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Highlights from Fermilab

Stephen J. Parke

Theoretical Physics Department,
Fermi National Accelerator Laboratory
P.O.Box 500, Batavia, IL 60510, USA
parke@fnal.gov

ABSTRACT

In these two lectures I will chose some highlights from the Tevatron experiments (CDF/D0) and the Neutrino experiments and then discuss the future direction of physics at Fermilab after the Tevatron collider era.

1. Tevatron Highlights:

Although there are many highlights of the Tevatron program, I have chosen to speak about those that are relevant for the Tevatron Higgs search: W-boson mass, Top quark mass, single Top production, di-Vector boson production and the Higgs search. But first I would like to say a little about the current status of the machine and the prospects for the future. Currently, the Tevatron has delivered ~ 7 fb^{-1} of data to each experiment with a peak luminosity of 3.5×10^{32} cm^{-2}sec^{-1}. The expectation is that by the end of fiscal 2011 (9/2012) each of the Tevatron experiments will have ~ 12 fb^{-1} of data of tape, essentially doubling the current amount of data collected.

At the peak instantaneous luminosity the number of anti-protons burnt by collisions is 7.0×10^7 sec^{-1} ($2 \times 3.5 \times 10^{32}$ cm^{-2} sec^{-1} $\times$ 100 mb $\approx 7.0 \times 10^7$ sec^{-1}) which is very close to the peak anti-proton collection rate of 7×10^7 sec^{-1}. Of course this a statement about the peak luminosity and peak collection rates but I think it illustrates the issue very effectively and thus, only modest increases in the luminosity of the Tevatron can be envisaged over the remaining life of the machine without significant improvements in the collection and handling of anti-proton.

In the Standard Model (SM) the Higgs mass is related to the mass of the W-boson and Top quark mass through radiative corrections. Thus, a precise determination of the W-boson mass and the Top quark mass will tell us the mass of the SM Higgs boson. However, the precision required is extreme, especially for the W-boson where a 6 MeV uncertainty is equivalent to a 1 GeV uncertainty on the Top quark mass on the range of allowed Higg masses.

At the Tevatron the cross section for producing a Higgs boson is at the pb level so that one needs to observe a number of background processes which have larger cross sections such as single top quark production and di-Vector boson production. Both of these two cross sections will be discussed before addressing the Tevatron Higgs

searches. Many of the results reported in this section for the Tevatron experiments can be found the slides and proceedings of Lepton-Photon 2009[1)].

1.1. W-boson Mass

Determination of the W-boson mass at the Tevatron requires a detailed understanding of the detector response to both the charge lepton and jet P_T. The Tevatron Average (CDF+D0) for W-boson mass is

$$m_W = 80420 \pm 31 \text{ MeV}. \tag{1}$$

See Fig. 1. This result has a smaller uncertainty than the LEP2 average! When combine with LEP2 gives the World Average W-boson mass is

$$m_W = 80399 \pm 23 \text{ MeV}. \tag{2}$$

As will be seen shortly the uncertainty in the W-boson mass dominates our uncertainty on the expected mass of the SM Higgs boson.

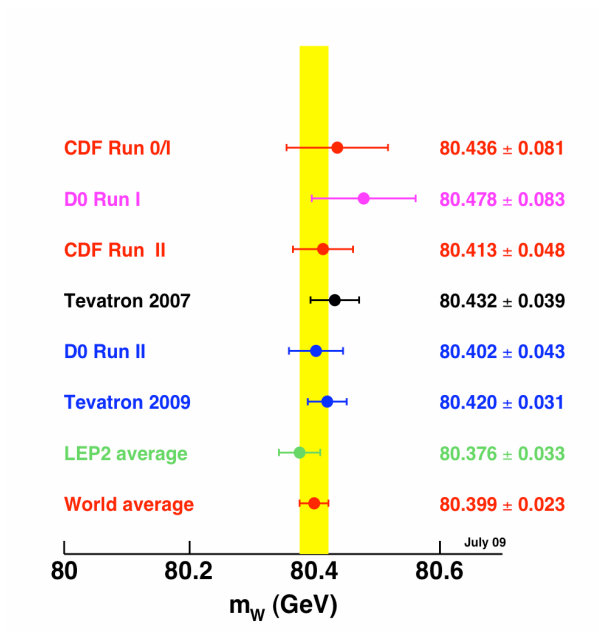

Figure 1: Summary of W-boson mass measurements from the various experiments.

1.2. Top Quark Mass

The mass of the Top quark has been measured in numerous channels and with a variety of techniques, see Fig. 2, and the Tevatron Average Top quark mass is given

by

$$m_t = 173.1 \pm 1.3 \text{ GeV}. \tag{3}$$

D0 has also measured the difference in the mass of the Top and Anti-Top quarks and finds that the difference is given by

$$\Delta m_t = 3.8 \pm 3.7 \text{ GeV}. \tag{4}$$

The symmetry CPT implies that the mass difference between the Top and the anti-Top quarks should be strictly zero, hence, there is no evidence for CPT violation in the mass of the Top and anti-Top quarks.

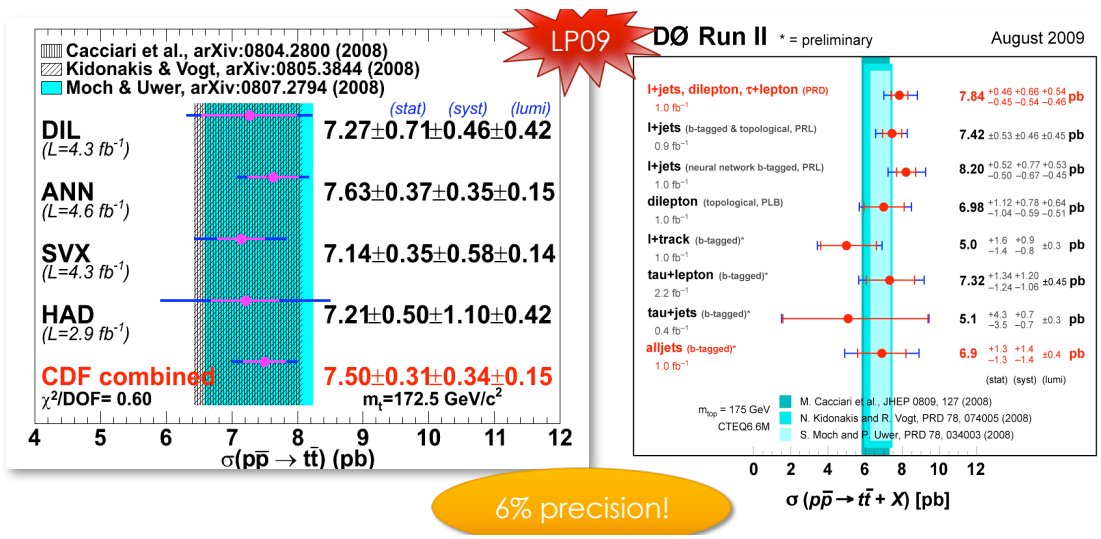

Figure 2: Summary of top quark mass measurements from the various channels in CDF and D0 as presented at LP09.

1.3. Single Top Production

One of the backgrounds for searches for the Higgs is single top quark production. Both CDF and D0 have better than 5σ evidence for the production of single top quarks. The combined CDF and D0 result for the sum of the s and t channel cross sections is given as

$$\sigma_t = 2.76^{+0.58}_{-0.47} \text{ pb}. \tag{5}$$

See Fig. 3. Understanding how to extract this signal is a very important milestone on the way to discovering the Higgs boson.

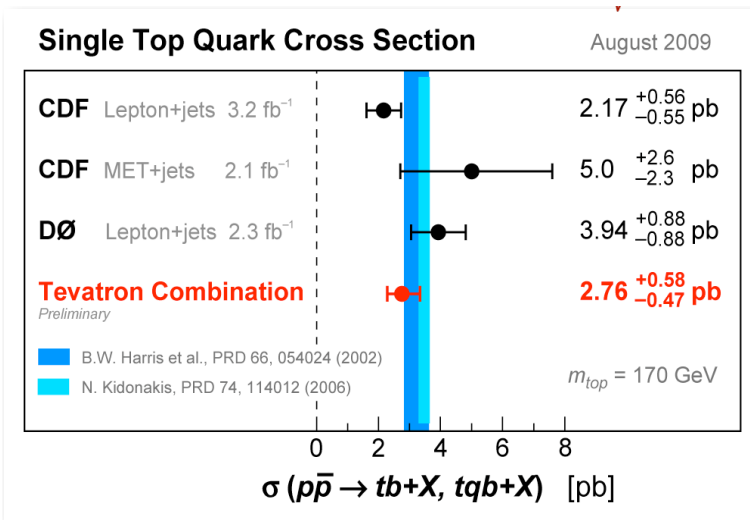

Figure 3: The single top cross section for CDF and D0 for the combined s and t channel processes.

1.4. Cross Sections for VV

Another milestone on the way to discovery of the Higgs boson is the observation of $WW/WZ/ZZ$. Both CDF and D0 have observed ZZ in the four charged lepton channel with a significance greater than 5σ. The cross sections are consistent with the SM cross section of 1.4 ± 0.1 pb. ZZ to dilepton plus dijets as well as ZZ dijets plus neutrinos have not been observed so far.

For the $WW/WZ/ZZ$ channels, CDF has observed then in the mode where one of the vector bosons decays hadronically recoiling against the leptonic decay of the other vector boson, see Fig. 4. The measured cross section is

$$\sigma(WW/WZ/ZZ) = 18.0 \pm 2.8 \pm 2.6 \text{ pb}. \tag{6}$$

The next milestone in Higgs search is to look for WZ and ZZ with $Z \to b\bar{b}$ the last benchmark before observation of the low mass Higgs in WH and ZH channels.

1.5. Search for the Higgs Boson

For the constraint coming from the mass of W boson and top quark see Fig. 5. For masses of the Higgs boson below 135 GeV, the dominant decay mode is $H \to b\bar{b}$ whereas for masses above 135 GeV the dominant decay mode is WW^*. For the high mass Higgs one can use the events from gluon fusion $gg \to H$ whereas for low mass Higgs one uses $q\bar{q} \to H + W$ or Z with the W or Z decaying leptonically. See Fig. 6. The combined current Tevatron limit is given in Fig. 7.

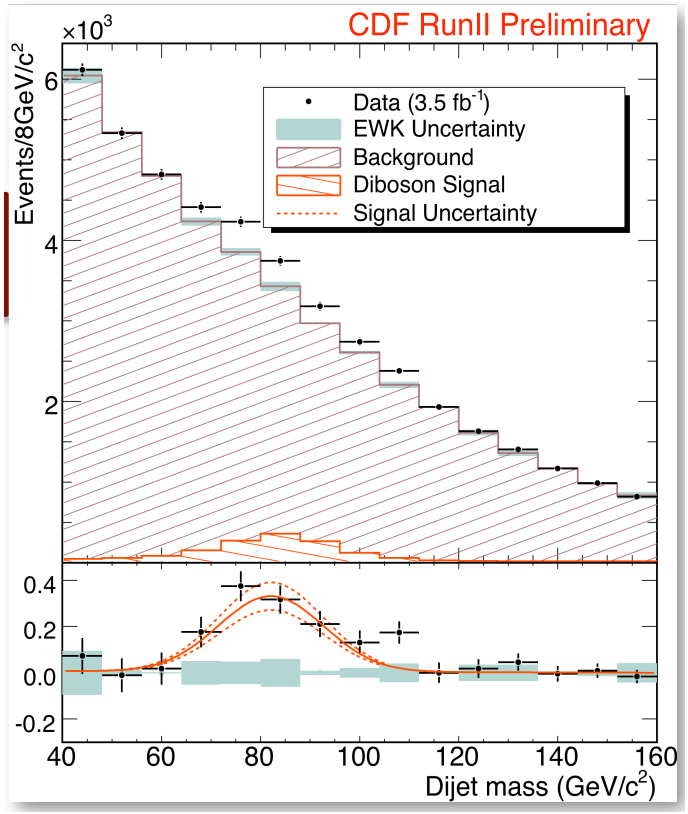

Figure 4: The dijet invariant mass distribution showing the contribution from W and Z bosons..

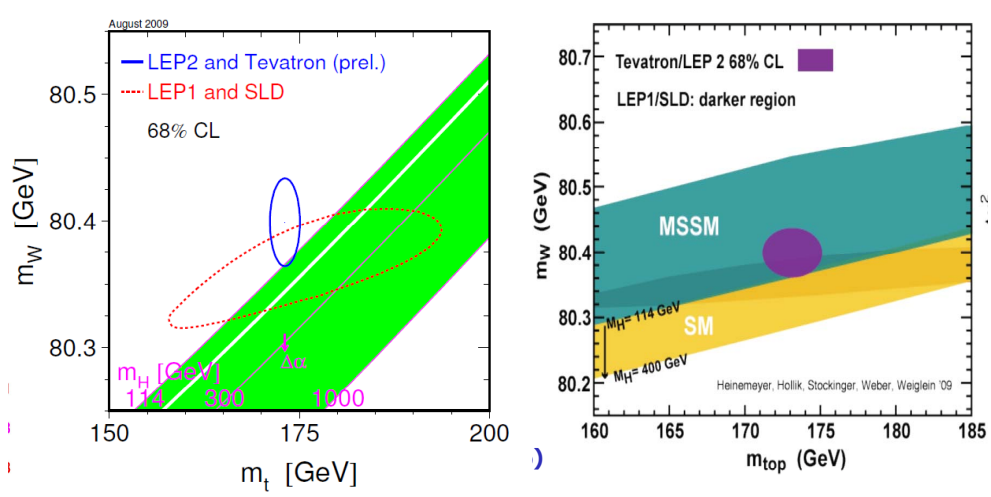

Figure 5: The constraint on the Higgs mass coming from the mass of the W-boson and the top quark. Left panel is for the Standard Model only whereas the right panel includes the allowed region for SUSY models. In the Standard Model the mass data favors light Higgs masses.

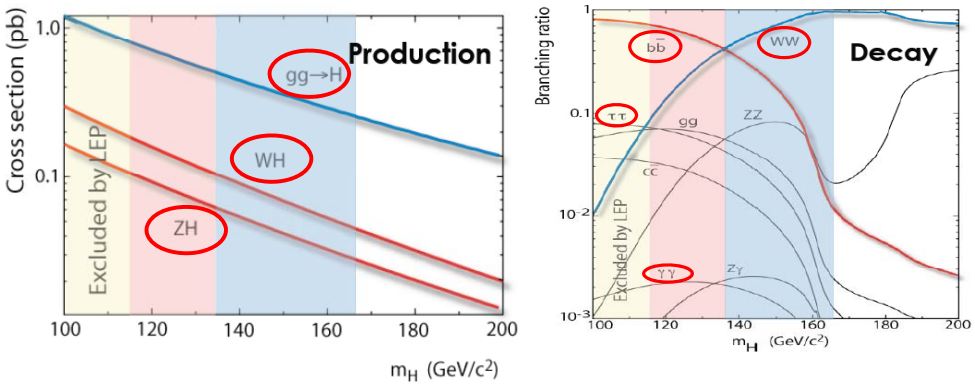

Figure 6: The production cross sections for the Higgs boson at the Tevatron along with the Higgs branching fraction to various decay modes.

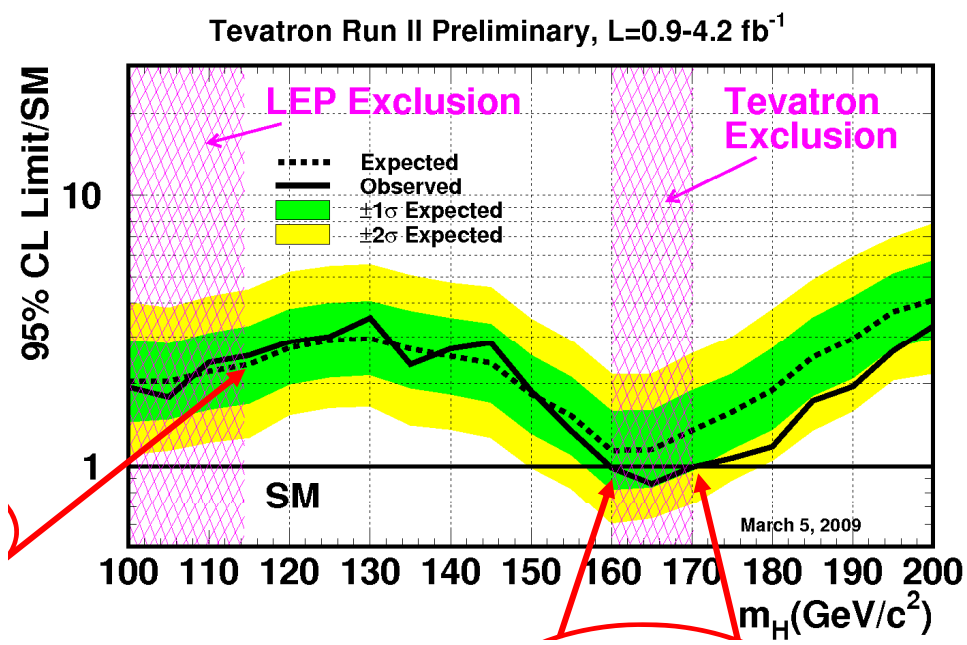

Figure 7: The combined CDF and D0 exclusion limits for the Higgs boson. At the 95% C.L. the SM Higgs is excluded between 160 and 170 GeV.

2. Fermilab Neutrinos, Future Program & Long Term Strategy:

2.1. Current Neutrino Program

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 it's 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 NOνA 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.

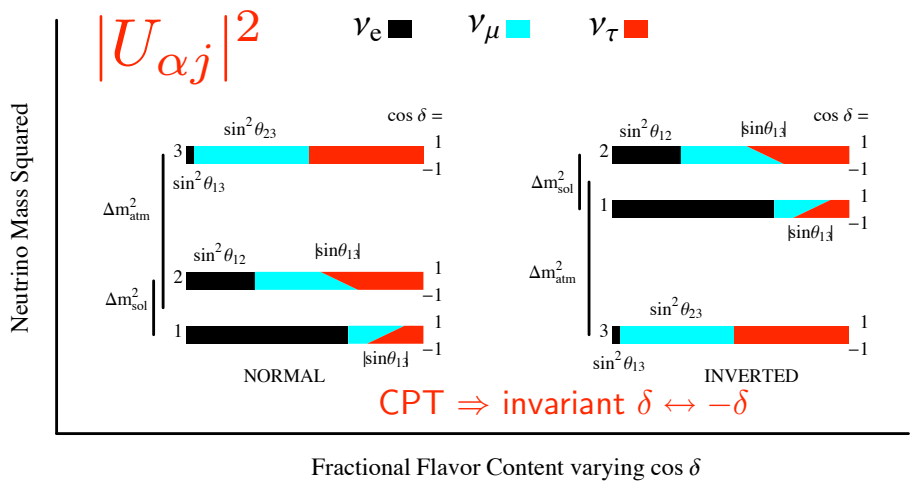

Figure 8: The flavor content of the neutrino mass eigenstates[3]. The width of the lines is used to show how these fractions change as $\cos\delta_{CP}$ varies from -1 to +1. Of course, this figure must be the same for neutrinos and anti-neutrinos if CPT is conserved.

MINOS uses 120 GeV protons from the main injector with a nominal beam power of 300kW and currently has the world's best measurement of $|\Delta m^2_{32}|$ and is currently running in anti-neutrino mode to check whether or not CPT is violated in the neutrino sector. 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.

2.2. Neutrino Standard Model

The flavor content of the three neutrino mass eigenstates is given in Fig. 8. The current questions in this model are what is the size of

$$\sin^2\theta_{13}, \quad (\sin^2\theta_{23} - \frac{1}{2}), \quad (\sin^2\theta_{12} - \frac{1}{3}), \quad \mathrm{sign}(\delta m^2_{31}) \quad \text{and} \quad \sin\delta_{CP} \tag{7}$$

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 $(\sin^2\theta_{23} - \frac{1}{2})$ 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.

2.3. NOνA

The NOνA 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 NOνA detector in Ash River, 810 km from Fermilab, so as to explore both $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ at the sub 1% level. This will put a limit on $\sin^2 2\theta_{13}$ at the 0.01 level, see Fig. 9. This 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 δ_{CP}, see Fig. 10.

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 oscillations.

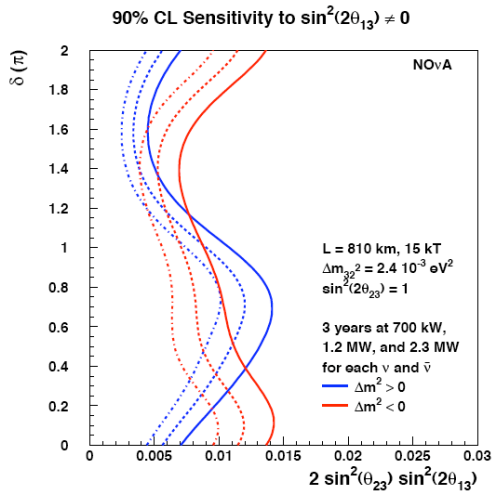

Figure 9: The 90% sensitivity to $\sin^2 2\theta_{13}$ for NOνA [2] assuming equal running time for neutrinos and anti-neutrinos. The blue (red) curves is for the normal (inverted) hierarchy. The three lines from right to left are for 0.7, 1,2 and 2.3 MW of protons on target respectively. These curves correspond to $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ at the sub 1% level.

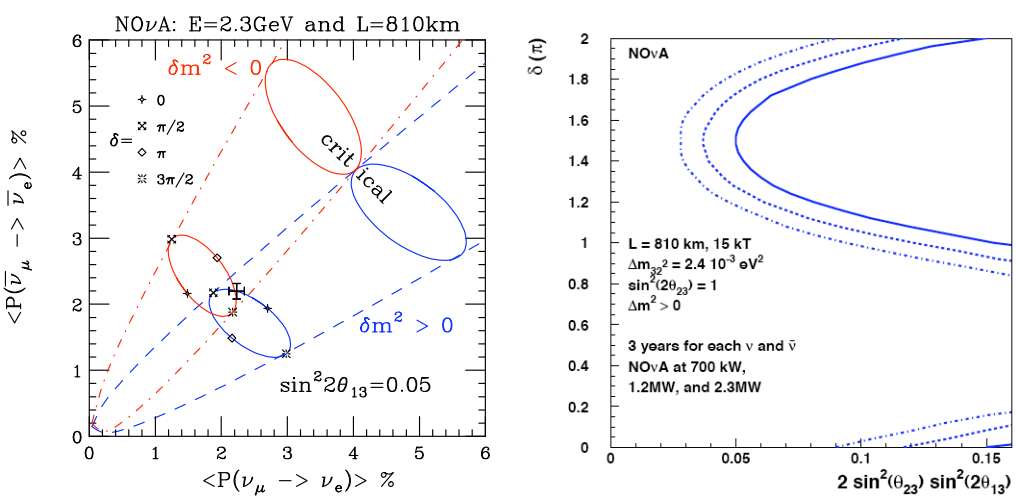

Figure 10: The left panel is the bi-probability plot, $\nu_\mu \to \nu_e$ verses $\bar{\nu}_\mu \to \bar{\nu}_e$ for the NOνA experiment showing the critical value of θ_{13} ($\sin^2 2\theta_{13} = 0.11$) as well as two (out of four) of the ellipses which pass through the data point (large cross) with $\sin^2 2\theta_{13} = 0.05$ [3] . The right panel shows the parameters in $\sin^2 2\theta_{13}$ v δ plane that NOνA [2] determines the hierarchy assuming it is normal.

2.4. The Physics of Long Baseline: $\boldsymbol{\nu_\mu \longrightarrow \nu_e}$

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[5)]

$$P(\nu_\mu \to \nu_e) \;\approx\; \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2 . \tag{8}$$

Δ_{jk} is used as a shorthand for the the kinematic phase, $\delta m^2_{jk} L/4E$. As the notation suggests the amplitude $\sqrt{P_{atm}}$ only depends on δm^2_{31} and $\sqrt{P_{sol}}$ only depends on δm^2_{21}. For propagation in the matter, these amplitudes are simple given by

$$\begin{aligned} \sqrt{P_{atm}} &= \sin\theta_{23}\ \sin 2\theta_{13}\ \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\ \Delta_{31} \\ \sqrt{P_{sol}} &= \cos\theta_{23}\ \sin 2\theta_{12}\ \frac{\sin(aL)}{(aL)}\ \Delta_{21}. \end{aligned} \tag{9}$$

The matter potential is given by $a = G_F N_e/\sqrt{2} \approx (4000\ km)^{-1}$ and the sign of Δ_{31} (and Δ_{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.11 [6)].

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

$$2\sqrt{P_{atm}}\sqrt{P_{sol}}\cos(\Delta_{32} + \delta) \;\;\Rightarrow\;\; 2\sqrt{P_{atm}}\sqrt{P_{sol}}\cos(\Delta_{32} - \delta). \tag{10}$$

Expanding $\cos(\Delta_{32} \pm \delta)$, one has a CP conserving part $2\sqrt{P_{atm}}\sqrt{P_{sol}}\cos\Delta_{32}\cos\delta$ and the CP violating part

$$\mp 2\sqrt{P_{atm}}\sqrt{P_{sol}}\sin\Delta_{32}\sin\delta. \tag{11}$$

Therefore CP violation is maximum when $\Delta_{32} = (2n+1)\frac{\pi}{2}$ and grows as n grows. Notice also, that for this term to be non-zero the kinematical phase Δ_{32} cannot be $n\pi$. The first person who emails me having noticed this statement will get a prize. I'm 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 $\sqrt{P_{atm}} = \sqrt{P_{sol}}$. 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_{sol} and thus observing the effects of non-zero $\sin^2 2\theta_{13}$ become increasing more challenging.

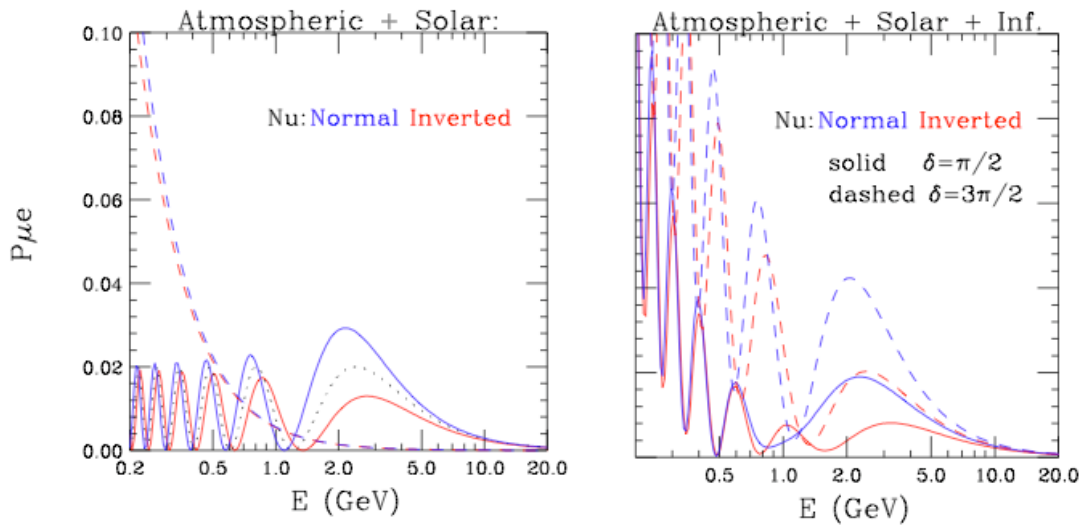

Figure 11: The left panel shows the two components P_{atm} and P_{sol} in matter for the normal and inverted hierarchies for $\sin^2 2\theta_{13} = 0.04$ and a baseline of 1200 km. The right panel shows the total probability including the interference term between the two components for various values of the CP phase δ 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.

2.5. 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, δ_{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 Cerenkov 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 cerenkov similar to SuperK or a LAr TPC or a combination of both. The water cerenkov detector could be built with little R&D but would have to be larger than LAr due to it's lower efficiency. Whereas substantial R&D is required for a large LAr TPC but this technology has a higher efficiency than water cervenkov due to it's better discrimination of electron and gamma (π^0) events. LAr also has a enhanced sensitivity to proton decay in the $K^+\nu$ channel over water Cerenkov which also makes it an attractive alternative assuming a

successful R&D program. For both detector technology 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.12.

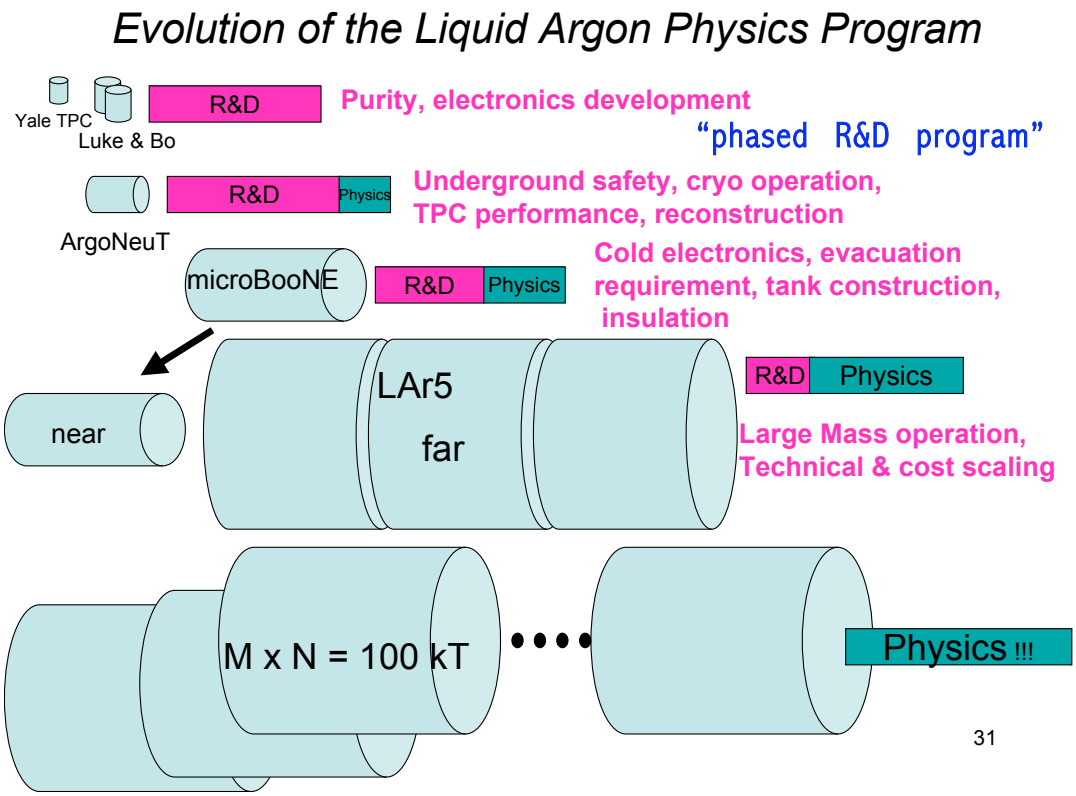

Figure 12: Possible evolution of a Liquid Argon detector program[4)] in North America.

The reach for $\sin^2 2\theta_{13}$, the mass hierarchy and CP violating for the Fermilab Project X program is given in Fig.13. 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 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 θ_{13}, the

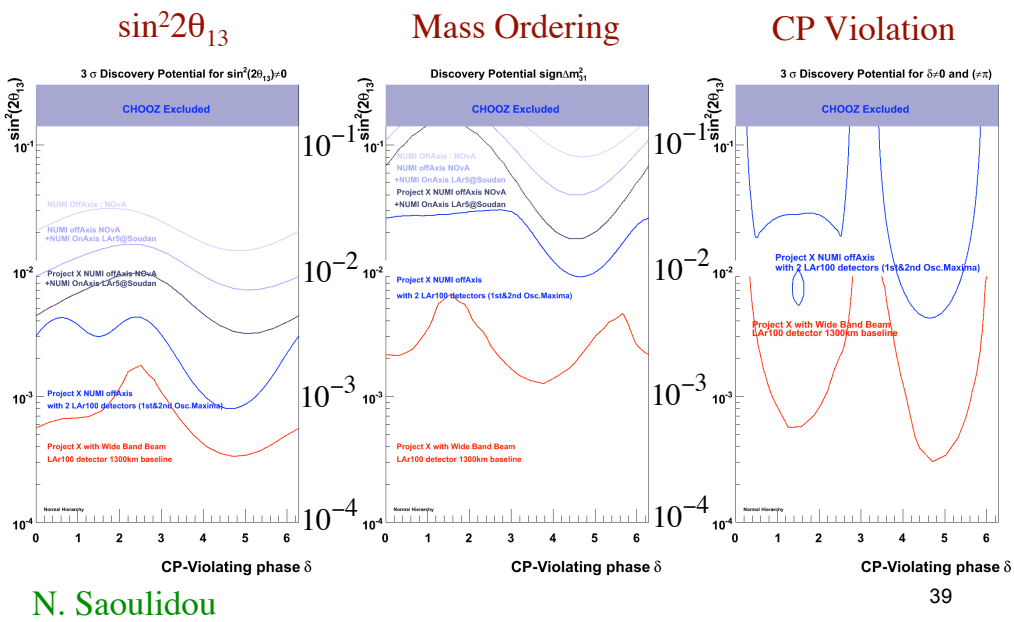

Figure 13: The evolution of the reach for $\sin^2 2\theta_{13}$, the mass hierarchy and CP violating for the Fermilab Project X program [7] .

neutrino mass hierarchy and the CP violation in the neutrino sector.

2.6. Project X Summary

Project X with it's multi-megawatt high energy beams for neutrino physics and it's 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 $(\text{g-2})_\mu$. 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. It is an exciting project, why don't you come an join us?

3. Dedication

I would like to dedicate this article to my thesis advisor, Sidney Coleman, who was a regular lecturer at this school and was always voted "best lecturer" whenever he appeared. I owe a great deal to Sidney. He demonstrated to me how theoretical physics research is performed by a true master. He also shared many other aspects of life as a theoretical physicist.

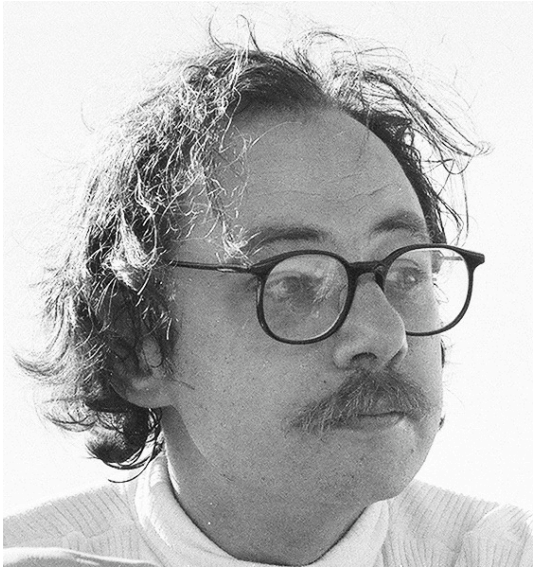

Figure 14: Sidney Coleman on the top of Mt. Monadnock, New Hampshire, USA in the fall of 1978. (Photo by S. Parke.)

Students[8)] of Sidney Coleman

Robert Socolow 1964	Wu-Yang Tsai 1971	Stephen Parke 1980	Robert Mawhinney 1987
Jeffrey Mandula 1966	Erick Weinberg 1973	Fred Posner 1980	Alexander Safian 1987
Leonard Parker 1967	David Politzer* 1974	TheodorosTomaras 1980	Brian Hill 1988
Stephen Fels 1968	James Butler 1974	Bernard Grossman 1981	Paul Renteln 1988
Carl Bender 1969	Eldad Gildener 1975	Ahmed Abouelsaood 1984	Mark Alford 1990
Arnold Cantor 1970	Paul Steinhardt 1978	Philip Nelson 1984	John March-Russel 1990
Anthony Zee 1970	Ian Affleck 1979	Richard Woodard 1984	Katherine Benson 1991
John Mansfield 1970	Frank DeLuccia 1979	Gregory Moore 1985	Shane Hughes 1993
David Griffiths 1970	Lee Smolin 1979	MinosAxenides 1987	Stelios Smirnakis 1997
Lawrence Thebaud 1971	Gerald Sobelman 1979	Jacques Distler 1987	Nathan Salwen 2001

4. Acknowledgements

I would like to thank the Directors of this school, Prof. Zichichi and Prof. 't Hooft, for the opportunity to present the highlights from the Fermilab program at this school as well as to Fabiola Gianotti for showing me how to do this in an effective manner.

5. References

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