FLAVOR PHYSICS

The Flavor Physics (P2) Working Group

Prepared for the Snowmass 2001 Proceedings by:

Marina Artuso
Syracuse University, Syracuse, NY 13244, USA

Belen Gavela
Univ. Autonoma de Madrid, Madrid 28049, Spain

Boris Kayser
Fermilab, Bativia, IL 60510, USA

Clark McGrew
State Univ. of New York, Stony Brook, NY 11794, USA

Patricia Rankin and Eric D. Zimmerman
University of Colorado, Boulder, CO 80309, USA

(Dated: April 12, 2002)

Flavor physics has recently made striking advances. The Snowmass Flavor Physics Working Group has attempted to identify the important open questions in this field, and to describe the diverse future program that would address them.

EXECUTIVE SUMMARY

Flavor physics—the study of the quark and leptonic constituents of matter—is in a rapidly-advancing discovery phase. At Snowmass 2001, the Flavor Physics Working Group considered how best to build on the dramatic recent discoveries in this field to attack its major puzzles. In this executive summary, we summarize the findings and recommendations of this group.

Two particularly striking recent flavor-physics discoveries are the observation of very large CP violation in B meson decays, and the finding of compelling evidence for neutrino mass.

For a third of a century, CP violation has been seen only as a tiny effect in the decays of K mesons. However, according to the Standard Model (SM) description of the quarks and leptons and their interactions, CP violation is by no means a peculiarity of the K system, and its smallness in that system is just an accident. The SM predicts large CP violation in the B system. This prediction has now been confirmed.

Neutrinos appear to be close relatives of the quarks and charged leptons. Therefore, one expects that the neutrinos, like all the quarks and charged leptons, have nonzero masses. At long last, this expectation has been confirmed. The confirmation comes from strong evidence that both the atmospheric and solar neutrinos oscillate between different flavors. Neutrino oscillation implies neutrino mass. The explanation of this neutrino mass will almost certainly entail new physics beyond the SM.

Flavor physics, and the things we learn by studying it, can have profound consequences. For example, because the d quark weighs more than the u quark, the neutron is heavier than the proton. Had it been the other way around, there could have been no water, so life as we know it would not have been possible. A second example is the most stringent bound on CPT violation, which has been obtained by studying mixing and CP violation in the neutral K system. A third is the excess of matter over antimatter in the universe. This excess, on which our existence depends, grew out of the flavor physics of the early universe. We do not yet know how, and finding out—a major goal for flavor physics—will be very interesting, to say the least.

The open flavor-physics questions one would like to see answered include—

- Why is there flavor? How many flavors, including both active and "sterile" ones, are there? What has led to the number of flavors being what it is?

- Are there high mass scales whose physics influences the properties of the quarks and leptons? If so, what are these scales, and what physics resides at them? Is there a Grand Unified Scale where the quarks and leptons become unified?

- Are C and CP the only matter-antimatter symmetries violated in nature, or is CPT violated as well? What physics is responsible for the violation of the matter-antimatter symmetries?

- We know the masses of the (known) quarks and charged leptons. What are the masses of the neutrinos? To what new high mass scale do these masses point, and what physics would one find there?

- Is each neutrino identical to its antiparticle?

- Why is there such a striking hierarchy of quark masses, with Mass(up) / Mass(top) $\sim 3 \times 10^{-5}$? Why is there also a hierarchy of charged lepton masses, with Mass(e) / Mass(τ) $\sim 3 \times 10^{-4}$? Why are the neutrinos so much lighter than the quarks or charged leptons?

- Exactly what are the quark mixing angles and their leptonic counterparts? What explains all these angles? Why are quark and lepton mixing so strikingly different from each other? All three quark mixing angles are small, but at least one and most probably two of the three lepton mixing angles are very large.

- Is the beautiful quantum-mechanical mixing in the neutral B and K systems due entirely to SM mixing among quarks, or does it also involve new physics beyond the SM?

- Can CP violation in the B and K systems be fully explained in terms of the SM, or does it arise in whole or in part from new physics such as supersymmetry?

- Is there also CP violation in the lepton sector? Does neutrino oscillation violate CP? Does neutrinoless double beta decay?

- What caused baryogenesis in the early universe? Was it a result of CP violation among quarks? Among leptons? Something else entirely? What as-yet-unknown particles and interactions were involved?

- Can neutrinos, which may have the almost unique ability to travel in extra spatial dimensions, reveal the presence of such dimensions?

Finding the answers to these questions requires a diversity of approaches. Some involve experiments at the high-energy frontier, while others entail searches for rare low-energy phenomena, or precision studies of not-so-rare ones. The important research includes accelerator experiments, non-accelerator (often underground) experiments, astrophysical observations, and theoretical explorations.

To learn whether the leptons violate CP as the quarks do, one must compare the oscillations of neutrinos and antineutrinos. This will require accelerator-created neutrino beams much more intense than the present ones. To determine the masses of the individual neutrinos, and thereby the scale of neutrino mass, one will need to perform such non-accelerator experiments as the very precise study of the beta spectrum in tritium beta decay. To find out whether each neutrino is identical to its antiparticle, one will have to seek neutrinoless double beta decay in an underground laboratory. To test the SM of CP violation among the quarks, one will need to study certain B-system CP asymmetries at a low-energy electron-positron collider, other such asymmetries at a high-energy hadron collider, extremely rare K-meson decays at a low-energy proton accelerator, still further phenomena at other facilities, and then see whether all the results are related to one another as demanded by the SM. These examples illustrate how the elucidation of flavor physics depends on diverse techniques and facilities.

Using flavor physics to search for the so-far very elusive physics beyond the SM will be a major priority. This search will be conducted quite differently in different sectors. In the quark and charged-lepton sectors, one can look for new physics by trying to see whether an effect that the SM predicts to be small (e.g., a rare decay) is actually much larger. One can also seek new physics by overconstraining a system, as just described. In the neutrino sector, nonzero neutrino masses are almost certainly due to physics beyond the SM, so in this sector, consequences of new physics have already been observed. To study this new physics, one will need to determine the neutrino mass spectrum, and the related neutrino properties such as mixing angles.

The Snowmass Flavor Physics Working Group sought to find efficient and effective ways to address the open questions through future research. To this end, we found it practical to divide into a Quark Sub-Group and a Lepton Sub-Group. The conclusions and recommendations of these Sub-Groups are as follows:

Quark Sub-Group Recommendations

Full and precise exploration of quark flavor physics requires a diverse program of experiments at both e^+e^- and hadron accelerators.

- The current e^+e^- program at BABAR, BELLE, and CLEO has been highly successful. It is this program that has shown that CP violation in the B system is large. Operation and upgrades of BABAR and BELLE should be pursued vigorously. CLEO-c should explore charm physics at a new level of sensitivity. R& D on B factories at a luminosity of 10^{36} should be initiated.

- The current hadron collider experiments CDF and D0 are poised to make important contributions to B and top physics in Run II. Top physics will be a significant part of the program at the LHC and at a linear collider. The dedicated hadron collider experiments BTeV and LHCb are the next frontier in B physics and should be built expeditiously.

- Studies of the K system have and will continue to provide important information on CP violation and CKM matrix elements.

- With recent methodological improvements in lattice QCD, precise calculations of hadronic matrix elements, necessary to distinguish between new and

SM physics, are close at hand. The accuracy of these calculations should keep pace with precision measurements in the charm and bottom sectors.

Lepton Sub-Group Recommendations

The investigation of the full range of neutrino properties requires a diverse program of both accelerator and non-accelerator experiments.

- The non-accelerator program has been highly successful. It is this program that has yielded compelling evidence for neutrino oscillation, hence neutrino mass. This program should be actively pursued. Results, including those from next-generation neutrinoless double beta decay, tritium decay and astrophysics experiments, will add fundamental knowledge.
- On the accelerator side, an important next step is the development of a higher-intensity conventional beam (super-beam). A complementary step is the development of a next-generation atmospheric neutrino detector that can serve as a far detector for a high-intensity beam.
- Experimental results over the next few years are likely to demonstrate the need for a neutrino factory. The development of the needed technologies requires a long lead time and should be pursued now.

Summary

Flavor physics—a facet of the mystery of the origin of mass—is one of the great puzzles of modern physics. It is also a powerful probe of physics beyond the Standard Model. While the nature and origin of flavor remain enigmatic, the study of this enigma has entered a very interesting stage, thanks to the experimental breakthoughs on CP violation and neutrino mass. Continued progress requires a broad program of diverse measurements in both the quark and neutrino sectors, and associated theoretical developments.

I. QUARK FLAVOR PHYSICS

A. Introduction

The pattern of masses and interactions of quarks is easily accommodated in the Yukawa sector of the Standard Model, but its origin is almost a complete mystery. In addition, many new physics models such as supersymmetry predict measurable deviations from the Standard Model predictions for quark mixing and CP-violation phenomena.

Key experimentally addressable topics in quark flavor physics include, but are not limited to:

- The extension of searches for nucleon decay to total proton lifetimes exceeding 10^{34} y, with partial lifetimes for key modes approaching 10^{35} y;
- The study of rare K decays such as $K \to \pi\nu\bar{\nu}$ and $K \to \pi l\bar{l}$ which provide potential windows on quark mixings;
- The investigation of mixing and CP violation in charmed meson decays, expected to be small in the Standard Model;
- The detailed study of B decays and associated CP violation for processes with branching ratios as low as 10^{-7} or less, which can provide key insights into not only quark mixing but also "engineering" questions such as rescattering and final-state phases;
- The study of the electric dipole moment of the neutron, which provides some of the best reach for new physics in theories such as supersymmetry.

The experiments which address these questions are diverse not only in approach but also in scale. They range from table-top electric dipole moment searches to b physics at the largest LHC experiments. A diverse experimental strategy is key to a broad understanding of flavor phenomena and therefore of the higher-energy physics from which they derive. A healthy global high-energy physics program should include proposed specialized experiments, including dedicated b experiments at hadron colliders, high-intensity B production in e^+e^- collisions, rare kaon decay searches, τ/charm facilities, and dipole moment studies.

B. Quark Physics as a Compass in the New Physics Maze

Although the Standard Model's predictive power has been confirmed by a vast body of data, the search for a more complete effective theory is vigorously pursued. One strong motivation for this quest is related to the number of Standard Model parameters that are constants of nature and need to be determined experimentally.

Several avenues have been proposed to achieve a more complete effective theory. They address individual shortcomings of the Standard Model and they introduce a variety of additional uncertainties. A typical example is super-symmetry (SUSY), that is popular for its solution of the hierarchy problem [1] but introduces a flavor problem of its own, given the proliferation of exotic particles introduced by this theory. In addition, the number of effective theories within the SUSY general framework, requires an experimental strategy to identify the scenario consistent with the true pattern of fundamental particles and their interactions.

While data at the energy frontier will explore direct searches for new exotic matter, the exploration of flavor physics, in particular the CP violation in charm and beauty physics and some crucial rare and forbidden decay processes will provide complementary information, often competitive in sorting out alternative scenarios as will be illustrated below.

1. The Cabibbo-Kobayashi-Maskawa matrix now

In the Standard Model masses are produced via the Higgs mechanism through the Yukawa couplings. The complex Yukawa coupling constants are related to 10 independent physical quantities, the six quark masses and four quark mixing parameters. The latter can be described by three Euler-like angles and an imaginary phase. These parameters are not predicted by the Standard Model, but are fundamental constants of nature that need to be extracted from experimental data.

Many theoretical models have tried to uncover a more fundamental explanation for flavor. For example, some of the many variations of Supersymmetry [1] incorporate the known hierarchy of quark masses and mixing parameters. In addition, the replication problem has been addressed by postulating a new deeper level of matter [2]. In this approach, the multitude of quarks can be understood as a sort of periodic table of the composite structures that are indeed bound states of more fundamental particles. In addition, a geometrical origin [3] of flavor has been proposed.

An important feature of the fundamental interactions explored in flavor physics is CP violation. After several decades when the only experimental evidence for CP violation was provided by studies of neutral K decays, this year evidence for CP violation in B decays has been obtained by the two e^+e^- b-factory experiments, BaBar at PEP-II and Belle at KEK-B. These experiments presented positive evidence for CP asymmetry in B decays measuring:

$$\begin{array}{ll} \sin 2\beta = 0.59 \pm 0.14(\mathrm{stat}) \pm 0.05(\mathrm{sys}) & \text{[BaBar][4]} \\ \sin 2\beta = 0.99 \pm 0.14(\mathrm{stat}) \pm 0.06(\mathrm{sys}) & \text{[Belle][5]} \end{array} \tag{1}$$

Thus a new era in CP violation studies has just begun.

Fig. 1 shows the 6 unitarity triangles that can be constructed to check this property. The expected lengths of the sides are suggested. The bottom two triangles give a hint on the optimal strategy to test the CKM sector of the Standard Model. The three sides are of comparable length and thus all the angles and sides are more amenable to experimental measurement. Aleksan, Kayser and London [6] pointed out that we can cast the four independent CKM parameters as phases that can be determined from the CP asymmetries that will be measured in the planned heavy flavor experimental program.

TABLE I: Precision of our present experimental knowledge of the absolute value of the quark mixing parameters

$\mathbf{V}_{ud}$ β-decay 0.9739 ± 0.0009	$\mathbf{V}_{us}$ $K \to \pi \ell \nu$ 0.2200 ± 0.0025	$\mathbf{V}_{ub}$ $b \to u \ell \nu$ $\approx 0.0035 \pm 0.001$
$\mathbf{V}_{cd}$ $\nu d \to \ell c$ 0.224 ± 0.016	$\mathbf{V}_{cs}$ $D \to K e \nu$ $W \to X_c X$ 0.97 ± 0.11	$\mathbf{V}_{cb}$ $b \to c \ell \nu$ 0.041 ± 0.003
$\mathbf{V}_{td}$ B mixing 0.0083 ± 0.0016	$\mathbf{V}_{ts}$ Unitarity 0.04 ± 0.01	$\mathbf{V}_{tb}$ Unitarity 0.9990 to 0.9993

These phases, shown in Fig. 1, are:

$$\beta = arg\left(-\frac{V_{cb}^{\star}V_{cd}}{V_{tb}^{\star}V_{td}}\right) \tag{2}$$

$$\gamma = arg\left(-\frac{V_{ub}^{\star}V_{ud}}{V_{cb}^{\star}V_{cd}}\right) \tag{3}$$

$$\chi = arg\left(-\frac{V_{cs}^{\star}V_{cb}}{V_{ts}^{\star}V_{tb}}\right) \tag{4}$$

$$\chi' = arg\left(-\frac{V_{ud}^{\star}V_{us}}{V_{cd}^{\star}V_{cs}}\right) \tag{5}$$

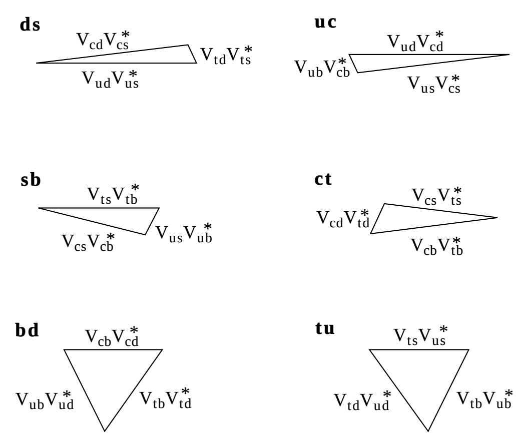

FIG. 1: The six CKM "unitarity triangles". The bold labels, e.g. **ds**, refer to the rows or columns used in the unitarity relationship.

Table I summarizes our present knowledge of the absolute values of the quark mixing parameters. In some cases the values reported are the result of direct measurements, in a few cases the parameter is inferred from the other elements in the row and the assumption of unitarity. This shows that there is still a large room for improvement. An important goal of the next generation of precision experiments would be to fill up this matrix with direct measurements of each individual parameter that would allow us to verify all the relationships between different elements imposed by the unitary nature of this matrix.

The ratio of V_{ts} and V_{td} will be eventually determined through the study of $B_s - \overline{B_s}$ flavor oscillations, which can then be compared to the known $B_d - \overline{B_d}$ oscillations. This requires significant boost and great time resolution, achievable at hadron collider facilities. The other CKM parameter presently determined through unitarity constraints, V_{tb}, will be determined studying single top production processes such as $W^* \to t\bar{b}$ (at hadron colliders) and $e^-\gamma \to \nu_e b\bar{t}$ (at a linear collider). Vast opportunities for high precision top decay studies will be available at the Tevatron, LHC and the proposed linear collider. It can be seen also that considerable room for improvement is left in several direct measurements included in Table I. The dominant uncertainty is often theoretical in nature, due to the difficulty in performing precise calculations of the QCD matrix element. Thus a program to evaluate the relevant hadronic physics in the framework of a full QCD calculation with controlled and objective errors is a crucial ingredient of the flavor physics of the next decade. Although continuum physics has provided significant progress in our understanding of heavy flavor phenomenology, unquenched lattice gauge calculations represent a very important contribution expected in the next few years.

2. *Quark Masses*

The hierarchy of the quark masses is very puzzling. The mass of the heaviest quark is about 100,000 bigger than the lightest one. The determination of these masses has many challenges and is a good illustration of the different roles played by QCD in different hadronic processes. The parameter that defines how QCD affects our ability of measuring fundamental properties is the mass scale $\Lambda_{QCD} \approx 200$ MeV. Thus, for very heavy mass scales QCD corrections are not very important and can be evaluated using perturbative methods. As the mass decreases, non-perturbative effects become more important and the extrapolation process becomes more uncertain. This interplay will be illustrated below. The quark masses and mixing parameters arise from the Yukawa Lagrangian, that is the Standard Model sector that includes the largest group of unpredicted parameters. The patterns of quark masses and mixing parameters is known with different degrees of accuracy, of the order of 4-20%. This knowledge is based either on direct experimental measurements or is inferred from unitarity constraints. The magnitude of the elements in the unitary matrix that relates the weak eigenstates to the mass eigenstates also shows a very remarkable pattern: the diagonal elements are close to 1 and the further 'off diagonal' elements are the smaller they are. Attempts to relate this specific structure with a more comprehensive theory have been made [7]. In this approach quark mass textures, i.e. specific patterns of zeros in quark mass matrices, relate the origing of flavor to a spontaneously broken symmetry, thus inferring relationships between quark masses and quark mixing parameters. For example, Barbieri, Hall and Romanino [8] explored the constraints in the $\rho - \eta$ plane produced by the relationships:

$$\left|\frac{V_{ub}}{V_{cb}}\right| = \left(\frac{m_u}{m_c}\right)^{1/2} \tag{6}$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = \left(\frac{m_d}{m_s}\right)^{1/2} \tag{7}$$

Although the present knowledge of the quark masses and mixing parameters does not allow for precision tests using this strategy, it represents an interesting line of investigation for future studies.

3. *New Physics and Rare Decays*

"Rare" decays encompass a large class of decay modes, with branching fractions not necessarily exceedingly small, where a suppression mechanism reduces the rate compared to the dominant "tree diagram." In b decays, these diagrams include "box diagrams" mediating flavor oscillations, definitely not "rare". On the other hand, in charm decays short distance diagrams for these high order processes are highly suppressed. In this case the analysis of the implication of possible enhancements is complicated by long distance hadronic effects that preclude precise predictions of the expected rates. Rare and forbidden decays may provide insight into new physics, as they are often mediated by loop diagrams, which may include additional contributions from exotic particles such as new gauge bosons or extended Higgs sector.

Flavor-changing neutral currents lead to the transitions $b \to s$ and $b \to d$. These can be described in the Standard Model by one-loop diagrams, known as "penguin" diagrams, where a W^- is emitted and reabsorbed. The first such process to be observed was $b \to s\gamma$, described by the diagram in Figure 2(c), where the γ can be radiated from any internal charged particle line. Another process which is important in rare b decays is $b \to sg$, where g designates a gluon radiated from a quark line [Figure 2(d)]. A third example of such processes is the transition $b \to s\ell^+\ell^-$ which can occur through the diagrams shown in Figures 2(e) and 2(f).

There are several reasons why the study of rare b decays is very important. First of all, the suppression involved in loop diagrams makes it possible for these Standard Model processes to interfere with decay diagrams mediated by exotic mechanisms due to 'beyond Standard Model' interactions. In addition, loop diagrams and CKM suppression can affect our ability of measuring CP violation asymmetries.

The decay $b \to s\gamma$ was the first inclusive rare b decay to be measured [9] and stirred a lot of theoretical interest. It is a powerful constraint on theories "beyond the Standard Model." The Standard Model predicts no CP asymmetry in $b \to s\gamma$. The closeness between the original CLEO result and the Standard Model predictions did not leave much room for exotic contributions. However recent suggestions to use the running quark mass in the

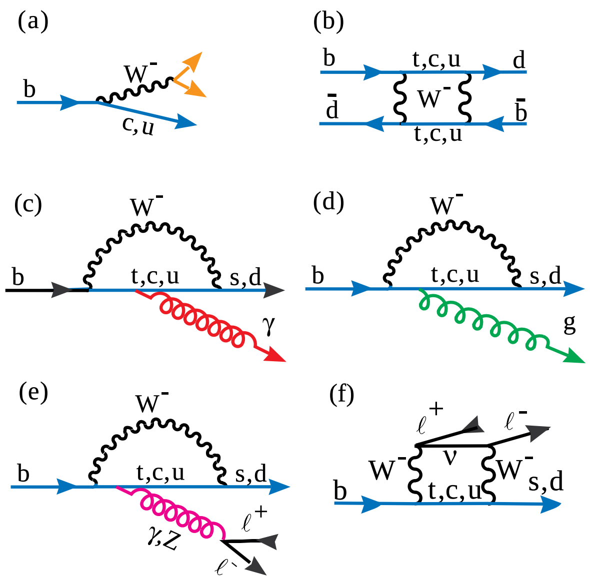

FIG. 2: Feynman Diagrams for b Decays

ratio m_c/m_b raised the Standard Model prediction from $(3.35 \pm 0.30) \times 10^{-4}$ to $(3.73 \pm 0.30) \times 10^{-4}$. The most recent CLEO result, still dominating the world average, is $(2.85 \pm 0.35 \pm 0.22) \times 10^{-4}$ [10]. This hint of new physics is not at all conclusive, of course, but is intriguing.

Moreover, recent theoretical work [11] suggested that non-Standard Model physics may induce a significant CP aysmmetry. Thus a search for CP asymmetry has been performed by CLEO. A preliminary results of $\mathcal{A} = (0.16 \pm 0.14 \pm 0.05) \times (1.0 \pm 0.04)$ has been reported by CLEO [12]. The first number is the central value, followed by the statistical error and an additive systematic error. The multiplicative error is related to the uncertainty in the mistagging rate correction. From this result a 90% C.L. limit on the CP asymmetry $\mathcal{A}$ of $-0.09 < \mathcal{A} < 0.42$ is derived. These results are based on ≈ 3.1 fb^{-1} of data.

Another related decay mode that is quite important in constraining new physics is the decay $b \to s(d)\ell^+\ell^-$ and the related exclusive channels $B \to K^{(\star)}(\rho, \omega)\ell^+\ell^-$. These processes have been studied both at CLEO and at CDF and D0. Some of the upper limits are very close to the theoretical predictions, and it is likely that future high statistics b experiments will measure these rates. With enough statistics not only the branching fraction will be uncovered, but also we will be able to measure specific properties of these decays, such as differential rate as a function of the dilepton invariant mass.

Similarly, the companion class of decays in the charm sector can be explored. The charm physics reach of physics beyond the Standard Model is complicated by the interplay between short range operators, corresponding to very highly suppressed rates, and long range operators, quite uncertain but possibly producing very large enhancements. However high statistics studies will allow the study of the differential decay rate as a function of the di-lepton invariant mass. Theoretical studies indicate that there are intervals in the invariant mass domain where new physics may produce unambiguous enhancements [13].

4. The Challenge of the Hadronic Matrix Element

Our progress in extracting the Yukawa Lagrangian parameters is a complex interplay between experimental ingenuity, in devising a variety of measurement techniques to study these unknown Standard Model constants, and theoretical progress in tackling the calculation of QCD matrix elements in the challenging non-perturbative domain.

The first stage of the complex theoretical saga relied on “QCD inspired” model building. Several form factor models [14] addressed a variety of decays. In particular, they described semileptonic decays with “form factors”, parameterizing the relevant amplitudes in terms of functions of q^2, the $\ell\nu$ invariant mass squared, where normalization factors were obtained in a variety of quark models and the q^2 dependence was guessed.

A step towards model independence was achieved with the advent of Heavy Quark Effective Theory (HQET) [15], an effective theory based on QCD, exact in the limit of infinitely heavy quark masses. The degree to which the “heavy flavors”, most notably the b and c quark, can be considered infinitely heavy is process dependent, but a remarkable number of its predictions have received experimental confirmation [16] in heavy to heavy transitions.

In parallel, a theoretical approach similar in nature but not equivalent to HQET, the heavy quark expansion (HQE) has been developed to study inclusive transitions [17]. In particular, it has been used to extract the fundamental parameters V_{cb} and V_{ub}. A full discussion of this method, its key parameters and their determination is beyond the scope of this review. A critical aspect of this approach that is presently being actively investigated is the uncertainty inherent in the quark-hadron duality assumption, an inevitable ingredient of these calculations. While some authors [18] conjecture that it is negligible, others [19] suspect that big duality violations will be uncovered. A recent review article [20] addresses future tests that may shed more light on this issue.

Unfortunately, several processes of interest in determining important parameters, most notably the magnitude of V_{ub}, involve heavy to light transition, such as $b \to d(u)$. In this case several approaches have been tried, no conclusive assessment of the theoretical errors and model dependence of the results obtained has been achieved.

While continuum approaches have lead to great progress, in particular in identifying approaches that lead to less model dependence in the measured fundamental parameters, the evaluation of the QCD matrix element is a critical step towards a precision determination of all the fundamental parameters. This cannot be tackled analytically, but a variety of numerical approaches, lattice gauge theories, has been pursued for a number of years. The history of lattice QCD has been very complex, and through the development of more powerful computers, and, perhaps more importantly, the development of more sophisticated algorithms [21], has reached the era of "precision calculations". In particular, an assumption that until recently was necessary to achieve significant statistical accuracy (the "quenching approximation") will be removed [22]. A detailed plan of predictions in the heavy flavor sectors down to a few % accuracy has been proposed, in parallel to an experimental program that should verify these predictions with comparable precision [23]. This program is important to check our strategy to pin down the sides of the CKM triangle.

C. The CP Violation Puzzle

CP violation is crucial to our understanding of the history of the universe. In particular, it is a necessary ingredient of our understanding of the origin of the matter dominated universe [24]. A CP violating phase is naturally incorporated in the Standard Model within the Cabibbo- Kobayashi-Maskawa matrix. Thus several models attempt to explain the baryon asymmetry of the universe as due to a CP violating process occurring at the scale of the electro-weak symmetry breaking. A rough order of magnitude estimate of the expected effect of the CKM induced CP violation on the baryon asymmetry can be obtained by constructing a variable $d_{\rm CP}$ that incorporates all the features of this violation: it vanishes when any pair of quarks of like charge are degenerate in mass and when any CKM angle vanishes. $d_{\rm CP}$ is defined as:

$$\begin{aligned} d_{\rm CP} = \ & \sin\theta_{12}\sin\theta_{23}\sin\theta_{13}\sin\delta_{CP} \\ & (m_t^2-m_c^2)(m_t^2-m_u^2)(m_c^2-m_u^2) \\ & (m_b^2-m_s^2)(m_b^2-m_d^2)(m_s^2-m_d^2), \end{aligned} \tag{8}$$

where θ_{ij} are three real "Euler-like" angles defining the CKM matrix together with the imaginary phase δ_{CP}.

The $d_{\rm CP}$ parameter that we have just defined is a dimensional quantity, and it is conceivable [25] that the natural normalization parameter to transform it into a pure number is the temperature at which the electroweak symmetry breaking occurred. Thus the figure of merit of the strength of the CKM induced CP violating effect is given by:

$$d^T_{\rm CP} = d_{\rm CP}/(kT)^{12}_{ew} \approx 10^{-18}, \tag{9}$$

where T_{ew} represents the temperature at the time the electro-weak symmetry breaking occurred and k is the Boltzmann constant. This suggests that CKM CP violation is an effect too small to account for the known baryon asymmetry of the universe,

$$\left|\frac{N_B - N_{\overline{B}}}{N_B + N_{\overline{B}}}\right|_{t\approx 10^{-6}s} \approx \left|\frac{N_B}{N_\gamma}\right|. \tag{10}$$

This discrepancy is very qualitative in nature and may have a number of explanations. However a very tantalizing hypothesis is the presence of additional CP violating phases produced by mechanisms beyond the Standard Model. The recent data pointing to a leptonic mixing matrix similar in nature but with a very different hierarchical structure than the quark mixing matrix has motivated theoretical developments seeking these new phases in the lepton sector, as will be discussed below. Thus the experimental exploration of CP violation in the lepton and quark sectors is a crucial area of experimental research in the high energy physics experimental program as it has a good chance to provide powerful constraints that will help in narrowing the options in the vast landscape of effective theories now being considered viable.

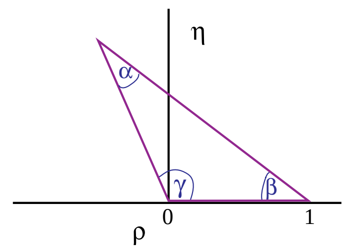

FIG. 3: The normalized db unitarity triangle.

A rescaled db unitarity triangle, shown in Fig. 3, is often used to analyze CP violation tests. One powerful way to challenge the CKM picture is through redundant measurement of its interior angles,α, β and γ. A first important question that we need to address is whether $\alpha+\beta+\gamma = 180°$ is a sufficient validation of the Standard Model picture of CP violation. While an inequality would be a significant manifestation of new physics, a confirmation of this relationship would not necessarily be a Standard Model success. New phases may intervene with opposite sign in altering the value of two CKM angles, e.g. β and α, with a deceiving null result. This realization has prompted theoretical effort towards a less ambiguous test. Through the work of Aleksan, Kayser, and London, and of Silva and Wolfenstein [6, 26], a relationship has emerged as a promising unambiguous test for new physics:

$$\sin\chi = \lambda^2 \frac{\sin\beta\sin\gamma}{\sin(\beta+\gamma)} \tag{11}$$

This is a very precise test because $\lambda = 0.2196 \pm 0.0023$ [27] is very well known. It involves the measurement of the angle χ, that is expected to be very small. The most promising experimental technique involves the study of $B_S \to \psi\eta^{(\prime)}$ and $B_S \to \psi\phi$. The measurement is within reach when the proposed dedicated b experiments, BTeV and LHCb, will be operative.

TABLE II: Predictions of different SUSY models

Model	$\frac{d_N}{10^{-25}\ e\,\mathrm{cm}}$	θ_M	θ_D	$a_{D\to K\pi}$	$a_{K\to\pi\nu\bar{\nu}}$
Standard Model	$\lesssim 10^{-6}$	0	0	0	$\mathcal{O}(1)$
Exact Univrsalty	$\lesssim 10^{-6}$	0	0	0	=SM
Approx. Unvrslty	$\gtrsim 10^{-2}$	$\mathcal{O}(0.2)$	$\mathcal{O}(1)$	0	≈SM
Alignment	$\gtrsim 10^{-3}$	$\mathcal{O}(0.2)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	≈SM
Heavy Squarks	$\sim 10^{-1}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(10^{-2})$	≈SM
Approximate CP	$\sim 10^{-1}$	$-\beta$	0	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-5})$

TABLE III: Comparison of CP Reach of Hadron Collider Experiments per Snowmass year and each asymmetric e^+e^- collider through 2005. (The BTeV reach has been obtained for the one-arm version of BTeV).

	BTeV 10^7s	LHCb 10^7s	BaBar Belle (2005)
$\sin 2\beta$	0.017	0.020	0.037
$\sin 2\alpha$	0.04	0.05	0.14
$\gamma\,[B_s(D_sK)]$	$\sim 8^o$		
$\gamma\,[B(DK)]$	$\sim 13^o$		$\sim 20^o$
$\sin 2\chi$	0.02	0.04	-
BR$(B\to\pi^o\pi^o)$	-	-	~20%
V_{ub}	-	-	~2.3%

A variety of new CP violation scenarios can be envisaged depending upon the assumed pattern of new physics implementation. New physics may introduce new phases both in $B^0\bar{B}^0$ mixing (θ_M), and in the decay amplitude (θ_D). Moreover, CP violation in charm decays, a probe of new physics in the u-quark sector, can be enhanced through the appearance of a novel phase $\phi_{K\pi}$. It is interesting to note that different "Beyond the Standard Model" scenarios involve quite different expectations for the magnitude of these parameters. For example, Table II [28] shows a comparison between the predictions from different SUSY implementations. For completeness the predictions of these models for other exotic processes such as the neutron electric dipole moment have been included. This illustrates how heavy flavor physics and small scale precision measurements can be a powerful tool to identify a path towards a more complete effective theory of the fundamental interactions.

A comprehensive study of the CP violation observables in b and c decays is planned for the next decade. This will involve complementary experiments at hadronic and e^+e^- facilities. Early results from the hadronic facilities will come from the existing Fermilab collider detectors, which hopefully will determine the frequency of $B_s-\overline{B_s}$ oscillation. When BTeV and LHC-b begin, a rich and diverse set of measurements will be performed with a high degree of accuracy, as shown in Table III.

In parallel, precision experiments are planned, addressing rare K decays that offer a complementary and intriguing exploration of the CKM phases. Fig. 4 shows an example on how the study of $K^o\to\pi^o\nu\bar{\nu}$ can provide an independent measurement of the apex of the unitarity triangle. These measurements have also small theoretical uncertainties, independent of the ones affecting b decay observables, thus a consistency check between these two approaches provides a powerful Standard Model test.

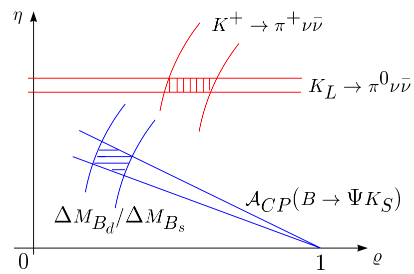

FIG. 4: Schematic determination of the unitarity triangle vertex (ϱ, η) from $K\to\pi\nu\bar{\nu}$ (vertically hatched) and from the B system (horizontally hatched), that illustrates a hypothetical discrepancy that would suggest new physics [29].

This short survey of opportunities for CP violation measurements in the quark sector is by no means comprehensive, but it illustrates the importance of pursuing a deeper understanding of this asymmetry. Its importance for cosmology has been noted elsewhere [30]. Moreover, the power of CP violation observables to discriminate between different new physics scenarios is receiving increasing theoretical attention [31].

D. Quark Physics Perspective on the Next Decade: The Quark Sub-Group Recommendations

This succinct survey has shown the vitality of the flavor physics program that we hope will be carried out in the next decade. In particular, rare decays and CP violation observables are powerful constraints that may provide unique evidence for new physics. These studies complement direct observations of new particles at high energy colliders. Given what needs to be done to address the outstanding questions, the Quark Sub-Group of the Snowmass Flavor Physics Working Group would like to make the recommendations given in the Executive Summary.

II. NEUTRINO FLAVOR PHYSICS

Beautiful experiments performed during the last few years have shown that neutrinos almost certainly oscillate from one flavor to another. Since such oscillation implies neutrino mass and mixing, these experiments tell us that neutrinos almost certainly have nonzero masses and mix.

Particularly compelling evidence that neutrinos oscillate comes from the behavior of the atmospheric neutrinos. These are created in the earth's atmosphere by cosmic rays. At energies above a few GeV, these cosmic rays are isotropic. This isotropy is easily shown to imply that at these energies, an underground atmospheric ν_μ detector must see equal fluxes of upward- and downward-going neutrinos, *unless* some physical mechanism decreases (or increases) the ν_μ flux before the neutrinos reach the detector. Thus, the finding by the Super-Kamiokande detector (S-K) that [32]

$$\text{Upward } \nu_\mu \text{ flux / Downward } \nu_\mu \text{ flux} = 0.54 \pm 0.04 \quad (12)$$

immediately tells us that some mechanism does indeed modify the atmospheric ν_μ flux. The hypothesis that this mechanism is the oscillation $\nu_\mu \to \nu_\tau$ gives an excellent fit to a wealth of detailed atmospheric neutrino data [33].

Just before Snowmass 2001, the Sudbury Neutrino Observatory (SNO) reported a new result that implies that solar neutrinos oscillate too [34]. SNO measured the high-energy ν_e flux, ϕ_{ν_e}, arriving at the earth from the sun. Earlier, S-K had measured, for a similar neutrino energy range, the flux $\phi_{\nu_e} + (1/6.5)\,\phi_{\nu_{\mu,\tau}}$, where $\phi_{\nu_{\mu,\tau}}$ is the flux of ν_μ and/or ν_τ from the sun [35]. By subtracting the SNO result from that of S-K, one finds that $\phi_{\nu_{\mu,\tau}} = (3.69 \pm 1.13) \times 10^6/\text{cm}^2$-sec. That is, the flux of ν_μ and ν_τ coming from the direction of the sun differs from zero by more than three standard deviations. This increases to something like 3.5 standard deviations when radiative corrections to the cross section for the SNO detection reaction are taken into account [36]. Now, the sun makes only ν_e, not ν_μ or ν_τ. Thus, the ν_μ and/or ν_τ arriving here from the sun must have changed their flavor between their birth as ν_e in the core of the sun and their detection here on earth.

The atmospheric neutrino oscillation is well described by a neutrino (Mass)^2 splitting δM^2_{atm} of $\sim 3 \times 10^{-3}$ eV^2, and a neutrino mixing angle θ_{atm} that is at, or at least near, its maximum possible value, where $\sin^2 2\theta_{\text{atm}} = 1$ [33]. The solar neutrino oscillation requires a splitting δM^2_{sol} whose favored values range from 10^{-12} eV^2 through 10^{-4} eV^2. The corresonding mixing parameter, $\sin^2 2\theta_{\text{sol}}$, may be large or small. However, among the possible neutrino oscillation explanations for the behavior of solar neutrinos, the one that appears to be most favored by analyses of the solar data is the Large-Mixing-Angle version of the Mikheyev-Smirnov-Wolfenstein effect (LMA-MSW), with $0.66 \lesssim \sin^2 2\theta_{\text{sol}} \lesssim 0.93$ [37]. A three-neutrino mass/mixing scenario that embodies these atmospheric and solar mass splittings and mixing angles is shown in Fig. 5. There, the splitting between the mass eigenstates ν_1 and ν_2 is the one required to give the solar neutrino oscillation, while the one between the $\nu_1 - \nu_2$ pair and ν_3 gives the atmospheric oscillation. The $\nu_e - \nu_\mu - \nu_\tau$ flavor content of the various mass eigenstates reflects the favored large mixing angles θ_{atm} and θ_{sol}. The very small ν_e piece of ν_3 (shown in an artist's conception) reflects the third leptonic mixing angle, θ_{13}, about which we know only that $\sin^2 2\theta_{13} \lesssim 0.1$ [38].

If there are only three neutrino mass eigenstates, and θ_{sol} is indeed large, then the unitary leptonic mixing matrix U has the form

$$U = \begin{array}{c} \\ e \\ \mu \\ \tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} B & B & s \\ B & B & B \\ B & B & B \end{bmatrix} \end{array} , \quad (13)$$

where "B" denotes a matrix element that is big (i.e., non-negligible compared to unity), and "s" is one that is small. Interestingly, the corresponding quark mixing matrix V has the quite different form [see Table I]

$$V = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{bmatrix} 1 & s & s \\ s & 1 & s \\ s & s & 1 \end{bmatrix} \end{array} , \quad (14)$$

where s once again stands for a matrix element that is small. We do not know why the leptonic and quark mixing matrices are so different. The difference may be a clue about what lies behind mixing, but we do not yet know how to interpret this clue.

The Liquid Scintillator Neutrino Detector (LSND) experiment has reported an oscillation calling for a (Mass)^2 splitting δM^2_{LSND} of $\sim$ (0.2 to 7) eV^2, once constraints from other experiments are taken into account [39]. If this oscillation and the oscillations of the atmospheric and solar neutrinos are all genuine, then nature must contain at least four neutrino species, and the neutrino world becomes even more interesting than it is already.

The discovery that neutrinos almost certainly have masses and mix raises many basic questions about the physics of the neutrinos. If technical difficulty and cost were no object, and we were allowed to choose the questions we would most like to see answered, we would choose:

1. What is the scale of neutrino masses?

2. Is there CP violation in the leptonic sector?

3. How many neutrino species (active and sterile) are there?

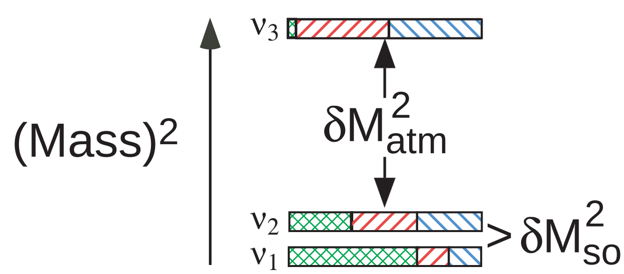

FIG. 5: A three-neutrino (Mass)^2 spectrum that accounts for the observed atmospheric and solar neutrino oscillations. The neutrinos $\nu_{1,2,3}$ are mass eigenstates. The ν_e fraction of each of them is cross-hatched, the ν_μ fraction is indicated by right-leaning hatching, and the ν_τ fraction by left-leaning hatching. An equally acceptable spectrum has the ν_1-ν_2 pair at the top rather than the bottom.

We believe that the answers to these questions would yield particularly far-reaching insights into the origins and consequences of flavor. Let us discuss the questions, and possible approaches to answering them, in turn.

Question 1: What is the neutrino mass scale? The nature and scale of neutrino mass is obviously a question of particular importance. How big are the masses of the individual neutrino mass eigenstates? Neutrino oscillation experiments, which can measure only $(\mathrm{Mass})^2$ differences, cannot answer this question. Are the mass eigenstates Majorana ($\overline{\nu} = \nu$) or Dirac ($\overline{\nu} \neq \nu$) particles? What physics is responsible for neutrino mass? What is the energy/mass scale of this underlying new physics? What are the implications of neutrino mass for both particle theory and cosmology?

In the Standard Model (SM), neutrino masses are taken to vanish. To be sure, the SM can easily be extended to accommodate them in the same way as it accommodates quark and charged lepton masses. One simply adds to the SM, which already contains a left-handed neutrino field ν_L, a right-handed neutrino field ν_R. The SM can then contain the Yukawa coupling

$$f_\nu \, \phi \, \overline{\nu_L} \, \nu_R \ , \tag{15}$$

where f_ν is the coupling constant and ϕ is the neutral Higgs field. Once ϕ develops its vacuum expectation value $\langle \phi \rangle_0 \sim 174$ GeV, this coupling produces a Dirac neutrino mass term.

If the masses of the neutrino mass eigenstates are not very much larger than they need to be to account for the $(\mathrm{Mass})^2$ splittings suggested by the oscillation experiments, then these masses are in the range 10^{-6} eV to 10 eV. To describe a mass in this range, a Dirac mass term of the form (15) requires a coupling constant f_ν between 10^{-17} and 10^{-10}. Such a *very* small coupling constant makes Dirac masses look somewhat implausible as an ultimate explanation of neutrino masses. In addition, once nature contains the right-handed neutrino field ν_R, so that she can contain the Dirac mass term (15), there is nothing to prevent her from also containing the Majorana mass term

$$M \, \overline{\nu_R^c} \, \nu_R \ , \tag{16}$$

where c denotes charge conjugation, and M can be a very large mass. A Majorana mass term of this kind is beyond the physics of the SM, and could reflect new physics at the high mass scale M. Diagonalizing a mass matrix that includes both the Dirac mass $f_\nu \langle \phi \rangle_0 \overline{\nu_L} \nu_R$ with a natural $f_\nu \sim 1$ and the Majorana mass term $M \, \overline{\nu_R^c} \, \nu_R$ with large M leads to a neutrino mass

$$m_\nu \sim \frac{\langle \phi \rangle_0^2}{M} \ . \tag{17}$$

This "see-saw relation" [40] between m_ν and the scale M of new physics yields

$$10^{-6} \text{ eV } < m_\nu < 10 \text{ eV} \tag{18}$$

for

$$10^{19} \text{ GeV } > M > 10^{12} \text{ eV} \ . \tag{19}$$

The latter range, from the Planck mass down to a few orders of magnitude below the GUT scale, is a very interesting regime in which to contemplate the presence of new physics.

Determining the masses of the individual mass eigenstates will be quite a challenge. If the oscillation reported by LSND is genuine, then at least one mass eigenstate ν_m has a mass M_m obeying

$$M_m \geq \sqrt{\delta M^2_{\mathrm{LSND}}} \geq \sqrt{0.2 \text{ eV}^2} \approx 0.4 \text{ eV} \ . \tag{20}$$

If this ν_m couples appreciably to an electron, then its mass will be reflected by the shape of the beta energy spectrum in tritium beta decay. A tritium experiment (KATRIN) that could see the reflection of a mass of order 0.15 eV or larger is planned [41].

If the oscillation reported by LSND turns out not to be genuine, then it could be that the heaviest ν_m has a mass no larger than

$$\sqrt{\delta M^2_{\mathrm{atm}}} \simeq \sqrt{3 \times 10^{-3} \text{ eV}^2} \approx 0.05 \text{ eV} \ . \tag{21}$$

This is well below the range that could be probed by presently foreseen tritium experiments. However, it is within the reach of several proposed searches for neutrinoless double beta decay ($\beta\beta_{0\nu}$). The observation of $\beta\beta_{0\nu}$ would extablish that nature contains at least one Majorana mass term [42]. Assuming CPT invariance, it would also demonstrate that the neutrino mass eigenstates ν_m are Majorana particles; that is, that $\overline{\nu_m} = \nu_m$ [43]. If the nuclear matrix element for a specific neutrinoless double beta decay can be calculated with reasonable accuracy, a measurement of the rate for this decay would determine the effective neutrino mass

$$M_{\beta\beta} = \left| \sum_m M_m \, U^2_{em} \right| \ . \tag{22}$$

Here, the sum runs over the mass eigenstates ν_m, M_m is the mass of ν_m, and U is the leptonic mixing matrix. Obviously, $M_{\beta\beta}$ is not the mass of any individual ν_m, but it does constrain the neutrino mass spectrum [44]. If we are lucky, it can even determine this spectrum. Given Eq. (21), it is desirable that $\beta\beta_{0\nu}$ searches be sensitive to $M_{\beta\beta} \sim (0.01 - 0.05)$eV. Proposed experiments with sensitivity in this range are enumerated and discussed in [45].

Shortly before this report was written, evidence for $\beta\beta_{0\nu}$, with $M_{\beta\beta} = (0.11 - 0.56)$ eV, was reported [46]. However, possible problems with this evidence have been pointed out [47].

Astrophysical and cosmological observations have already constrained the neutrino mass scale [48]. Perhaps future observations and analyses will succeed in constraining this scale much more tightly, or even in determining it.

Question 2: Is there CP violation in the leptonic sector?

So far, CP violation has been observed only in the quark sector, where it is thought to arise primarily from a complex phase factor in the quark mixing matrix V. An analogous factor in the leptonic mixing matrix U would lead to CP violation in neutrino oscillation. (If U is larger than 3×3, there could be more than one phase factor with this consequence.) The observation of CP violation in neutrino oscillation would establish that CP noninvariance is not a peculiarity of quarks.

If the neutrino mass eigenstates are Majorana particles, and N in number, then U can contain $N-1$ additional CP-violating phase factors that have no analogue in the quark mixing matrix. These additional "Majorana" CP phase factors do not affect neutrino oscillation, but do affect the rate for $\beta\beta_{0\nu}$. With luck, this rate, in combination with solar neutrino data and the measurement in tritium β decay of the absolute neutrino mass scale, would determine one of the Majorana phases [44].

During the evolution of our universe, a baryon asymmetry somehow developed. Its development required CP violation. Quite possibly, the required violation occurred in leptonic interactions. We shall elaborate on this possibility in Sec. III.

If there are only three species of neutrinos, then CP violation in neutrino oscillation requires the nonvanishing of all the leptonic mixing angles, including the small angle θ_{13}. Indeed, the phase δ that leads to CP violation in oscillation enters the 3×3 mixing matrix U only through the combination $e^{\pm i\delta}\sin\theta_{13}$. Thus, it is important to establish that θ_{13} is nonvanishing, so that CP-violating effects in oscillation can be nonvanishing, and to determine the size of θ_{13}, so that we will have a better idea of what size CP-violating effects to expect. What it will take to determine θ_{13} will depend, of course, on how big it is. The present bound is $\sin^2\theta_{13} \lesssim 3\times 10^{-2}$ [38]. The MINOS experiment could hopefully reach $\sin^2\theta_{13} \sim 1\times 10^{-2}$, super-intense conventional neutrino beams (super beams) aimed at suitably large detectors could reach Few $\times 10^{-3}$ or even Few $\times 10^{-4}$, and a neutrino factory based on a muon storage ring could probe the region around and below 1×10^{-4} [49].

In a conventional neutrino beam, sensitivity to θ_{13} (and other parameters) could be increased by placing a detector off axis. There, the beam can be quite monoenergetic, as illustrated in Fig. 6 [50]. For a given source-to-detector distance L, one can select an off-axis beam energy E so that one is working at the maximum of the oscillatory factor $\sin^2[1.27\,\delta M^2_{\rm atm}(L/E)]$ that characterizes neutrino oscillation when $L/E \sim (750\text{ km})/(2\text{ GeV})$. Sensitivity to the coefficient of this factor, which in the case of $\nu_\mu \to \nu_e$ oscillation is $2\sin^2\theta_{13}$, is then optimized [51].

Studies show [52] that, depending on how large the CP-violating asymmetries in neutrino oscillation actually prove to be, these very interesting asymmetries may be visible in experiments using intense conventional beams, or may require the beams from a neutrino factory. Once θ_{13}, $\delta M^2_{\rm sol}$, and $\theta_{\rm sol}$ are known, we will have a much better idea of how large these asymmetries can be. Quite likely, in depth studies of these asymmetries will require a neutrino factory, even if the asymmetries can first be seen without one.

Question 3: How many neutrino species (active and sterile) are there?

The LSND collaboration has reported evidence at the level of four standard deviations for $\overline{\nu_\mu} \to \overline{\nu_e}$ oscillation [53]. Taking other experiments' negative results into account [54–57], this oscillation must be governed by a splitting $\delta M^2_{\rm LSND}$ between 0.2 and 7 eV^2 and a mixing parameter $\sin^2 2\theta_{\rm LSND}$ between 0.003 and 0.03. As noted above, this large $\delta M^2_{\rm LSND}$ is incompatible with the solar and atmospheric δM^2 values in a world with only three neutrino masses.

There have been multiple theoretical attempts to solve this problem. Most have involved the introduction of one or more sterile (non-weakly interacting) neutrinos. The noninteracting nature of the extra neutrinos is mandated by LEP and SLD measurements of the invisible width of the Z^0 [48], which restrict the number of light, weakly interacting neutrinos to three. Recent results from SNO [34] and Super-Kamiokande [58] have indicated that it is unlikely either the atmospheric or solar neutrino disappearance phenomena involve oscillation primarily to sterile neutrinos. This behavior is readily accommodated by the "3+1" models [59] in which three mass states are clustered relatively close together, separated by the solar and atmospheric mass differences. These three mass states are predominantly mixtures of the three active flavors. The fourth state is separated from the others by the large LSND δM^2, and is mostly sterile.

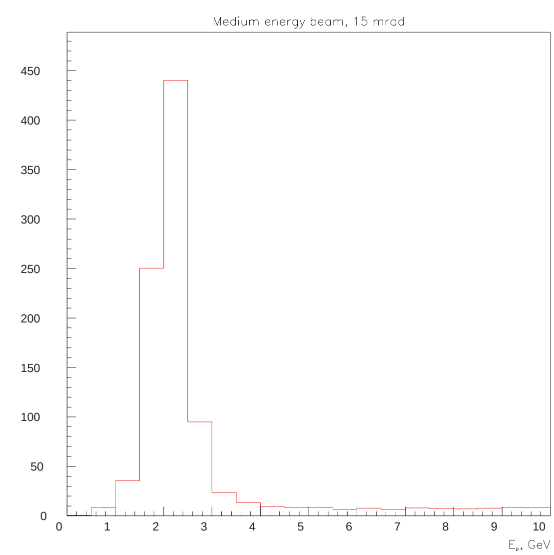

FIG. 6: Event rate vs. neutrino energy 15 mr from the NuMI beam line axis.

A more recent suggestion [60] is motivated by large extra dimensions and branes. In this model, CPT is violated in the neutrino mass matrix, giving different masses for neutrinos and antineutrinos. The neutrino mass hierarchy consists of a small δM^2 splitting corresponding to solar neutrino oscillations and a larger δM^2 splitting corresponding to atmospheric oscillations. On the antineutrino side, there is a very large splitting for LSND and a smaller one for atmospheric antineutrino oscillations. The strict bounds on CPT violation from kaon mixing experiments are not relevant to the neutrino sector under the extra dimensions scenario because neutrinos are free to propagate in the extra dimensions while quarks, being charged, are confined to the brane.

The situation should be clarified markedly in the next several years with results from the KamLAND and BooNE experiments. MiniBooNE(E898) will address the LSND result definitively using a pion decay-in-flight neutrino beam at Fermilab. Antineutrino running at E898 may also confirm or refute the CPT violation models. KamLAND will not search directly for high-δM^2 oscillations, but by searching for solar-scale oscillations with antineutrinos, it can address the CPT-violating oscillations if the large mixing angle solar oscillation solution proves to be correct.

If LSND is confirmed, then a model such as the new physics models mentioned above (or a different idea entirely) will be required to explain the data. This will represent a fundamental change in our concept of the lepton sector, and theoretical and experimental efforts to understand oscillations at short baselines should intensify over the coming decade. Depending on the scenario (CPT conserving or violating), the experimental program would look very different, though in either case an obvious initial step would be a two-detector BooNE upgrade. Confirmation of LSND, and therefore neutrino mass at the eV scale, would also improve the prospects for observing $\beta\beta_{0\nu}$ and neutrino mass in tritium β decay.

Lepton Sub-Group Recommendations

As we have seen, there has been dramatic progress in our knowledge of neutrinos, opening a whole new world to explore. Given what we have learned, and what we would like to learn, the Lepton Sub-Group of the Snowmass Flavor Physics Working Group would like to make the recommendations given in the Executive Summary [61].

III. WE EXIST—A CONSEQUENCE OF FLAVOR PHYSICS

We would like to conclude this report with an illustration of the profound consequences of flavor physics. The illustration we choose is our existence. This existence depends on the fact that the universe contains much more matter than antimatter. That is, it depends on the fact that $\Delta B \equiv \#(\text{Baryons}) - \#(\text{Antibaryons})$ does not vanish. Symmetry considerations suggest that at time $t = 0$, when the universe was born in the Big Bang, ΔB was zero. Thus, the baryon asymmetry $\Delta B \neq 0$ must have somehow developed during the subsequent evolution of the universe. This development required CP violation (assuming no CPT violation). To see why, suppose, for example, that protons were produced in the decays of a heavy particle X^+. Then antiprotons would have been produced in the decays of the antiparticle X^-. In the absence of CP noninvariance, the rates for the decays $X^+ \to p + \ldots$ and $X^- \to \overline{p} + \ldots$ would have been equal. Thus, equal numbers of protons and antiprotons would have been produced, so that $X^\pm$ decays would not have contributed anything to the asymmetry $\Delta B \neq 0$.

We do not know whether the CP violation that led to the observed $\Delta B \neq 0$ occurred in the quark sector or in the leptonic one. An interesting possibility is that it occurred in the leptonic sector, and the baryon asymmetry arose through a two-step process: First, a lepton asymmetry $\Delta L \equiv \#(\text{Leptons}) - \#(\text{Antileptons}) \neq 0$ arose through leptonic CP violation before the universe cooled through the electroweak phase transition at a temperature of ~ 100 GeV. Second, this $\Delta L \neq 0$ was converted to a $\Delta B \neq 0$ by expected $B - L$ conserving processes during the electroweak phase transition. The creation of the initial lepton asymmetry, $\Delta L \neq 0$, could have been due to the decays $N \to \ell^\mp + H^\pm$ of a hypothetical *heavy* Majorana neutral lepton N. Here, $\ell^\mp$ is a charged lepton and $H^\pm$ a charged Higgs particle. The violation of CP in these leptonic decays could have led to $\Gamma(N \to \ell^- + H^+) > \Gamma(N \to \ell^+ + H^-)$, so that a lepton excess, $\Delta L > 0$, was produced [62].

What experimental observations would build a case that this two-step scenario is how we came to be here? First, the observation of neutrinoless double beta decay would establish that the light neutrinos are Majorana particles. Thus, we would know that nature does contain such particles. Secondly, the observation of CP violation in neutrino oscillation would establish that CP violation is indeed present in the leptonic sector. The specific leptonic CP-violating phases needed in order to have $\Gamma(N \to \ell^- + H^+) \neq \Gamma(N \to \ell^+ + H^-)$ are the special "Majorana" CP phases that can occur only when neutral leptons are Majorana particles. The observation of CP violation in neutrinoless double beta decay would establish that nature does contain CP-violating phases of this kind.

To be sure, the connection between CP violation in heavy N decay and CP violation in neutrino oscillation and in $\beta\beta_{0\nu}$ is model-dependent [63]. Nevertheless, the future neutrino physics program could demonstrate that nature contains the ingredients that could have led to the present-day baryon asymmetry through a lepton asymmetry in the early universe.

IV. SUMMARY

Flavor physics is a powerful probe of physics beyond the Standard Model, and can have profound consequences. The nature and origin of flavor remain enigmatic. But the study of the mystery of flavor has entered a very interesting stage. Recent results on CP violation in quark interactions, and on neutrino mass and mixing, have been dramatic. Continued progress calls for a broad program of diverse measurements in both the quark and neutrino sectors, and for associated theoretical developments.

Acknowledgments

We are extremely grateful to Susan Kayser for her crucial help with the preparation of this report.

[1] P. Fayet and S. Ferrara *Phys. Rep.* **C32c**, 249 (1977); H. E. Haber and K. L. Kane *Phys. Rep.* **C117C**, 1 (1987).

[2] D. B. Kaplan, F. Lepeintre and M. Schmaltz *Phys. Rev.* **D56**, 7193 (1997).

[3] Ringwald, Scherempp and C. Wetterich *Nucl. Phys.* **B365**, 3 (1991).

[4] B. Aubert *et al.*, hep-ex/0201020.

[5] K. Abe *et al.* (BELLE), *Phys. Rev. Lett.* **87**, 091802 (2001).

[6] R. Aleksan, B. Kayser and D. London, *Phys. Rev. Lett.* **73**, 18 (1994).

[7] R. G. Roberts, A. Romanino, G. G. Ross, L. Velasco-Sevilla, *Nucl. Phys.* **B615**, 358 (2001).

[8] R. Barbieri, L. J. Hall and A. Romanino, *Nucl. Phys.* **B551**, 93 (1999).

[9] M. S. Alam, *et al.*, *Phys. Rev. Lett.* **74**, 2885 (1995).

[10] S. Chen *et al.*, (CLEO), *Phys. Rev. Lett.* **87**, 251807 (2001).

[11] A. L .Kagan and M. Neubert, *Phys. Rev.* **D1998**, 58 (094012); M. Aoki G. Cho and N. Oshimo, *Phys. Rev.* **D1999**, 60 (035004), *Phys. Lett.* **B1998**, 436 (344).

[12] S. Ahmed *et al.*, 1999 it CLEO CONF 99-10; hep-ex/9908022.

[13] G. Burdman, E. Golowich, J. Hewett and S. Pakvasa, hep-ph/0112235 (2001).

[14] D. Scora, N. Isgur, *Phys. Rev.* **D52**, 2793 (1995) and references therein; D. Melikhov, B. Stech, *Phys. Rev.* **D62**, 014006 (2000) and references therein.

[15] N. Isgur and M. Wise, in *B Decays, 2nd ed.*, S. Stone editor (Singapore: World Scientific), (1994).

[16] J. Richman and P. Burchat, *Rev.Mod.Phys.* **67** 893, (1995).

[17] I. I. Bigi *et al.*, *Phys. Rev.* **D50**, 2234 (1994).

[18] I. I. Bigi, M. Shifman and N. Uralsev, *Annu. Rev. Nuc. Part. Sci.* **47** (1997), 591.

[19] N. Isgur, *Phys. Lett.* **B448**, 111 (1999).

[20] I. I. Bigi and N. Uraltsev, *Int.J.Mod.Phys.* **A16** 5201(2001).

[21] S. Ryad, *Nucl.Phys.Proc.Suppl.* **106** 86(2002).

[22] G. Peter Lepage, *Talk given at joint P2-E2 working group session*, Summer Study on the Future of Particle Physics (Snowmass 2001), Snowmass, Colorado, 30 Jun - 21 Jul 2001.

[23] CESR-c taskforce,CLEO-c taskforce and CLEO collaboration, *Cornell Preprint* CLNS 01/1742 (2001).

[24] A. D. Sakharov *Sov.Phys.Usp.* **34**417 1991.

[25] G. Farrar *Nucl. Phys. Proc. Suppl.* **43** 312 (1995).

[26] J. Silva and L. Wolfenstein, *Phys. Rev.* **D55**, 5331 (1997).

[27] Particle Data Group, D. Groom, *et al.*, *Eur. Phys. J.* **C15** 1, (2000).

[28] Y. Nir, *Lectures given in the XXVII SLAC Summer Institute on Particle Physics*, July 7 - 16, 1999.

[29] A. Buchalla, CERN-TH/2001-292 (2001); hep-ph/0110313.

[30] D. Akerib *et al.*, Summary P4 Working Group, Summer Study on the Future of Particle Physics (Snowmass 2001), Snowmass, Colorado, 30 Jun - 21 Jul 2001; hep-ph/0201178.

[31] A. Masiero, *Ann.Rev.Nucl.Part.Sci* **51** 161, (2001).

[32] E. Kearns, Proceedings of ICHEP 2000 (World Scientific, Singapore, 2001) p.172.

[33] J. Goodman, talk presented at the 2002 Aspen Winter Conference on Particle Physics.

[34] SNO Collaboration (Q. R. Ahmad *et al.*), *Phys. Rev. Lett.* **87**, 071301 (2001).

[35] S. Fukuda *et al.*, *Phys. Rev. Lett.* **86**, 5651 (2001).

[36] J. Beacom and S. Parke, *Phys. Rev.* **D64**, 091302 (2001); A. Kurylov, M. Ramsey-Musolf, and P. Vogel, nucl-th/0110051.

[37] G. Fogli, E. Lisi, D. Montanino, and A. Palazzo, *Phys. Rev.* **D64**, 093007 (2001); P. Krastev and A. Smirnov, hep-ph/0108177; J. Bahcall, M. C. Gonzalez-Garcia, and C. Peña-Garay, hep-ph/0111150.

[38] CHOOZ Collaboration (M. Apollonio *et al.*), *Phys. Lett.* **B466**, 415 (1999); F. Boehm *et al.*, *Phys. Rev.* **D64**, 112001 (2001).

[39] LSND Collaboration (A. Aguilar *et al.*), *Phys. Rev.* **D64**, 112007 (2001); KARMEN Collaboration (B. Armbruster *et al.*), hep-ex/0203021; E. Church, K. Eitel, G. Mills, and M. Steidl, hep-ex/0203023.

[40] M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity*, eds. D. Freedman and P. van Nieuwenhuizen (North Holland, Amsterdam, 1979) 315; T. Yanagida, in *Proceedings of the Workshop on Unified Theory and Baryon Number in the Universe,* eds. O. Sawada and A. Sugamoto (KEK, Tsukuba, Japan, 1979); R. Mohapatra and G. Senjanović, *Phys. Rev. Lett.* **44**, 912 (1980).

[41] KATRIN Collaboration, hep-ex/0109033.

[42] J. Schechter and J. Valle, *Phys. Rev.* **D25**, 2951 (1982); E. Takasugi, *Phys. Lett.* **B149**, 372 (1984).

[43] This implication no longer follows if CPT invariance is broken. See G. Barenboim, J. Beacom, L. Borissov, and B. Kayser, hep-ph/0203261.

[44] S. Petcov and A. Smirnov, *Phys. Lett.* **B322**, 109 (1994); V. Barger and K. Whisnant, *Phys. Lett.* **B456**, 194 (1999); F. Vissani, JHEP **9906**, 022 (1999); C. Giunti, *Phys. Rev.* **D61**, 036002 (2000); S. Bilenky, C. Giunti, W. Grimus, B. Kayser, and S. Petcov, *Phys. Lett.* **B465**,

193 (1999); H. V. Klapdor-Kleingrothaus, H. Päs, and A. Smirnov, *Phys. Rev.* **D63**, 073005 (2001); S. Bilenky, S. Pascoli, and S. Petcov, *Phys. Rev.* **D64**, 053010 (2001) and *Phys. Rev.* **D64**, 113003 (2001); Y. Farzan, O. Peres, and A. Smirnov, *Nucl. Phys.* **B612**, 59 (2001); S. Pascoli, S. Petcov, and L. Wolfenstein, *Phys. Lett.* **B524**, 319 (2002).

[45] S. Elliott and P. Vogel, hep-ph/0202264.

[46] H. V. Klapdor-Kleingrothaus, A. Dietz, H. Harney, and I. Krivosheina, *Mod. Phys. Lett.* **A16**, 2409 (2001).

[47] C. Aalseth *et al.*, hep-ex/0202018.

[48] See for example, Particle Data Group, Ref. [27].

[49] See the E1 Working Group Summary by T. Adams *et al.* (hep-ph/0111030) in this Volume, and references therein. We thank D. Harris for innumerable very helpful conversations on this matter.

[50] We thank A. Para for this figure.

[51] The off-axis possibility has been discussed in D. Beavis *et al.*, Brookhaven National Laboratory Report 52459, April, 1995; in Y. Itow *et al.*, hep-ex/0106019; and within the MINOS Collaboration and a Fermilab-Northwestern University Study Group.

[52] See, for example, the E1 Working Group Summary, Ref. [49], and the references therein.

[53] LSND Collaboration, Ref. [39].

[54] KARMEN Collaboration, Ref. [39].

[55] A. Romosan *et al.*, *Phys. Rev. Lett.* **78**, 2912 (1997).

[56] B. Achkar *et al.*, *Nucl. Phys.* **B434**, 503 (1995).

[57] E. Church *et al.*, Ref. [39].

[58] C. Walter, private communication.

[59] S. Bilenky, C. Giunti, and W. Grimus, *Eur. Phys. J.* **C1**, 247 (1998); S. Bilenky *et al.*, *Phys. Rev.* **D60**, 073007 (1999); V. Barger, S. Pakvasa, T. Weiler, and K. Whisnant, *Phys. Rev.* **D58**, 093016 (1998); V. Barger, T. Weiler, and K. Whisnant, *Phys. Lett.* **B427**, 97 (1998); V. Barger. B. Kayser. J. Learned. T. Weiler. and K. Whisnant, *Phys. Lett.* **B489**, 345 (2000); O. Peres and A. Smirnov, *Nucl. Phys.* **B599**, 3 (2001); C. Giunti, *Nucl. Phys. Proc. Suppl.* **100**, 244 (2001); W. Grimus and T. Schwetz, *Eur. Phys. J.* **C20**, 1 (2001); M Maltoni, T. Schwetz, and J. Valle, *Phys. Lett.* **B518**, 252 (2001).

[60] H. Murayama and T. Yanagida, *Phys. Lett.* **B520**, 263 (2001); G. Barenboim, L. Borissov, J. Lykken, and A. Smirnov, hep-ph/0108199; G. Barenboim, L. Borissov, and J. Lykken, hep-ph/0201080.

[61] Due to manpower limitations, the Lepton Sub-Group focussed almost exclusively on neutrino physics, where the recent progress has been striking. However, it is clearly important to pursue charged lepton physics as well. Rare processes and tiny effects in the charged lepton sector can provide very sensitive probes of new physics beyond the SM.

[62] M. Fukugita and T. Yanagida, *Phys. Lett.* **B174**, 45 (1986); W. Buchmüller and M. Plümacher, *Phys. Lett.* **B389**, 73 (1996).

[63] Leptogenesis via heavy N decay, and its connection to CP violation in light neutrino physics, was discussed at Snowmass by L. N. Chang, J. Ellis, B. Gavela, B. Kayser, P. Langacker, and H. Murayama. The model-dependence of the connection was observed. For an analysis showing how experimental studies of charged lepton decays could help, see J. Ellis, J. Hisano, S. Lola, and M. Raidal, *Nucl. Phys.* **B621**, 208 (2002).