B_s^0 \rightarrow J/\psi \eta \text{ decays and sensitivity to the } B_s^0 \text{ mixing phase at LHCb}

Benjamin Carron

Monday Seminar - January 30 2006

Mixing and CP violation

The LHCb experiment

Selection of the B_s^0 \rightarrow J/\psi \eta \text{ decays}

Sensitivity to the B_s^0 \text{ mixing phase}

Summary and conclusion
CP violation and $\bar{b} \rightarrow \bar{c}c\bar{s}$ transitions

- $B_s^0$ decays into CP self-conjugate final states caused by $\bar{b} \rightarrow \bar{c}c\bar{s}$ quark-level transitions
  - $B_s^0 \rightarrow J/\psi \phi$: admixture of CP eigenstates ($\eta_{J/\psi\phi} = +1, -1, +1$)
  - $B_s^0 \rightarrow \eta_c \phi$, $B_s^0 \rightarrow J/\psi \eta^{(')}$: pure CP-even eigenstates

Dominated by only one tree CKM phase $\phi_D \equiv -\arg[V_{cb}^*V_{cs}]$ (penguins suppressed $\rightarrow$ no direct CP violation); small effect of indirect CP violation can be neglected ($\rightarrow |p/q| = 1$)

- “Mixing-induced CP violation” phase mismatch $\phi_{CKM} = \phi_s - 2\phi_D \approx \phi_s \neq 0, \pi$

\[ \begin{array}{ccc}
  b & V_{tb} & t \\
  \bar{B}_s^0 & W & V_{ts}^* \\
  \bar{s} & V_{ts}^* & V_{tb} \\
  \end{array} \quad \begin{array}{ccc}
  s & V_{cs} \\
  B_s^0 & W^+ & c \\
  \bar{b} & V_{cb}^* \\
  \end{array} \]

$\phi, \eta^{(')}$

$J/\psi, \eta_c$

$\rightarrow$ CP-asymmetry directly measures the weak mixing phase $\phi_s \equiv 2\arg[V_{ts}^*V_{tb}]$

- $\phi_s \approx -2\chi \equiv -2\arg\left[-\frac{V_{cb}^*V_{cs}^*}{V_{tb}^*V_{ts}^*}\right] \leftrightarrow$ strange counterpart of $\sin (2\beta)$ measurement for $B_d^0$ ($\phi_d \approx 2\beta$)

- In the Standard Model, $\phi_s \approx -2\lambda^2 \eta \sim \mathcal{O}(-0.04 \text{ rad})$ expected to be small

$\Rightarrow$ $B_s^0$ system represents a prime candidate for the discovery of New Physics
The LHCb experiment

- **LHC environment**
  - $p - p$ collisions at 14 TeV
  - $\mathcal{L}_{\text{LHC}} = 10^{34}$ cm$^{-2}$s$^{-1}$
  - $b\bar{b}$ both forward or backward in the beam direction

- **LHCb detector**
  - $\mathcal{L}_{\text{LHCb}}^{\text{av}} = 2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$
  - Good resolutions
    - $\sim 12$ MeV/$c^2$ on $m_B$
    - $\sim 40$ fs on proper time
  - RICH: $K/\pi$ separation
  - High $P_T$ tracks and high IP trigger
1. What is LHCb’s ability to reconstruct the $B^0_s \to J/\psi \eta$ decay channels?

- $J/\psi \to \mu^+ \mu^-$ → clear signature
  → high trigger efficiency

- $\eta \to \gamma \gamma$ → difficult to reconstruct (bad $\gamma$ momentum resolution / high multiplicity)
  → BR($\eta \to \gamma \gamma$): $(39.4 \pm 0.3)\%$

- $\eta \to \pi^+ \pi^- \pi^0$ → easier reconstruction (2 charged tracks) but with $\pi^0 \to \gamma \gamma$
  → BR($\eta \to \pi^+ \pi^- \pi^0$): $(22.6 \pm 0.4)\%$

- Offline selection with full Monte Carlo simulated data

- After the selection, application of a Kalman Filter fit
  → Refines the cascade fitters, with better propagation of $P_\gamma$ errors by recursive fit
  → Performs mass constrained fits on intermediate particles
After a loose preselection
- Re-normalized to have the same maximum for both distributions

\[
B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\gamma \gamma)
\]

\[
B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\pi^+ \pi^- \pi^0)
\]

\(P_T\) of the less energetic photon

\(P_T\) of the neutral pion

Associated signal – background candidates – Final cut

Huge amount of photon pairs (∼ 22 photons per event)
→ Need very tight cuts to remove the background combinations
Significance of a variable: its value divided by its error ($S_x = x/\sigma_x$)

→ Very important to remove prompt $J/\psi$ contributions

$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\gamma \gamma)$

$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\pi^+ \pi^- \pi^0)$

Associated signal – background candidates – Final cut
### $B_s^0 \rightarrow J/\psi \eta$ selection Cuts (DaVinci v12r12)

<table>
<thead>
<tr>
<th>Cuts</th>
<th>$B_s^0 \rightarrow J/\psi \eta$</th>
<th>$B_s^0 \rightarrow J/\psi \eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\eta \rightarrow \gamma\gamma$</td>
<td>$\eta \rightarrow \pi^+\pi^-\pi^0$</td>
</tr>
<tr>
<td>$\Delta\ln L_{\mu\pi} (\mu^+, \mu^-)$</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>$P_T (\mu^+, \mu^-)$ [MeV/c$^2$]</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>$IP/\sigma_{IP} (\mu^+, \mu^-)$</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>$\chi^2 (J/\psi)$</td>
<td>$&lt;$</td>
<td>$&lt;$</td>
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<tr>
<td>$P_T (J/\psi)$ [MeV/c]</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>$IP/\sigma_{IP} (J/\psi)$</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>$\delta(m) (J/\psi)$ [MeV/c$^2$]</td>
<td>$\pm$</td>
<td>$\pm$</td>
</tr>
<tr>
<td>$P_T (\gamma)$ [MeV/c]</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>$P_T (\pi^{\pm})$ [MeV/c]</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>$IP/\sigma_{IP} (\pi^{\pm})$</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
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<td>$P_T (\pi^0)$ [MeV/c]</td>
<td>$&gt;$</td>
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<td>$\delta(m) (\pi^0)$ [MeV/c$^2$]</td>
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<td>$P_T (\eta)$ [MeV/c]</td>
<td>$&gt;$</td>
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</tr>
<tr>
<td>$\delta(m) (\eta)$ [MeV/c$^2$]</td>
<td>$\pm$</td>
<td>$\pm$</td>
</tr>
<tr>
<td>$\chi^2 (B_s^0)$</td>
<td>$&lt;$</td>
<td>$&lt;$</td>
</tr>
<tr>
<td>$p (B_s^0)$ [MeV/c$^2$]</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>IPS ($B_s^0$)</td>
<td>$&lt;$</td>
<td>$&lt;$</td>
</tr>
<tr>
<td>FDS ($B_s^0$)</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>FD ($B_s^0$) [mm]</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>$\cos \theta_{Lp}$</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
</tr>
<tr>
<td>$\delta(m) (B_s^0)$ [MeV/c$^2$]</td>
<td>$\pm$</td>
<td>$\pm$</td>
</tr>
</tbody>
</table>

### Parameters

- $\mu^+, \mu^-$ selection
- $J/\psi$ selection
- $\gamma$ selection
- $\pi^+, \pi^-$ selection
- $\pi^0$ selection
- $\eta$ selection
- $B_s^0$ selection

### January 30 2006

**Monday Seminar − 7**

Benjamin Carron
$B_s^0$ mass resolutions with Kalman Filter fit

Single Gaussian fits on associated candidates

$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\gamma \gamma)$

- $\sigma = (33.6 \pm 0.7)$ MeV/$c^2$
- $\mu = (5369.4 \pm 0.8)$ MeV/$c^2$
- $\chi^2$/ndf = 68.8/36

Increased resolution: $53 \rightarrow 34$ MeV/$c^2$

No biases in the mean values (present before the Kalman Filter fit)

$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\pi^+ \pi^- \pi^0)$

- $\sigma = (20.0 \pm 0.7)$ MeV/$c^2$
- $\mu = (5370.9 \pm 0.6)$ MeV/$c^2$
- $\chi^2$/ndf = 177.5/42

Increased resolution: $45 \rightarrow 20$ MeV/$c^2$
Lifetime measurements \((\tau_{B_s^0}^{true} = 1.472 \text{ ps})\)

\[B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\gamma \gamma)\]

- Lifetime estimated by a \(\chi^2\) fit
  \[c \cdot t = m_{B_s^0} \cdot \frac{\vec{p}_{B_s^0} \cdot \vec{L}_{B_s^0}}{|\vec{p}_{B_s^0}|^2}\]
  - \(m_{B_s^0}\): mass of the reconstructed \(B_s^0\)
  - \(\vec{p}_{B_s^0}\): momentum of the reconstructed \(B_s^0\)
  - \(\vec{L}_{B_s^0}\): distance between creation and decay vertex of the reconstructed \(B_s^0\)

- Low lifetime distortion
  - Due to selection cuts (flight distance, ...)
  - Short lived \(B_s^0\) killed

\[\Rightarrow \text{Exponential} \cdot \text{Distortion}\]

\[\rightarrow \text{The distortion is called “acceptance”}\]

\(\star\) \(B_s^0\) lifetime fitted by:

\(\text{Exponential} \cdot \text{Acceptance}\)
Lifetime resolution with Kalman Filter fit

\[ B_s^0 \rightarrow J/\psi (\mu^+ \mu^-) \eta (\gamma \gamma) \]

\[ B_s^0 \rightarrow J/\psi (\mu^+ \mu^-) \eta (\pi^+ \pi^- \pi^0) \]

\[ \sigma = (35.7 \pm 0.8) \text{ fs} \]
\[ \mu = (1.5 \pm 0.8) \text{ fs} \]

Single Gaussian fit on associated candidates

Increased resolution: 121 → 36 fs

\[ \sigma = (32.9 \pm 0.9) \text{ fs} \]
\[ \mu = (1.1 \pm 0.9) \text{ fs} \]

Increased resolution: 68 → 33 fs
$B_s^0$ proper time pulls after Kalman Filter fit

★ Pull: residual divided by its error $(x_{\text{rec}} - x_{\text{true}})/\sigma_x \longrightarrow \text{normal Gaussian} (\sigma = 1, \mu = 0)$

$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\gamma \gamma)$

- $\sigma = (1.22 \pm 0.02)$
- $\mu = (0.06 \pm 0.03)$
- $\chi^2/\text{ndf}=27.9/36$

$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\pi^+ \pi^- \pi^0)$

- $\sigma = (1.32 \pm 0.03)$
- $\mu = (0.07 \pm 0.04)$
- $\chi^2/\text{ndf}=54.7/37$

⇒ Large under-estimation of the errors (22% and 32%)

~ 15% under-estimation present in all analyses \(\longrightarrow\) reconstruction problem
**Acceptance to no cuts:**

\[ \varepsilon_t = \text{accamp} \cdot \frac{(\text{accslope} \cdot t_{MC})^3}{1 + (\text{accslope} \cdot t_{MC})^3}. \]

\[ B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\gamma \gamma) \]

\[ B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\pi^+ \pi^- \pi^0) \]

\( \text{acc}_{\text{slope}} = (1.86 \pm 0.06) \text{ps}^{-1} \)

\( \chi^2/\text{ndf} = 6.1/9 \)

\( \text{acc}_{\text{slope}} = (1.54 \pm 0.05) \text{ps}^{-1} \)

\( \chi^2/\text{ndf} = 4.6/8 \)

\( \text{acc}_{\text{slope}} \) under-estimated lifetime errors and acceptance function

→ Inputs of model for the sensitivity study
Selection efficiencies and yields

- Selection optimization determined comparing associated signal to $b\bar{b}$ background distributions
- $B_s^0 \rightarrow J/\psi \eta$ total selection efficiency

<table>
<thead>
<tr>
<th>$B_s^0 \rightarrow J/\psi \eta$</th>
<th>Factors (in%) forming $\varepsilon_{\text{tot}}$ (in%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\varepsilon_{\text{det}}$</td>
</tr>
<tr>
<td>$\eta \rightarrow \gamma \gamma$</td>
<td>$10.02 \pm 0.30$</td>
</tr>
<tr>
<td>$\eta \rightarrow \pi^+ \pi^- \pi^0$</td>
<td>$7.41 \pm 0.26$</td>
</tr>
</tbody>
</table>

- Untagged signal yields for 2 $fb^{-1}$ (one year at $L_{\text{LHCb}}^{\text{av}}$)

<table>
<thead>
<tr>
<th>$B_s^0 \rightarrow J/\psi \eta$ ($\theta_P$)</th>
<th>$\text{BR} \ (10^{-6})$</th>
<th>$N^{2 fb^{-1}}_{\text{phys}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta \rightarrow \gamma \gamma \quad (-15^\circ)$</td>
<td>$10.5 \pm 4.3$</td>
<td>$8'900 \pm 4'000$</td>
</tr>
<tr>
<td>$\eta \rightarrow \pi^+ \pi^- \pi^0 \quad (-15^\circ)$</td>
<td>$6.1 \pm 2.6$</td>
<td>$3'100 \pm 1'400$</td>
</tr>
</tbody>
</table>

- $\eta$ mixing angle $\theta_P$: angle between ground-state of pseudoscalar octet $\eta_8$ and pseudoscalar singlet $\eta_1$, $\theta_P \in [-20^\circ; -10^\circ]$

\[ \eta = \eta_8 \cos \theta_P - \eta_1 \sin \theta_P \]
Flavor tagging

★ When a signal $B$ is reconstructed, we need to know its initial flavor ⇒ flavor tagging

- **opposite-side** tagging: identify the $b$-hadron containing the other $b$ (lepton, kaon, vertex tag)

- **same-side** tagging: use the companion of the $b$ quark in the signal $B$ (kaon tag)

★ The tagging procedure does not always give an answer: tagging efficiency $\varepsilon_{\text{tag}}$

★ Even if there is a tag, our identification could be incorrect: wrong tag fraction $\omega$

⇒ The tagging will dilute the theoretical decay asymmetry $A^{th}_{\text{CP}}(t)$ between the $\bar{B}_s^0$ and the $B_s^0$ by a factor $D$:

$$A^{obs}_{\text{CP}}(t) = D \cdot A^{th}_{\text{CP}}(t)$$

which reduces to $D = (1 - 2\omega)$ for a perfect resolution and no background
Tagging and trigger efficiencies

Tagging efficiency $\varepsilon_{\text{tag}}$ and wrong tag fraction $\omega$

<table>
<thead>
<tr>
<th>$\mathcal{B}_s^0 \to J/\psi(\mu^+ \mu^-) \eta(\gamma \gamma)$ after HLT</th>
<th>$\mathcal{B}_s^0 \to J/\psi(\mu^+ \mu^-) \eta(\pi^+ \pi^- \pi^0)$ after HLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{tag}}$ [%]</td>
<td>62.7 ± 1.2</td>
</tr>
<tr>
<td>$\omega$ [%]</td>
<td>35.2 ± 1.5</td>
</tr>
</tbody>
</table>

→ For comparison: $\mathcal{B}_s^0 \to \eta_c \phi$ after HLT: $\varepsilon_{\text{tag}} \sim 66.4\%$ and $\omega \sim 31.2\%$

Relative efficiency of each trigger ($\varepsilon_{\text{trg/sel}} = \varepsilon_{L0/\text{sel}} \times \varepsilon_{L1/L0} \times \varepsilon_{\text{HLT/L1}}$)

<table>
<thead>
<tr>
<th>$\mathcal{B}_s^0 \to J/\psi \eta$</th>
<th>$\varepsilon_{L0/\text{sel}}$</th>
<th>$\varepsilon_{L1/L0}$</th>
<th>$\varepsilon_{\text{HLT/L1}}$</th>
<th>$\varepsilon_{\text{HLT/sel}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta \to \gamma \gamma$</td>
<td>97.0 ± 0.4</td>
<td>86.5 ± 0.8</td>
<td>91.2 ± 0.7</td>
<td>76.5 ± 0.9</td>
</tr>
<tr>
<td>$\eta \to \pi^+ \pi^- \pi^0$</td>
<td>94.4 ± 0.6</td>
<td>93.5 ± 0.7</td>
<td>90.2 ± 0.8</td>
<td>79.6 ± 1.0</td>
</tr>
</tbody>
</table>

Muon and $J/\psi$: very efficient triggers!

→ For comparison: $\mathcal{B}_s^0 \to \eta_c \phi$ after HLT: $\varepsilon_{\text{HLT/sel}} \sim 30\%$
Various background contributions

- **Minimum bias events:** high statistics ($\sim 2 \cdot 10^{14}$ per year)
  → Killed by appropriate selection cuts

- **Inclusive $b\bar{b}$ events:** high statistics ($\sim 10^{12}$ per year) and displaced vertices
  → Main source of background for $B$ decays

- **Inclusive $H_b \to J/\psi X$ events:** presence of a $J/\psi$ and displaced vertices
  → Most polluting background for the $B_s^0 \to J/\psi \eta$ channels

- **Prompt $J/\psi$:** large production yield ($\sim 0.4 \cdot 10^{12}$ per year) and presence of a $J/\psi$
  → Killed by appropriate selection cuts (flight distance, ...)

$\star$ $b\bar{b}$ events ($\pm 600$ MeV/c$^2$) – Central value and 90% confidence level upper limit ($\theta_p = -15^\circ$)

<table>
<thead>
<tr>
<th>Decays</th>
<th>Selected events on $\sim 30M$</th>
<th>B/S Before triggers</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \to J/\psi(\mu^+ \mu^-) \eta(\gamma \gamma)$</td>
<td>16</td>
<td>$2.2 \pm 1.1$</td>
</tr>
<tr>
<td>$B_s^0 \to J/\psi(\mu^+ \mu^-) \eta(\pi^+ \pi^- \pi^0)$</td>
<td>3</td>
<td>$&lt; 3.3$</td>
</tr>
</tbody>
</table>

$\rightarrow$ All selected events of $H_b \to J/\psi X$ category
1. What is LHCb's ability to reconstruct the $B_s^0 \rightarrow J/\psi \eta$ decay channels?

- $J/\psi \rightarrow \mu^+ \mu^-$
- $\eta \rightarrow \gamma \gamma$
- $\eta \rightarrow \pi^+ \pi^- \pi^0$

$\Rightarrow$ Good reconstruction expected

2. What is LHCb's sensitivity to $\phi_s$?

- using decays to pure CP eigenstates such as $B_s^0 \rightarrow J/\psi \eta^{(')}$, $B_s^0 \rightarrow \eta_c \phi$
- using $B_s^0 \rightarrow J/\psi \phi$, “The golden decay mode” but admixture of CP eigenstates

$\Rightarrow$ can the pure CP eigenstates help $B_s^0 \rightarrow J/\psi \phi$ and significantly improve $\phi_s$ sensitivity?

$\star$ Sensitivities assessed by means of (fast) toy MC simulations
Physics model: $\bar{b} \rightarrow \bar{c}c\bar{s}$ to pure CP eigenstates

☆ Final states $f = J/\psi \eta, \eta_c \phi, J/\psi \eta'$ CP-even eigenstates: $(CP)|f\rangle = \eta_f |f\rangle$, $\eta_f = +1$

☆ Transition rates of initially pure $B_s^0$ and $\overline{B}_s^0$ states (perfect resolution)

$$R\left(B_s^0(t) \rightarrow f\right) = |A_f(0)|^2 \times e^{-\Gamma_s t}$$

$$\times \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - \eta_f \cos(\phi_s) \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) + qD \eta_f \sin(\phi_s) \sin(\Delta M_s t) \right]$$

- tagging categories: $q = +1$ for $R(B_s^0(t) \rightarrow f)$, $q = -1$ for $R(\overline{B}_s^0(t) \rightarrow f)$ and $q = 0$ untagged

- $A_f(0) \equiv A(B_s^0 \rightarrow f)$: instantaneous decay amplitude

- $D = (1 - 2\omega)$: tagging dilution factor; $\omega$: wrong tag fraction

☆ Both $D$ and $\phi_s$ modulate the oscillating term → need a control channel to extract $\omega$

→ $B_s^0 \rightarrow D_s\pi$ is used

☆ Untagged events also give access to $\Delta \Gamma_s$ and $\phi_s$ (small sensitivity for $\phi_s$, since $O(\phi_s^2)$)
Decay rates: $\bar{b} \to \bar{c}c\bar{s}$ to pure CP eigenstates

- $\Delta M_s = 20\text{ps}^{-1}$, $\Delta \Gamma_s/\Gamma_s = 10\%$, (nominal parameters) and $\phi_s = -0.4 \text{ rad}$ ($10 \times$ larger)
- Case study: $\omega = 30\%$, $acc_{slope} = 1.3 \text{ ps}^{-1}$, resolution $\sigma_\tau = 40 \text{ fs}$

Transition decay rates (including $\omega$)

With proper time resolution

With acceptance function

$B_s^0$: blue (dashed) – $\bar{B}_s^0$: red (solid). Arbitrary vertical scales
Unbinned (extended) likelihood fit to $\mathcal{L}_{\text{tot}}^{\bar{b}\to\bar{c}c\bar{s}}$

1. The mass distributions are fitted to determine signal and background probabilities. Parameters obtained are fixed
2. Sidebands: background parameters determined, acceptance fitted. Parameters obtained are fixed
3. Signal window: physics parameters $\vec{\alpha} = (\Delta \Gamma_s / \Gamma_s, \Delta M_s, \phi_s, \tau_{B_s^0} - R_T)$ and wrong tag fraction $\omega$ are fitted

Generate and fit $\sim 250$ toy experiments corresponding to 1 year data taking at $2 \text{ fb}^{-1}$

$\mathcal{L}_{\text{tot}}^{\bar{b}\to\bar{c}c\bar{s}}$ is simultaneously maximized with likelihood of the $B_s^0 \to D_s \pi$ control sample

Caveats:

- Resolution scale factor fixed
  Scale factor $S$: proper time pull distribution width multiplying the event-by-event proper time error
- Mistag rate assumed to be the same for signal and control channels
  → systematic uncertainty . . .
- Same per-event lifetime errors for signal and control channels, taken from the signal channel
  → probably not well suited for $B_s^0 \to J/\psi \eta$
**Likelihood: mass terms**

\[
\mathcal{L}_m^{\text{sig}}(m_i; N_{\text{sig}}, m_{B^0_s}, \sigma_{B^0_s}) \propto (N_{\text{sig}})^{N_{\text{obs}}} e^{-N_{\text{sig}} G(m_i; m_{B^0_s}, \sigma_{B^0_s})}
\]

\[
\mathcal{L}_m^{\text{bkg}}(m_i; N_{\text{bkg}}, \kappa_{\text{bkg}}) \propto (N_{\text{bkg}})^{N_{\text{obs}}} e^{-N_{\text{bkg}} E(m_i; \kappa_{\text{bkg}})}
\]

☆ Extended likelihood: Poisson distribution to ensure the correct B/S ratio in the signal region

☆ \(N_{\text{obs}}\): total number of events, \(N_{\text{sig}}\): signal yield, \(N_{\text{bkg}} = N_{\text{sig}} \times B/S\): background level

\[B_s^0 \rightarrow J/\psi \, \eta \text{ mass}\]

\[B_s^0 \rightarrow \eta_c \, \phi \text{ mass}\]

**Signal:** red, **Background:** black, **Total:** blue – |signal region|, sidebands|sidebands

☆ Background mass: exponential shape \(\kappa_{\text{bkg}} = -1.0 \ (\text{MeV}/c^2)^{-1}\) as example value
Likelihood: rates parts

\[ \mathcal{L}_{t,\text{even}}^{\text{sig}}(t_{i}^{\text{rec}}, \sigma_{t_i}, q_i | \vec{\alpha}, \omega, \text{accs}) \propto A(t_{i}^{\text{rec}}) \times \left[ (1 - \omega)\Gamma_{B_s^0 \to f}(t_{i}^{\text{true}}) + \omega\Gamma_{B_s^0 \to f}(t_{i}^{\text{true}}) \right] \]
\[ \otimes G(t_{i}^{\text{rec}} - t_{i}^{\text{true}}, S\sigma_{t_i}) \]

\[ \mathcal{L}_{t}^{\text{bkg}}(t_{i}^{\text{rec}}, \tau_{\text{bkg}}, \text{accs}) \propto A(t_{i}^{\text{rec}}) \times E(t_{i}^{\text{true}}; \tau_{\text{bkg}}) \otimes \delta(t_{i}^{\text{rec}} - t_{i}^{\text{true}}) \]

\[ \vec{\alpha} = (\Delta \Gamma_s / \Gamma_s, \Delta M_s, \phi_s, \tau_{B_s^0} - R_T): \text{vector of physics parameters} \]

\[ \star \sigma_{t_i}: \text{per-event errors} \]

\begin{itemize}
  \item \[ B_s^0 \to J/\psi \eta \text{ lifetime} \]
  \item \[ B_s^0 \to \eta_c \phi \text{ lifetime} \]
\end{itemize}

\[ \text{Signal: red, Background: black, Total: blue} \]

\[ \star \text{Background decay rate: exponential shape (} \tau_{\text{bkg}} = 1.0 \text{ ps}^{-1} \text{ as example value)} \]
Comparison of decay channels - from full MC simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>J/ψ η(γγ)</th>
<th>J/ψ η(π^+π^−π^0)</th>
<th>ηc φ</th>
<th>J/ψ φ</th>
<th>D_s^± π^±</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{sig}$ [k events]</td>
<td>8.9</td>
<td>3.1</td>
<td>3</td>
<td>125</td>
<td>69</td>
</tr>
<tr>
<td>$B/S$</td>
<td>2.0</td>
<td>3.0</td>
<td>0.7</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>$m_{tight}$ [MeV/c^2]</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$m_{sideband}$ [MeV/c^2]</td>
<td>150</td>
<td>150</td>
<td>75</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>$m_{loose}$ [MeV/c^2]</td>
<td>250</td>
<td>250</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>$\sigma_{B_s^0}$ [MeV/c^2]</td>
<td>34</td>
<td>20</td>
<td>12</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>$acc_{slope}$ after triggers [ps^{-1}]</td>
<td>1.9</td>
<td>1.5</td>
<td>1.3</td>
<td>2.9</td>
<td>1.3</td>
</tr>
<tr>
<td>$&lt;\sigma_{t\text{rec}}&gt;$ [fs]</td>
<td>30.4</td>
<td>25.5</td>
<td>26.2</td>
<td>35.8</td>
<td>33.5</td>
</tr>
<tr>
<td>$S$</td>
<td>1.2</td>
<td>1.3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\omega_{tag}$ [%]</td>
<td>35</td>
<td>30</td>
<td>31</td>
<td>33</td>
<td>31</td>
</tr>
<tr>
<td>$\varepsilon_{tag}$ [%]</td>
<td>63</td>
<td>62</td>
<td>66</td>
<td>60</td>
<td>65</td>
</tr>
</tbody>
</table>

Using $\theta_P = -15^\circ$ ($\theta_P \in [-20^\circ, -10^\circ]$) for $BR(B_s^0 \rightarrow J/\psi \eta)$

$B_s^0 \rightarrow J/\psi \phi$

- **pro**: nice signature, yield (and trigger), proper time resolution
- **con**: angular analysis to disentangle the CP eigenstates

Pure CP eigenstates

- **pro**: no angular analysis needed
- **con**: lower yields, worse B/S when $\gamma/\pi^0$ in final state
Sensitivities

Nominal parameters, input values

<table>
<thead>
<tr>
<th>$\phi_s$ [rad]</th>
<th>$\Delta M_s$ [ps$^{-1}$]</th>
<th>$\Delta \Gamma_s/\Gamma_s$</th>
<th>$\tau_{B_s^0}$ [ps]</th>
<th>$R_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.04</td>
<td>20.0</td>
<td>0.1</td>
<td>1.472</td>
<td>0.2</td>
</tr>
</tbody>
</table>

$R_T$: fraction of CP-odd decays for the $B_s^0 \to J/\psi \phi$

Sensitivities: fit results

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>$J/\psi \eta(\gamma\gamma)$</th>
<th>$J/\psi \eta(3\pi)$</th>
<th>$\eta_c\phi$</th>
<th>$J/\psi \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(\phi_s)$ [rad]</td>
<td>0.112</td>
<td>0.148</td>
<td>0.106</td>
<td>0.031</td>
</tr>
<tr>
<td>$\sigma(\Delta \Gamma_s/\Gamma_s)$</td>
<td>0.019</td>
<td>0.024</td>
<td>0.025</td>
<td>0.011</td>
</tr>
<tr>
<td>$\sigma(\Delta M_s)$ [ps$^{-1}$]</td>
<td>0.0122</td>
<td>0.0084</td>
<td>0.0084</td>
<td>0.0113</td>
</tr>
<tr>
<td>$\sigma(\tau_{B_s^0})$ [ps]</td>
<td>0.0057</td>
<td>0.0059</td>
<td>0.0062</td>
<td>0.0041</td>
</tr>
<tr>
<td>$\sigma(\omega)$</td>
<td>0.0049</td>
<td>0.0046</td>
<td>0.0046</td>
<td>0.0056</td>
</tr>
<tr>
<td>$\sigma(R_T)$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.0047</td>
</tr>
</tbody>
</table>
Parameters scan

★ Nominal parameters, input values

<table>
<thead>
<tr>
<th>$\phi_s$ [rad]</th>
<th>$\Delta M_s$ [ps$^{-1}$]</th>
<th>$\Delta \Gamma_s/\Gamma_s$</th>
<th>$\tau_{B^0_s}$ [ps]</th>
<th>$R_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.04</td>
<td>20.0</td>
<td>0.1</td>
<td>1.472</td>
<td>0.2</td>
</tr>
</tbody>
</table>

★ Sensitivities: scan results on parameters not well determined

<table>
<thead>
<tr>
<th>$\sigma(\phi_s)$ [rad]</th>
<th>Nominal</th>
<th>$\Delta M_s = 15$ ps$^{-1}$</th>
<th>$\Delta M_s = 25$ ps$^{-1}$</th>
<th>$\Delta \Gamma_s/\Gamma_s = 0.2$</th>
<th>$R_T = 0$</th>
<th>$R_T = 0.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \eta(\gamma\gamma)$</td>
<td>0.112</td>
<td>0.102</td>
<td>0.126</td>
<td>0.099</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$J/\psi \eta(\pi^+\pi^-\pi^0)$</td>
<td>0.148</td>
<td>0.136</td>
<td>0.161</td>
<td>0.139</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\eta_c \phi$</td>
<td>0.106</td>
<td>0.100</td>
<td>0.113</td>
<td>0.097</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$J/\psi \phi$</td>
<td>0.031</td>
<td>0.028</td>
<td>0.034</td>
<td>0.030</td>
<td>0.021</td>
<td>0.062</td>
</tr>
</tbody>
</table>

★ $\Delta M_s = 15$ ps$^{-1}$: increases sensitivity to $\phi_s$ ($\sim 10\%$)
★ $\Delta M_s = 25$ ps$^{-1}$: decreases sensitivity to $\phi_s$ ($\sim 10\%$)
★ $\Delta \Gamma_s/\Gamma_s = 0.2$: increases sensitivity to $\phi_s$
★ $R_T = 0$: pure CP eigenstate limit for $B^0_s \to J/\psi \phi$, $\sigma(\phi_s)$ 1.5 times better w.r.t nominal
★ $R_T = 0.5$: $\sigma(\phi_s)$ for $B^0_s \to J/\psi \phi$ gets 2 times worse for equal CP-even and CP-odd fractions

January 30 2006
Monday Seminar – 25
Benjamin Carron
Conclusion: $B^0_s \to J/\psi \eta$ selections

Selection results summary

<table>
<thead>
<tr>
<th>$B^0_s \to J/\psi \eta$</th>
<th>$\theta_P$</th>
<th>$\eta \to \gamma\gamma$</th>
<th>$\eta \to \pi^+\pi^-\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s$ mass resolution (after KF fit) [MeV/c^2]</td>
<td></td>
<td>34</td>
<td>20</td>
</tr>
<tr>
<td>Proper time resolution (after KF fit) [fs]</td>
<td></td>
<td>36</td>
<td>33</td>
</tr>
<tr>
<td>Proper time pull width</td>
<td></td>
<td>1.22</td>
<td>1.32</td>
</tr>
<tr>
<td>Tagging efficiency (after triggers) [%]</td>
<td></td>
<td>63</td>
<td>62</td>
</tr>
<tr>
<td>Wrong tag fraction (after triggers) [%]</td>
<td></td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Annual signal yield (untagged)</td>
<td>$-15^\circ$</td>
<td>8’900</td>
<td>3’100</td>
</tr>
<tr>
<td>$B/S$ from $b\bar{b}$ incl. (no triggers)</td>
<td>$-15^\circ$</td>
<td>2.2</td>
<td>$&lt; 3.3$</td>
</tr>
</tbody>
</table>

Very promising results — with expected improvements:

- Photon reconstruction
- Proper time fitting strategies
**Conclusion: φ_s expected sensitivities**

- Statistical precisions for 2 fb$^{-1}$ (nominal parameters)

\[ \frac{1}{\sigma} = \sqrt{\sum_i \frac{1}{\sigma_i^2}} \]

<table>
<thead>
<tr>
<th>Channels</th>
<th>(\sigma(\phi_s)) [rad]</th>
<th>Contribution [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_s^0 \to J/\psi \eta(\gamma \gamma))</td>
<td>0.112</td>
<td>6.4</td>
</tr>
<tr>
<td>(B_s^0 \to J/\psi \eta(\pi^+ \pi^- \pi^0))</td>
<td>0.148</td>
<td>3.6</td>
</tr>
<tr>
<td>(B_s^0 \to \eta_c \phi)</td>
<td>0.106</td>
<td>7.1</td>
</tr>
<tr>
<td>Combined three pure CP eigenstates channels</td>
<td>0.068</td>
<td>17.1</td>
</tr>
<tr>
<td>(B_s^0 \to J/\psi \phi)</td>
<td>0.031</td>
<td>82.9</td>
</tr>
<tr>
<td>Combined all four CP eigenstates channels</td>
<td>0.028</td>
<td>100.0</td>
</tr>
</tbody>
</table>

- Conclusion: contributions from pure CP eigenstates not negligible: \(\sim 17\%\)

- Other channels could be added
  - \(B_s^0 \to J/\psi \eta'\), however same performances as \(B_s^0 \to J/\psi \eta\) expected
  - \(B_s^0 \to J/\psi(e^+e^-) \phi\)

- At 10 fb$^{-1}$ (5 years): \(\sigma(\phi_s) \sim 0.013\) rad \(\to\) \(\sim 3\sigma\) for \(\phi_s = -0.04\) rad (SM)
  - Very good precision after one year for larger \(\phi_s\) \(\to\) more than 5σ for \(\phi_s > 0.15\) rad

January 30 2006  Monday Seminar – 27  Benjamin Carron
Visible branching ratio

⭐ η and η’ definition ($\theta_P \in [-20^\circ; -10^\circ]$):

$$
\eta = \eta_8 \cos \theta_P - \eta_1 \sin \theta_P \\
\eta' = \eta_8 \sin \theta_P + \eta_1 \cos \theta_P
$$

$$
\langle \eta_1 \rangle = \frac{1}{\sqrt{3}} \langle u\bar{u} + d\bar{d} + s\bar{s} \rangle \\
\langle \eta_8 \rangle = \frac{1}{\sqrt{6}} \langle u\bar{u} + d\bar{d} - 2s\bar{s} \rangle
$$

⭐ $\mathcal{B}\mathcal{R}_{B_s^0 \rightarrow J/\psi \eta}$ calculation based on the quark topologies method (the $\lambda$ are form factors)

$$
\mathcal{B}\mathcal{R}_{B_s^0 \rightarrow J/\psi \eta} = |S_\eta|^2 \mathcal{B}\mathcal{R}_{B_d^0 \rightarrow J/\psi K_S^0} \frac{m_{B_0^0}^3}{m_{B_s^0}^3} \left( \frac{\lambda(m_{B_0^0}^2, m_{J/\psi}^2, m_{\eta}^2)}{\lambda(m_{B_d^0}^2, m_{J/\psi}^2, m_{K_S^0}^2)} \right)^{3/2}
$$

⭐ Visible branching fractions

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching fraction</th>
<th>$\theta_p = -20^\circ$</th>
<th>$\theta_p = -10^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \rightarrow J/\psi \eta$</td>
<td>(3.1 ± 1.2) · 10^{-4}</td>
<td>(4.8 ± 1.9) · 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\gamma \gamma)$</td>
<td>(8.3 ± 3.5) · 10^{-6}</td>
<td>(12.8 ± 5.3) · 10^{-6}</td>
<td></td>
</tr>
<tr>
<td>$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\pi^+ \pi^- \pi^0)$</td>
<td>(4.7 ± 2.0) · 10^{-6}</td>
<td>(7.3 ± 3.1) · 10^{-6}</td>
<td></td>
</tr>
</tbody>
</table>
Number of selected events - signal and background

Number of selected signal events

<table>
<thead>
<tr>
<th>$B_s^0 \rightarrow J/\psi \eta$</th>
<th>$N_{gen}$</th>
<th>$N_{ible}$</th>
<th>$N_{ed}$</th>
<th>$N_{ible&amp;\prime_{ed}}$</th>
<th>$N_{sel}$</th>
<th>$N_{trg}$</th>
<th>$N_{tag}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta \rightarrow \gamma\gamma$</td>
<td>139'500</td>
<td>25'590</td>
<td>34'484</td>
<td>21'907</td>
<td>2'084</td>
<td>1'595</td>
<td>995</td>
</tr>
<tr>
<td>$\eta \rightarrow \pi^+\pi^-\pi^0$</td>
<td>171'000</td>
<td>26'109</td>
<td>27'635</td>
<td>19'718</td>
<td>1'486</td>
<td>1'183</td>
<td>728</td>
</tr>
</tbody>
</table>

Number of selected background events after random seed bug corrections

<table>
<thead>
<tr>
<th>$B_s^0 \rightarrow J/\psi \eta$</th>
<th>$\eta \rightarrow \gamma\gamma$</th>
<th>$\eta \rightarrow \pi^+\pi^-\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{gen}$</td>
<td>$N_{sel}$</td>
<td>$N_{HLT}$</td>
</tr>
<tr>
<td>inclusive $b\bar{b}$</td>
<td>30'500'000</td>
<td>16</td>
</tr>
<tr>
<td>$\rightarrow$ inclusive $b\bar{b}$ v1</td>
<td>10'500'000</td>
<td>0</td>
</tr>
<tr>
<td>$\rightarrow$ inclusive $b\bar{b}$ v2</td>
<td>20'000'000</td>
<td>16</td>
</tr>
<tr>
<td>$B_d^0 \rightarrow J/\psi(\mu^+\mu^-) K^+(K^+\pi^-)$</td>
<td>641'000</td>
<td>25</td>
</tr>
<tr>
<td>$B_d^0 \rightarrow J/\psi(\mu^+\mu^-) K_S^0(\pi^+\pi^-)$</td>
<td>89'000</td>
<td>3</td>
</tr>
<tr>
<td>$B^+ \rightarrow J/\psi(\mu^+\mu^-) K^+$</td>
<td>200'000</td>
<td>3</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow J/\psi(\mu^+\mu^-) \phi(K^+K^-)$</td>
<td>366'000</td>
<td>10</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow J/\psi(\mu^+\mu^-) \eta'(\pi^+\pi^-\eta)$</td>
<td>100'000</td>
<td>2</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow J/\psi \Lambda$</td>
<td>100'000</td>
<td>6</td>
</tr>
<tr>
<td>inclusive $J/\psi$</td>
<td>1'800'000</td>
<td>6</td>
</tr>
<tr>
<td>$\rightarrow H_b \rightarrow J/\psi X$</td>
<td>128'000</td>
<td>6</td>
</tr>
<tr>
<td>$\rightarrow$ prompt $J/\psi$</td>
<td>1'672'000</td>
<td>0</td>
</tr>
</tbody>
</table>
Inclusive $b\bar{b}$ background contribution

- $b\bar{b}$ events – principal source of bkg due to the high statistics and multiplicity of tracks

\[
\left( \frac{B}{S} \right)_{\text{signal}}^{b\bar{b}} = \frac{\varepsilon_{\text{gen}}^{b\bar{b}}}{\varepsilon_{\text{gen}}^{\text{signal}}} \cdot \frac{f_{\text{prod}}^{H_b\rightarrow J/\psi X}}{2 \cdot f_{B_s^0} \cdot BR_{\text{vis}}^{\text{signal}}} \cdot \frac{(N_{\text{sel}}^{b\bar{b}}/F)/N_{\text{gen}}^{b\bar{b}}}{N_{\text{signal}}^{\text{sel}}/N_{\text{gen}}^{\text{signal}}}
\]

- $\varepsilon_{\text{gen}}^{b\bar{b}} = 0.4321$ and $\varepsilon_{\text{gen}}^{\text{signal}} = 0.3471$: 400 mrad cut efficiency at generator level
- $f_{B_s^0} = 0.1$: $BR(b\rightarrow B_s^0)$
- $f_{\text{prod}}^{H_b\rightarrow J/\psi X}$: production correction factor (over-estimation of $H_b \rightarrow J/\psi X$ production)
- $F = 6$: enlargement factor due to the larger $B_s^0$ mass window for $b\bar{b}$

- Central value and 90% confidence level upper limit before triggers

<table>
<thead>
<tr>
<th>Decays</th>
<th>Selected events on ~ 30M</th>
<th>$\theta_p = -15^\circ$ Before triggers</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\gamma \gamma)$</td>
<td>16</td>
<td>2.2 $\pm$ 1.1</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\pi^+ \pi^- \pi^0)$</td>
<td>3</td>
<td>$&lt; 3.3$</td>
</tr>
</tbody>
</table>

$\implies$ All selected events of $H_b \rightarrow J/\psi X$ category
Inclusive $H_b \rightarrow J/\psi \ X$ background contribution

- $b\bar{b}$ events — principal source of bkg due to the high statistics and multiplicity of tracks

\[
\left( \frac{B}{S} \right)_{signal}^{H_b \rightarrow J/\psi \ X} = \frac{\varepsilon_{gen}^{incl. J/\psi}}{\varepsilon_{gen}^{signal}} \frac{f_{incl. J/\psi}}{f_{B_s^0}} \frac{BR_{vis}^{J/\psi \rightarrow \mu^+ \mu^-}}{BR_{vis}^{signal}} \frac{N_{sel}^{H_b \rightarrow J/\psi \ X}}{N_{sel}^{signal}} / \frac{N_{gen}^{H_b \rightarrow J/\psi \ X}}{N_{gen}^{signal}}
\]

- $\varepsilon_{gen}^{incl. J/\psi} = 0.399$ and $\varepsilon_{gen}^{signal} = 0.3471$: 400 mrad cut efficiency at generator level
- $f_{incl. J/\psi}$ fraction of b-hadrons decaying into $J/\psi \ X$

90% confidence level intervals before triggers

<table>
<thead>
<tr>
<th>Decays</th>
<th>Selected events on $\sim 125k$</th>
<th>$\theta_p = -20^\circ$ Before triggers</th>
<th>$\theta_p = -10^\circ$ Before triggers</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\gamma \gamma)$</td>
<td>6</td>
<td>[1.2; 6.3]</td>
<td>[0.8; 5.4]</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\pi^+ \pi^- \pi^0)$</td>
<td>1</td>
<td>[0.2; 7.6]</td>
<td>[0.1; 5.0]</td>
</tr>
</tbody>
</table>

Results compatible with inclusive b\bar{b} background estimations

January 30 2006
Monday Seminar – 32
Benjamin Carron
Physics model: $B_0^s \rightarrow D_s \pi$

- $B_0^s \rightarrow D_s^- \pi^+$: flavor specific decay in which a single tree diagram contributes $(V_{cb}^* V_{ud})$
  - $B_0^s$ decays instantaneously as $f = D_s^- \pi^+$ and $\overline{B}_0^s$ instantaneously as $D_s^+ \pi^-$

- This decay will be used as a control channel to extract $\omega$

- Transition decay rates with a possible mistag probability $\omega$
  
  $$R_f(t) = R_{{B}_0^s \rightarrow f}(t) = |A_f(0)|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) + q(1 - 2\omega) \cos (\Delta M_s t) \right]$$

  - tagging categories: $q = +1$ for $R_f(t) = R_{{B}_0^s \rightarrow f}$, $q = -1$ for $\overline{R}_f = R_{{\overline{B}}_0^s \rightarrow f}$ and $q = 0$ untagged
  - $R \rightarrow \Gamma$ analytical rates by setting $\omega = 0$

- Observed flavor asymmetry $A^{obs}_f$

  $$A^{obs}_f(t) = -\overline{D} \cdot \frac{\cos (\Delta M_s t)}{\cosh (\frac{\Delta \Gamma_s t}{2})}$$

  where the dilution factor $\overline{D}$ reduces to $D = (1 - 2\omega)$ in case of a perfect resolution
Decay rates: $B_s^0 \rightarrow D_s\pi$

- $\Delta M_s = 20\text{ps}^{-1}$, $\Delta \Gamma_s/\Gamma_s = 10\%$, (nominal parameters)
- Case study: $\omega = 30\%$, $acc_s = 1.3\text{ ps}^{-1}$, resolution scale factor $\sigma_r = 40\text{fs}$

Transition decay rates (including $\omega$)

With proper time resolution

With acceptance function

With acceptance and resolution

$B_s^0$: blue (dashed) and $\bar{B}_s^0$: red (solid). Arbitrary vertical scales
Physics model: $B_0^s \rightarrow J/\psi \phi$

- Final state $f$ is an admixture of CP eigenstates
  - $f = 0, \parallel$: CP-even configuration, $\eta_f = +1$
  - $f = \perp$: CP-odd configuration, $\eta_f = -1$

- Linear polarization amplitudes: $A_f(t)$
  - Fraction of CP-odd decays defined as $R_T \equiv |A_\perp(0)|^2 / \sum_{i=0,\parallel,\perp} |A_f(0)|^2 \sim \mathcal{O}(0.2)$
  - $R_T = (0.2 \pm 0.1)$, CDF Collaboration

- The one-angle $\theta_{tr}$ distribution enables to disentangle the different CP eigenstates

\[
\frac{d\Gamma(t)}{d(\cos(\theta_{tr}))} \propto \left[ |A_0(t)|^2 + |A_\parallel(t)|^2 \right] \frac{3}{8} (1 + \cos^2 \theta_{tr}) + |A_\perp(t)|^2 \frac{3}{4} \sin^2 \theta_{tr}
\]

Transversity angle $\theta_{tr}$: angle between positive lepton from the $J/\Psi$ and the $\phi$ decay plane, in the $J/\Psi$ rest frame
Decay rates: $B_s^0 \to J/\psi \phi$

- Decay rates biased by an acceptance and convoluted with a Gaussian lifetime resolution
- with a 10 times larger $\phi_s$ compared to SM expectation

$\bar{b} \to \bar{c}c\bar{s}$ pure CP eigenstate

$B_s^0 \to J/\psi \phi$ with $R_T = 0.2$

$B_s^0$: blue (dashed) and $\bar{B}_s^0$: red (solid). Arbitrary vertical scales

Wiggles’ amplitudes are slender in case of an admixture of CP eigenstates

In case of identical angular distributions for CP-odd and CP-even components, $R_T$ acts as a dilution factor $(1 - 2R_T)$
Pulls: mean and standard deviation of the fitted parameters are fine, except for a significant bias in the mean of $\Delta \Gamma_s/\Gamma_s$ (and $\tau_{B_s^0} = 1/\Gamma_s$)

- $\phi_s$ pull

$\Delta \Gamma_s/\Gamma_s$ pull

Bias for $\Delta \Gamma_s/\Gamma_s$ decreases with statistics (larger biases for decays to pure CP eigenstates)