MEASUREMENTS OF THE $B^0\overline{B}^0$ CP ASYMMETRY

VERA LÜTH
Superconducting Super Collider Laboratory
2550 Beckleymeade Avenue
Dallas, Texas 75237-3946, United States

A figure of merit for a measurement of CP violation is the error on the intrinsic asymmetry A_{CP}. The observed asymmetry A_{obs} will always be smaller than A_{CP} due to a number of effects that dilute the measurement. If we define

$$A_{obs} = D \cdot A_{CP},$$

where D represents the product of all dilution factors, then the error on A_{CP} is given by[1]

$$\delta A_{CP} = \frac{1}{D}\sqrt{\frac{1-A_{obs}^2}{N_{obs}}} = \frac{1}{D\sqrt{N_{obs}}} = \frac{1}{D\sqrt{\varepsilon\, Br\, N_{prod}}}.$$

In other words, N_{prod}, the number of produced B^0 or $\overline{B}^0$ needed to obtain a given error on δA_{CP} is given by

$$N_{prod} = \frac{1}{\delta^2 A_{CP}} \cdot \frac{1}{D^2 \cdot \varepsilon\, Br}.$$

Thus, to determine the figure of merit for a particular decay mode one must determine the number of reconstructed events N_{obs} and calculate the corresponding dilution factor D. N_{obs} depends on the luminosity and production cross section, on the branching ratio of the B^0 or $\overline{B}^0$ into the specific final state under study, Br, and on ε, the reconstruction efficiency for both the combination of the signal CP state and any tagging signal. The production rate N_{prod}, the dilution factor D, and the efficiency ε, differ substantially in magnitude as a function of energy and detector layout. The detection efficiency and dilution factor can both be written as a product of several factors that can be estimated for a particular experiment. These factors depend critically on the decay mode under study, the tagging method, the detector configuration, and more generally on the production process, backgrounds, and detector performance. Furthermore, our present knowledge of these quantities varies largely, as well our ability to ultimately measure the dilution factor which relates the experimentally observed asymmetry to the true CP asymmetry.

B^0 AND $\overline{B}^0$ PRODUCTION RATE.

The number of produced B^0 / $\overline{B}^0$ per year is given by the following relation,

$$N_{prod} = \int L dt \cdot \sigma_{b\bar{b}} \cdot 2 f_0$$

where

$\int L dt$ represents the luminosity integrated over $10^7 s$,

$\sigma_{b\bar{b}}$ is the cross section for $b\bar{b}$ production, and

f_0 is the fraction of neutral $B^0_{d,s}$ mesons produced per b or $\bar{b}$.

Predictions for hadro-production cross-sections exist, though the inclusive $b\bar{b}$ production measured at the Tevatron, over a limited acceptance, is substantially larger than theoretically predicted. The fraction of B_d^0 mesons is assumed to be of the order of 0.38 in high energy hadro-production. The production cross sections for various experiments are listed in Table I.

Table I: Cross sections for $b\bar{b}$ production in pp interactions.

	c.m. Energy (GeV)	Cross section cm^2
HERA proton beam	40	$2 \cdot 10^{-32}$
Tevatron F.T.	63	$4 \cdot 10^{-32}$
LHC FT	123	$1 \cdot 10^{-30}$
SSC FT	195	$2 \cdot 10^{-30}$
Tevatron Collider	1800	$5 \cdot 10^{-29}$
LHC Collider	14,000	$3 \cdot 10^{-28}$
SSC Collider	40,000	$1 \cdot 10^{-27}$

B^0 BRANCHING RATIOS

Only a few of the branching ratios to CP eigenenstates have been measured. Most of them are derived following the assumption of BSW. The values to be used in this workshop are listed in Table II.

Table II: B^0 Branching Ratios

Final State	Branching Ratio
ψK_s	$4 \cdot 10^{-4}$
ψK^{*0}	$1.5 \cdot 10^{-4}$
$\psi' K_s$	$4 \cdot 10^{-4}$
D^+D^-	$6 \cdot 10^{-4}$
$\pi^+\pi^-$	$2 \cdot 10^{-5}$
$\rho^{\pm}\pi^{\mp}$	$6 \cdot 10^{-5}$
$a^{\pm}\pi^{\mp}$	$6 \cdot 10^{-5}$

EFFICIENCIES.

The total detection efficiency, excluding the generally poorly known branching ratio for the decay to the CP eigenstate under study, can be conveniently factored as

$$\varepsilon = \varepsilon_{dec} \cdot \varepsilon_{trig} \cdot \varepsilon_{CP} \cdot \varepsilon_{tag}$$

with the following definitions:

ε_{dec} is the branching ratio for the specific final state that is observable for the decay to a CP eigenstate.

ε_{trig} is the efficiency to trigger on the event.

ε_{CP} is the efficiency to detect and fully reconstruct a specific CP eigenstate, and

ε_{tag} is the efficiency for obtaining a B flavor tag in the $b\bar{b}$ event with the detected specific final state.

Obviously, ε depends on the detailed layout and performance of the assumed detectors, including the effects of background. The factorization of ε is useful to obtain insight into the performance of an experiment, though the specific values for the factored efficiencies will be correlated (e.g., other factors depend on the trigger).

DILUTION FACTORS

The dilution of the measured asymmetry can be attributed to three principal sources,

$$D = d_{mix} \cdot d_{tag} \cdot d_{bg}$$

with the following definitions:

d_{mix} accounts for the mixing of the neutral B meson prior to its decay;

$d_{tag} = 1 - 2w$ results from the fraction w of decays that are incorrectly tagged; and

$d_{bg} = \sqrt{S/S+B}$ results from the presence of background in the observed sample of $N_{obs} = S + B$ decays.

Both d_{tag} and d_{bg} depend strongly on the CP decay mode under study and the tagging method, thus they are very closely linked to the respective detection efficiencies.

Dilution Due To Evolution With Time. At a hadron machine, the b and $\bar{b}$ evolve incoherently and hadronize nearly independently. The rate for a single neutral B meson decaying to a CP eigenstate is

$$R(B^0 \rightarrow f_{CP}) \propto e^{-\Gamma t}\{1 + \sin 2\phi_{CP} \sin(x\Gamma t)\}$$

or

$$R(\overline{B}^0 \rightarrow f_{CP}) \propto e^{-\Gamma t}\{1 - \sin 2\phi_{CP} \sin(x\Gamma t)\}.$$

Due to mixing of the neutral B mesons, the observed asymmetry is

$$A_{obs}(t) = D' \sin x\Gamma t \sin 2\,\phi_{cp}$$

where $D' = d_{tag} \cdot d_{bg}$. The asymmetry $A_{obs}(t)$ is zero for $t = 0$ and rises to a maximum at $t = \pi / 2x\Gamma$, resulting in an overall dilution of the measurement. Still, the asymmetry integrated over all decay time does not vanish and in principle no measurement of the decay time is required. In this case, the dilution due to the mixing is $d_{mix} = x / 1 + x^2)$, resulting in a value $d_{mix} = 0.47\ (0.14)$ for $x = 0.7(7.0)$. If on the other hand, the decay times are measured, the time dependence of the asymmetry can be fit, resulting in a dilution of

$$d_{mix}^2 = \frac{1 + 4x^2 + 2x \sin 2x\,\Gamma t_o - \cos 2x\Gamma t_o}{2(1 + 4x^2)}.$$

Here t_0 is the lifetime cut, applied to reject background. For t_0=0, one obtains $d_{mix} = \sqrt{2x^2 / 1 + 4x^2}$ resulting in $d_{mix} = 0.58$ (0.50) for $x = 0.7$ (7.0).

Of course, a cut in the decay times ($t_0 > 0$) will also affect the detection efficiency and thereby the statistical error on the asymmetry measurement. Furthermore, the resolution of the decay time measurement will impact on the fit and thereby d_{mix}. For large x, the time dependent fit will result in $d_{mix} \to 0.5$ while the time integrated measurement will result in a very small dilution factor. More importantly, the observation of the time dependence of the asymmetry will provide the very important verification of the origin of the asymmetry and will significantly enhance the credibility of the measurement.

Dilution Due To Tagging Errors. The flavor of the B^0 or $\overline{B}^0$ can be tagged by the decay of the second B particle, either through its semi-leptonic decay or through the flavor of a decay charm particle, most readily by the charge of the secondary kaon. A fraction of B decays will be incorrectly tagged either because the tagging B mixes into the wrong flavor or because the tagging lepton does not originate from the decay of the B, but instead from the cascade decay of a charmed meson (resulting in the wrong sign). In addition, lepton and kaon signals may originate either from particles not associated with the B decay or cascade decay, or can be due to accidental or other background sources. Prompt muon signals can be faked by backgrounds such as π and K decay or hadronic punch through (resulting in a wrong sign tag 50% of the time). In general, as one improves the purity of the tagging sample by stricter selection criteria the corresponding efficiencies decrease.

As an example, we give results from a study performed by Natalie Roe of the D0 group.[2] It is assumed that b quarks hadronize as B_d, B_u, B_s, and Λ_b in the ratio $f_u : f_d : f_s : f_\Lambda = 0.38 : 0.38 : 0.14 : 0.10$. If we denote the fraction of tags due to semi-leptonic decay from a mixed B decay, due to cascade decays of charm, from pion or kaon decay and hadron punch through as F_B, F_C, F_D, and F_P, respectively, then the wrong-sign tagging fraction is given by

$$w = \alpha \cdot F_B + (1-\alpha) \cdot F_C + \frac{(F_D + F_P)}{2}.$$

The relative signal and background contributions to the lepton tag vary strongly as a function of the cut on transverse momentum. For instance, Monte Carlo studies for the upgraded D0 detector indicate that the optimum ratio of the signal and background contribution is obtained for a cut at $p_t = 2\,GeV/c$, resulting in $F_B = 0.80, F_C = 0.17$, $F_D = 0.03$ and $F_P = 0.0$. The fraction of tagging B's which mixes to give a wrong-sign tag is given by $\alpha = f_s / 2 + x_d^2 / 2(1 + x_d^2) \cdot f_d = 0.14$. It is assumed that the B_s mesons are fully mixed ($x_s \geq 5$). The term $(1-\alpha)$ F_C takes into account that cascade leptons have the correct sign if the B meson mixes before it decays. The D0 Monte Carlo simulation results in $w = 0.27$ and $d_{tag} = 0.44$ with a cut at $p_t = 2\,GeV/c$ on the muon transverse momentum. It is assumed that the backgrounds due to punch through and pion and kaon decay are charged symmetric and that the rates of B^0 and $\overline{B}^0$ production are equal over the whole detector. Both of these assumptions need to be experimentally verified, especially in the case of pp as opposed to $\bar{p}p$ collisions..

Dilution Due To Background. The presence of background in the sample of reconstructed CP decays dilutes the measured asymmetry by a factor $S/S+B$. However, the number of observed decays, N_{obs}, increases as $(S+B)/S$ so that the effect of the background is $d_{bg} = \sqrt{S/S+B}$, even if the background is charge symmetric.

The level of background remains an open experimental question for most decay modes. The CDF group reported a ratio of $S/S+B \approx 0.5$ for the observed sample of $J/\psi K^\pm$ decays. A constraint on the K_S mass plus the requirement of a lepton tag and additional cuts on the decay vertex are sure to improve this ratio substantially, though at a significant loss in efficiency. On the other hand, lowering the p_t requirements for the multi-lepton trigger and less stringent cuts on the track reconstruction may increase the level of background. This is an area where more study and actual experimental data are necessary to improve our understanding of the potential for B physics at hadron accelerators.

SUMMARY TABLE

To provide a basis for a comparison of different experiments, Table III gives a list of the above parameters that determine a figure of merit for the measurement of CP violation for a given decay mode in a given detector model. The data in the table represent the expectations for an e^+e^- B Factory like those presently under study at Cornell, KEK, and SLAC. It is hoped that as a result of this workshop similar data will become available for all the proposed experiments under study, for a variety of decay modes related to different angles in the unitarity triangle.

---

[1] See also: D. Hitlin, F. Porter, N. Roe, J. Dorfan, V. Lüth, A. Snyder, Babar Note #81, SLAC (1992).

[2] N. Roe, DO Note #1122 (1991).

Table III: Measurement of CP Asymmetry: Angle b

Experiment	PEP B FACTORY
Energy E_{cm} (TeV)	0.010
Luminosity $L (10^{33} cm^{-2} s^{-1})$	3.0
Cross section $\sigma_{b\bar{b}} (\mu b)$	0.0012
Cross section $\sigma_{tot} (mb)$	0.005
B^0 fraction, f_0	0.5
$N_{prod} / 10^7 s$	$3.6 \cdot 10^7$
$Br(J/\psi K_s)$	$4 \cdot 10^{-4}$
CP final state	$l^+ l^- \pi^+ \pi^-$
B flavor tag	$l^\pm, K^\pm$
ε_{det}	0.14
ε_{trig}	0.98
ε_{CP}	0.57
ε_{tag}	0.45
d_{mix}	$0.47 \rightarrow 0.57$
d_{tag}	0.84
d_{bg}	1.00
Total efficiency ε	$3.6 \cdot 10^{-2}$
Total dilution D	$0.40 \rightarrow 0.48$
Figure of Merit, $1/D^2\varepsilon$	$5.6 \rightarrow 3.8 \cdot 10^{-3}$
N_{prod} for $\delta A_{CP} = 0.1$	$4.4 \leftarrow 3.0 \cdot 10^7$
Time for measurement ($10^7 s$)	$1.24 \leftarrow 0.84$