Fermilab FERMILAB-CONF-05-248-E CDF and D0

B_s OSCILLATION AND PROSPECTS FOR Δm_s AT THE TEVATRON

Stephanie Menzemer
Massachusetts Institute of Technology
for the CDF and D0 Collaboration

Abstract

Till the start of the LHC, the Tevatron is the only running accelerator which produces enough B_s mesons to perform Δm_s measurements. The status - as it was at the time of the conference - of two different Δm_s analysis performed both by the CDF and D0 collaboration will be presented.

1 Introduction

The Tevatron collider (Fermilab, Batavia, USA) has a huge b production rate which is 3 orders of magnitudes higher than the production rate at e^+e^- colliders running on the $\Upsilon(4S)$ resonance. Among the produced B particles there are as well heavy and excited states which are currently uniquely accessible at the Tevatron, such as for example B_s, B_c, Λ_b, θ_b, B^{**} or B_s^{**}. Dedicated triggers are able to pick 1 B event out of 1000 QCD events by selecting leptons and or events with displaced vertices already on hardware level.

The aim of the B physics program of the Tevatron experiments CDF and D0 is to provide constraint to the CKM matrix which takes advantage of the unique features of a hadron collider.

One of the flagship analysis for the Tevatron experiments is to exploit the B_s system in order to measure the mass difference (Δm_s) of the heavy and the light B_s mass eigenstate. Two different analysis were performed to access Δm_s: fitting for the B_s oscillation and measuring the lifetime difference of the heavy and light B_s mass eigenstate. The status of those will be discussed in the following.

2 Detectors and Triggers

After a 5 year shutdown with major detector and accelerator upgrade, CDF and D0 restarted data taking in March 2001.

Both the CDF and the D0 detector are symmetric multi-purpose detectors having both silicon vertex detectors, high resolution tracking in a magnetic field and lepton identification.

CDF is for the first time in an hadronic environment able to trigger already on hardware level on large track impact parameters which indicates displaced vertices (Figure 1, 2). Thus it is very powerfull in fully hadronic B modes. A Time-of-Flight system and the energy-loss measurements in the drift chamber provide particle identification. The CDF detector has a large extension of the tracking system in radial direction which provides a good mass resolution.

D0 has an excellent muon coverage and very good forward tracking which makes it very strong in J/Ψ and semileptonic modes. Additionally the good muon identification contributes significantly to the performance of the opposite side muon tagger. D0 is currently commissioning a displaced vertex trigger in order to get better access to fully reconstructed modes, too.

3 Motivation

Figure 3 shows the current status of a common fit of the CKM triangle from all measurements performed so far. The side of the unitarity triangle opposite

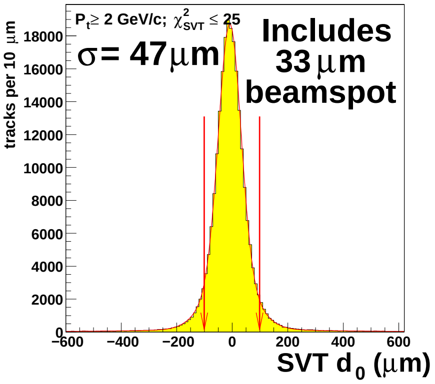

Figure 1: *Impact parameter resolution of the secondary vertex trigger (CDF).*

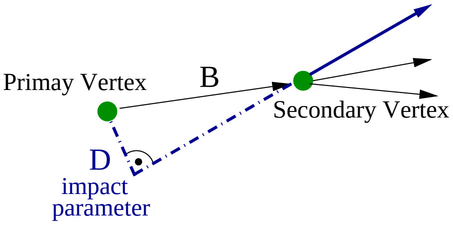

Figure 2: *Sketch of the impact parameter of tracks from secondary vertex.*

to the angle γ is determined by the measurement of the mass difference of the B_d system, Δm_d, and the lower limits on Δm_s. The length of this side is proportional to the CKM matrix-elements $|V_{td}V_{tb}^*|$. The angle γ and $|V_{td}V_{tb}^*|$ are the less well determined quantities of the triangle, thus measuring them is crucial to test its unitarity. While the determination of $|V_{td}V_{tb}^*|$ from Δm_d suffers from large theoretical uncertainties a lot of them cancel in studying $\Delta m_d/\Delta m_s$. A measurement of this ratio would determine the related CKM elements with 5 % uncertainty only (e.g. see the hatched area in Figure 3).
The range for Δm_s predicted by the Standard Model is $\Delta m_s \leq 24$ ps^{-1} while all Standard Model extentions predict a larger value of at least 30 ps^{-1}. Thus the measurement of Δm_s provides a handle to either confirm the Standard Model or to find evidence for New Physics beyond the Standard Model.
Two different analysis measuring/constraining Δm_s are uniquely able to be performed at the Tevatron. The first one is the B_s mixing analysis ($\mathcal{A}(t) \sim \mathcal{D} \times \cos(\Delta m_s t)$) which is especially sensitive to lower Δm_s values. The second one is the measurement of the B_s decay width difference $\Delta\Gamma_s$, which is related to Δm_s (in the Standard Model) via the theoretical very clean relation:

$$\frac{\Delta m_s}{\Delta\Gamma_s} \approx \frac{2}{3\pi}\frac{m_t^2}{m_b^2}(1-\frac{8}{3}\frac{m_c^2}{m_b^2})^{-1}h(\frac{m_t^2}{M_W^2}) \tag{1}$$

This measurement is at the Tevatron sensitive to high values of Δm_s.

β

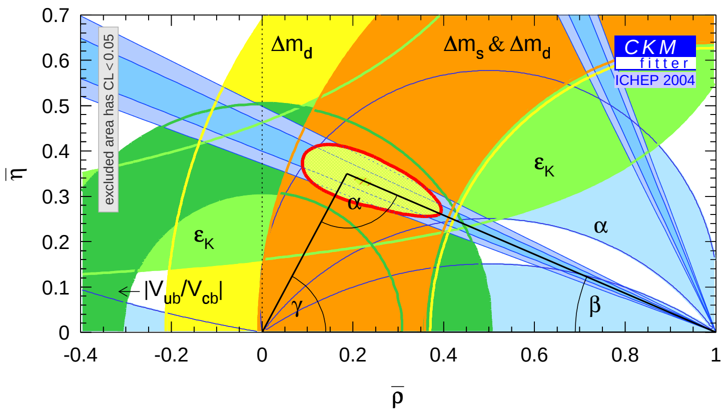

Figure 3: *Status of the fit for the CKM triangle at the time of the XIX Rencontres de Physics.*

4 $\Delta\Gamma$ Measurement in $B_s \to J/\Psi\phi$

In order to measure the decay width difference $\Delta\Gamma_s$ we need to disantangle the heavy and light B_s mass eigentstates and measure their lifetimes separately. In the B_s system CP violation is supposed to be small ($\delta\phi_s \approx 0$). Thus the heavy and light B_s mass eigenstates directly correspond to the CP even and CP odd eigenstates. So the separation of the B_s mass eigenstates can be done by identifying the CP even and CP odd contributions.

Generally final states are mixtures of CP even and odd states, but for pseudoscalar particles such as the B_s decaying into two vector particles such as the J/Ψ and the ϕ it is possible to disantangle the CP even and CP odd eigenstates by an angular analysis. The decay amplitude decomposes into 3 linear polarization states with the amplitudes $A_0, A_\parallel$ and $A_\perp$ with

$$|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1. \tag{2}$$

A_0 and $A_\parallel$ correspond to the S and D wave and are therefore the CP even contribution, while $A_\perp$ corresponds to the P wave and thus to the CP odd component.

Fitting at the same time for the angular distributions and for the lifetimes it is possible to measure the lifetimes of the heavy and light B_s mass eigenstate.

A similar angular analysis has been already performed by the BABAR and BELLE collaboration in the $B_d \to J/\Psi K^{*0}$ mode. This mode has as well been studied at the Tevatron as a cross check for the $B_s \to J/\Psi\phi$ analysis (Figure 4).

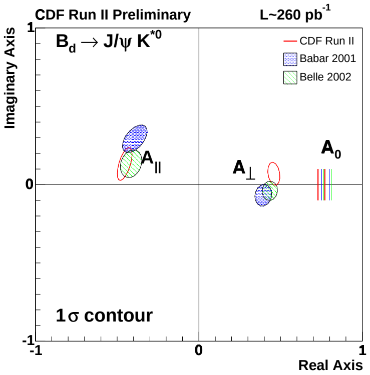

Figure 4: *Angular analysis of the* $B_d \rightarrow J/\Psi K^{*0}$ *mode. BABAR, BELLE and CDF results are in good agreement.*

In order to perform this analysis first of all a $B_s \rightarrow J/\Psi\phi$ signal has to be established. Both experiments have measured the B_s mass and lifetime (Figure 5, 6) and obtain the following results, where the lifetime τ_s is measured with respect to τ_d from the topological similar decay $B_d \rightarrow J/\Psi K^{*0}$:

$$M(B_s) = 5360 \pm 5 MeV/c^2 \ (D0) \tag{3}$$
$$M(B_s) = 5366.01 \pm 0.73(stat) \pm 0.033(syst) MeV/c^2 \ (CDF) \tag{4}$$
$$\tau_s/\tau_d = 0.980^{+0.075}_{-0.070}(stat) \pm 0.0003(syst) \ (D0) \tag{5}$$
$$\tau_s/\tau_d = 0.980 \pm 0.072(tot) \ (CDF) \tag{6}$$

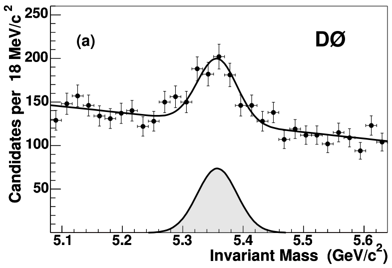

Figure 5: *Mass of* $B_s \rightarrow J/\Psi\phi$ *candidates from D0.*

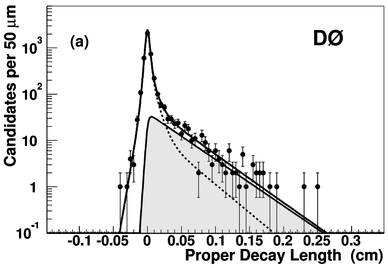

Figure 6: *Average lifetime of* $B_s \rightarrow J/\Psi\phi$ *candidates from D0.*

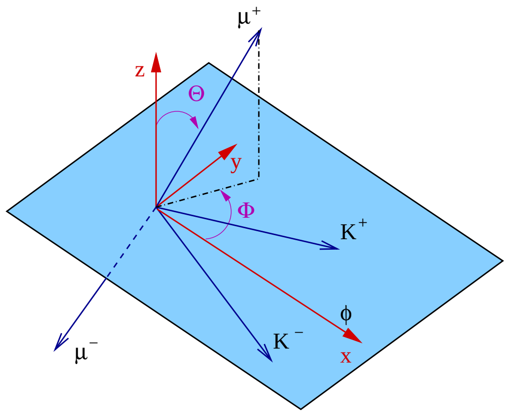

Figure 7: *Definition of the transversity frame and the transversity angles.*

The angular analysis has been performed in the transversity basis in the J/Ψ rest-frame which is introduced in Figure 7. The both kaons of the ϕ decay define the x-y plane, the flight direction of the ϕ defines the positive x-axis and the positively charged kaon the positive y-axis. The flight direction of the positively charged muon of the J/Ψ decay defines the positive z-axis. The angles used in this analysis are θ and Φ, the polar and azimuthal angle of the μ^+ and Ψ the helicity angle of the ϕ.

The fit projections of the common fit of the both lifetimes and the angular distributions for the CDF and for the D0 analysis are shown in Figure 8.

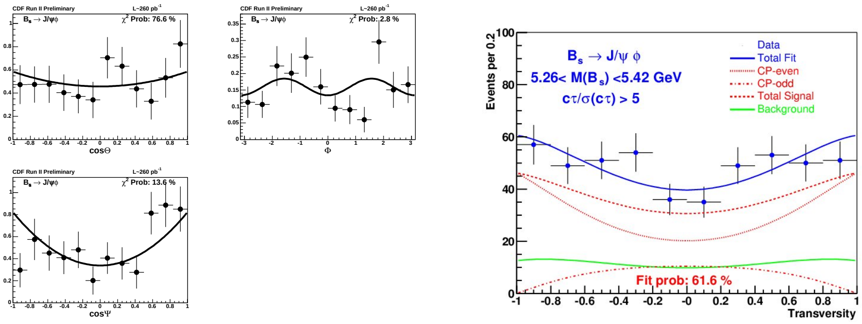

Figure 8: *Fit projections of the common fit of the angular distribution in the transversity frame and the two different B_s lifetimes, CDF (left), D0 (right).*

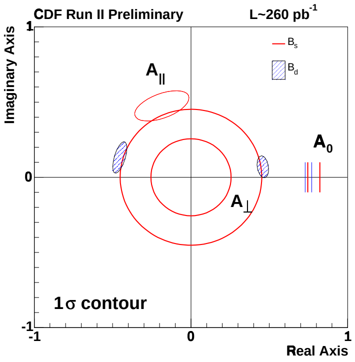

Figure 9: *Fit result of the angular amplitudes of the* $B_s \to J/\Psi\phi$ *and* $B_d \to J/\Psi K^{*0}$ *decays (CDF).*

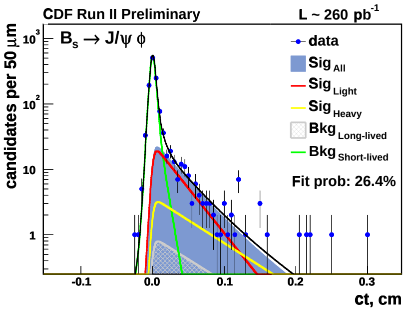

Figure 10: *Fit projections of the common fit of the lifetime and angular distribution in the transversity frame (CDF).*

The following results are obtained by the CDF analysis [1] (Figure 9, 10):

$$
\begin{aligned}
|A_\perp| &= 0.354 \pm 0.098 \pm 0.003 && (7)\\
A_0 &= 0.784 \pm 0.039 \pm 0.007 && (8)\\
\tau_L &= 1.05^{+0.16}_{-0.13} \pm 0.02ps && (9)\\
\tau_H &= 2.07^{+0.58}_{-0.40} \pm 0.03ps && (10)\\
\Delta\Gamma/\Gamma &= 0.65^{+0.25}_{-0.33} \pm 0.01 && (11)\\
\Delta\Gamma &= 0.47^{+0.19}_{-0.24} \pm 0.01ps^{-1} && (12)
\end{aligned}
$$

With about 200 signal events CDF finds a large value for the lifetime difference which is about 2.5 σ way from being zero and about 2σ away from the Standard Model predictions of $\Delta\Gamma_s/\Gamma_s = 0.12$. The CDF results favors high values of Δm_s but is currently statistically limited. The systematic uncertainties are very small thus this is a beautiful measurement ones more data is available. The D0 result of this analysis was on the way but not yet available at the time of this conference. It can be found in [2].

5 *B* Mixing

The dominant Feynman diagrams describing the mixing processes are shown in Figure 11. The probability that a B meson decays at proper time t and has

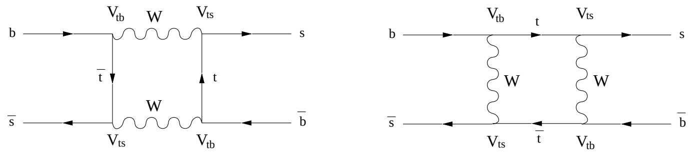

Figure 11: *Feynman diagrams for dominant B_s mixing processes.*

or has not already mixed to the $\bar{B}$ state is given by:

$$P_{unmix}(t) \approx \frac{1}{2}(1+\cos\Delta m t), \tag{13}$$

$$P_{mix}(t) \approx \frac{1}{2}(1-\cos\Delta m t). \tag{14}$$

The canonical B mixing analysis, in which oscillations are observed and the mixing frequency, Δm, is measured, proceeds as follows. The B meson flavor at the time of its decay is determined by exclusive reconstruction of the final state. The proper time, $t = m_B L/pc$, at which the decay occurred is determined by measuring the decay length, L, and the B momentum, p. Finally the production flavor must be tagged in order to classify the decay as being mixed or unmixed at the time of its decay.
Oscillation manifests itself in a time dependence of, for example, the mixed asymmetry:

$$\mathcal{A}_{mix}(t) = \frac{N_{mixed}(t) - N_{unmixed}(t)}{N_{mixed}(t) + N_{unmixed}(t)} = -\cos\Delta m t \tag{15}$$

In practice, the production flavor will be correctly tagged with a probability P_{tag} which is significantly smaller than one but larger than one half (which corresponds to a random tag). The measured mixing asymmetry in terms of dilution, $\mathcal{D}$, is

$$\mathcal{A}^{meas}_{mix}(t) = \mathcal{D}\mathcal{A}_{mix} = -\mathcal{D}\cos\Delta m t \tag{16}$$

where $\mathcal{D} = 2P_{tag} - 1$.

Figure 12 illustrates the mixed asymmetry for $\Delta m_d = 0.5$ ps $^{-1}$ and for a fictive Δm_s value of 20 ps^{-1}, which is within the Standard Model expectations. This clearly demonstrates the need for good proper decay time resolution in order to resolve such a high Δm_s mixing frequency.
The second important ingredient for a mixing analysis is the flavor tagging. As the examined decays are flavor specific modes the decay flavor can be determined via the decay products. But for the production flavor additional

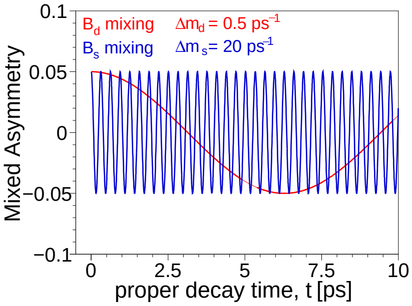

Figure 12: *Example of mixed asymmetry for a B_d like and a fictive B_s like mixing frequency with a dilution $\mathcal{D} = 5\ \%$.*

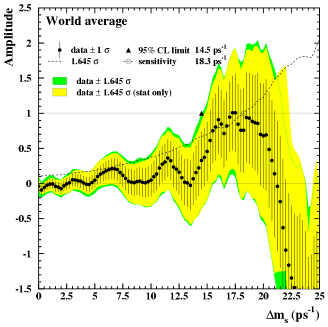

Figure 13: *World average of the current B_s mixing analysis.*

information from the event has to be evaluated in order to tag the event. A good and well measured tagging performance is needed to set a limit on Δm_s. The last component are the B_s candidates. Sufficient statistic is need to be sensitive to high mixing frequencies.

Figure 13 shows the current status of the B_s mixing measurement. The world average for the mass difference Δm_s is 14.5 ps^{-1} @ 95 % CL which is a combination of 13 measurements from LEP, SLD and CDF I.

5.1 Flavor Tagging

There are two different kinds of flavor tagging algorithms, opposite side tagging (OST) and same side tagging (SST), which are illustrated in Figure 14. OST algorithms use the fact that b quarks are mostly produced in $b\bar{b}$ pairs, therefore the flavor of the second (opposite side) b can be used to determine the flavor of the b quark on the signal side.

5.1.1 Jet-Charge Tagging

The average charge of an opposite side b-jet is weakly correlated to the charge of the opposite b quark and can thus be used to determine the opposite side b flavor. The main challenge of this tagger is to select the b-jet. Information of a displaced vertex or displaced tracks in the jet help to identify b-jets. This tagging algorithm has a very high tagging efficiency but the dilution is relatively

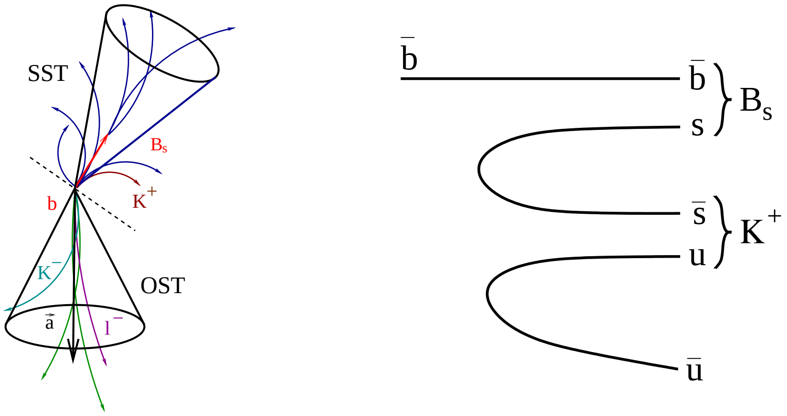

Figure 14: *Left: Sketch of different tagging algorithms; Right: Same-side kaon tagging.*

low. By separating sets of tagged events of different qualities e.g. how b like the jet is, it is possible to increase the overall tagging performance.

5.1.2 Soft-Lepton-Tagging

In 20 % of cases the opposite b decays semileptonically either into an electron or a muon ($b \rightarrow l^- X$). The charge of the lepton is correlated to the charge of the decaying B meson. Depending on the type of the B meson there is a certain probability of oscillation between production and decay (0 % for $B^\pm$, 17.5 % for B_d and 50 % for B_s). Therefore this tagging algorithm already contains an intrinsic dilution. Another potential source of miss-tag is the transition of the b quark into a c quark which then forms a D meson and subsequently decays semileptonically ($\bar{b} \rightarrow \bar{c} \rightarrow l^- X$). Due to the different decay length and momentum distribution of B and D meson decays this source of miss-tag can mostly be eliminated.

5.1.3 Kaon-Tagging

Due to the transition chain $b \rightarrow c \rightarrow s$ it is more likely that a $\bar{B}$ meson contains a K^- than a K^+ in the final state. Therefore a K^- on the opposite side is a hint, that there was a $\bar{b}$ quark on the signal side. This tagging algorithm heavily relies on the kaon identification power and the capability of separating kaons from the fragmentation by kaons from the opposite B decay by a good vertex resolution. At the moment non of the both Tevatron experiments use an opposite side kaon tagger.

$\epsilon D^2(\%)$	CDF semileptonic channels	D0
SST(B_d)	$1.04 \pm 0.35 \pm 0.06$	1.00 ± 0.36
Soft μ	0.56 ± 0.05	1.00 ± 0.38
Soft e	0.29 ± 0.03	-
Jet-Q	0.57 ± 0.06	~ 1 (measured combined with SST)

Table 1: *Tagger performance of the CDF and D0 experiments as measured on semileptonic B_d and B_u samples.*

5.1.4 Same-Side-Tagging

During fragmentation and the formation of the $B_{s/d}$ meson there is a left over $\bar{s}/\bar{d}$ quark which is likely to form a K^+/π^+ (Figure 14). So if there is a near by charged particle, which is additionally identified as a kaon/pion, it is quite likely that it is the leading fragmentation track and its charge is then correlated to the flavor of the $B_{s/d}$ meson. While the performance of the opposite side tagger does not depend on the flavor of the B on the signal side the SST performance heavily depends on the signal fragmentation processes. Therefore the opposite side performance can be measured in B_d mixing and can then be used for setting a limit on the B_s mixing frequency. But for using the SST for a limit on Δm_s we have to heavily rely on Monte Carlo simulation. The SST potentially has the best tagger performance, but before using it for a limit, fragmentation processes have to be carefully understood.

5.2 Δm_d Measurement and Calibration of Taggers

For setting a limit on Δm_s the knowledge of the tagger performance is crucial. Therefore it has to be measured in kinematically similar B_d and B^+ samples.

The Δm_s and Δm_d analysis is a complex fit with up to 500 parameters which combine several B flavor and several decay modes, various different taggers and deals with complex templates for mass and lifetime fits for various sources of background. Therefore the measurement of Δm_d is beside the calibration of the opposite side taggers very important to test and trust the fitter framework although the actual Δm_d result at the Tevatron is not competitive with the B factories.

D0 measured Δm_d applying combined opposite and same side taggers in semileptonic decay channels with 250 pb^{-1} of data and obtained 3)

$$\Delta m_d = 0.456 \pm 0.034\ (stat) \pm 0.025\ (syst)\ ps^{-1} \tag{17}$$

CDF performed two measurements using opposite side taggers only based on

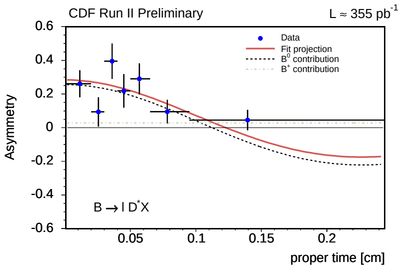

Figure 15: *Asymmetry fit projection for Δm_d using opposite side muon tagger in semileptonic decays (CDF).*

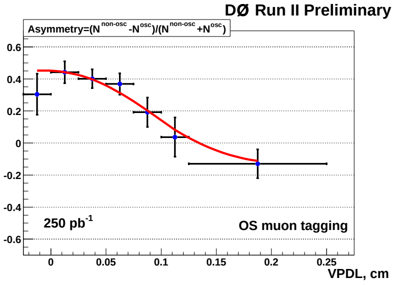

Figure 16: *Asymmetry fit projection for Δm_d using opposite side muon tagger in semileptonic decays (D0).*

semileptonic [4] and hadronic channels [5] respectively using 355 pb^{-1} of data:

$$\Delta m_d = 0.497 \pm 0.028\ (stat) \pm 0.015\ (sys)\ ps^{-1}\ (semileptonic) \quad (18)$$

$$\Delta m_d = 0.503 \pm 0.063\ (stat) \pm 0.015\ (sys)\ ps^{-1}\ (hadronic) \quad (19)$$

An example of the fitted asymmetry using the opposite side muon tagger on the semileptonic decay modes is displayed in Figures 15, 16. The measured tagging performances are listed in Table 1.

5.3 Amplitude Scan

An alternative method for studying neutral B meson oscillations is the so called "amplitude scan", which is explained in detail in Reference [6]. The likelihood term describing the tagged proper decay time of a neutral B meson is modified by including an additional parameter multiplying the cosine; the so-called amplitude A.

The signal oscillation term in the likelihood of the Δm thus becomes

$$\mathcal{L} \propto \frac{1 \pm A\mathcal{D}\cos(\Delta m t)}{2} \quad (20)$$

The parameter A is left free in the fit while $\mathcal{D}$ is supposed to be known and fixed in the scan. The method involves performing one such A-fit for each value of the parameter Δm, which is fixed at each step; in the case of infinite statistics, optimal resolution and perfect tagger parameterization and calibration, one would expect A to be unit for the true oscillation frequency and zero for the remaining of the probed spectrum. In practice, the output

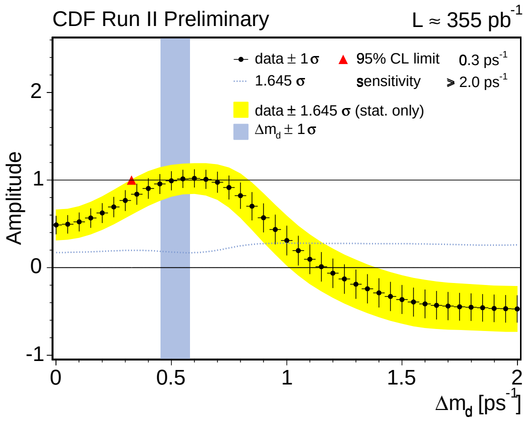

Figure 17: *Amplitude scan for Δm_d in hadronic decay modes (CDF). The scan is compatible with 1 around the result of the actual Δm_d fit.*

of the procedure is accordingly a list of fitted values $(A,\ \sigma_A)$ for each Δm hypothesis. Such a Δm hypothesis is excluded to a 95% confidence level in case the following relation is observed,

$$A + 1.645 \cdot \sigma_A < 1$$

The sensitivity of a mixing measurement is defined as the lowest Δm value for which $1.645 \cdot \sigma_A = 1$.

The amplitude method will be employed in the ensuing B_s mixing analysis. One of its main advantages is the fact that it allows easy combination among different measurements and experiments.

The plot shown in Figure 17 is obtained when the method is applied to the hadronic B_d samples of the CDF experiment, using the exclusively combined opposite side tagging algorithms. The expected compatibility of the measured amplitude with unit in the vicinity of the true frequency, $\Delta m_d = 0.5$ ps^{-1}, is confirmed.

However, we observe the expected increase in the amplitude uncertainty for higher oscillation frequency hypotheses. This is equivalent to saying that the significance is reduced with increasing frequency.

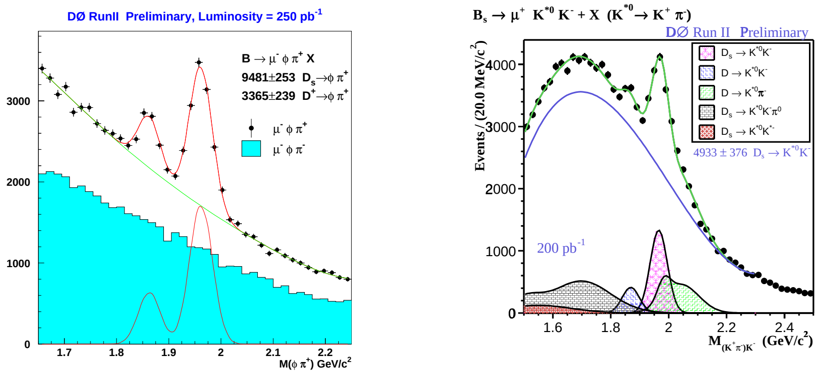

Figure 18: *Reconstructed semileptonic B_s decays for Δm_s analysis (D0).*

5.4 Reconstructed B_s Decays

D0 exploits the high statistics muon trigger to study semileptonic B_s decays. About 10,000 B_s candidates have been reconstructed in the $B_s \to \mu X D_s, (D_s \to \phi\pi)$ mode in 250 pb^{-1} of data. Additionally 5,000 B_s candidates were reconstructed when $D_s \to K^{*0}K, (K^{*0} \to K\pi)$ decays were added (Figure 18).
Due to the missing neutrino the B_s momentum in semileptonic decays is not fully reconstructed. Thus a correction factor obtained from Monte Carlo simulation (K factor) has to be introduced in order to extract the proper decay time of the B_s meson.

$$c\tau = \frac{L_{xy} * M(B)}{p_T(B)} = \frac{L_{xy} * M(B)}{p_T(\ell D)} * K \tag{21}$$

This introduced an additional uncertainty on the proper decay time. The maximal reach of sensitivity of the B_s mixing for semileptonic modes is limited by the proper decay time resolution.
D0 is currently working on reconstructing fully hadronic B_s decays on the non trigger side in this sample and profiting from the trigger muon as opposite side muon tag.

CDF performs the B_s mixing analysis using both fully reconstructed B_s decays ($B_s \to D_s\pi$) obtained by the two track trigger and semileptonic decays ($B_s \to \ell X D_s$) collected in the lepton+displaced track trigger (Figure 19). In both cases the D_s is reconstructed in the $D_s \to \phi\pi$, $D_s \to K^{*0}K$ and $D_s \to \pi\pi\pi$ modes. Altogether those are about 700 hadronic and 8000 semileptonic B_s candidates in 355 pb^{-1} of data. The proper modelling of the background

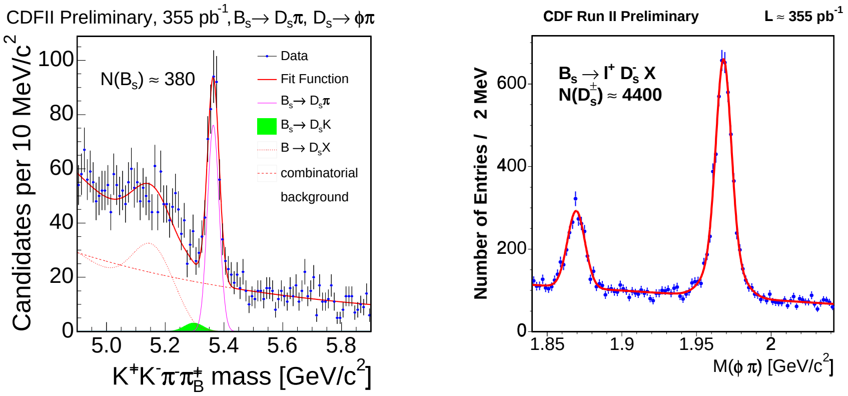

Figure 19: *Reconstructed B_s decays for Δm_s analysis (CDF) in the $D_s \to \phi\pi$ mode.*

especially in the hadronic modes from reflections and partial reconstructed B candidates is one of the challenges on the way to the B_s mixing analysis.
For the semileptonic decays the background including a real D_s meson is hard to reject and to measure and thus is the largest source of systematic uncertainties, although the mixing analysis is by far dominated by the statistic uncertainties.

The results of the B_s mixing analysis from both experiments, CDF and D0, using those decays were not ready in time for this conference, but they have been presented a few days later and can be found in [8], [7].
For the first time in RUN II CDF and D0 have performed a Δm_s mixing analysis, which is a very complex measurement. We have prooven to be able to do it and further improvements are expected, e.g. by adding additional decay modes and by using same side tagging.

6 Conclusion

Two different analysis to measure Δm_s have been presented, which are performed both by the CDF and D0 collaboration. The measurement of the decay width difference $\Delta\Gamma_s$ of the heavy and light B_s mass eigenstate is especially sensitive to high Δm_s values. The B_s mixing analysis is sensitive to lower values. Together they have the ptotential to cover the hole range of possible Δm_s values in the Standard Model and as well beyond. Those analysis currently suffer from lack of statistics, but there principle feasability has been demonstrated, thus we expect soon to get further constraints on Δm_s from the Tevatron experiments.

7 Acknowledgments

I would like to thank the organizers Giorgio Bellettini, Giorgio Chiarelli and Mario Greco for a very enjoyable conference.

References

1. The CDF Collaboration, Phys. Rev. Lett. **94** (2005) 101803, hep-ex/0412057
2. The D0 Collaboration, http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B17
3. The D0 Collaboration, http://www-d0.fnal.gov/Run2Physcis/WWW/results/prelim/B/B15
4. The CDF Collaboration, http://www-cdf.fnal.gov/physics/new/bottom/050224blessed-mix-bld
5. The CDF Collaboration, http://www-cdf.fnal.gov/physics/new/bottom/050224.blessed-hadr-ost
6. H.G. Moser, A.Roussrie, *Mathematical methods for* $B^0\bar{B}^0$ *osciallation analysed*, NIM A384 (1997), 491-505
7. The CDF Collaboration, http://www-cdf.fnal.gov/physics/new/bottom/050310.bsmix-combined
8. The D0 Collaboration, http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B20