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B Physics Prospects at Hadron Colliders

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Abstract: This talk is a brief summary of the B physics prospects anticipated over the next decade for experiments at the Fermilab Tevatron and the CERN Large Hadron Collider. Of particular interest is the complementarity of these experiments with those at the $\Upsilon(4S)$ B-factories

1. Introduction

A rich program of B physics is expected over the next decade at the Fermilab and CERN hadron colliders. This program will exploit the very large B-production cross sections in $\overline{p}p$ and pp collisions; it will also provide a unique window on the B_s meson sector, thus providing an essential complement to the $\Upsilon(4S)$ B-factories. The Tevatron experiments, CDF and D0, are currently in commission, and will accumulate roughly 15 fb^{-1} before LHC turnon. Later in the decade, two dedicated B-hadron experiments, BTeV at the Tevatron and LHCb at LHC, are planned with superior triggering, data acquisition, and particle identification. In addition, the general purpose LHC experiments, ATLAS and CMS, will focus on B physics measurements during the lower luminosity LHC startup. The physics goals, as for the B factories, are to overconstrain the standard model CKM matrix by precision measurements of the CP-violation angles, 2β, $2\beta_s$, γ; the B_s mixing amplitudes, M_{12} and Γ_{12}, and rare decay rates and asymmetries. Extensive theoretical and experimental studies on all of these topics can be found in the CERN LHC [1] and Fermilab Tevatron [2] workshop “Yellow Books”, which are the primary sources for this talk.

2. Experimental Issues

The primary experimental issue at hadron colliders is efficent triggering. Whereas the $B\overline{B}$ production rate is 10 Hz at the B-factories at $\mathcal{L} = 10^{34}$, it is approximately 20 kHz at

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the Tevatron and 100 kHz at LHC at $\mathcal{L} = 2\ 10^{32}$; this is accompanied by QCD backgrounds that are $\sim 1000\times$ larger. Thus, even with kinematic restrictions $|y| < 1, p_T(B) > 6$ GeV/c, the B rate would be 2.5 kHz at CDF, substantially more than the peak rate to tape of 75 Hz. One approach common to all hadron experiments is the use of efficient single and dilepton triggers, for example for $J/\psi \to \ell^+\ell^-$ and rare decay modes; this gives a big statistical advantage over the B factories for these channels because of the low BR. A second approach adopted by CDF, BTeV, and LHCb is the use of high precision vertex triggers. This allows typically $\times 100$ enrichment in the $B\overline{B}$ fraction at the trigger level, and is efficient for hadronic decay modes such as $B^0 \to \pi^+\pi^-$ or $B_s^0 \to D_s^-\pi^+$. For example, the CDF trigger, which has been demonstrated in recent commissioning, would yield a total rate of 10^8 $B\overline{B}$ events per fb^{-1} with roughly $1:1$ signal:background, comparable to the $B\overline{B}$ production rate per year at $\mathcal{L} = 10^{34}$ at the B factories. We note that while the general purpose detectors have limited data output bandwidth of typically $\leq 100\ Hz$ for all physics triggers, the BTeV and LHCb experiments are aiming for 1000 and 200 Hz to tape, respectively, dedicated solely to heavy flavor physics.

Particle identification is critical for channels such as $B^0 \to \pi^+\pi^-, K^+\pi^-$ and $B_s^0 \to D_s^-K^+$. CDF has time of flight and relativistic rise dE/dx which provides low p_T kaon separation and statistical separation for $B^0 \to \pi^+\pi^-/K^+\pi^-$. BTeV and LHCb will have excellent $\pi - K$ separation over the full momentum range needed for the forward geometry, essential for channels like $B_s^0 \to D_s^-K^+$. These detectors also feature excellent electromagnetic calorimetry for identification of channels such as $B_s^0 \to J/\psi\eta$ and $B^0 \to \pi^+\pi^-\pi^0$.

3. Measurement of CP asymmetries: $\sin 2\beta$ and γ

The major theme in B physics is testing the consistency of the sides and angles of the unitarity triangle(s) with *precision* measurements. A secondary theme is direct search for non-standard model physics, such as large CP asymmetries in B_s^0 mixing or anomalous rare decay rates. The crucial precision measurements are: the angles β and γ, from CP asymmetries, and the sides $\frac{|V_{ub}|}{|V_{cb}|}$ and $\frac{|V_{td}|}{|V_{ts}|}$ from $b \to u$ transitions and B^0 and B_s^0 mixing. Of these, $\sin 2\beta$ and $\frac{|V_{td}|}{|V_{ts}|}$ can be measured with high experimental precision and minimal theoretical uncertainty. As is well known, the other two parameters, $\frac{|V_{ub}|}{|V_{cb}|}$ and γ are difficult both experimentally and theoretically.

Precision measurement of $\sin 2\beta$, using the time-dependent CP asymmetry in $B^0 \to J/\psi K_S^0$, requires high statistics, good flavor tagging efficiency, and precise calibration of the flavor tagging dilution D ($D = 1 - 2\mathcal{W}$, where $\mathcal{W}$= mistag rate). The hadron collider experiments can compete favorably with the B factories in signal yield, but have intrinsically poorer tagging efficiency ("ϵD^2"). Table 1 summarizes the $\sin 2\beta$ reach projected for the hadron collider experiments [1, 2], together with current BaBaR results.

Thus, it should be possible to measure a world-average $\sin 2\beta$ to ± 0.01 accuracy. At this level of precision, it will be important to resolve the four-fold ambiguity on β (for example, via interference asymmetries in $J/\psi K^{*0}$) and to verify that the direct asymmetry, proportional to $\cos \Delta M t$, is consistent with the standard model expectation. Besides test-

Exp.	$\sigma(\sin 2\beta)$	$N_{\psi K_s}$	ϵD^2	Luminosity
CDF	0.045	28K	0.091	2 fb^{-1}
D0	.040	34K	0.10	2 fb^{-1}
BTeV	0.025	80K	0.10	1 Yr.$\times$ 2 10^{32}
LHCb	0.021	88K	0.064	1 Yr.$\times$ 2 10^{32}
CMS	0.015	433K	0.054	1 Yr.$\times$ 10^{33}
ATLAS	0.017	165K	0.033	1 Yr.$\times$ 10^{33}
BaBaR	0.149	(1030)	0.261	32 10^6 $B\overline{B}$

Table 1: Projected $\sin 2\beta$ reach. Only a subset of tags are used in ATLAS and LHCb studies.

ing the consistency of the unitarity triangle, the phase 2β is a critical input for measurement of γ in $B^0 \to \pi^+\pi^-, \pi^+\pi^-\pi^0$.

Experimental determination of the angle γ (=argV_{ub} in the Wolfenstein representation) is more difficult, and theoretical uncertainties are such that it will be necessary to demonstrate consistent results in a variety of channels. Three prominent channels have been explored, for which hadron colliders have unique capabilities.

(1) $\underline{\gamma \text{ from } B_s^0 \to D_s^\pm K^\mp}$: this channel is unique to hadron colliders. It almost certainly will require the quality of K/π separation planned for BTeV and LHCb. It has the advantage that the decays are expected to be predominantly tree-level and impervious to new physics from penguin diagrams. It relies on the fact that B_s^0 and $\overline{B_s^0}$ can each decay to both $D_s^\pm K^\mp$ final states, giving four time-dependent decay distributions. Because the final states are flavor specific, the time dependence includes ordinary mixing as well as CP asymmetry. For example, using current estimates of the Wolfenstein parameters, the expected asymmetry is approximately:

$$\mathcal{A} = \frac{(B_s^0 \to f) - (\overline{B_s^0} \to f)}{(B_s^0 \to f) + (\overline{B_s^0} \to f)} = R\cos x_s t \mp \sqrt{1-R^2}\cos\left(2\beta_s + \gamma \pm \delta\right)\sin x_s t; \qquad (3.1)$$

here, f refers to the two final states $D_s^\pm K^\mp$, which correspond to the $\pm$ terms in the $\sin x_s t$ term; x_s is the B_s mixing frequency; $2\beta_s, \sim 0$ in the standard model, is the CP violating phase in B_s mixing; δ is the unknown strong phase difference; R is related to the ratio of Cabibbo suppressed and allowed decays and is determined from the $\cos x_s t$ mixing term. Numerically, $R \sim 0.74$, $\sqrt{1-R^2} \sim 0.67$, is expected, assuming central values for the Wolfenstein parameters. If the width difference $\Delta\Gamma_s$ is large, then there is an additional asymmetry for the total (untagged) $B_s^0 + \overline{B_s^0}$ decay rates that may allow resolution of discrete ambiguities. In toy Monte Carlo studies, depending on the input values of γ, δ, x_s, $\Delta\Gamma_s$, and R, both BTeV and LHCb estimate similar uncertainties of $6 - 15^\circ$ on γ.

An analogous mode, $B^0 \to D^{(*)\pm}\pi^\mp$ has also been modeled. Here the expected statistics are much higher, but the Cabibbo suppression is such that $R \sim 1$, and $\sqrt{1-R^2}$ cannot be determined from the mixing term, but must be input using Wolfenstein parameter estimates. The net CP asymmetry, before flavor tagging dilution is included, is tiny,

$\sqrt{1-R^2} \sim 0.016$. Nevertheless, LHCb estimates uncertainties on the order of 15-30° per year on the angle $2\beta + \gamma$.

(2) $\underline{\gamma \text{ from } B^0 \to \pi^+\pi^-\pi^0}$: This mode measures the combination $2(\beta+\gamma) = 2\alpha$ via both $\cos 2\alpha$ and $\sin 2\alpha$. The decays into $\rho\pi$ modes are used to determine five complex decay amplitudes together with the CP asymmetry angle 2α. BaBar has estimated an uncertainty of order $\sigma(\alpha) \sim 5°$ for a 2000 event sample [3]. From toy Monte Carlo scans, BTeV and LHCb expect errors of 10° and $2.5-4.9°$ per year, respectively. The advantage of the hadron collider experiments over the B factories is high statistics, assuming that combinatoric backgrounds can be controlled.

(3) $\underline{\gamma \text{ from } B^0 \to \pi^+\pi^- \text{ and } B_s^0 \to K^+K^-}$: This method, originally proposed by Fleischer [4], uses the time dependent CP asymmetries in these two modes, together with independently measured values of 2β, $2\beta_s$, and x_s to determine γ and one complex strong amplitude. Both tree and penguin amplitudes contribute to each of the two decays

$$B^0 \to \pi^+\pi^- \sim T + \lambda P,$$
$$B_s^0 \to K^+K^- \sim \lambda T + P.$$

The crucial assumption is that the *ratio* $\frac{P}{T}$ is the same for both (U-spin symmetry). The experimental measurements are the time-dependent asymmetries for the two decays, both "direct" ($\cos xt$) and "mixed" ($\sin xt$). The very different time dependences ($x_d << x_s$) allow separation of the two asymmetries. At CDF the strategy is to first determine the fractions of the different two-body decay channels- $\pi^+\pi^-, K^+K^-, K^\pm\pi^\mp$- using relativistic rise dE/dx on the untagged sample, and then use this constraint to normalize the measured asymmetries in the flavor tagged sample. The trigger is provided by the silicon vertex detector. The main issue experimentally, besides the trigger performance, is combinatoric backgrounds from ordinary QCD processes with mismeasured vertices.

CDF has estimated the precision on γ assuming nominal branching fractions and QCD combinatoric backgrounds for the different modes, and nominal inputs for the external variables β and x_s and the internal variables γ and $\frac{P}{T}$. The sensitivity to nominal parameter values is obtained from toy Monte Carlo experiments, and the U-spin symmetry is allowed to be broken within a physically reasonable (20%) range. This results in an estimate of $\sigma_\gamma \simeq \pm 7° \pm 3°$(U-spin) for 2 fb^{-1}. The LHC projections are quite similar, both in reach and in the effects of U-spin breaking. The combined error for LHCb, ATLAS, and CMS is estimated at $\sim 4.8°$/year for x_s=30. It should be noted that the U-spin assumptions can be constrained from measurements of the branching ratios for these modes. Since this determination involves penguin amplitudes, unlike $B_s \to D_s^\pm K^\mp$, it is sensitive to possible new physics.

4. B_s Mixing

Since the B_s system is unique to hadron colliders, the physics goals are to measure in detail all features of the B_s mixing amplitude $M_{12} - i\frac{\Gamma_{12}}{2}$,including $x_s = \frac{\Delta M_s}{\Gamma_s}$, $\Delta\Gamma_s$, and $\sin 2\beta_s$. New physics is not expected in the Γ_{12} amplitude, but could show up in M_{12}, for example anomalously large x_s or $2\beta_s$. The first critical measurement is the mixing frequence x_s;

the ratio $\frac{\Delta M_d}{\Delta M_s}$ will constrain one side of the unitarity triangle ($\frac{|V_{td|}}{|V_{ts|}}$) to within about 6%, limited by theoretical uncertainties.

Indirect fits to the CKM matrix predict $x_s \sim 26$, with 15.0< ΔM_s <41.3 ps^{-1}[5]. To measure such a rapid oscillation frequency, excellent decay time resolution is essential. For example, using semileptonic decays, $B_s \to D_s \ell \nu$, introduces large smearing of the time resolution due to the missing neutrino momentum, with the result that only very short decay-time events are useful. The method of choice is to use fully reconstructed decays such as $B^0_s \to D^-_s \pi^+$. To trigger on these events efficiently, CDF, BTeV, and LHCb will rely on secondary vertex triggers. D0, CMS, and ATLAS have considered lepton triggers used as flavor tags, followed by a search for the second B decay to the hadronic final state. The experimental technique involves a scan of the amplitude $\mathcal{A}$ for $B^0_s \to \overline{B^0_s} = 1 - \mathcal{A} \cos x_s t/\tau$ as a function of the mixing frequency x_s. With expected time resolution of 45 fs, CDF projects an ultimate (2 fb^{-1}) reach of $x_s \sim 60$ for a 5-σ observation with samples of 30,000-90,000 events; this takes into account uncertainties on signal-to-background, flavor tagging efficiency, and decay branching ratios. It is worth noting that the statistical error on x_s itself is related to the statistical error on the observed mixing amplitude; for a 5-σ significance on the amplitude, the error on x_s is $\sigma(x_s)$=$\frac{1}{5\sqrt{2}}$, and $\frac{\sigma(x_s)}{x_s}$ <1% for largex_s. That is, once a significant oscillation is observed, it is measured over many cycles and the frequency uncertainty is very small. BTeV and LHCb project similar sensitivity to x_s, depending on integrated luminosity, so we expect that if x_s is in the standard model range, it will be measured easily.

In the standard model the complex amplitudes M_{12} and Γ_{12} are expected to be proportional in magnitude and approximately in phase. The lifetime difference in the B_s sector is expected to be much larger than for B_0 because of the much larger mixing frequency- $\Delta M_s >> \Delta M_d$; eg. $\frac{\Delta \Gamma_s}{\Delta M_s} \sim$ 0.003-0.008, and $\frac{\Delta \Gamma_s}{\Gamma_s}$ ~0.15. An anomalous CP violating phase in $M_{12}(B_s)$ would show up as a CP asymmetry $\sin 2\beta_s$ in the self-conjugate channels $B_s \to J/\psi\phi$ and $B_s \to J/\psi\eta^{(')}$. It would also show up as a reduction in $\Delta\Gamma_s$ ($\Delta\Gamma_s \propto Re(M^*_{12}\Gamma_{12}) \propto \cos 2\beta_s$). $\Delta\Gamma_s$ can be obtained by comparing a predominantly CP even decay mode ($J/\psi\phi$), or a pure CP even mode ($J/\psi\eta^{(')}$), with a CP-mixed decay mode ($D^-_s\pi^+$). It can also be extracted in principle, together with $\sin 2\beta_s$ and the CP even/odd fractions, from a joint fit to the $B_s \to J/\psi\phi$ decay angular distributions. Table 2 summarizes the sensitivity expected for these parameters for the collider experiments.

`Exp.`	5σ x_s	$\sigma_t(fs)$	ϵD^2	$\sigma(\frac{\Delta\Gamma}{\Gamma})$	$\sigma(\sin 2\beta_s)$	N($\psi\phi/\eta$)
`CDF`	59	45	0.09	0.024	0.15	6000(2 fb^{-1})
`BTeV`	75	43	0.10	0.020	0.033	9200(1 Yr.× 2 10^{32})
`LHCb`	75	43	0.09	0.014	0.030	370K(5 Yr.× 2 10^{32})
`CMS`	42	65	0.61	0.012	0.030	300K(3 Yr.× 10^{33})
`ATLAS`	46	50/93	0.61	0.018	0.050	300K(3 Yr.× 10^{33})

Table 2: Projected reach for x_s, $\sin 2\beta_s$, and $\frac{\Delta\Gamma_s}{\Gamma_s}$ for the hadron collider experiments. The CMS, ATLAS, and LHCb projections for $\sin 2\beta_s$ and $\frac{\Delta\Gamma_s}{\Gamma_s}$ are based on a multiparameter fit to $J/\psi\phi$ alone; BTev is based on the $J/\psi\eta^{(')}$ and $D_s\pi$ channels; CDF is based on the $J/\psi\phi$ and $D_s\pi$ channels.

5. Rare Decays

At hadron colliders it is generally conceded that inclusive rare decays, eg. $b \to s\gamma, s\mu^+\mu^-$ will not be extricated from backgrounds. However, the ability to trigger on the $\mu^+\mu^-$ combination (including displaced vertex triggers) gives the hadron collider experiments a clear advantage over the B factories in branching ratio measurements for exclusive modes (high rates, no flavor tagging penalty).

CDF and D0 project of order 100's of rare decays in $K^{(*)}\mu^+\mu^-$ and also (using conversion photons) $K^{*0}\gamma, \phi\gamma$. BTeV and the LHC experiments project several thousand $K^{(*)}\mu^+\mu^-$ per year. BTeV and LHCb also project of order 25,000 $B^0 \to K^{*0}\gamma$ per year. Finally, with LHC at design luminosity, the combined LHC yield for $B_s^0 \to \mu^+\mu^-$ is expected to be of order 27 events/year for the standard model BR. Note that CMS and ATLAS depend primarily on muon triggers and are designed for $\mathcal{L}$=10^{34}, which should provide them a special advantage for this physics.

6. Summary

With CDF and D0 already underway at the Tevatron, we can expect a great deal of progress on B_s mixing and on the efficacy of vertex triggers for modes like $B^0 \to \pi^+\pi^-$. Both the very large production cross sections and the unique sensitivity to B_s physics make the hadron collider experiments complementary to the B factories. In the LHC era, we can expect the dedicated detectors, BTeV and LHCb, to apply vertex triggering, excellent particle identification, and high data acquisition rates to more difficult channels like $B_s \to D_s^- K^+$ and $B^0 \to \pi^+\pi^-\pi^0$. Finally, with design LHC luminosity, we can expect clear observation and study of exclusive rare decays.

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