The Feasibility of Measuring B_s^0 Mixing Using Trigger Muons as a Flavor Tag

J. Reid Mumford

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Abstract

In this proposal, a brief theoretical introduction to the Standard Model (SM) is given. The formalism for B_s^0 mixing is outlined. Components of the Collider Detector at Fermilab (CDF), critical to the measurement of B_s^0 mixing, are described. A technique using muons as a flavor tag, in $220pb^{-1}$ of data triggered with a muon and a displaced track, is explored. Further steps for a complete B_s^0 mixing measurement are described and sensitivity to Δm_s is estimated.

1 Standard Model

For decades, the Standard Model (SM) has been the theoretical tool used to describe fundamental particles and their interactions. The SM describes three families of particles. These particles interact with three fundamental forces; the strong, electro-magnetic, and weak[1]. Interactions between particles and forces are mediated by force carrying bosons, the most familiar of which is the photon, the force carrier for the electro-magnetic force. A summary of the particles that populate the SM are given in Table 1.

Type	I	II	III	Spin	Charge	Forces
Leptons	e	μ	τ	$\pm 1/2$	± 1	EM, Weak
	ν_e	ν_μ	ν_τ	$\pm 1/2$	0	Weak
Quarks	u	c	t	$\pm 1/2$	$+2/3$	EM, Weak, Strong
	d	s	b	$\pm 1/2$	$-1/3$	EM, Weak, Strong
Bosons	γ			1	0	EM
	$W^\pm, Z^0$			1	$\pm 1, 0$	Weak
	g			1	0	Strong

Table 1: Fundamental Particles of the SM

Quarks and gluons are combined, by the strong force into hadrons. Because of the nature of the strong force, quarks are never found in un-bound, free states; they are most commonly found in pairs (called mesons) or in groups of three (called baryons).

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[1] The fourth known force, gravity, has yet to be incorporated within the Standard Model

Much of the recent effort in experimental particle physics has been dedicated to high precision measurements of SM parameters. Measurements that do not agree with SM predictions would indicate physics beyond the scope of the current theory and would open the door for new theories.

2 B_s Mixing

One interesting situation arises with neutral mesons and their antiparticles. In 1955 Gell-Mann and Pais proposed that neutral Kaons oscillate between the $K^0 = d\bar{s}$ and $\overline{K^0} = \bar{d}s$ state[1]. Therefore, the particles observed experimentally were not simply K^0 or $\overline{K^0}$ but a mixture of the two states. Mixing is not unique to the neutral Kaon system. In addition to the $K^0\overline{K^0}$ system, it has been observed in $B^0\overline{B^0}$, and has been hypothesized in $D^0\overline{D^0}$, and $B_s^0\overline{B_s^0}$ systems.

The basic formalism of the $B_s^0 \leftrightarrow \overline{B_s^0}$ system is very similar to that of the $K^0 \leftrightarrow \overline{K^0}$ system. We can describe the mesons in terms of two distinct eigenstates. *Flavor eigenstates*, or strong-interaction eigenstates, are states with definite quark content. When mesons are created, they are created in *flavor eigenstates* which, for the B_s^0 system, are given by

$$|B_s^0 >= \bar{b}s \qquad\qquad |\overline{B_s^0} >= b\bar{s}.$$

Mass eigenstates are a super-position of the flavor eigenstates. These states have measurable lifetimes and masses.

$$|B_{s_L} >= p|B_s^0 > +q|\overline{B_s^0} > \qquad\qquad |B_{s_H} >= p|B_s^0 > -q|\overline{B_s^0} >,$$

where p and q are complex coefficients that satisfy the following relation

$$|p|^2 + |q|^2 = 1.$$

B_{s_L} and B_{s_H} are the light and heavy mass eigenstates respectively. We can also define the mass difference, Δm_s, and the width difference[2], $\Delta\Gamma_s$, between the two states

$$\Delta m_s \equiv M_H - M_L$$

$$\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H.$$

The probability that a B_s^0 meson at production (t=0) decays in the same state or oscillates to decay in the $\overline{B_s^0}$ state as a function of proper time, t, is given by

$$P_{unmix}(t) = \frac{1}{2}(1 + cos(\Delta m_s t)),$$

$$P_{mix}(t) = \frac{1}{2}(1 - cos(\Delta m_s t)).$$

The frequency of oscillation is determined by the mass difference between the two states. The current world average of all B_s^0 mixing measurements puts a limit of $\Delta m_s > 14.1 ps^{-1}$[2]. Because of the large mass difference B_s^0 oscillations are extremely rapid making them a challenge to measure experimentally. In addition to an accurate flavor tag at production, proper time resolution is critical to the mixing analysis. In order to accurately measure the proper time, we must be able to resolve primary and secondary vertices and precisely measure particle momenta.

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[2] The width of a particle, Γ, is defined as the inverse of the lifetime, τ. $\Gamma = 1/\tau$.

3 CDF II Detector

The Run II Collider Detector at Fermilab (CDF II) is a general purpose solenoidal detector which combines precision charged particle tracking with fast projective calorimetry and fine-grained muon detection. Figure 1 shows a solid cutaway view of the detector. CDF II started collecting data in March 2001 with the Tevatron running at a center-of-mass energy of just under 2.0 TeV. The accelerated beam flies along the z-axis. CDF uses layers of detector sub-systems, surrounding the beam, to track different species of stable particles. Several CDF components, relevant to the search for B_s^0 mixing, are the Silicon Vertex Detector (SVX II) , Central Outer Tracker (COT), and the muon systems.

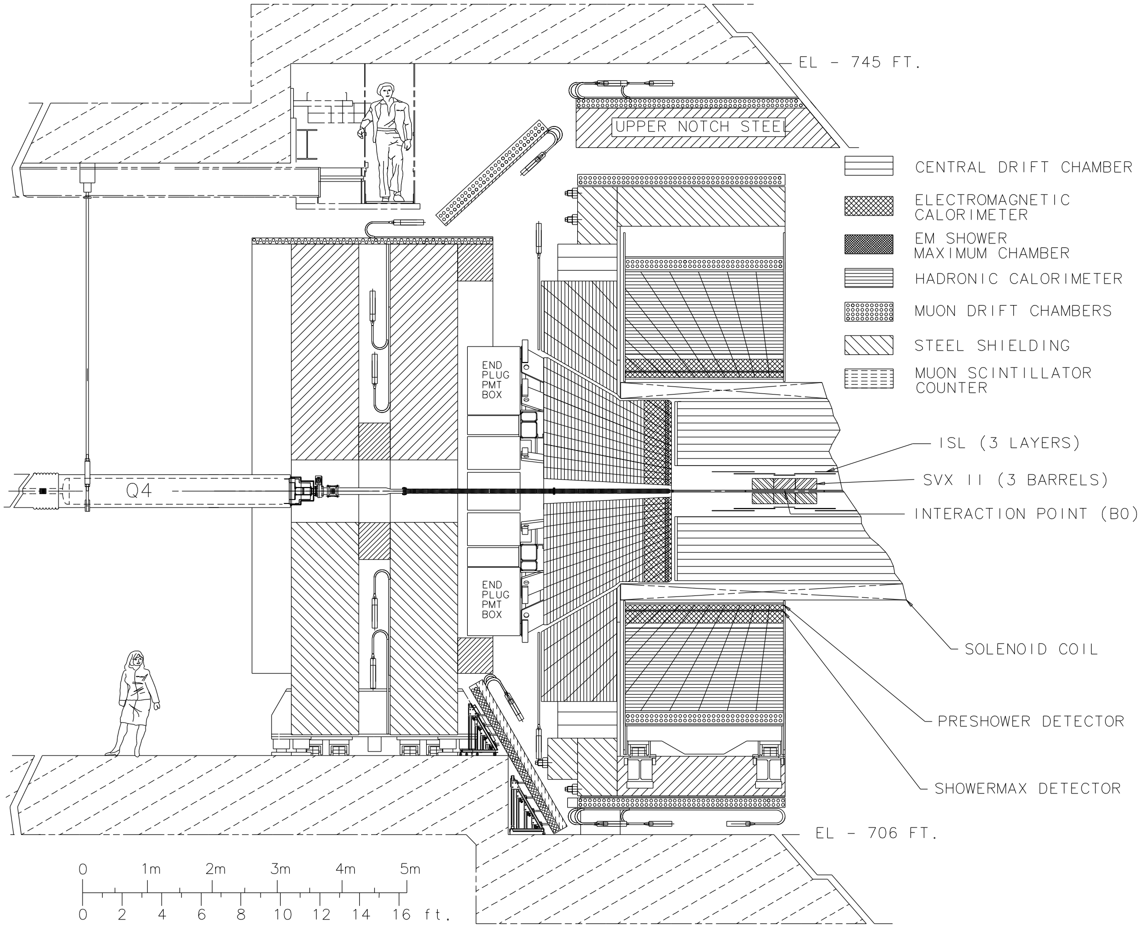

Figure 1: Elevation view of one half of the CDF II detector.

The SVX II and COT are located within a superconducting solenoid with a magnetic field of 1.4 Tesla. The SVX II is the closest detector to the beam; consisting of 5 cylindrical silicon layers that extend to a radius of 11 cm. Outside of the SVX II are the Intermediate Silicon Layers (ISL). The ISL has a central layer and two forward layers that extend the silicon coverage to a radius of 28cm. The SVX II and ISL detectors provide tracking information and precise resolution of decay vertices.

The COT is an open cell drift chamber, covering radii between 44 and 132 cm. The COT is composed of cylindrical superlayers. Each superlayer is composed of cells consisting of high-voltage sense wires. Axial and small angle stereo cells allow the COT to track in both the polar (η) and azimuthal (ϕ) directions.

Calorimeters are used to measure electron, photon, and jet energies and the net transverse energy in an event. They consist of many layers of steel or iron absorbers and plastic scintillator for readout. Muon detectors are located at the largest radii at CDF, outside of the solenoid and calorimeters. The muon system consists of several layers of single-wire drift tubes. Since muons are massive and interact weakly, they are generally the only particles able to punch through the calorimeters to the drift tubes.

High p_T pairs of b or c quarks are often produced in Tevatron collisions, however they are a thousand times more rare than other soft QCD processes. A sophisticated triggering system has therefore been implemented to produce samples that are rich in B events. B mesons decay weakly and therefore have relatively long lifetimes (on the order of 10^{-12} seconds). At high momentum, long lifetime translates to decay lengths on the order of a millimeter. The Silicon Vertex Tracker (SVT) is a hardware based tracking system that is able to quickly and efficiently identify displaced vertices. The SVT tracks used in this analysis have a transverse[3] momentum (p_T) greater than $2.0GeV$ and an impact parameter[4] (d_0) between $120\mu m$ and $1mm$.

4 Searching for $B_s^0 \leftrightarrow \overline{B_s^0}$ Oscillations

$B_s^0 \leftrightarrow \overline{B_s^0}$ mixing is quantified by the measurement of Δm_s. In order to extract the mass difference, three issues must be addressed; the reconstruction of the signal, the measurement of the B_s^0 decay time, and tagging the flavor of the B_s^0 at production.

4.1 Reconstructing the Signal

This study uses the μ+SVT sample which requires a muon with $p_T > 4.0$ and a displaced (SVT) track. We assume that in the original interaction, b quarks are made in quark-antiquark pairs which combine into different hadrons. The charge of the muon is used to determine whether a b (positive muon) or a $\bar{b}$ quark is produced on one side. On the opposite side, we reconstruct the B_s^0 or $\overline{B_s^0}$ in the channel,

$$B_s^0 \to D_s^- X(D_s^- \to \phi\pi^-, \phi \to K^+K^-).$$

Where X represents at least one extra track. A cartoon of the decay is shown in Figure 2. This analysis uses approximately $220pb^{-1}$ of data collected from CDF run II. First, general quality cuts are made on track direction, track quality, and momentum. Next, the D_s mass peak is reconstructed. After fitting the signal with a Gaussian, and the background with a linear function, we see a signal of 452 ± 55 events (see Figure 3). At this stage, the signal-to-background (S:B) is about $1:5$. It is expected that the S:B will improve considerably when we understand the backgrounds more completely.

Several distinct processes contribute to the peak in Figure 3. The width of the peak is determined by the intrinsic mass resolution of CDF. There are also a large number of background events polluting our $B_s^0 \to D_s\,\pi$ signal. A complete study of the background

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[3] The transverse plane is perpendicular to the z-axis which is parallel to the Tevatron beam.

[4] The impact parameter is defined as the distance of closest approach to the beam-spot

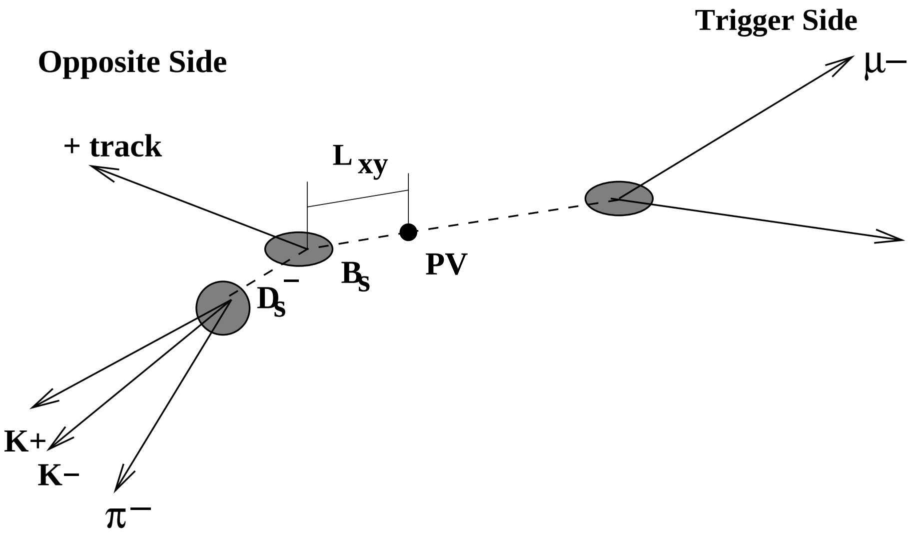

Figure 2: A cartoon of the reconstructed decay. PV is the primary vertex. On one side, a $\overline{B_s^0}$ decays to a lepton. On the opposite side, B_s^0 decays to a D_s and at least one charged track.

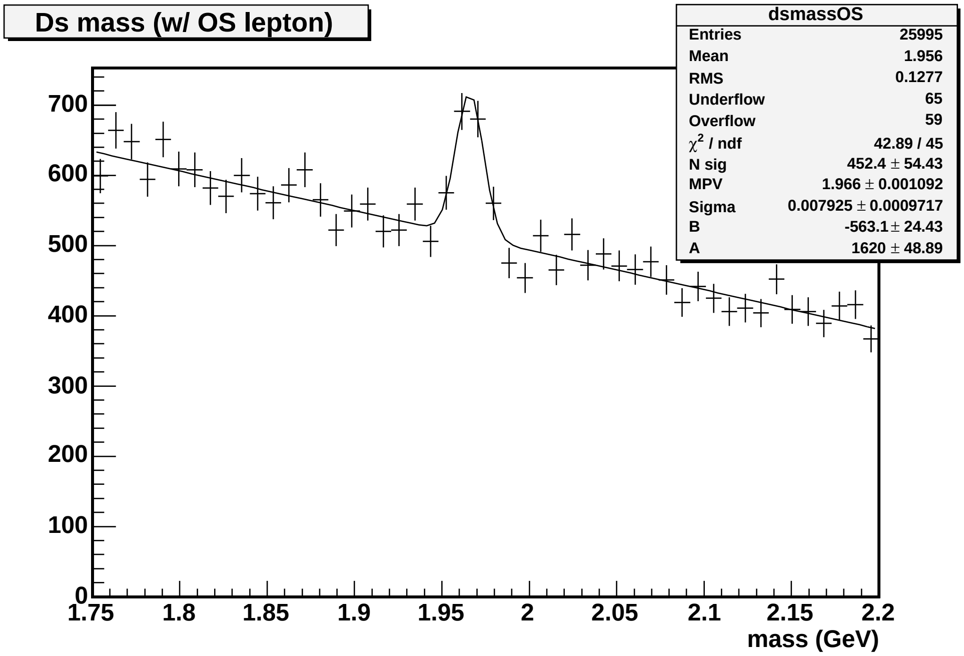

Figure 3: D_s mass peak. Signal is fit with a Gaussian with a linear background.

remains to be done, but we expect that prompt charm production, $B^0 \rightarrow DD_s$, and $B_s^0 \rightarrow DD_s$ will all contribute significantly. Decays from $\Lambda_b \rightarrow \Lambda_c D_s$ are also expected to populate the background.

Prompt charm is produced when a pair of charm quarks, created in the primary interaction, form D mesons. The decay of a prompt D_s will be reconstructed, but since it was not parented by a B_s^0 , it will pollute the signal (see Figure 4i). The $B^0 \rightarrow DD_s$ and $\Lambda_b \rightarrow \Lambda_c D_s$ decays are a similar problem. Another background is $B_s^0 \rightarrow DD_s$. Although the D_s comes from a B_s^0 , the extra charmed meson in the event will cause us to mis-tag the decay flavor (Figure 4ii).

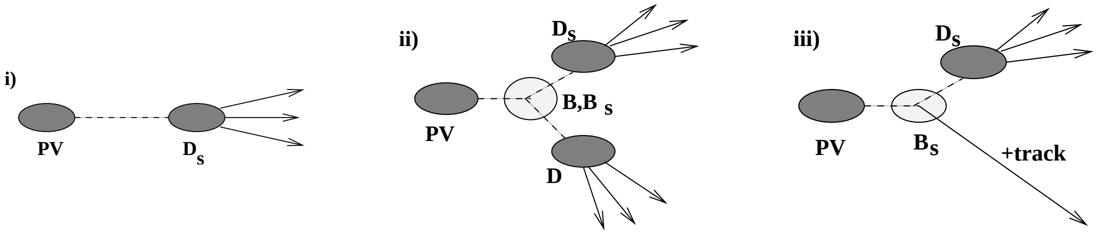

Figure 4: Possible topologies for expected background and signal events. *i*) illustrates the decay from prompt charm production. *ii*) shows the $B/B_s^0 \rightarrow D_s\, D$ background decay. *iii*) shows what we expect for the $B_s^0 \rightarrow D_s\, X$ signal.

We hope to be able to suppress these backgrounds by examining the topology of each event. In our signal, the B_s^0 decay vertex can be estimated by intersecting the best track, whose sign is opposite that of the D_s, with the B_s^0 trajectory (Figure 4iii). Background events will also have a D_s vertex but might be missing a charged track from B_s^0 decay or might include another charm vertex. After suppressing the background, we hope to be left with a large number of signal events, $B_s^0 \rightarrow D_s\, \pi$, and a large S:B in order to maximize our sensitivity to Δm_s as discussed in section 4.4

4.2 Measuring the B_s^0 Decay Time

In order to measure the decay time(t) in the rest frame of the B_s^0 , it is important to understand the absolute length, and momentum scales of the CDF detector. The proper time is given by

$$t = \frac{L_{xy} M_{Bs}}{p_T}$$

where L_{xy} is the decay length and M_{Bs} is the B_s^0 mass. We measure the absolute length and momentum resolutions of CDF by studying decays that are already well understood. σ_{Lxy} was recently measured at CDF to be $50 \mu m$[3] by using a $B_s^0 \rightarrow D_s\, \pi$ sample. The proper time resolution depends on our ability to accurately measure the B_s^0 momentum. In order to do this well, a deeper understanding of our sample composition is required. For this analysis, reasonable estimates for the proper time resolution (σ_t) are between 50 and 100 fs [4].

4.3 Determining the B Flavor at Production

The effectiveness of flavor tags are generally quantified in terms of ϵD^2. ϵ is the efficiency of the tag or the fraction of events that are possible to tag. Since the muon is used to tag the production flavor, and our μ + SVT data set guarantees that each event has a tag-able muon, the efficiency is 1. The Dilution, D, describes the fraction of correctly tagged events.

$$D = 2P_{correct} - 1$$

where $P_{correct}$ is the probability for a correct tag[5] A careful measurement of D still remains to be done but a conservative estimate is $D = 0.55$. We therefore expect

$$\epsilon D^2 = 1 \times (0.55)^2 = 0.3.$$

4.4 Extracting Δm_s

There are many possibilities for extracting Δm_s from the analysis. All of the options will require extensive testing with Monte Carlo data samples before applying the technique to the real data. However, using the above estimates and the current D_s mass signal, we can calculate the sensitivity to the measurement of Δm_s. The sensitivity can be described in terms of the statistical significance of our measurement. Statistical significance is measured in units of standard deviation and describes the probability that the result is not merely due to chance. For example, a measurement with a significance of 4, or 4 σ, only has a 0.0001% chance of being a fluctuation. The expected significance for this study is given by

$$Significance(\Delta m_s) = \sqrt{\frac{S\epsilon D^2}{2}} \cdot e^{-\frac{1}{2}(\Delta m_s \sigma_t)^2} \cdot \sqrt{\frac{S}{S+B}}$$

where S and B are the number of signal and background events respectively. Using $\epsilon D^2 = 0.3$ and values of $\sigma_t = 50$ and 100 fs as estimates of the flavor tag quality and proper time resolution, we plot the significance of Δm_s as a function of Δm_s in Figure 5. The current signal is represented by the solid curve. Other curves predict the significance for improved S:B and larger signals. Much of the work required to actually measure Δm_s remains to be done. The calculated sensitivity represents an optimistic upper-limit for the capabilities of this analysis.

By comparing the panels in Figure 5, we see that good proper time resolution is critical to a successful measurement of Δm_s. The resolution not only depends on detector performance but on the type of B_s^0 decay we are able to reconstruct. Work to understand the proper time resolution for this analysis is on-going, however the estimated sensitivity is encouraging. The study suggests that with improvements in signal to background and more data, we will be able to make a competitive measurement of Δm_s.

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[5] Dilution is defined on the range, $0 \leq D \leq 1$. A perfect tag ($P_{correct} = 1$) will yield a dilution of 1. A completely random tag ($P_{correct} = 0.5$) drives the dilution to zero.

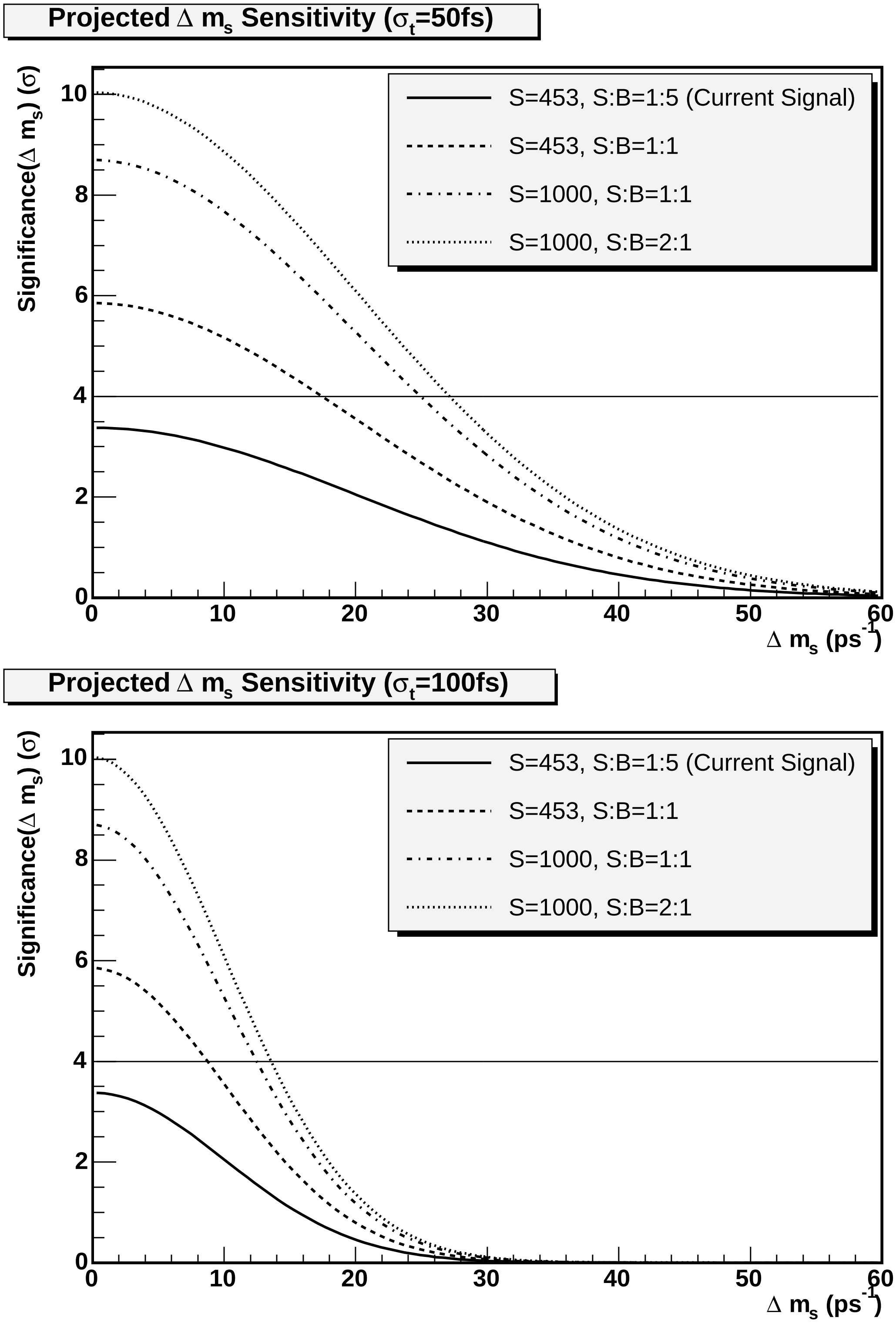

Figure 5: Significance of Δm_s as a function of Δm_s. The effect of proper time resolution can be seen in the two plots. In the top panel, $\sigma_t = 50$fs while $\sigma_t = 100$fs in the lower. In both panels, the solid curve represents the current signal of 453 events with S:B=0.2. Also shown are estimates for increased luminosity and improvements in S:B. The horizontal line shows a significance of 4σ.

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