New measurement of the $B^0_s$ mixing phase and observation of suppressed $B^0_s$ decays at CDF

Louise Oakes, for the CDF collaboration
Technische Universität München

DISCRETE2010
Rome, 10th December 2010
Recent CDF $B_s^0$ analyses:

- Updated measurement of $\sin(2\beta_s)$
  - Using 5.2 fb$^{-1}$ integrated luminosity
  - Improved Particle ID and flavour tagging

- Calibration of Same Side Kaon Tagger through $B_s^0$ mixing measurement
  - Important flavour tagger for $\beta_s$ analysis

- Observation of 2 suppressed $B_s^0$ decay channels
  - $B_s \rightarrow J/\psi K^*$
  - $B_s \rightarrow J/\psi K_s$
CDF at the Tevatron

- p-pbar collisions at 1.96TeV
- Constantly improving luminosity performance
  - peak instantaneous luminosity $>3 \times 10^{32}$ cm$^{-2}$s$^{-1}$
  - $\sim 8$ fb$^{-1}$ delivered to the experiments

B physics at CDF:
- Particle ID: dE/dx and TOF
- Excellent vertex resolution
  - $\sim 23\mu$m and $p_T$ resolution: $\sigma (p_T)/p_T^2 \sim 0.1\%$
- Di-muon trigger important for $B \rightarrow J/\psi X$ analyses
Latest CDF $\sin(2\beta_s)$ results with 5.2 fb$^{-1}$
New particles could enter weak mixing box diagrams and enhance CP violation.

Time evolution of flavour tagged $B_s \rightarrow J/\psi \phi$ decays is very sensitive to New Physics.

- Decay width difference, $\Delta \Gamma$ and mixing phase would be effected by additional NP phase.
Previous measurements

CDF: 1.3 fb⁻¹ result
P-value for SM point = 15% -> significance 1.5σ

CDF: 2.8 fb⁻¹ result
P-value for SM point = 7% -> significance 1.8σ

Tevatron combination: probability of observed deviation from SM = 3.4% (2.12σ)

PRL 100, 161802 (2008)

Behaviour of likelihood fit prevents giving $\beta_s$ measurement as a point value - instead produce likelihood contours

CDF Public Note 9787

CDF Public Note 9458
Analysis overview

Reconstruct $B_s \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) \phi (\rightarrow K^+ K^-)$

Di-muon trigger

NN selection

Simultaneous mass, angular, time dependent, flavour tagged fit

$B_s$ mass fit to separate signal from bkg

Angular separation of CP eigenstates

Time dependence of decay

Flavour tagging to separate $B_s$ and $\overline{B}_s$ decays

10th December 2010
Data sample and selection for update

Statistically limited analysis - high quality selection is essential:

- Key role of particle ID
  - recalibrated for this result
- Neural network selection
  - optimised on pseudo experiments to minimise statistical errors on $\beta_s$

- Integrated luminosity: 5.2 fb$^{-1}$
- Signal events: ~6500 (c.f. 2.8 fb$^{-1}$ with ~3150 signal events)

10th December 2010
**B flavour tagging and the likelihood fit**

### Opposite side tag (OST):
- Jet charge and lepton charge taggers
- Tag flavour of opposite side $b$ quark
- $\varepsilon D^2 \approx 1.2\%$

### Same side tag (SST):
- Kaon tags flavour of $s$ quark in $B_s$
- $\varepsilon D^2 \approx 3.2\%$

Fit without flavour tagging, has four fold ambiguity:
- $\beta_s$ and $\Delta \Gamma$ symmetric
- strong phases symmetric about pi

\[
\begin{align*}
\beta_s & \rightarrow \frac{\pi}{2} - \beta_s \\
\Delta \Gamma & \rightarrow - \Delta \Gamma \\
\phi_{||} & \rightarrow 2\pi - \phi_{||} \\
\phi_{\perp} & \rightarrow \pi - \phi_{\perp}
\end{align*}
\]

Addition of flavour tagging allows us to follow time dependence of $B_s$ and $B_s$ separately

$\rightarrow$ Removes half of the ambiguity

CDF pseudo experiments

<table>
<thead>
<tr>
<th>2$\beta_s$ (rad)</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>-0.2</td>
</tr>
<tr>
<td>2</td>
<td>-0.4</td>
</tr>
<tr>
<td>2</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

- 95% CL tagged fit
- 68% CL tagged fit
- 95% CL untagged fit
- 68% CL untagged fit
B flavour tagging: SSKT calibration

- SSKT updated for this analysis
- calibrated on $B_s$ mixing measurement
- $B_s$ mixing measured with $5.2\text{fb}^{-1}$
- First CDF calibration of a SSKT on data
- Uses several decay modes:

\[
B_s^0 \to D_s^- \pi^+, \ D_s^- \to \phi^0\pi^-, \ \phi^0 \to K^+K^- \\
B_s^0 \to D_s^- \pi^+, \ D_s^- \to K^K-, \ K^* \to K^+\pi^- \\
B_s^0 \to D_s^- \pi^+, \ D_s^- \to (3\pi)^- \\
B_s^0 \to D_s^- (3\pi)^+, \ D_s^- \to \phi^0\pi^-, \ \phi^0 \to K^+K^- \\
\]

12877±113 combined signal events

B flavour tagging: SSKT calibration

- Mixing amplitude $\approx 1$:
  - Tagger assesses its performance accurately
- Amplitude $> 1$
  - Tagger underestimates its power
- Amplitude $< 1$
  - Tagger overestimates performance
- Measured amplitude used to scale event by event tagging dilution

Agreement between this and the published CDF measurement is very good

$A = 0.94 \pm 0.15 \text{ (stat.)} \pm 0.13 \text{ (syst.)}$

$\Delta m_s = 17.79 \pm 0.07 \text{ ps}^{-1} \text{ (stat. only)}$

$\epsilon A^2 D^2 \approx 3.2 \pm 1.4 \%$
S-wave contamination

- Potential contamination of $B_s \rightarrow J/\psi \phi$ signal by: $B_s \rightarrow J/\psi$ KK (KK non-resonant) and $B_s \rightarrow J/\psi f^0$ where KK and $f^0$ are S-wave states
- Contamination could bias towards SM value of $\beta_s$
- S-wave KK component has been added to full angular, time-dependent likelihood fit.

The fitted fraction of KK S-wave contamination in the signal is $< 6.7\%$ at the 95% CL
Checking the fitter: projections

Fit projections on physical parameters such as $B_s$ lifetime used to check performance of the likelihood fit.

- Angular distributions are used to separate CP odd and even final states.
- Angular projections used to check our parameterisation of the angular distributions.

$B_s$ lifetime distribution consisting of:
- $B_s^H$ (short lived)
- $B_s^L$ (long lived)
Flavour tagged fit with $\beta_s = 0.0$

- Tagged $B_s \rightarrow J/\psi \phi$ likelihood fit
- CP violating phase, $\beta_s = 0$, set to SM prediction

PDG value:

$$\tau_s = 1.47^{+0.026}_{-0.027} \text{ ps}$$

CDF II Preliminary 5.2 fb$^{-1}$

$$\tau_s = 1.53 \pm 0.025 \text{ (stat.)} \pm 0.012 \text{ (syst.) ps}$$

$$\Delta \Gamma = 0.075 \pm 0.035 \text{ (stat.)} \pm 0.01 \text{ (syst.) ps}^{-1}$$

$$|A_{||}(0)|^2 = 0.231 \pm 0.014 \text{ (stat.)} \pm 0.015 \text{ (syst.)}$$

$$|A_0(0)|^2 = 0.524 \pm 0.013 \text{ (stat.)} \pm 0.015 \text{ (syst.)}$$

$$\phi_\perp = 2.95 \pm 0.64 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$$

World’s most precise single measurement of $B_s$ lifetime and decay width difference
New CDF measurement of $\beta_s$

Coverage adjusted 2D likelihood contours for $\beta_s$ and $\Delta \Gamma$

P-value for SM point: 44% (0.8$\sigma$ deviation)

(68% CL):

$[0.02, 0.52] \cup [1.08, 1.55]$

(95% CL):

$[-0.13, 0.68] \cup [0.89, \pi/2]$

$\cup [-\pi/2, -1.44]$
Comparisons

new CDF result

2D likelihood contours for $\beta_s$ and $\Delta \Gamma$ without coverage adjustment

Inclusion in the fit of S-wave KK ($f^0$) contamination to phi meson signal has small effect on likelihood contours
Future prospects

- Tevatron delivering record luminosity, CDF records \( \sim 60 \text{pb}^{-1} \) per week

- End of 2011: double again the dataset, further improvements to analysis

- Search for NP in \( B_s^0 \) mixing at CDF has potential to observe/exclude wide range of non-SM mixing phase values

- Investigating other channels related to this physics – such as recently observed

\[ B_s \rightarrow J/\Psi K_s \text{ and } B_s \rightarrow J/\Psi K^* \]
Observation of new suppressed $B_s^0$ decays and measurement of their branching ratios
Observation of previously unseen $B_s$ decays:

$B_s^0 \rightarrow J/\Psi K_s$
$B_s^0 \rightarrow J/\Psi K^*$

- Binned maximum likelihood fit to find ratios of $B^0$ and $B_s^0$ to each final state
- Exploit strong mass and lifetime resolution
- 3 Gaussian templates used to model both $B^0$ and $B_s^0$
- Exponential models combinatorial background
- Relative acceptance factor calculated from MC

Suppressed $B_s$ decays

$B_s \rightarrow J/\psi \ K^*$

- Admixture of $CP$ states
- Possible extraction of $\sin(2\beta_s)$
- $8 \sigma$ significance
- Yield: $151 \pm 25$
- $B^0\rightarrow J/\psi \ K^*$ yield: $9530\pm110$

\[
\frac{BR(B^0_s \rightarrow J/\psi K^*)}{BR(B^0 \rightarrow J/\psi K^*)} = (0.041 \pm 0.007 \text{ (stat.)} \pm 0.004 \text{ (syst.)} \pm 0.005 \text{ (frag.)})
\]
Suppressed $B_s$ decays

$B_s \rightarrow J/\psi \ K_s$

- pure $CP$ odd state
- access to $B_s^H$ lifetime
- access to unitarity triangle angle $\gamma$
- 7.2 $\sigma$ significance
- Yield: $64 \pm 14$
  - $B^0 \rightarrow J/\psi \ K_s$ yield: $5954 \pm 79$

\[
\frac{BR(B_s^0 \rightarrow J/\psi K^0)}{BR(B^0 \rightarrow J/\psi K^0)} = (0.062 \pm 0.009 \text{ (stat.)} \pm 0.025 \text{ (syst.)} \pm 0.008 \text{ (frag.)})
\]
Summary

Updated CDF search for NP in $B_s^0 \rightarrow J/\psi\phi$

- Tightened constraints on CP violating phase $\beta_s$
  
  \begin{align*}
  [0.02, 0.52] & \cup [1.08, 1.55] \quad (68\% \text{ CL}) \\
  [-0.13, 0.68] & \cup [0.89, \pi/2] \cup [-\pi/2, -1.44] \quad (95\% \text{ CL})
  \end{align*}

- P-value for SM point: 44\% (0.8\sigma)

- World’s best measurement of $B_s$ lifetime and decay width
difference in hypothesis of no CP violation

- SSKT calibrated on updated $B_s$ mixing measurement

First observation of 2 suppressed $B_s$ decays, with high
significance

- Measurement of Branching Ratios

  \begin{align*}
  BR(B_s^0 \rightarrow J/\psi K^*) &= (8.3 \pm 1.2 \text{ (stat.)} \pm 3.3 \text{ (syst.)} \pm 1.0 \text{ (frag.)} \pm 0.4 \text{ (PDG)}) \times 10^{-5} \\
  BR(B_s^0 \rightarrow J/\psi K^0) &= (3.53 \pm 0.61 \text{ (stat.)} \pm 0.35 \text{ (syst.)} \pm 0.43 \text{ (frag.)} \pm 0.13 \text{ (PDG)}) \times 10^{-5}
  \end{align*}

- With sufficient statistics, both could be used to extract
parameters of interest for CP violation measurements
Back up
Opposite side tag (OST):

- b quarks are pair produced (strong interaction -> flavour conservation)
- Can deduce properties of the candidate $B$ meson from decay of the $B$ hadron formed by the pair produced partner of its $b$ quark
- $b$ or $\bar{b}$ content of charged opposite side $B$ can be identified by
  - Jet charge
  - Lepton charge ($e$, $\mu$)
- $\epsilon D^2 \approx 1.2\%$

Same side kaon tag (SSKT):

- Sign of kaon from primary vertex of candidate $B$ can tag $B_s$ or $\bar{B}_s$ flavour
- Kaon contains the pair produced $s$ ($\bar{s}$) quark of the $B_s$
- $\epsilon D^2 \approx 3.2\%$

Important tagging parameters:
tag decision, tagging dilution (weight) and tagging efficiency
Inclusion of S-wave KK component

- S-wave KK component has been added to full angular, time-dependent likelihood fit.
- Both $f_0$ and non-resonant KK are considered flat in mass within the small selection window,
- $\Phi$ meson mass is modelled by asymmetric, relativistic Breit Wigner
- $J/\psi$ KK ($f_0$) is pure CP odd state $\rightarrow$ follows time dependence of CP odd component of $B_s \rightarrow \Psi \phi$
- KK mass is NOT a fit parameter

The fitted fraction of KK S-wave contamination in the signal is $< 6.7\%$ at the 95% CL
Potential NP contributions

- 4th generation could enhance the weak mixing diagram in the neutral $B_s$ system
- George W.S. Hou suggests the $t'$ as a possible contribution to the mixing box diagrams
- SM contains the ingredients to generate the 100% Baryon Asymmetry of the Universe (BAU)
- Predicted CP violation from 3 generations is negligible compared to what is observed in BAU
- 4th generation of quarks would lead to “unitarity quadrangle”
  -> enhances SM CP violation by 10 orders of magnitude!

arXiv:0803.1234v3  George W.S. Hou
Systematic study for point estimates uses pseudo experiments to estimate potential effects of any mis-parameterisations in the fitter.

2 techniques used:

- Generating pseudo experiments using an altered parameterisation, fitting with default model
- Generating pseudo experiments according to histograms of real data distribution

| Systematic                               | $\Delta \Gamma$ | $c\tau_s$ | $|A_{\|}(0)|^2$ | $|A_{\perp}(0)|^2$ | $\phi_{\perp}$ |
|-----------------------------------------|----------------|-----------|----------------|----------------|--------------|
| Signal efficiency:                      |                |           |                |                |              |
| Parameterisation                        | 0.0024         | 0.96      | 0.0076         | 0.008          | 0.016        |
| MC reweighting                          | 0.0008         | 0.94      | 0.0129         | 0.0129         | 0.022        |
| Signal mass model                       | 0.0013         | 0.26      | 0.0009         | 0.0011         | 0.009        |
| Background mass model                   | 0.0009         | 1.4       | 0.0004         | 0.0005         | 0.004        |
| Resolution model                        | 0.0004         | 0.69      | 0.0002         | 0.0003         | 0.022        |
| Background lifetime model               | 0.0036         | 2.0       | 0.0007         | 0.0011         | 0.058        |
| Background angular distribution:        |                |           |                |                |              |
| Parameterisation                        | 0.0002         | 0.02      | 0.0001         | 0.0001         | 0.001        |
| $\sigma(c\tau)$ correlation            | 0.0002         | 0.14      | 0.0007         | 0.0007         | 0.006        |
| Non-factorisation                       | 0.0001         | 0.06      | 0.0004         | 0.0004         | 0.003        |
| $B^0 \rightarrow J/\psi K^*$ crossfeed | 0.0014         | 0.24      | 0.0007         | 0.0010         | 0.006        |
| SVX alignment                           | 0.0006         | 2.0       | 0.0001         | 0.0002         | 0.002        |
| Mass error                              | 0.0001         | 0.58      | 0.0004         | 0.0004         | 0.002        |
| $c\tau$ error                           | 0.0012         | 0.17      | 0.0005         | 0.0007         | 0.013        |
| Pull bias                               | 0.0028         |           | 0.0013         | 0.0021         |              |
| **Totals**                              | 0.01           | 3.6       | 0.015          | 0.015          | 0.07         |
### Point estimates: results comparison

<table>
<thead>
<tr>
<th></th>
<th>Tagged, with S-wave</th>
<th>Tagged, no S-wave</th>
<th>Untagged, with S-wave</th>
<th>Untagged, no S-wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c\tau$</td>
<td>$458.64 \pm 7.54$ (stat.) $\mu m$</td>
<td>$459.1 \pm 7.7$ (stat.) $\mu m$</td>
<td>$456.93 \pm 7.69$ (stat.) $\mu m$</td>
<td>$457.2 \pm 7.9$ (stat.) $\mu m$</td>
</tr>
<tr>
<td>$\Delta \Gamma$</td>
<td>$0.075 \pm 0.035$ (stat.) $ps^{-1}$</td>
<td>$0.073 \pm 0.03$ (stat.) $ps^{-1}$</td>
<td>$0.071 \pm 0.036$ (stat.) $ps^{-1}$</td>
<td>$0.070 \pm 0.04$ (stat.) $ps^{-1}$</td>
</tr>
<tr>
<td>$</td>
<td>A_\parallel</td>
<td>^2$</td>
<td>$0.231 \pm 0.014$ (stat.)</td>
<td>$0.232 \pm 0.014$ (stat.)</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
<td>^2$</td>
<td>$0.524 \pm 0.013$ (stat.)</td>
<td>$0.523 \pm 0.012$ (stat.)</td>
</tr>
<tr>
<td>$\phi_\perp$</td>
<td>$2.95 \pm 0.64$ (stat.)</td>
<td>$2.80 \pm 0.56$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Measurement of $\beta_s$: coverage adjustment

Use likelihood ratio ordering technique to account for non-Gaussian behaviour (ensure confidence regions not under-covered) and to include effect of systematics on the errors:

- Generate pseudo experiments at the SM point in the $\Delta\Gamma-\beta_s$ plane.
- Fit with all parameters floating
- Fit again with $\Delta\Gamma$ and $\beta_s$ fixed to the SM point
- Form a likelihood ratio:

$$\mathcal{L}\mathcal{R} = 2 \log \frac{\mathcal{L}(\beta_s^{J/\psi\phi}, \Delta\Gamma, \tilde{\xi})}{\mathcal{L}(\tilde{\xi})}$$
Measurement of $\beta_s$

- Ideal case: produce fit value of $\beta_s$ as we do for lifetime, etc.
- At current statistical level, fit shows some bias for $\beta_s$
- Instead, produce 2D likelihood contours in $\beta_s$ - $\Delta \Gamma$ space
  - Perform fits on data with $\beta_s$ and $\Delta \Gamma$ fixed at 400 points on 20x20 grid
  - Ratio of log likelihood value for fit at each point to the global minimum used to construct likelihood contour plots
  - Use profile-likelihood ratio ordering technique to ensure coverage
**CP violation in neutral $B_s$ system**

Flavour eigenstates:

$|B_s^0\rangle = (\bar{b}s)$

$|\bar{B}_s^0\rangle = (b\bar{s})$

Mixing of flavour eigenstates is governed by:

$$\frac{d}{dt} \left( \frac{B_s^0(t)}{\bar{B}_s^0(t)} \right) = H \left( \frac{B_s^0(t)}{\bar{B}_s^0(t)} \right) = \left[ \begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix} \right] \left( \frac{B_s^0(t)}{\bar{B}_s^0(t)} \right)$$

Mass matrix

Decay matrix

Flavour eigenstates are not mass eigenstates:

$$|B_s^H\rangle = p |B_s^0\rangle - q |\bar{B}_s^0\rangle$$

$$|B_s^L\rangle = p |B_s^0\rangle + q |\bar{B}_s^0\rangle$$

Different masses $\rightarrow$ mixing frequency:

$$\Delta m_s = m_H - m_L \approx 2|M_{12}|$$

$\rightarrow$ phase:

$$\varphi_s^{SM} = \text{arg}(-M_{12}/\Gamma_{12}) \approx 0.004$$

Different decay widths:

$$\Delta \Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}| \cos(2\varphi_s^{SM})$$
Fit function: angular separation

Final state is a mixture of CP even (~75%) and odd (~25%) states.

Three angular momentum states of $J/\psi$ phi:
- L=0  S-wave   CP even
- L=1  P-wave   CP odd
- L=2  D-wave   CP even

Can separate final CP states using angular variables

Transversity basis describes these contributions as: $A_0$, $A_//$(CP even), $A_{\perp}$(CP odd) according to their polarisation.

Can be separated using the angular distributions of the final state particles
Comparison of data periods

- Data 0-1.35 fb⁻¹
- S-wave not included

- Data 1.35-2.8 fb⁻¹
- S-wave not included

- Data 2.8-5.2 fb⁻¹
- S-wave not included