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Can a 3+2 model explain the NuTeV anomaly

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Abstract:

The $\sin^2\theta_w$ result from NuTeV was three standard deviations away from the standard model predicted value . A possible explanation could be the oscillation of electron neutrinos in the NuTeV beam. We examine seeral cases of masses and mixings in a 3+2 neturino oscillation model. We conclude that electron to sterile neturino oscillations can account for only half of a standard deviation between the Standard Model and Nutev values of $\sin^2\theta_w$

A Small Review

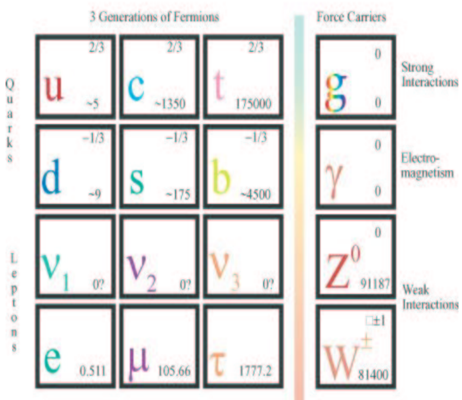


Illustration 1 The Standard Model of Fundamental Particles

The neutrino is one of the most elusive particles of today. The foundations of particle physics so far have been incorporated into a single Standard Model of Elementary Particles. This standard model consists of 16 known particles in two groups, fermions and bosons. Bosons are force carrier particles. This set of particles includes the gluon, photon, and the W and Z bosons. Gluons mediate the strong force between quarks- their exchange causes 'colour change'. This force holds gluons in colour neutral combinations, like protons and neutrons. Photons are responsible for the electromagnetic force, and the W and Z bosons mediate the descriptively named weak force, which is studied in this report. It is the W and Z bosons large mass that makes the weak force so weak and its range so small. The W and Z bosons differ in both mass and electromagnetic properties(see Illustration 1) , giving rise to different kinds of weak force interactions. Fermions, can be separated into two subgroups: quarks and leptons. Quarks (which are called up, down, charm, strange, top and bottom) interact with all the force carriers, while leptons only interact electromagnetically and weakly. Actually, leptons come in two varieties, the charged particles, and neutrinos. Neutrinos carry no charge and therefore do not interact electromagnetically. They are perfect candidates for studying weak interactions, as they don't interact in any other way. The weak force, however is very weak (hence the name) and neutrinos hardly ever interact with matter. Each neutrino is associated with the charged lepton , (electron muon or tau) whose "flavor" is the same.

These associations make up three families (electron muon or tau) and within particle interactions and decay, such lepton family numbers are conserved.

Neutrinos with Mass

Until recently, it was thought that neutrinos were massless particles, however recent discoveries by solar and then atmospheric neutrino experiments suggest that neutrinos have mass eigenstates. Though no values have been set for these mass states, it is now well accepted within the physics community that, not only do neutrinos have mass, but they oscillate between these mass states. The flavours of neutrinos once thought unchanging, now are seen as certain superpositioning of neutrino masses. Whether a neutrino is a electron muon or tau flavour, depends not only on its source, but on the probability that it has oscillated away from that flavour.(which is dependent on distance and the mass splitting.) Since there are only three known neutrinos, it can be reasoned that there are only two independent mass splittings (since the third must be the sum of the first two), however a result from the Liquid Scintillator Neutrino Detector (LSND) poses a third, independent splitting. Currently this result is being verified by MiniBooNE, however this result has stirred the physics community into rethinking neutrinos and their interactions.

3+ models and the neutrinos

Illustration 2:3+2 model splitting diagram

A new independent mass splitting obviously points to the possibility of a new mass state, yet to be discovered. However, there is no charged lepton for this neutrino to be associated with. The LEP experiment also limits the number of active neutrinos with mass less than 45 GeV to three. Therefore, this neutrino must be nonactive . It is 'sterile' in fact, and can not be detected directly.

A model that has been very successful in fitting the world data of neutrino experiments is the 3+2 model. This model requires two sterile neutrinos for a total of 4 independent mass splittings. The size of the mass splittings and their mixings determine how likely a neutrino will oscillate for a given distance and energy of the neutrino beam. [1]

NuTeV General

The NuTeV experiment [2] was an experiment, conducted to understand weak force interactions through neutrinos. It used a beam of muon neutrinos or muon antineutrinos aimed at a detector that was designed to tell the difference between W and Z boson events. The W and Z bosons that mediate the weak force can be related through the weak mixing angle , $\sin^2\theta_w$. This value can indirectly calculate the mass of the W boson, where

$$\sin^2\theta_w = 1 - \frac{M_w^2}{M_z^2} \tag{1}$$

Precise measurement of $\sin^2\theta_w$ tests the standard model of elementary particles and puts unique and important boundaries on physical processes beyond what is the standard model. Previous measurements of $\sin^2\theta_w$ were found by electron experiments . From global electroweak fits to other data, $\sin^2\theta_w$ has been measured as [3]

$$\sin^2\theta_w = 0.2227 \pm 0.00037 \tag{2}$$

The primary goal of NuTeV was to obtain a precise measurement of $\sin^2\theta_w$ through the study of neutrinos and compare that value to predictions from global electroweak fits.

NuTeV Physics- Deep Inelastic Scattering [4]

Because interaction rates depend on the mass of the force carrier or exchanged particle, one can study the W and Z boson masses and thus $\sin^2\theta_w$ thorough their interactions. Though the W and Z bosons both mediate weak force interactions, the resultant particles differ. The W boson has charge of +/- 1, while the Z boson has no charge. Thus, the interactions they induce can be identified and differentiated by which events result in a final state with a charged particle, and which do not. These interactions are called charged current events (CC) and neutral current (NC) respectively. The Feynman diagrams below depict charged and neutral current events.

Illustration 3 Feynman diagrams of charged current(left) and neutral current (right) Deep Inelastic Scattering. Time moves from left to right..

Both interactions produce a hadron shower of particles, however for one interaction, this is produced with an undetectable neutrino (NC) and in the other interaction, a muon (for the muon neutrinos of NuTeV's experiment) is also produced and will create a long track within the detector. In the standard electroweak theory, the ratio of neutral current to charged current events relates directly to $\sin^2\theta_w$ by[5]:

$$R_{\nu} = \frac{1}{2} - \sin^2\theta_w + \frac{5}{9}(1+r)\sin^4\theta_w \tag{3}$$

for neutrinos and

$$R_{\bar{\nu}} = \frac{1}{2} - \sin^2\theta_w + \frac{5}{9}\left(1+\frac{1}{r}\right)\sin^4\theta_w \tag{4}$$

for antineutrinos, where R_{ν} and $R_{\nu\text{-bar}}$ is the ratio of neutral current to charged current events for neutrino and anti neutrino mode and r is the ratio of muon neutrino and antineutrino charged current cross sections.

$$R = \frac{\sigma(\nu_\mu + N \rightarrow \nu_\mu + X)}{\sigma(\nu_\mu + N \rightarrow \mu + X)} \tag{5}$$

$$r = \frac{\sigma(\bar{\nu}_\mu + N \rightarrow \mu^+ + X)}{\sigma(\nu_\mu + N \rightarrow \mu^- + X)} \tag{6}$$

The paschos- wolfenstein combination provides a much easier equation for calculating sin2thw that is much less dependent on parameters that have large uncertainties like the charm quark mass. This equation is:

$$\frac{R_{\nu} - rR_{\bar{\nu}}}{1-r} = \frac{1}{2} - \sin^2\theta_w \tag{7}$$

NuTeV Apparatus[6]

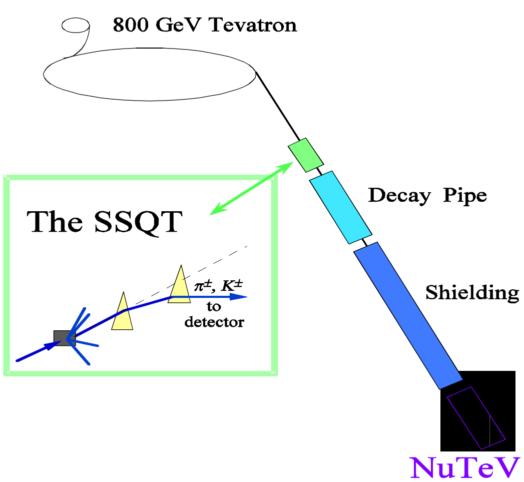


Illustration 4:Schematic of the NuTeV beam

NuTeV operated in the Neutrino Center beamline at Fermi National Accelerator Laboratory. The protons originate from a hydrogen ion beam and are accelerated to 800 GeV before being directed towards the neutrino fixed target experimental area. Protons sent down the neutrino beamline were directed thorough the Sign Selected Quadrapole Train (SSQT). The SSQT was designed to reduce systematics that had plagued earlier neutrino experiments. Protons were directed towards a twelve inch long, one inch diameter beryllium oxide rod. Neutrinos are the result of decay, mostly from pions and kaons, that were "sign selected" by dipole magnets. (π,κ—> μ+ ν) Through distance and shielding, only neutrinos reach the NuTeV detector. There is a small amount of contamination from antineutrinos in the neutrino beam (0.03%) and neutrinos in the antineutrino beam (0.4%). This separation of neutrino and antineutrinos is used to reduce the uncertainty caused by the production of heavy charm quarks.

The NuTeV detector is located 1450m downstream from the proton target. It weighs over 1000 tons to ensure that the weakly interacting neutrinos interact with the detector. Only a few of every billion neutrinos passing through are detected. The detector is made with an 18 m long steel-scintillator (3mx3m in area) and a 10 meter long toroid spectrometer. The target contains 168 steel plates interspersed with 84 liquid scintillation counters and 42 drift chambers. The steel plates act as the main targets for the neutrinos, while the scintillators and drift counters provide information about the energy, length, position information. After the target follows the spectrometer. For CC events, the curvature of the muon in the magnetic field determines the charge sign and momentum of the particle. Illustration 5 shows a schematic of the NuTeV detector.

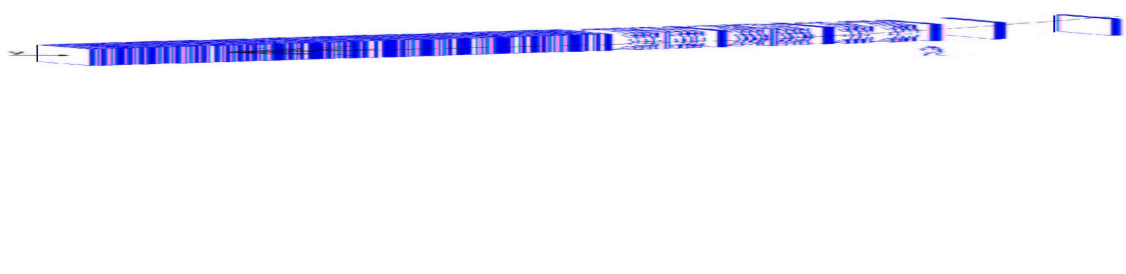
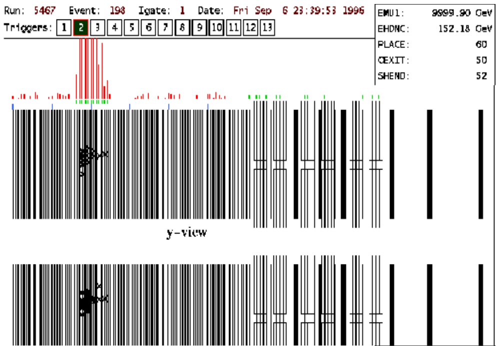


Illustration 5: NuTeV detector schematic where neutrinos enter on the left and exit on the right. the black lines represent what a charged current event might look like going though the detector.

NuTeV background[4]

Below are examples of charged current (figure 2) and neutral current (figure

1) events as they appear in the NuTeV detector. The difference in the two events is obvious in these images- the charged current event has one long track, which we have identified to be a muon. Both events have a small shower of tracks close to the interaction point. Since there are thousands of events total, it is impossible for NuTeV to personally pick each NC and CC event that has the requisite criteria to be included in the final data. Therefore, we separate and select events by their energy, point of interaction (place and transverse position), and length (given by its place and point of exit). Interactions can be generally separated into NC and CC events by the length of the event-NC events are said to be short events (with length roughly less than 20 liquid scintillators) and CC events are said to be all long events. ($R^{\nu}_{exp} = {}^{short}/_{long}$)This is because of the long muon tracks charged current events leave within the detector. To ensure the best quality events, X, Y, and Z spatial cuts and hadron energy cuts were made on the NuTeV data. The interaction point (PLACE) must be within 40 inches of the center of the detector on the X axis (horizontal axis) , and within 45 inches of the center of the detector on the Y axis (vertical axis). Longitudinal (Z axis) place selections were dependent on energy- the more energy, the farther PLACE had to be from the downstream of the detector- however PLACE must generally lay within 2 meters of upstream and downstream calorimeters to ensure that the event was induced (upstream) and could be discriminated into a NC or CC event. The hadronic energy (E_{had}) was required to be within 20 and 180 GeV. Ideally, the final events after these cuts are made look similar to the events shown below, where the interaction is in the middle of the detector in X and Y and charged muons create tracks that continue into the spectrometer.



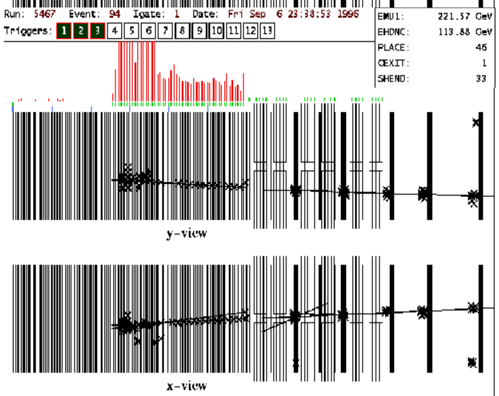


Figure 1 A neutral current event detected by NuTeV. The small shower of hits represents the hadronic shower after a neutral current event. The departing neutrino leaves no track.
Figure 2A Charged Current Event as detected by NuTeV. This event has both a small hadronic shower and a long muon track, which goes through the spectrometer

Although these cuts reduce a significant amount of bad events, there are however still more background elements that must be corrected for. These include cosmic rays, short charged current events that are classified as neutral current events, and vice versa. During times when the neutrino beam is off, data is taken to count the amount of cosmic events per measured interval of time. Cosmic events generally leave nearly vertical tracks within the detector. These events would typically be classified as short events because their vertical path leave short tracks (horizontal Z direction) within the detector. About 94% of cosmic ray events qualify as short events. They make roughly 0.9% (4.7%) of the short events that make fiducial cuts. Misidentified muon neutrino (antineutrino) events make up 17.2% (6.6%) of short events and 0.7% (0.7%) of long events. Most of these are charged current events that had wide angle muons that exited out the side of the detector. Neutral current events with long hadronic showers make the small amount of similar background in the charged current candidates.

The largest background in the NuTeV analysis after fiducial cuts is provided by electron neutrinos in the beam. Electron neutrinos in the beam account for about 1.6% of the beam and constitute about 5.1% of events in neutrino and 6% in antineutrino mode. Most of these are the result of Kaon decay. The NuTeV detector was designed to distinguish between muon neutrino events that exchange W or Z bosons. Electron neutrino events can not be distinguished in the NuTeV detector because charged current electron neutrino events produce electrons as their charged particle. Since electrons interact more with the detector, they decay faster and their tracks cannot be distinguished from the tracks of the hadron shower particles. These events therefore need to be subtracted from the short events (NC candidates) and the ratio of NC to CC events becomes

$$R^{-} = \frac{N_S - N_E}{N_L} \tag{8}$$

where N_S and N_L are the number of short and long events respectively (for neutrino interactions in the case above) and N_E is the number of electron neutrino events from a Monte Carlo simulation. It is this background that is of most interest to this paper.

The Paschos-Wolfenstein relation, related before in (7) , where R is as related in (8) has for a 1C $\sin^2\theta_w$ fit, an x value of 0.249 and a $dR^-/d\sin^2\theta_w$ of -0.617, where

$$R^{-} = R^{\nu}_{\exp} - x * R^{\bar{\nu}}_{\exp} \tag{9}$$

so that the 1 C fit for solving the change in $\sin^2\theta_w$ from the NuTeV value is

$$\frac{R^{\nu}_{\exp} - 0.249 * R^{\bar{\nu}}_{\exp}}{0.617} = \sin^2\theta_{w(nutev)} \tag{10}$$

This last equation (10) is pricipally how we calculate the shift in the NuTeV $\sin^2\theta_w$. When the 3+2 model correction is relayed to the Monte Carlo, we obtain the shift in NC to CC ratios for neutrino and antineutrino running. With (10), we can use these shifts to find the corrected value of $\sin^2\theta_w$

NuTeV results

The final value of $\sin^2\theta_w$ calculated by NuTeV[7] was anomalously high, at

$$\sin^2\theta_w = 0.2277 \pm 0.0016 \tag{11}$$

The NuTeV value of $\sin^2\theta_w$ stands currently as the most precise determination in neutrino-nucleon scattering experiments. This value of $\sin^2\theta_w$ is roughly 3 standard deviations above the standard model value (2) that has been verified by experiments such as LEP. The probability that this value is consistent with the standard model is one in four hundred or about 0.25%. Suggestions as to the explanation of this value have been made. It may be that neutrino couplings are not as predicted in the standard model [8]. Another idea by Giunti et all [9] offered that electron neutrinos were oscillating into sterile neutrinos and that therefore the ratio (8) overestimates the amount of electron neutrinos within the beam. This $\nu_e \rightarrow \nu_s$ oscilliation could cause such an overestimation, it would reduce the value of R_ν and $R_{\nu bar}$ and raise the value of $\sin^2\theta_w$.(7)

This seems to be the trend of the result. Giunti, used a 3+1 sterile neutrino model. He demonstrated that the allowed range to explain NuTeV is not consistent with the world's oscillation results. Although Giunti demonstrated that a 3+1 sterile neutrino model is unable to explain the NuTeV result, a 3+2 model still hasn't been disproved. 3+2 models, which fit well with the rest of the worlds neutrino data, may explain the anomalous high value of $\sin^2\theta_w$.

Procedure

3+2 models can have many different mass splittings and mixing values. Values for the masses and mixing for favored 3+2 models according to short- baseline results were reproduced. Illustration 6 shows 90% (dark grey) and 99% (light grey) allowed regions in the Δm_{15}^2, U_{e5} (mixing) space for CP conseving 3+2 models based on the results of seven short-baseline neutrino oscillation experiments: Bugey[10], CCFR84[11], CDHS[12], CHOOZ[13], KARMEN2[14], LSND[15], NOMAD[16]. The values of the four points marked on the graph designate the values we used for the analysis. Their values are listed below in Table (1).

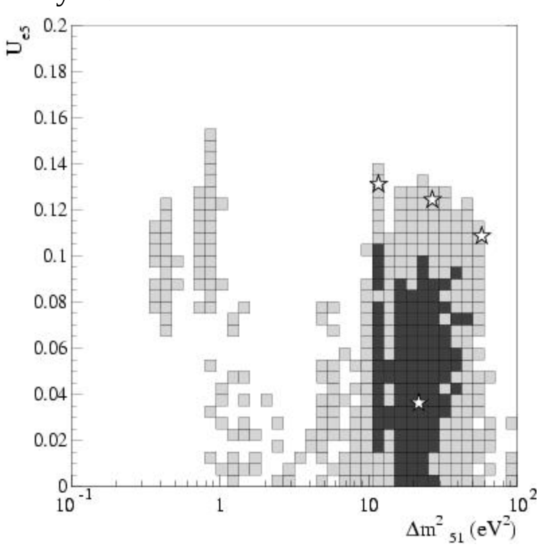


Illustration 6: a plot of 3+2 models , mass spitting squared vs mixing energy for 90% and 99% models

The goal of this analysis is to find the ν_e flux in the NuTeV beam for a 3+2 model. We are interested in the probability of survival P_s, not oscillation, P_o of the ν_e flux. This survival probability, is just the opposite of the oscillation probability

$$1 - P_o = P_s \tag{12}$$

and the value of the 3+2 model ν_e flux can be written as

$$_e^{(3+2)} = P_s * \ _e^{MC} \tag{13}$$

In order to demonstrate the effect of a 3+2 model on the NuTeV data we took four points as indicated on Illustration (6) . These points represent a best fit model (A), a high mixing model with lower mass(B), a high mixing model with higher mass(C), and a high mass model(D). In fact, point A was not fully analyzed because it represented such a small correction to the unoscillated flux that it was recognized to not have an impact. The probability of survival was calculated with a kumac file which depend on these parameters.

$$ModelA: \Delta m_{51}^2 = 20.3, U_{e5} = 0.0394 \quad ModelB: \Delta m_{51}^2 = 11.6, U_{e5} = 0.1311$$
$$ModelC: \Delta m_{51}^2 = 26.7, U_{e5} = 0.1243 \quad ModelD: \Delta m_{51}^2 = 57.4, U_{e5} = 0.1086$$

Table 1: Values for Model A BC and D

All following processes were performed in Physics Analysis Workshop (PAW). After calculating the survival probability, we multiplied the Monte Carlo ν_e flux by the survival probability as in equation (13). The difference in flux is very small and can barely be seen in Illustration 7, which is the Monte Carlo flux before and after being multiplied by the "ModelD" survival probability.(The dotted line is before the multiplication) A ratio is made of the before and after fluxes. (oscillation/nonoscillation) This ratio returns a curve like shape, which we fit with a polynomial function over a given region that clearly deviates from the value 1. Most fits were taken between 20GeV and some upper bound as all values lower than 20 GeV are cut from all the NuTeV data used to calculate $\sin^2\theta_W$. the ratio is unity in the oscillation/nonoscillation graph where the 3+2 model did not affect the flux. Illustration 8 is the 3+2 ν_e flux divided by the original monte carlo ν_e flux for model D. The obvious dip implies that the 3+2 model lowers the amount of ν_e at that energy bin. The slight bump on the left end is an artifact of polynomial fit, not a behaviour of the function. A cut on energy will remove this effect.

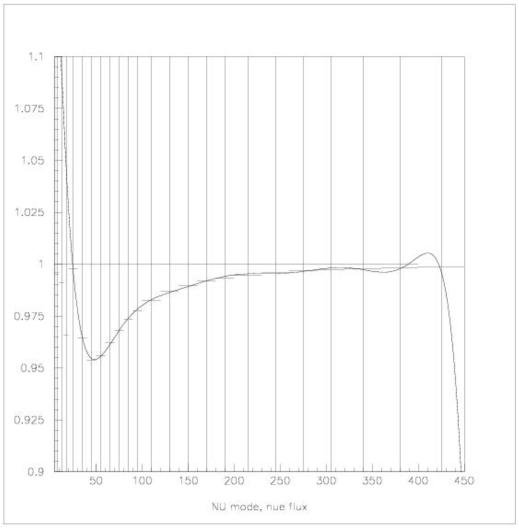


Illustration8:The ratio of before and after the model D correction versus energy

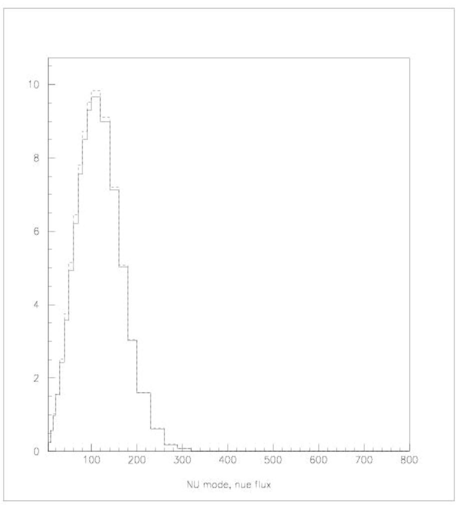


Illustration 7:The electron neutrino flux (per hadronic energy) before and after a model d correction. A very slight difference can be seen. (dotted line is before and straight line is after)

The final polynomial fit is used as a correction to the ν_e flux in the Monte Carlo between the relevant energies. The Monte Carlo produces output including the experimental ν_e and $\nu_{e\text{-bar}}$ flux. We calculate the standard deviation and probability of agreement.

Model B	*Value*	*Deviations from SM*	*Probability of Consistency*
R^{n}_{exp}	0.3917 ± 0.0013	-2.570	1.01%
$R^{n-\mathrm{bar}}_{\mathrm{exp}}$	0.4051 ± 0.0028	-0.535	59.26%
$\sin^{2}\ _{w}$	0.2276 ± 0.0016	2.999	0.27%

Model C	*Value*	*Deviations from SM*	*Probability of Consistency*
R^{n}_{exp}	0.3183 ± 0.0013	-2.434	1.49%
$R^{n-\mathrm{bar}}_{\mathrm{exp}}$	0.4053 ± 0.0028	-0.442	65.73%
$\sin^{2}\ _{w}$	0.2274 ± 0.0016	2.897	0.37%

Model D	*Value*	*Deviations from SM*	*Probability of Consistency*
R^{n}_{exp}	0.3965 ± 0.0013	-2.212	2.69%
$R^{n-\mathrm{bar}}_{\mathrm{exp}}$	0.4056 ± 0.0028	-0.325	74.46%
$\sin^{2}\ _{w}$	0.2271 ± 0.0016	2.687	0.72%

NuTeV original	*Value*	*Deviations from SM*	*Probability of Consistency*
R^{n}_{exp}	0.3916 ± 0.0013	-2.615	0.89%
$R^{n-\mathrm{bar}}_{\mathrm{exp}}$	0.4050 ± 0.0028	-0.571	56.77%
$\sin^{2}\ _{w}$	0.2277 ± 0.0016	3.032	0.24%

Conclusions

We report the standard deviation and probability of agreement with the standard model above. We find that all adjusted fluxes moves $\sin^2\theta_w$ in NuTeV towards the standard model prediction. Model D creates the largest difference in $\sin^2\theta_w$, changing the discrepancy from the standard model from 3.031 to 2.68 standard deviations.

We find that these representative of extreme masses and mixings within the allowed region did not seem to make a significant enough impact on $\sin^2\theta_w$. The largest difference in $\sin^2\theta_w$ is created by a high mass model, like model D. Even such a high mass model will only affect the NuTeV value for $\sin^2\theta_w$ by a fraction of a standard deviation. Therefore we conclude that a 3+2 model with $\nu_e \rightarrow \nu_s$ can not explain the NuTeV anomaly by itself.

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