# ACCELERATOR NEUTRINO PROGRAMME AT FERMILAB*

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The accelerator neutrino programme in the USA consists primarily of the Fermilab neutrino programme. Currently, Fermilab operates two neutrino beamlines, the Booster neutrino beamline and the NuMI neutrino beamline and is the planning stages for a third neutrino beam to send neutrinos to DUSEL. The experiments in the Booster neutrino beamline are miniBooNE, SciBooNE and in the future microBooNE, whereas in the NuMI beamline we have MINOS, ArgoNut, MINERVA and coming soon NO$\nu$A. The major experiment in the beamline to DUSEL will be LBNE.

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## 1. Neutrino standard model

The flavor content of the three neutrino mass eigenstates is given in Fig. 1. The current questions in this model are what is the size of

$$\sin^2\theta_{13}\,,\quad \left(\sin^2\theta_{23}-\tfrac{1}{2}\right)\,,\quad \left(\sin^2\theta_{12}-\tfrac{1}{3}\right)\,,\quad \mathrm{sign}\left(\delta m^2_{31}\right)\ \text{and}\ \sin\delta_{\mathrm{CP}}\,. \tag{1}$$

It is possible that the first three of these are related to some small parameter like $\delta m^2_{21}/\delta m^2_{31}\approx 0.03$ raised to some power, $n$. From current experiments the size of this power is constrained to be larger than one, $n>1$, except for $(\sin^2\theta_{23}-1/2)$ where the lower bound is weaker, approximately $n>1/2$.

This could be due to some broken Tri-Bi-Maximal symmetry which would be very interesting and exciting. Another possibility is that it is coincidental which would be much less interesting from a theorists perspective.

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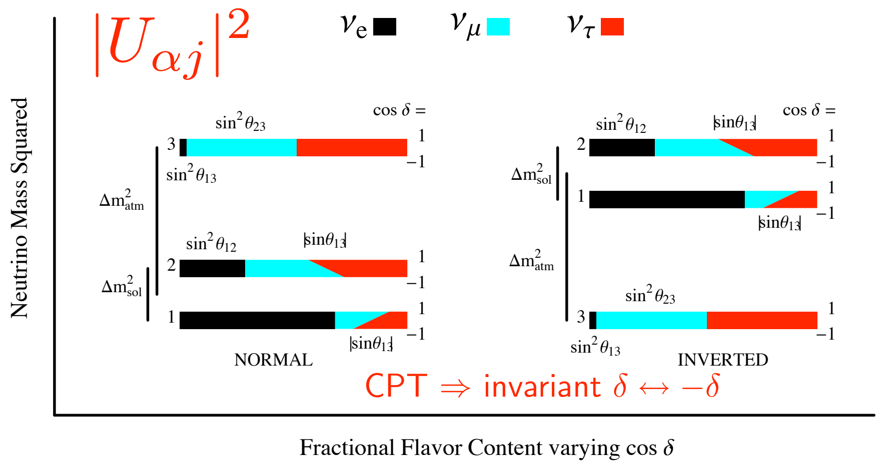


Fig. 1. The flavor content of the neutrino mass eigenstates [1]. The width of the lines is used to show how these fractions change as $\cos\delta_{\rm CP}$ varies from $-1$ to $+1$. Of course, this figure must be the same for neutrinos and anti-neutrinos if CPT is conserved.

## 2. Current neutrino program at Fermilab

Currently there are two operating neutrino beamlines at Fermilab with another being proposed. These are:

- The Booster Neutrino Beamline which uses 8 GeV protons from the Booster. Currently only miniBooNE is taking data in this beamline since SciBooNE has completed its data taking and mircoBooNE is still in the approval process.

- NuMI (Neutrinos from the Main Injector) which uses 120 GeV protons from the main injector. This beamline sends neutrinos to the MINOS near and far detectors. Also in the near detector hall is ArgoNut and MINERVA. ArgoNut is taking data and MINERVA will start data taking in 2010. The NO$\nu$A near and far detectors will also use neutrinos from this beamline.

- In addition, there is a proposal to build a third neutrino beamline to send a neutrino beam from Fermilab to DUSEL in the Homestake mine. This beamline will initially be powered by protons from the main injector but will eventually be powered by a very high intensity proton beam (>2MW) from Project X.

MINOS uses 120 GeV protons from the main injector with a nominal beam power of 300 kW and currently has the world's best measurement of $|\Delta m^2_{32}|$ using the neutrino beam [2],

$$\left|\Delta m^2_{32}\right| = 2.43 \pm 0.13 \times 10^{-3}\ \mathrm{eV}^2\,, \tag{2}$$

and is currently running in anti-neutrino mode to check whether or not CPT is violated in the neutrino sector, see Fig. 2.

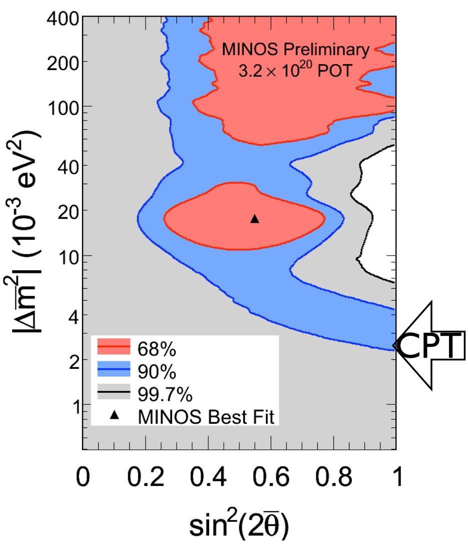


Fig. 2. The $\delta m^2_{32}$ *versus* $\sin^2 2\theta_{23}$ allowed region obtained using the anti-neutrinos in the neutrino beam. The CPT conserving point is within the 90% contour. MINOS has now finished a dedicated run with anti-neutrinos to tighten the contours on this plot.

MiniBooNE and SciBooNE are measuring neutrino cross-sections relevant for future neutrino experiments. Also, MiniBooNE is also looking for deviations from the three active neutrino Standard Model that has been assembled in the last ten years and in particular to confirming or refuting the LSND anomaly. No evidence in support of LSND has been found but an unexplained low energy excess in the 200 to 475 MeV was observed [3],

$$\text{Excess Events (200 to 475MeV)} = 128.8 \pm 20.4 \pm 38.3\,. \tag{3}$$

While in the anti-neutrino channel the evidence for an excess is inconclusive.

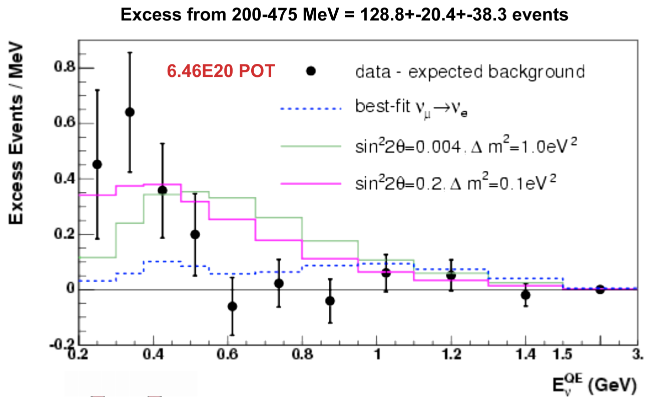


Fig. 3. The excess events as seen in neutrino running at MiniBooNE. Between 200 and 475 MeV, a clear excess is seen.

### *2.1. NO$\nu$A*

The NO$\nu$A project consists of increasing the beam power in NuMI (Neutrinos from the Main Injector) from 300 kW to 700 kW and to build the 15 kton liquid scintillator NO$\nu$A detector in Ash River, 810 km from Fermilab, so as to explore both $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at the sub 1% level. This will put a limit on $\sin^2 2\theta_{13}$ at the 0.01 level, see Fig. 4. This

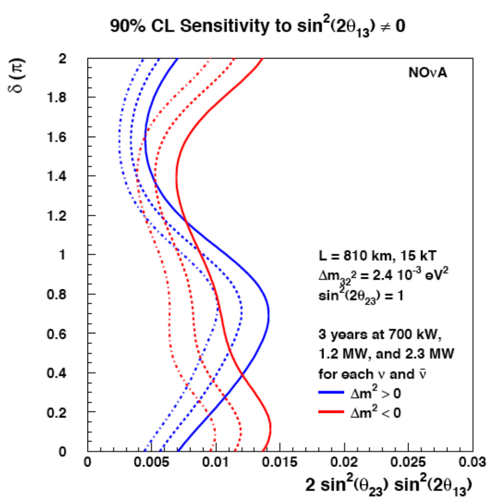


Fig. 4. The 90% sensitivity to $\sin^2 2\theta_{13}$ for NO$\nu$A [4] assuming equal running time for neutrinos and anti-neutrinos. The darker (lighter) curves are for the normal (inverted) hierarchy. In each set the three lines from right to left are for 0.7, 1,2 and 2.3 MW of protons on target respectively. These curves correspond to $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at the sub 1% level.

experiment will also give us the first glimpse of the neutrino mass hierarchy and/or the first restrictions of the range of the CP-violating phase $\delta_{\rm CP}$, see Fig. 5.

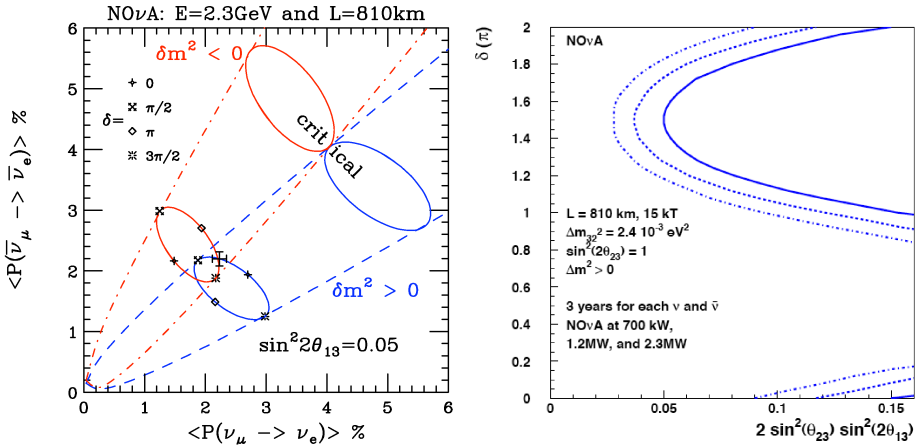


Fig. 5. The left panel is the bi-probability plot, $\nu_\mu \to \nu_e$ *versus* $\bar{\nu}_\mu \to \bar{\nu}_e$ for the NO$\nu$A experiment showing the critical value of $\theta_{13}$ ($\sin^2 2\theta_{13} = 0.11$) as well as two (out of four) of the ellipses which pass through the data point (large cross) with $\sin^2 2\theta_{13} = 0.05$ [1]. The right panel shows the parameters in $\sin^2 2\theta_{13}$ *versus* $\delta$ plane that NO$\nu$A [4] determines assuming the hierarchy is normal.

Also the MINERvA experiment operating in the NuMI near detector hall will perform precision measurements of neutrino cross-sections above 1 GeV on various nuclear targets. The information obtained from this experiment will be invaluable for future very long baseline neutrino oscillation experiments.

### 2.2. The physics of long baseline: $\nu_\mu \to \nu_e$

The amplitude for $\nu_\mu \to \nu_e$ can be simple written a sum of three amplitudes, one associated with each neutrino mass eigenstate,

$$U^*_{\mu 1} e^{-im_1^2 L/2E} U_{e1} + U^*_{\mu 2} e^{-im_2^2 L/2E} U_{e2} + U^*_{\mu 3} e^{-im_3^2 L/2E} U_{e3}\,.$$

The first term can be eliminated using the unitarity of the MNS matrix and thus the appearance probability can be written as follows [6]

$$P(\nu_\mu \to \nu_e) \;\approx\; \left| \sqrt{P_{\rm atm}} e^{-i(\varDelta_{32}+\delta)} + \sqrt{P_{\rm sol}} \right|^2 . \tag{4}$$

$\varDelta_{jk}$ is used as a shorthand for the the kinematic phase, $\delta m^2_{jk} L/4E$. As the notation suggests the amplitude $\sqrt{P_{\rm atm}}$ only depends on $\delta m^2_{31}$ and $\sqrt{P_{\rm sol}}$

only depends on $\delta m^2_{21}$. For propagation in the matter, these amplitudes are simple given by:

$$\sqrt{P_{\rm atm}} = \sin\theta_{23}\ \sin 2\theta_{13}\ \frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\ \Delta_{31}\,,$$
$$\sqrt{P_{\rm sol}} = \cos\theta_{23}\ \sin 2\theta_{12}\ \frac{\sin(aL)}{(aL)}\ \Delta_{21}\,. \quad (5)$$

The matter potential is given by $a = G_{\rm F}N_e/\sqrt{2} \approx (4000\ \text{km})^{-1}$ and the sign of $\Delta_{31}$ (and $\Delta_{32}$) determines the hierarchy; normal $\Delta_{31} > 0$ whereas inverted $\Delta_{31} < 0$. When $a$ is set to zero one recovers the vacuum result. See Fig. 6 [7].

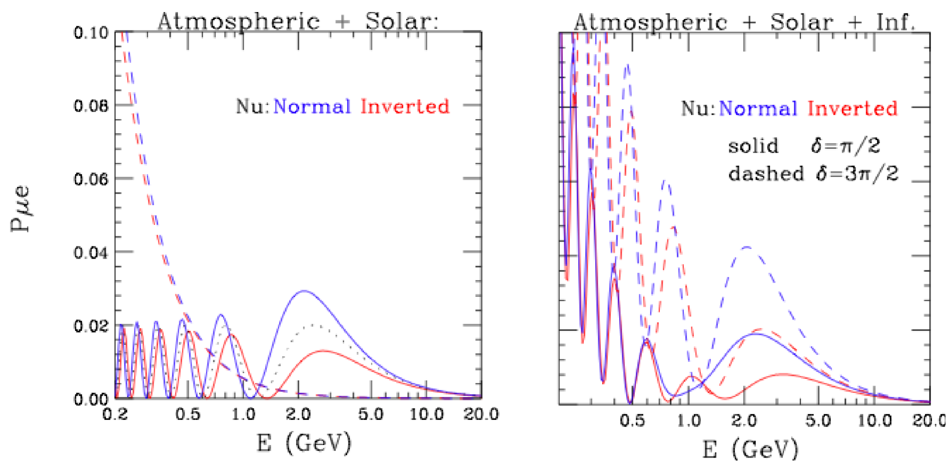


Fig. 6. The left panel shows the two components $P_{\rm atm}$ and $P_{\rm sol}$ in matter for the normal and inverted hierarchies for $\sin^2 2\theta_{13} = 0.04$ and a baseline of 1200 km. The right panel shows the total probability including the interference term between the two components for various values of the CP phase $\delta$ for the neutrino. Notice that the coherent sum of two amplitudes shows a rich structure depending on the hierarchy and value of CP phase. These curves can also be interpreted as anti-neutrino probabilities if one interchanges the hierarchy AND the values of the CP phase.

For anti-neutrinos $a \to -a$ and $\delta \to -\delta$. Thus the phase between $\sqrt{P_{\rm atm}}$ and $\sqrt{P_{\rm sol}}$ changes from $(\Delta_{32}+\delta)$ to $(\Delta_{32}-\delta)$. This changes the interference term from

$$2\sqrt{P_{\rm atm}}\sqrt{P_{\rm sol}}\cos(\Delta_{32}+\delta)\ \Rightarrow\ 2\sqrt{P_{\rm atm}}\sqrt{P_{\rm sol}}\cos(\Delta_{32}-\delta)\,. \quad (6)$$

Expanding $\cos(\Delta_{32}\pm\delta)$, one has a CP conserving part

$$2\sqrt{P_{\rm atm}}\sqrt{P_{\rm sol}}\cos\Delta_{32}\cos\delta \quad (7)$$

and the CP-violating part

$$\mp 2\sqrt{P_{\rm atm}}\sqrt{P_{\rm sol}}\sin\Delta_{32}\sin\delta\,. \tag{8}$$

Therefore, CP violation is maximum when $\Delta_{32} = (2n+1)\,\pi/2$ and grows as $\delta$ grows. Notice also, that for this term to be non-zero the kinematical phase $\Delta_{32}$ cannot be $n\pi$. The first person who emails me having noticed this statement will get a prize. I am checking to see if anybody reads these things. This is the neutrino counter part to the non-zero strong phase requirement for CP violation in the quark sector.

The asymmetry between $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ is a maximum when $\sqrt{P_{\rm atm}} = \sqrt{P_{\rm sol}}$. At the first oscillation maximum, $\Delta_{31} = \pi/2$, this occurs when $\sin^2 2\theta_{13} = 0.002$ in vacuum. For values of $\sin^2 2\theta_{13} < 0.002$ the oscillation probabilities are dominated by $P_{\rm sol}$ and thus observing the effects of non-zero $\sin^2 2\theta_{13}$ becomes increasingly more challenging.

### *2.3. DUSEL and LBNE*

Even if $\sin^2 2\theta_{13} > 0.01$, a further experiment will be needed to determine the precise value of the CP-violating phase, $\delta_{\rm CP}$. Fermilab has proposed to build a new neutrino beamline to DUSEL and to build a large neutrino detector there. This experiment is called the Long Baseline Neutrino Experiment (LBNE). The detector would consist of 300 ktons of water Čerenkov detectors or 50 ktons of Liquid Argon detectors or some combination of both.

The new neutrino beamline would be initially powered by the main injector but then by Project X which would deliver 2.2 MW of protons at 50–120 GeV. Project X in addition could provide up to 2 MW of protons at 2–3 GeV for Kaon, Muon and other experiments.

The detector technology would be either water Čerenkov similar to SuperK or a LAr TPC or a combination of both. The water Čerenkov detector could be built with little R&D but would have to be larger than LAr due to its lower efficiency. Whereas substantial R&D is required for a large LAr TPC but this technology has a higher efficiency than water Čerenkov due to its better discrimination of electron and gamma ($\pi^0$) events. LAr also has an enhanced sensitivity to proton decay in the $K^+\nu$ channel over water Čerenkov which also makes it an attractive alternative assuming a successful R&D program. For both detector technologies a modular design is probably necessary to get the very large fiducial volumes required. If affordable, a combination of both detectors would be very powerful. For a possible evolution of this R&D see Fig. 7.

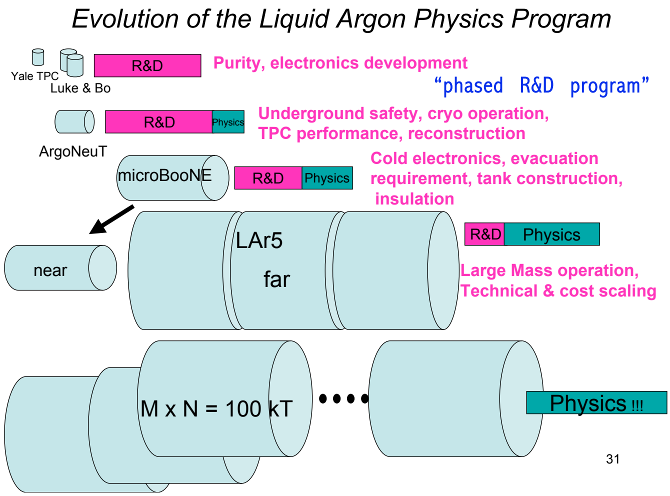


Fig. 7. Possible evolution of a Liquid Argon detector program [5] in North America.

The reach for $\sin^2 2\theta_{13}$, the mass hierarchy and CP-violating for the Fermilab Project X program is given in Fig. 8. If $\sin^2 2\theta_{13}$ is significantly smaller than $10^{-3}$ or precision measurements of the oscillation parameters are required then protons from Project X could be used for a neutrino factory with detector(s) at DUSEL. With further technical developments these facilities could also be used for a future multi-TeV muon collider.

A brief outline of Project X is given and of a possible neutrino program that could be performed. At this stage many options need to be studied in detail especially with regard to various funding profiles. However, it is clear that an intense neutrino source combined with very massive detectors is required to explore the size of $\theta_{13}$, the neutrino mass hierarchy and the CP violation in the neutrino sector.

### *2.4. Project X summary*

Project X with its multi-megawatt high energy beams for neutrino physics and its multi-megawatt low energy beams for rare Kaon physics, Muon physics and possibly other projects is a true Intensity Frontier Machine. The neutrino experiments have a clear goal to determine CP violation in the neutrino sector and determine the neutrino mass hierarchy. The Kaon program would look for 1000 events in both $K^+ \to \pi^+\nu\bar{\nu}$ and $K^0 \to \pi^0\nu\bar{\nu}$. The Muon program would look for $\mu + N \to e + N$ at unprecedented sensitivity as well as to push for a more precise measurement of $(g-2)_\mu$. Further in time is the possibility to use Project X to power a neutrino factory and then to regain the energy frontier with a multi-TeV muon collider.

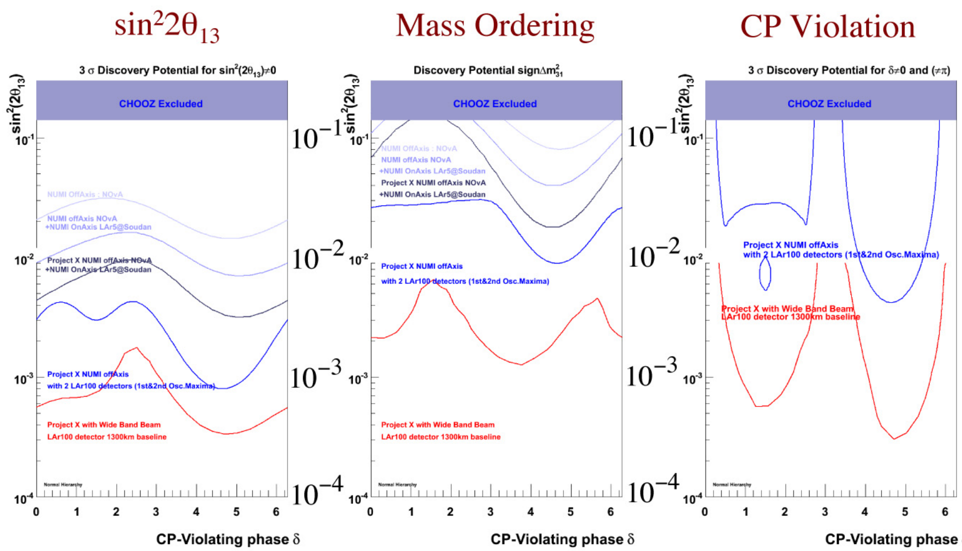


Fig. 8. The evolution of the reach for $\sin^2 2\theta_{13}$, the mass hierarchy and CP-violating for the Fermilab Project X program [8].

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## REFERENCES


[1] O. Mena, S.J. Parke, *Phys. Rev.* **D70**, 093011 (2004) `[arXiv:hep-ph/0408070]`.

[2] P. Adamson *et al.* [MINOS Collaboration], *Phys. Rev. Lett.* **101**, 131802 (2008) `[arXiv:0806.2237[hep-ex]]`.

[3] A.A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], *Phys. Rev. Lett.* **102**, 101802 (2009) `[arXiv:0812.2243[hep-ex]]`.

[4] D.S. Ayres *et al.* [NOvA Collaboration], `arXiv:hep-ex/0503053`.

[5] From the "Project X Workshop Series", FNAL, 2007–2008.

[6] A. Cervera, A. Donini, M.B. Gavela, J.J. Gomez Cadenas, P. Hernandez, O. Mena, S. Rigolin, *Nucl. Phys.* **B579**, 17 (2000) [Erratum Nucl. Phys. **B593**, 731 (2001)] `[arXiv:hep-ph/0002108]`.

[7] H. Nunokawa, S.J. Parke, J.W.F. Valle, *Prog. Part. Nucl. Phys.* **60**, 338 (2008) `[arXiv:0710.0554[hep-ph]]`.

[8] Fermilab Steering Group Report, FERMILAB-PUB-07-672-DO.