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Search for $B_s^0 - \overline{B_s^0}$ oscillations. An update

Preliminary

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Abstract

An update of the Δm_s lower limit is given using a new $D_s\ell$ analysis. Combining this analysis with the previous $Q_j\ell$ and $\ell\ell$ analyses the limit turns out to be:

$$\Delta m_s > 8.1 \text{ ps}^{-1} \text{ at } 95\% \text{ C.L.}$$

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1 Introduction

In the Standard Model, $B_s^0 - \overline{B_s^0}$ mixing is a direct consequence of second order weak interactions. Starting with a B_s^0 meson produced at time t=0, the probability, $\mathcal{P}$, to observe a B_s^0 or a $\overline{B}_s^0$ decaying at the proper time t can be written, neglecting effects from CP violation and a possible difference between the lifetimes of the heavy and light eigenstates :

$$\mathcal{P}_{B_s^0}^{unmix.(mix.)} = \mathcal{P}(B_s^0 \rightarrow B_s^0(\overline{B}_s^0)) = \frac{1}{2\tau_{B_s^0}} e^{-\frac{t}{\tau_{B_s^0}}} [1 \pm \cos(\Delta m_s t)] \qquad (1)$$

Three important quantities have to be considered in this analysis:

- the determination of the sign of the b quark at production time (production tag)
- the determination of the sign of the b quark inside the B meson at decay time (decay tag)
- the measurement of the B decay proper time.

In the previous publication [1] three analyses were performed using events containing a lepton emitted at large p_t relative to its jet axis. In two of them ($\ell - Q_{hem.}$ and $\ell - \ell$) the proper time was measured using an inclusive vertex algorithm to reconstruct the decay distance and the energy of the candidate B hadron. In the $\ell - Q_{hem.}$ analysis the "production tag" was obtained from the value of the hemisphere charge measured in the hemisphere opposite to the lepton and the lepton charge was used to define the "decay tag". The $\ell - \ell$ analysis used events with two high p_t leptons, identified in opposite hemispheres, and it was not possible to separate the notions of "decay" and "production" tags. In the third analysis, $(\ell, D_s) - Q_{hem.}$, the identified lepton was accompanied, in the same hemisphere, by an exclusively reconstructed D_s. The "production tag" was obtained from the value of the hemisphere charge measured using both hemispheres.

This note presents an update of the (ℓ, D_s) analysis using 94-95 data and corresponding to 2.2M hadronic Z^0 decays. The improvements with respect to the previous analysis come from :

- the use of the data reprocessed with an improved tracking algorithm,
- the use of a new algorithm to define the "production tag".

The previous analysis of the data registered between 1991 and 1993 is included to obtain the final limit on Δm_s

2 The new $D_s^{\pm}, \ell^{\mp}$ analysis

B_s^0 [1] were selected using an exclusively reconstructed D_s meson correlated with a lepton of opposite charge emitted in the same hemisphere:

[1]Unless explicitely stated otherwise, charge conjugate states are always implied.

$$\overline{\mathrm{B}^0_{\mathrm{s}}} \longrightarrow \mathrm{D}_s^+ \ell^- \overline{\nu} X.$$

D_s mesons were identified in four non-leptonic and two semileptonic decay modes:

$$\begin{array}{lll}
\mathrm{D_s^+} \longrightarrow \phi\pi^+ & \phi \longrightarrow \mathrm{K^+K^-}; & \\
\mathrm{D_s^+} \longrightarrow \overline{\mathrm{K}}^{\star 0}\mathrm{K}^+ & \overline{\mathrm{K}}^{\star 0} \longrightarrow \mathrm{K}^-\pi^+; & \\
\mathrm{D_s^+} \longrightarrow \mathrm{K}^0_S\mathrm{K}^+ & \mathrm{K}^0_S \longrightarrow \pi^+\pi^-; & \\
\mathrm{D_s^+} \longrightarrow \overline{\mathrm{K}}^{\star 0}\mathrm{K}^{\star +} & \overline{\mathrm{K}}^{\star 0} \longrightarrow \mathrm{K}^-\pi^+, & \mathrm{K}^{\star +} \longrightarrow \mathrm{K}^0_S\pi^+; \\
\mathrm{D_s^+} \longrightarrow \phi e^+\nu_e & \phi \longrightarrow \mathrm{K^+K^-}; & \\
\mathrm{D_s^+} \longrightarrow \phi \mu^+\nu_\mu & \phi \longrightarrow \mathrm{K^+K^-}. &
\end{array}$$

The selection criteria used for the different channels were already presented in [1],[2] and are not given explicitely here. In the $\mathrm{D_s}^+$ mass region, a clear excess of "right-sign" combinations $(\mathrm{D_s^\pm}, \ell^\mp)$ over "wrong-sign" combinations $(\mathrm{D_s^\pm}, \ell^\pm)$ was observed in each channel. Fig. 1 shows the signals obtained in the old analyses using 91-93 data. Fig. 2 shows the new signals obtained with 94-95 data. The mass distribution for non-leptonic decays was fitted using two Gaussian distributions of equal widths to account for the $\mathrm{D_s}$ and $\mathrm{D^+}$ signals and an exponential for the combinatorial background. The $\mathrm{D^+}$ mass was fixed to the nominal value of 1.869 GeV/c^2 [3]. For $\mathrm{D_s}$ semileptonic decay modes, the $\mathrm{K^+K^-}$ invariant mass distribution for "right sign" events was fitted with a Breit–Wigner distribution to account for the signal, and a polynomial function to describe the combinatorial background.

Tab. 1 gives the measured number of events (background subtracted) in the $\mathrm{D_s}^+$ signal and the ratio between the numbers of combinatorial background events and the total.

$\mathrm{D_s}$ decay modes	Estimated signal 91-93 data	Estimated signal 94-95 data
$\mathrm{D_s} \longrightarrow \phi\pi^+$	15 ± 5 $(40 \pm 8\%)$	45 ± 9 $(40 \pm 13\%)$
$\mathrm{D_s} \longrightarrow \overline{\mathrm{K}}^{\star 0}\mathrm{K}^+$	13 ± 5 $(36 \pm 9\%)$	35 ± 9 $(47 \pm 13\%)$
$\mathrm{D_s} \longrightarrow \mathrm{K}^0_S\mathrm{K}^+$	18 ± 6 $(38 \pm 13\%)$	17 ± 5 $(23 \pm 5\%)$
$\mathrm{D_s} \longrightarrow \overline{\mathrm{K}}^{\star 0}\mathrm{K}^{\star +}$	-	16 ± 5 $(45 \pm 10\%)$
$\mathrm{D_s} \longrightarrow \phi\ell^+\nu$	19 ± 9 $(38 \pm 12\%)$	42 ± 11 $(21 \pm 7\%)$

Table 1: Numbers of $\mathrm{D_s}$ signal events and ratios between the numbers of combinatorial background events and the total (in parentheses) for different $\mathrm{D_s}$ decay channels. The level of the combinatorial background was evaluated using a mass interval of $\pm 2\sigma$ $(\pm 1\Gamma)$ centred on the measured $\mathrm{D_s}$ (ϕ) mass.

The time resolution for the different $\mathrm{D_s}$ decay modes corresponding to the 94-95 data analysis is summarized in Tab. 2.

D_s decay Channel	First Gaussian fraction (%)	First Gaussian (σ_1) resolution (ps)	Second Gaussian (σ_2) resolution (ps)
$K^0_S K^+$ (94-95)	68	$\sqrt{(0.155^2 + 0.071^2\ t^2)}$	$3.6\sigma_1$
other non-leptonic (94-95)	83	$\sqrt{(0.108^2 + 0.074^2\ t^2)}$	$2.9\sigma_1$
$\phi\ell^+\nu$ (94-95)	76	$\sqrt{(0.128^2 + 0.069^2\ t^2)}$	$3.6\sigma_1$

Table 2: Time resolution for different D_s decay modes parametrized using the sum of two Gaussian distributions. The width of the narrower Gaussian depends on the generated proper time. The width of the other distribution is proportional to the width of the narrower one.

3 The new tagging procedure for $D_s^{\pm}, \ell^{\mp}$ analysis

The signature of the initial production of a $b(\bar{b})$ quark in the jet containing the B^0_s or $\bar{B}^0_s$ candidate was determined using a combination of different variables sensitive to the initial quark state. For each individual variable X_i, the probability density functions $f_b(X_i)$ ($f_{\bar{b}}(X_i)$) for b ($\bar{b}$) quarks were built and the ratio $R_i = f_{\bar{b}}(X_i)/f_b(X_i)$ was computed. The combined tagging variable was defined as:

$$x_{tag} = \frac{1-R}{1+R} \quad \text{, where } \; R = \prod R_i. \qquad (2)$$

The variable x_{tag} varies between -1 and 1. High values of x_{tag} correspond to a high probability that a given hemisphere contained a b quark in the initial state. If some of the variables X_i are not defined for a given event, the corresponding ratios R_i are set to 1, corresponding to equal probabilities for the initial state to be b or $\bar{b}$. Definition (2) of x_{tag} provides an optimal separation between b and $\bar{b}$ initial states if the individual discriminating variables X_i are independent.
A set of 9 discriminating variables was selected for this analysis. The event was divided into 2 hemispheres by the plane perpendicular to the direction of the B^0_s candidate. One set (3 variables) was determined in the hemisphere which contains the B^0_s meson, the other set (5 variables) in the hemisphere opposite to the B^0_s meson, and 1 variable was common to both hemispheres.

All reconstructed charged tracks were used in the opposite hemisphere, and the following variables were defined:

- the mean jet charge which is defined as :

$$Q_{hem} = \frac{\sum_{i=1}^{n} q_i (\vec{p_i} \cdot \vec{e_s})^{\kappa}}{\sum_{i=1}^{n} (\vec{p_i} \cdot \vec{e_s})^{\kappa}} \qquad (3)$$

  where q_i and $\vec{p_i}$ are the charge and the momentum of particle i, $\vec{e_s}$ is the unit vector along the thrust axis, and κ=0.6;

- the weighted sum of charges of particles identified as kaon candidates: $Q_k = \sum q_i (\vec{p_i} \cdot \vec{e_s})^{\kappa}$;

- the sum of the charges of tracks having significant impact parameters with respect to the primary event vertex;
- the sum of the charges of the tracks compatible with the primary event vertex;
- the transverse momentum multiplied by the charge of the identified lepton candidate with highest momentum.

Only tracks not included in the B_s^0 candidate decay products were used to define the variables in the same hemisphere. They were:

- the mean jet charge, computed using (3) with $\vec{e_s}$ directed along the reconstructed momentum of the B_s^0 candidate;
- the rapidity with respect to the direction of the thrust axis multiplied by the charge of the identified kaon candidate with the highest momentum having a trajectory compatible with the primary vertex,
- the momentum of any reconstructed Λ^0 candidate multiplied by the charge of the proton from its decay.

The last variable, common to both hemispheres, was the polar angle of the direction of the thrust axis. The average tagging purity of the x_{tag} variable, calculated on MC for true $\overline{B_s^0} \to D_s^+ \ell^- \overline{\nu} X$ decays, was $74.2 \pm 0.3\%$.

4 Results from the $D_s^\pm, \ell^\mp$ analysis

The sample composition, the measurement of the B meson proper time, and the fitting procedure have all been explained in detail in the previous publication [1].
In the fitting procedure the information of the tagging purity is used on an event by event basis, using the distribution of the discriminating variable x_{tag} (Fig. 3). In this case the tagging purity of the x_{tag} variable, calculated on MC for true $\overline{B_s^0} \to D_s^+ \ell^- \nu X$ decays, is equivalent to $78.0 \pm 0.3\%$.
The plot of the variation of the oscillation amplitude A as a function of Δm_s is shown in (Fig. 4). Considering only statistical uncertainties, the lower limit on Δm_s is :

$$\Delta m_s > 8.3 \text{ ps}^{-1} \quad \text{at 95\% C.L..} \tag{4}$$

The exclusion probability for this limit is 40%. The expected limit at 50% exclusion probability corresponds to $\Delta m_s > 7.2$ ps^{-1}.

4.1 Study of systematic uncertainties

Systematic uncertainties were evaluated by varying the parameters which were kept constant in the fit according to their measured or expected errors.

- Systematics from the tagging purity.
  The evaluation of systematics coming from the control of the tagging purity is still preliminary. The functions which give the tagging probabilities versus the discriminating variable for b and $\overline{b}$ were modified to obtain a variation on the averaged value

of the tagging purity of $\pm 3.0\%$. This variation was done by keeping the functions fixed for the values -1,0,1 of the discriminating variable. The range of variation of the tagging purity corresponds to differences observed between data and simulation in previous analyses.

- Systematics from the background level.
  $f_{bkg.}$ was varied according to the statistical uncertainty of the fitted combinatorial background fractions present in the different $\mathrm{D_s}$ or $\mathrm{K^+K^-}$ mass distributions.

- Systematics from the $\mathrm{B_s^0}$ purity.
  f_{B_s} is the fraction of events in which D_s mesons are expected to come from B_s semileptonic decays. $f_{\mathrm{D}_s\mathrm{D}}$ is the expected fraction of cascade decays $\mathrm{B} \to \overline{\mathrm{D}}^{(*)}\mathrm{D}_s{}^{(*)+}\mathrm{X}$ followed by the semileptonic decay $\overline{\mathrm{D}}^{(*)} \to \ell^- \overline{\nu} X$ which gives right-sign $\mathrm{D_s^\pm}, \ell^\mp$ pairs. After the selection cuts, the relative fractions are $f_{\mathrm{D}_s\mathrm{D}}/f_{B_s} = 0.106 \pm 0.020$ for non-leptonic $\mathrm{D_s}$ decays and $f_{\mathrm{D}_s\ \mathrm{D}}/f_{B_s} = 0.102 \pm 0.022$ for semileptonic decays, as obtained from the simulation. The statistical errors on these two fractions were taken to evaluate the systematics.

- Systematics from the resolution on the B decay proper time.
  The systematic error coming from the uncertainties on the resolution functions was evaluated by varying by 10% the two parameters describing the quadratic time dependence of the narrower Gaussian (see Tab. 2). A variation of 10% of the resolution for background events was also considered.

Including these systematic uncertainties does not change the excluded Δm_s regions significantly.

5 Combined limit on Δm_s

The result presented in the previous section was combined with the result from the $\ell - Q_{hem.}$ and $\ell{-}\ell$ analyses [1], taking into account correlations between the event samples and between systematic uncertainties in the different amplitude measurements. The resulting amplitude plot is shown in (Fig. 5) which corresponds to the limit:

$$\Delta m_s > 8.1 \ \mathrm{ps}^{-1} \text{ at } 95\% \text{ C.L.} \tag{5}$$

The exclusion probability for this limit is 46%. The limit at 50% exclusion probability corresponds to $\Delta m_s > 7.6\ \mathrm{ps}^{-1}$.

References

[1] DELPHI Coll. "Search for $B_s^0 - \overline{B_s^0}$ oscillations" Internal-DRAFT2 to be published

[2] DELPHI Coll., P. Abreu et al., Z. Phys. **C71** (1996) 11.

[3] Particle Data Group, R. M. Barnett et al., Phys. Rev. **D54** (1996) 1.

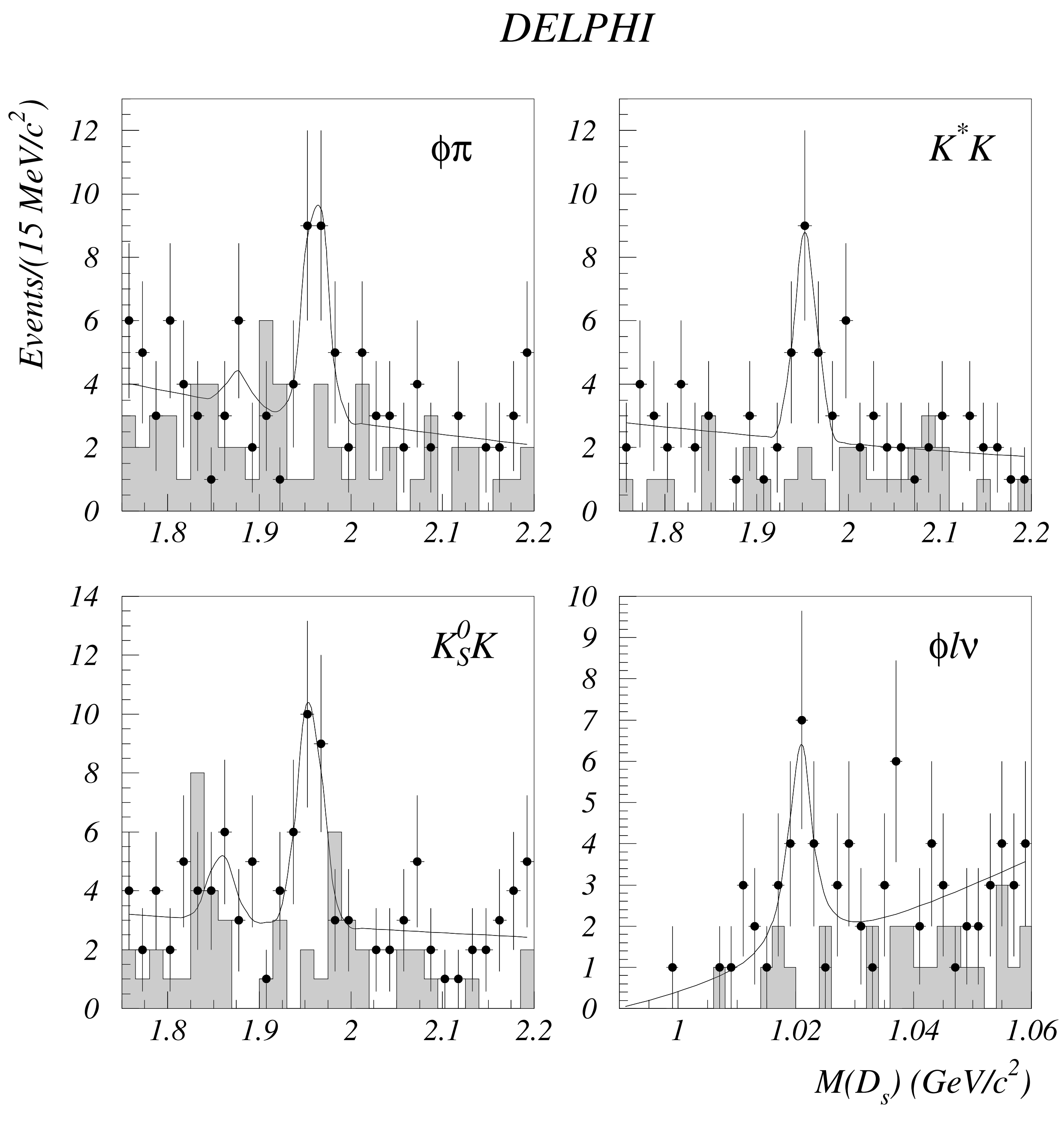

Figure 1: $D_s^{\pm}\ell^{\mp}$ analysis (91-93 data):
The first three plots show the invariant mass distributions for D_s candidates in three non-leptonic decay modes. The fourth plot shows the K^+K^- invariant mass distribution for D_s candidates selected in the two semileptonic decay modes. The D_s candidates selected are accompanied with a lepton of opposite electric charge identified in the same hemisphere and with p_t^{out} above 1.1 GeV/c. The wrong-sign combinations are given by the *shaded histograms*. The curves show the fits described in the text.

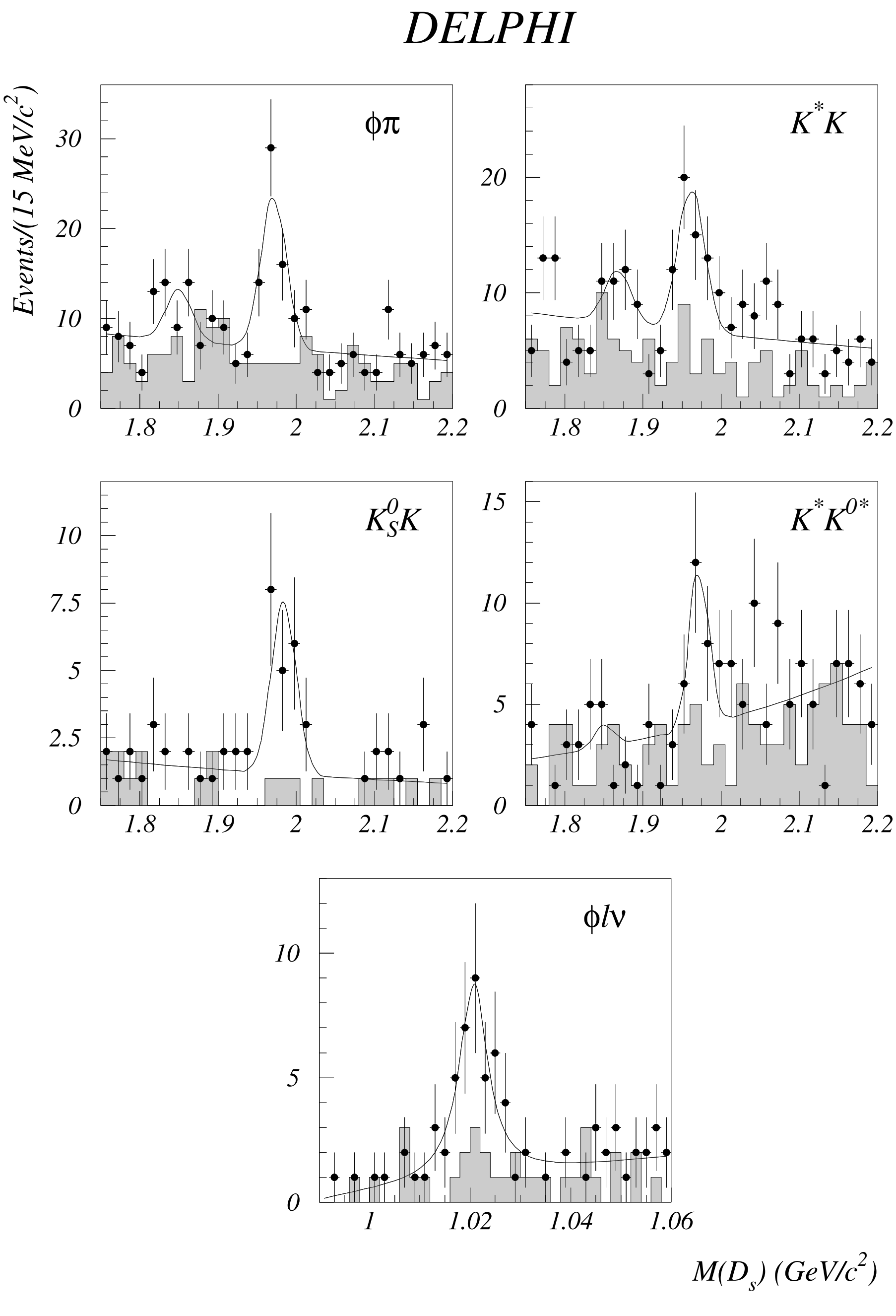

Figure 2: $D_s^{\pm}\ell^{\mp}$ analysis (94-95 data):
The first four plots show the invariant mass distributions for D_s candidates in four non-leptonic decay modes. The fifth plot shows the K^+K^- invariant mass distribution for D_s candidates selected in the two semileptonic decay modes. The D_s candidates selected are accompanied with a lepton of opposite electric charge identified in the same hemisphere and with p_t^{out} above 1.1 GeV/c. The wrong-sign combinations are given by the *shaded histograms*. The curves show the fits described in the text.

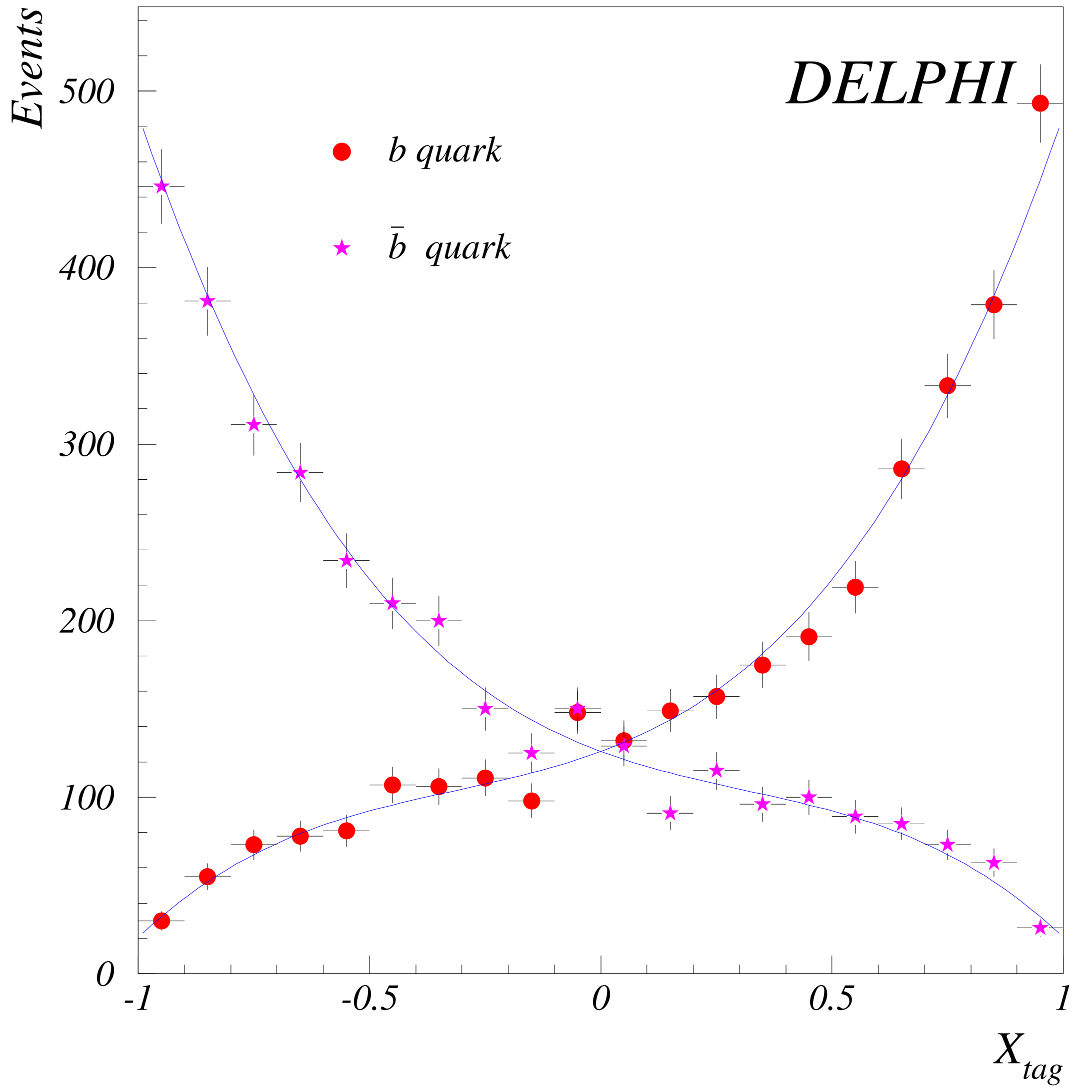

Figure 3: $D_s^{\pm}\ell^{\mp}$ analysis:
Distributions of the tagging variable x_{tag} for b and $\bar{b}$ initial states. They were calculated on a dedicated simulated sample of events of the type $\overline{B_s^0} \to D_s^+ \ell^- \nu X$. The parametrization used in the amplitude fit is superimposed.

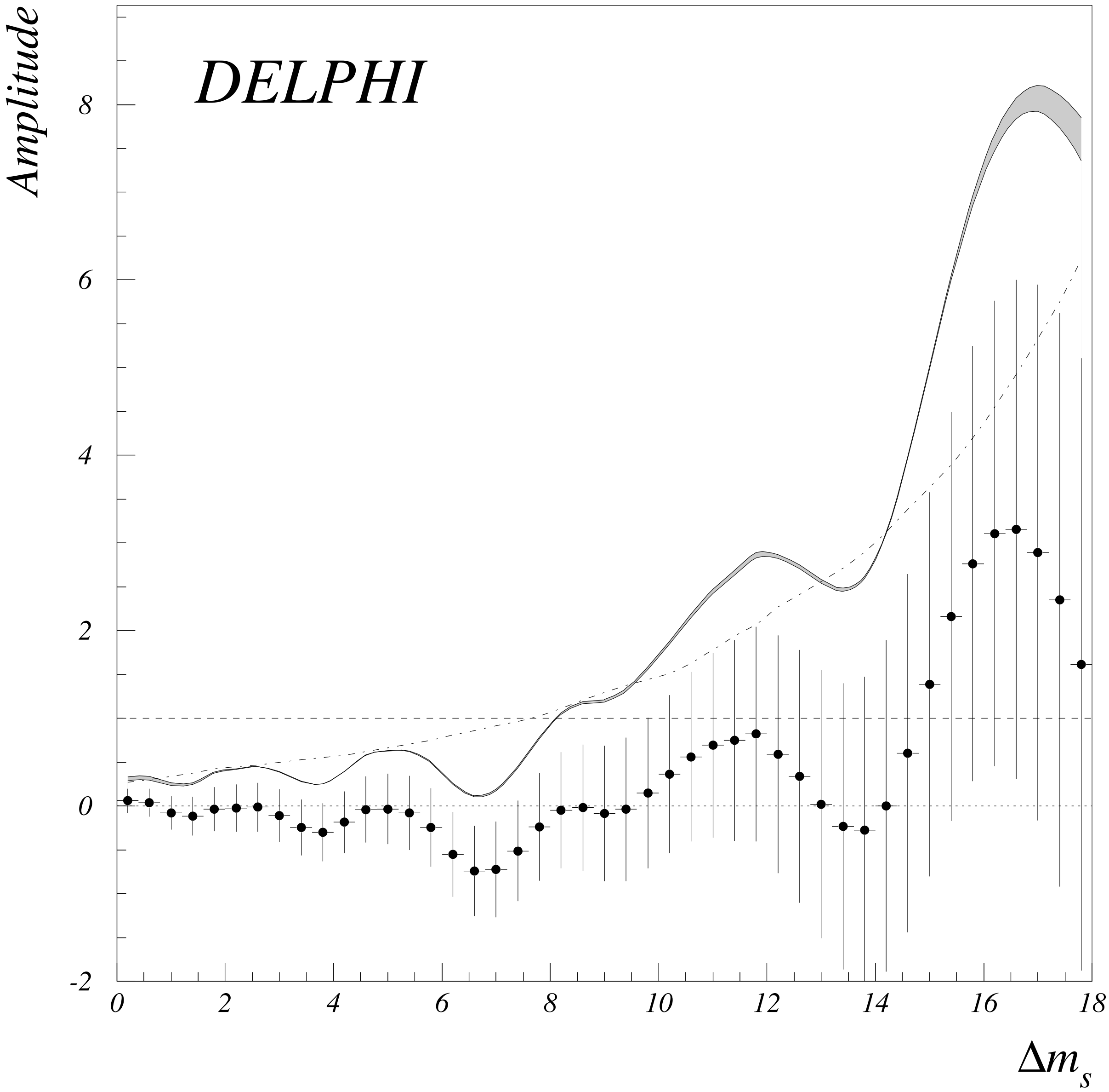

Figure 4: $D_s^{\pm}\ell^{\mp}$ analysis:
Variation of the oscillation amplitude A as a function of Δm_s. The lower continous line corresponds to $A+1.645\sigma_A$ with statistical uncertainties only, while the shaded area shows the contribution from systematics. The dashed-dotted line shows the sensitivity curve. The lines at A=0 and A=1 are also given

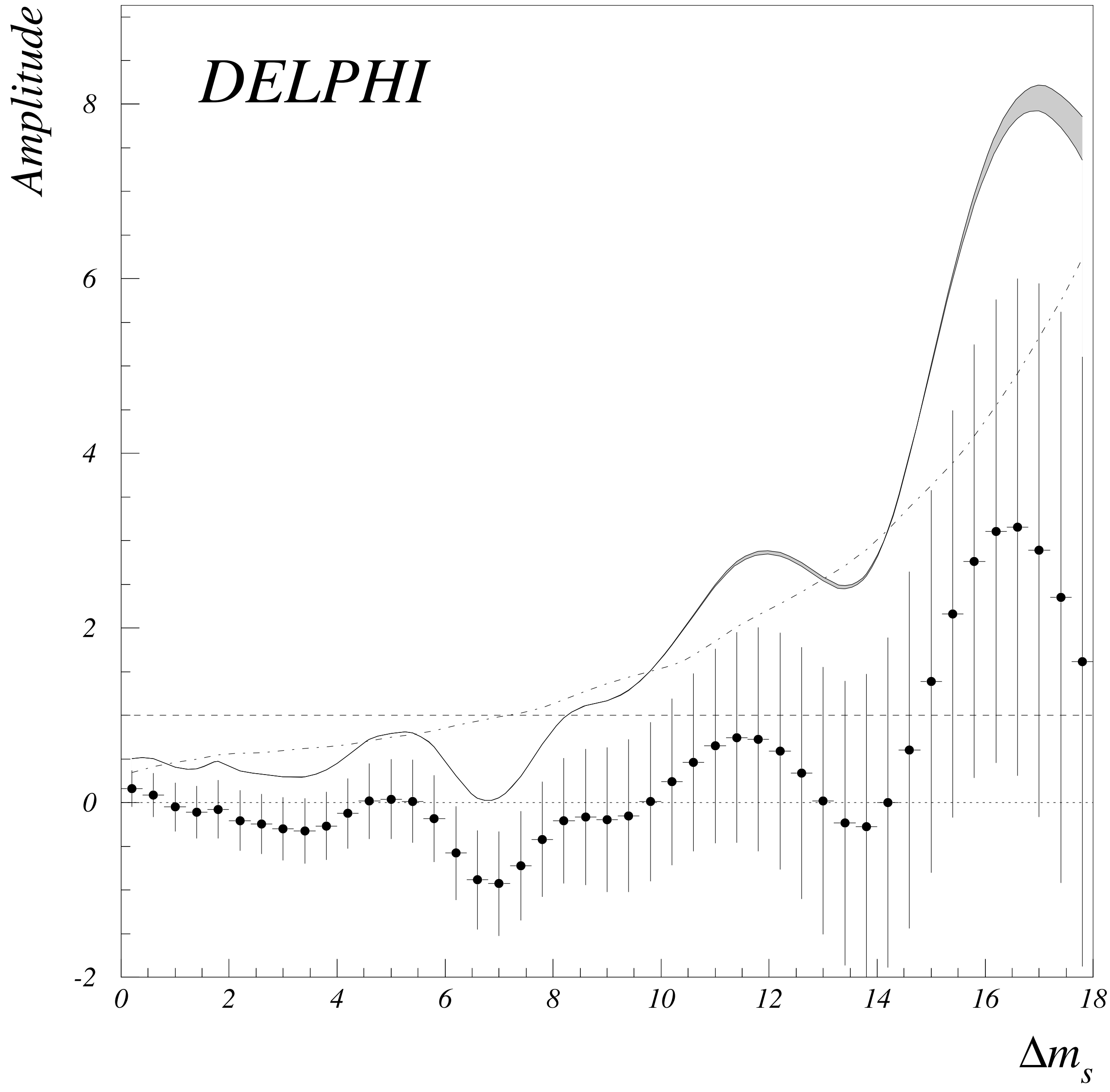

Figure 5: Combination of the three analyses using the amplitude method:
Variation of the oscillation amplitude A as a function of Δm_s.The lower continous line corresponds to $A+1.645\sigma_A$ with statistical uncertainties only, while the shaded area shows the contribution from systematics. The dashed-dotted line shows the sensitivity curve. The lines at A=0 and A=1 are also given