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Experimental Summary

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The Beauty 2009 Conference falls at a very interesting time for the field of flavor physics. As we continue to reap the benefits of a very successful generation of experiments at the Tevatron and e^+e^- B-factories, we are poised to see a new generation of experiments which will further our understanding of the field. In the immediate future, the LHC offers exciting prospects for flavor physics. In this summary, I put some of the experimental issues presented at this conference into an overall historical context.

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[1] Speaker

1. Introduction

This conference featured a number of extremely interesting talks and results, along with a number of presentations regarding the exciting future for flavor physics. In this summary talk, I have not attempted to do full justice to the material presented at this conference. Instead I have tried to focus on how these results fit into our field within a broader and somewhat historical context. Old timers might find this history to be well known, but perhaps it is of use for younger scientists to know where this field has been and where it might be going.

2. History

This conference takes place in the wake of the 2008 Nobel Prize in Physics awarded to Makato Kobayashi and Toshihide Maskawa for, "the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature." Their work, published in 1973, predicted a third generation of quarks in order to explain *CP* violation in the kaon system [1]. The generalized unitary matrix, now known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix is written as:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \tag{1.1}$$

which relates the flavor eigenstates to the weak eigenstates. In general, a 3x3 unitary matrix of this type requires at least one complex phase. At the time, the magnitudes of the various elements were unknown, but the existence of a third generation (at least) would permit, through a complex phase, *CP* violation. Today, more than 38 years later, we understand the complex phase in the CKM matrix to explain all forms of *CP* violation observed to date.

Two major discoveries in 1974 and 1975 set us on the path towards modern flavor physics. First, in 1974, experiments at Brookhaven and SLAC announced the discovery of a new resonance at 3.1 GeV/c^2 which was dubbed the J/ψ [2]. Although there was originally some question as to what this resonance was, for example some thought it might be the Higgs boson, it was relatively quickly understood to be a charm-anticharm $(c\overline{c})$ bound state. The J/ψ observation completed the 2nd generation and provided validation of the Glashow-Iliopolous-Miani (GIM) mechanism that explained the suppression of flavor changing neutral currents in kaon decays [3].

Following the discovery of the J/ψ, weakly decaying open charm was observed, as was the τ lepton [4, 5]. The τ lepton was the first observed constituent of the third generation, and led to further speculation that another doublet in the quark sector was not far away.

The field of *B* physics truly began with the discovery of the Υ(1s) state in 1977, just 32 years ago [6]. The discovery experiment, E-288 at Fermilab, measured the dimuon mass spectrum in fixed target interactions. A high energy proton beam was brought into collision

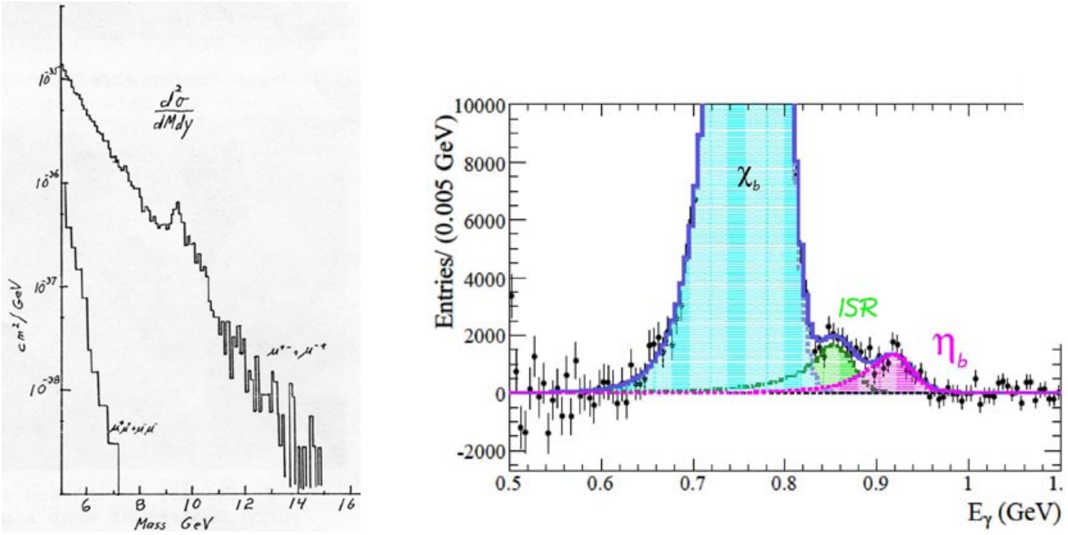

Figure 1. Left: First observation of $\Upsilon(1s)\to\mu^+\mu^-$ in 1977 by the E-288 experiment at Fermilab. Right: First observation of the η_b in $\Upsilon(3s) \to \eta_b\,\gamma$ by the Babar experiment at SLAC. The luminosity used in this analysis was 25.6 fb^{-1}, corresponding to 109 million $\Upsilon(3s)$ decays.

with a beryllium target. The mass spectrum is shown in Fig. 1. A large peak just below 10 GeV/c^2 was the first observation of bottom quark production. In hindsight, it seems clear that the E-288 mass spectrum showed evidence for the $\Upsilon(2s)$ and $\Upsilon(3s)$ states as well, but lacked sufficient mass resolution to resolve the nearby states.

The Cornell Electron Storage Ring (CESR) turned on a few years later, and in 1980, the $\Upsilon(4s)$ state was observed, which yielded the first observation of weakly decaying open beauty hadrons, B^+ and B^0 mesons [7]. This began the field of *B* physics that has yielded an incredibly rich program of results over the subsequent 30 years.

One of the things that we understand to make the *B* system unique is its long lifetime. Without a *B* lifetime of $\mathcal{O}(1.5$ ps$)$, many of the important observables in the *B* system (*e.g.* mixing) would not be observable. In the early 1980s, conventional wisdom placed the top quark mass somewhere around 15-20 GeV/c^2, which implied a *B* lifetime of about 0.1 ps. The first lifetime measurements were performed at PEP, an e^+e^- storage ring at SLAC with center of mass energy of 29 GeV. These measurements were performed almost a decade before silicon microvertex detectors arrived on the scene, so lifetime resolution was limited by today's standards. The MARK-II and MAC experiments at PEP were the first to show a *B* lifetime of 1-2 ps [8].

Based upon empirical information and the mass hierarchy in the quark sector, in 1983 Lincoln Wolfenstein posed the now famous, and quite commonly utilized, parameterization of the CKM matrix [9]:

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4), \tag{1.2}$$

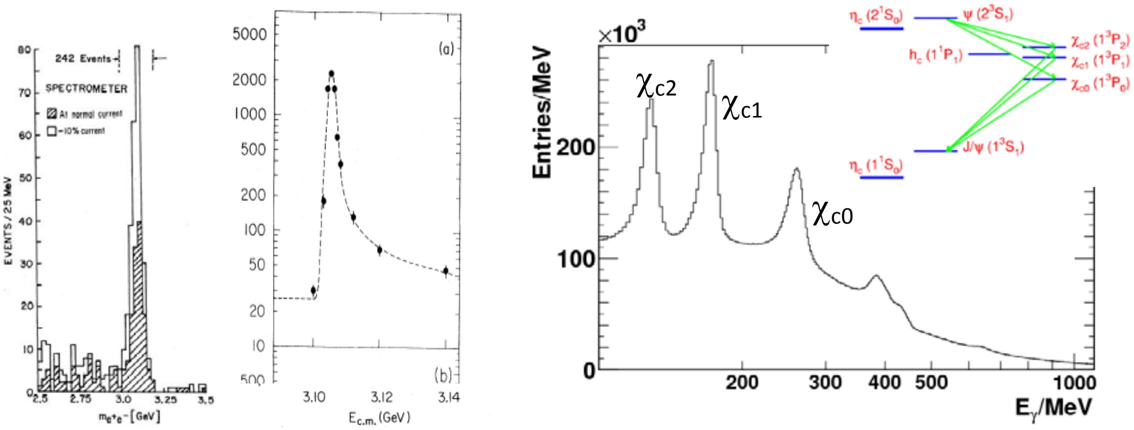

Figure 2. Left: First observation of $J/\psi \to e^+e^-$ in 1974 at Brookhaven. Middle: First observation of $J/\psi \to \mu^+\mu^-$ in 1974 at SLAC. Right: Recent results showing transitions from the $\psi(2s)$ state down to various χ_c states at BES.

where the expansion in terms of $\lambda = \sin\theta_C \approx 0.23$ is the sine of the Cabibbo angle. At order λ^3, the complex phase, η, appears in V_{ub} and V_{td} matrix elements which have been of great interest over the last two decades. At higher orders in λ, the complex phase also appears in V_{cd}, V_{cs} and V_{ts}. The V_{ts} matrix element has been of significant interest in this conference, thanks to the recent D0 and CDF measurements of the *CP* asymmetry in $B_s \to J/\psi\,\phi$ [10].

In the early 1980s, Sanda, Carter and Bigi published papers that showed the possibility of large *CP* violating effects in the *B* system [11]. These papers, along with the experimental achievements described above, began an era where flavor physics has played a central role in our understanding of the Standard Model and placed stringent limits on physics beyond the Standard Model. The subsequent 30 years has seen remarkable advances in accelerator technology, experimental methods, analytical techniques and theoretical understanding.

3. From Yesterday to Today

While the history of flavor physics is fascinating, and not so long in the past, it is really interesting to see just how far we've come in the last few decades. For example, in Fig. 1 we can compare the first observation of the Υ(1s) to the recent Babar observation of the 0^{-+} $\eta_b(1s)$ state through a magnetic dipole transition from the Υ(3s) state [12]. From a handful of events in 1977 to hundreds of millions of events today, we have learned a great deal about the bottomonium system. As another example, Fig. 2 shows a similar comparison between the original J/ψ observations and recent results on other $c\bar{c}$ resonances at BES [13]. As an example of how far we have come, BES anticipates a future experimental program based upon 10^{10} J/ψ events!

Hadron machines have also played an important role in our progress. Measurements at UA1 gave the first indication that the B_s oscillation frequency was high [14], and more than 20 years later, CDF was able to precisely measure the B_s oscillation frequency [15]. Precision lifetime and mass measurements, and the majority of our knowledge on heavier *B* hadrons (B_s, B_c, *b*-

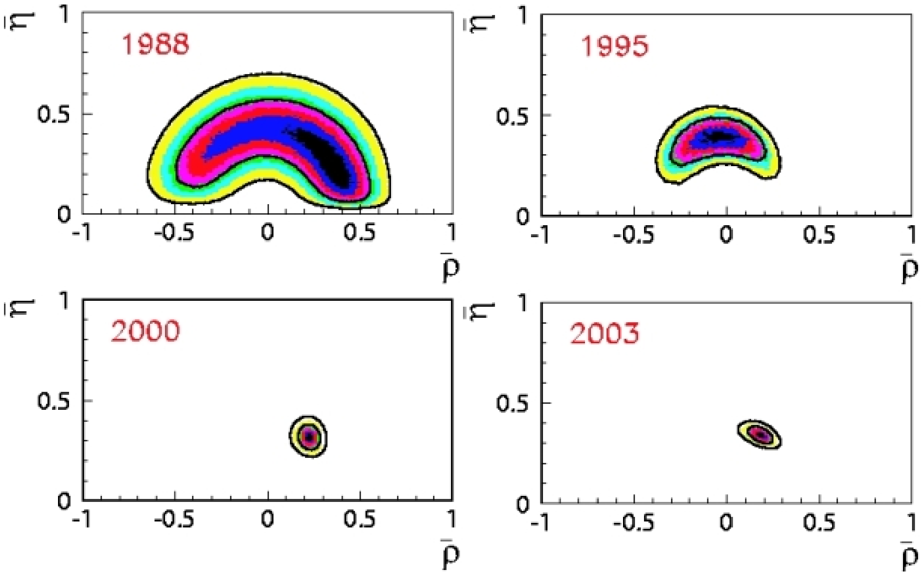

Figure 3. Historical evolution of the constraints on the (ρ,η) plane. A nonzero value for η is indicative of Standard Model *CP* violation.

baryons) have come from hadron machines. Although sometimes dismissed as an environment too messy to perform precision flavor physics, the hadron collider environment has proven to be an essential player in charm and *B* physics.

The evolution of the field has been an ongoing success story of accelerators and detectors. It was about 20 years from the suggestion of large *CP* violating effects in the *B* system to when they were unambiguously identified. Progress towards precisely quantifying the CKM matrix has been significant and the historical evolution of the constraints on the (ρ,η) plane are shown in Fig. 3. [16].

Two measurements which contribute significantly to our knowledge of ρ and η are the *CP* asymmetry in $B^0/\bar{B}^0 \to J/\psi K_S^0$ from Belle and Babar [17] and the observation of $B_s - \bar{B}_s$ flavor oscillations at the Tevatron [15]. Examples of these measurements are shown in Fig. 4. From these and other measurements, along with significant progress on the theoretical front, the current state of the art in ρ - η constraints is shown in Fig. 5 [18]. As we continue to shrink the uncertainties on the measurements (and theoretical inputs) we continue to test the Standard Model CKM picture at higher and higher precision.

4. The Evolution of Accelerators

The brief history outlined above is far from complete, and does not do justice to some of the important theoretical and experimental milestones that were achieved. For example, the 1980 and 1990s provided measurements of flavor oscillations in the *B* system, observation of penguin decays, first observations of *b*-baryons and a host of other measurements. Progress in the field has been rapid over the years, and has arisen from several fronts: accelerators, detectors and analysis techniques.

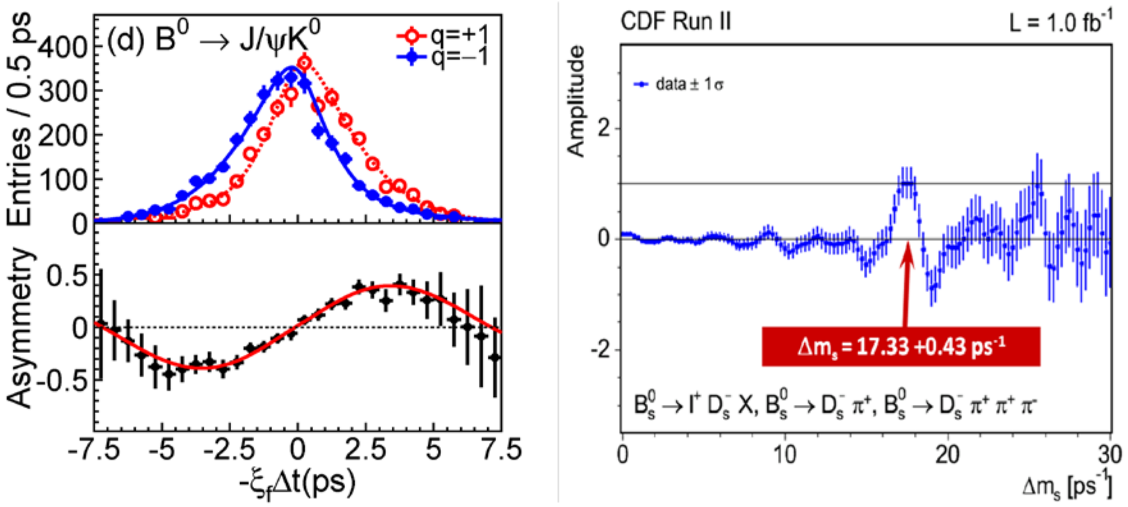

Figure 4. Two recent results that contribute significantly to current constraints on ρ and η. **Left.** Recent results on *CP* violation in $B^0 \to J/\psi\, K^0$ decays from BELLE. The top plot shows the $\overline{B}^0$ versus B^0 decays as function of decay time difference (Δt). The asymmetry is formed for the bottom plot. The frequency of the sine curve is the mass difference Δm_d, the amplitude is the *CP* violating asymmetry. **Right.** The amplitude scan from CDF for B_s flavor oscillations. The amplitude is zero at values of Δm_s inconsistent with the true mixing frequency, and the amplitude becomes unity at the mixing frequency.

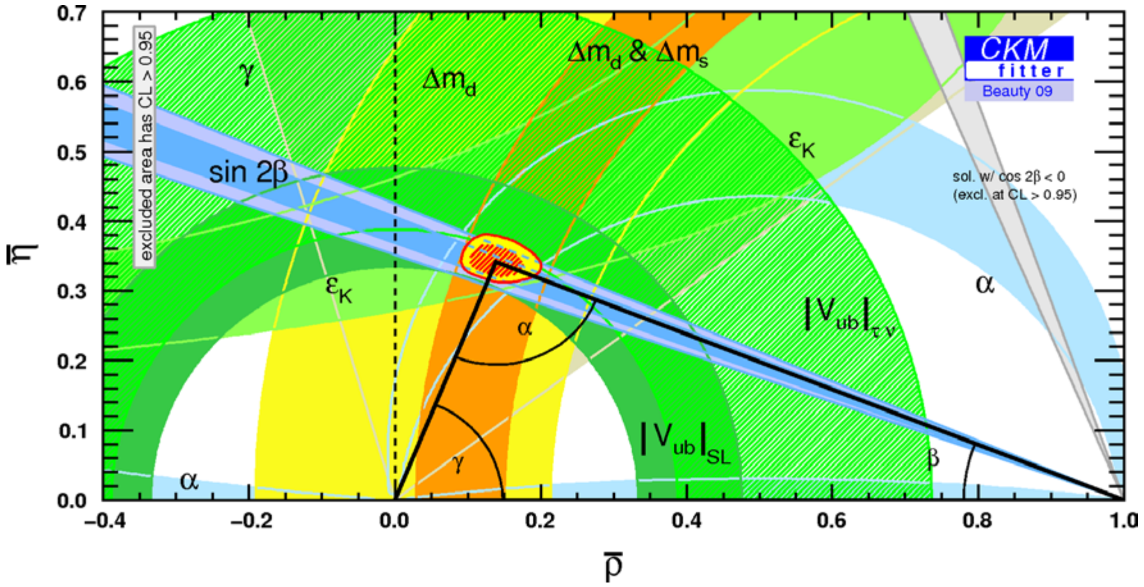

Figure 5. The state of the art, as of Beauty 2009, in constraints on ρ and η. The level of precision and level of consistency is striking.

Table 1. The accelerators that have contributed significantly to *B* physics. The dates are approximate, and the terminology utilized is non-standard.

Decade (approx)	Generation	What	Machines
1980's	**0th**	**B factories**	**CESR/DORIS/PEP/PETRA/SppS**
1990's	**1st**	**Super B factories**	**CESR/DORIS/LEP/SLC/Tevatron**
2000's	**2nd**	**Super-duper B factories**	**CESR/PEP-II/KEK-B/Tevatron**
2010's	**3rd**	**Really super-duper B factories**	**SuperB/Super KEK-B/LHC**

Table 1 shows an abbreviated history of accelerators which provided *B* physics results from the 1980's onward. Although we typically think of PEP-II and KEK-B as "*B* factories", I take a bit of liberty with terminology to point out that each successive decade has brought us to a new level of experimental precision, through improvements to an existing accelerator (*e.g.* CESR) or the development of a new machine. The dates listed are approximate for the different machines, but is particularly interesting to note that CESR and the Tevatron, two very different machines, have been delivering flavor physics results for multiple decades! Machine improvements leading to significantly higher luminosities have transformed these machines into devices that ultimately performed orders of magnitude beyond their original design considerations.

Although Table 1 is listed for *B* physics machines, we could easily make a similar list for charm machines which would span SPEAR/DORIS/fixed target/CESR-c/BEPC and also include the machines listed in Table 1.

5. Beauty 2009

The above history is the context in which we consider the results and prospects presented in this conference. As I said at the outset, I will not attempt to do justice to all of the exciting results shown at this conference. I do, however, want to comment on where we are at and where we are heading.

The most recent decade, the one I dubbed the decade of the "super-duper *B* factories" has provided us with an incredible amount of knowledge about the *B* system. For example, in the year 2000, the B^0 section of the Particle Data Book was 57 pages in length. In 2008, it was 170 pages [19]!

This conference featured talks on some of the most recent advances, including:

- the observation of $B \to \tau\nu_\tau$,
- the forward-backward asymmetry in $B \to K^* l^+ l^-$,
- results on the *CP* asymmetry in $B_s \to J/\psi\ \phi$,
- results on $D^0 - \bar{D}^0$ mixing,
- improved measurements of the *CP* angle γ,
- constraints on new physics from the improved limit on $B_s \to \mu^+\mu^-$,
- study and observation of *X*, *Y* and *Z* states.

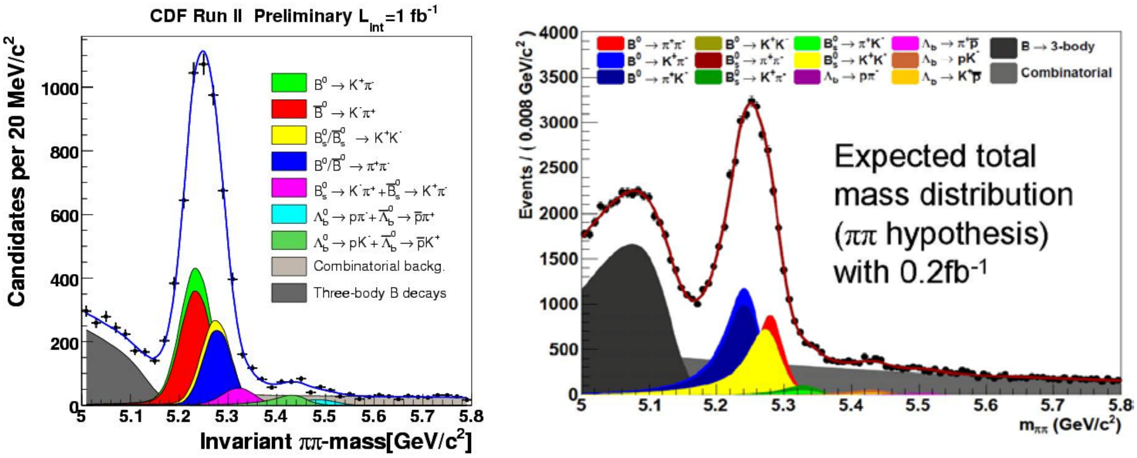

Figure 6. Examples of two-body charmless decay spectra. **Left:** Results from 1 fb^{-1} of data at CDF. This sample yielded the first observation of two-body charmless decays of Λ_b baryons among other modes. **Right:** The anticipated spectrum from LHCb. Note the vertical scale in comparison with CDF, LHCb expects to acquire enormous samples in the very near future.

This is an incomplete list, and as mentioned above, I cannot do justice to any of these results. From this partial list, it is clear we are continuing to make progress at an impressive rate. For as much progress as we have made in recent years, we will need to continue to progress to get at the new physics that we anticipate is hiding in the flavor sector.

6. From Today to Tomorrow

Table 1 lists the "3rd generation" *B* physics machines as coming online in the next ten years. One of the most exciting aspects to this conference is the intersection in time between the success of Babar/Belle/CDF/D0 and the prospects of the LHC and SuperB/SuperKEKB. In addition to many talks on the latest results from the current generation of experiments, this conference also featured a number of talks on the future of our field.

Two successful ventures, the Standard Model and the field of flavor physics, have put us in a challenging situation. We have completed an exhaustive, unprecedented series of measurements to probe flavor physics: decay dynamics, rare processes, oscillations, and *CP* violation only to find that the Standard Model has passed every test. While some two sigma effects linger, after this amazing period of flavor physics we do not have any smoking gun telling us where the new physics lies. However, we know it has to be out there.

The LHC and the next generation of e^+e^- machines will again take us to the next level of precision and understanding. The technology involved in the accelerators and detectors continues a multi-decade trend. In the coming years, measurements which used to be beyond our wildest dreams will be made with percent level precision.

Much of the excitement about the future of the field arises from the turn on of the LHC and the exciting prospects for the LHCb experiment. The LHCb experiment will benefit from a very large forward $b\overline{b}$ cross section and utilize excellent tracking and particle identification to perform measurements with an incredible precision. As an example, Fig. 6 shows that LHCb

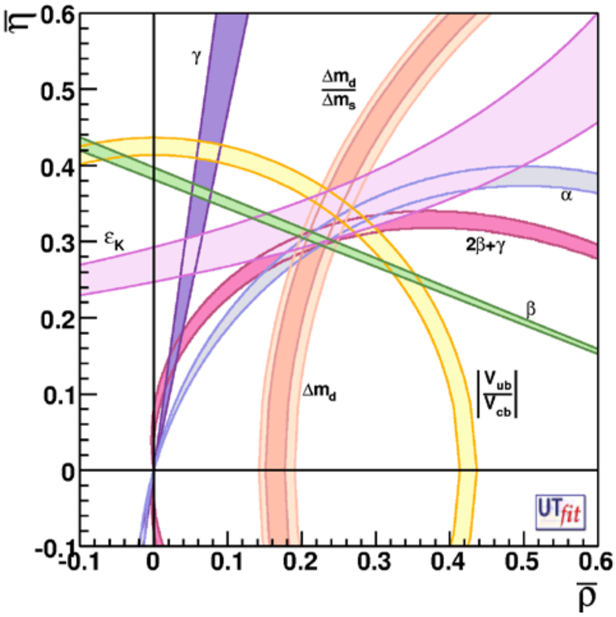

Figure 7. A possible look into the future of the (ρ,η) plane. Taking the central values of current measurements, with assumed improvements in precision from measurements and theoretical inputs, the plot gives and example of what our understanding might look like in the future.

expects to acquire two-body charmless decays [20] at a rate that is more than an order of magnitude larger than that of CDF [21]!

In the coming decade, we will see two important trends continue.

- We will continue to see complementarity between hadron and e^+e^- collider flavor physics. The different experimental environments, each with their strengths and challenges, have provided an important stereoscopic view of our field. With the LHC and the next generation of e^+e^- machines, this trend will continue.
- The coming decade will also continue the trend of complementarity between flavor physics and "energy frontier" physics. The success of the Standard Model and our understanding is through a combination of direct, high energy searches for new physics and measurements of massive particles (*W*, *Z*, top) and the lower energy probe provided by *K*, charm and *B* physics. In the coming decade, this trend will continue around the world at *B* factories, charm factories and fixed target experiments in the kaon and muon sectors.

In the coming years, we can anticipate improved sensitivity in many areas, including searches for rare processes, improved measurements of CP violating asymmetries and significant progress on the theoretical front. Figure 7 shows an example of what the future of unitarity triangle measurements might look like [22]. This plot takes current central values and shows improved theoretical and experimental uncertainties that might be obtained in the coming years. As discrepancies begin to emerge, the flavor sector will help us to uncover and untangle physics beyond the Standard Model. In addition to the quantities shown in Fig. 7, it will be possible to test the consistency of individual elements. For example, LHCb will be able to measure the angle γ using tree level processes and loop level processes. Consistency between these various extractions of γ will provide yet another important test of the CKM picture. Of course, not all of the exciting measurements in the flavor sector are encoded in the unitarity triangle. A host of other measurements will additionally provide further insight into new physics.

7. Conclusion

This conference provided an excellent snapshot of where flavor physics stands as we embark upon the second decade of the new century. The successful programs leading up to this date have put us in a position where we are in some ways victims of our own experimental and theoretical success. The overwhelming accuracy of the Standard Model means that we need to dig at least one more layer deeper to find the new physics. With the advent of the LHC and the prospects for SuperB/SuperKEKB, we appear to have the tools to continue digging. It’s with great anticipation that we await the next find!

Beauty 2009, sitting at the boundary between the "super duper" and "really super duper" era, has given us a glimpse of the best of what we have done, what we are doing and what we will do.

I wish to thank Ulrich Uwer and the local organizers at the University of Heidelberg for an outstanding conference. Their tireless efforts to put together a smooth conference along with their hospitality will not be forgotten. I also would like to thank Neville Harnew, Samim Erham and the international advisory committee for their efforts in assembling a very interesting program. Thanks also to the speakers and participants. The excellent talks and lively discussion were truly stimulating.

This conference series has had a very successful history (see Appendix) thanks to the vision, energy and enthusiasm of the late Peter Schlein. We appreciate his professional contributions to our field and this conference series, and we also appreciate him as a friend. It is great to see this conference series continue in his honor.

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Appendix

In preparing this summary talk, conference organizers [23] provided me with a history of the Beauty Conference series. I thought it would be worthwhile to reproduce it here for posterity.

I. Leblice, Czechoslovakia, 18-22 Jan 1993
II. Le Mont Saint Michel, France, 24-29 April 1994
III. Oxford, England, 10-14 July 1995
IV. Rome, Italy, 17-21 June 1996
V. Santa Monica (UCLA), USA, 13-17 October 1997
VI. Bled Slovenia, 21-25 June 1999
VII. Sea of Galilee, Israel, 13-18 September 2000
VIII. Santiago de Compostela, Spain, 17-21 June 2002
IX. Pittsburgh (Carnegie Mellon), USA 14-18 October 2003
X. Assisi, Italy, 20-24 June 2005
XI. Oxford, England, 25-29 September 2006
XII. Heidelberg, Germany, 7-11 September 2009