., Segar, A., Seibert, N., Sekulin, R., Shellard, R. C., Sheridan, A., Siebel, M., Silvestre, R., Simard, L., Simonetto, F., Sisakian, A., Skaali, T. B., Smadja, G., Smirnov, N., Smirnova, O., Smith, G. R., Sokolov, A., Sopczak, A., Sosnowski, R., Spassov, T., Spiriti, E., Sponholz, P., Squarcia, S., Stampfer, D., Stanescu, C., Stanic, S., Stanitzki, M., Stapnes, S., Stevenson, K., Stocchi, A., Strauss, J., Strub, R., Stugu, B., Szczekowski, M., Szeptycka, M., Szumlak, T., Tabarelli, T., Taffard, A. C., Tegenfeldt, F., Terranova, F., Thomas, J., Tilquin, A., Timmermans, J., Tinti, N., Tkatchev, L., Tobin, M., Todorov, T., Todorovova, S., Toet, D. Z., Tomaradze, A., Tome, B., Tonazzo, A., Tortora, L., Tortosa, P., Transtromer, G., Travnicek, P., Treille, D., Tristram, G., Trochimczuk, M., Trombini, A., Troncon, C., Tsirou, A., Turluer, M. L., Tyapkin, I. A., Tyapkin, P., Tzamarias, S., Ullaland, O., Uvarov, V., Valenti, G., Vallazza, E., Vander Velde, C., van Apeldoorn, G. W., van Dam, P., Van den Boeck, W., Van Doninck, W. K., van Eldik, J., Van Lysebetten, A., van Remortel, N., van Vulpen, I., Vassilopoulos, N., Vegni, G., Veloso, F., Ventura, L., Venus, W., Verbeure, F., Verdier, P., Verlato, M., Vertogradov, L. S., Verzi, V., Vilanova, D., Vitale, L., Vlasov, E., Vodopyanov, A. S., Vollmer, C., Voulgaris, G., Vrba, V., Wahlen, H., Walck, C., Washbrook, A. J., Weiser, C., Wetherell, A. M., Wicke, D., Wickens, J., Wilkinson, G., Winter, M., Witek, M., Wlodek, T., Wolf, G., Yi, J., Yushchenko, O., Zaitsev, A., Zalewska, A., Zalewski, P., Zavrtanik, D., Zevgolatakos, E., Zhuravlov, V., Zimin, N. I., Zintchenko, A., Zoller, P., Zucchelli, G. C., Zumerle, G., Zupan, M., Acciarri, M., Achard, P., Adriani, O., Aguilar-Benitez, M., Alcaraz, J., Alemanni, G., Allaby, J., Aloisio, A., Alviggi, M. G., Ambrosi, G., Anderhub, H., Andreev, V. P., Angelescu, T., Anselmo, F., Arefiev, A., Azemoon, T., Aziz, T., Bagnaia, P., Bajo, A., Baksay, G., Baksay, L., Balandras, A., Baldew, S. V., Ball, R. C., Banerjee, S., Banerjee, S. W., Barczyk, A., Barill?re, R., Barone, L., Bartalini, P., Basile, M., Batalova, N., Battiston, R., Bay, A., Becattini, F., Becker, U., Behner, F., Bellucci, L., Berbeco, R., Berdugo, J., Berges, P., Bertucci, B., Betev, B. L., Bhattacharya, S., Biasini, M., Biglietti, M., Biland, A., Blaising, J. J., Blyth, S. C., Bobbink, G. J., B??hm, A., Boldizar, L., Borgia, B., Bottai, S., Bourilkov, D., Bourquin, M., Braccini, S., Branson, J. G., Brigljevic, V., Brochu, F., Brock, I. C., Buffini, A., Buijs, A., Burger, J. D., Burger, W. J., Button, A., Cai, X. D., Campanelli, M., Capell, M., Cara Romeo, G., Carlino, G., Cartacci, A., Casaus, J., Castellini, G., Cavallari, F., Cavallo, N., Cecchi, C., Cerrada, M., Cesaroni, F., Chamizo, M., Chang, Y. H., Chaturvedi, U. K., Chemarin, M., Chen, A., Chen, G., Chen, G. M., Chen, H. F., Chen, H. S., Chiefari, G., Cifarelli, L., Cindolo, F., Civinini, C., Clare, I., Clare, R., Coignet, G., Colijn, A. P., Colino, N., Costantini, S., Cotorobai, F., Cozzoni, B., de la Cruz, B., Csilling, A., Cucciarelli, S., Dai, T. S., van Dalen, J. A., D'Alessandro, R., de Asmundis, R., Debreczeni, J., D??glon, P., Degr??, A., Dehmelt, K., Deiters, K., della Volpe, D., Delmeire, E., Denes, P., DeNotaristefani, F., de Salvo, A., Diemoz, M., Dierckxsens, M., van Dierendonck, D., di Lodovico, F., Dionisi, C., Dittmar, M., Dominguez, A., Doria, A., Dova, M. T., Duchesneau, D., Dufournaud, D., Duda, M., Duinker, P., Duran, I., Dutta, S., Echenard, B., Eline, A., El Hage, A., El Mamouni, H., Engler, A., Eppling, F. J., Ern??, F. C., Extermann, P., Fabre, M., Faccini, R., Falagan, M. A., Falciano, S., Favara, A., Fay, J., Fedin, O., Felcini, M., Ferguson, T., Ferroni, F., Fesefeldt, H., Fiandrini, E., Field, J. H., Filthaut, F., Fisher, P. H., Fisher, W., Fisk, I., Forconi, G., Fredj, L., Freudenreich, K., Furetta, C., Galaktionov, Y., Ganguli, S. N., Garcia-Abia, P., Gataullin, M., Gau, S. S., Gentile, S., Gheordanescu, N., Giagu, S., Gong, Z. F., Grenier, G., Grimm, O., Gruenewald, M. W., Guida, M., van Gulik, R.,

- Gupta, V. K., Gurtu, A., Gutay, L. J., Haas, D., Hasan, A., Hatzifotiadou, D., Hebbeker, T., Hervé, A., Hidas, P., Hirschfelder, J., Hofer, H., Hohlmann, M., Holzner, G., Hoorani, H., Hou, S. R., Iashvili, I., Innocente, V., Jin, B. N., Jindal, P., Jones, L. W., DeJong, P., Josa-Mutuberré, I., Khan, R. A., Kaur, M., Kienzle-Focacci, M. N., Kim, D., Kim, J. K., Kirkby, J., Kiss, D., Kittel, W., Klimentov, A., Knie, A. C., Koffeman, E., Kopal, M., Kopp, A., Koutsenko, V., Krüger, M., Kraemer, R. W., Krenz, W., Krüger, A., Kuijten, H., Kunin, A., Ladron de Guevara, P., Laktineh, I., Landi, G., Lassila-Perini, K., Lebeau, M., Lebedev, A., Lebrun, P., Lecomte, P., Lecoq, P., le Coultre, P., Lee, H. J., le Goff, J. M., Leiste, R., Leonardi, E., Levchenko, M., Levchenko, P., Li, C., Likhoded, S., Lin, C. H., Lin, W. T., Linde, F. L., Lista, L., Liu, Z. A., Lohmann, W., Longo, E., Lu, Y. S., Lu, W., Lübel, K., Luci, C., Luckey, D., Luminari, L., Lugnier, L., Luster, W., Ma, W. G., Maity, M., Malgeri, L., Malinin, A., Marín, C., Mangeol, D., Mans, J., Marchesini, P., Marian, G., Martin, J. P., Marzano, F., Massaro, G. G. G., Mazumdar, K., McNeil, R. R., Mele, S., Merola, L., Merk, M., Meschini, M., Metzger, W. J., von der Mey, M., Mihul, A., Milcent, H., Mirabelli, G., Mnich, J., Mohanty, G. B., Molnar, P., Monteleoni, B., Moulik, T., Muanza, G. S., Muheim, F., Muijs, A. J. M., Musicar, B., Musy, M., Nagy, S., Natale, S., Napolitano, M., Nessi-Tedaldi, F., Newman, H., Niessen, T., Nisati, A., Novak, T., Nowak, H., Ofierzynski, R., Organtini, G., Oulianov, A., Pal, I., Palomares, C., Pandoulas, D., Paoletti, S., Paoloni, A., Paolucci, P., Paramatti, R., Park, H. K., Park, I. H., Pascale, G., Passaleva, G., Patricelli, S., Paul, T., Pauluzzi, M., Paus, C., Pauss, F., Peach, D., Pedace, M., Pensotti, S., Perret-Gallix, D., Petersen, B., Piccolo, D., Pierella, F., Pieri, M., Pioppi, M., Piroué, P. A., Pistolesi, E., Plyaskin, V., Pohl, M., Pojidaev, V., Postema, H., Pothier, J., Produit, N., Prokofiev, D. O., Prokofiev, D., Quartieri, J., Rahal-Callot, G., Rahaman, M. A., Raics, P., Raja, N., Ramelli, R., Rancoita, P. G., Ranieri, R., Raspereza, A., Razis, P., Ren, D., Rescigno, M., Reucroft, S., van Rhee, T., Riemann, S., Riles, K., Robohm, A (2006). Precision electroweak measurements on the Z resonance. *Physics Reports*, 427(5-6):257–454.
- [51] Tope, T., Adamowski, M., Carls, B., Hahn, A., Jaskierny, W., Jostlein, H., Kendziora, C., Lockwitz, S., Pahlka, B., Plunkett, R., Pordes, S., Rebel, B., Schmitt, R., Skup, E., Stancari, M., and Yang, T. (2014). Extreme argon purity in a large, non-evacuated cryostat. 1169(2014):1169–1175.
- [52] Wilson, F. (1968). Fermi’s Theory of Beta Decay. *American Journal of Physics*, 36(12):1150–1160.
- [53] Wolfenstein, L. (1978). Neutrino oscillations in matter. *Phys. Rev. D*, 17(9):2369–2374.