⋄ Monograph Excerpt ⋄

Matter Antimatter Fluctuations

search, discovery and analysis of Bs flavor oscillations

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	$K^0\bar{K}^0$	$B^0\bar{B}^0$	$B_s\bar{B}_s$
mass [MeV/c^2]	497.648 ± 0.022	5279.4 ± 0.5	5369.6 ± 2.4
lifetime [ps]	89.53 ± 0.06, 51800 ± 400	1.536 ± 0.014	1.461 ± 0.057
Δm [$(\hbar/c^2)s^{-1}$]	$(0.5292 \pm 0.0010) \cdot 10^{10}$	$(0.507 \pm 0.005) \cdot 10^{12}$	$> 14.4 \cdot 10^{12}$
Δm [eV/c^2]	$(3.483 \pm 0.006) \cdot 10^{-6}$	$(3.337 \pm 0.033) \cdot 10^{-4}$	$> 94.8 \cdot 10^{-4}$

Table 1.1: Parameters of the oscillating kaon and bottom meson systems.

1.2 History note

Particle–antiparticle oscillations have been established in other neutral meson systems. The oscillation frequencies are very well measured for the K^0 and B^0 systems, while for the B_s the oscillations are very rapid and their frequency had yet to be detected.

Oscillations were first proposed for the kaon system in 1955 [16]. This lead to predicting the existence of a long-lived strange particle, the K_L^0, which was subsequently observed in 1956 [17]. The first CKM element, the Cabibbo quark mixing angle identified with θ_{12} in (2.39), was introduced in 1963 [4] to explain the small decay rates for particles carrying strangeness. This further lead in 1970 to the introduction of the unitarity quark mixing ansatz used by GIM [18] to postulate the existence of a fourth quark (charm). In 1973 Kobayashi and Maskawa [5] added to the model a third generation of quarks, motivated by the earlier discovery of CP violation in 1964 in K^0 decays [19]. The bottom and top quarks were subsequently discovered in 1977 [20] and 1995 [21], respectively, at Fermilab.

Evidence of neutral B meson mixing was first reported in 1987 by UA1 [22]. This consisted of a time-integrated analysis, based on the measurement of the ratio of like-sign muon pairs to unlike-sign muon pairs. The first observation of B^0 oscillations was published by ARGUS [23] in that same year, and included the unambiguous identification of a B^0B^0 pair. Confirmation of those results was provided by CLEO [24] in 1989. Various other time-integrated mixing analyses followed, at PEP, PETRA, and LEP experiments, as well as at CDF. Time-dependent measurements of B^0 mixing have since then yielded a precise determination of the oscillation frequency Δm_d. A compilation is presented in Figure 1.5. The world average value for Δm_d is 0.507 ± 0.005 ps^{-1} [25], being dominated by BaBar and Belle measurements [26].

That B_s mesons undergo oscillations could be inferred from early measurements. The above mentioned measurements by ARGUS and CLEO, which operate at e^+e^- colliders tuned to the $\Upsilon(4S)$ resonance, provided the time integrated probability that a B^0 oscillates. When these were compared with inclusive measurements performed at LEP, for instance, where in addition to B^0 also B_s mesons are produced, a significant contribution to the mixing signal from the latter was deduced. Subsequent time-dependent measurements, performed at LEP and SLD operating at the Z-pole, and at CDF in the previous data taking stage of the Tevatron operating at an energy $\sqrt{s} = 1.8$ TeV, established lower exclusion bounds on the oscillation frequency of the B_s system.

For the purpose of combining exclusion regions from the various experiments in a convenient and consistent fashion, the results on B_s oscillations are presented in terms of amplitude measurements for a spectrum of probe frequencies. Such a procedure [33] essentially entails searching for a peak in the power spectrum of the data as a function of frequency. The combined results prior to the CDF II contribution are presented in Figure 1.6, giving a world average exclusion limit of $\Delta m_s > 14.4$ ps^{-1} at 95% C.L. [25]. Contributions from ALEPH, DELPHI, OPAL, SLD, and CDF I are included. The corresponding combined sensitivity given by the measured amplitude uncertainties is 18.2 ps^{-1}.

In Table 1.1 we summarize the values of Δm for the kaon and bottom neutral systems. While it may well be expressed in units of mass, Δm will be revealed in the data as an oscillaiton frequency. Accordingly, througout this document, unless otherwise specified, the Δm observable will be expressed in units of inverse-(pico)second.

Expectations for Δm_s may be derived within appropriate theory-based frameworks. In particular, global fits to the standard model relations, connecting the CKM elements with the various experimental observables and theory calculations, have been performed, and resulting expectations produced. A summary of such predictions spanning more than a decade is illustrated in Figure 1.4 [82].

The first preliminary results from the Tevatron experiments appear by the summer conferences 2005 [31]. These yield already significant contributions to the combined world averages. In March of 2006, the DØ Collaboration reported direct limits on the B_s oscillation frequency [92]. Using a sample of $B_s \to D_s l$ partially reconstructed decays, in a dataset of 1fb^{-1} integrated luminosity, the lower limit $\Delta m_s > 14.8\,\text{ps}^{-1}$, at 95% C.L., was obtained along with an analysis sensitivity of $14.1\,\text{ps}^{-1}$. A direct two-sided bound, $17 < \Delta m_s < 21\,\text{ps}^{-1}$ (90% C.L.), was also reported. The measured amplitude scan is shown in Figure 1.7.

In June of 2006, based on a $1\,\text{fb}^{-1}$ data sample of partially and fully reconstructed decays, the CDF Collaboration reports [101] the first measurement of the B_s oscillation frequency $\Delta m_s = 17.31^{+0.33}_{-0.18}(\text{stat.}) \pm 0.07(\text{syst.})\,\text{ps}^{-1}$. Three months later, in September 2006, an updated iteration of the same analysis, applied to the same $1\,\text{fb}^{-1}$ dataset and after incorporating few additional refinements, yielded a further precise measurement [101], $\Delta m_s = 17.77 \pm 0.10(\text{stat.}) \pm 0.07(\text{syst.})\,\text{ps}^{-1}$. The probability that random fluctuations could produce a comparable signal was estimated to be $8 \cdot 10^{-8}$, corresponding to a significance in excess of $5\,\sigma$. The CDF analysis corresponds accordingly to the first, long-sought, definitive observation of B_s oscillations.

In Figure 1.8 the amplitude measurements, at the specified probe frequency, performed by various experiments are compared. In Figure 1.9 the CDF amplitude scan is compared to the world combined results. The overshadowing contribution of the CDF analysis is striking. The stated purpose of the current monograph is to provide the detailed description of the analysis developed and carried out at CDF.

At the moment the current research took place, the Tevatron was the only particle collider producing significant samples of B_s mesons. The CDF and DØ collaborations stood therefore in unique positions to explore the B_s system. A first and precise determination of its oscillation frequency, or the exclusion of the SM favored region, was a stated priority of the Tevatron Run II physics program.

The B_s meson is too heavy to be produced in decays of the $\Upsilon(4S)$ resonance, and cannot thus be studied at the B factories which operate at that energy. The kinematical threshold is satisfied though by the $\Upsilon(5S)$ resonance, which may be explored. For instance, the asymmetric e^+e^- KEKB collider was recently operated at this resonance in an engineering run, which allowed the Belle experiment to take first B_s data [32]. The excitement of further studying the B_s meson is expected to be transferred in the future to the Large Hadron Collider (LHC) experiments at CERN – namely LHCb, and also ATLAS and CMS. Not only will it be possible to corroborate the Tevatron results to a higher precision, but novel flavor measurements will be achievable. The exploration of the B_s system undertaken at the Tevatron will accordingly be complemented and deepened at the LHC.

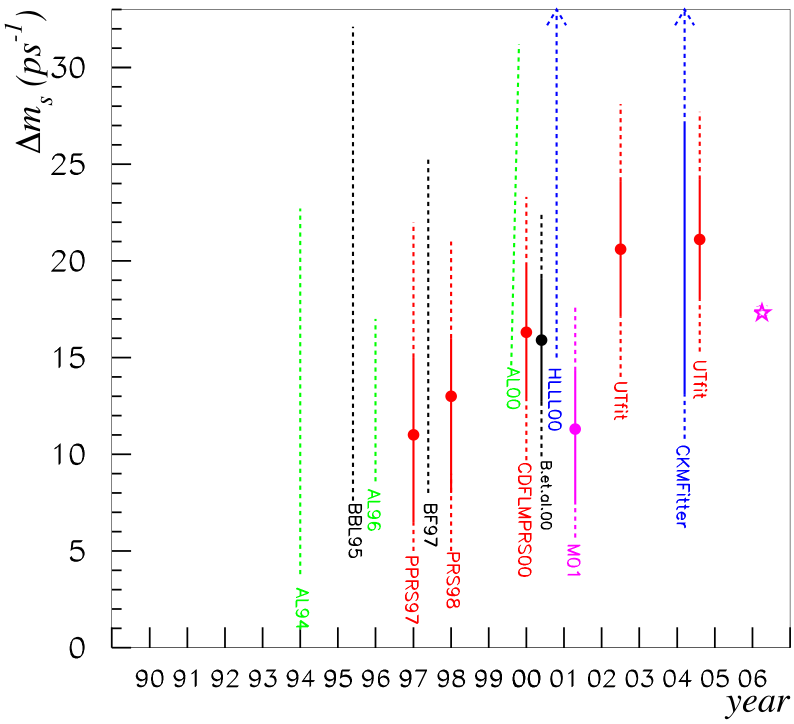

Figure 1.4: History of Δm_s predictions.

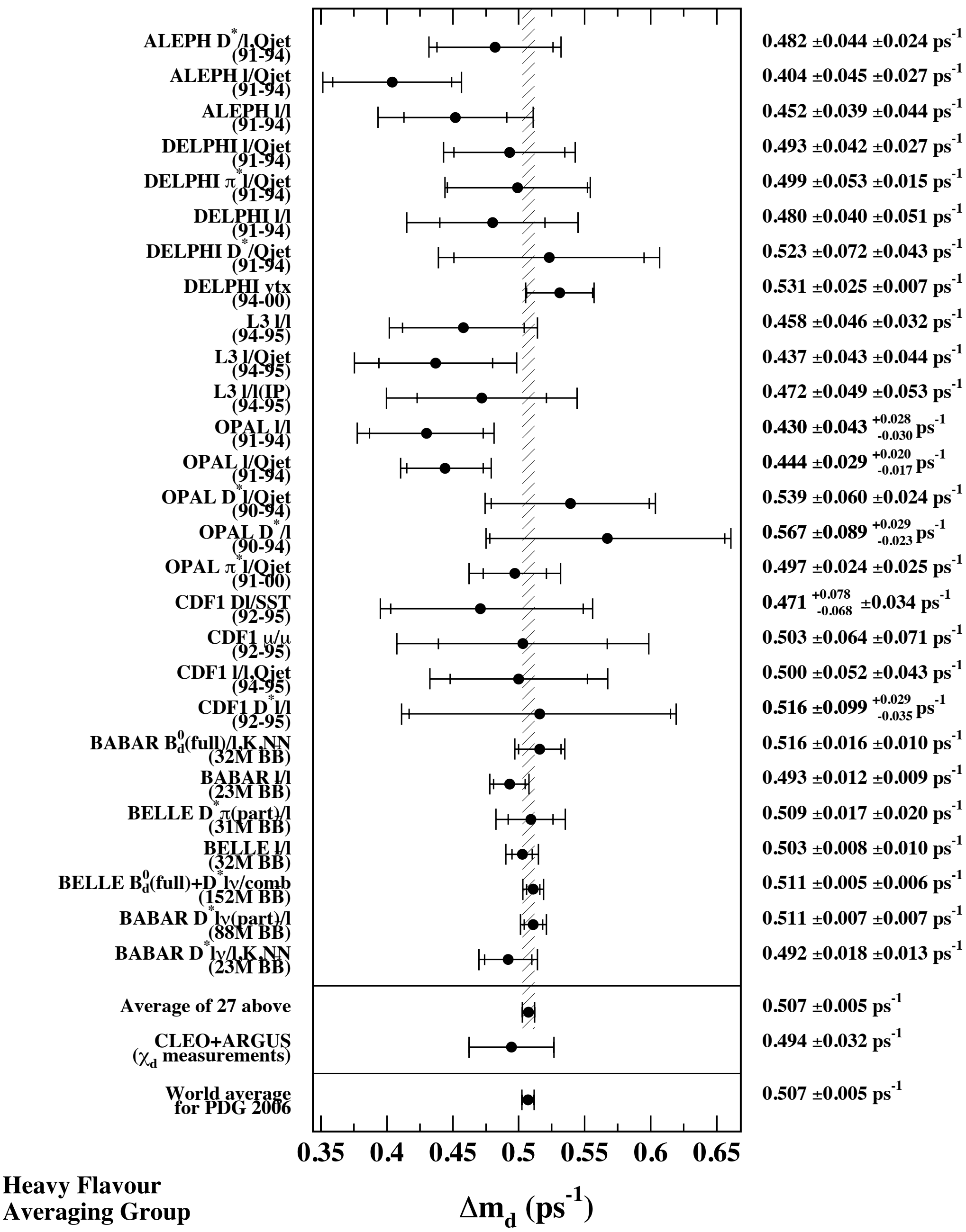

Figure 1.5: Experimental measurements of Δm_d.

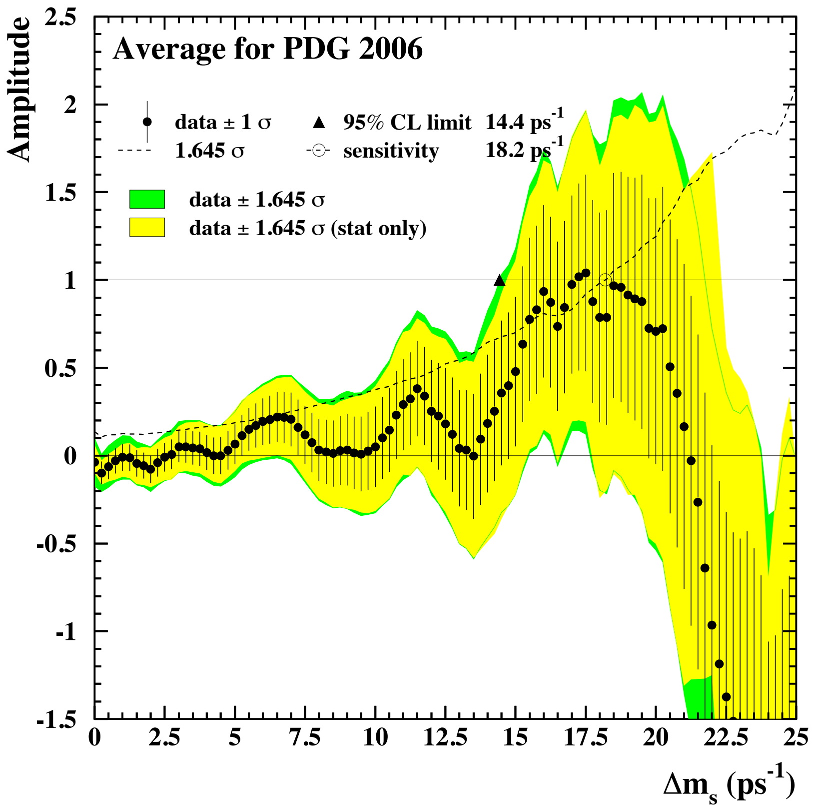

Figure 1.6: World combined amplitude results on B_s oscillations, prior to the CDF II measurement.

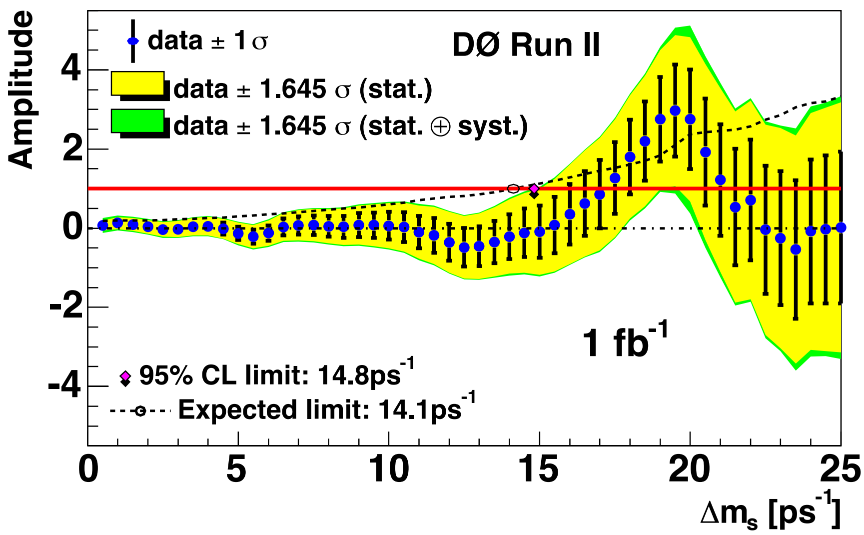

Figure 1.7: Amplitude scan reported by the DØ Collaboration.

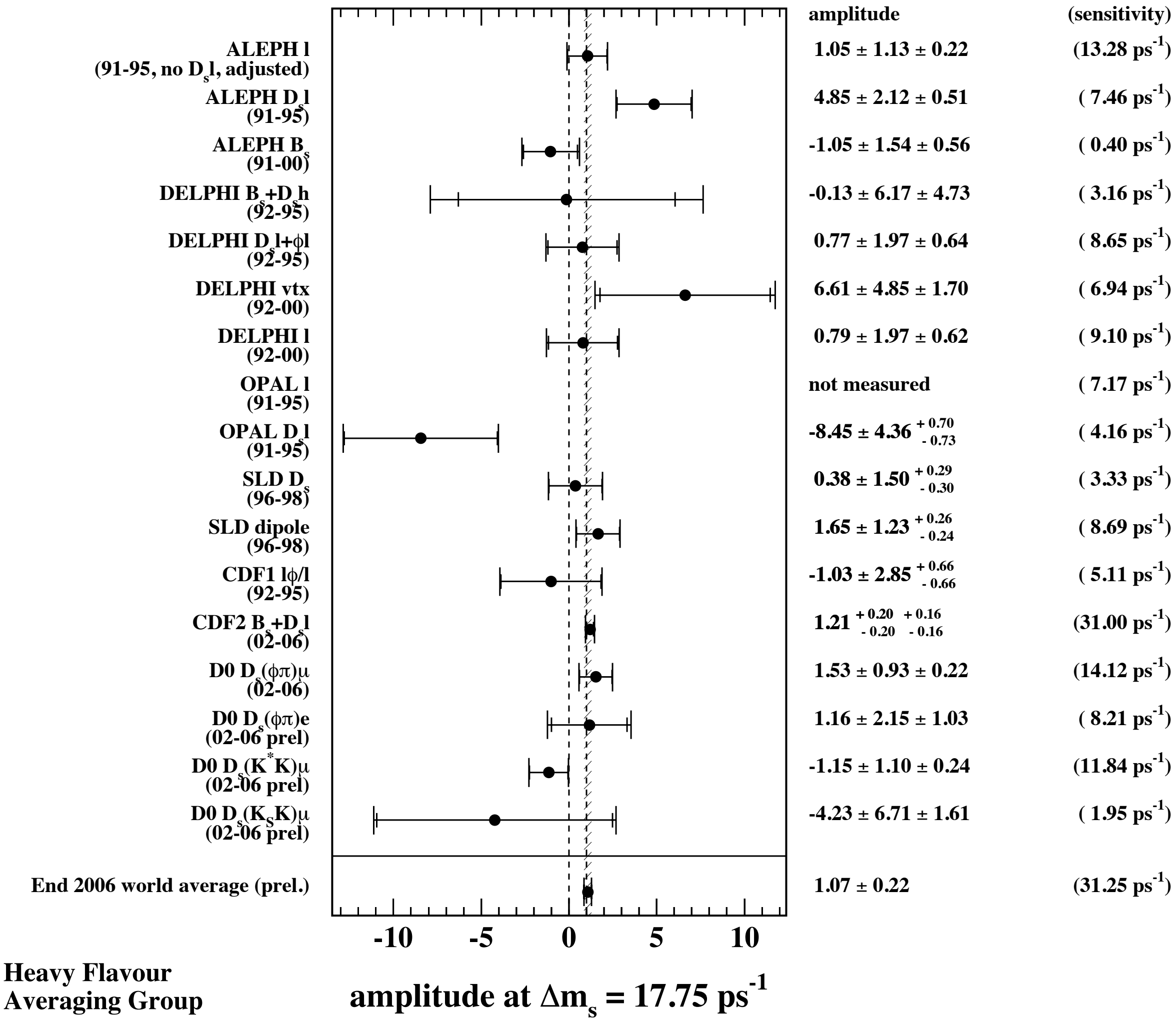

Figure 1.8: Experimental amplitudes and sensitivities at the Δm_s probe frequency 17.75 ps^{-1}.

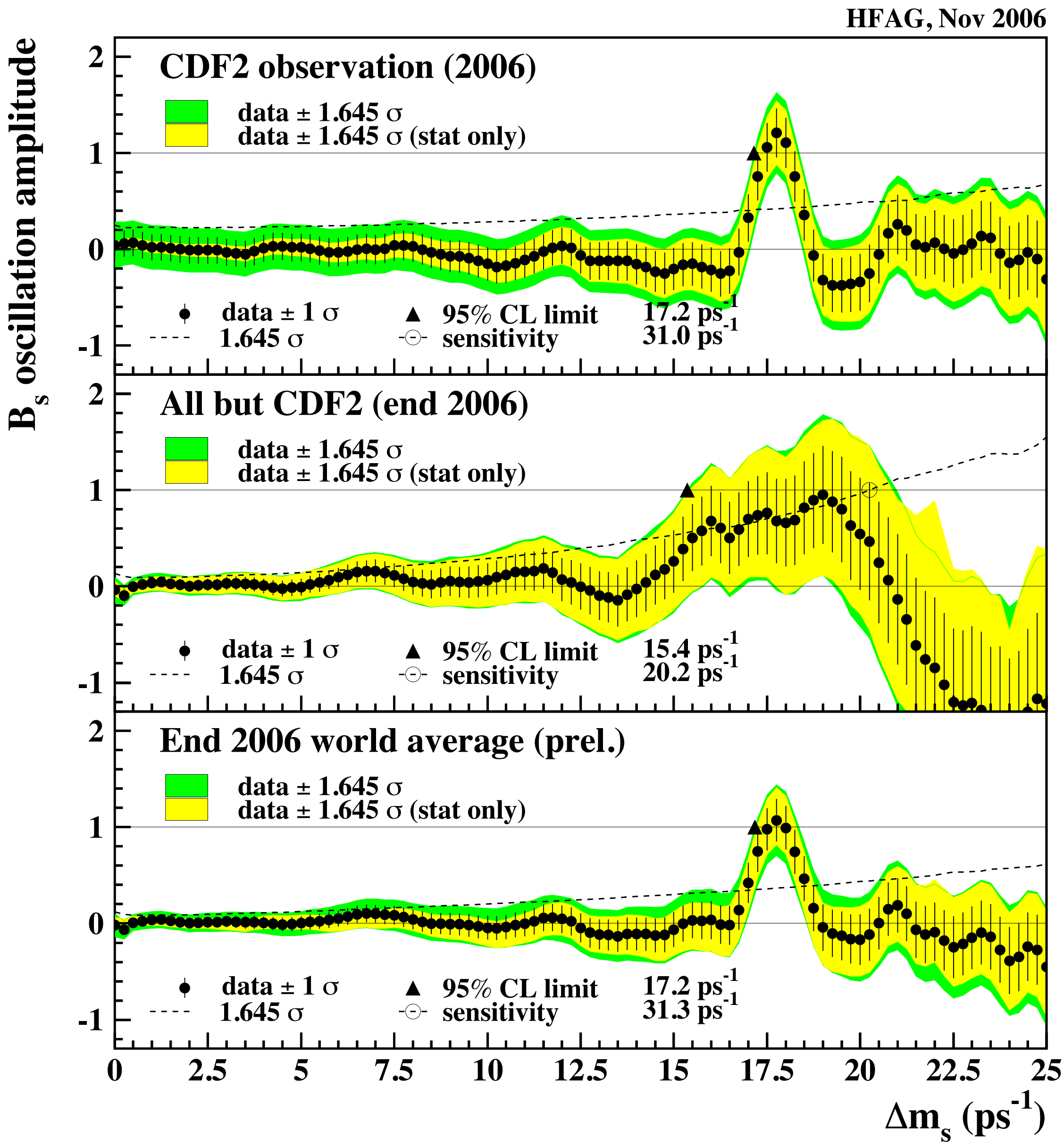

Figure 1.9: Amplitude scan showing the CDF measurement and comparison to the world combined results.