Measurement of the $\bar{B}^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+$ decay branching fraction

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experimental discrepancy on $\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)$ w.r.t. SM prediction

- $BABAR$, Belle and LHCb have measured $R[D^{(*)}] = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$

- combining all results, $4.0\sigma$ discrepancy w.r.t. $R^{(*)}_{SM}$ (HFAG Winter 2016)

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Improve experimental precision on $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_{\tau})$ at hadronic collider

- existing LHCb measurement selects $\bar{B}^0 \rightarrow D^{*+}\tau^- (\rightarrow \mu\bar{\nu}_{\mu}\nu_{\tau})\bar{\nu}_{\tau}$
- can improve measuring $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\tau^- (\rightarrow \pi\pi\pi\nu_{\tau})\bar{\nu}_{\tau})$ at hadronic collider

Normalization branching fraction $\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+)$

- hadronic collider $\Rightarrow$ normalization branching ratio needed to reach required precision
  - similar topology
  - well measured in absolute value
- $\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+)$
  - $\mathcal{B} = (7.0 \pm 0.8) \cdot 10^{-3}$ PDG 2015 (11.4% precision)
  - $\mathcal{B} = (7.27 \pm 0.50) \cdot 10^{-3}$ LHCb, PRD 87 092001 (2013): (8.8% precision)
    - not in PDG average
    - [actually, LHCb measures $\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+)/\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+)$]
- cannot get competitive result with present uncertainties on $\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+)$
- $\Rightarrow$ improved precision measurement of $\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+)$ by BABAR
**B* detector at PEP-II, SLAC National Accelerator Laboratory**

**Measurement of** \( \mathcal{B}(\bar{B}^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+) \)

**Main focus:** study of *CP* violation in *B* mesons
Measurement of $\mathcal{B}(\bar{B}^0 \rightarrow D^* \pi^+ \pi^- \pi^+)$

**BABAR**: CM energy, collected luminosity

**center-of-mass energies**

<table>
<thead>
<tr>
<th>$\Upsilon(nS)$ resonances (CUSB)</th>
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<tbody>
<tr>
<td>$E_{CM}[\text{GeV}]$</td>
</tr>
<tr>
<td>9.44</td>
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<tr>
<td>9.46</td>
</tr>
<tr>
<td>10.00</td>
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<tr>
<td>10.02</td>
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<td>10.34</td>
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<td>10.37</td>
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<td>10.54</td>
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<tr>
<td>10.58</td>
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<tr>
<td>10.62</td>
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</tbody>
</table>

**Integrated luminosity over time**

<table>
<thead>
<tr>
<th>Integrated Luminosity [fb$^{-1}$]</th>
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<tbody>
<tr>
<td>Delivered Luminosity</td>
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<tr>
<td>Recorded Luminosity</td>
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<tr>
<td>Recorded Luminosity $\Upsilon(4S)$</td>
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<tr>
<td>Recorded Luminosity $\Upsilon(3S)$</td>
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<tr>
<td>Recorded Luminosity $\Upsilon(2S)$</td>
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<td>Off Peak</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>$\mathcal{L}(\text{fb}^{-1})$</th>
<th>events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(4S)$</td>
<td>424 $\cdot 10^6$</td>
</tr>
<tr>
<td>$\Upsilon(3S)$</td>
<td>28 $\cdot 10^6$</td>
</tr>
<tr>
<td>$\Upsilon(2S)$</td>
<td>14 $\cdot 10^6$</td>
</tr>
<tr>
<td>off-peak</td>
<td>48</td>
</tr>
</tbody>
</table>

$e^+ e^- \rightarrow c\bar{c}$ $\sim 650 \cdot 10^6$

$e^+ e^- \rightarrow \tau^+ \tau^-$ $\sim 450 \cdot 10^6$

large clean data sample

data-taking ended in April 2008
Measurement of $\mathcal{B}(\bar{B}^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+)$

Decay chain reconstruction

- data sample: $e^+ e^-$ collisions, $424.2 \pm 1.8 \text{fb}^{-1}$ luminosity, $(470.9 \pm 2.8) \cdot 10^6 \ B\bar{B}$ pairs

- reconstruct $\bar{D}^0 \rightarrow K^+ \pi^-$ candidates from
  - 1 positive-charged identified $K$
  - 1 negative-charged track, assumed to be a $\pi$ (no pion identification)
  - candidate $m(K\pi)$ must match nominal $m(D^0)$ within 20 MeV

- reconstruct $D^{*-} \rightarrow \bar{D}^0 \pi^-$ candidates from
  - 1 $\bar{D}^0$ candidate
  - 1 negative-charged track with $p < 0.45$ GeV
  - $D^{*-} \rightarrow \bar{D}^0$ candidates mass difference must lie between 0.1435 and 0.1475 GeV

- reconstruct $\bar{B}^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+$ candidates from
  - 1 $D^{*-}$ candidate
  - 3 tracks with total charge $+1$ (no pion identification)
  - candidate $E(\bar{B}^0)$ must match $\sqrt{s}/2$ within 90 MeV

- all remaining objects: rest-of-event (ROE)
Suppression of non-$B\bar{B}$ backgrounds

- multilayer perceptron (MLP) classifier with 9 variables, in center-of-mass (CM) frame
  - cosine of angle $B^0$ decay products thrust axis w.r.t. beam axis
  - sphericity of $B^0$ decay products
  - thrust of the ROE
  - $\sum p_i$ in ROE
  - $\sum (3\cos^2 \theta_i - 1)p_i$ in ROE
  - cosine of angle of $B^0$ decay products thrust axis w.r.t. ROE thrust axis
  - cosine of angle of $B^0$ decay products sphericity axis w.r.t. ROE thrust axis
  - 2nd-order Fox-Wolfram moment using all re-constructed particles
  - cosine of the angle of the event thrust axis w.r.t. the beam axis

- cut on MLP output, retains 80% of $B\bar{B}$ events and rejects 69% of non-$B\bar{B}$ events
Signal yield and fit on $m_{ES} = \sqrt{s/4 - p_B^2}$

$m_{ES}$: data, simulation and fit on data

- **Unbinned extended max. likelihood fit**
  - Signal: Crystal Ball function
    - Shape parameters from MC
    - Fit mean, width & normalization
  - Non-peaking background: ARGUS f.
    - Fit normalization & curvature param.
  - Peaking backgrounds: 2 Gaussians
    - All parameters fixed on MC
    - 1445 ± 1272 from $B^0 \bar{B}^0$
    - 592 ± 121 from $B^+ B^-$

Fit results

- Number of signal events: 17767 ± 324 candidates
Background-subtracted 3 pion invariant mass distribution

- background-subtracted 3 pion mass distribution:
  - distribution of events in signal region
  - subtracted with distribution of events in sideband region normalized to the events in the fitted background in the signal region
- regions: signal $5.273 < m_{ES}[\text{GeV}] < 5.285$ sideband $5.240 < m_{ES}[\text{GeV}] < 5.270

Background subtraction region (on the $m_{ES}$ plot of previous page)
Background-subtracted 3 pion invariant mass distribution (2)

3 pion mass distribution

![Graph showing the 3 pion mass distribution with peaks at certain masses.]

- dominated by $a_1$ resonance
- peak at $\sim 2$ GeV from $\bar{B}^0 \rightarrow D^{*-} D^+_s (\rightarrow 3\pi)$ (expected dominant exclusive contribution)
- hint of $\pi(1800)$ contribution
- (this study does not aim at studying the structure of this distribution)

$m(a^+_1) = 1230 \pm 40 \text{ MeV/c}^2$ (PDG)
Branching fraction determination

\[ \mathcal{B} = \frac{N_{\text{signal}}}{\epsilon \cdot \mathcal{B}(D^{*-} \rightarrow D^0 \pi^-) \cdot \mathcal{B}(\bar{D}^0 \rightarrow K^+ \pi^-)} \]

- efficiency \( \epsilon \)
  - estimated in Monte Carlo as function of \( m(3\pi) \)
  - corrected for data \( m(3\pi) \) distribution

Measurement / subtraction of exclusive contribution \( \bar{B}^0 \rightarrow D^{*-} D^+ (\rightarrow 3\pi) \)

- the yield of \( \bar{B}^0 \rightarrow D^{*-} D^+ (\rightarrow 3\pi) \) is measured by computing the excess of candidates in the interval 1.9–2.0 GeV of the \( 3\pi \) mass distribution over the extrapolation of the neighbouring bins
Systematics

- 2.4% Fit algorithm and peaking backgrounds subtraction
  ▶ normalization, mean & width of the two Gaussians for $B^0 \bar{B}^0$ and $B^+ B^-$ peaking backgrounds, determined by Monte Carlo
  ▶ signal’s Crystal Ball PDF cutoff and power parameters (fixed on Monte Carlo)
- 2.0% Track-finding
  ▶ uncertainty on track efficiency from BABAR studies on data control samples
- 1.7% $3\pi$ invariant mass modeling
  ▶ 100% of the shift in efficiency when going from MC to data for the $3\pi$ mass distribution
- 0.7% $3\pi$ invariant mass sideband subtraction
  ▶ background subtraction uncertainty, estimated in Monte Carlo
- 1.3% $D^{*+}$ and $\bar{D}^0$ branching fractions uncertainties (PDG 2015)
- 1.2% $\mathcal{B}(\Upsilon(4S) \to B^0 \bar{B}^0)$ uncertainty (PDG 2015)
- 1.1% $K$ identification, as estimated by BABAR using data control samples
- 0.9% signal efficiency Monte Carlo statistics
- 0.6% estimate of the number of $\Upsilon(4S) \to B \bar{B}$ decays
- 4.3% total
Results

- $\mathcal{B}(\bar{B}^0 \to D^{*-} \pi^+ \pi^- \pi^+) = (7.37 \pm 0.11 \pm 0.31) \cdot 10^{-3}$
  - total uncertainty 4.5%, to be compared with 11.4% in PDG 2015
  - includes exclusive contributions like $B^0 \to D^{*-} D_s^+ (\to \pi^+ \pi^- \pi^+)$

- $\mathcal{B}(\bar{B}^0 \to D^{*-} \pi^+ \pi^- \pi^+ \text{ (ex. } D_s^+ \to \pi^+ \pi^- \pi^+)) = (7.26 \pm 0.11 \pm 0.31) \cdot 10^{-3}$

- to be submitted to PRD

Thanks for your attention
Measurement of $B(\bar{B}^0 \to D^{*-}\pi^+\pi^-\pi^+)$
• measurements of $R^{(*)} = \frac{\mathcal{B}(B \to D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)} \ell^- \bar{\nu}_\ell)}$
  
  ▶ HFAG Winter 2016 averages, 
  http://www.slac.stanford.edu/xorg/hfag/semi/winter16/winter16_dtaunu.html