Search for the $B$-meson decay to four baryons

$B^0 \rightarrow p \bar{p} p \bar{p} p$ at BABAR

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on behalf of the BABAR Collaboration
Outline

- BABAR experiment
- Motivation
- Analysis Method
- Result
- Conclusion

 Submitted to PRD!
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Experiments at the B-factories

**B-factories**: dedicated experiments at \(e^+e^-\) asymmetric-energy colliders for the production of quantum coherent \(B\bar{B}\) pairs \(\rightarrow\) CPV studies and NP indirect searches.

\[ e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \]

First generation of B-factories

- **at the KEKB collider**, KEK, Japan
- **at the PEP II collider**, SLAC, California

In its 9-year operation (1999-2008), the BaBar experiment collected:

- **424 fb\(^{-1}\) on-peak** at \(\Upsilon(4S)\) mass, \(\sqrt{s} = 10.58\) GeV \(\rightarrow\) 471 million \(B\bar{B}\) pairs.
- **44 fb\(^{-1}\) off-peak**, below \(B\bar{B}\) threshold, \(\sqrt{s} = 10.54\) GeV
The *BABAR* Detector

**Detector of Internally Reflected Cherenkov light:** quartz bars and PMTs for Cherenkov angle measurement and charged-particle identification (p, K, π)

Clean environment allows **outstanding tracking** and **vertex reconstruction**; dE/dx, cosθ_C measurements provide **excellent Particle IDentification** performance → high efficiency with pion mis-identification rate below 1% at any momentum.
Motivation

• B-mesons have large mass and they are able to decay to final states with \textit{baryons} \\
  \rightarrow \text{optimal laboratory for better understanding the mechanism of \textit{hadronization into baryons}} (\text{theoretical models poorly understood})

\textbf{Baryon puzzle:} inclusive branching fraction ($\sim 7\%$) $\neq \Sigma$ exclusive branching fraction of baryonic channels ($\sim 1\%$)

• Experimental features: \textit{threshold enhancement} and \textit{branching fraction (BF) hierarchy}

Why $B^0 \rightarrow p \ p \ p \ p$?

Previous measurement at **BABAR**:

- Upper limit on $\text{BF}(\bar{B}^0 \rightarrow \Lambda_c^+ \ p \ p \ p) < 2.8 \times 10^{-6}$ at 90% CL


Estimate of the $\text{BF}(B^0 \rightarrow p \ p \ p \ p)$:

- Cabibbo suppression, $b \rightarrow u$ decay
- Phase space contribution, using the Q-values of the 2 reactions

Working hypothesis for selection optimization:

$$\mathcal{B}(B^0 \rightarrow pp\bar{p}\bar{p}) \approx \mathcal{B}^{UL}(\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p}p\bar{p}) \cdot \frac{|V_{ub}|^2}{|V_{cb}|^2} \cdot \frac{Q_{pp\bar{p}\bar{p}}}{Q_{\Lambda_c^+ \bar{p}p\bar{p}}} \sim 10^{-7}$$

No PDG limit yet!
Analysis Strategy and Dataset

**DATA:**
- Full dataset (on-peak data, 471M BB)
- Performed as blind analysis, without looking at the signal region in data
  \((5.27 < \text{m}_{ES} < 5.29 \text{ GeV/c}^2)\)
- Side band region data
  \((\text{m}_{ES} < 5.27 \text{ GeV/c}^2)\) used to validate background MC samples

**MONTE CARLO (MC):**
- (At least 3 x data luminosity)
- Generic B decays from \(\Upsilon(4S)\) \([\text{EvtGen}]\)
- continuum events \(e^+e^- \rightarrow q\bar{q}\) \([\text{JetSet}]\)
- Signal sample: \(e^+e^- \rightarrow \bar{B}^0B^0\), with one B decaying to pppp
  \(\rightarrow\) efficiency estimate and modeling of the signal shape

**1) Event reconstruction:** 4 protons fitted to a common vertex
**2) Selection:** kinematic variables related to B decays, angular distribution and event shape
**3) Fitting procedure:** modeling signal shape in \(m_{ES}\)
**4) Signal yield extraction** and branching fraction calculation
The Event Reconstruction

- Four oppositely charged tracks, coming from a common vertex, identified as two protons and two anti-protons
- Kinematic fit to the common vertex with $\chi^2$ probability larger than 0.1 %
- Loose selection on kinematic variables

Beam energy substituted mass

$$m_{ES} = \sqrt{(E_{beam}^*)^2 - |p_B^*|^2}$$

Energy difference

$$\Delta E = E_B^* - E_{beam}^*$$

Preliminary

Babar Preliminary

Events/2 MeV/c^2

Events/4 MeV

$\pi_{had}/\pi_{MC}$
The Event Variables

- Mainly **combinatorial background** due to real protons from *continuum events* $e^+e^- \rightarrow q\bar{q}$

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**BB event**

- Spherical shape

**Continuum event**

- Jet-like shape

**Kinematic and angular variables**

- $BB$ event: peaking at 0
- $e^+e^- \rightarrow q\bar{q}$ event: flat in $\Delta E$

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**$BB$**

- $q = u,d,s,c$

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**$BB$**

- $sin^2\theta^*_B$
- $e^+e^- \rightarrow \bar{q}q$ event: flat in $cos\theta^*_B$

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L.Zani for BaBar Collaboration – ICHEP2018, Seoul
The Event Variables (II)

$\theta_{\text{THRUST}}$, angle between the *thrust axis* of the $B_{\text{sig}}$ and that of the ROE.

$R_2$ provides information about particle direction correlations.

$R_2 = \frac{H_2}{H_0}$

$H_k$, $k$-order moment of the FoxWolfram discriminant

$$\theta_{\text{THRUST}} = \sum_{i=1}^{N} |\vec{T} \cdot \vec{p}_i|$$

$$T = \frac{\sum_{i=1}^{N} |\vec{T} \cdot \vec{p}_i|}{\sum_{i=1}^{N} |\vec{p}_i|}$$

$P_k(cos\theta_{ij}) = \frac{|p_i^2||p_j^2|E_iE_j}{E_iE_j}$

Event-shape variables

$BB$

$q\bar{q}$ continuum

$B\bar{B}$

$q\bar{q}$ continuum

$\tau^+\tau^-$

$\mu^+\mu^-(\gamma)$

$e^+e^-\gamma$
The Event Selection

- Further background rejection achieved by selecting on the output of a Boosted Decision Tree (BDT) algorithm.
- The training is performed on event shape variables ($R_2$, $|\cos\theta_{\text{THRUST}}|$), on kinematic and angular variables ($\Delta E$, $\cos\theta^*_B$).

\[
\text{Total Signal efficiency: } \epsilon = 21\% \\
\text{Background reduction: } 1 - \epsilon_{\text{BDT}} > 98\%
\]
The Fitting Procedure

- The signal yield is extracted from an *unbinned extended maximum likelihood fit* to the on-peak data $m_{ES}$ distribution, in the range $5.2 < m_{ES} < 5.3$ GeV/$c^2$, after the BDT selection.

$$
\log L(N_{\text{sig}}, N_{\text{bkg}}; x) = -(N_{\text{sig}} + N_{\text{bkg}}) + \sum_{i=1}^{n} \log(N_{\text{sig}} \cdot f_{\text{sig}}(x_i) + N_{\text{bkg}} \cdot f_{\text{bkg}}(x_i))
$$

*Total Probability Density Function (PDF) : signal PDF + background PDF*

- Signal PDF ($f_{\text{sig}}$) → Gaussian function
- Background PDF ($f_{\text{bkg}}$) → empirical ARGUS function, depending on 2 parameters: the *cutoff* (fixed to the endpoint 5.289 GeV/$c^2$ of the $m_{ES}$ distribution) and the *shape parameter*.
- The *shape parameter, the background and signal yields* ($N_{\text{bkg}}$, $N_{\text{sig}}$) are extracted from the fit to the data.
The signal yield extraction and the BF estimate

The fit to the $m_{ES}$ distribution gives $N_{\text{sig}} = (11.1 \pm 4.6)$, with a 2.9σ significance.

$$BF = \frac{N_{\text{sig}}}{\epsilon N_{BB}} = (1.14 \pm 0.47 \pm 0.17) \times 10^{-7}$$

→ The statistical uncertainty on $N_{\text{sig}}$ is the main source of uncertainty on the branching fraction.

→ The statistical uncertainty already includes the impact of the ARGUS shape parameter, determined in the fit to the data.

→ Systematic uncertainties contribute as a further 15% relative uncertainty in the BF.
The analysis for the search of the $B^0 \to p\,p\,p\,p$ decay has been performed on 471 million $B\overline{B}$ pairs at $BABAR$:

- 11 signal events have been found from the fit to the data $m_{ES}$ distribution, with a significance of 2.9 standard deviations.
- The branching fraction has been computed and the upper limit at 90% CL, including systematic variation, is obtained:

$$BF_{UL} = 2 \times 10^{-7} \text{ at 90\% CL}$$

→ The first upper limit on this channel!

**SUBMITTED TO PRD, arXiv:1803.10378**
Thanks for your attention.
The Systematic Uncertainties

- Systematic uncertainties contribute as a further 15% relative uncertainty in the BF.

- Measured with the $B$ counting technique, the main uncertainty is due to the hadronic event selection efficiency.

- Signal pdf choice, found to be negligible

- ARGUS cutoff fixed in the fit to the data

- MC-data differences are the major source of systematic uncertainty on the signal selection efficiency, coming from: Tracking, PID, BDT efficiencies, the decay model implemented in the Signal MC generation.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Source</th>
<th>Relative systematic uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{BB}$</td>
<td>$B$ counting</td>
<td>0.6</td>
</tr>
<tr>
<td>$N_{\text{sig}}$</td>
<td>ARGUS cutoff</td>
<td>0.9</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>MC statistics</td>
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<tr>
<td>$\epsilon$</td>
<td>PID efficiency</td>
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<td>$\epsilon$</td>
<td>Track finding efficiency</td>
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<td>$\epsilon$</td>
<td>BDT selection</td>
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<tr>
<td>$\epsilon$</td>
<td>Decay model</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>15</td>
</tr>
</tbody>
</table>
**Weighting technique**

- for each input variable distribution, **BEFORE** THE BDT, define bin by bin weights comparing the background MC samples to the side band region data:

  \[
  C = \frac{N_{\text{sigMC}}}{\sum N_{i}^{\text{MC}} \cdot N_{i}^{\text{data}}}
  \]

- Apply the weights to the Signal MC distribution for the given variable **AFTER** THE BDT cut → recalculate efficiency → take as uncertainty the difference between *un-weighted and weighted efficiencies*.

- Uncertainty contributions from all the 4 input variables are summed in quadrature, taking into account the correlation coefficients.

  → **BDT relative uncertainty on \( \varepsilon = 2.2\% \)**
Decay model uncertainty study

- There are no specific four-body baryonic decay models currently known.

- Default implemented in simulated signal MC: Phase space model, meaning proton momentum probability is flat in the phase space.

- NO PROTON RELATED VARIABLES (momentum, energy, angular distributions) directly exploited in the analysis may relax the dependence of the selection efficiency on the decay model.

- However, systematic studies conservately estimate the contribution from the decay model to the relative systematic uncertainty on BF to be 14%.

Implemented with the re-weighting technique: based on the comparison between the resulting proton momentum spectra from 2 different decay models:

- Default (phase space)
- Assuming a different decay model (e.g., intermediate resonances: $B \rightarrow XX(\rightarrow pp)$)

Weights: bin by bin, normalized ratio of the new spectrum to the default one.

Weights are applied to the signal MC sample after the BDT cut → the difference in the efficiencies with/without weights is assumed as systematic uncertainty.