Charmless $B$ decays at CDF

BEAUTY 2009
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for the CDF Collaboration
Main Entry: *charm *

Pronunciation: \cherm\n
Function: noun

Etymology: Middle English *charme*, from Anglo-French, from Latin *carmen* song, from *canere* to sing — more at CHANT

Date: 14th century

1 a: the chanting or reciting of a magic spell: INCANTATION b: a practice or expression believed to have magic power

2: something worn about the person to ward off evil or ensure good fortune: AMULET

3 a: a trait that fascinates, allures, or delights b: a physical grace or attraction — used in plural <her feminine charms> c: compelling attractiveness <the island possessed great charm>

4: a small ornament worn on a bracelet or chain

5: a fundamental quark that has an electric charge of +2/3 and a measured energy of approximately 1.5 GeV; also: the flavor characterizing this particle

- charm-less \cherm\-less \cherm\-less adjective
Charmless $B$ decays

Most popular processes in HF. Many open channels into similar final states allow constraining hadronic unknowns. $b \rightarrow u$ sensitive to CKM angle $\gamma$. Penguins enhance sensitivity to NP in loops.

V On the Autonomy of $B_s$ Dynamics

original paradigm: need $B_d$ & $B_s$ to determine all 3 angles

$\phi_2/\alpha$, $\phi_1/\beta$ from $B_d$ vs. $\phi_3/\gamma$ from $B_s$

new paradigm: can get all angles from $B_d$

Furthermore NP in general will not obey SM relations between $B$ and $B_s$ decays

$B_s(t) \rightarrow \psi\phi$, $\psi\eta$, $\phi\phi$ not a repetition of lessons from $B_d$ & $B_u$ decays!

stolen from I. Bigi, CERN Theory Institute, May 26, 2008
CDF a.k.a. charmless $B^0_s$ pioneers

This talk

Recent update of $B^0_s \rightarrow \phi \phi$ analysis;

Results on $B^0_{(s)} \rightarrow h^+ h^-$ decays;

Prospects.
The Tevatron

Superconducting proton-synchrotron: $36 (p) \times 36 (\bar{p})$ bunches collide every 396 ns at $\sqrt{s} = 1.96$ TeV

interactions/bunch-crossing .............. $< N >_{\text{poisson}} = 2$ (at $10^{32}$ cm$^{-2}$s$^{-1}$)

Luminous region size ...................... 30 cm (beam) $\times$ 30 µm (transverse)

need long Si-vertex small wrt $\tau(B) \sim 450$ µm

Luminosity ................................. record peak is $3.6 \times 10^{32}$ cm$^{-2}$ s$^{-1}$

> 50 pb$^{-1}$/ week on tape

5.7 fb$^{-1}$ on tape now.

Details on environment and detector in M. Kreps talk

BEAUTY2009, Sep 7, 2009
Hadronic trigger

1.5 ps lifetime of $b$-hadrons: a powerful signature.

Sufficiently boosted $B$ fly a path resolvable with vertex detectors before decaying.

Exploit it at the trigger level - an experimental challenge that requires:

1. **High resolution** vertex detector
2. **Read out** silicon (212,000 channels);
3. **Do pattern recognition** and **track fitting** within 25 $\mu$s
$B^0_s \rightarrow \phi \phi$
\( \bar{b} \rightarrow c\bar{c}s \quad B_s^0 \rightarrow J/\psi K^0_s \quad B_s^0 \rightarrow J/\psi \phi \quad \text{mixing} \)

\( b \rightarrow s\bar{s}s \quad B^0 \rightarrow \phi K^0_s \quad B^0 \rightarrow \eta' K^0_s \quad B_s^0 \rightarrow \phi \phi \quad \text{mixing or penguin} \)

Lots of statistics required. Polarization analysis already sensitive to NP.
Status

Some theory predictions
BR \sim 0.4-25 \times 10^{-6} \quad \text{PRD 59, 074003 (1999)}
BR \sim 37 \times 10^{-6} \quad \text{PRD 68, 114015 (2003)}

First (and only) evidence, CDF 2005
180 \text{ pb}^{-1}, 8 \text{ signal events}
BR = (14^{+6}_{-5} \pm 6) \times 10^{-6}

…some “post-dictions”
BR \sim 18-60 \times 10^{-6} \quad \text{PRD 76, 074018 (2007)}
BR \sim 4-53 \times 10^{-6} \quad \text{NPB 774, 64 (2007)}

CDF has now accumulated a factor of \sim 25 more in statistics
The measurement

Fit to mass in data

$$\frac{\text{BR}(B_s^0 \rightarrow \phi \phi)}{\text{BR}(B_s^0 \rightarrow J/\psi \phi)} = \frac{N_{\phi \phi}}{N_{J/\psi \phi}} \frac{\text{BR}(J/\psi \rightarrow \mu \mu)}{\text{BR}(\phi \rightarrow KK)} \frac{\epsilon_{\psi \phi}}{\epsilon_{\phi \phi}}$$

Use $B_s^0 \rightarrow J/\psi \phi$ as a reference rather than e.g. $B^0 \rightarrow \phi K^*$. Avoid dependence on fragmentation probabilities $f_s/f_d$.
Fresh off the trigger

$\phi\phi$-mass after trigger cuts
All you need is tracking

1.4T in 132 cm lever-arm. 96 drift chamber + 6 silicon samplings.

1st layer 1.5 cm from beam
Optimizing the selection

Unbiased maximization of $S/\sqrt{S+B}$.

$S$ is the number of simulated events. $B$ is the number of background events extrapolated from mass sidebands. Done separately for signal and reference mode.

Look for stiff kaons

Look for long-lived
The signal

$L_{xy} > 330 \, \mu m$

$IP_{\text{max}}(K) > 85 \, \mu m$

$IP(B) < 65 \, \mu m$

$p_T(K) > 0.7 \, \text{GeV/c}$

$Vtx \chi^2 < 17$

**Backgrounds**

- Combinatorics dominant
- $2.5\% B^0 \rightarrow \phi K^{*0}$ reflection
- $B^0_s \rightarrow K^{*0} K^{*0}$ negligible

40× increase in statistics since published result
Optimized reference \((B^0_s \rightarrow J/\psi \phi)\)

\[
L_{xy} > 290 \mu m \\
\text{IP}(B) < 65 \mu m \\
\text{Vtx } \chi^2 < 18 \\
p_T(J/\psi) > 2.0 \text{ GeV/c} \\
p_T(\phi) > 1.4 \text{ GeV/c}
\]

Aside: this adds +25% to sample collected in di-muon trigger.
Increase statistics for \(\sin 2\beta_s\) analysis.

Backgrounds
Combinatorics dominant

4% \(B^0 \rightarrow J/\psi K^{*0}\) reflections
Relative efficiency: trigger and selection

\[
\frac{\text{BR}(B_s^0 \rightarrow \phi \phi)}{\text{BR}(B_s^0 \rightarrow J/\psi \phi)} = \frac{N_{\phi\phi}}{N_{\psi\phi}} \frac{\text{BR}(J/\psi \rightarrow \mu \mu)}{\text{BR}(\phi \rightarrow KK)} \frac{\epsilon_{\psi\phi}}{\epsilon_{\phi\phi}} \epsilon_{\phi\phi}.
\]

Simulated signal reweighted in $p_T(B)$ and to reproduce trigger mix of data.

\[
\frac{\epsilon_{\psi\phi}}{\epsilon_{\phi\phi}} = 0.939 \pm 0.030 \pm 0.009
\]

- First uncertainty: finite statistics collected by each trigger.
- Second uncertainty: reweighing.
Relative efficiency: muon-ID

\[
\frac{\text{BR}(B^0_s \to \phi\phi)}{\text{BR}(B^0_s \to J/\psi\phi)} = \frac{N_{\phi\phi}}{N_{J/\psi\phi}} \frac{\text{BR}(J/\psi \to \mu\mu)}{\text{BR}(\phi \to KK)} \frac{\epsilon_{\psi\phi}}{\epsilon_{\phi\phi}} \epsilon_{\psi\phi},
\]

\[\epsilon_{\psi\phi}^{\mu} = 0.8695 \pm 0.0044 \text{(stat)}\]

Extracted from $J/\phi$ data as a function of $p_T$ and muon-detector.
Systematic uncertainties

✓ 6-7% from unknown polarization of $B \to VV$, which impacts acceptance;
✓ 3-4% from $K/\mu$ difference in trigger efficiency due to different ionization probability in the tracking chamber;
✓ 3% signal mass parameterization;
✓ 3% unmodeled backgrounds;
✓ 1% from $p_T$ reweighing, background subtraction etc…

$$N_{\phi\phi} = 295 \pm 20\text{(stat)} \pm 12\text{(syst)}$$
$$N_{J/\psi} = 1766 \pm 48\text{(stat)} \pm 41\text{(syst)}$$
Results

\[
\frac{BR(B_s^0 \to \phi \phi)}{BR(B_s^0 \to J/\psi \phi)} = [1.78 \pm 0.14(stat) \pm 0.20(syst)] \cdot 10^{-2}
\]

Use \(BR(B_s^0 \to J/\psi \phi)\) from PDG, updated to current values of \(f_s/f_d\)

\[
BR(B_s^0 \to \phi \phi) = [2.40 \pm 0.21(stat) \pm 0.27(syst) \pm 0.82(BR)] \cdot 10^{-5}
\]

Compare with \((BR/10^{-5})\)

<table>
<thead>
<tr>
<th>previous CDF result</th>
<th>1.4 (^{+0.6}_{-0.5}) (\pm) 0.6</th>
<th>PRL 95 031801 (2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>theory (QCD)</td>
<td>2.18 (\pm) 0.1 (^{+3.04}_{-1.78})</td>
<td>NP B774, 64, (2007)</td>
</tr>
<tr>
<td>theory (pQCD)</td>
<td>3.53 (^{+0.83}<em>{-0.69}) (^{+1.67}</em>{-1.02})</td>
<td>PR D76, 074018 (2007)</td>
</tr>
</tbody>
</table>
Working at the polarization analysis.

$B^0_s$ (pseudoscalar) $\rightarrow \phi$ (vector) $\phi$ (vector). Final states CP-even (S- or D-wave, short-lived and light) and CP-odd (P-wave, long-lived, heavy).

Rich structure: presence of both CP-states provides additional information on underlying dynamics and sensitivity to NP.
Polarization

Anomaly: measured \( f_T = 1 - f_L \sim 0.5 \) in \( B_0^{(+)} \rightarrow \phi K^{*(+)} \) disagree with 1st order estimate from theory

\[
\bar{A}_0 : \bar{A}_- : \bar{A}_+ = 1: \frac{\Lambda}{m_b} : \left( \frac{\Lambda}{m_b} \right)^2 \quad 1 - f_L = \mathcal{O} \left( \frac{m_V^2}{m_B^2} \right), \quad \frac{f_\perp}{f_\parallel} = 1 + \mathcal{O} \left( \frac{m_V}{m_B} \right)
\]


All above are model dependent or not conclusive: NP option still valid: e.g. scalar interaction or SUSY would introduce \( 1 + \gamma^5 \) terms in amplitude.

Further experimental info key to discriminate. \( B_0^s \rightarrow \phi \phi + \text{SU(3)} \) checks for "penguin annihilation" EPJ C60 (2009)

Analysis in progress - \( \mathcal{O}(5\%) \) resolution on amplitudes expected.
$B^0_{(s)} \rightarrow h^+ h'^-$
Two-body charmless decays

$B^0$ and $B^0_s \rightarrow K^+K^-, \pi^+\pi^-, K\pi$ and sensitive to $\gamma$ (PL B459, 306 (1999)) and NP (PL B492, 297 (2000), PL B621,126, (2005)). Theory and exp. uncertainties largely cancel thanks to flavor symmetries and similar final states.

CDF has world’s largest sample:

4K $B^0 \rightarrow K^+\pi$ and 1.3K $B^0_s \rightarrow K^+K^-$ per fb$^{-1}$.

Unique joint access to large samples of charmless $B^0$ and $B^0_s$.

Challenging analysis but fruitful:

✓ observation of 4 new modes (so far)
✓ unique access to direct CPV in $B^0_s$
✓ competitive in direct CPV in $B^0$
# Two-body charmless results (1 fb$^{-1}$)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Relative $\mathcal{B}$</th>
<th>Absolute $\mathcal{B}$ (10$^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to K^- \pi^+$</td>
<td>$f_1 \frac{\mathcal{B}(B^0 \to K^- \pi^+)}{\mathcal{B}(B^0 \to K^- \pi^-)} = 0.071 \pm 0.010 \pm 0.007$</td>
<td>$5.0 \pm 0.7 \pm 0.8$</td>
</tr>
<tr>
<td>$B^0 \to \pi^+ \pi^-$</td>
<td>$f_2 \frac{\mathcal{B}(B^0 \to \pi^+ \pi^-)}{\mathcal{B}(B^0 \to K^- \pi^-)} = 0.007 \pm 0.004 \pm 0.005$</td>
<td>$0.49 \pm 0.28 \pm 0.36 (&lt; 1.2$ at 90% C.L.)</td>
</tr>
<tr>
<td>$B^0 \to K^+ K^-$</td>
<td>$f_3 \frac{\mathcal{B}(B^0 \to K^+ K^-)}{\mathcal{B}(B^0 \to K^- \pi^-)} = 0.020 \pm 0.008 \pm 0.006$</td>
<td>$0.39 \pm 0.16 \pm 0.12 (&lt; 0.7$ at 90% C.L.)</td>
</tr>
<tr>
<td>$\Lambda_b^0 \to pK^-$</td>
<td>$f_4 \frac{\mathcal{B}(\Lambda_b^0 \to pK^-)}{\mathcal{B}(\Lambda_b^0 \to pK^+)} = 0.066 \pm 0.009 \pm 0.008$</td>
<td>$5.6 \pm 0.8 \pm 1.5$</td>
</tr>
<tr>
<td>$\Lambda_b^0 \to p\pi^-$</td>
<td>$f_5 \frac{\mathcal{B}(\Lambda_b^0 \to p\pi^-)}{\mathcal{B}(\Lambda_b^0 \to p\pi^+)} = 0.042 \pm 0.007 \pm 0.006$</td>
<td>$3.5 \pm 0.6 \pm 0.9$</td>
</tr>
</tbody>
</table>

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**Mode**

<table>
<thead>
<tr>
<th>$B^0 \to \pi^+ \pi^-$</th>
<th>Relative $\mathcal{B}$</th>
<th>Absolute $\mathcal{B}$ (10$^{-6}$)</th>
</tr>
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<tbody>
<tr>
<td>$B^0 \to \pi^+ \pi^-$</td>
<td>$\frac{\mathcal{B}(B^0 \to \pi^+ \pi^-)}{\mathcal{B}(B^0 \to K^+ \pi^-)} = 0.259 \pm 0.017 \pm 0.016$</td>
<td>$5.02 \pm 0.33 \pm 0.35$</td>
</tr>
<tr>
<td>$B_s^0 \to K^+ K^-$</td>
<td>$f_s \frac{\mathcal{B}(B_s^0 \to K^+ K^-)}{\mathcal{B}(B_s^0 \to K^+ \pi^-)} = 0.347 \pm 0.020 \pm 0.021$</td>
<td>$24.4 \pm 1.4 \pm 3.5$</td>
</tr>
</tbody>
</table>

**Mode**

<table>
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<tr>
<th>$B^0 \to K^+ \pi^-$</th>
<th>$\text{CP-asymmetry}$</th>
</tr>
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<tr>
<td>$B^0 \to K^+ \pi^-$</td>
<td>$\frac{\mathcal{B}(B^0 \to K^+ \pi^-) - \mathcal{B}(B^0 \to K^+ \pi^+)}{\mathcal{B}(B^0 \to K^+ \pi^-) + \mathcal{B}(B^0 \to K^+ \pi^+)} = -0.086 \pm 0.023 \pm 0.009$</td>
</tr>
<tr>
<td>$B_s^0 \to K^- \pi^+$</td>
<td>$\frac{\mathcal{B}(B_s^0 \to K^- \pi^+) - \mathcal{B}(B_s^0 \to K^- \pi^-)}{\mathcal{B}(B_s^0 \to K^- \pi^+) + \mathcal{B}(B_s^0 \to K^- \pi^-)} = +0.39 \pm 0.15 \pm 0.08$</td>
</tr>
<tr>
<td>$\Lambda_b^0 \to pK^-$</td>
<td>$\frac{\mathcal{B}(\Lambda_b^0 \to pK^-) - \mathcal{B}(\Lambda_b^0 \to pK^+)}{\mathcal{B}(\Lambda_b^0 \to pK^-) + \mathcal{B}(\Lambda_b^0 \to pK^+)} = +0.37 \pm 0.17 \pm 0.03$</td>
</tr>
<tr>
<td>$\Lambda_b^0 \to p\pi^-$</td>
<td>$\frac{\mathcal{B}(\Lambda_b^0 \to p\pi^-) - \mathcal{B}(\Lambda_b^0 \to p\pi^+)}{\mathcal{B}(\Lambda_b^0 \to p\pi^-) + \mathcal{B}(\Lambda_b^0 \to p\pi^+)} = +0.03 \pm 0.17 \pm 0.05$</td>
</tr>
</tbody>
</table>

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**BEAUTY2009, Sep 7, 2009**

D. Tonelli
5 fb\(^{-1}\) analysis in progress

- Expect observation of DCPV in \(B^0_s\).
- DCPV in \(B^0\) competitive with Belle.
- Precision measurement of rare modes’ BR.
- Observe new modes? (aim at \(B^0_s \to \pi^+\pi^-\))
Outlook

More than 8 fb\(^{-1}\) of physics-quality data on tape by end of 2010. 10 fb\(^{-1}\) by 2011, if Run II further extended.

2.7x-8x (3.5x-10x) increase in currently analyzed samples.
CDF keep harvesting from rich and unique program on charmless $B^0_s$. Recent 2.9 fb$^{-1}$ update of $B^0_s \rightarrow \phi\phi$ – NP in $b \rightarrow s\bar{s}s$ penguin or mixing:

- ~halved BR uncertainty. Polarization analysis in progress.

Charmless $B^0_{(s)} \rightarrow h^+h^-$ - test for NP and constrain hadronic unknowns for $\gamma$ from penguins:

- Many new decays observed - BR and DCPV measured. 5 fb$^{-1}$ analysis in progress.

Only 1/8 – 1/3 of data expected by end 2010 shown. Analyses steadily improving. Psychological advantage: lots of data, complex analyses already set up, all pressure is on CERN.

Sitting on goldmine of data: a few exciting years of competition with LHCb are coming.
The CDF II detector

- 7 to 8 silicon layers
- $1.6 < r < 28$ cm, $|z|<45$ cm
- $|\eta| \leq 2.0$  $\sigma$(hit) $\sim 15 \, \mu$m

1.6 T magnetic field
Lever arm 132 cm

132 ns front end chamber tracks at L1
silicon tracks at L2
25000 / 300 / 100 Hz
with dead time < 5%

time-of-flight
110 ps at 150 cm
$p, K, \pi$ identific.
$2\sigma$ at $p_T<1.6$ GeV

Some resolutions:
- $p_T\sim0.15\% \, p_T$ (c/GeV)
- $J/\Psi$ mass $\sim14$ MeV
- $IP\sim 40 \, \mu$m
(includes beam spot)

96 layer drift chamber $|\eta| \leq 1.0$
- $44 < r < 132$ cm, $|z|<155$ cm
- 30k channels, $\sigma$(hit) $\sim 140 \, \mu$m
- $dE/dx$ for $p, K, \pi$ identification

$\mu$ coverage
- $|\eta| \leq 1.5$
- 84% in $\phi$
$B^0_s \rightarrow \phi \phi$ - optimization
$B^0_{(s)} \rightarrow h^+ h'^-$ - the second challenge

Insufficient mass and PID resolution to discriminate decay modes on a per-event basis
\[ B^0 (s) \rightarrow h^+ h' - \text{ depuzzling sample composition} \]

Any (arbitrary) mass assignment correlated with and momentum imbalance

Output pulse-width of 96 COT samplings \( \propto \log(Q) \). 1.5\( \sigma \) K/\( \pi \) separation at \( p > 2 \text{ GeV/c} \)

Statistical separation using kinematics and PID folded in a 5-dimensional ML fit.
\[ B^0_{(s)} \rightarrow h^+ h' \] - a model independent NP test

Unitarity of CKM matrix implies:

\[ \text{Im}(V_{ub}^* V_{us} V_{cb} V_{cs}^*) = -\text{Im}(V_{ub}^* V_{ud} V_{cb} V_{cd}^*) \]

It implies relation between differences of CP-rates that is valid only in the SM. Unambiguous check if DCPV is induced by NP vs SM amplitudes.

\[ \Gamma(\bar{B}^0 \rightarrow K^- \pi^+) - \Gamma(B^0 \rightarrow K^+ \pi^-) = \Gamma(B^0_s \rightarrow K^- \pi^+) - \Gamma(\bar{B}^0_s \rightarrow K^+ \pi^-) \]

We measure:

\[ \frac{\Gamma(\bar{B}^0 \rightarrow K^- \pi^+) - \Gamma(B^0 \rightarrow K^+ \pi^-)}{\Gamma(\bar{B}^0_s \rightarrow K^+ \pi^-) - \Gamma(B^0_s \rightarrow K^- \pi^+)} = -0.83 \pm 0.41(\text{stat.}) \pm 0.12(\text{syst.}) \]

(-1 in the SM)

Still limited by statistics. Now, with 5x more data on tape promising chance to probe NP in these decays.