Searching for CP Violation

In semileptonic B_s^0 decays

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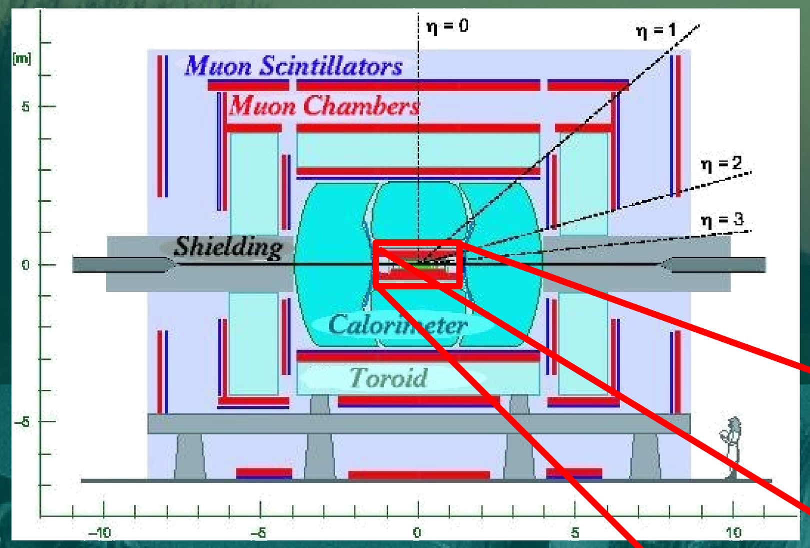
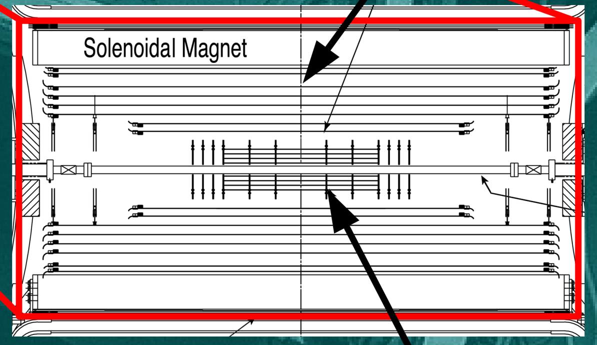
The D0 Detector



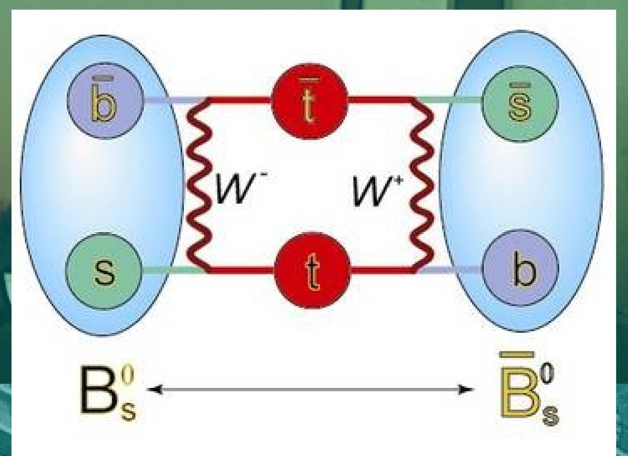
The D0 detector is a typical example of a collider detector, with tracking, calorimetry and muon systems. For this analysis, we make extensive use of the tracking and muon systems, but only limited use of the calorimeter.

The tracking system is composed of an inner silicon detector and a scintillating fiber tracker within a 2T solenoid field. The tracking system provides momenta determination and vertexing for the B_s^0 and $D_s^{\pm}$ decays (see the decay below).



The muon system is composed of three layers of scintillator tiles and drift tube detectors. A toroid between the 1st and 2nd layers curves the muon tracks aiding in momentum determination. Hits in the muon layers are used to trigger the detector. The toroid polarity is reversed on a regular basis allowing the determination of the detector asymmetry separate from the CP asymmetry.

Flavour Oscillations in B_s^0 Mesons

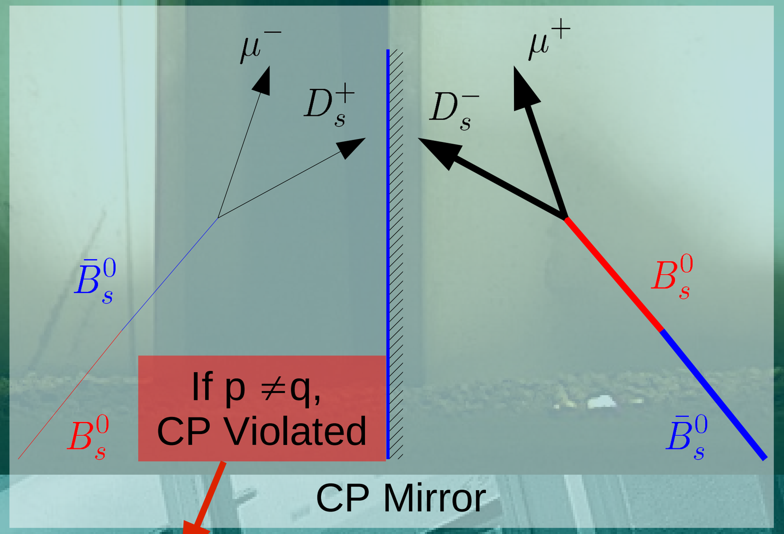


All Flavoured Neutral mesons 'mix' with their anti-partners. These flavour transitions mean that the flavour states B_s^0 and $\bar{B}_s^0$ are not eigenstates of the Hamiltonian:

$$i\frac{d}{dt}\begin{pmatrix}|B(t)\rangle\\|\bar{B}(t)\rangle\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix}|B(t)\rangle\\|\bar{B}(t)\rangle\end{pmatrix}$$

The eigenstates are superpositions of the flavour states with mass/lifetime M_H/Γ_H and M_L/Γ_L:

$$|B_H\rangle = p|B\rangle - q|\bar{B}\rangle$$
$$|B_L\rangle = p|B\rangle + q|\bar{B}\rangle$$



The parameters p, q describe the mass (CP) eigenstates in relation to the flavour states. In the event that $|p|\neq|q|$, $|B_H\rangle$ and $|B_L\rangle$ are not orthogonal, and CP is broken.

Solving for the time dependence of the system, the CP violation manifests as a difference in the mixed decay rate for B_s^0 / $\bar{B}_s^0$. That is, the mixing prefers to go in one direction or the other.

Decay Rates

$$\Gamma(B_s^0 \to \bar{B}_s^0)(t) = \left|\frac{q}{p}\right|^2 \frac{e^{-\Gamma_s t}}{2}\left(\cosh\frac{\Delta\Gamma_s t}{2} - \cos\Delta m_s t\right)$$
$$\Gamma(\bar{B}_s^0 \to B_s^0)(t) = \left|\frac{p}{q}\right|^2 \frac{e^{-\Gamma_s t}}{2}\left(\cosh\frac{\Delta\Gamma_s t}{2} - \cos\Delta m_s t\right)$$

$$\Delta m_s = M_H - M_L \quad \Delta\Gamma_s = \Gamma_H - \Gamma_L \quad \Gamma_s = \frac{\Gamma_H + \Gamma_L}{2}$$

Define a decay rate asymmetry:

$$a_{sl}(t) = \frac{\Gamma(B_s^0 \to \bar{B}_s^0) - \Gamma(\bar{B}_s^0 \to B_s^0)}{\Gamma(B_s^0 \to \bar{B}_s^0) + \Gamma(\bar{B}_s^0 \to B_s^0)}$$

This asymmetry is the quantity that we seek to measure.

Fitting Procedure:

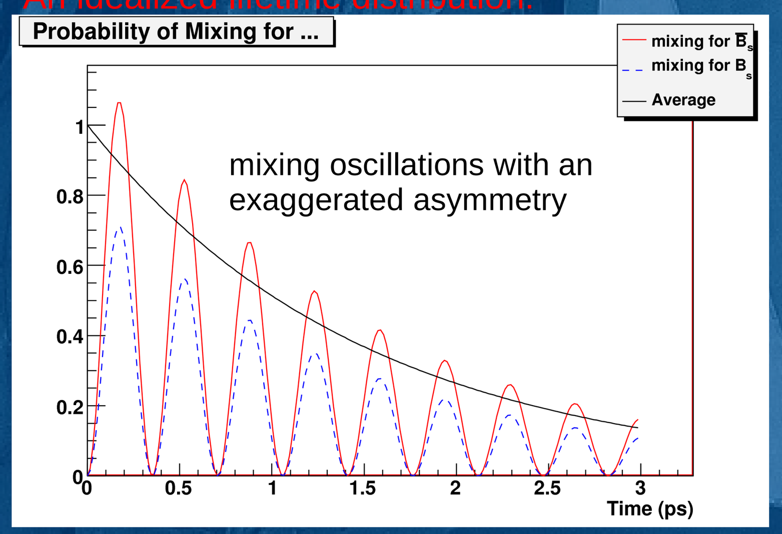
The asymmetry is defined as a function of the decay rate, however, we could alternatively define the decay rate (or lifetime distribution) as a function of the asymmetry. It can be shown that the asymmetry is constant in time, so we define the lifetime distribution function in terms of a semileptonic B_s asymmetry parameter (A_{sl}^s).

$$\Gamma(t) = (1 \pm \delta A_{sl}^s)e^{-\Gamma t}(\cosh\Delta\Gamma_s t/2 \pm \cos\Delta m_s t)$$

The signs on A_{sl}^s and the cosine depend on the charge of the muon and btag. δ is zero if the charges are opposite.

The basic idea is to fit to the lifetime distribution to extract the asymmetry parameter. The problem is complicated by our inability to isolate the mixed decays. Most events lack a btag, and those that have one are often of low confidence. The presence of unmixed decays in the data sample will dilute the asymmetry and must be accounted for. Furthermore, this introduces a time dependence in the measured asymmetry.

An idealized lifetime distribution:

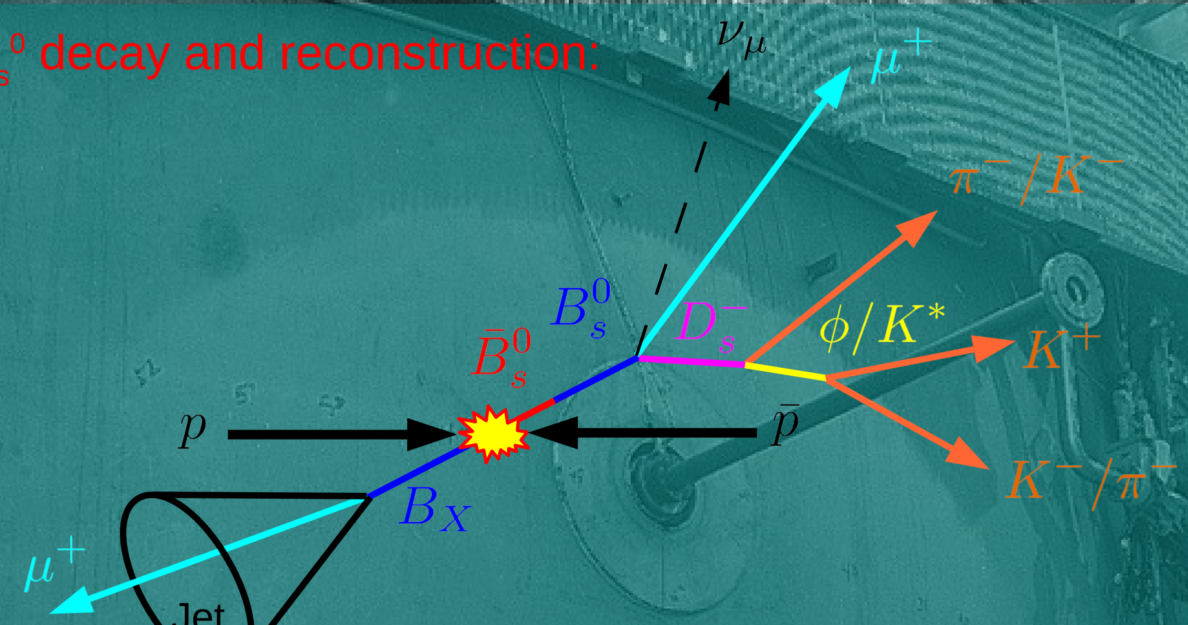


The problem is further complicated when background sources are considered. The B^0 and B^+ decay to similar (or identical) final states and have their own asymmetries. $D^- \to K\pi\pi$ decays may be mistakenly identified as $KK\pi$ and assigned a D_s^- mass (see mass plot at far right). To discriminate against these backgrounds, additional probability functions are included in the fit function. These functions must be determined independently before the fit to extract the asymmetry.

$$\text{Fit Func} = \Gamma(t, A_{sl}^s) \otimes P(\text{resolution}) \times P(\text{mass}) \times P(\text{others})$$

And finally, in order to model the lifetime distribution correctly, we must also consider the resolution (or uncertainty) in the lifetime. The resolution is determined event by event, and has the effect of 'smearing' the oscillations in the lifetime distribution. The Gaussian resolution function is convoluted with the lifetime distribution.

B_s^0 decay and reconstruction



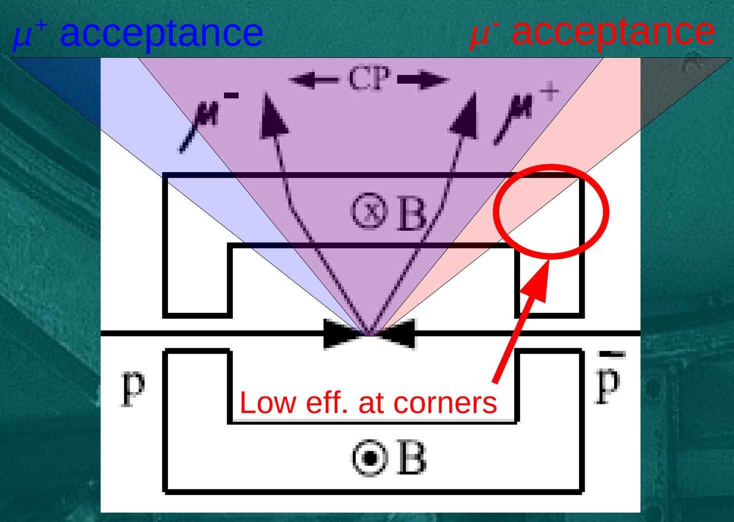
The $p\bar{p}$ collision creates a $b\bar{b}$ pair, the hadronization process is uncorrelated for the two quarks resulting in a $\bar{B}_s^0$ and some other B hadron (B_X). In this example the $\bar{B}_s^0$ oscillates into a B_s^0 and then decays. The actual oscillation frequency is much higher, the B_s will typically oscillate several times before decaying. The charge of the muon from this decay indicates the final state B_s flavour.

On the other side of the detector, the B_x decays to a jet and (possibly) a lepton. The charge of this lepton (or jet) indicates the flavour of the B hadron on this side, and hence the initial flavour on the side we are interested in. In short, a pair of like charge muons indicates a B_s^0 decaying in an oscillated state. The charge from the opposite side decay is referred to as the btag.

We consider two D_s^- decay channels:

$$D_s^- \to \phi(K^+K^-)\pi^-$$
$$D_s^- \to K^{*0}(K^+\pi^-)K^-$$

The final states are the same, but the different intermediate state (ϕ/K*) have different backgrounds and must be treated differently.

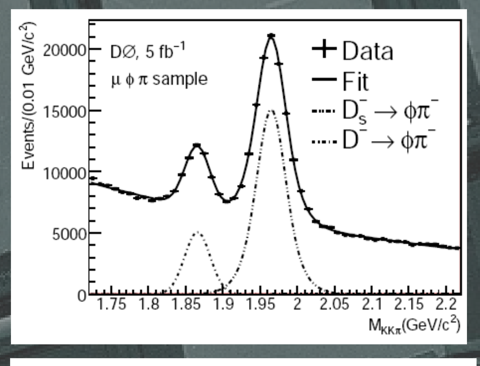


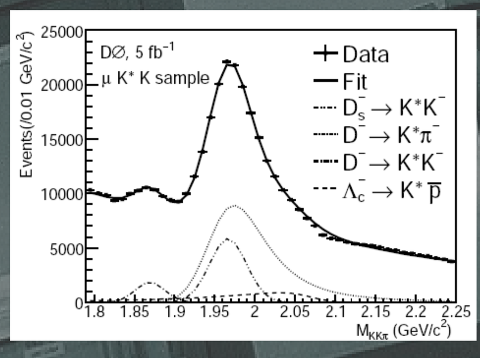
Detector Asymmetry

Muons bend in the toroid towards/away from the beam axis. However, corner regions of the muon system have lower efficiency. This introduces a muon asymmetry due to different acceptance for muons depending on direction, charge and toroid polartity. The toroid polarity is reversed regularily, so we can measure this contribution to the asymmetry.

Results:

These plots show the mass distribution of the D_s^- candidate in the two decay channels. In addition to the signal $D_s^- \to K^+K^-\pi^-$ decay, there are other peaks from a variety of sources. The D^- peaks and the exponential background are assigned their own asymmetry parameters which are fitted with the signal asymmetry.





The final fit for the asymmetry is a loglikelihood fit. The fits are done independently for each channel and again with the two samples combined.

	$\mu^+\phi\pi^-$	$\mu^+K^{*0}K^-$	Combined
$a_{fs}^s \times 10^3$	-7.0 ± 9.9	20.3 ± 24.9	-1.7 ± 9.1
$a_{fs}^d \times 10^3$	-21.4 ± 36.3	50.1 ± 19.5	40.5 ± 16.5
$a_{bg} \times 10^3$	-2.2 ± 10.6	-0.1 ± 13.5	-3.1 ± 8.3
$A_{fb} \times 10^3$	-1.8 ± 1.5	-2.0 ± 1.5	-1.9 ± 1.1
$A_{det} \times 10^3$	3.2 ± 1.5	3.1 ± 1.5	3.1 ± 1.1
$A_{ro} \times 10^3$	-36.7 ± 1.5	-30.2 ± 1.5	-33.3 ± 1.1
$A_{\beta\gamma} \times 10^3$	1.1 ± 1.5	0.2 ± 1.5	0.6 ± 1.1
$A_{q\beta} \times 10^3$	4.3 ± 1.5	2.0 ± 1.5	3.1 ± 1.1

Detector asymmetries

The weak phase ϕ_s is the 'real' CP violating parameter in the SM. Asymmetry measurements constrain this parameter:

$$A_{sl}^s = \frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$$

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Already included in the HFAG world average: