Measurement of the Forward-Backward Asymmetry in $B^\pm$ Meson Production at the DØ Experiment

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DØ Detector

- Central tracking: silicon microstrip & fiber trackers
- Liquid argon / uranium calorimeter
- Independent muon tracking

- Run II → ~10 years of $pp$ collisions at $\sqrt{s} = 1.96$ TeV
- Data: 10.7 fb$^{-1}$ recorded, this analysis uses 10.4 fb$^{-1}$ (tracker+muon quality)
**A_{FB} in \bar{b}b Production**

- Do heavy quarks have a preference to move in the proton direction?

- Forward-backward asymmetry arises from interference of higher-order diagrams with color factors that are not $Q \leftrightarrow \bar{Q}$ symmetric:
  - No $A_{FB}$ created at leading order in the SM, only appears at higher orders
  - Dominant source is interference of tree and box diagrams $\rightarrow A_{FB} > 0$

- In $pp$ collisions, forward = $b, B^{-}$ (\(\bar{b}, B^{+}\)) following $p$ ($\bar{p}$) direction

$$A_{FB}(B^{\pm}) = \frac{N(-q_B \eta_B > 0) - N(-q_B \eta_B < 0)}{N(-q_B \eta_B > 0) + N(-q_B \eta_B < 0)}$$
Motivation

- $A_{FB}$ of $t\bar{t}$ production created a lot of interest
  - Early measurements $>>$ SM, still some tension between CDF and SM
  - BSM models to explain excess can also predict $b\bar{b}$ asymmetry $\rightarrow$ same sources
  - SM Prediction: $A_{FB}(b\bar{b}) = (0.34 \pm 0.10 \pm 0.01)\%$, $M(b\bar{b}) \approx 35 - 75$ GeV (PRL 111 062003)

- Still at the beginning of hadron collider measurements for $b\bar{b}$!
  - LHCb: forward-central asymmetry in mass range around Z peak (PRL 113 082003)
  - CDF: forward-backward asymmetry in $M(b\bar{b}) > 130$ GeV (CDF/ANAL/TOP/PUB/11092)

- Fully reconstructed $B^\pm$ decays tag $b/\bar{b}$ exactly
  - No precision lost to mis-ID or $B^0/\bar{B}^0$ oscillations

- DØ has many practical advantages:
  - History of precise CPV asymmetry results
  - $pp$ initial state, reversing magnet polarities, extensive $\mu$ coverage

Figure from arXiv:1411.3007
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Reconstructing $B^\pm \rightarrow J/\psi K^\pm$

- $\mu^+\mu^-$ pair ($J/\psi$) + track ($K^\pm$) = $B^\pm$
  - $B^\pm$ decay length significance > 3$\sigma$
- F/B definition: $q_{FB} = -q_B \text{sign}(\eta_B)$
  - Ambiguous near $|\eta| = 0$ due to finite resolution
- Rejecting $|\eta_B| < 0.1$ (2% of data) gives:
  - 100% $q_{FB}(\text{MC@NLO } B^\pm) = q_{FB}(\text{reco } B^\pm)$
  - 99.5% $q_{FB}(\text{MC@NLO } b, \bar{b}) = q_{FB}(\text{reco } B^\pm)$
- $B^\pm$ kinematics closely match $b$ kinematics:
  - Reco. $B^\pm$ vs generated $b, \bar{b}$
  - $A_{FB}(B^\pm)$ affected minimally by hadronization
**Maximum Likelihood Fit**

- Boosted Decision Tree to reduce background
- Unbinned fit over all $B^\pm$ candidates
- Events weighted to correct for reconstruction asymmetries (next slides)
- 4 components, each with an event fraction $f$ and asymmetry $A$

$$\mathcal{L}_n = \alpha \left[ f_S (1 + q_{FB} A_S) S(M_{J/\psi K}, E_K) + f_P (1 + q_{FB} A_P) P(M_{J/\psi K}, E_K) ight]$$

$$+ f_T (1 + q_{FB} A_T) T(M_{J/\psi K})$$

$$+ [1 - \alpha (f_S + f_P + f_T)] (1 + q_{FB} A_E) E(M_{J/\psi K}, E_K)$$

**Signal**: $B^\pm \rightarrow J/\psi K^\pm$ double Gaussian

**Pion**: $B^\pm \rightarrow J/\psi \pi^\pm$ shifted double Gaussian

**Threshold**: partial $B$ reconstruction

**Exponential**: combinatoric background
Reconstruction Asymmetries

- Asymmetries in the detector or reco of $J/\psi$ or $K^\pm$ must be corrected
- Forward-backward asymmetry is a combination of charge asymmetry and “north-south" asymmetry
- Deal with $A_C$: $w_{\text{magnet}}$
  - Equalize $N(B^\pm)$ in 4 magnet polarity settings to remove tracking asymmetries
  - Set $N(B^+)=N(B^-)$ to correct for $K^\pm$ detector interaction cross-section differences → 1% $A_C$
- Deal with $A_{NS}$: $w_{J/\psi}w_K$
  - Measure asymmetries in samples without expected production asymmetry
  - set $\varepsilon_{\eta<0}=\varepsilon_{\eta>0}$ with a corrective weight, based on event-by-event kinematics
  - Effects on $A_{FB}(B^\pm)$ are small: $B^+$ and $B^-$ on same side have opposite $q_{FB}$, so $A_{NS}$ corrections mostly cancel
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**Reconstruction Asymmetries**

- $A_{NS}(J/\psi)$: prompt $J/\psi \to \mu^+\mu^-$, measure in bins of $|\eta|$ and $p_T$
  - identical selection with requirement of low decay length significance
  - Est. 2% $B$ decay fraction
- $A_{NS}$ calculated by counting after sideband subtraction in each bin of $|\eta|$
- Low $p_T$ $A_{NS}$ traced to inactive material causing $\langle p_T(\mu) N \rangle > \langle p_T(\mu) S \rangle$
Reconstruction Asymmetries

- $A_{NS}(K^\pm)$: sample of $\varphi \rightarrow K^+K^-$ decays selected to reproduce kinematics of kaons in $B^{\pm} \rightarrow J/\psi \ K^{\pm}$
- Binned by charge and $|\eta|$ of leading kaon
- $A_{NS}$ is a parameter in simultaneous $\chi^2$ fits to north and south side data in each $|\eta|$ bin:
Extraction of $A_{FB}(B^{\pm})$

$$A_{FB}(B^{\pm}) = [-0.24 \pm 0.41\text{(stat)} \pm 0.19\text{(syst)}]\%$$

- 89328 signal evts / 160360 candidates
- $\chi^2 / \text{d.o.f} = 249 / 214$

**TABLE I: Summary of uncertainties on $A_{FB}(B^{\pm})$ in data.**

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EXTRACTION OF $A_{FB}(B^\pm)$

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Back-of-the-envelope comparison:
agrees with SM = $(0.34 \pm 0.10)\%$
at the $1\sigma$ level.

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$A_{FB}(B^\pm)$ Estimate from MC@NLO

- 16M QCD $p\bar{p} \rightarrow b\bar{b}X$ events generated with MC@NLO + HERWIG for hadronization
- Identical $B^\pm \rightarrow J/\psi K^\pm$ selection as in data
  - Add requirement that $J/K^\pm$ reconstructed tracks match generated $B^\pm \rightarrow J/\psi K^\pm$ tracks (leaves only signal)
  - Correct for unmodeled muon trigger effects
  - Correct for MC reconstruction asymmetries

\[ A_{FB}(B^\pm) = [2.31 \pm 0.34(\text{stat}) \pm 0.51(\text{syst})]\% \]

- Systematic uncertainties: PDF, energy scale, fragmentation
  - Renormalization & factorization energy scale variations: 0.44%
  - Fragmentation model variations: 0.25%
  - PDF eigenvector uncertainty shifts: 0.03%
**$A_{FB}(B^{\pm})$ Estimate from MC@NLO**

- Also measured in bins of $|\eta|$ and $p_T$
  - $\langle p_T(B^{\pm}) \rangle = 12.9$ GeV
  - $A_{FB}$ in data systematically lower than in MC

\[ \text{Data} = (-0.24 \pm 0.45)\% \quad \text{MC} = (2.31 \pm 0.61)\% \]
\[ \text{Difference} = (2.55 \pm 0.76)\% \approx 3\sigma \]

- MC suggests $A_{FB}(B^{\pm}) \approx A_{FB}(b\bar{b})$, but doesn't align with theorists' $A_{FB}(b\bar{b})$ predictions at low $M(bb)$
- Not optimal for an SM prediction in this channel
First Tevatron measurement of a forward-backward asymmetry in the $b$ sector

$$A_{FB}(B^\pm) = (-0.24 \pm 0.41 \pm 0.19)\%$$

- Precision reflects DØ's excellent heavy flavor asymmetry program
- Agrees with preliminary results from CDF → asymmetry consistent with zero
- Extends and complements CDF high mass measurement

Less room for new physics causing anomalous forward-backward asymmetries (top and bottom)

- DØ $A_{FB}(tt)$ measurements and SM predictions have moved toward each other
- Our result suggests agreement with theorist's SM predictions of $A_{FB}(b\bar{b})$
Summary

- First Tevatron measurement of a forward-backward asymmetry in the $b$ sector:

  \[ A_{FB}(B^\pm) = (-0.24 \pm 0.41 \pm 0.19)\% \]

  - Precision reflects DØ's excellent heavy flavor asymmetry program
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- Less room for new physics causing anomalous forward-backward asymmetries (top and bottom)

  - DØ $A_{FB}(tt)$ measurements and SM predictions have moved toward each other
  - Our result suggests agreement with theorist's SM predictions of $A_{FB}(b\bar{b})$

Thank You!
Backup
REFERENCES

- $A_{FB}$ mechanisms: Kuhn/Rodrigo, PRD 59, 054017 (1999)
- Top standard model: arXiv:1411.3007
- LHCb measurement: PRL 113, 082003 (2014)
- CDF preliminary note: CDF/ANAL/TOP/PUB/11092
- Theory Predictions
  - Grinstein/Murphy: PRL 111, 062003 (2013)
  - Manohar/Trott: PLB 711, 313 (2012)
- Full list in PRL 114 05813 (2015), arXiv:1411.3021
**Theoretical Predictions**

- Closest energy range: $A_{FB}(b\bar{b}) = (0.34 \pm 0.10 \pm 0.01)\%$
  - $M(b\bar{b}) = 35 – 75 \text{ GeV}$, or $p(b) > \sim 15 \text{ GeV}$
  - Increases to 2% – 4% near/above $M(Z)$
- New physics particles could replace gluons in $q\bar{q} \rightarrow b\bar{b}$ interactions
- NP which agrees with CDF $A_{FB}(t\bar{t})$ give $A_{FB}(b\bar{b}) = \sim 0\% – 0.8\%$

- We produce a SM estimate using MC@NLO: QCD $p\bar{p} \rightarrow b\bar{b}X$
  - Allows direct calculation of asymmetry for $B^\pm$ mesons
  - Ensures identical kinematics to our data sample
  - Lets us compare between $A_{FB}(B^\pm)$ and $A_{FB}(b\bar{b})$

Figure from PRL 111 062003 (2013).
Reconstructing $B^\pm \rightarrow J/\psi K^\pm$

- All DØ data from Tevatron Run II, 10.4 fb$^{-1}$
- $\mu^+\mu^-$ pair ($J/\psi$) + track ($K^\pm$) = $B^\pm$ candidate
- $\mu^\pm$: $p_T > 1.5$ GeV; $|\eta| < 2.1$
- $K^\pm$: $p_T > 0.7$ GeV; $|\eta| < 2.1$
- $J/\psi$: Mass = 2.7 – 3.45 GeV
  - Decay length uncertainty < 0.1 cm
  - $\cos(2D \text{ Pointing Angle}) > 0$
- $B^\pm$: Mass = 4.0 – 7.0 GeV
  - decay length significance > 3
  - vertex fit $\chi^2 < 16 / 3$ d.o.f
  - $\cos(2D \text{ Pointing Angle}) > 0.8$

(more background reduction not shown in the plot)
**Boosted Decision Tree**

- Background taken from data in sidebands
  - Mostly partial reconstruction and combinatoric background
- Signal MC (leading-order) generated with Pythia
  - Match kinematics as closely as possible with expected data signal (from sideband subtraction) using weights
  - Ex: muon $p_T$, trigger effects aren't modeled
- BDT trained using 40 variables:
  - Momenta, decay lengths, impact parameters, pointing angles, vertex fit $\chi^2$, isolation, and $\Delta\phi$ for several particle pairs
- Cut on discriminant chosen to minimize $A_{FB}(B^\pm)$ statistical uncertainty
**Maximum Likelihood Fit**

- Particle masses don't match between north ($\eta < 0$) and south ($\eta > 0$) sides of the detector: $M(\text{north})$ always $< M(\text{south})$
  - Ex: $M(J/\psi) \rightarrow \Delta M$ significant based on errors, but small compared to peak width:

![Graph showing $M(\mu\mu)$ distribution with North and South data](image)

- Solenoid field asymmetric along $z$, but not included in the field map
- Solution: signal distribution has a **unique parameter set on each side**
Maximum Likelihood Fit

- Until the analysis methods were approved, asymmetries were blinded by randomizing sign(\(\eta\)) of the \(B^\pm\)

- Statistical uncertainty from the fit is 0.41%, confirmed with an ensemble of 1000 trials

- Performance of the algorithm is tested by injecting asymmetries and comparing with fit results

\[
\begin{align*}
\mu &= (-0.010 \pm 0.013)\% \\
\sigma &= (0.399 \pm 0.011)\% \\
\chi^2 &= 21.8/22
\end{align*}
\]
**RECONSTRUCTION ASYMMETRIES**

- Large negative asymmetries at low momentum appear to be caused by extraneous detector material asymmetries (cable bunches, etc).

- Excess of low $p_T$ muons on the south side, and that side has lower average $p \rightarrow$ momentum threshold is higher on the north side.

\[ \langle p \rangle = (4.018 \pm 0.002) \text{ GeV} \]

\[ \langle p \rangle = (4.039 \pm 0.002) \text{ GeV} \]
Reconstruction Asymmetries

- Standard method:
  - $A_{\text{physics}} = A_{\text{raw}} - A_{\text{reco}}$
    - 1st order simplification of multiplying efficiencies
    - $A_{\text{reco}}$ calculated from a weighted average over $A_{\text{NS}}$ bins:
      $$A_{\text{FB}}(\text{reco}) = \frac{1}{N} \sum_{\text{bins}} n_i A_i$$
- Cross-check $\rightarrow A_{\text{reco}}$ agrees with new weight method
- Uncertainty: $\sim 0.13\%$
  - Directly from $A_{\text{NS}}$ errors in $A_{\text{reco}}$

- Our method: weight so $\varepsilon_{\eta < 0} = \varepsilon_{\eta > 0}$:
  $$w_{\text{north}} = \frac{1 - A_{\text{NS}}}{1 + A_{\text{NS}}}$$
- Event kinematics determine the bin of $A_{\text{NS}}(J/\psi)$ and $A_{\text{NS}}(K^\pm)$
- Uncertainty: $0.003\%$
  - Ensemble of Gaussian variations to $A_{\text{NS}}$
**Extraction of $A_{FB}(B^\pm)$**

- Result is stable over time and with $B^+/B^-$ fitted separately
- Background asymmetries also consistent with zero
- $A_{FB}(B^\pm) = [-0.24 \pm 0.41{\text{(stat)}} \pm 0.19{\text{(syst)}}]\%$

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- Trained with different background samples or variables
- Mass range, $E_K$ dependences, float/fix specific parameters
- Alternate fits, cuts, bins, etc
- Test of injecting asymmetries into blinded data
\[ A_{FB}(B^\pm) \text{ Estimate from MC@NLO} \]

- Energy scale choice: 0.44%
  \[ \mu_0 = \sqrt{\frac{1}{2} \left[ 2m^2(b) + p_T^2(b) + p_T^2(\bar{b}) \right]} \]
  - Vary renormalization and factorization scales from \( \mu_0/2 \) to \( 2\mu_0 \)
  - Compared to default magnet polarity: \( A_{FB}(B^\pm) = (1.39 + 0.40)\% \)

- Fragmentation function: 0.25%
  - Weight \( z = p(B)_\parallel / p(b) \) to match LEP or SLD tuned Bowler function
  \[ f_B(z) \propto \frac{1}{z^{1+bm_q^2}} (1 - z)^a \exp(-bm_T^2/z) \]