# Measurements of b–hadron lifetimes and b–meson oscillations

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The current status of b–hadron lifetimes and b–meson oscillations measurements is reviewed. World averages are presented. Implications for the CKM matrix elements are briefly discussed.

## I. INTRODUCTION

In the spectator model, where the weak decay of the heavy quark is described neglecting the strong interactions with the light quark(s) in the heavy–flavoured hadron, all the hadrons containing the same heavy quark are predicted to have equal lifetimes. This model fails dramatically for charmed particles. Non–spectator effects like weak annihilation, W exchange and final state quark interference induce a lifetime difference between the species. These effects are calculated with the Heavy Quark Expansion formalism; differences arise at the order $1/m_{\mathrm{Q}}^2$ between mesons and baryons, at order $1/m_{\mathrm{Q}}^3$ between different mesons. HQE can explain the ratio $\tau_{\mathrm{D}^+}/\tau_{\mathrm{D}^0} = 2.55 \pm 0.04$, and is expected to be more reliable in the bottom sector, due to the larger quark mass. The predicted hierarchy is $\tau_{\Lambda_\mathrm{b}} < \tau_{\mathrm{B}^0} \approx \tau_{\mathrm{B_s}} < \tau_{\mathrm{B}^+}$, where differences are expected to be of the order of a few percents. This sets the scale of the experimental precision required. Comparisons of theoretical calculations and experimental measurements of lifetimes of individual b–hadron species will eventually provide a conclusive test of our understanding of hadron dynamics.

Neutral b meson oscillation frequency is proportional to the square of the CKM matrix elements $\mid V_{\mathrm{td}} \mid^2$ and $\mid V_{\mathrm{ts}} \mid^2$ for the $\mathrm{B_d^0}$ and $\mathrm{B_s^0}$ respectively. Long–distance QCD effects intervening in the oscillation process make the extraction of the quark mixing matrix elements difficult and uncertain. For this reason it is of high interest to try and measure the oscillation frequency for both neutral b meson species: most of the QCD uncertainty is in common, and the ratio $\mid V_{\mathrm{ts}}/V_{\mathrm{td}} \mid^2$ can be extracted in a more straightforward way from the ratio of frequencies.

A precise knowledge of the CKM matrix elements is one of the primary goals in heavy flavour physics. Within the Standard Model, CP violation is allowed by the structure of the CKM matrix, and is given, using the Wolfenstein parametrisation, by a non–zero imaginary part of the elements $V_{\mathrm{ub}}$ and $V_{\mathrm{td}}$.

Available experimental measurements on the topics discussed come from the four LEP Collaborations, the SLD and the CDF Collaborations. The LEP running around the Z peak ended in 1995, yielding about 4 million Z decays delivered to each detector. The analysis of these data samples is in a very advanced stage, but not yet finalised.

SLD has taken data still in 1998, reaching statistics of about 400 thousand Z decays, of which 250 thousand with the latest improved tracking. Beam polarisation and higher tracking precision near the interaction point make this smaller sample competitive or better than the LEP samples in a few specific physics measurements. Data analysis is still underway, and major results are expected in the near future.

CDF ended the “run I” in 1994, collecting a total of about 130 $\mathrm{pb}^{-1}$. The cross section for $\mathrm{b\bar{b}}$ production in $\mathrm{p\bar{p}}$ collisions at the TEVATRON is about 4000 times higher than in $\mathrm{e^+e^-}$ collisions at the Z peak, but only represents about 0.1% of the total inelastic cross section: triggering is therefore a major issue. CDF has competitive results in channels containing one or two muons in the final state.

## II. LIFETIME MEASUREMENTS

### A. Individual bottom hadron lifetimes

The lifetime of a specific bottom hadron is usually measured from a fit to the reconstructed proper time distribution of selected candidates. The proper time is computed from the estimated decay length and the reconstructed momentum. The decay length resolution is determined by the precision of the tracking system in the vicinity of the interaction point, but also by the size of the luminous region. In this respect SLD/SLC have by far the most favourable conditions, with an interaction region of $1 \times 2 \times 700\ \mu m^3$ and a high precision CCD pixel detector installed at a minimum radius of 2.5 cm. Momentum reconstruction involves identification of the bottom hadron decay products, and estimation of the neutrino energy in the case of semileptonic decays; needs high performance tracking and calorimetry at the same time. Fitting the proper time compared to extracting the lifetime from the decay length distribution, gives in general higher statistical power and significantly lower dependence on the knowledge of the b quark fragmentation.

The simplest way to measure the lifetime of a given bottom hadron species is to fully reconstruct some specific decay modes [1] – [3]. The background is only combinatorial and can be controlled from the sidebands of the observed mass peak; the precision in the decay length measurement and momentum reconstruction are basically given by the intrinsic performance of the detector. The limitation of this method is the reduced statistics deriving from the branching ratios of the decay modes chosen. At present, interesting results with this method are obtained only at CDF in the channels for which the trigger is available, *e.g.* the exclusive reconstruction of $B^0$ and $B^+$ mesons in final states $J/\psi\ K^{(*)}$.

An approach which provides larger statistics is the selection of semileptonic b decays, where a fully reconstructed charmed particle is associated to a nearby lepton candidate with the appropriate charge correlation [4] – [19]. The decay length resolution is still good due to the presence of the lepton, that comes from the b decay vertex, but the momentum reconstruction is spoiled by the missing decay products (the neutrino at least). The mass is not reconstructed and the estimate of the background becomes a more difficult issue, with uncertainties related to the modelling of the b hadron decay (typical example: the cross contamination of the $B^0/B^+$ samples selected with $D^{(*)}\ell$ correlations due to the production of $D^{**}$ in B decays). This method is used by the LEP experiments and CDF for all the hadron species. Some variants have been elaborated to further increase the statistics, aiming to a partial reconstruction of the charmed state ($B_s$ lifetime with $\phi\,\ell$ correlations, or $\Lambda_b$ lifetime with $\Lambda\,\ell\,\ell$ correlations), or dropping the request for the lepton candidate ($B_s$ lifetime with inclusive $D_s$ sample). These techniques are currently the best for the measurements of $B_s$, $\Lambda_b$ and inclusive b–baryon lifetimes.

A third approach, suitable in particular for the measurement of $B^0/B^+$ lifetimes, is based on topological vertex reconstruction [20] – [24]. Secondary vertices are reconstructed inclusively and the b meson charge is computed from the charge of the tracks associated with the vertex. The method is very efficient, but relies on the simulation to estimate sample composition and resolution. The vertex reconstruction introduces a sizeable bias in the decay length of reconstructed vertices, which has to be unfolded to measure unbiased lifetimes. This approach is particularly suitable for SLD, but has been successfully used at LEP as well.

Results and averages for lifetimes of $B^+$, $B^0$, $B_s$, $\Lambda_b$ and b–baryons are given in Fig. 1. The measured ratio $\tau_b/\tau_{B^0}$ is also shown, and a comparison of measured lifetimes ratios and theoretical calculations is displayed. Averages are calculated using the programs developed by the Lifetime Working Group [25].

Among the $B^0/B^+$ analyses, one of the most interesting is the SLD inclusive reconstruction. Thanks to the excellent capability of secondary vertex reconstruction, this analysis gives the world's best lifetime ratio, despite the relatively small sample. Individual lifetimes are comparatively less precise because measurements are extracted from the decay length distributions, instead of the proper time, which causes a larger dependence on the b quark fragmentation. This uncertainty however cancels out in the ratio. A similar technique has been recently used also by OPAL. In this case the momentum is reconstructed and the fit to the proper time distribution yields the world's most precise $B^+$ lifetime. The error on the $B^0$ lifetime, significantly larger, dominates the uncertainty in the ratio. ALEPH has recently produced a new result using $D^{(*)}\ell$ correlations, taking advantage of the re-processing of the whole data sample, which provided increased tracking and secondary vertex finding capability [1]. The analysis gives competitive results for both lifetimes and the world's second best value for the ratio.

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[1] This result was made available about one month after the Conference, and therefore was not shown in my presentation.

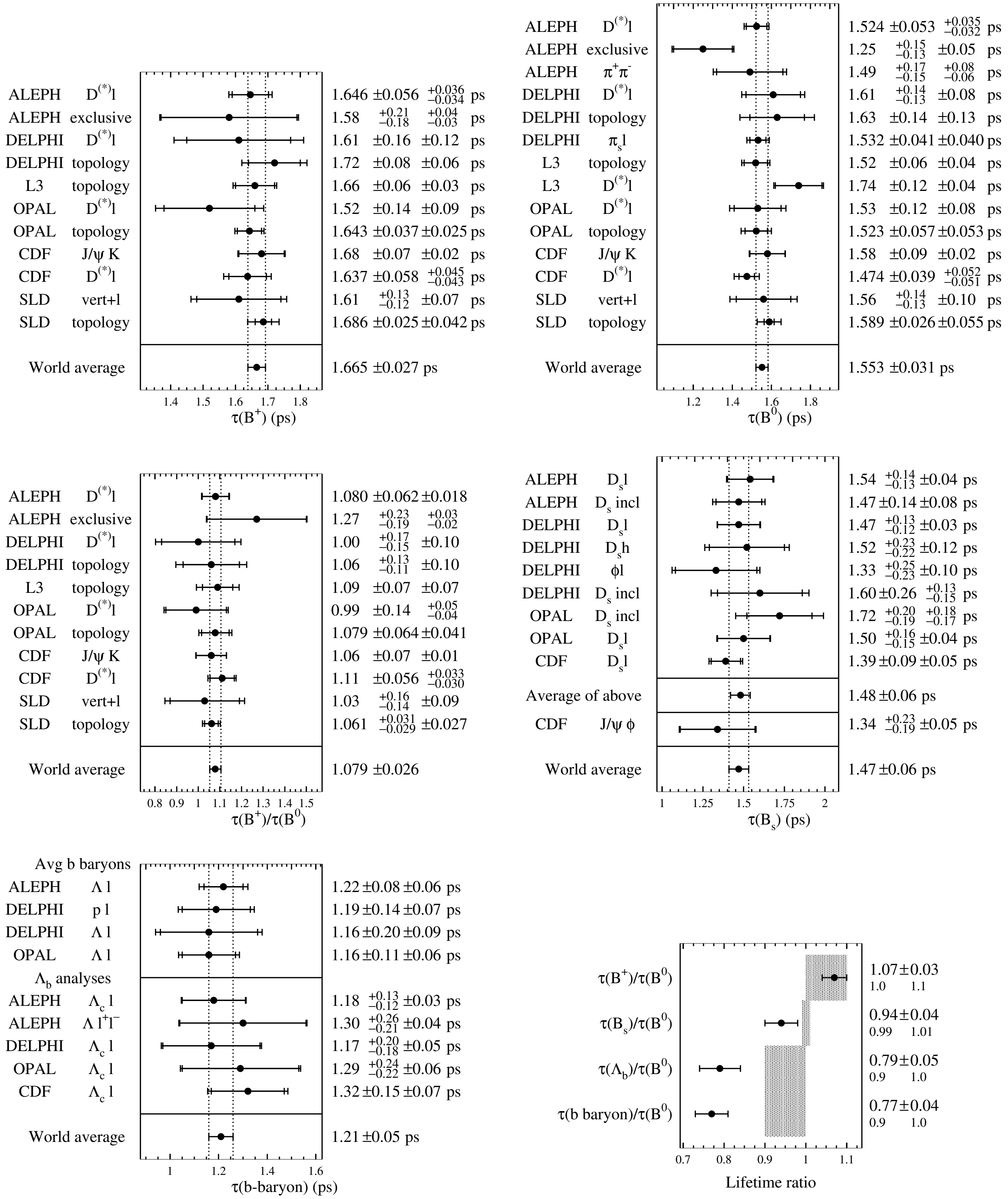


FIG. 1. Individual b hadron lifetimes and averages. The measured ratios between $B^+$ and $B^0$ lifetimes are also given. The ratios between all other b hadron lifetimes and the $B^0$ lifetime are compared to theoretical predictions.

The $B_s$ lifetime average is dominated by measurements with $D_s\,\ell$ correlation. CDF has the most precise value, taking advantage of the larger statistics.

The most precise $\Lambda_b$ lifetime measurements come from ALEPH and CDF, using $\Lambda_c\,\ell$ correlations. The LEP experiments have also measured the average b baryon lifetime using $\Lambda\,\ell$ or $p\,\ell$ correlations. The two results cannot be distinguished with the present experimental precision.

Comparison of measured lifetime ratios with theoretical calculations show a good agreement for mesons, while baryons have a significantly lower lifetime than expected. This deviation could be an indication of a problem in heavy quark theory.

The $B_c$ meson has been recently observed by CDF [26] in the decay channel $J/\psi\,\ell\,X$. From an estimated signal of $20.4\,^{+6.2}_{-5.5}$ events, the lifetime is measured to be

$$\tau_{B_c} = 0.46\,^{+0.18}_{-0.16} \pm 0.05 \text{ ps} ,$$

where the first error is statistical and the second is systematic, in good agreement with theoretical predictions.

### B. Average b hadron lifetime

Some measurements of the average b hadron lifetime $\tau_b$ are based on a fit to the impact parameter distribution of leptons with high transverse momentum with respect to the reconstructed jet axis [27] – [29]. The impact parameter is on average proportional to the lifetime and has little dependence on the b hadron boost. Alternatively, the b hadron decay vertex is reconstructed inclusively to estimate the decay length [30] – [34]; in this case a good estimate of the (average) boost is crucial for a precise lifetime measurement. Results currently available are reported in Fig. 2: the uncertainty is in general dominated by systematic errors.

Different analyses do not necessarily select the same mixture of hadrons. Assuming that semileptonic branching ratios scale with lifetimes, measurements based on leptons should have a lower baryonic component, and therefore give a higher observed lifetime (by about 0.7%), while the opposite trend is found in the data.

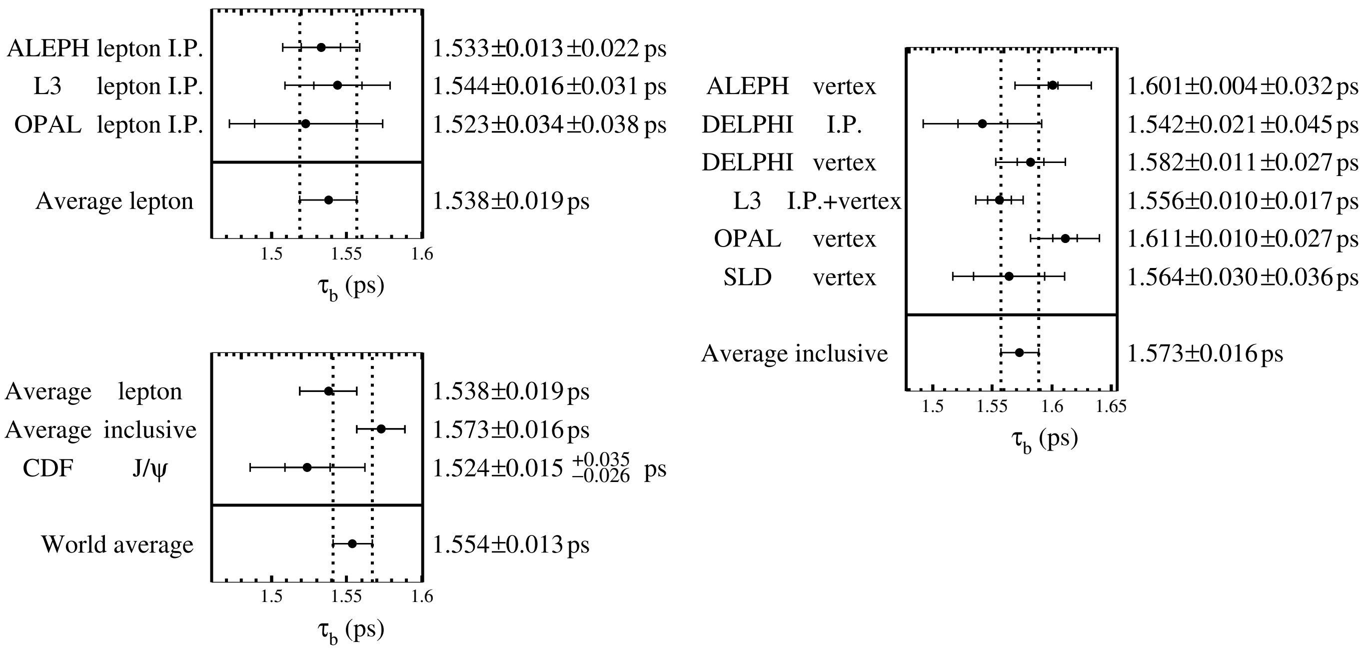


FIG. 2. Average bottom hadron lifetime measurements and averages.

## III. MEASUREMENTS OF B MESON MIXING

Neutral b meson mixing occurs via second order weak interactions (*box diagrams*) dominated by virtual top quark exchange. In the analyses, a possible lifetime difference between the two mass eigenstates is neglected, and the decay probability is written, as a function of proper time, as

$$P(t) = \frac{1}{\tau}\, e^{-t/\tau}\, \frac{1}{2}\, (1 \,\pm\, \cos\Delta m\, t) \ ,$$

where the "+" sign applies to unmixed states and the "−" to mixed states.

The statistical significance $\mathcal{S}$ of an oscillation signal can be approximated with

$$\mathcal{S} = \sqrt{N/2}\, f_{\rm sig}\, (1-2\eta_i)(1-2\eta_f) \ , \ e^{-(\Delta m\, \sigma_t)^2/2} \tag{1}$$

where $N$ is the total number of candidates used in the analysis, $f_{\rm sig}$ is the fraction of signal events in the selected sample, $\eta_i$ and $\eta_f$ are the mistag probabilities at production and decay time, respectively, and $\sigma_t$ is the proper time resolution, which can be written as

$$\sigma_t = m_{\rm B}\, \frac{\sigma_d}{p_{\rm B}} \,\oplus\, t\, \frac{\sigma_{p_{\rm B}}}{p_{\rm B}} \ .$$

The term coming from the decay length resolution (typically $0.1 - 0.3$ ps) is constant with proper time, while the contribution from the B momentum resolution (typically $10 - 20\%$) increases linearly with $t$. The two terms have equal size after about one lifetime.

For a slow oscillation like in the case of the $\mathrm{B^0_d}$ ($\Delta m_{\rm d} \approx 0.47$ ps$^{-1}$ implies a period of about 13 ps, which corresponds to more than eight mean lifetimes), the sensitivity comes from events at large proper time, and the resolution is therefore completely dominated by the momentum reconstruction.

For the fast $\mathrm{B^0_s}$ oscillation the situation is reversed. Assuming a "typical" value around 15 ps$^{-1}$ for $\Delta m_{\rm s}$, the number of complete oscillations per mean lifetime is between three and four with a period around 0.4 ps. The argument of the exponential reaches $-1$ for $\sigma_t = 0.1$ ps, which implies that only events with particularly precise decay length determination and with small proper time (and therefore small contribution from the momentum resolution) can contribute to the sensitivity. In this case the decay length resolution is a lot more crucial than all the other parameters in Formula (1).

In order to tag a B candidate as mixed or unmixed, its particle–antiparticle nature has to be identified both at production and decay time.

In inclusive lepton analyses the final state tag is provided by the charge of the lepton. In this case the major contamination comes from "cascade" semileptonic decays ($\mathrm{b \to c \to} \ell$). When the charmed particle ($\mathrm{D^*}$ or $\mathrm{D_s}$) is fully reconstructed (with or without the lepton) its charge provides the final state tag as well. For fully inclusive analyses, final state tagging is performed using jet charge and vertex charge techniques, and charge dipole reconstruction (only at SLD so far).

The initial state can be identified using information from both the opposite and the same hemisphere. In the opposite hemisphere high transverse momentum leptons, kaons from $\mathrm{b \to c \to s}$ decays and jet charge estimators can be used, in order of increasing efficiency and mistag rate. The performance of the lepton and the kaon tags depend also on the average time–integrated mixing. On the same side, a pion (in the case of $\mathrm{B^0_d}$) or a kaon (for the $\mathrm{B^0_s}$) collinear with the reconstructed bottom system can be searched for. This mostly selects particles coming from the strong decay of heavier bottom states, or the first particles produced in the fragmentation chain, which therefore carry information about the particle–antiparticle nature of the produced meson. Jet charge algorithms can be also tuned to have some initial state tagging power on the same side. At SLD, the beam polarisation produces a sizeable forward–backward asymmetry in the $\mathrm{b\bar{b}}$ production, which turns out to be a very powerful initial state tag.

In the case of the $\mathrm{B^0_d}$ oscillations [30], [35] – [43], the results are typically obtained from a maximum likelihood fit to the proper time distributions of mixed and unmixed events, where $\Delta m_{\rm d}$ is the free parameter.

No experiment until now has been able to observe a statistically significant $B_s^0$ oscillation. Originally, lower limits were placed by studying the likelihood as a function of $\Delta m_s$. The limits obtained were, however, difficult to be combined. A new method was then developed in which an amplitude $\mathcal{A}$ is measured for each *fixed* value of $\Delta m_s$. The physics functions are therefore

$$P(t) = \frac{1}{\tau_{B_s}} \, e^{-t/\tau_{B_s}} \, \frac{1}{2} \, (1 \pm \mathcal{A} \cos \Delta m_s \, t) \ ,$$

where the expected value for the free parameter $\mathcal{A}$ is zero (within errors) when $\Delta m_s$ is far from its true value and one for $\Delta m_s = \Delta m_s^{\rm true}$. The error on $\mathcal{A}$ is to a very good approximation Gaussian and equal to $1/\mathcal{S}$. The sensitivity of a given analysis extends up to the value of $\Delta m_s$ for which it can significantly distinguish $\mathcal{A} = 0$ from $\mathcal{A} = 1$; at 95% C.L. this translates to $1.645\sigma_{\mathcal{A}}(\Delta m_s) < 1$. The values of $\Delta m_s$ that can be excluded are those for which $\mathcal{A} + 1.645\sigma_{\mathcal{A}} < 1$. With this method the combination of different analyses [5,6,9,10], [44] – [49], is a straightforward average of the measured amplitudes at each value of the $\Delta m_s$ scan.

The results of $\Delta m_d$ and $\Delta m_s$ analyses are presented in Fig 3. The averages are calculated by the Oscillation Working Group [50].

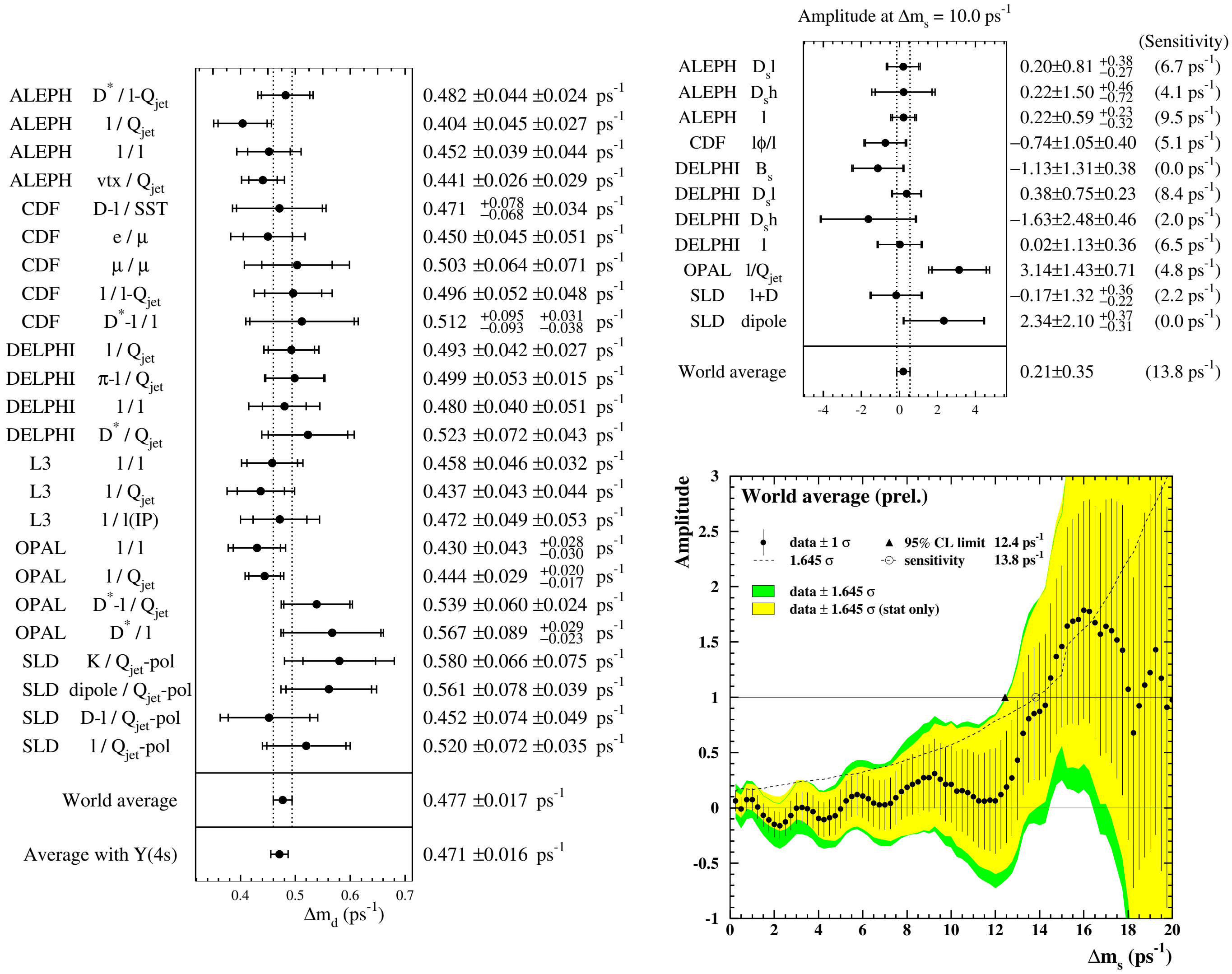


FIG. 3. Summary of $\Delta m_d$ measurements and averages. A world average including $\Upsilon(4s)$ data is also given.
Summary and average for measured $B_s^0$ oscillation amplitudes at $\Delta m_s = 10$ ps$^{-1}$.
Combined amplitude as a function of $\Delta m_s$, expected limit ( *i.e.* sensitivity) and derived limit.

A total of 23 $\Delta m_{\rm d}$ analyses are available at the moment, from the four LEP experiments, SLD and CDF. They have similar precision, and systematic errors are not negligible: major contributions come from uncertainties in the sample composition, mistag probabilities, and lifetimes of different hadron species. The uncertainty in the average is dominated by the systematic error. The precision of these oscillation measurements is such that adding the time–integrated mixing measurements at the $\Upsilon(4s)$ improves marginally the knowledge of $\mathrm{B}^0_{\rm d}$ mixing.

The $\Delta m_{\rm s}$ analysis which currently gives the highest sensitivity is the ALEPH inclusive lepton analysis. About 30000 reconstructed decays are used in the fit. Preselection cuts ensure a good decay length resolution, and the statistical power is improved by dividing the sample in subsamples with different $\mathrm{B}^0_{\rm s}$ enrichment (according to the charged multiplicity and number of kaon candidates found in the inclusively reconstructed charmed particle). Analyses which uses $\mathrm{D_s}\,\ell$ correlations work with only a few hundred events, but yield comparable sensitivity due to the higher signal purity and lower final state mistag rate, together with a somewhat better decay length and momentum reconstruction. A recent DELPHI analysis on a sample of 26 fully reconstructed $\mathrm{B_s}$ candidates is not able to exclude any $\Delta m_{\rm s}$ value by itself, but contributes useful information for high $\Delta m_{\rm s}$, where it yields a precision on the measured amplitude equal or better than analyses which use inclusive $\mathrm{D_s}$ events. The current 95% C.L. limit of 12.4 $\mathrm{ps}^{-1}$ is lower than the sensitivity (13.8 $\mathrm{ps}^{-1}$). This is due to a positive excursion of the average combined amplitude in the region 13–18 $\mathrm{ps}^{-1}$, where the true value of $\Delta m_{\rm s}$ is predicted to be in the Standard Model. However the significance of this excursion is not enough to claim a signal, the value $\mathcal{A} = 0$ being excluded in a range where the measured amplitude approaches $\mathcal{A} = 2$.

Several new analyses are expected in the near future from the SLD experiment, which has a great improvement potential, due to the high precision tracking. The SLD experiment alone is expected to eventually reach a sensitivity comparable to the present LEP combination, which could help clarifying the meaning of the positive amplitude values currently found for $\Delta m_{\rm s} > 13$ $\mathrm{ps}^{-1}$.

## IV. CONSTRAINTS ON THE QUARK MIXING MATRIX

The CKM matrix element $V_{\rm td}$ can be extracted from the measured $\Delta m_{\rm d}$ using the relation obtained from the box diagram calculations. The error on the extracted value of $\mid V_{\rm td} \mid$ is completely dominated by the uncertainty on QCD effects. A similar relation links $\Delta m_{\rm s}$ to $V_{\rm ts}$, and the ratio can be written as

$$\frac{\Delta m_{\rm s}}{\Delta m_{\rm d}} = \frac{m_{\mathrm{B}^0_{\rm s}}}{m_{\mathrm{B}^0_{\rm d}}}\,\xi^2 \left|\frac{V_{\rm ts}}{V_{\rm td}}\right|^2 ,$$

where the parameter $\xi$, which contains all the residual hadronic uncertainty, is calculated using lattice QCD and QCD sum rules to be $\xi = 1.11 \pm 0.06$.

The extracted value of $\mid V_{\rm td} \mid$ and the lower limit on $\mid V_{\rm ts}/V_{\rm td} \mid$ can be combined with measurements of CP violation in the kaon system and measurements of $\mid V_{\rm ub}/V_{\rm cb} \mid$ to give a preferred area in the $(\bar{\rho}, \bar{\eta})$ plane [51], as shown in Fig. 4. The various constraints appear to be well compatible and the value $\bar{\eta} = 0$ is excluded with large significance.

If the limit on $\mid V_{\rm ts}/V_{\rm td} \mid$ is not used, the allowed region in the $(\bar{\rho}, \bar{\eta})$ plane can be turned into a probability density for $\Delta m_{\rm s}$, which is as well shown in Fig. 4. Present analyses are exploring the range where $\Delta m_{\rm s}$ is predicted to be; SLD results are expected to improve significantly the reach of the combined analysis.

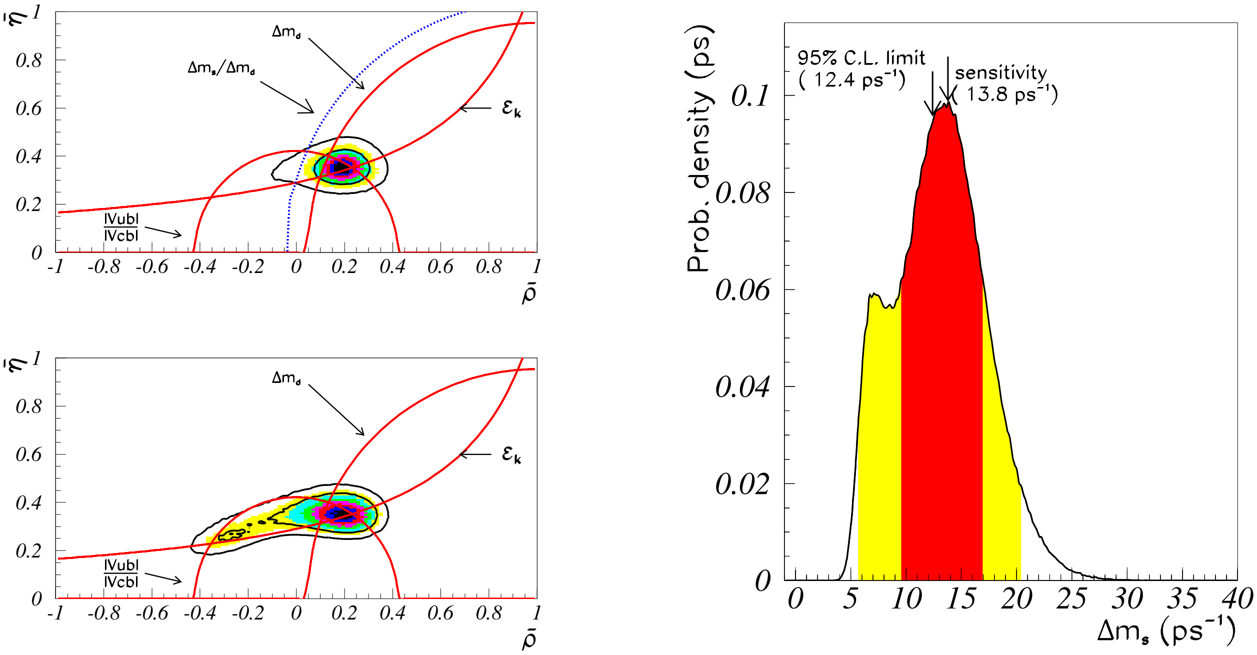


FIG. 4. Constraints on the position of the unitarity triangle apex coming from measurements of CP violation in kaon decays, measurements of $\mid V_{\rm ub}/V_{\rm cb} \mid$, $\mid V_{\rm td} \mid$ from $\rm B^0_d$ oscillations and the 95% C.L. limit on $\mid V_{\rm ts}/V_{\rm td} \mid$ from the $\Delta m_{\rm s}$ limit. When the constraint on $\mid V_{\rm ts}/V_{\rm td} \mid$ is removed, the allowed region in the $(\bar\rho, \bar\eta)$ plane (which becomes significantly larger), can be translated to a probability density for $\Delta m_{\rm s}$.

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