NEW RESULTS ON $B_s$ MIXING FROM LEP

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OUTLINE

• $B_s$ Mixing Phenomenology
• LEP and the LEP Experiments
• Experimental Strategy
• New/Improved Analyses from ALEPH (2002)
• Results and Interpretation
• Conclusion
\( \Delta m_s \) oscillation frequency proportional to mass difference \( \Delta m_s \)

Measurement of \( \Delta m_s \) (and \( \Delta m_d \)) permits extraction of CKM elements

\[
\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \cdot \frac{|V_{ts}|^2}{|V_{td}|^2} \cdot \frac{F_{B_s}^2 B_{B_s}}{F_{B_d}^2 B_{B_d}}
\]

Time-dependent asymmetry between "mixed" and "unmixed" decays

\[
P_{B_s \rightarrow B_s}^{\text{mix}}(t) = P_{B_s \rightarrow B_s}^{\text{unmix}}(t) = \Gamma_s \frac{e^{-\Gamma_st}}{2} [1 + \cos(\Delta m_s t)]
\]

Assuming CP conservation and small lifetime differences
Large Electron Positron (LEP) Collider

LEP1: 1989-1995 at $E_{cm}$ close to 91 GeV
LEP2: 1995-2000 at $E_{cm} = 130-209$ GeV

LEP1 Data used for Heavy Flavour Analyses: 1991-1995
4 Million Hadronic Z Decays per exp.

LEP Accelerator and Experiments dismantled to make way for LHC
e^+e^- \rightarrow Z \rightarrow b\bar{b} (if no mix)
EXPERIMENTAL STRATEGY

Select $B_S$ Candidates and Determine their Event Purity

Tag Initial and Final States

Measure Proper Time

Fit $\Delta m_S$

Select $B_S$ Candidates and Determine their Event Purity

Tag Initial and Final States

Measure Proper Time

Fit $\Delta m_S$
**B_s SELECTION AT LEP**

4 selection categories of increasing sample size/decreasing purity

**Fully Exclusive**

- **ALEPH, DELPHI**
- Criteria: Fully reconstructed:
  - $B_s \rightarrow D^{(*)-} (\pi^+, a^+_1, \rho^+)$
  - $B_s \rightarrow D^0 K^- (\pi^+, a^+_1)$
  - Sample Size/Purity: • 50 - 80 candidates
  • 50 - 80% purity
  • small sample size is compensated by excellent resolution

**Semi-Exclusive**

- **ALEPH, DELPHI, OPAL**
- Criteria: $B_s \rightarrow D_s^{(*)-} l^+\nu_l$
  - $B_s \rightarrow D_s^{(*)-} + hadrons$
  - Sample Size/Purity: • 10^2 - 10^3 candidates
  • 40 - 60% purity

**Semi-Inclusive**

- **ALEPH, DELPHI, OPAL**
- Criteria: $B_s \rightarrow l^+ + X$
  - Sample Size/Purity: • 10^4 - 10^5 candidates
  • 10 - 20% purity

**Fully Inclusive**

- **DELPHI**
- Criteria: Inclusive secondary vertices
  - Sample Size/Purity: • 5x10^5 candidates
  • 10% purity ("natural")

3 new/improved ALEPH analyses
NEW ALEPH FULLY EXCLUSIVE $B_S$ SELECTION

$B_S \rightarrow D_s^{(*)-} (\pi^+, a_1^+, \rho^+)$

**Main Peak**

$B_S \rightarrow D_s^- \pi^+ (\pi^0, \gamma)$

**Satellite Region**

$B_S \rightarrow D_s^- a_1^+ (\pi^0, \gamma)$

**Combined**

- **Event Purity**
  - 12 event classes based on decay
  - Purity from helicity angle, $m(D_S)$

- **Candidate Events**
  - 32 candidates in main peak
  - 48 candidates in satellite region

- 11 candidates with purity > 80%
**IMPROVED ALEPH SEMI-EXCLUSIVE $B_S$ SELECTION**

$B_S \rightarrow D_s^{(*)} l^+ \nu_l$

**Topology**

- $B_S \rightarrow D_s^- \rightarrow l^+ \nu$
- $D_s \rightarrow \phi l^+ \nu$

**Event Purity**
- $m(D_s$ or $\phi)$ resonant fraction
- NN based discriminant for signal vs $b \rightarrow D_s DX (D \rightarrow l)$

**Ds Reco. Mass (GeV/c^2)**

- **Ds → hadronic**
  - 297 candidates
  - ALEPH
  - Data
  - Fit
  - Wrong sign

- **Ds → φl^+ν**
  - 36 candidates
  - ALEPH
  - Data
  - Fit
  - Wrong sign

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Page 8
**IMPROVED ALEPH SEMI-INCLUSIVE B_{S} SELECTION**

**NN-based b→l candidate**
- lepton p and p_{T}
- E_{miss} \approx E_{\nu}
- Jet/Track kinematics
- lepton impact parameter w.r.t. Charm vertex

**Inclusive Charm candidate**

**NN-based Event b-tag using b-Hadron content of Same and Opposite Sides**
- Track Impact Parameters
- Secondary Vertices
- b Hadron Mass
- lepton p and p_{T}

**Selection yields:**
74, 026 candidates
**IMPROVED ALEPH SEMI-INCLUSIVE $B_s$ SELECTION**

**Event Purity determined with NN-based discriminant**

Vertex charge and charge multiplicity: \( q_l \sum w_i^{K^1} q_i, \sum w_i^{K^2}, q_l \sum w_i p_i^{K^3} q_i \)

\( K \) from Fragmentation and B Decay: \( K^\pm \) (w.r.t. \( l \) charge), \( K^0 \) estimators, \( m(K^+K^-) \)

**Graphical Representation**

- **q̅q simulation**
- **Data**
- **u, d, s, c**
- **B_d**
- **B_u**
- **b baryons**
- **B^+**

**ALEPH simulation**

17% sample has purity above 20%

**Event Purity**

- **Neural Network Output**
- **Event Purity determined with NN-based discriminant**
INITIAL AND FINAL STATE TAGGING

Determine Particle/Antiparticle State of $B_s$ at Production (Decay)

FINAL STATE TAGGING

**Fully Exclusive**

*ALEPH, DELPHI*

$B_s \rightarrow D_s^{(*)-} (\pi^+, a_1^+, \rho^+)$

$B_s \rightarrow D^0 K^- (\pi^+, a_1^+)$

**Semi-Exclusive**

*ALEPH, DELPHI, OPAL*

$B_s \rightarrow D_s^{(*)-} l^+ \nu_l : \text{lepton charge}$

$B_s \rightarrow D_s^{(*)-} + \text{hadrons} : D_s^{(*) \text{charge}}$

**Semi-Inclusive**

*ALEPH, DELPHI, OPAL*

$B_s \rightarrow l^+ + X : \text{lepton charge (account for } b \rightarrow c \rightarrow l \text{ mistag)}$

**Fully Inclusive**

*DELPHI*

NN-based charge dipole method

Charges of Decay Products
**INITIAL STATE TAGGING**

*Draw upon information from both Same and Opposite sides*

**Same Side Information**
- Primary Vertex charge
- Fragmentation Kaon

**Opposite Side Information**
- Hemisphere "Jet" charge
- Primary Vertex charge
- Secondary Vertex charge
- $K^\pm$ and $l^\pm$ charge(s)

Combine all information into single Tagging discriminant: performance evaluated as Mistag Rate $\eta$
NEW ALEPH INITIAL STATE TAGGING

Opposite Side Information combined using NN:

Additional Same Side Information:
- Fragmentation Kaon (NN selected, charge signed)
- "Jet" charges (excluding B_s decay products)
- \( \cos \theta(B_s), p(B_s), N_{\text{tracks}} \)
**PROPER TIME MEASUREMENT**

Determine Proper Time (i.e., $B_s$ meson lifetime in its rest frame)

\[
t = \frac{l m}{p}
\]

\[
\sigma_t = \sqrt{\left(\frac{m}{p} \sigma l\right)^2 + \left(\frac{t \sigma p}{p}\right)^2}
\]

Term diminished as $B_s$ osc. $\ll \tau B_s$

**Two Ingredients**

- **$B_s$ Decay Length ($l$): Distance from Primary to Secondary Vertex**
  - Primary Vertex independent of analysis
  - Secondary Vertex dependent upon event selection (impact upon resolution)
  \[\text{typical } \sigma_l = 250 \mu m\]

- **$B_s$ Momentum ($p$)**
  - Event Selection Dependent
    - Fully Enclusive: sum of decay products
    - Inclusive:
      - Jet momentum
      - Correct for $p_V$ in semileptonic (event energy-momentum cons.)

OSCILLATION FIT

Construct $B_S$ Signal Likelihood:

for every candidate $i$:  
$$L_i = \sum_{j}^{N_{\text{comp}}} f_j^i \left[ (1 - \eta_j^i) P_j^{\text{unmix}}(t_i) + \eta_j^i P_j^{\text{mix}}(t_i) \right]$$

$j$ denotes signal and background components  
- oscillating $B_S$  
- oscillating $B_d$  
- non-osc. b Hadrons  
- udsc events  

$f_j^i$: prob. of candidate $i$ from $j$  
$\eta_j^i$: prob. of candidate $i$ osc. if from $j$  
$p.d.f.$ of decay proper time for unmixed/mixed candidates in component $j$ with experimental effects (e.g., $\sigma_l$, $\sigma_p$)

Elements of the Likelihood are evaluated event-by-event
THE AMPLITUDE METHOD

Introduce an Amplitude $A$ into probabilities:

$$P_{\text{unmix}}^{\text{mix}}(t) = \Gamma_s \frac{e^{-\Gamma_st}}{2} [1 \mp \cos(\Delta m_s t)] \rightarrow \Gamma_s \frac{e^{-\Gamma_st}}{2} [1 \mp A \cos(\omega_t)]$$

Maximize Likelihood with respect to Amplitude $A$ for a given test frequency $\omega$

Permits combination of different analyses/experiments results

- $A = 0$ for $\omega \ll \Delta m_s$
- $A = 1$ for $\omega = \Delta m_s$

$\omega$ excluded at 95% C.L. if $A + 1.645\sigma_A < 1$

Analysis Sensitivity: expected limit at 95% C.L.
RESULTS OF THE THREE NEW ALEPH ANALYSES

Fully Exclusive

Semi-Exclusive (D_s lepton)

Semi-Inclusive (lepton)

\[ \Delta m_s \text{ Observed} \quad (\text{Expected}) \quad \text{Lower Limits at 95\% C.L.} \]

\[ \Delta m_s > 2.4 \text{ ps}^{-1} \ (0.3 \text{ ps}^{-1}) \]

NEW!

\[ \Delta m_s > 7.2 \text{ ps}^{-1} \ (7.4 \text{ ps}^{-1}) \]

(was 7.2 ps\(^{-1}\) (6.6 ps\(^{-1}\))

\[ \Delta m_s > 11.4 \text{ ps}^{-1} \ (14.0 \text{ ps}^{-1}) \]

(was 9.5 ps\(^{-1}\) (9.8 ps\(^{-1}\))

COMBINATION OF THREE ALEPH ANALYSES

\[ \Delta m_s > 10.9 \text{ ps}^{-1} \ (15.7 \text{ ps}^{-1}) \]
DELPHI AND OPAL RESULTS

\[ \Delta m_s > 7.4 \text{ps}^{-1} (8.1 \text{ps}^{-1}) \]

Also

Fully and Semi-Exclusive: \( \Delta m_s > 4.0 \text{ps}^{-1} (3.2 \text{ps}^{-1}) \)

Semi-Inclusive: \( \Delta m_s > 7.3 \text{ps}^{-1} (10.6 \text{ps}^{-1}) \)

Fully Inclusive: \( \Delta m_s > 1.1 \text{ps}^{-1} (6.1 \text{ps}^{-1}) \)

\[ \Delta m_s > 1.0 \text{ps}^{-1} (4.1 \text{ps}^{-1}) \]

Semi-Inclusive: \( \Delta m_s > 5.1 \text{ps}^{-1} (6.7 \text{ps}^{-1}) \)


Combine LEP (new ALEPH, DELPHI, OPAL) with CDF and SLD

**World average (prel.)**

- data ± 1 σ
- 1.645 σ
- 95% CL limit 14.9 ps⁻¹
- sensitivity 19.3 ps⁻¹

**World average (prel.)**

- data ± 1.645 σ
- data ± 1.645 σ (stat only)

**Amplitude vs. \( \Delta m_s \) (ps⁻¹)**

- B Oscillations Working Group

**Amplitude at \( \Delta m_s = 15.0 \) ps⁻¹**

- ALEPH 1 (91-95, no D₁, adjusted)
- ALEPH D 1 (91-95)
- ALEPH B (91-95)
- CDF l+D (92-95)
- DELPHI B + D h (92-95)
- DELPHI D₁+φ (92-95, prel)
- DELPHI v+ (92-95, prel)
- OPAL 1 (91-95)
- OPAL D 1 (91-95)
- SLD l+D (96-98, prel.)
- SLD dipole (96-98, prel.)
- SLD D (96-98, prel.)

- Amplitude (sensitivity)

- ALEPH 1 (91-95, no D₁, adjusted) 0.43 ± 0.69 ± 0.16 (13.7 ps⁻¹)
- ALEPH D 1 (91-95) 3.83 ± 1.49 ± 0.32 (7.5 ps⁻¹)
- ALEPH B (91-95) -0.47 ± 1.15 ± 0.47 (0.4 ps⁻¹)
- CDF l+D (92-95) -0.14 ± 2.00 ± 0.51 (5.1 ps⁻¹)
- DELPHI B + D h (92-95) 0.45 ± 3.58 ± 1.93 (3.2 ps⁻¹)
- DELPHI D₁+φ (92-95, prel) -0.43 ± 1.51 ± 0.35 (8.7 ps⁻¹)
- DELPHI v+ (92-95, prel) -0.19 ± 1.18 ± 0.19 (9.9 ps⁻¹)
- OPAL 1 (91-95) -0.43 ± 3.67 ± 0.56 (6.1 ps⁻¹)
- OPAL D 1 (91-95) -1.25 ± 2.34 ± 1.91 (7.2 ps⁻¹)
- SLD l+D (96-98, prel.) -3.63 ± 3.05 ± 0.40 (4.2 ps⁻¹)
- SLD dipole (96-98, prel.) 0.67 ± 1.07 ± 0.25 (6.3 ps⁻¹)
- SLD D (96-98, prel.) 0.41 ± 0.99 ± 0.21 (8.6 ps⁻¹)
- SLD dipole (96-98, prel.) 1.38 ± 1.75 ± 0.45 (1.7 ps⁻¹)
- SLD D (96-98, prel.) 0.39 ± 0.39 (19.3 ps⁻¹)

\( \Delta m_S > 14.9 \) ps⁻¹ (19.3 ps⁻¹) at 95% C.L.

No measurement, but data are consistent with signal expectation around \( \Delta m_S = 16 \) to 18 ps⁻¹
CONCLUSIONS

• No observation of $B_S$ mixing

• $B_S$ mixing analyses continue to improve
  – New/Improved ALEPH results (2002)

• Lower Limit of $\Delta m_S > 14.9 \text{ ps}^{-1}$
  – far below sensitivity of 19.3 ps$^{-1}$

• Possible hint of signal between 16 - 18 ps$^{-1}$

• Look forward to new results from CDF and DØ