Measurement of CP violation in $B$-meson decays at DØ

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http://www-d0.fnal.gov/~rakitin/SLAC.pdf
Why study CP-violation?

• To explain baryon asymmetry of the Universe we need sources of CP-violation from beyond the Standard Model

• SM predicts CPV effects to be relatively small

• Many New Physics models may significantly increase these effects [hep-ph/9803370]:
  - Multi-Higgs Doublet models with no “Natural Flavor Conservation”
  - Supersymmetric models with “Effective SUSY”
  - Supersymmetric models with “R-Parity Violation”
  - Left-Right Symmetric models
  - 4th generation models
  - $Z$-mediated Flavor Changing Neutral Currents

Measurement of the large CPV where it is predicted to be small may reveal NP
Why CP-violation in $B$ mesons?

- $B$-factories excluded large NP contributions from tree-level $B$-decays
- SM predicts small CP phases at loop-level $B$-decays but large phases from NP are still possible [hep-ph/9803370, hep-ph/0210167]
- SM also predicts small direct CP asymmetries in $B$ mesons, which NP may increase
- The decays $B_s \rightarrow J/\psi \phi$ (CP-violating phase) and $B^+ \rightarrow J/\psi K$ (CP asymmetry) are ideal for investigating these effects

I am going to talk about these two analyses performed at DØ experiment at Tevatron
Tevatron Collider at Fermilab

- 36 × 36 \( p\bar{p} \) bunches, \( 10^{12} (10^{10}) \) \( p \) (\( \bar{p} \)) per bunch
- Bunches collide every 396 ns at CM energy 1.96 TeV
- Record \( \mathcal{L}_{\text{inst}} = 315 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1} \)
- \( \int \mathcal{L} dt \) up to 50 pb\(^{-1}\)/week!
- Integrated \( \mathcal{L} \sim 3.4 \text{ fb}^{-1} \) on tape, up to \( \sim 2.8 \text{ fb}^{-1} \) used
DØ Detector

- Silicon and fiber trackers immersed into 2 T solenoid, coverage $|\eta| < 3$
  - Precise vertexing and tracking
  - New Layer 0 silicon on beam pipe in 2006 improves impact parameter resolution
- Muon system (central + forward), coverage $|\eta| < 2$
  - Includes its own magnet – toroid
- Two magnets – solenoid and toroid – flip polarities every two weeks
  - Unique feature of DØ
  - Diminishes detector asymmetries
Measurement of direct CP-violation in $B^+ \rightarrow J/\psi K^+$ decay
The decay $B^\pm \rightarrow J/\psi K^\pm$ goes via two diagrams:

- Their interference produces small asymmetry $A_{CP} = 0.003$
- New Physics can significantly enhance this asymmetry
Analysis outline

- We divide \( J/\psi K \) sample into 8 categories according to:
  - Solenoid polarity, \( \beta \)
  - Sign of kaon pseudorapidity, \( \gamma \)
  - Kaon charge, \( q \)

- Number of events in each category:
  \[
  n^{\beta\gamma}_q = \frac{1}{4} N \epsilon^\beta (1 + q A^{raw}) (1 + \gamma A_{det}) (1 + q \gamma A_{fb}) (1 + q \beta A_{q\beta}) (1 + \beta \gamma A_{\beta\gamma}) (1 + q \beta \gamma A_{\beta\gamma} A_{ro})
  \]
  where
  - \( N \) - number of signal events in the sample
  - \( \epsilon^\beta \) - fraction of integrated luminosity with magnet polarity \( \beta \) (\( \epsilon^+ + \epsilon^- = 1 \))
  - \( A^{raw} \) - integrated raw charge asymmetry we want to measure
  - \( A_{fb} \) - forward-backward asymmetry (more kaons go in proton direction)
  - \( A_{det} \) - north-south asymmetry of the detector
  - \( A_{q\beta\gamma} \) - decrease of acceptance of kaons bent by the magnet
  - \( A_{\beta\gamma} \) - detector forward-backward asymmetry remaining after magnet polarity flip
  - \( A_{q\beta} \) - change in kaon reconstruction efficiency after magnet polarity flip

- Fit for 8 \( n^{\beta\gamma}_q \) \( \Rightarrow \) obtain 8 equations with 8 unknowns
- Solve for \( A^{raw} \) \( \Rightarrow \) obtain \( A_{CP}(B^+ \to J/\psi K^+) \)
Mass distribution of $J/\psi K$

Unbinned likelihood fit of the inv. mass distribution of $\mu\mu K$ system

<table>
<thead>
<tr>
<th>$\beta\gamma q$</th>
<th>$J/\psi K$</th>
<th>$J/\psi\pi$</th>
<th>$J/\psi K^*0$</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ + +</td>
<td>5104±87</td>
<td>337 ± 44</td>
<td>692 ± 77</td>
<td>4079 ± 151</td>
</tr>
<tr>
<td>+ — +</td>
<td>5131±87</td>
<td>222 ± 42</td>
<td>689 ± 78</td>
<td>4170 ± 151</td>
</tr>
<tr>
<td>+ + —</td>
<td>4999±85</td>
<td>212 ± 40</td>
<td>767 ± 76</td>
<td>3978 ± 149</td>
</tr>
<tr>
<td>+ — —</td>
<td>5098±86</td>
<td>144 ± 38</td>
<td>523 ± 77</td>
<td>4395 ± 150</td>
</tr>
<tr>
<td>— + +</td>
<td>4973±86</td>
<td>158 ± 41</td>
<td>578 ± 78</td>
<td>4397 ± 151</td>
</tr>
<tr>
<td>— — +</td>
<td>5039±86</td>
<td>127 ± 39</td>
<td>663 ± 78</td>
<td>4281 ± 150</td>
</tr>
<tr>
<td>— + —</td>
<td>4965±85</td>
<td>242 ± 41</td>
<td>794 ± 76</td>
<td>3880 ± 148</td>
</tr>
<tr>
<td>— — —</td>
<td>4906±84</td>
<td>138 ± 39</td>
<td>724 ± 75</td>
<td>4006 ± 147</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>40222 ± 242</strong></td>
<td><strong>1578 ± 119</strong></td>
<td><strong>5429 ± 217</strong></td>
<td><strong>33192 ± 425</strong></td>
</tr>
</tbody>
</table>
### Asymmetries

<table>
<thead>
<tr>
<th></th>
<th>( J/\psi K )</th>
<th>( J/\psi \pi )</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N )</td>
<td>40217(\pm)243</td>
<td>1577(\pm)118</td>
<td>33189(\pm)424</td>
</tr>
<tr>
<td>( \epsilon^+ )</td>
<td>0.5060(\pm)0.0030</td>
<td>0.5060(\pm)0.0030</td>
<td>0.5010(\pm)0.0064</td>
</tr>
<tr>
<td>( A^{raw} )</td>
<td>-0.0070(\pm)0.0060</td>
<td>-0.0887(\pm)0.0807</td>
<td>-0.0205(\pm)0.0128</td>
</tr>
<tr>
<td>( A_{fb} )</td>
<td>0.0013(\pm)0.0060</td>
<td>0.0453(\pm)0.0890</td>
<td>-0.0170(\pm)0.0128</td>
</tr>
<tr>
<td>( A_{det} )</td>
<td>-0.0033(\pm)0.0060</td>
<td>0.2061(\pm)0.0826</td>
<td>-0.0158(\pm)0.0128</td>
</tr>
<tr>
<td>( A_{ro} )</td>
<td>-0.0050(\pm)0.0060</td>
<td>-0.0207(\pm)0.0873</td>
<td>-0.0024(\pm)0.0128</td>
</tr>
<tr>
<td>( A_{\beta\gamma} )</td>
<td>0.0001(\pm)0.0060</td>
<td>-0.1896(\pm)0.0823</td>
<td>0.0274(\pm)0.0128</td>
</tr>
<tr>
<td>( A_{q\beta} )</td>
<td>-0.0030(\pm)0.0060</td>
<td>0.0499(\pm)0.0801</td>
<td>-0.0145(\pm)0.0128</td>
</tr>
</tbody>
</table>

Kaonic \( A^{raw} \) has to be corrected for kaon asymmetry:

- Reaction \( K^- + N \rightarrow \text{hyperon} + \pi \) has no analog \( K^+ + N \), therefore \( N(K^+) > N(K^-) \)
Correction for kaon asymmetry

- This asymmetry measured in the channel
  \( c \rightarrow D^{*+} \rightarrow D^0 \pi^+ , D^0 \rightarrow \mu^+ \nu K^- \) (2.8 fb\(^{-1}\))
- No CPV is expected in this decay [hep-ph/0311371]

- Plot \( \Delta m = m(\mu K\pi) - m(\mu K) \) distributions: wrong-sign (\( q_\mu, q_\pi, q_K \) are the same) and right-sign (\( q_K \) is different)
- Width of the right-sign peak depends on \( m(\mu K) \rightarrow \) bin in \( m(\mu K) \)
- Background under the peak is sideband-subtracted using events at high \( \Delta m \) (far from the peak)
- For every \( \beta\gamma q \) combination perform sideband-subtraction in all \( m(\mu K) \) bins, sum the results \( \rightarrow \) obtain 8 numbers \( N_{q\beta\gamma} \)
- Solve for corresponding raw kaon asymmetry
**Correction for kaon asymmetry**

This raw kaon asymmetry must be

- corrected for sample composition
- averaged over kaon momentum
  - Cross-section $\sigma(K + N)$ and, therefore, the kaon asymmetry itself depend on kaon momentum
- subtracted from $A_{raw}$


\[
A_{CP}(B^+ \rightarrow J/\psi K^+) = 0.0075 \pm 0.0061({\text{stat.}}) \pm 0.0027({\text{syst.}})
\]

For pions such correction is covered by systematic error:

\[
A_{CP}(B^+ \rightarrow J/\psi \pi^+) = -0.0887 \pm 0.0807({\text{stat.}}) \pm 0.0283({\text{syst.}})
\]
Results

- Asymmetry $A_{CP}(B^+ \to J/\psi K^+)$ is consistent with zero
- Precision is of the order of SM prediction
- Consistent with current PDG value $A_{CP} = 0.015 \pm 0.017$, but factor of three better precision

- Asymmetry $A_{CP}(B^+ \to J/\psi \pi^+)$ is also consistent with zero
- Also consistent with PDG value $A_{CP} = 0.09 \pm 0.08$
- Has a competitive precision
Measurement of CP-violation in $B_s \to J/\psi\phi$ decay
CKM matrix

CKM matrix relates quark weak flavor and mass eigenstates:

$$V_{CKM} = \begin{vmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{vmatrix} =$$

$$= \begin{vmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{vmatrix} + \mathcal{O}(\lambda^4)$$

- In SM CP-violation is governed by only one parameter $\eta$
  (complex phase)
- NP may provide plenty of new complex phases
CKM Matrix Unitarity Condition

\[ V_{CKM}^\dagger V_{CKM} = 1 \]

This translates into:

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]
\[ V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \]

- Both triangles have the same area, proportional to CPV level
- The triangles involve different elements of CKM matrix
  - First triangle provides for measurement of \( \sin 2\beta \) from \( B_d \to J/\psi K_S \) decay
  - Similarly, 2nd triangle provides for \( \sin 2\beta_s \) from \( B_s \to J/\psi \phi \) (harder to do)
**B_s-mixing**

Weak eigenstates: \[ i \frac{d}{dt} \left( \begin{array}{c} \overline{B}_s(t) \\ B_s(t) \end{array} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \begin{array}{c} \overline{B}_s(t) \\ B_s(t) \end{array} \right) \]

CP eigenstates: \[ |B_s^{odd}\rangle = |B_s(t)\rangle - |\overline{B}_s(t)\rangle \]
\[ |B_s^{even}\rangle = |B_s(t)\rangle + |\overline{B}_s(t)\rangle \]

Mass eigenstates: \[ |B_s^{Heavy}\rangle = p |B_s(t)\rangle - q |\overline{B}_s(t)\rangle \]
\[ |B_s^{Light}\rangle = p |B_s(t)\rangle + q |\overline{B}_s(t)\rangle \]

Observables:
- \( \Delta M_s = M_H - M_L \approx 2|M_{12}^s| \)
- \( \Delta \Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \approx 2|\Gamma_{12}^s| \)
- \( \Delta \Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}^s| \cos \phi_s \)
  where CP-violating phase \( \phi_s = \arg \left( -\frac{M_{12}^s}{\Gamma_{12}^s} \right) \approx 0.004 \) in SM
- Average lifetime \( \overline{\tau} \equiv 1/\overline{\Gamma} \), where \( \overline{\Gamma} = \frac{1}{2}(\Gamma_L + \Gamma_H) \)
New Physics Phase $\phi^NP$  

- In Standard Model both $\beta^SM_s = 0.02$ and $\phi^SM_s = -0.004$ are small, beyond current experimental reach
- New Physics may introduce a new phase $\phi^NP_s$ such that:
  - $2\beta_s = 2\beta^SM_s - \phi^NP_s$
  - $\phi_s = \phi^SM_s + \phi^NP_s$
- If $\phi^NP_s$ is large then $\phi_s \approx -2\beta_s \approx \phi^NP_s$

We use $B_s \rightarrow J/\psi\phi$ decay to measure this phase
Vector amplitudes

$B_s \rightarrow J/\psi + \phi$

Spin $0 \rightarrow 1 + 1 \ (\ell = 0, 1, 2)$

$J/\psi \phi$ system is a mixture of three different states with following time-dependent amplitudes:

- $A_0(t)$ – longitudinal polarization, $\ell = 0, 2$, CP = +
- $A_{||}(t)$ – transverse polarization with parallel spin orientation, $\ell = 0, 2$, CP = +
- $A_{\perp}(t)$ – transverse polarization with perpendicular spin orientation, $\ell = 1$, CP = −

$$|A_0(0)|^2 + |A_{||}(0)|^2 + |A_{\perp}(0)|^2 = 1$$

Observables:

- $|A_{\perp}(0)|$
- $|A_0(0)|^2 - |A_{||}(0)|^2$
- $\delta_1 \equiv \arg(A_{||}^*(0)A_{\perp}(0)) = -\delta_{||} + \delta_{\perp}$
- $\delta_2 \equiv \arg(A_0^*(0)A_{\perp}(0)) = -\delta_0 + \delta_{\perp}$

$\delta_1$ and $\delta_2$ are CP-conserving strong phases
Angles

- $x$-axis – direction of $\phi$ momentum in $J/\psi$ rest frame
- $x$-$y$ plane – defined by $K^+$ and $K^-$ momenta in $J/\psi$ rest frame
- Angle $\theta$ (transversity) – between $z$-axis and $\mu^+$ (in $J/\psi$ rest frame)
- Angle $\phi$ – between $K^+$ and $\mu^+$ projection (in $J/\psi$ rest frame)

- Angle $\psi$ – between $x$-axis and $K^+$ (in $\phi$ rest frame)
Differential rate

Time-dependent differential rate:

\[
\frac{d^4 \Gamma}{d \cos \theta \, d\phi \, d \cos \psi \, dt} = 2 \cos^2 \psi (1 - \sin^2 \theta \cos^2 \phi) \cdot |A_0(t)|^2 \\
+ \sin^2 \psi (1 - \sin^2 \theta \sin^2 \phi) \cdot |A_{||}(t)|^2 \\
+ \sin^2 \psi \sin^2 \theta \cdot |A_{\perp}(t)|^2 \\
+ \frac{1}{\sqrt{2}} \sin 2\psi \sin^2 \theta \sin 2\phi \cdot \text{Re}(A_0^*(t)A_{||}(t)) \\
+ \frac{1}{\sqrt{2}} \sin 2\psi \sin^2 \theta \sin 2\theta \cos \phi \cdot \text{Im}(A_0^*(t)A_{\perp}(t)) \\
- \sin^2 \psi \sin 2\theta \sin \phi \cdot \text{Im}(A_{||}^*(t)A_{\perp}(t))
\]
Amplitudes
(no $B_s$ initial flavor tagging)

\[ |A_0(t)|^2 = |A_0(0)|^2 \cdot T_+ \]
\[ |A_\parallel(t)|^2 = |A_\parallel(0)|^2 \cdot T_+ \]
\[ |A_\perp(t)|^2 = |A_\perp(0)|^2 \cdot T_- \]
\[ \text{Re}(A_0^*(t)A_\parallel(t)) = |A_0(0)| \cdot |A_\parallel(0)| \cdot \cos(\delta_2 - \delta_1) \cdot T_+ \]
\[ \text{Im}(A_0^*(t)A_\perp(t)) = |A_0(0)| \cdot |A_\perp(0)| \cdot \left[ -\frac{1}{2}(e^{-\Gamma_H t} - e^{-\Gamma_L t}) \sin \phi_s \cos \delta_2 \right] \]
\[ \text{Im}(A_\parallel^*(t)A_\perp(t)) = |A_\parallel(0)| \cdot |A_\perp(0)| \cdot \left[ -\frac{1}{2}(e^{-\Gamma_H t} - e^{-\Gamma_L t}) \sin \phi_s \cos \delta_1 \right] \]

where

\[ T_\pm = \frac{1}{2}[(1 \pm \cos \phi_s)e^{-\Gamma_L t} + (1 \mp \cos \phi_s)e^{-\Gamma_H t}] \]

- Sensitive to $\Gamma_L, \Gamma_H, \phi_s, \delta_1, \delta_2$
- Not sensitive to $\Delta M_s$
- Equations are invariant under simultaneous transformation $\phi_s \rightarrow \pi - \phi_s$, $\Delta \Gamma \rightarrow -\Delta \Gamma, \delta_1 \rightarrow \pi - \delta_1$ and $\delta_2 \rightarrow \pi - \delta_2 \implies$ four-fold ambiguity
Amplitudes
(with $B_s$ initial flavor tagging)

Upper signs: $B_s(0) = |B^0_s\rangle$, lower signs: $B_s(0) = |\bar{B}^0_s\rangle$

$|A_0(t)|^2 = |A_0(0)|^2 \cdot [T_\pm e^{-\Gamma t} \sin \phi_s \sin(\Delta M_{st})]$

$|A_\parallel(t)|^2 = |A_\parallel(0)|^2 \cdot [T_+ e^{-\Gamma t} \sin \phi_s \sin(\Delta M_{st})]$  

$|A_\perp(t)|^2 = |A_\perp(0)|^2 \cdot [T_- e^{-\Gamma t} \sin \phi_s \sin(\Delta M_{st})]$

$\text{Re}(A_0^*(t)A_\parallel(t)) = |A_0(0)| \cdot |A_\parallel(0)| \cdot \cos(\delta_2 - \delta_1)[T_+ e^{-\Gamma t} \sin \phi_s \sin(\Delta M_{st})]$

$\text{Im}(A_0^*(t)A_\perp(t)) = |A_0(0)| \cdot |A_\perp(0)| \cdot [e^{-\Gamma t}(\pm \sin \delta_2 \cos(\Delta M_{st}) \mp \cos \delta_2 \sin(\Delta M_{st}) \cos \phi_s) - \frac{1}{2}(e^{-\Gamma H t} - e^{-\Gamma L t}) \sin \phi_s \cos \delta_2]$  

$\text{Im}(A_\parallel^*(t)A_\perp(t)) = |A_\parallel(0)| \cdot |A_\perp(0)| \cdot [e^{-\Gamma t}(\pm \sin \delta_1 \cos(\Delta M_{st}) \mp \cos \delta_1 \sin(\Delta M_{st}) \cos \phi_s) - \frac{1}{2}(e^{-\Gamma H t} - e^{-\Gamma L t}) \sin \phi_s \cos \delta_1]$  

where

$T_\pm = \frac{1}{2}[(1 \pm \cos \phi_s)e^{-\Gamma L t} + (1 \mp \cos \phi_s)e^{-\Gamma H t}]$
Amplitudes (with $B_s$ initial flavor tagging)

- Sensitive to $\Gamma_L, \Gamma_H, \phi_s, \delta_1, \delta_2, \Delta M_s$
- But we do not determine $\Delta M_s$, but fix it to CDF’s measurement \[PRL 97, 242003 (2006)\]
- Sign ambiguity for $\phi_s$ for given $\Delta \Gamma$ is resolved $\Rightarrow$ two-fold ambiguity

☞ For given tagged event:

$$\text{rate} = p(B_s) \cdot \text{rate} (B_s) + (1 - p(B_s)) \cdot \text{rate} (\overline{B_s})$$

☞ If event is not tagged $p(B_s) = 0.5 \Rightarrow$ all $B_s$ flavor terms cancel
A few words about $B_s$ flavor tagging
**$B_s$** flavor tagging

We need to determine (tag) $B_s$ meson production flavor which may be different from decay flavor.

Two main classes of tagging methods:

- **Same-Side Tagging:** “One-track”, $Q_{same}$...
- **Opposite-Side Tagging:** jet-charge, soft-lepton, $Q_{opp}$...

We develop “Comb. SST”, “Comb. OST” and merge them into single “All” tagger.
Tagging characteristics:

- Number of Right-Sign ($B_s-K^+$ and $\overline{B}_s-K^-$) correlations, $N_{RS}$
- Number of mistagged Wrong-Sign (e.g., $B_s-K^-$ and $\overline{B}_s-K^+$) correlations, $N_{WS}$
- Number of events with no tag found, $N_{NT}$
- Tagging efficiency $\epsilon = \frac{N_{tagged}}{N_{total}} = \frac{N_{RS} + N_{WS}}{N_{RS} + N_{WS} + N_{NT}}$
  and dilution $D = \frac{N_{RS} - N_{WS}}{N_{RS} + N_{WS}}$
- Tagging power $\epsilon D^2 \leftarrow$ to be maximized
Tagging in MC and data

- Same-side tagging:
  - $B_s$ production flavor is obtained from MC truth information
  - SST analysis can only be done on MC
  - SST can be verified on self-tagging $B_u \rightarrow J/\psi K$ sample
    - $B_u$ flavor is determined from kaon charge in both data and MC
    - The agreement between dilutions in data and MC is reasonably good which justifies using SST in $B_s$ decays

- Opposite-side tagging:
  - Opposite-side flavor tagging does not depend on the $B$-meson flavor
  - Can use $B_d \rightarrow \nu \mu D^*$ data sample to develop OST for $B_s$ [PRD74, 112002 (2006)]
Taggers’ combination

• To obtain “Combined SST” we merge different SST algorithms by using likelihood ratio method

• Similar thing is done for “Combined OST”
  – Unfortunately, OST has low efficiency
  – So, when OST is not present, we use the $Q_{\text{opp}}$ obtained as $p_t$-weighted $\sum q_i$ of all tracks on opposite side
  – The $Q_{\text{opp}}$ has 100% tagging efficiency, but lower dilution

• Finally, both “combined SST” and “combined OST” / $Q_{\text{opp}}$ are amalgamated into single “All” tagger

• This single tagger has pretty high power $\epsilon D^2 \approx 4-5\%$
Tagger verification on data/MC

SST in $B_u \rightarrow J/\psi K$

OST in $B_u \rightarrow J/\psi K$
and $B_d \rightarrow \nu \mu D^{*-}$ (data)

$Q_{opp}$ in $B_u \rightarrow J/\psi K$

"All" tagger in $B_u \rightarrow J/\psi K$
Back to $B_s \rightarrow J/\psi \phi$ Analysis
Likelihood function

☞ We perform simultaneous unbinned likelihood fit to the $B_s$ mass, lifetime and three angles.
☞ Altogether, there are 33 free parameters in the fit.

\[ L = \prod_{i=1}^{N} [f_{\text{sig}}F_{\text{sig}}^i + (1 - f_{\text{sig}})F_{\text{bkg}}^i], \]

where

- $N$ – total number of events
- $f_{\text{sig}}$ – signal fraction
- $F_{\text{sig}/\text{bkg}}^i$ – signal/background distribution the fit variables

Background:
- “Prompt” $J/\psi$ coming directly from primary vertex
- “Non-prompt” $J/\psi$ coming from a $b$-hadron
Fit constraints

- Mixing parameter $\Delta M_s$ is constrained to CDF’s measurement
  
  [PRL 97, 242003 (2006)]

- Strong phases $\delta_1$ and $\delta_2$ are constrained from BaBar’s measurements in $B \to J/\psi K^{*0}$ [hep-ex/0704.0522]
  
  - We have two-fold ambiguity
    
    $\Delta \Gamma > 0, \cos \phi_s > 0, \cos \delta_1 > 0, \cos \delta_2 < 0$
    
    $\Delta \Gamma < 0, \cos \phi_s < 0, \cos \delta_1 < 0, \cos \delta_2 > 0$

  - For $B \to J/\psi K^{*0}$ the values $\delta_1 = -0.46$ and $\delta_2 = 2.92$ are preferred over $\delta_1 = 3.60$ and $\delta_2 = 0.22$ on both theoretical and experimental grounds [hep-ex/0704.3575, page 153], [PRD 64, 117503]

  - We constrain $\delta_1 = -0.46$ and $\delta_2 = 2.92$ with narrow Gaussians to allow for SU(2) symmetry breaking
Fit results

Invariant mass of \( J/\psi \phi \) system

\[ N = 1967 \pm 65{\text{(stat.)}} \text{ events} \]
Fit results

\[ \Delta \Gamma = 0.14 \pm 0.07 \text{(stat. + syst.)} \text{ ps}^{-1} \quad (\text{when } \phi_s \equiv \phi_s^{SM}) \]

\[ \bar{\tau} = 1.53 \pm 0.05 \pm 0.01 \text{ ps} \]
Fit results

$D\bar{O}, 2.8 \text{ fb}^{-1}$

$B^0_s \rightarrow J/\psi \phi$

$5.26 < M(B_s) < 5.46 \text{ GeV}$

t$/sigma(t ct) > 5$

Events per 0.10

Events per 0.17

A. Rakitin, Lancaster University, SLAC Experimental Seminar, May 27, 2008
Fit results

**DØ, 2.8 fb⁻¹**

\[ B_s^0 \to J/\psi \phi \]

5.26 < \( M(B_s) \) < 5.46 GeV

\( \frac{ct}{\sigma(ct)} > 5 \)

- **Data**
- **Total Fit**
- **Total Signal**
- **Background**

**φ rest frame**

J/ψ, K⁻ → ϕ, K⁺
Main result:

\[ \Delta \Gamma_s = 0.19 \pm 0.07^{+0.02}_{-0.01} \text{ ps}^{-1}, \phi_s = -0.57^{+0.24}_{-0.30}^{+0.07}_{-0.02} \]

[hep-ex/0802.2255, Sub. to PRL]

Probability of SM value is \( \sim 7\% \)
Fit results

Likelihood profiles:

(b) 

(c) 

\( \phi_s \) (radian) 

\( \Delta \Gamma_s \) (ps\(^{-1}\))
## Numerical results

| Variable | Free $\phi_s$ | $\phi_s \equiv \phi_s^{SM}$ | $\Delta \Gamma_s \equiv \Delta \Gamma_s^{SM} \cdot |\cos \phi_s|$ |
|----------|---------------|-----------------------------|----------------------------------|
| $\tau$, ps | 1.52±0.06     | 1.53±0.06                   | 1.49±0.05                        |
| $\Delta \Gamma_s$ (ps$^{-1}$) | 0.19±0.07     | 0.14±0.07                   | 0.083±0.018                      |
| $A_{\perp}(0)$ | 0.41±0.04     | 0.4±0.04                     | 0.45±0.03                        |
| $|A_0(0)|^2 - |A_\parallel(0)|^2$ | 0.34±0.05     | 0.35±0.04                     | 0.33±0.04                        |
| $\delta_1$ | -0.52±0.42    | -0.48±0.45                   | -0.47±0.42                       |
| $\delta_2$ | 3.17±0.39     | 3.19±0.43                    | 3.21±0.40                        |
| $\phi_s$ | $\equiv -0.57^{+0.24}_{-0.30}$ | $\equiv -0.04$ | $\equiv -0.46\pm0.28$ |
| $\Delta M_s$ (ps$^{-1}$) | $\equiv 17.77$ | $\equiv 17.77$ | $\equiv 17.77$ |
Results without tagging

For comparison: **untagged 1.1 fb$^{-1}$ analysis**
Comparison to other experiments

Shown is the DØ sign convention for $\phi_s$, which is opposite to the CDF’s $2\beta_s$ [hep-ex/0712.2397]

- CDF did not provide central value, but only variation limits for $2\beta_s$
- CDF is hoping to have an updated result with a larger dataset by ICHEP’08
New Physics?

NP may change $B_s$ Hamiltonian parameters by introducing a complex number $\Delta_s \equiv |\Delta_s| \cdot e^{i\phi_s^{NP}}$ [hep-ph/0612167] as follows:

- $\Delta M_s = \Delta M_s^{SM} \cdot |\Delta_s|$
- $\phi_s = \phi_s^{SM} + \phi_s^{NP}$

$\Delta_s = 1$ in SM

- Red: from CDF’s $\Delta M_s$ measurement [PRL 97, 242003 (2006)]
- Yellow: from $\Delta \Gamma_s / \Delta M_s$ with $\Delta \Gamma_s$ from DØ [PRL98, 121801 (2007)] - untagged 1.1 fb$^{-1}$ analysis
- Blue: from DØ ’s $a_{SL}^s$ measurement [PRD 76, 057101 (2007)]
- Forward and backward regions: from sign of $\Delta \Gamma_s$ from DØ [PRL98, 121801 (2007)] - untagged 1.1 fb$^{-1}$ analysis
- Dashed wedge: from $\phi_s$ from DØ [PRL98, 121801 (2007)] - untagged 1.1 fb$^{-1}$ analysis
- In SM all regions should intersect in point (1,0)

Experimental situation (black area) shows some deviation from SM which may grow as the uncertainties decrease
Conclusion

• Measured large CP-violation where it is predicted to be small may reveal New Physics
• Direct CP asymmetry in $B \rightarrow J/\psi K$ decay is consistent with zero
• The uncertainty on this asymmetry is of order of SM prediction
• The large phase $\phi_s$ in $B_s \rightarrow J/\psi \phi$ decay may indicate New Physics
• The uncertainty on $\phi_s$ is statistically dominated $\implies$ more data needs to be analyzed to be sure that we actually see the New Physics
• This will happen in the nearest future
Backup
Toroid polarity

- Reversing magnet polarity helps reduce detector asymmetries in muon reconstruction
- Systematics is also diminished
Obtaining $D^*$ asymmetry

- For each $\beta\gamma q$ combination we bin the sample in $m(\mu K)$
- For each bin in $m(\mu K)$ we choose signal and sideband regions for right-sign and wrong-sign charge correlations
- Signal region is chosen to maximize $S/\sqrt{S+B}$ for each $m(\mu K)$ bin
- Sideband region is chosen to be $0.19 \text{ GeV}/c^2 < \Delta m < 0.22 \text{ GeV}/c^2$
- $B = N_{\text{sig.reg. wrong}}^\text{right} \frac{N_{\text{sideband}}}{N_{\text{wrong}}}$
- $S = N_{\text{sig.reg. right}} - B$
- Then numbers of signal events in all $m(\mu K)$ bins are added up
  $\implies$ obtain $n_{\beta\gamma}^q$
- Solve system of equations to find asymmetry
### $D^*$ sample composition

<table>
<thead>
<tr>
<th>Mode</th>
<th>Branching, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+ K^- \nu$</td>
<td>3.51 ± 0.11</td>
</tr>
<tr>
<td>$\mu^+ K^{*-} \nu$</td>
<td>2.17 ± 0.16</td>
</tr>
<tr>
<td>$K^{*-} \rightarrow K^- \pi^0$</td>
<td>1/3 · Br($K^*$)</td>
</tr>
<tr>
<td>$K^{*-} \rightarrow K^0 \pi^-$</td>
<td>2/3 · Br($K^*$)</td>
</tr>
<tr>
<td>$\mu^+ \pi^- \nu$</td>
<td>0.28 ± 0.02</td>
</tr>
<tr>
<td>$\mu^+ \rho^- \nu$, $\rho^- \rightarrow \pi^- \pi^0$</td>
<td>0.19±0.04</td>
</tr>
</tbody>
</table>

**Corrected kaon asymmetry**

$$A_K(D^*) = A(D^*)/f_K$$
The average kaon asymmetry is

\[ A_K = \sum_{i=1}^{N_{bins}} A_{K,i}(D^*) \frac{N_i(J/\psi K)}{N(J/\psi K)} = -0.0145 \pm 0.0010 \text{(stat.)} \]
## Direct CPV systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>$J/\psi K$</th>
<th>$J/\psi \pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variation of fixed fit parameters by $\pm 1\sigma$</td>
<td>0.0002</td>
<td>0.0004</td>
</tr>
<tr>
<td>Variation of fitting range</td>
<td>0.0004</td>
<td>0.0129</td>
</tr>
<tr>
<td>Shape of $J/\psi \pi$ and $J/\psi K^*$ contribution</td>
<td>0.0025</td>
<td>0.0252</td>
</tr>
<tr>
<td>Bkg from $q_\mu \cdot q_\pi &lt; 0$</td>
<td>0.0008</td>
<td>–</td>
</tr>
<tr>
<td>Varying rec. eff. for $D^0$ contribution to $D^*$ sample</td>
<td>0.0005</td>
<td>–</td>
</tr>
<tr>
<td>Asymmetry in $\pi$ reconstruction</td>
<td>–</td>
<td>0.0002</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.0027</strong></td>
<td><strong>0.0283</strong></td>
</tr>
</tbody>
</table>
SST Algorithms

All used SST algorithms can be divided into two groups:

1. **One-track algorithms** which select a particular track and infer $b$-quark flavor from its charge

2. **Many-track algorithms** which use $p_t$-weighted average charge of all tracks around $\vec{p}(B_s)$: $Q_{SST}(p_t, \kappa) = \frac{\sum q \cdot p^\kappa_t}{\sum p^\kappa_t}$

- Often different one-track taggers pick up the same track $\Rightarrow$ highly correlated
- Let’s pick the best tagger from each group
- Best one-track tagger: “Min. $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$”
- Best many-track tagger: $Q_{SST}(p_t, \kappa = 0.6)$”
- Let’s combine both these taggers together to improve $\epsilon D^2$
List of used same-side taggers:

We are using the following SSTs (one-track and many-track taggers):

- Min. $p_t^{\text{rel}}$
- Max. $p_L^{\text{rel}}$
- Max. $p_t$
- Min. $|\Delta \vec{p}| \equiv |\vec{p}(B_s) - \vec{p}(K)|$
- Best: Min. $\Delta R$
- Max. $\cos \alpha$
- Min. $\cos \theta^*$
- Max. $\cos \theta^*$
- Min. $m(B_sK)$
- Random track

Best: Min. $\Delta R$

- One-track: $p_t^{\text{rel}}$ and $p_L^{\text{rel}}$ are $\perp$ and $||$ components of SST candidate’s momentum $\vec{p}(K)$ w.r.t $\vec{p}(B_sK)$
- $\Delta R \equiv \sqrt{\Delta \phi^2 + \Delta \eta^2}$ and angle $\alpha$ are taken between $\vec{p}(B_s)$ and $\vec{p}(K)$
- $\theta^*$ – decay angle of $B_sK$-system, i.e. angle between directions of $\vec{p}(B_sK)$ and $\vec{p}(B_s)$ in reference frame of $B_sK$ system
- $\kappa = 0.0, 0.1, 0.2, \ldots 1.0$
- $Q_{\text{jet}}$: $p_t^{\text{rel}}$ and $p_L^{\text{rel}}$ are $\perp$ and $||$ components of SST candidate’s momentum $\vec{p}(K)$ w.r.t $\vec{p}(B_s)$
Combination of two SST methods

- We obtain P.D.F.s of $q \cdot \Delta R$ for “Min. $\Delta R$” tracks with charge $q$ for $b$ and $\bar{b}$ quarks.
- If their ratio $y_{\Delta R} = \frac{f(b)}{f(\bar{b})} > 1$ then it was $b$-quark, otherwise $\bar{b}$-quark.
- Calculate “joint P.D.F. ratio” for “Min. $\Delta R$” and $Q_{SST}(p_t, \kappa = 0.6)$ taggers: $y_{sst} = y_{\Delta R} \cdot y_Q$.
- Introduce a variable $d_{sst} = \frac{1-y_{sst}}{1+y_{sst}}$ and determine $b$-quark flavor for each event from its sign.
- Calculate even-by-event dilution $D$ as a function of $d_{sst}$.
\( \epsilon D^2 \) for combined SST

<table>
<thead>
<tr>
<th>MC</th>
<th>Tagger</th>
<th>( \epsilon ), ( % )</th>
<th>( D ), ( % )</th>
<th>“Unbinned” ( \epsilon D^2 ), ( % )</th>
<th>“Binned” ( \epsilon D^2 ), ( % )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data</strong></td>
<td>“Min. ( \Delta R )”</td>
<td>( 82.1 \pm 1.1 )</td>
<td>( 20.2 \pm 0.7 )</td>
<td>( 3.34 \pm 0.22 )</td>
<td>( 3.73 \pm 0.24 )</td>
</tr>
<tr>
<td></td>
<td>“( Q_{jet}(pt, 0.6) )”</td>
<td>( 88.4 \pm 1.2 )</td>
<td>( 19.3 \pm 0.6 )</td>
<td>( 3.28 \pm 0.22 )</td>
<td>( 4.06 \pm 0.24 )</td>
</tr>
<tr>
<td></td>
<td>“Comb. SST”</td>
<td>( 88.4 \pm 1.2 )</td>
<td>( 19.0 \pm 0.6 )</td>
<td>( 3.19 \pm 0.22 )</td>
<td>( 4.81 \pm 0.26 )</td>
</tr>
<tr>
<td><strong>Monte Carlo</strong></td>
<td>“Min. ( \Delta R )”</td>
<td>( 79.2 \pm 0.5 )</td>
<td>( 18.6 \pm 0.5 )</td>
<td>( 2.74 \pm 0.15 )</td>
<td>( 2.82 \pm 0.15 )</td>
</tr>
<tr>
<td></td>
<td>“( Q_{jet}(pt, 0.6) )”</td>
<td>( 89.0 \pm 0.6 )</td>
<td>( 19.6 \pm 0.5 )</td>
<td>( 3.43 \pm 0.17 )</td>
<td>( 3.92 \pm 0.17 )</td>
</tr>
<tr>
<td></td>
<td>“Comb. SST”</td>
<td>( 89.1 \pm 0.6 )</td>
<td>( 17.8 \pm 0.5 )</td>
<td>( 2.82 \pm 0.15 )</td>
<td>( 4.02 \pm 0.17 )</td>
</tr>
<tr>
<td><strong>( B_s \rightarrow J/\psi \phi ) Monte Carlo</strong></td>
<td>“Min. ( \Delta R )”</td>
<td>( 84.9 \pm 0.6 )</td>
<td>( 14.8 \pm 0.5 )</td>
<td>( 1.86 \pm 0.14 )</td>
<td>( 1.96 \pm 0.14 )</td>
</tr>
<tr>
<td></td>
<td>“( Q_{jet}(pt, 0.6) )”</td>
<td>( 93.0 \pm 0.7 )</td>
<td>( 13.9 \pm 0.5 )</td>
<td>( 1.80 \pm 0.14 )</td>
<td>( 2.25 \pm 0.15 )</td>
</tr>
<tr>
<td></td>
<td>“Comb. SST”</td>
<td>( 93.0 \pm 0.7 )</td>
<td>( 14.2 \pm 0.5 )</td>
<td>( 1.86 \pm 0.14 )</td>
<td>( 2.49 \pm 0.16 )</td>
</tr>
<tr>
<td><strong>( B_s \rightarrow J/\psi K ) Monte Carlo</strong></td>
<td>“Min. ( \Delta R )”</td>
<td>( 78.7 \pm 0.7 )</td>
<td>( 13.4 \pm 0.7 )</td>
<td>( 1.41 \pm 0.14 )</td>
<td>( 1.57 \pm 0.15 )</td>
</tr>
<tr>
<td></td>
<td>“( Q_{jet}(pt, 0.6) )”</td>
<td>( 81.5 \pm 0.7 )</td>
<td>( 13.8 \pm 0.6 )</td>
<td>( 1.55 \pm 0.15 )</td>
<td>( 1.84 \pm 0.16 )</td>
</tr>
<tr>
<td></td>
<td>“Comb. SST”</td>
<td>( 81.5 \pm 0.7 )</td>
<td>( 13.1 \pm 0.6 )</td>
<td>( 1.40 \pm 0.14 )</td>
<td>( 2.01 \pm 0.16 )</td>
</tr>
</tbody>
</table>

- “Unbinned” \( \epsilon D^2 \) is a direct product of \( \epsilon \) and \( D^2 \)
- “Binned” \( \epsilon D^2 \) is a sum of \( \epsilon D^2 \)'s in \(|d|\) bins
- We see some improvement in “binned” \( \epsilon D^2 \) due to SST combination for all decay signatures
OST

- OST was developed on $B_d \rightarrow \mu D^*$ data sample [PRD74, 112002 (2006)]
- Must be the same for $B_d$ and $B_s$
- Also, a combination of a few taggers:
  - soft muon
  - soft electron
  - secondary-vertex
Combination SST + OST/Q_{\text{opp}}

- Same combination technique as for SST
- If OST present make “joint P.D.F.” \( y_{\text{comb}} = y_{\text{sst}} \cdot y_{\text{ost}} \)
- If OST not present take \( y_{\text{comb}} = y_{\text{sst}} \cdot y_{\text{opp}} \)
- Introduce variable \( d_{\text{comb}} = \frac{1-y_{\text{comb}}}{1+y_{\text{comb}}} \)
- Infer \( b \)-quark production flavor from sign of \( d_{\text{comb}} \)
- Obtain event-by-event dilution with function \( D(d_{\text{comb}}) \)
$\epsilon D^2$ for SST + OST/$Q_{opp}$

- SST + OST/$Q_{opp}$ are also combined using P.D.F.s

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tagger</th>
<th>$\epsilon$, %</th>
<th>$D$, %</th>
<th>Unbinned $\epsilon D^2$, %</th>
<th>Binned $\epsilon D^2$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monte Carlo $B_{u} \to J/\psi K$</td>
<td>“Comb. SST”</td>
<td>89.1 ± 0.6</td>
<td>17.8 ± 0.5</td>
<td>2.82 ± 0.15</td>
<td>4.02 ± 0.17</td>
</tr>
<tr>
<td></td>
<td>“Comb. OST”</td>
<td>18.3 ± 0.2</td>
<td>22.2 ± 1.1</td>
<td>0.90 ± 0.09</td>
<td>1.26 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>“$Q_{opp}$”</td>
<td>99.9 ± 0.6</td>
<td>10.3 ± 0.5</td>
<td>1.06 ± 0.09</td>
<td>1.31 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>“All”</td>
<td>100.0 ± 0.6</td>
<td>18.3 ± 0.5</td>
<td>3.33 ± 0.17</td>
<td>4.76 ± 0.18</td>
</tr>
<tr>
<td>Data</td>
<td>“Comb. SST”</td>
<td>88.4 ± 1.2</td>
<td>19.0 ± 0.6</td>
<td>3.19 ± 0.22</td>
<td>4.81 ± 0.26</td>
</tr>
<tr>
<td></td>
<td>“Comb. OST”</td>
<td>16.9 ± 0.3</td>
<td>26.8 ± 1.4</td>
<td>1.21 ± 0.13</td>
<td>1.91 ± 0.15</td>
</tr>
<tr>
<td></td>
<td>“$Q_{opp}$”</td>
<td>100.0 ± 1.3</td>
<td>9.8 ± 0.6</td>
<td>0.97 ± 0.12</td>
<td>1.36 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>“All”</td>
<td>100.0 ± 1.3</td>
<td>18.9 ± 0.6</td>
<td>3.58 ± 0.23</td>
<td>5.79 ± 0.27</td>
</tr>
<tr>
<td>Monte Carlo $B_{s} \to J/\psi \phi$</td>
<td>“Comb. SST”</td>
<td>93.0 ± 0.7</td>
<td>14.2 ± 0.5</td>
<td>1.86 ± 0.14</td>
<td>2.49 ± 0.16</td>
</tr>
<tr>
<td></td>
<td>“Comb. OST”</td>
<td>25.4 ± 0.3</td>
<td>23.2 ± 1.0</td>
<td>1.37 ± 0.12</td>
<td>2.02 ± 0.13</td>
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<tr>
<td></td>
<td>“$Q_{opp}$”</td>
<td>99.9 ± 0.7</td>
<td>6.9 ± 0.5</td>
<td>0.48 ± 0.07</td>
<td>0.78 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>“All”</td>
<td>100.0 ± 0.7</td>
<td>14.8 ± 0.5</td>
<td>2.20 ± 0.15</td>
<td>3.86 ± 0.19</td>
</tr>
<tr>
<td>Monte Carlo $B_{s} \to J/\psi \phi$</td>
<td>“Comb. SST”</td>
<td>81.5 ± 0.7</td>
<td>13.1 ± 0.6</td>
<td>1.40 ± 0.14</td>
<td>2.01 ± 0.16</td>
</tr>
<tr>
<td></td>
<td>“Comb. OST”</td>
<td>24.4 ± 0.3</td>
<td>27.6 ± 1.1</td>
<td>1.86 ± 0.16</td>
<td>2.70 ± 0.17</td>
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<tr>
<td></td>
<td>“$Q_{opp}$”</td>
<td>98.3 ± 0.8</td>
<td>9.3 ± 0.6</td>
<td>0.84 ± 0.11</td>
<td>1.24 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>“All”</td>
<td>98.3 ± 0.8</td>
<td>15.7 ± 0.6</td>
<td>2.43 ± 0.18</td>
<td>4.43 ± 0.23</td>
</tr>
</tbody>
</table>

- Tagging power $\epsilon D^2$ grows as a result of combination
- Combined tagging power for both $B_s$ decay modes is $(4.09 \pm 0.14)\%$
Calibration curves

To obtain event-by-event dilution for $B_s$ we:

- plot $D(d_{\text{comb}})$ dependence for $B_s \rightarrow \mu D_s(\phi \pi)$ Monte Carlo (black)
- plot $D(d_{\text{comb}})$ dependence for $B_s \rightarrow J/\psi \phi$ Monte Carlo (red)
- obtain weighted-average points from both plots (SST fragmentation does not depend on the $B_s$ decay mode)
- fit them with parabola + constant (blue)

Dilution grows as $|d_{\text{comb}}|$ grows, quite close to ideal case $D = 100\% \cdot |d_{\text{comb}}|$
## All likelihood parameters

<table>
<thead>
<tr>
<th>Number</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$f_{sig}$ ((N_{sig}))</td>
<td>0.0409±0.0013 (1967±65)</td>
</tr>
<tr>
<td>2,3</td>
<td>$M, \sigma$ (MeV/c²)</td>
<td>5361.4±1.0, 30.1±1.0</td>
</tr>
<tr>
<td>4</td>
<td>$\tau$ ((\mu m))</td>
<td>456±17</td>
</tr>
<tr>
<td>5</td>
<td>$\Delta \Gamma$((ps^{-1}))</td>
<td>0.19±0.07</td>
</tr>
<tr>
<td>6</td>
<td>$</td>
<td>A_{\perp}(0)</td>
</tr>
<tr>
<td>7</td>
<td>$</td>
<td>A_{0}(0)</td>
</tr>
<tr>
<td>8,9</td>
<td>$\delta_1, \delta_2$</td>
<td>-0.52±0.42, 3.17±0.39</td>
</tr>
<tr>
<td>10</td>
<td>$\phi_s$</td>
<td>-0.57+0.24, -0.30</td>
</tr>
<tr>
<td>11</td>
<td>$\Delta M_s$((ps^{-1}))</td>
<td>17.77=17.77</td>
</tr>
<tr>
<td>12</td>
<td>$S$</td>
<td>1.24±0.01</td>
</tr>
<tr>
<td>13, 14, 15</td>
<td>Bkg mass polynom: $a_{1p}, a_{1l}, a_{2l}$</td>
<td>-0.06±0.03, -1.45±0.08, 0.68±0.11</td>
</tr>
<tr>
<td>16, 17, 18</td>
<td>Bkg time exp. norm.: $f_{-}, f_{+}, f_{++}$</td>
<td>0.049±0.004, 0.155±0.004, 0.035±0.003</td>
</tr>
<tr>
<td>19, 20, 21</td>
<td>Bkg time exp. slope: $b_{-}, b_{+}, b_{++}$((\mu m))</td>
<td>65±3, 88±3, 399±21</td>
</tr>
<tr>
<td>22, 23, 24, 25</td>
<td>Transversity polynom: $X_{2p}, X_{4p}, X_{2l}, X_{4l}$</td>
<td>0.85±0.09, -0.60±0.09, 0.39±0.17, -0.23±0.19</td>
</tr>
<tr>
<td>26, 27, 28, 29</td>
<td>$\phi$ polynom: $Y_{1p}, Y_{2p}, Y_{1l}, Y_{2l}$</td>
<td>-0.23±0.01, -0.10±0.02, -0.15±0.02, -0.00±0.04</td>
</tr>
<tr>
<td>30, 31</td>
<td>$\psi$ polynom: $Z_{2p}, Z_{2l}$</td>
<td>0.05±0.02, 0.27±0.06</td>
</tr>
<tr>
<td>32, 33</td>
<td>Interference-like terms in bkg: $Int_p, Int_l$</td>
<td>-0.011±0.003, -0.018±0.001</td>
</tr>
</tbody>
</table>
Comparison DØ and CDF

\[ \phi_s = -2\beta_s \]
$B_s \rightarrow J/\psi\phi$ systematics

| Source                          | $\tilde{\tau}$ (ps) | $\Delta \Gamma_s$ (ps$^{-1}$) | $A_{\perp}(0)$  | $|A_0(0)|^2 - |A_{\parallel}(0)|^2$ | $\phi_s$ |
|---------------------------------|----------------------|-------------------------------|-----------------|-----------------------------------|---------|
| Acceptance                      | $\pm 0.003$          | $\pm 0.003$               | $\pm 0.005$    | $\pm 0.03$                        | $\pm 0.005$ |
| Signal mass model              | $-0.01$              | $+0.006$                   | $-0.003$       | $-0.001$                          | $-0.006$ |
| Flavor purity estimate         | $\pm 0.001$          | $\pm 0.001$               | $\pm 0.001$    | $\pm 0.001$                       | $\pm 0.01$ |
| Background model               | $+0.003$             | $+0.02$                   | $-0.02$        | $-0.01$                           | $+0.02$  |
| $\Delta M_s$ input            | $\pm 0.01$           | $\pm 0.001$               | $\pm 0.001$    | $\pm 0.001$                       | $\pm 0.01$ |
| Total                          | $\pm 0.01$           | $+0.02$                   | $+0.01$        | $\pm 0.03$                        | $+0.07$ |

$|A_0(0)|^2 - |A_{\parallel}(0)|^2$ = $|A_{\perp}(0)|^2$, $\phi_s = \phi_s$.