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Oscillations of neutral B mesons systems

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Abstract

The oscillation phenomenon in the neutral B mesons systems is now well established. The motivations and principles of the measurements are given; then the most recent results from the LEP experiments, the CDF collaboration at Fermilab and the SLD collaboration at SLAC are reviewed. The present world average of the B_d^0 meson oscillation frequency is $\Delta m_d = 0.471 \pm 0.016 \text{ ps}^{-1}$ and the lower limit on the B_s^0 oscillation frequency is $\Delta m_s > 12.4 \text{ ps}^{-1}$ at 95% CL.

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1 Physics motivations

It is known since a long time that $B_d^0(d\bar{b})$ and $B_s^0(s\bar{b})$ mesons can undergo particle-antiparticle mixing, due to second-order weak interactions which involve box diagrams. If CP violation is neglected, the CP eigenstates of the $B^0 - \bar{B}^0$ system are also mass eigenstates and the probability that a purely B^0 state produced at time $t=0$ will decay as a B^0 or \bar{B}^0 at time t is:

$$p(t, \mu) = \frac{e^{-(t/\tau)} [1 + \mu \cos(\Delta m t)]}{2\tau} \quad (1)$$

The oscillation frequency Δm is the mass difference between the two mass eigenstates, τ is the average lifetime and $\mu = +1$ (resp -1) if the final state is a B^0 (resp \bar{B}^0).

In the framework of the Standard Model, Δm may be computed with a rather large uncertainty coming from QCD correction factors. The ratio of the oscillation frequencies is under better control:

$$\frac{\Delta m_s}{\Delta m_d} = \xi^2 \frac{m_{B_s}}{m_{B_d}} \left| \frac{V_{ts}}{V_{td}} \right|^2 \quad (2)$$

where $\xi = 1.16 \pm 0.10$ contains all theoretical uncertainties. Therefore the measurement of B_d^0 and B_s^0 oscillation frequencies should give constraints on the poorly known CKM matrix elements V_{ts} and V_{td} . These constraints are conveniently expressed in the framework of the Wolfenstein parametrisation of the CKM matrix, introducing the so-called Unitarity Triangle.

2 Experiments and data

2.1 LEP experiments

The four LEP experiments ALEPH, DELPHI, L3 and OPAL use data taken at the Z peak from 1991 to 1995. They have accumulated about 4 million hadronic Z decays each, i.e. about one million pairs of B mesons, with the following properties:

- B mesons are produced with a large boost (mean momentum around 35 GeV/c), giving a decay length around 2 to 3 mm;
- All experiments have good Silicon vertex detectors and obtain a resolution on the decay length around 300 micrometers;
- The particle identification, which is very important for B_s^0 studies, is done through dE/dx measurements in ALEPH and OPAL, and using a RICH (Ring Imaging Cerenkov counter) in DELPHI.

2.2 CDF

The Collider Detector Facility at Fermilab has collected 130 pb^{-1} of $p\bar{p}$ collisions at centre of mass energy 1.8 TeV since 1992. At the Collider there is a huge B meson

production rate, with a huge background. The B mesons are produced with a boost which is less favourable than at LEP/SLC (mean momentum around 15 GeV/c).

2.3 SLD

The SLD collaboration at SLAC has taken around 500000 hadronic Z0 decays between 1993 and 1997, 350000 of which are analyzed. The excellent performances of the SLD vertex detector allow a much better decay length resolution than LEP experiments (around 50-100 micrometers). In addition, the electron beam polarisation may be used as a powerful tool for the B meson tagging [1]. The particle identification is done using a Ring Imaging Cerenkov counter.

3 Time-dependent oscillation measurements

All analyses require reconstruction of the decay time of the B^0 mesons. This is done by the measurement of the decay length and of the momentum of the B^0 . As it is impossible to describe in detail all existing measurements, only the basic principles are given in this section.

3.1 B^0 meson identification

The B^0 meson is in general identified by the detection of a high energy, high Pt lepton.

Inclusive lepton analyses demand that this lepton has a large impact parameter with respect to the interaction point. This gives several tens of thousands of events, but with a low purity (e.g. 10% for the B_s^0).

In addition, one can search for the exclusive decay of a charmed meson. For instance for B_d^0 decays one looks for a $D^{*-}l^+$ final state, with $D^{*-} \rightarrow D^0\pi^-$; the D^0 meson is then searched for via its hadronic decays e.g. $K^-\pi^+$. For B_s^0 decays one looks for a $D_s^-l^+$ final state, then for D_s hadronic decays such as $\phi\pi$. The charmed meson is used together with the lepton to reconstruct the B^0 decay vertex; then the decay length is computed from this vertex and the event interaction point. These semi-exclusive analyses give some hundreds of events per experiment, with a purity which may be as high as 50%.

In a recent analysis DELPHI [2] reconstructs fully hadronic decays of the B_s^0 . This gives some tens of events, with a very high purity.

3.2 Decay time measurement and error

The B^0 boost is computed using the lepton, the reconstructed charmed meson and, when possible, the neutrino energy estimated from the missing energy. Typical values of the decay time resolution for LEP experiments are around 0.3 ps for inclusive lepton analyses, 0.15 ps for charm-lepton analyses, and 0.06 ps for the DELPHI exclusive B_s^0 reconstruction. SLD obtains a resolution of 0.06 ps for $D_s l$ events.

3.3 Tagging of the B^0 at decay

One has to know if the detected B^0 meson has oscillated or not before decaying; therefore it is necessary to tag it both at production and at decay time.

The tagging of the B^0 at decay time is obtained simply by the charge of the energetic lepton, since e.g. a positive lepton l^+ is the signature of the decay of a B^0 meson. This final state tagging is not perfect since one may detect a lepton from a $b \rightarrow c \rightarrow l$ decay; the corresponding mistag probability is computed from simulated events.

3.4 Tagging of the B^0 at production

This is much more complicated. Usually one divides the event in two opposite hemispheres defined with respect to the event thrust axis; several tags are used in each hemisphere:

- In the B^0 hemisphere, the nature and the charge of the most energetic fragmentation track carries information on the production state of the B^0 meson: e.g. an energetic K^+ is produced in association with a B_s^0 . One can also use the sign of the jet charge in this hemisphere.
- In the hemisphere opposite to the detected B^0 , several tags may be used. First, one can search for an energetic lepton with large Pt and impact parameter. One can also use the jet charge of the hemisphere. The sign of the lepton and of the jet charge indicate if a b or \bar{b} quark was produced in this hemisphere.

This initial state tagging is far from being perfect. There are experimental difficulties: particle misidentification, incorrect attribution of a charged track to the primary vertex, etc.. and possible mistags due to physics: the b quark in the opposite hemisphere may give a B^0 meson which may oscillate before decay, or the detected lepton may come from the decay of a charmed hadron. All these mistag probabilities must be carefully computed using the simulation.

4 Results

There are presently about 35 different time-dependent B^0 oscillation analyses, some of them being presented for the first time at this conference. The oscillation frequency is fitted from a likelihood fit to the complicated decay probability function which includes all the tags, mistag probabilities and efficiencies coming from detailed Monte Carlo studies.

4.1 Measurement of Δm_d

Four new measurements are available since the 1997 Summer conferences:

- one from CDF [3], using Dl and D^*l correlations with the following result:

$$\Delta m_d = 0.471_{-0.068}^{+0.078}(\text{stat}) \pm 0.034(\text{syst}) \text{ ps}^{-1} \quad (3)$$

- from L3 [4], three analyses using lepton-lepton decay length, lepton-jet charge and lepton-lepton impact parameter, giving:

$$\Delta m_d = 0.444 \pm 0.028(\text{stat}) \pm 0.028(\text{syst}) \text{ ps}^{-1} \quad (4)$$

These new results are combined with all the previously published ones, resulting in an average of 24 Δm_d measurements:

$$\Delta m_d = 0.477 \pm 0.017 \text{ ps}^{-1} \text{ (preliminary)} \quad (5)$$

This average may be combined with the time-integrated mixing measurements made by CLEO and ARGUS at the Υ_{4s} resonance, giving the following world average:

$$\Delta m_d = 0.471 \pm 0.016 \text{ ps}^{-1}(\text{preliminary}) \quad (6)$$

This world average is now dominated by systematics (0.013 ps^{-1} systematic error, whereas the statistical error is 0.010 ps^{-1} , at the 2% level).

Figure 1 gives the average of the measurements of Δm_d obtained by each experiment.

4.2 Limits on Δm_s

From Eq. (2), the B_s^0 oscillation frequency is expected to be about 20 times greater than that of the B_d^0 . As the B_s^0 meson production rate is about 1/4 that of the B_d^0 , the search for B_s^0 oscillations is therefore an experimental challenge. Up to now, no measurement of Δm_s is available; only lower limits are obtained from 11 existing analyses.

At this conference, the results described below have been presented for the first time. All limits given below are 95% Confidence Level limits.

- DELPHI [5] has presented a new limit using 280 $D_s l$ events, the D_s being reconstructed in 6 hadronic and 2 semileptonic decay modes. They obtain a lower limit of $\Delta m_s > 7.4 \text{ps}^{-1}$.

- DELPHI [2] gives a lower limit of $\Delta m_s > 2.4 \text{ps}^{-1}$ from fully reconstructed B_s^0 mesons (they have 17 ± 8 events reconstructed in 8 decay channels). These events give an important contribution for high Δm_s values (above 10 ps^{-1}) due to their excellent proper time resolution.

- SLD [1] has presented three analyses: lepton - D , charged dipole, lepton + tracks. They exclude the following regions:

$$\Delta m_s < 1.3 \text{ps}^{-1} \text{ and } 2.7 < \Delta m_s < 5.3 \text{ps}^{-1} \quad (7)$$

- CDF [6] has presented 1068 \pm 70 events with ϕl correlations, from which they obtain a lower limit of $\Delta m_s > 5.8 \text{ps}^{-1}$.

At the time of the conference, the overall combination could not yet be done. This has been done since that time by the LEP Working Group, using the method defined in [7]. The resulting preliminary world average of the amplitudes is displayed in Figure 2, and the preliminary lower limit is [8]:

$$\Delta m_s > 12.4 \text{ ps}^{-1} \text{ at } 95\% \text{ CL} \quad (8)$$

with a sensitivity of 13.8 ps^{-1} .

5 Consequences on the Unitarity Triangle

F. Parodi et al. [9] have studied the consequences of the above results for the Unitarity Triangle. They find rather strong constraints on the triangle apex position: $\rho = 0.189 \pm 0.074$, $\eta = 0.354 \pm 0.045$ and also a strong constraint on the β angle: $\sin(2\beta) = 0.73 \pm 0.08$. This is especially interesting before the starting up of the B-factories at SLAC and KEK, which will measure this angle directly.

They find also that within the present knowledge of all parameters, the allowed range of Δm_s is $6 < \Delta m_s < 21 \text{ ps}^{-1}$ at 95% CL. This means that half of the allowed range is already experimentally excluded.

6 Future prospects

The most recent individual measurements of the B_d^0 oscillation frequency from L3 and CDF are impressively precise. However the present world average has a precision around 3%, and therefore future improvements are expected to be modest.

The limit on Δm_s should improve appreciably in the near future. The LEP experiments still have room for improvement, especially ALEPH and OPAL. SLD should also give new limits using their full statistics on tape and CDF will give more results on their present data using new channels.

In a more distant future (2 years), new results should come from SLD if they run in 1999 (expected sensitivity around 20 ps^{-1}). In year 2000, the HERA B experiment at DESY will have data, and at the Fermilab Collider the CDF and D0 collaborations will collect new data with an expected sensitivity of 25 ps^{-1} . This would explore the full domain allowed to Δm_s by the Standard Model.

7 Conclusions

Using the most recent CDF and L3 measurements, the B_d^0 oscillation frequency is now measured with an accuracy of almost 3%:

$$\Delta m_d = 0.471 \pm 0.016 \text{ ps}^{-1} \text{ (preliminary)} \quad (9)$$

New analyses on the B_s^0 oscillation frequency give the following combined new lower limit:

$$\Delta m_s > 12.4 \text{ ps}^{-1} \text{ at 95\% CL (preliminary)} \quad (10)$$

This result excludes already half of the allowed region for Δm_s in the Standard Model, and gives efficient constraints on the Unitarity Triangle. Improvements on the Δm_s limit are expected from updated LEP analyses and from new data at SLD and at the Fermilab Collider.

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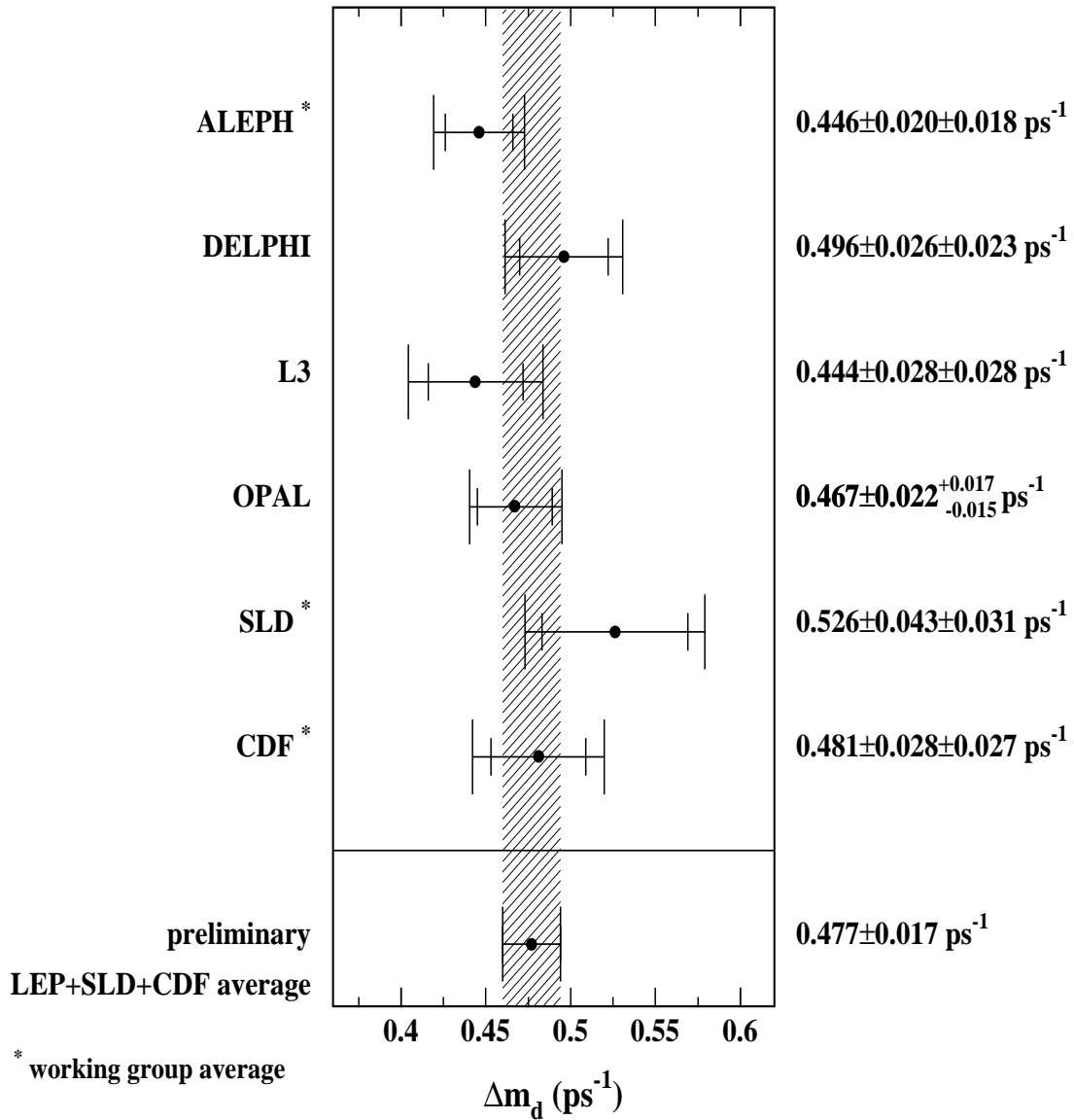


Figure 1: Average Δm_d value per experiment. This figure has been provided by the LEP Working Group on B Oscillations [8].

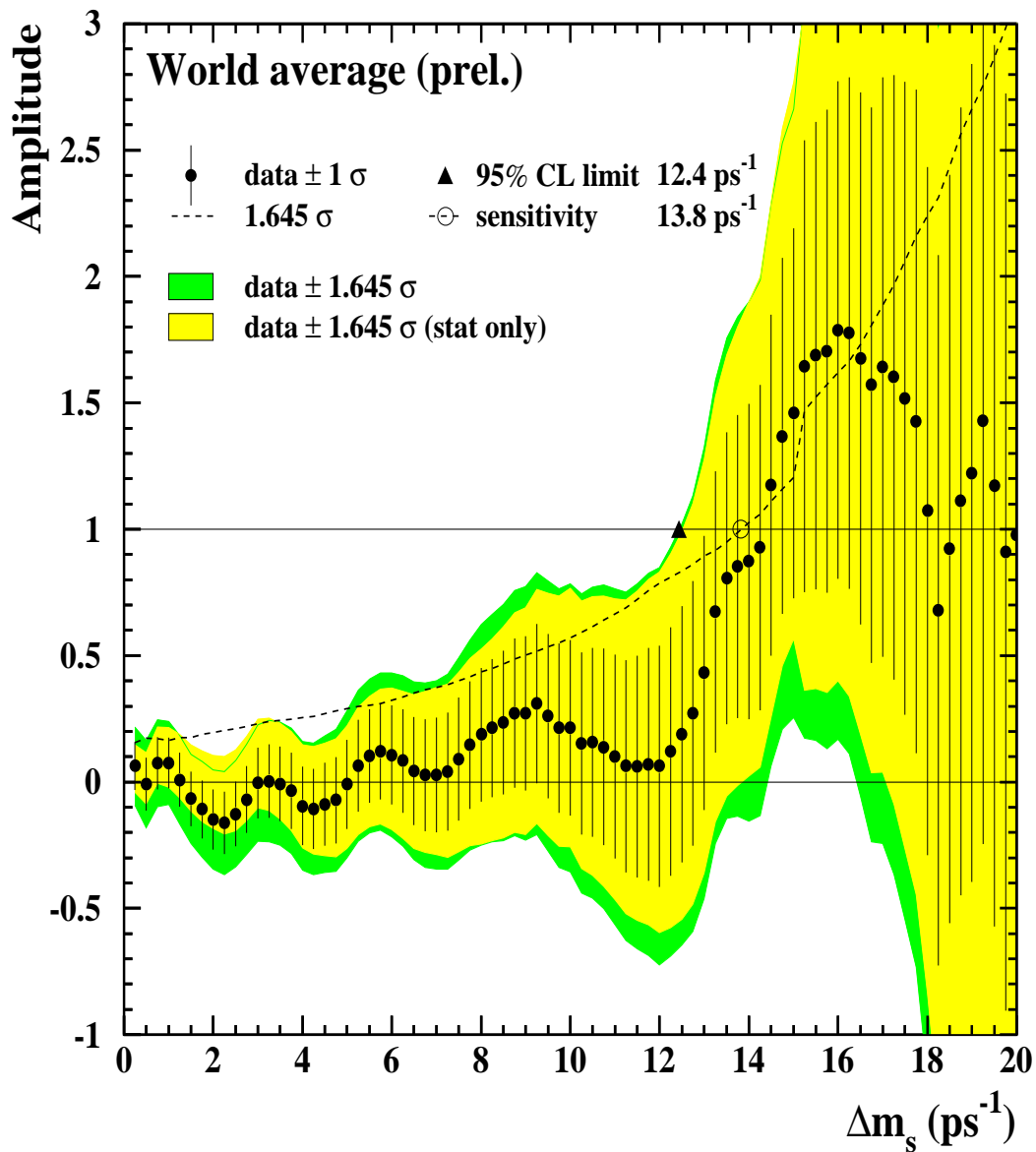


Figure 2: Combined B_s^0 oscillation amplitude spectrum as a function of Δm_s . A 95% CL lower limit of 12.4 ps⁻¹ on Δm_s is derived from this spectrum. All published or preliminary results known as of July 13th 1998 are included in this figure, provided by the LEP Working Group on B Oscillations [8].