January 22, 2015

Charmless Hadronic B Decays
Summary WG5

Martin Beneke (TUM)
Cheng-Wei Chiang (NCU)
Pablo Goldenzweig (KIT)

1st B2TIP Meeting
KEK, Japan
Oct. 30-31, 2014

1 Introduction

The scope of WG5 covers the studies of branching fractions ($\mathcal{B}$), angular analysis, and direct CP violation in charmless hadronic B decays. We organize the channels into the following 3 categories, including both B and B_s decays:

- 2-body:
    - Long-lived final states, such as, $B \to K\pi$, KK.
- Quasi-2-body:
    - Decays in which one or both of the decay products are resonances.
    - Final state particles which have been measured include: scalar; pseudoscalar; vector; and axial-vector particles.
    - Angular analysis performed whenever possible.
- 3-body:
    - Final states with π or K and other resonances.
    - Dalitz methods employed to study the effects of interference.

There are a total of ≈ 200 decay channels. Our efforts are focused on those which contain neutral particles in the final state, where Belle II is expected to supercede LHCb. We do not momentarily include the $\pi\pi$, $\rho\rho$, and $a_1\pi$ systems, nor $B \to \phi K_\mathrm{s}$, $\eta' K_\mathrm{s}$, and $K_\mathrm{s}K_\mathrm{s}K_\mathrm{s}$ decays, as they fall under the mandate of WG3 (ϕ_2).

2 Contributions

This document is based on discussions resulting from the following presentations:

- Gagan Mohanty, "$B \to hh'$ decays and the $K\pi$ puzzle"
- Alakabha Datta, "Angular analysis in $B \to VV$ decays"
- Hai-Yang Cheng, "Large local CP asymmetries in Dalitz analyses of 3-body B decays"
- Tobias Huber, "NLO calculation of direct CP asymmetries"
- Satoshi Mishima, "New physics in rare B decays"
- Pablo Goldenzweig, "Charmless hadronic B decays - Experiment"

3 $K\pi$ Puzzle

The measurement of direct CP violation in $B^+ \to K^+\pi^0$ has been found to be different than in $B^0 \to K^+\pi^-$, contrary to the naive expectation from the presence of electroweak penguin diagrams. Belle measured $A_{CP}^{K^+\pi^0} - A_{CP}^{K^+\pi^-} = 0.112 \pm 0.027 \pm 0.007 \ \ (4\sigma)$ with 772M $B\overline{B}$ pairs [1]. Including contributions from BaBar and LHCb, the world average stands at $0.127 \pm 0.022 \quad (6\sigma)$. This difference could be due to strong interaction effects in the color-suppressed tree amplitude contributing to the $B^\pm$ decay mode, or some unknown new physics (NP) effect that violates isospin. In combination with other $K\pi$ measurements and with the larger Belle II dataset, strong interaction effects can be better controlled and the validitiy of the standard model (SM) can be tested in a less model-dependent way.

The following sum rule for NP [2], which is nearly free of theoretical uncertainties, can test the SM by measuring all observables:

$$A_{CP}^{K^+\pi^-} + A_{CP}^{K^0\pi^+} \frac{\mathcal{B}(B^+\to K^0\pi^+)\tau_{B^0}}{\mathcal{B}(B^0\to K^+\pi^-)\tau_{B^+}} = A_{CP}^{K^+\pi^0} \frac{2\,\mathcal{B}(B^+\to K^+\pi^0)\tau_{B^0}}{\mathcal{B}(B^0\to K^+\pi^-)\tau_{B^+}} + A_{CP}^{K^0\pi^0} \frac{2\,\mathcal{B}(B^0\to K^0\pi^0)}{\mathcal{B}(B^0\to K^+\pi^-)},$$

The most demanding measurement is the $K^0\pi^0$ final state. Using their most recent branching fraction measurement [3] and the most recent world averages for the other parameters [4], Belle predicts $A_{CP}^{K^0\pi^0} = -0.15 \pm 0.04$ from the sum rule. Comparing this with Belle's measurment of $A_{CP}^{K^0\pi^0} = +0.14 \pm 0.13 \pm 0.06$, the isopsin relationship is found to to be only marginally satisfied, with a level of disagreement of 1.9σ [3]. The $A_{CP}^{K^0\pi^0}$ result is dominated by the statistical error, and among the sources of systematics, the tag-side interference is the largest contributor. With Belle II, the uncertainty on $A_{CP}^{K^0\pi^0}$ from a time-depependent analysis is expected to reach $\sim 4\%$, which is sufficient for NP studies [5].

One can construct similar sum rules by replacing $K \to K^*$ and $\pi \to \rho$. The additional challenge lies in performing a Dalitz-plot study involving one or more π^0's in the following final states: $K^+\pi^-\pi^+$, $K^+\pi^-\pi^0$, $K_s^0\pi^+\pi^0$, $K_s^0\pi^0\pi^0$, $K^+\pi^0\pi^0$, $K_s^0\pi^+\pi^-$. Within uncertainty, A_{CP} shows the opposite trend with respect to the $K\pi$ system [6]. Improved precision in $A_{CP}^{K^{*+}\pi^0}$ and to lesser extent in $A_{CP}^{K^{*+}\pi^-}$ are necessary to settle the ΔA_{CP} issue and resolve the sum rule.

4 $B \to VV$ Decays

Decays to spin-1 final states with pairs formed from ω, K^*, ρ, and ϕ can be used to determine the helicity amplitudes of the decay. These channels have low $\mathcal{B}$ and high background. Full angular analyses of $B \to VV$ decays at Belle and Babar have been limited to high-statistics decays, e.g., $B \to \phi K^*$ [7]. Several additional VV channels were limited to integrating over the angle between the decay planes Φ, and only measuring the longitudinal polarization fraction (f_L).

A hierarchy of f_L has been observed with tree-dominated modes ($\rho\rho$) near 1, and penguin-dominated modes (ϕK^{*0}) near 0.5. Furthermore, a hierarchy based on the masses of the vector mesons has been observed, with larger masses having smaller f_L. These are tantalizing results, which require the measurements from other channels to understand these patterns. Notably, a full angular analysis of $K^*\rho$ decays could reveal whether there is an enhanced contribution proportional to electromagnetic penguins [8].

Furthermore, with Belle II's large dataset, it will be possible to calculate triple-product asymmetries in additional channels, which provides a measure of CP violation that does not require flavor tagging or a time-dependent analysis [9].

5 CP violation in $B \to 3h$

Recent results from LHCb have shown CP violating effects which are not associated with resonances, where QCD effects need to be understood. Notably, an unidentified structure in the $m^2_{K^+K^-}$ projection in $KK\pi$ decays at < 1.5 GeV$^2/c^4$ has been observed. This enhancement is only present in the B^+ mass projection and gives rise to a large local CP asymmetry [10].

Motivated by these large local asymettries, theoretical predictions have been calculated for $\pi^+\pi^-\pi^-$, $K^+K^-K^-$, $K^-\pi^+\pi^-$, and $K^+K^-\pi^-$, where the sign of the asymmetry agrees with experiment, but the magnitude can differ significantly. These channels will all be measured with high precision at LHCb.

The following 3-body decays, in which Belle II is expected to dominate, have the potential to reveal similar effects: $B^0 \to K^0_s K^+K^-$, $B^0 \to K^+K^-\pi^0$, $B^+ \to K^+\pi^0\pi^0$, $B^+ \to K^0_s\pi^+\pi^0$ [11]. However, theoretical predictions of large local asymmetries do not exist, and will likely not be performed unless it is motivated by an observation at Belle II.

6 Charmless B_s decays

Υ(5S) decays are well-suited for studying large multiplicity B_s decays due to the lower particle momenta, the almost 100% trigger efficiency, and the excellent π/K separation. Branching fractions may exhibit direct CP asymmetries, as have been observed in $B_d \to K\pi$. The Belle II experiment is especially well suited to study $B_s \to K^0\overline{K}^0$. With 23.6 fb^{-1}, Belle measures a yield of $5.2^{+5.5}_{-4.3}$ events, from which an upper limit of $\mathcal{B} < 6.6 \times 10^{-6}$ is obtained [12]. This is currently being updated with the full 121.4 fb^{-1} dataset, and will provide us with a charmless hadronic benchmark for B_s decays at Belle II.

Among additional channels of interest is the color-suppressed, pure electroweak penguin decay $B_s \to \phi\pi^0$. Currently, there is the following tension between varying theoretical predictions: calculations from L. Hofer *et al.* [13] claim that if $\mathcal{B}$ is at 10^{-6} level it is a possible signal for NP; while results from H.-Y. Cheng *et al.* [14] state that a high $\mathcal{B}$ is due to an enhancement in the color-suppressed amplitude.

7 NLO calculation of direct CP asymmetries

Contributed by T. Huber:
Flavour symmetries of the light quarks on the one hand and QCD factorisation [16] on the other hand constitute the two main approaches to two-body charmless non-leptonic B-decays. In the latter framework the amplitudes have been completed to NLO more than a decade ago [17]. Since the direct CP asymmetries only start at this order, one has to know the amplitudes to NNLO in order to reduce scale uncertainties etc. Hence NNLO is NLO for the direct CP asymmetries.

Most of the NNLO contributions to the decay amplitudes have been completed in recent years. One of the most prominent ingredients that is still missing at leading power is the two-loop NNLO correction to the vertex kernel of the penguin amplitudes α_4^u and α_4^c. Recent efforts in this direction [18, 19] have led to a *preliminary* prediction for the penguin amplitudes α_4^u and α_4^c, where up to now only the current-current operators $Q_{1,2}$ from the effective weak Hamiltonian have been considered in the NNLO vertex correction. The result is shown in Figure 1.

Despite the fact that the new NNLO contributions are quite sizable – e.g., the NNLO imaginary part in $\alpha_4^u(\pi K)$ is half the size of the NLO one – this does not indicate a breakdown of the perturbative series. This can be seen from the fact that amplitude ratios (P/T, C/T, etc.), branching fractions and direct CP asymmetries receive only moderate corrections at NNLO compared to NLO [19]. The overall agreement with experimental data is remarkable, given the fact that there are several dozens of observables. However, the theory predictions for many observables still suffer from rather large uncertainties which stem from poorly known power-suppressed terms. The updated phenomenology of two-body charmless final states based on NNLO amplitudes is expected before the start of Belle II.

8 Summary of Golden Modes

- $B \to K\pi$ system:
  Emphasis on $K^0\pi^0$. Test of sum rule. Preliminary Belle II feasibility study for $K^0\pi^0$ (including b-tagging) is targeted for the Feb. 2015 BPAC.

- $B \to K^*\pi$ and $B \to K\rho$ systems:
  Improved precision in all A_{CP} measurements, especially $A_{CP}^{K^{*+}\pi^0}$ and $A_{CP}^{K^{*+}\pi^-}$. Analogous test of sum rules as in $K\pi$ system.

Channel	Observables	Belle + BaBar (2014)	Belle II	
			5 ab^{-1}	50 ab^{-1}
$B^0 \to K^0\pi^0$	$A_{CP}^{K^0\pi^0}$	$-0.05 \pm 0.14 \pm 0.05$	0.07	0.04

- $B \to K^*\rho$ system:
  Measurements of $\mathcal{B}$, f_L and performance of full angular analysis. Polarization analysis may reveal an enhanced contribution proportional to electromagnetic penguins.

- 3-body decays $B^0 \to K_s^0 K^+K^-$, $B^0 \to K^+K^-\pi^0$, $B^+ \to K^+\pi^0\pi^0$, $B^+ \to K_s^0\pi^+\pi^0$:
  Observables of interest are the $\mathcal{B}$ and A_{CP}. Large local CP asymmetries have been observed in similar 3-body decays by LHCb. There are no existing theoretical predictions for large local CP asymmetries in these channels.

- $B_s \to K^0\overline{K}^0$:
  Belle set an upper limit with 23.6 fb^{-1} with $5.2^{+5.5}_{-4.3}$ measured events. The observable of immediate interest is the $\mathcal{B}$, which, if found to be larger than theoretical predictions, could point to NP. An update with full 121.4 fb^{-1} dataset is underway.

Channel	Observables	Belle 23.6 fb^{-1}	Theory
$B_s \to K^0\overline{K}^0$	$\mathcal{B}$	$< 6.6 \times 10^{-6}$	$(1.7 - 2.6) \times 10^{-6}$

- $B_s \to \phi\pi^0$:
  Tension between different theoretical models. No existing measurement. Analysis using Belle's full 121.4 fb^{-1} dataset is underway.

Channel	Observables	Belle 121.4 fb^{-1}	Theory
$B_s \to \phi\pi^0$	$\mathcal{B}$	In Progress	$(0.09 - 1.94) \times 10^{-6}$

List to be enlarged.

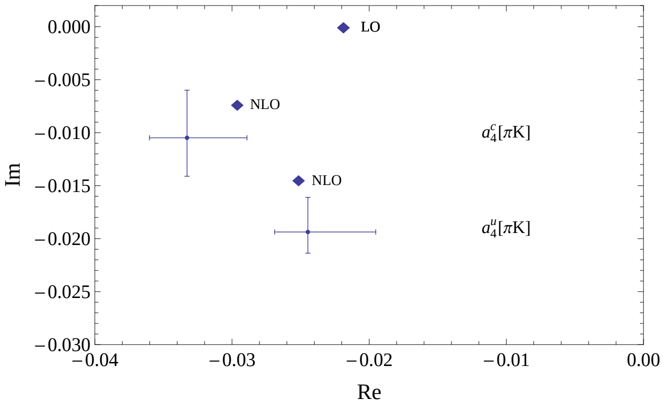

Figure 1: The penguin amplitudes $\alpha_4^{u,c}(\pi K)$ to NNLO (results preliminary).

9 Projections of Belle results to Belle II

Systematic uncertainties scale primarily with integrated luminosity, with the exception of A_{CP} measurements of channels with K_s^0, where the asymmetry of $K^0/\ \overline{K}^0$ interactions in material introduces a factor of $\sigma_{ired} \approx 0.2\%$ [15]. In extrapolating to higher luminosity, one would ideally separate the reducible and irreducible systematic errors, the latter remaining unchanged throughout data accumulation. However, few modes are systematically limited. As a first approximation we treat all systematic errors as reducible and apply the following scaling to all statistical and systematic errors, thereby extrapolating Belle's measurements to 5 and 50 ab^{-1}: $\sigma_{Belle\ II} = \sqrt{(\sigma_{stat}^2 + \sigma_{syst}^2)\frac{\mathcal{L}_{Belle}}{\mathcal{L}_{BelleII}} + \sigma_{ired}^2}$.

This scaling is applied to all Belle $\mathcal{B}$, f_L, and A_{CP} measurements listed in the 2013 HFAG table [4], and the resutls are appended to the "Charmless hadronic B decays - Experiment" talk. This will be repeated once the 2014 HFAG tables become available, where special care will be given to the golden modes.

References

[1] Belle Collaboration, Y.-T. Duh *et al.*, Phys. Rev. D **87**, 031103 (2013).

[2] S. Baek *et al.*, Phys. Lett. B **678**, 97 (2009); M. Gronau, Phys. Lett. B **627**, 82 (2005); D. Atwood, A. Soni, Phys. Rev. D **58**, 036005 (1998).

[3] Belle Collaboration, M. Fujikawa *et al.*, Phys. Rev. D **81**, 011101 (2010).

[4] E. Barberio *et al.*, arXiv:0808.1297 and online web updates http://www.slac.stanford.edu/xorg/hfag/rare/index.html.

[5] T. Aushev *et al.*, arXiv:1002.5012.

[6] BaBar Collaboration, J.P. Lees *et al.*, Phys. Rev. D **84**, 092007 (2011); BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. D **78**, 012004 (2008); Belle Collaboration, A. Garmash *et al.*, Phys. Rev. Lett. **96**, 251803 (2006).

[7] Belle Collaboration, M. Prim *et al.*, Phys. Rev. D **88**, 072004 (2013); BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **99**, 201802 (2007).

[8] M. Beneke, J. Rohrer, D. Yang, Phys. Rev. Lett. **96** 141801 (2006).

[9] M. Gronau, J. Rosner, Phys. Rev. D **84**, 096013 (2011); A. Datta, M. Duraisamy, D. London, Phys. Lett. B **701**, 357 (2011).

[10] LHCb Collaboration, R. Aaij *et al.*, Phys. Rev. D **90**, 112004 (2014).

[11] Private communication with H.-Y. Cheng.

[12] C.C. Peng *et al.*, Phys. Rev. D **82** 072007(R) (2010).

[13] L. Hofer, D. Scherer, L. Vernazza **JHEP** 1102 080, (2011).

[14] H.-Y. Cheng, C.-W. Chiang, A.-L. Kuo, arXiv:1409.5026.

[15] B.R. Ko, E. Won, B. Golob, P. Pakhlov, Phys. Rev. D **84**, 111501 (2011).

[16] M. Beneke, G. Buchalla, M. Neubert and C.T. Sachrajda, Phys. Rev. Lett. **83**, 1914 (1999).

[17] M. Beneke and M. Neubert, Nucl. Phys. B **675** 333 (2003).

[18] G. Bell and T. Huber, arXiv:1410.2804 [hep-ph].

[19] G. Bell, M. Beneke, T. Huber, and X.-Q. Li, *in preparation.*