pp physics, RWTH, WS 2003/04, T.Hebbeker

2004-01-15

In the following some selected physics topics will be presented.

2.1. Bottom physics

References:
- CERN yellow report CERN 2000-004, G. Altarelli and M.L. Mangano (editors), ‘Proceedings of the workshop on standard model physics (and more) at the LHC’
- M. Paulini, ‘B Lifetimes, Mixing and CP Violation at CDF’, Int. J. Mod. Phys. A14, 2791 (1999)

Bottom Physics (= b physics) at p p colliders can serve two purposes:
a) exploration of the properties of b quarks and b hadrons
b) using b final states to identify particles as top quarks or higgs bosons.

We concentrate here on the first aspect.

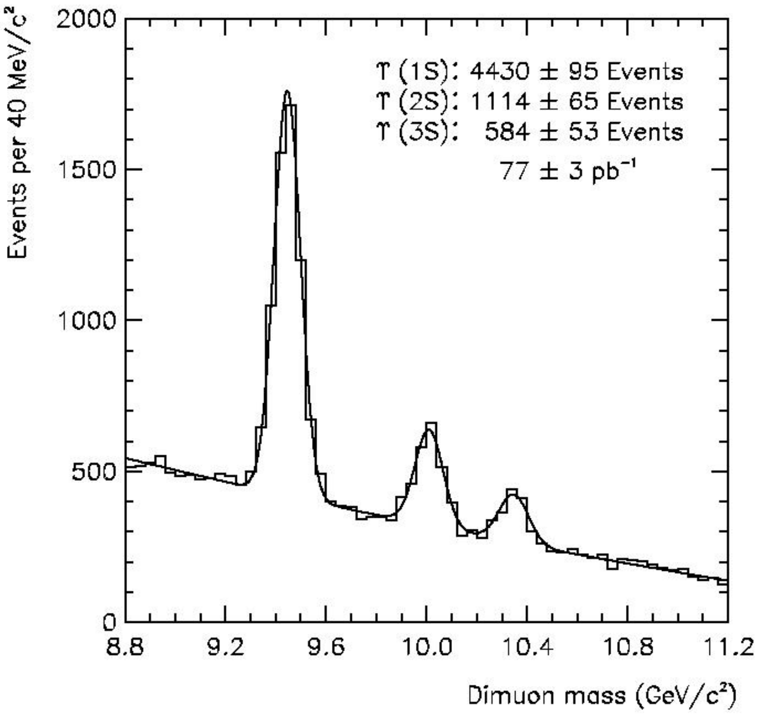
2.1.1 b hadrons and b jets

Sometimes it is possible to identify the b hadron explicitly (full reconstruction), in other cases ‘only’ the jet containing the b can be identified (e.g. via a secondary vertex); of course the two methods don’t exclude each other.

2.1.1.1 b hadrons

- The Upsilon particles Υ contain a $b\bar{b}$ pair with parallel spins. Since they are short lived (elm. and strong decays, $\Gamma > 25\,\mathrm{keV}, c\,\tau < 10^{-11}\,\mathrm{m}$), a secondary vertex is not measurable; these states can be identified via their leptonic decays ($\mathrm{Br}(\Upsilon(1s) \rightarrow l^+l^-) = 2.5\%$). Similar arguments hold for the χ_b states (spins antiparallel).

  Υ production has been seen in CDF and D0. The CDF $\mu^+\mu^-$ invariant mass peaks at $1.8\,\mathrm{TeV}$ are shown here:



- Hadrons with ‘open’ bottom quantum numbers are either mesons or baryons. The mesons can contain - apart from the b - a light quark (u,d), or a quark from the second family (s,c), which is indicated by a subscript, e.g. B_s^0. b hadrons are produced in their ground state or in excited states, labelled B^* or B^{**}. In their ground state they decay weakly and ‘profit’ from the smallness of the CKM matrix elements V_{ub}, V_{cb}, such that their lifetime is rather long ($\sim$ 1ps), translating into decay lengths of a few mm. The following table[1] summarizes the properties of some b hadrons.

state	J^P	mass/GeV	τ/ps	quarks	decay (BR) [example!]
B^+	0^-	5.2790 ± 0.0005	1.674 ± 0.018	$u\bar{b}$	$\overline{D^0}\, l^+\, \nu(10\%)$
$B^0 \equiv B_d^0$	0^-	5.2794 ± 0.0005	1.542 ± 0.016	$d\bar{b}$	$D^-\, l^+\, \nu(2\%)$
B_s^0	0^-	5.369 ± 0.0024	1.461 ± 0.057	$s\bar{b}$	$D_s^-\, l^+\, \nu(8\%)$
B_c	0^-	6.4 ± 0.4	0.47 ± 0.17	$c\bar{b}$	$J/\Psi\, l^+\, \nu\, X(\ll 1\%)$
Λ_b	$\frac{1}{2}^+$	5.624 ± 0.009	1.29 ± 0.080	udb	$\Lambda_c\, l^-\, \bar{\nu}(8\%)$

A B^{**} analysis result from D0 is shown here:

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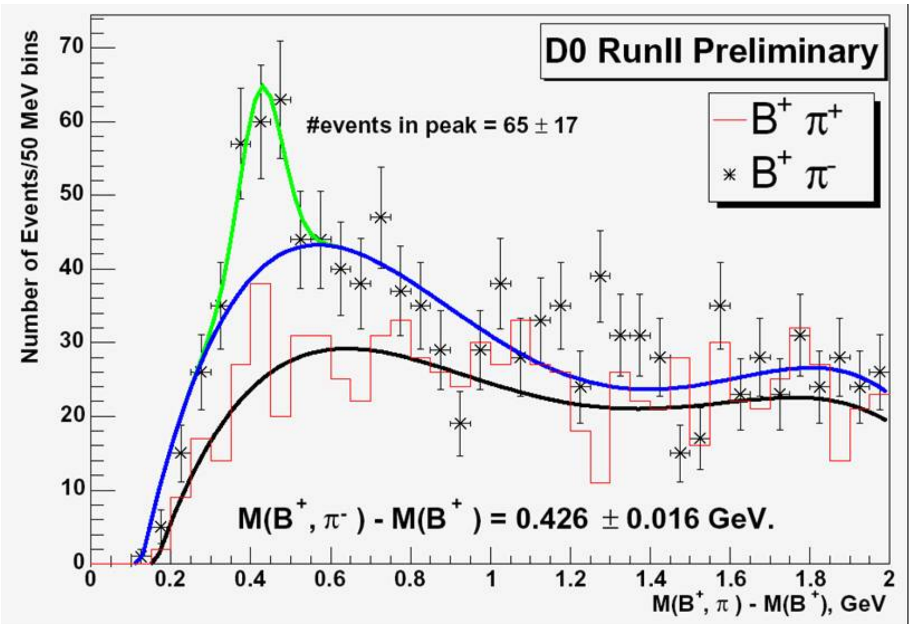
[1] Note: For the neutral B mesons mixing has to be taken into account, see below.



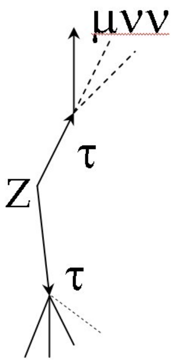
The neutral B_d^{**} decays strongly into $B^+\,\pi^-$. Its mass is measured (see plot) to $5.710 \pm 0.016\,\mathrm{GeV}$. The B^+ can be reconstructed e.g. via its decay $J/\Psi\,K^+$. Instead of plotting the invariant mass constructed from all decay products of the B_d^{**}, a more precise mass determination can be obtained from the difference $m(B_d^{**}) - m(B^+)$, since here the measurement errors drop out to a large extent! B^* mesons are spin-1 particles with zero orbital momentum and the two (anti)quark spins aligned. B^{**} denotes spin-1 mesons with orbital momentum 1 (p-wave) - however spin and quantum numbers have not yet been measured for the B_d^{**}, which was observed also at LEP and by CDF.

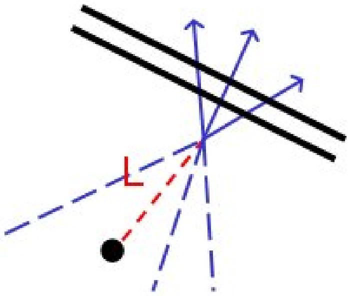
2.1.1.2 b jets

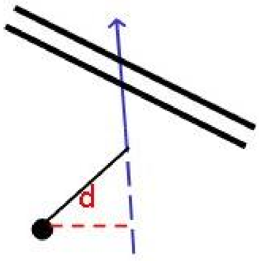
A b-jet can be identified by (a combination of) the following signatures, in decreasing importance:

- lifetime / decay length / impact parameter
- lepton (from $B \longrightarrow l\,X$)
- jet topology (slightly fatter than for light quarks)

We will briefly discuss the lifetime tag. There are two possibilities:



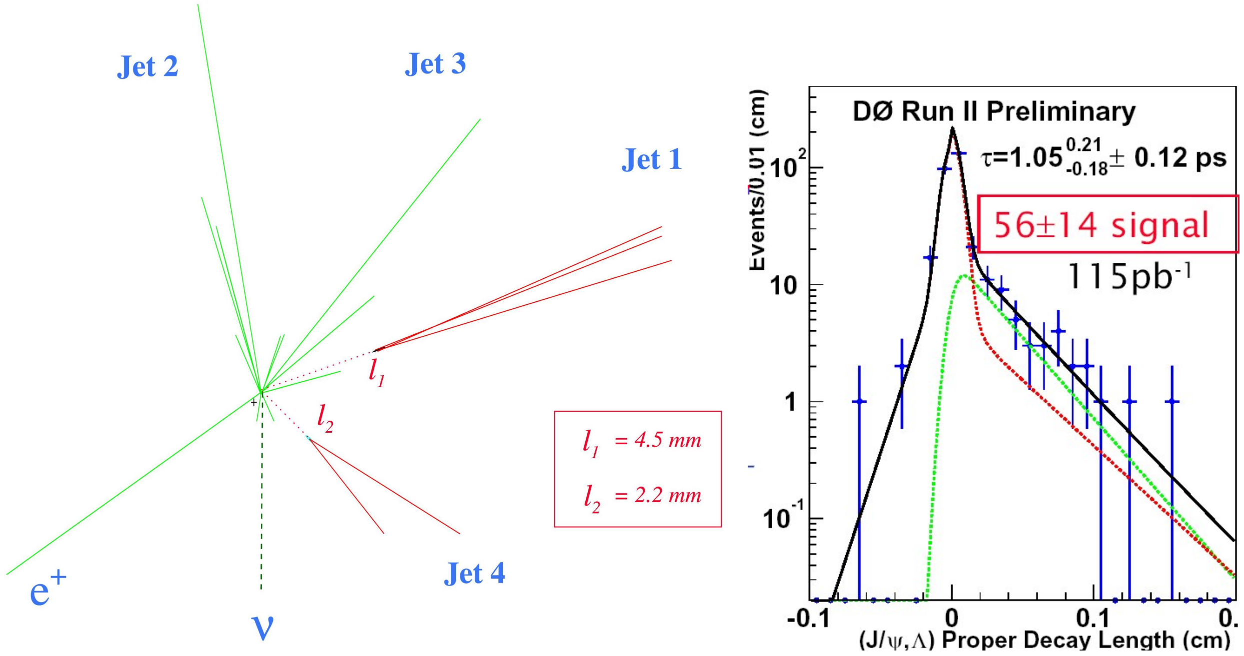




- decay length method
  If several tracks of the final state can be reconstructed, the decay path
  $$L = t\gamma\beta \approx t\,\frac{E}{m} \tag{1}$$
  can be measured. E is the energy of the decaying particle, m its mass and t its lifetime. We assume $\beta \longrightarrow 1$.

- impact parameter (= distance of closest approach) method
  A single track that does not pass through the primary vertex indicates the decay of a long lived particle. For a relativistic particle the distance of closest approach is given by
  $$d \sim L \cdot \frac{p_s^*}{p} \sim L \cdot const\,\frac{m}{p} = const \cdot t \tag{2}$$
  p_s^* is the momentum of the daughter particle in the rest frame of the mother particle. Note that d is independent of the energy E of the decaying particle!

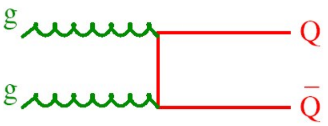
Examples:

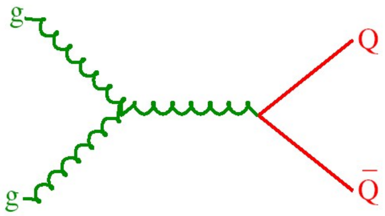


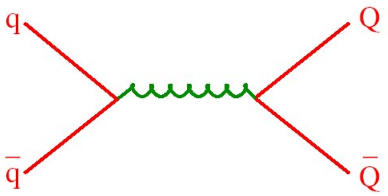
The CDF event (figure, left) shows a top candidate from run I. The Λ_b (figure, right) was reconstructed via $\Lambda_b \longrightarrow J/\Psi\ \Lambda \longrightarrow \mu^+\mu^-\ p\pi$.

2.1.2 bottom production

In most cases a $b\bar{b}$ is produced, in particular via strong processes like



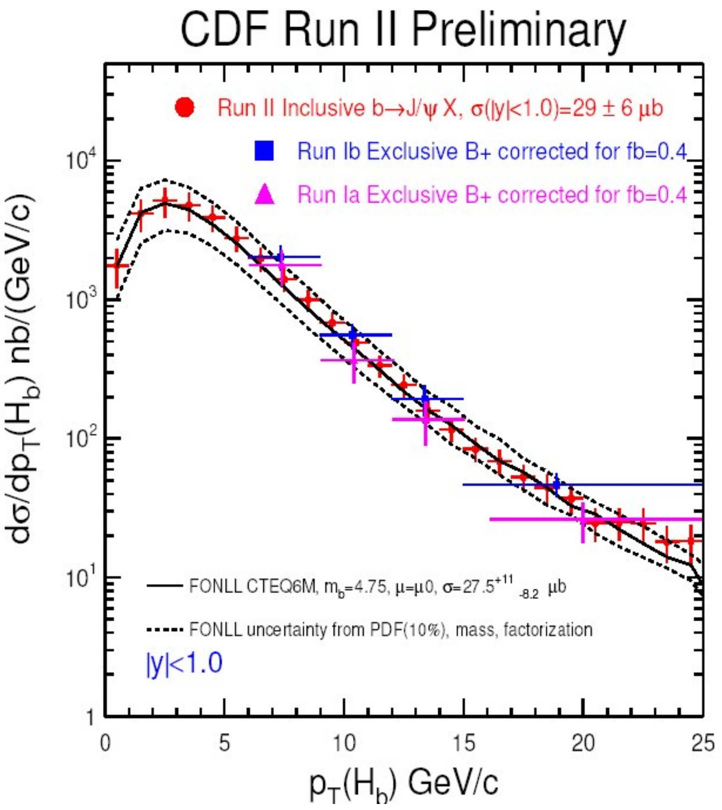




Two b quarks can also arise from $t\bar{t}$ or Z decays. Single b quark production (e.g. via $W^* \to t\bar{b}$) is rare.

In the following we consider only direct pair production. Note that in pp collsions the final state will always contain additional hadrons (beyond the two B particles), so that the two B hadrons are **NOT** ‘entangled’[2].

The cross section for inclusive b production is large, $\sim 10\mu\mathrm{b}$ at the SPS, $\sim 50\mu\mathrm{b}$ at the Tevatron and even larger at the LHC. These numbers should be compared to the exclusive $\Upsilon(4s)$ cross section in e^+e^- machines (1 nb) and the b xsection on the Z resonance (7 nb).



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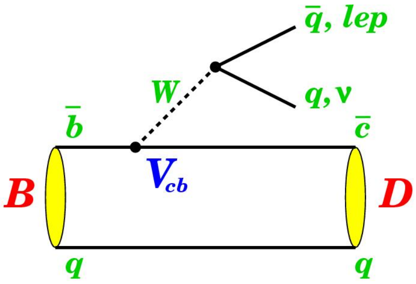
[2] This is different for $e^+e^- \to \Upsilon(4s) \to BB$

There is good agreement between QCD predictions[3] and CDF measurements[4].

2.1.3 B decays

Many lifetimes and branching fractions have already been measured and fill the tables of the Particle Data Book. Most decay modes can be described by a simple ‘spectator’ diagram as shown here:

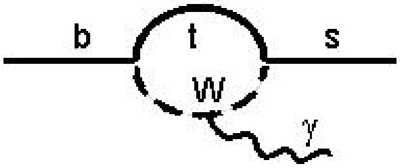


More interesting are ‘rare decays’, which are sensitive to ‘small’ CKM matrix elements and/or ‘new physics’.

We present two examples:

2.1.3.1 $b \longrightarrow s\,\gamma$

A direct $b \longrightarrow s$ transition via Z exchange is not possible (unitarity of CKM quark mixing matrix). Such a a Flavor Changing Neutral Current (FCNC) can be accomplished through higer order ‘penguin diagrams’ such as



Note that the γ (or a gluon) is needed for 4-momentum conservation. This process is interesting since it allows the determination of the small matrix element $|V_{ts}|$ and/or to set limits on new particles like charged higgs bosons, which would also contribute (same diagram with $W^+ \longrightarrow H^+$).

The $BR(B \longrightarrow K^*\gamma)$ has been measured[5] already in 1993 to $\sim 5 \cdot 10^{-5}$ by the CLEO collaboration at the $\Upsilon(4s)$ resonance. At the Tevatron so far only upper limits could be set, the most recent one is $< 1.4 \cdot 10^{-4}$ (95%) from the CDF experiment. The goal at LHC will be to reach a high statistical accuracy so that a precise determination of the corresponding branching fraction can be achieved.

In principle the same argument can be made for a V_{td} measurement through $b \longrightarrow d\gamma$ $(B \longrightarrow \rho\gamma)$, however theoretical uncertainties (QCD corrections) are large, so that the interpretation is difficult. Also, the branching fraction is smaller by $|V_{td}/V_{ts}|^2 = \mathcal{O}(0.01)$.

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[3] FONLL = Fixed Order next-to-leading order terms + Next-to-Leading-Log large-p_T resummation

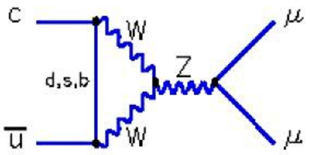
[4] this was not always the case - part of the differences could be traced down to the wrong use of a fragmentation model

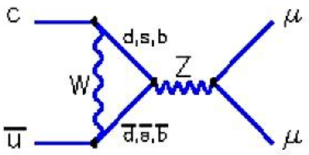
[5] note that the s in the final state combines with the ‘spectator quark’ d to form a K meson - which is in an excited state since the photon radiation has reversed the quark spin ($b \longrightarrow s$).

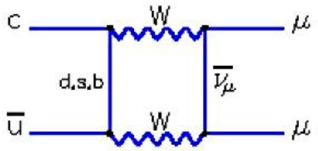
2.1.3.2 $B_s \rightarrow \mu^+\mu^-$

Neutral mesons (apart from the π^0) can - to first oder - not decay into a lepton-antilepton pair, since this would require a FCNC.

Higher oder diagrams make these decays possible, however with small branching fractions. Example $D^0 \rightarrow \mu^+\mu^-$:

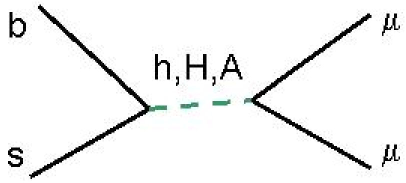






The SM prediction for the branching fraction $B_s \rightarrow \mu^+\mu^-$ is very small ($\sim 3 \cdot 10^{-9}$), and cannot be measured at the Tevatron, however it might be possible at the LHC. The dominant contribution is given by the heaviest virtual quark exchange (top). Since $BR(B_s \rightarrow \mu^+\mu^-)$ is proportional to $|V_{ts}|^2$ it is expected to be a factor of ~ 30 bigger than the corresponding BR for B_d decays.

However, in SUSY models this branching fraction can be enhanced by up to 3 orders of magnitude, through higgs mediated FCNC diagrams like this one:



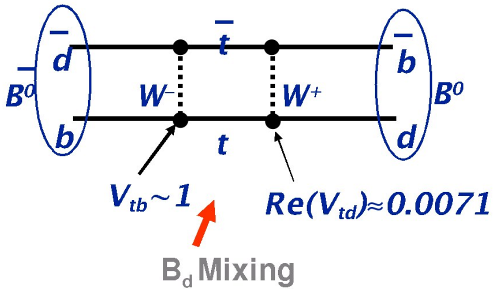
The BR grows with $\tan^6\beta$ (ratio of vacuum expectation values of higgs doublets)!

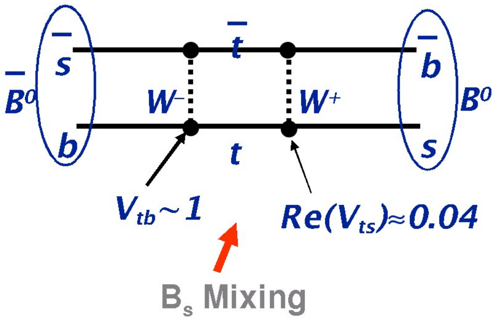
CDF has searched (in vain) for the this decay in the run II data and set the following upper limit:

$$BR(B_s \rightarrow \mu^+\mu^-) < 1.2 \cdot 10^{-6} \qquad (95\%\ CL) \tag{3}$$

2.1.4 B mixing

The neutral B mesons (both B^0 and B^0_s) can ‘mix’ and ‘oscillate’,





a phenomenon well known from the Kaon system and in principle also expected for neutral D mesons. It is a weak process changing s, c or b quantum numbers by ± 2.

Since this topic is one of the 'hot' ones at the Tevatron, we will discuss it in some detail here.

In the next sections we will assume that CP violation does not exist!

2.1.4.1 Phenomenology

Let's review first the neutral K sector with $K^0 = d\bar{s}$ and $\overline{K^0} = s\bar{d}$. Oscillations in the kaon system have been predicted by Gell-Mann and Pais in 1955; they were verified by several experiments (Brookhaven) in the following years.

The new neutral K mesons are neither C nor CP eigenstates[6]:

$$CP(K^0) = \overline{K^0} \qquad CP(\overline{K^0}) = K^0 \tag{4}$$

However, the neutral kaons are observed to decay (weakly) into CP eigenstates like $\pi\,\pi$ (+1) or $\pi\,\pi\,\pi$ (-1). So, at this moment the mother particle must be in a CP eigenstate. We can construct CP eigenstates as linear combinations:

$$K_1 \equiv K_s = \frac{1}{\sqrt{2}} \cdot (K^0 + \overline{K^0}) \qquad K_2 \equiv K_l = \frac{1}{\sqrt{2}} \cdot (K^0 - \overline{K^0}) \tag{5}$$

or

$$K^0 = \frac{1}{\sqrt{2}} (K_s + K_l) \qquad \overline{K^0} = \frac{1}{\sqrt{2}} (K_s - K_l) \tag{6}$$

Obviously:

$$CP(K_s) = +K_s \qquad CP(K_l) = -K_l \tag{7}$$

These two states have different masses and lifetimes/decay widths, which can be written in form of the dimensionless quantities

$$y = \frac{\Gamma_s - \Gamma_l}{2\,\Gamma} \qquad x = \frac{m_s - m_l}{\Gamma} \tag{8}$$

where $\Gamma = 0.5\,(\Gamma_s + \Gamma_l)$. The reason for relating $\Delta m = m_s - m_l$ to Γ in the definition of x will become clear soon (both Δm and Γ determine the time dependence). Note that while $|y| < 1$ no such constraint exists for x!

We can now apply the laws of quantum mechanics to calculate the time evolution of the kaon states. In their rest system the CP eigenstates have this time dependence:

$$K_i(t) = K_i(0) \cdot e^{-im_i t - \Gamma_i/2 \cdot t} \qquad \Gamma_i = 1/\tau_i \tag{9}$$

The mass = energy term (imaginary) describes the quantum mechanical oscillation of the phase, the part containing Γ (real) stands for the decay. The amplitude A for finding at proper time t a $\overline{\mathrm{K}^0}$ state in a beam containing only K^0 at $t = 0$ is given by

$$A_{\overline{K}^0}(t) \equiv \overline{\mathrm{K}^0}(t) = \frac{1}{\sqrt{2}} (\mathrm{K_s}(t) - \mathrm{K_l}(t)) \tag{10}$$

$$= \frac{1}{2} \mathrm{K}^0 \cdot \left(e^{-im_s t - \Gamma_s t/2} - e^{-im_l t - \Gamma_l t/2}\right) \tag{11}$$

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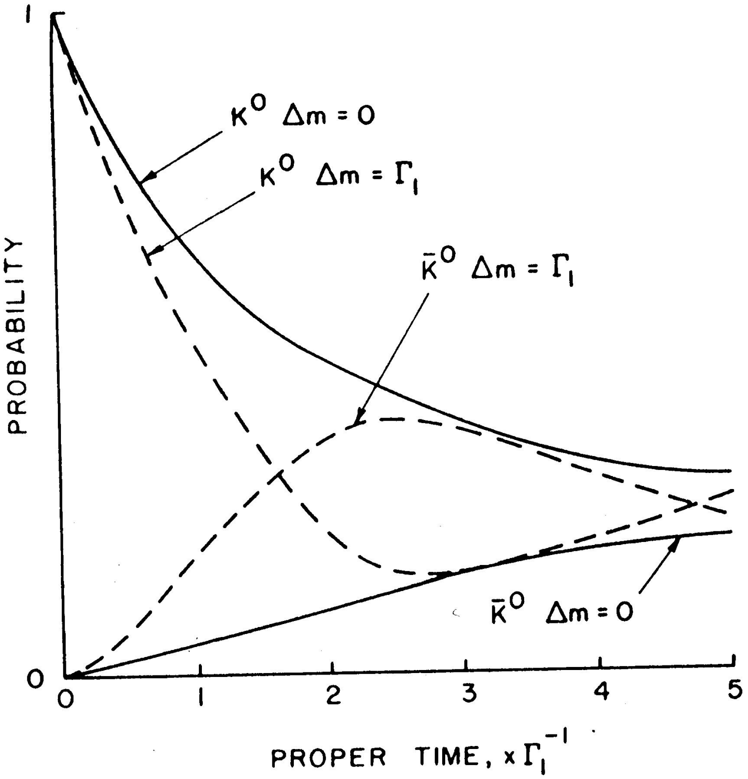
[6] sign is convention dependent

The corresponding probability $P = AA^*$ for finding a $\overline{K^0}$ at proper time t is thus

$$P_{\overline{K}^0}(t) \;=\; \frac{1}{4} \cdot \left(e^{-\Gamma_s t} + e^{-\Gamma_l t} - 2e^{-\Gamma t} \cdot \cos(\Delta m\; t)\right) \tag{12}$$

A similar formula describes the K^0 probability. Note that the sign of Δm cannot be measured this way[7]. The figure shows schematically the time evolution.



Experimentally, the states K^0 and $\overline{K^0}$ can be distinguished through their strong interactions or semileptonic decays. Result of those measurements (average over many experiments):

$$\tau(K_s) = 8.9 \cdot 10^{-11}\,\mathrm{s} \qquad \tau(K_l) = 5.2 \cdot 10^{-8}\,\mathrm{s} \tag{13}$$

$$m = 0.5\,(m_s + m_l) = 498\,\mathrm{MeV} \qquad \Delta m = 3.5 \cdot 10^{-6}\,\mathrm{eV} = 5.3 \cdot 10^9/\mathrm{s} \tag{14}$$

or

$$x = 0.95 \qquad y = 0.997 \tag{15}$$

Thus the mass difference is much smaller than the average mass, while the lifetime difference is huge! Therefore the CP eigenstates can be be distinguished best through their lifetimes (and not their masses!), the indices l and s mean ‘long’ and ‘short’. $x = \mathcal{O}(1)$ implies that the oscillation period and the decay time constant are of the same order of magnitude.

Now we turn to the neutral B sector, or, more precisely, the two sectors B_d and B_s. B_d^0 oscillations have been discovered 1986 by UA1 and the Argus $e^+e^- \longrightarrow \Upsilon(4s)$ experiment at DESY. The B_s

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[7] In K system: from regeneration experiments, in B system: so far only from theory.

oscillations, which occur ‘faster’ and are more difficult to measure, have not been observed yet. The CP eigenstates are named $B_1 = B_L, B_2 = B_H$.

In principle the phenomenology is the same as for the kaon sector - just the numbers are quite different! B^0_d sector:

$$\tau_d = 1.54 \cdot 10^{-12}\,\mathrm{s} \tag{16}$$

$$m_d = 5280\,\mathrm{MeV} \qquad \Delta m_d = 3.2 \cdot 10^{-4}\,\mathrm{eV} = 4.9 \cdot 10^{11}/\mathrm{s} \tag{17}$$

or

$$x_d = 0.76 \tag{18}$$

So far the lifetime difference could not be measured, experimental upper limits ($y < 0.4$) are crude. Theoretical expectations are of the order of $y \sim 0.01$. The mass difference is still small compared to the absolute mass, but the oscillation curve (12) is now dominated by the Δm term since $y \to 0$. Therefore, we distinguish the B^0 CP eigenstates by their mass and call them ‘Heavy’ (H) and ‘Light’ (L).

For the B^0_s system only lower limits on Δm_s and $x \equiv x_s$ exist:

$$\tau_s = 1.46 \cdot 10^{-12}\,\mathrm{s} \tag{19}$$

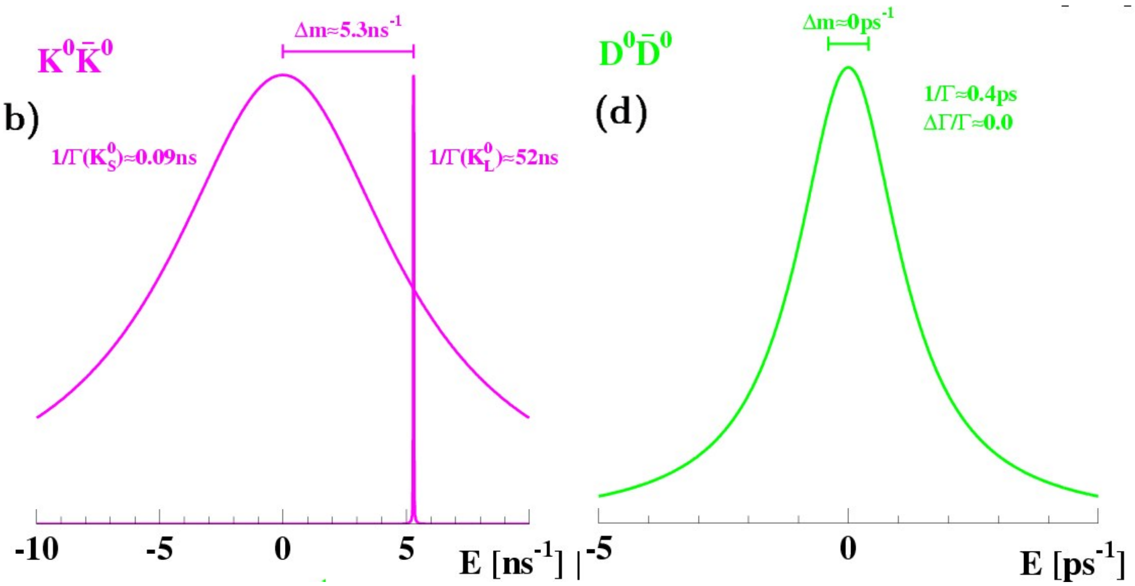
$$m_s = 5370\,\mathrm{MeV} \qquad \Delta m_s > 8.6 \cdot 10^{-3}\,\mathrm{eV} = 1.3 \cdot 10^{13}/\mathrm{s} \tag{20}$$

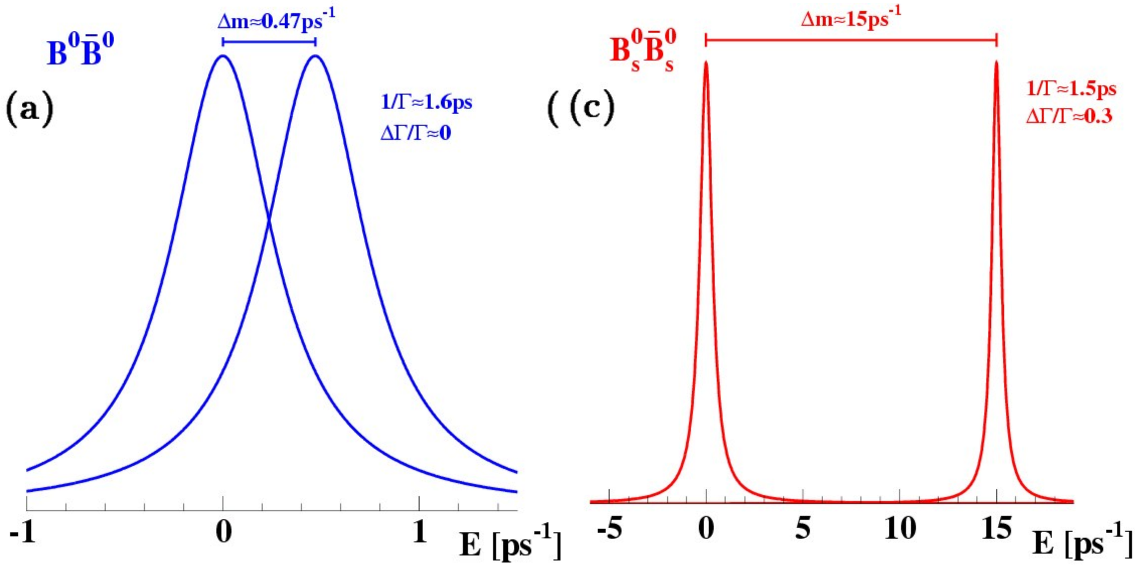
or

$$x_s > 19 \quad (95\% CL) \tag{21}$$

Again, the lifetime difference is unknown. Theory predicts $y \sim 0.1$. New: Here the oscillation period is much shorter than the decay time, thus it will be possible to observe several oscillations before the B_s decays!

A nice graphical comparison (from Paulini) of the different neutral meson systems is shown here:




$B^0\bar{B}^0$
(a)
$\Delta m \approx 0.47 ps^{-1}$
$1/\Gamma \approx 1.6 ps$
$\Delta\Gamma/\Gamma \approx 0$
-1
0
1
E [ps^{-1}]
$B_s^0\bar{B}_s^0$
((c)
$\Delta m \approx 15 ps^{-1}$
$1/\Gamma \approx 1.5 ps$
$\Delta\Gamma/\Gamma \approx 0.3$
-5
0
5
10
15
E [ps^{-1}]