Discussion of $B_s$ oscillations and the recent $\Delta m_s$ result from D0

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Presentation given at the LHCb Tuesday meeting, March 21, 2006
+ a few additional slides (introduction on mixing, at the beginning)
**B_s oscillations**

- **Neutral B meson system (B_d or B_s):**
  - B^0 and B^0 are quantum superposition of two mass eigenstates B^H_L and B^L_L:
  - Produce B^0 and observe its decay in a flavour-specific final state at proper time t (assume CP conserved):
  \[
  \text{Prob}(B^0 \rightarrow B^0) = \frac{e^{-t/\tau}}{2\tau} \left[ \cosh\left(\frac{\Delta \Gamma}{2} t\right) + \cos(\Delta m t) \right]
  \]
  \[
  \text{Prob}(B^0 \rightarrow \bar{B}^0) = \frac{e^{-t/\tau}}{2\tau} \left[ \cosh\left(\frac{\Delta \Gamma}{2} t\right) - \cos(\Delta m t) \right]
  \]
  \[
  \Delta \Gamma = \frac{\Gamma_L + \Gamma_H}{2} = \frac{1}{\tau}
  \]
  \[
  \Delta m = m^H_L - m^L_L
  \]

- **Slow B_d oscillations:**
  - very well measured: \(\Delta m_d = 0.5\) ps^{-1}

- **Fast B_s oscillations:**
  - not measured yet: \(\Delta m_s > 15\) ps^{-1}
  - experimentally very challenging
  - NB: we know effect is there since \(\chi_s\) has been measured to be \(\sim 1/2\)

\[
\chi_s = \int \text{Prob}(B^0_s \rightarrow \bar{B}^0_s) dt
\]

**Example:**
- \(\Delta m = 15\) ps^{-1}
- \(\Delta \Gamma = 0\)
- \(\tau = 1.5\) ps
B mixing in Standard Model

- 2nd-order weak process, box diagrams dominated by virtual top quark exchange

\[ \Delta m_q = \frac{G_F^2 m_W^2 \eta_B S(m_t^2/m_W^2)}{6\pi^2} m_{Bq} f_{Bq}^2 B_{Bq} |V_{tq} V_{tb}^*|^2 \]

\[ \Rightarrow \frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2} \text{ where } \xi = \frac{f_{B_s} \sqrt{B_{B_s}}}{f_{B_d} \sqrt{B_{B_d}}} \]

- Theory uncertainty (Lattice QCD):
  \[ f_{B_d} \sqrt{B_{B_d}} = 244 \pm 26 \text{ MeV} \rightarrow \sim 11\% \]
  \[ \xi = 1.210 + 0.047 - 0.035 \rightarrow \sim 4\% \]
  [M. Okamoto, hep-lat/0510113]

- Experimental accuracy:
  \[ \Delta m_d = 0.507 \pm 0.004 \text{ ps}^{-1} \rightarrow 0.9\% \]
  \[ \sigma(\Delta m_s) \text{ will be } < 0.1 \text{ ps}^{-1} \rightarrow 0.5\% \]
  as soon as measured

Extraction of \(|V_{td}| \) and \(|V_{ts}| \) from B mixing dominated by hadronic uncertainties
Constraining CKM unitarity triangle with B mixing

\[ \Delta m_d \propto |V_{td}V_{tb}^*|^2 = |V_{td}|^2 \]
\[ \Delta m_s \propto |V_{ts}V_{tb}^*|^2 = |V_{ts}|^2 = |V_{cb}|^2 \]

\[ \Rightarrow |V_{td}|/|V_{cb}| \text{ ratio} \]
\[ \Rightarrow \text{length of right side} \]

Global CKM fit without measurements of angles \( \alpha, \beta, \gamma \)

(CKM fitter, Summer 2005)
Standard Model prediction of $\Delta m_s$

- From fits of unitarity triangle, assuming Standard Model and using all available information (except from $\Delta m_s$ analyses):
  - $\Delta m_s = 21.2 \pm 3.2$ ps$^{-1}$
  - $\Delta m_s \in [15.4, 27.8]$ ps$^{-1}$ at 95% CL
  - $\Delta m_s \in [13.8, 30.0]$ ps$^{-1}$ at 99% CL

M. Bona et al (Uttfit collaboration), hep-ph/0501199, Feb 2005

New Physics?

- $B_s^0 \rightarrow \bar{b} \rightarrow \bar{s}$
- $B_s^0 \rightarrow s \rightarrow b$

$\Delta m_s = \Delta m_s^{SM} \propto |V_{ts}^2|

\phi_s = \phi_s^{SM} = -\text{arg}(V_{ts}^2)$

Not valid if new physics in $B$ mixing
Experimental effects dilute statistical significance of $B_s$ oscillations:

- Flavour tagging effective efficiency $\varepsilon_{\text{eff}}$: 
  \[ \varepsilon_{\text{eff}} = \varepsilon D^2 = \varepsilon (1 - 2w)^2 \]
  $\varepsilon$ = tagging efficiency
  $D$ = dilution
  $w$ = wrong tag probability

- Proper time resolution $\sigma_t$: 
  \[ t = \ell \frac{m}{p} \Rightarrow \sigma_t = \frac{m}{p} \sigma_{\ell} + \frac{\sigma_p}{p} \]
  $\ell$ = $B_s$ decay length
  $m$ = $B_s$ mass

- Signal purity (before tagging): 
  \[ \frac{S}{S + B} \]
  $S$ = number of $B_s$ signal events
  $B$ = number of background events

Somewhat naïve but extremely useful formula:

\[ \text{significance} = \sqrt{ \frac{S \varepsilon_{\text{eff}}}{2} \exp \left( - \frac{(\Delta m_s \sigma_t)^2}{2} \right) \frac{S}{S + B} } \]

- Because $\Delta m_s$ is large, very strong dependence on the resolution
  - need to be able to resolve the fast oscillations
- If significance too low, set lower limit on $\Delta m_s$
  - need to have a good knowledge of $\sigma_t$ and $\varepsilon_{\text{eff}}$
B_s oscillation amplitude

- Amplitude method:
  - Replace “cos(Δm_s t)” with “A cos(Δm_s t)” in mixing expressions
  - Fit tagged rates for A, at many different test values of Δm_s
  - Plot A ± σ_A versus Δm_s (similar to Fourier transform of mixing asymmetry)
  - A=1 (within error) at true Δm_s, otherwise A consistent with 0
  - Significance = 1/σ_A
  - If no significant signal, exclude values of Δm_s for which A=1 is excluded

- Example: D0 result Summer 2005:
  - No signal, exclude all values of Δm_s in this range at 95% CL
New D0 result on $\Delta m_s$

V.M. Abazov et al. (D0 collaboration),
“First Direct Two-Sided Bound on the $B_s$ Oscillation Frequency”
hep-ex/0603029, March 15, 2006, submitted to PRL

- 1 fb$^{-1}$ of data (April 2002–October 2005)
- $B_s \rightarrow D_s^{(*)} \mu^+\nu X, D_s^- \rightarrow \phi(K^+K^-)\pi$
- 26.7 k signal events
- proper decay length measured in transverse plane
- use MC “K factor” to correct $p_T(D_s,\mu)$ to $p_T(B_s)$
- opposite-side tagging, $\varepsilon D^2 = (2.48 \pm 0.21 \pm 0.07)$%

Preferred value: $\Delta m_s = 19 \text{ ps}^{-1}$
17 < $\Delta m_s$ < 21 ps$^{-1}$ at 90% CL
Claim: “This is the first 2-sided bound”

“A true value of $\Delta m_s$ above the sensitive region (i.e. > 22 ps$^{-1}$)
has a 5% probability to produce a likelihood similar to the one
observed in the interval 16 < $\Delta m_s$ < 22 ps$^{-1}$.”
Although D0 do not claim a measurement, their result is perceived as such by several people!

No sensitivity yet to observe a signal above 10 ps$^{-1}$

Need 10 times more data (or equivalent analysis improvements) for a 3σ observation at 19 ps$^{-1}$

Current D0 data display a “lucky” fluctuation at 19 ps$^{-1}$

— Bump in amplitude spectrum is either a 2.5σ fluctuation on top of nothing, or a 1.6σ fluctuation on top of a signal at $\Delta m_s = 19$ ps$^{-1}$

With more data, I expect the significance of this effect to first go down

— My guess it that it will be a while until D0 submits a second paper on $\Delta m_s$!
The measured negative log-likelihood difference (with respect to $\Delta m_s = \infty$) can be retrieved from the measured amplitude spectrum:

$$\Delta(\ln L) = -\ln(L(\Delta m_s)) - (-\ln(L(\infty))) = \frac{0.5 - A}{\sigma_A^2} \pm \frac{1}{\sigma_A}$$

The “lucky” fluctuation reflects in the $\Delta(\ln L)$ curve with a minimum deeper than expected:

- Expected depth is 0.40 for a signal at 19 ps$^{-1}$
- Observed depth is $1.80 \pm 0.89$ (stat.+syst.)
Effect of new D0 result on world average

End 2005

World average (prel.)

- data ± 1 σ
- 95% CL limit 16.6 ps⁻¹
- 1.645 σ
- sensitivity 20.0 ps⁻¹

Now

World average (prel.)

- data ± 1 σ
- 95% CL limit 16.6 ps⁻¹
- 1.645 σ
- sensitivity 20.1 ps⁻¹

| World average end 2005 | ± 0.54 |
| New D0 result alone | ± 1.12 |
| World average now | ± 0.49 |

σ_{tot}(A) at Δmₘ = 19 ps⁻¹

Sensitivity of world average

5σ observation of Δmₘ up to 10.5 ps⁻¹
3σ observation of Δmₘ up to 14.0 ps⁻¹
Comparisons

**Sensitivity for 95% CL exclusion:**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Sensitivity (ps⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>14.4</td>
</tr>
<tr>
<td>DELPHI</td>
<td>11.9</td>
</tr>
<tr>
<td>OPAL</td>
<td>7.9</td>
</tr>
<tr>
<td>SLD</td>
<td>11.5</td>
</tr>
<tr>
<td>CDF1</td>
<td>5.1</td>
</tr>
<tr>
<td>CDF2</td>
<td>13.0</td>
</tr>
<tr>
<td>D0</td>
<td>14.1</td>
</tr>
<tr>
<td>LEP</td>
<td>16.9</td>
</tr>
</tbody>
</table>

**World**

20.1 ps⁻¹

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**Weight in world average at 19 ps⁻¹:**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>22%</td>
</tr>
<tr>
<td>DELPHI</td>
<td>9%</td>
</tr>
<tr>
<td>OPAL</td>
<td>1%</td>
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<td>22%</td>
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<td>2%</td>
</tr>
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<td>CDF2</td>
<td>25%</td>
</tr>
<tr>
<td>D0</td>
<td>19%</td>
</tr>
<tr>
<td>LEP</td>
<td>32%</td>
</tr>
<tr>
<td>SLC</td>
<td>22%</td>
</tr>
<tr>
<td>World</td>
<td>100%</td>
</tr>
</tbody>
</table>

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**NEW**

Weight in world average at 19 ps⁻¹:

46%

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- CDF is experiment with largest weight at 19 ps⁻¹ because of fully reconstructed $B_s$ sample (but CDF used only 0.355 fb⁻¹ so far)
- Can D0 also use fully reconstructed $B_s$?
Combined amplitude spectrum

- Combined amplitude displays a signal-like bump in SM region
- Could still be a fluctuation at $\sim 2\sigma$ level ... or the hint of a signal
- But this feature has been around for years!

Max. deviation from $A=0$ in range 17–21 ps$^{-1}$:

<table>
<thead>
<tr>
<th>Year</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Now</td>
<td>2.1σ</td>
</tr>
<tr>
<td>End '05</td>
<td>1.6σ</td>
</tr>
<tr>
<td>Summer '05</td>
<td>2.3σ</td>
</tr>
<tr>
<td>Summer '04</td>
<td>1.9σ</td>
</tr>
<tr>
<td>Summer '03</td>
<td>2.2σ</td>
</tr>
<tr>
<td>Summer '02</td>
<td>2.3σ</td>
</tr>
<tr>
<td>Summer '01</td>
<td>2.7σ</td>
</tr>
<tr>
<td>Summer '00</td>
<td>2.7σ</td>
</tr>
<tr>
<td>Summer '99</td>
<td>1.9σ</td>
</tr>
<tr>
<td>Summer '98</td>
<td>1.9σ</td>
</tr>
<tr>
<td>Summer '97</td>
<td>1.9σ</td>
</tr>
</tbody>
</table>

- Summer 2000
- Now
The combined negative log-likelihood difference (with respect to $\Delta m_s = \infty$) can be retrieved from the combined amplitude spectrum:

- At 19 ps$^{-1}$ (D0’s preferred value)
  - Expected depth is 2.0 for a signal at 19 ps$^{-1}$
  - Observed depth is $1.8 \pm 2.0$

- At 19.5 ps$^{-1}$ (world’s preferred value)
  - Expected depth is 1.7 for a signal at 19.5 ps$^{-1}$
  - Observed depth is $2.1 \pm 1.8$

Expected depth for a signal at 19 ps$^{-1}$
What to expect in the near future

- Simple extrapolation based on current Run II results from CDF and D0:
  - assume 1/sqrt(N) dependence on total amplitude error
  - possible analysis improvements not taken into account

- Bottom line:
  - With 5 fb⁻¹, CDF will definitely have the sensitivity to observe $\Delta m_s$, if $\Delta m_s < 20 \text{ ps}^{-1}$

![Graph showing $\Delta m_s$ reach at Tevatron Run II with integrated luminosity on tape, arbitrary parabolic and power law extrapolations.](image)
Conclusion

- **For the world:**
  - New D0 result welcome, weighs ~20% in the new world average (at 19 ps⁻¹)
  - Δmₚs not yet measured!
    - don’t be intimidated by “first upper bound”, etc … This is just noise!
  - Available data consistent with SM prediction
  - If you believe SM is wrong …
    … you must also believe a 2σ fluctuation (but that’s not much additional faith)

- **For LHCb:**
  - CDF+D0 will measure Δmₚs “soon”, unless Δmₚs is large
    - how soon depends on how much luminosity they get + analysis improvements
  - LHCb’s readiness to measure Δmₚs as early as possible in 2008 is important
  - Ask LHC to deliver sufficient luminosity at IP8 with high priority
    - 0.25 fb⁻¹ in principle enough for 5σ measurement up to 40 ps⁻¹ (beyond Tevatron’s reach)
    - should we foresee a safety factor (to cover possible worse performance at startup)?