Forward-Backward Asymmetry in $B^{\pm} \to J/\psi K^{\pm}$ Decays at the DØ Experiment

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We present a measurement of the forward-backward asymmetry $A_{FB}(B^{\pm})$ in $B^{\pm} \to J/\psi K^{\pm}$ decays at the DØ experiment, using 10.4 fb^{-1} of $p\bar{p}$ collision data from Run II of the Tevatron Collider at Fermilab. This asymmetry reflects the probability for $b\bar{b}$ pairs to be produced without directional bias. $A_{FB}(B^{\pm})$ is extracted from a maximum likelihood fit to the difference between forward and backward $B^{\pm}$ mass distributions, using a boosted decision tree to reduce background. Corrections are made for reconstruction asymmetries of the decay products. The central value is blinded and randomized pseudo-experiments are used to validate the fit method. $A_{FB}(B^{\pm}) = [?? \pm 0.434(stat.) \pm 0.140(syst.)]\%$.

1 Introduction

A forward-backward asymmetry is defined as: $A_{FB} = (N_F - N_B)/(N_F + N_B)$. In $p\bar{p}$ collisions the forward category indicates a quark traveling in the direction of the incoming proton or an anti-quark following the direction of the anti-proton. A forward-backward "charge" $q_{FB} = -q_B\,\mathrm{sgn}(y_B)$, where $\mathrm{sgn}(x)$ is the sign function, is used to identify the category of the $B^{\pm}$.

The forward-backward asymmetry in the production of heavy quarks is caused by interference between next-to-leading order processes, such as gluon radiation in $q\bar{q}$ interactions, and qg scattering [1]. This effect has been studied extensively in the top-quark sector [2].

For bottom quarks the situation is not as well studied. There are few explicit Standard Model predictions for $A_{FB}^{b\bar{b}}$ except for electroweak $b\bar{b}$ production [4]. $A_{FB}^{b\bar{b}}$ has not been measured thus far by hadron collider experiments, mainly due the difficulty in correctly identifying the initial quark content of b-jets. The $B^{\pm} \to J/\psi K^{\pm}$ channel is especially suited to this measurement since reconstructing a $B^{\pm}$ allows for direct quark flavor identification with no need to account for mixing. The DØ detector [3] has a high quality muon tracking system with a wide acceptance region and minimal background effects from hadron punch-through, providing efficient reconstruction of $J/\psi \to \mu\mu$ decays. Also, the regular reversal of solenoid and toroid magnet polarities allows for the cancellation of first order detector-based asymmetries.

2 Event Selection and Monte Carlo

Events containing $B^{\pm} \to J/\psi K^{\pm}$ candidates are selected from the full DØ Run II dataset. Candidates are reconstructed by identifying a pair of oppositely-charged muons (decay products of the J/ψ particle) which are produced along with a charged track at a common vertex. Displacement of this vertex from the primary beam interaction vertex is essential for identifying $B^{\pm}$ candidates. The selected mass range for this analysis is 5.05 GeV/$c^2 < M(B^{\pm}) <$ 5.65 GeV/c^2.

Generated $B^{\pm} \to J/\psi K^{\pm}$ Monte Carlo (MC) is processed through the same reconstruction code used for data. Because the definitions of forward and backward are tied directly to $\text{sgn}(y_B)$ (approximated by $\text{sgn}(\eta_B)$), the ambiguous region near $\eta = 0$ must be considered. A resolution study of η at production and reconstruction shows that rejecting events with $|\eta_B| < 0.1$ removes the ambiguity to a high degree.

Background rejection is achieved using a Boosted Decision Tree (BDT) trained on reweighted signal Monte Carlo and background events from $B^{\pm}$ sidebands above and below the selected mass range. A cut on the BDT qualifier is chosen to minimize the uncertainty of $A_{FB}(B^{\pm})$.

3 Maximum Log Likelihood Fit

A maximum log likelihood fit incorporating a signal distribution and three background distributions is used to extract $A_{FB}(B^{\pm})$. Each distribution is assigned an event fraction f_i and has a forward-backward asymmetry A_i. The sign of η_B is randomized to blind the asymmetry values.

The fit minimizes a quantity LLH, the negative log of the likelihood $\mathcal{L}_n$, over N events, each with weight w_n (Sec. 4). $\mathcal{L}_n$ has 26 floating parameters and is constructed to integrate to 1.

$$\text{LLH} = -2\sum_{n=1}^{N} w_n \ln(\mathcal{L}_n) \tag{1}$$

$$\mathcal{L}_n = \alpha[f_S(1 + q_{FB}A_S)S + f_P(1 + q_{FB}A_P)P + f_T(1 + q_{FB}A_T)T] + f_E(1 + q_{FB}A_E)E, \tag{2}$$

where $f_E = 1 - \alpha[f_S + f_T + f_P]$ and α describes the dependence of f_i on kaon energy [5].

The signal distribution S is modeled by a normalized double Gaussian distribution with widths that vary according to the energy of the kaon. The form of the kaon energy dependence was determined empirically by fitting in bins of kaon energy. To allow for mass shifts observed between the $\eta < 0$ and $\eta > 0$ regions a unique set of parameters is used for events in each region.

The background distribution P describes $B^{\pm} \to J/\psi\pi^{\pm}$ events in which the π is misidentified as a K, resulting in an artificially high $B^{\pm}$ mass. The distribution is a reflection of S with the mean shifted to recover the accurate pion mass and the widths shifted by a ratio of the means.

The background distribution T describes all partially reconstructed $B^{\pm}$ candidates. If a $B^{\pm}$ decay has a final state with four or more particles, the reconstructed candidate will be missing a portion of its mass. These decays are modeled using a hyperbolic tangent function with a floating inflection point: $T = 1 - \tanh[25(m_{B^{\pm}} - t)]$.

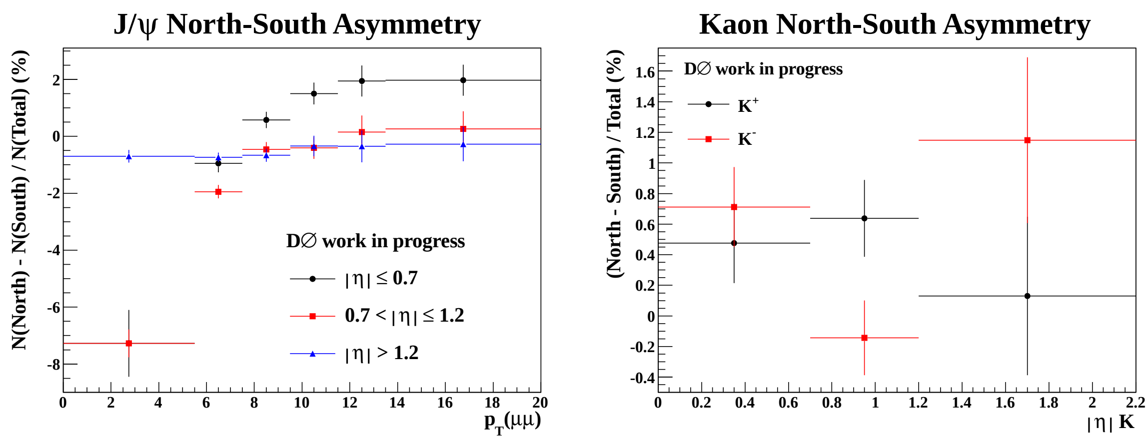
Finally, the background distribution E describes random combinations of particles. It is modeled using an exponential function, $E = \exp[s(m_{B^{\pm}} - 5.05)]$, with a slope which depends on kaon energy: $s = s_0[1 + s_1 \exp(-s_2 E_K)]$.

4 Corrective Weights for Reconstruction Asymmetries

Asymmetric detector performance can manifest itself in the reconstruction of J/ψ particles or kaon tracks. Asymmetries between $\eta < 0$ (the "south" half of DØ) and $\eta > 0$ (the "north" half) have been calculated from data samples with no production asymmetries. Prompt $J/\psi \to \mu^+\mu^-$ decays are used to measure $A_{NS}(J/\psi)$. Background events under the peak are removed with sideband subtraction and $A_{NS}(J/\psi)$ is calculated from a counting experiment (Fig. 1(a)).

The main source of large asymmetries seen at low p_T appears to be detector asymmetries, specifically near the support structures at the base of the detector. A study of J/ψ occupancy shows that gaps in the region of the support structure are not symmetric and the response of the reconstruction algorithms to these gaps is momentum dependent, as is the muon trigger.

Decays of $\phi \to K^+K^-$ are used to study $A_{NS}(K^{\pm})$. The $\phi \to K^+K^-$ signal is modeled by a relativistic Breit-Wigner resonance convoluted with a double Gaussian resolution. Background models are determined from Monte Carlo studies. A binned χ^2 minimization fit is performed simultaneously on north and south side data. $A_{NS}(K^{\pm})$ (Fig. 1(b)) does not show a significant dependence on p_T.



(a) J/ψ A_{NS}

(b) $K^{\pm}$ A_{NS}

Figure 1: Reconstruction asymmetries of prompt $J/\psi \to \mu^+\mu^-$ decays in bins of $|\eta|$ and p_T (a); and of $\phi \to K^+K^-$ decays in bins of leading kaon q and $|\eta|$.

The A_{NS} values are used to equalize the relative reconstruction efficiencies on both sides of the detector. South side particles are assigned efficiency $\varepsilon_S = 1$, and north side particles are weighted so that $\varepsilon_N = \varepsilon_S$. Since the background distributions could contain events without real J/ψ or $K^{\pm}$ particles (e.g. $B^{\pm} \to J/\psi\pi^{\pm}$ events), the value of A_{NS} in the corrective weight is scaled by the expected signal fraction f of the event.

The corrective weight for each event is $w_{\text{corr}} = w_{J/\psi}w_{K^{\pm}}$, where $w_{J/\psi}$ and $w_{K^{\pm}}$ are 1 for south side particles and $(1 - fA_{NS})/(1 + fA_{NS})$ for north side particles. The values of A_{NS} are determined by the kinematic bins of the J/ψ and $K^{\pm}$.

Reconstruction asymmetry corrections are calculated by comparing raw fits to weighted fits: $A_{FB}(\text{corr}) = A_{FB}(\text{raw}) - A_{FB}(\text{weighted})$. The corrective weighting method is cross-checked using a weighted average of $A_{NS}(J/\psi)$ and $A_{NS}(K^{\pm})$ over their kinematic bins [6], with the number of signal events per bin extracted from binned fits of the $B^{\pm} \to J/\psi K^{\pm}$ data. The observed values of $A_{FB}(\text{corr})$ are consistent with the expectations.

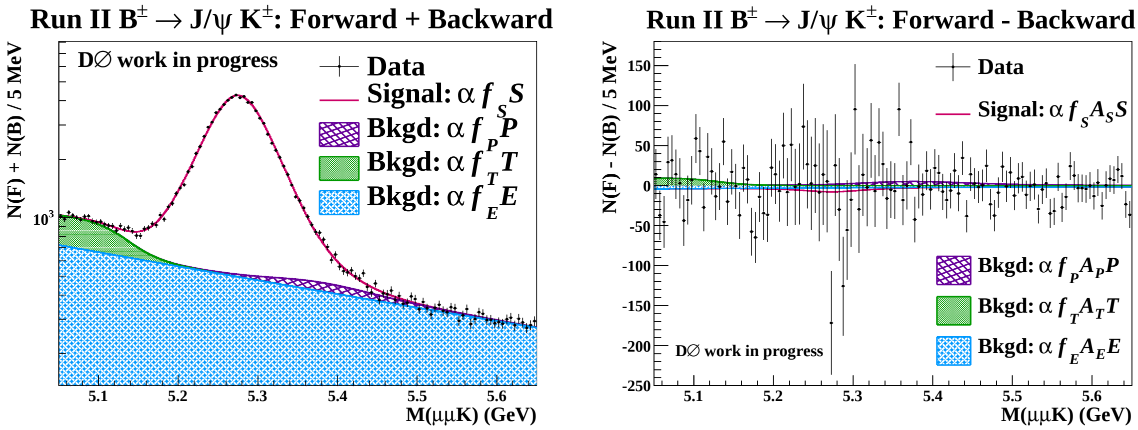
5 Fit Results

The $B^{\pm} \to J/\psi K^{\pm}$ fit, blinded by randomizing $\text{sgn}(\eta_B)$ and corrected for reconstruction asymmetries, has 78644 ± 854 signal events. The projection of the fit onto the forward + backward invariant mass distribution is shown in Fig. 2(a). Figure 2(b) shows the forward - backward mass distribution, where each data event is given a positive or negative weight according to q_{FB}.

Because of the randomized blinding, $A_{S,\,P,\,T,\,E}$ are all consistent with zero. A set of 1000 pseudo-experiments shows that $A_{FB}(B^{\pm})$ is Gaussian distributed with a mean value consistent with zero. The fit has a statistical uncertainty of 0.434%.

6 Systematic Uncertainties & Stability Tests

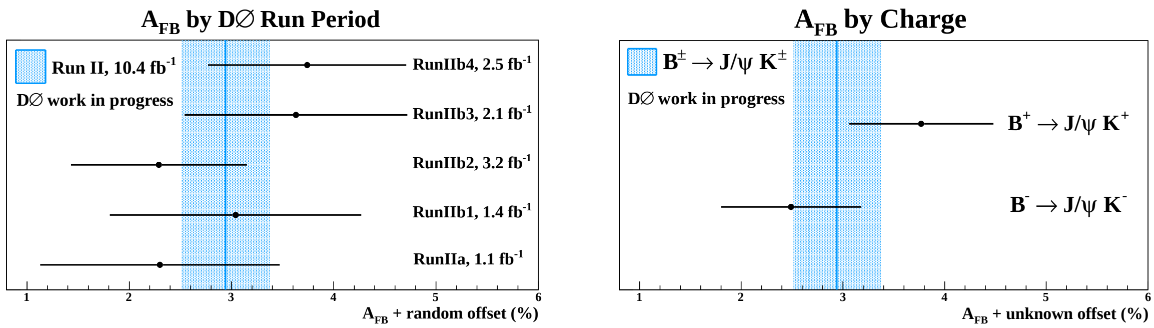
To determine systematic uncertainties a variety of reasonable variations are made to the fitting method, using a random offset blinding procedure rather than randomized data. Variations to several fit details and to the reconstruction asymmetry samples give an uncertainty of 0.105%. The uncertainty due to the reconstruction asymmetry weighting method is 0.093%. Combined, the systematic uncertainty on $A_{FB}(B^{\pm}) = 0.140\%$.



(a) Forward + Backward (b) Forward-Backward

Figure 2: $B^{\pm} \to J/\psi K^{\pm}$ invariant mass distribution of the final data sample (a). The four fit curves are drawn here with no asymmetry contribution. The forward-backward mass distribution (b) shows the randomized data and the fit curves multiplied by the asymmetry parameters.

The stability of the asymmetry measurement can be tested by dividing the data into subsets. Figure 3 shows the consistency of the measurement over time and with B^+ and B^- samples fitted separately.



(a) Run II time subsets (b) Separate charges

Figure 3: $A_{FB}(B^{\pm})$ in different Run II data epochs (a) and q_B settings (b). The full result is shown in blue.

7 Conclusions

The forward-backward asymmetry in $B^{\pm} \to J/\psi K^{\pm}$ decays is calculated from a maximum log likelihood fit. Fits of randomized data yield $A_{FB}(B^{\pm})$ consistent with zero. Observed corrections for reconstruction asymmetries agree with expectations from a weighted average. The final result of this blind analysis is $\mathbf{A_{FB}}(\mathbf{B}^{\pm}) = [?? \pm \mathbf{0.434}(\text{stat.}) \pm \mathbf{0.140}(\text{syst.})]\%$.

References

1. J.H. Kühn and G. Rodrigo, *Phys. Rev.* D **59**, 054017 (1999).
2. V.M. Abazov *et al*, *Phys. Rev.* D **84**, 112005 (2011).
3. V.M. Abazov *et al*, *Nucl. Instrum. Methods* **A565**, 463-537 (2006).
4. M. Baak *et al*, *Eur. Phys. J.* C **72**, 2205 (2012).
5. V.M. Abazov *et al*, *Phys. Rev. Lett.* **110**, 241801 (2013).
6. V.M. Abazov *et al*, *Phys. Rev.* D **86**, 072009 (2012).