Hadronization, spin and lifetimes

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ABSTRACT: Measurements of lifetimes can be done in two ways. For very short lived particles, the width can be measured. For long lived ones, the lifetime can be directly measured, for example, using a displaced vertex. Practically, the lifetime cannot be extracted for particles with intermediate lifetimes. We show that for such cases information about the lifetime can be extracted for heavy colored particles that can be produced with known polarization. For example, a t-like particle with intermediate lifetime hadronizes into a superposition of the lowest two hadronic states, T^* and T (the equivalent of B^* and B). Depolarization effects are governed by time scales that are much longer than the hadronization time scale, $\Lambda_{\mathrm{QCD}}^{-1}$. After a time of order $1/\Delta m$, with $\Delta m \equiv m(T^*) - m(T)$, half of the initial polarization is lost. The polarization is totally lost after a time of order $1/\Gamma_\gamma$, with $\Gamma_\gamma = \Gamma(T^* \to T\gamma)$. Thus, by comparing the initial and final polarization, we get information on the particle's lifetime.

KEYWORDS: Beyond Standard Model, Spin and Polarization Effects.

Contents

1. Introduction

There are strong motivations to hope that the LHC will find new particles with electroweak scale masses. Once such a new particle is discovered, the first task will be to determine its properties, in particular, mass, charges, spin and lifetime. Clearly, such determinations require much larger statistics than what is needed for discoveries of new states. The hope is that eventually, with enough data from the LHC and future machines, we will be able to determine these properties for all the new particles.

In this work we concentrate on determining lifetimes. There are basically two ways the lifetime of a particle can be determined. The first is to directly measure its width. This method works when the intrinsic width is larger than the experimental resolution. The experimental sensitivity depends on many factors, like the mass of the particle and its charge. Very roughly, for a particle with mass of a few hundred GeV, its width can be extracted when $\Gamma \gtrsim 1$ GeV. The other method to extract lifetimes is by looking for a displaced secondary vertex. This can be done, very roughly, for $\tau \gtrsim 1$ ps, that is, $\Gamma \lesssim 10^{-4}$ eV. We see that there is a very large window,

$$10^9 \text{ eV} \gtrsim \Gamma \gtrsim 10^{-4} \text{ eV},\tag{1.1}$$

which we denote as "the problematic region," where lifetimes cannot be extracted.

The fact that our ability to measure lifetimes is limited may not be a problem. For example, in a generic SUSY model we expect the LSP to be stable and all other superparticles to have widths that are larger than $1\,\text{GeV}$. This is the generic case in most available models of physics beyond the SM; the unstable particles are very short lived while other new particles are stable due to an exact symmetry. There are, however, exceptions. There are well motivated models with new, unstable particles with lifetimes that are much longer than the naive ones, such that their widths are within the problematic region. This is the case, for example, in Z'-mediated SUSY Breaking [1] (for the gluino and the NLSP Wino), in split SUSY [2] (for the gluino when $m_s \lesssim 1000$ TeV) and in GUTs in warped extra dimension [3, 4] (for the GUT partners).

Below we describe a way that, in principle, can tell us information about a lifetime of a particle in the problematic region. The basic idea is as follows. Consider a particle of mass m that is not a singlet of $SU(3)_C$ nor of the Lorentz group. Thus, if its lifetime is longer than the QCD scale, it hadronizes before it decays. If the particle is produced polarized, the fact that it is hadronizes could eventually reduce its initial polarization. In cases where the polarization can be measured and compared to the expected one, we can extract the amount of depolarization. Knowing the time scale associated with the loss of polarization, make it possible to determine if the lifetime is larger or smaller than that time scale.

We note that we expect the new physics not to conserve parity. For example, in models with extra dimensions, the KK tower of the right-handed and left handed quarks have different masses and different couplings to the light fermions. Therefore, it is very likely that these new particles will be produced with high degree of polarization, and decay in a way that can be used to measure this polarization.

The loss of polarization takes place at time scales much longer than the hadronization scale [5]. The typical time for hadronization is $\Lambda_{\text{QCD}}^{-1}$ while for depolarization it is $m\Lambda_{\text{QCD}}^{-2}$. This is similar to the case of the hydrogen atom. The energy scale associated with depolarization of the heavy proton is that of the hyperfine splitting and it is suppressed by m_e/m_P. In particle physics terms, the fact that the depolarization time scale is long is a manifestation of the heavy quark spin symmetry. In the $m \to \infty$ limit the spin of the heavy quark is conserved. Thus, it can be changed only on time scales that are associated with energy scales that are suppressed by at least $1/m$.

In fact, the loss of polarization is done in several stages. Thus, a more refined knowledge about the lifetime can be obtained. For the purpose of illustration we consider a world where the top quark has a long lifetime. We neglect hadronization into baryons, and consider the two lightest top-mesons, T^* and T (the analog of B^* and B). These two states form a doublet under the heavy quark spin symmetry [6]. We further consider a very clean environment where we know the initial top polarization. Then, the angular distribution of the decay products can be used to measure the top polarization. Depolarization effects caused by the fact that the top hadronizes, make the final polarization smaller than that of a free quark.

There are several time scales associated with hadronization and depolarization [5]:

1. $t_1^{-1} \sim \Lambda_{\text{QCD}}$: This is the time scale where hadronization occurs. That is, after that time the top quark is hadronized into a heavy hadron, which can be a superposition of T and T^*, and possibly many light hadrons. (There is a small probability to hadronized into a top baryon, which we neglect for now.) Since the mass difference between T and T^* is much smaller than Λ_{QCD}, the meson containing the top quark is not in a mass eigenstate but rather a coherent superposition of T and T^*.

2. $t_2^{-1} \sim \Delta m$: The next relevant time scale is that associated with the splitting between the two hadrons

$$\Delta m \equiv m(T^*) - m(T). \tag{1.2}$$

At this time the system starts to "feel" the mass difference between the two hadrons. The system oscillates between the two mass eigenstates, which practically means loss

of coherence. t_2 is the time scale that controls the first depolarization stage.[1] As we show below, at times much larger than t_2, half of the initial polarization is lost.

3. $t_3^{-1} \sim \Gamma_\gamma$: The last relevant time scale is the one that controls the $T^* \to T$ transition

$$\Gamma_\gamma \equiv \Gamma(T^* \to T\gamma). \tag{1.3}$$

Since the T is a scalar, once the T^* decay into a T, all the initial polarization information is lost.

By measuring the amount of depolarization we can get a rough idea about the width of the top quark, Γ. If no depolarization occurs, we know that $\Gamma \gg \Delta m$. If half of the polarization get lost, it implies that $\Gamma_\gamma \ll \Gamma \ll \Delta m$. All the initial polarization is lost when $\Gamma \ll \Gamma_\gamma$.

2. Formalism

We develop the formalism by considering a simple toy model. We comment about more realistic scenarios later, but a full study of a realistic model is left for a future work.

Our toy model consists of a heavy "top" quark, t, a massless "bottom" quark, b, and a massless scalar, ϕ. That is, the t and the b are spin half fermions that transform as 3 under $SU(3)_C$ while ϕ is a scalar and does not carry color. The interaction term is chiral

$$y_{tb} \, \bar{t} \, \frac{1 - \gamma_5}{2} \, b \, \phi. \tag{2.1}$$

We assume that the top is produced fully polarized and that we know its spin direction, which we denote as the z axis. We further take m_t to be known and to be of order a few hundred GeV. In this simple model we can measure the final top polarization by the angular dependence of the out going b quark

$$\frac{d\Gamma}{d\cos\theta} = \frac{m_t \, y_{tb}^2}{64\pi^2} \left(1 - 2 \langle s_Z \rangle \cos\theta\right). \tag{2.2}$$

Here θ is the standard azimuthal angle and the normalization is such that a polarized top has $\langle s_Z \rangle = 1/2$.

We emphasize that the angular distribution of the decay products depends on the spin of the top quark even after hadronization. It is a very good approximation to neglect spectator effects in the decay. Thus, the spin of the hadron is irrelevant in the decay, it is only the spin of the heavy top that counts.

Once m_t is known, we can use heavy quark symmetry to calculate Δm and Γ_γ (the details of the calculations are given in the next section). Thus, we assume that the following quantities are known:

$$m_t, \qquad \Delta m \equiv m(T^*) - m(T), \qquad \Gamma_\gamma \equiv \Gamma(T^* \to T\gamma), \tag{2.3}$$

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[1]It is often said that "the top keeps its spin since it decays before it hadronizes." While this statement is correct, it is misleading. The relevant time scale for depolarization is much longer than the hadronization time scale.

such that $m_t \gg \Delta m \gg \Gamma_\gamma$. In general, Γ_γ carries a flavor index, as it depends on the light quark. Here we further simplify by assuming that the t quark has only one way to hadronized, say into a T_d meson, and thus we omitted the flavor index. To a very good approximation both Δm and Γ, the weak decay rate of the top, are independent of the light degrees of freedom. Therefore, $\Gamma(T) = \Gamma$ and width different between the two mesons is

$$\Delta\Gamma \equiv \Gamma(T^*) - \Gamma(T) = \Gamma_\gamma. \tag{2.4}$$

It is useful to define two bases that describe the state of the heavy meson. The mass basis is spanned by the T^* and T mesons. In this basis the total spin and the total spin in the z direction are known. The spin basis is the one that is labeled by s_Z of both the top and the spectator d quark. We denote its eigenvectors by $|s_t, s_d\rangle$ with $s_t, s_d = +, -$. The relation between the two bases is

$$T^*(1,1) = |++\rangle\,, \qquad T^*(1,0) = \frac{|-+\rangle + |+-\rangle}{\sqrt{2}},$$

$$T^*(1,-1) = |--\rangle\,, \qquad T(0,0) = \frac{|-+\rangle - |+-\rangle}{\sqrt{2}}. \tag{2.5}$$

Next we move to calculate $\langle s_Z \rangle(t)$, the top polarization as a function of time. We set $t = 0$ as the time the top is produced and hadronizes. That is, we neglect the stage of hadronization which is very fast. We assume that the top is produced with a spin in the z direction. We further assume that the light quark in the meson is unpolarized, that is, it has equal probability to have spin up or down. See [7] for discussion on that point. Thus, the meson state $T(t)$ at time $t = 0$ is an equal incoherent sum of the following two states

$$|++\rangle\,, \qquad |+-\rangle\,. \tag{2.6}$$

In term of the mass eigenstates we have

$$|++\rangle = T^*(1,1), \qquad |+-\rangle = \frac{T^*(1,0) + T(0,0)}{\sqrt{2}}. \tag{2.7}$$

We assume that Δm and $\Delta\Gamma$ are known. Furthermore, we always have $\Delta m \gg \Delta\Gamma$. Thus, we can get the time dependences of the two states. Our interested lies in the top polarization as a function of time, $\langle s_Z \rangle(t)$. We find

$$\frac{\langle s_Z \rangle(t)}{\langle s_Z \rangle(t=0)} = \frac{1}{2} \times \left[\cos(\Delta m\, t) + e^{-\Delta\Gamma t} \right], \tag{2.8}$$

where we neglect $\Delta\Gamma$ compared to Δm.

A few points are in order regarding eq. (2.8):

1. At very short times, $t \ll 1/\Delta m$, the polarization is unchanged from its initial value.

2. At later times, $1/\Delta\Gamma \gg t \gg 1/\Delta m$ the oscillatory term is averaged to zero and we see that the polarization reduced to half its initial value. This result can be understood from the meson picture. At $t = 0$ the $T^*(1,0)$ and $T(0,0)$ are in a coherent state. At later times, $t \gg 1/\Delta m$, the state is effectively a decoherent sum of these two states, each with an average zero top polarization. The $T^*(1,1)$ state, however, stays polarized, and thus half of the original polarization is maintained.
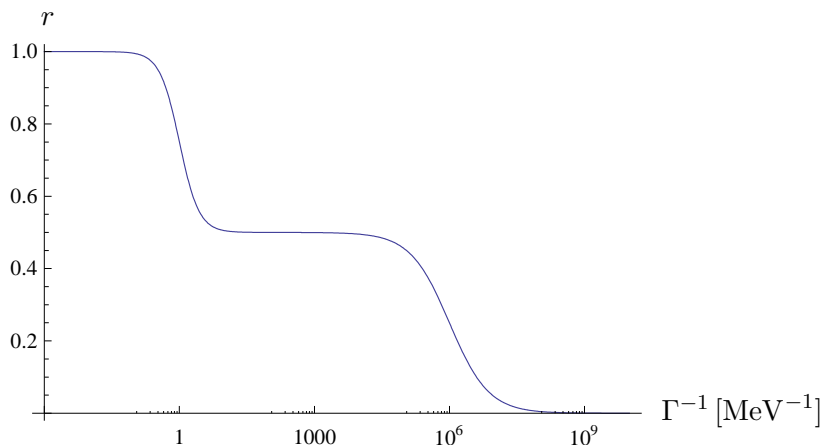
Figure 1: r as a function of Γ^{-1} (in MeV^{-1}). We use eq. (2.10) setting $\Delta m = 1\,\mathrm{MeV}$ and $\Delta\Gamma = \Gamma_\gamma = 1\,\mathrm{eV}$.

3. At very long times, $t \gg 1/\Delta\Gamma$, when the $T^* \to T\gamma$ decay takes place, there is complete depolarization.

Since in practice the time evolution of the meson cannot be traced, we have to integrate eq. (2.8) over time to get the average polarization. We define $\langle s_Z \rangle^{\text{free}}$ to be the average top polarization assuming no hadronization, and it is therefore not depend on time. (We factor out the trivial exponential decay.) We parametrize the amount of integrated remnant top polarization by

$$r \equiv \frac{\int dt \exp(-\Gamma t)\,\langle s_Z \rangle\,(t)}{\int dt \exp(-\Gamma t)\,\langle s_Z \rangle^{\text{free}}}, \tag{2.9}$$

such that $r = 1$ indicates that the initial polarization is maintained while $r = 0$ refers to a case that the top decayed after it was completely depolarized. We find

$$r = \frac{1}{2}\left(\frac{1}{1+x^2} + \frac{1}{1+y}\right), \tag{2.10}$$

where we defined

$$x \equiv \frac{\Delta m}{\Gamma}, \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}. \tag{2.11}$$

Eq. (2.10) is the main result of this section. It demonstrates how we can get information about the width of the top, Γ. In principle, by measuring r and using Δm and $\Delta\Gamma$ as inputs, we get Γ precisely using eq. (2.10). This is illustrated in figure 1. In practice, however, the Γ dependence of r is strong only near $x \sim 1$ and $y \sim 1$. Far away from these regions Γ cannot be practically probed. This can be seen in figure 1 where far from $x \sim 1$ and $y \sim 1$, r is very flat.

3. A more realistic scenario

In order to make the lifetime probe realistic, the following points have to be addressed:

1. How well can we calculate the initial polarization?

2. How well can the polarization at the time of decay be measured?

3. The hadronization can be into a baryon or a meson, and each of them has several different possibilities for the light degrees of freedom. How well do we know the flavor ratios after hadronization?

4. Given the mass, spin, and $SU(3)_C$ representation of the new heavy particle, how well can we calculate Δm and Γ_γ?

Regarding the first point. The initial polarization can be calculated within any specific model. That is, if we have a model we put to test, in principle, we know the initial polarization. Clearly, the amount of theoretical uncertainty depends on how well the model parameters are known. Our hope is that by the time the ideas we propose can be used, the initial polarization can be determined to high enough precision.

Moving to the second point. Discussion of ways to measure heavy particles spin and polarization have been studied before, see, for example, refs. [8 – 10], and for a recent review see [11]. The point is that these ideas can be carried out for the particles we are interested in.

Polarization measurements have been suggested (and used) to determine the spin of particles. To measure that, those methods do not have to be very sensitive to the accuracy of the measurement. To utilize them for our purpose, however, it is essential to have a good understanding of both experimental and theoretical errors. We have to address various questions, for example: Is the angular dependence being washed out by massive decay products? What the chirality of the decay vertex is [8]?

From now on we confine the discussion to the case of a spin half color triplet particle. We start by determining the flavor ratio after hadronization. Far from threshold it is reasonable to assume that the hadronization is independent of the mass of the heavy quark. Thus, we can use b data in order to predict the hadronization for a heavy color triplet spin half. Isospin symmetry tells us that at high energy the probability to hadronized into T_u and T_d is about the same. In the B case the two other significant hadronization modes are into B_s and baryons. Using the data [12] it is straightforward to predict $P(X)$, the probability to hadronized into the hadron X, as

$$P(T_u) \approx 40\%, \qquad P(T_d) \approx 40\%, \qquad P(T_s) \approx 10\%, \qquad P(\Lambda_t) \approx 10\%. \qquad (3.1)$$

We use standard notation extended to the top case. That is, T_q is a meson made of t and and $\bar{q}$ quark, while Λ_t is a baryon made out of a t and two light quarks. Note that close to threshold the situation might be different as phase space effects can be important. In principle, such effects can be estimated.

Next we discuss the determination of Δm and Γ_γ. We start with the baryons. The lowest state, denoted by Λ_t, is a spin half. The two light degrees of freedom are in a relative spin zero configuration, and therefore Λ_t is a singlet of the heavy quark spin symmetry. Since the light degrees of freedom are in a spin zero configuration the spin of the baryon

is the same as the spin of the heavy quark. Thus, the baryon keeps the initial polarization and hadronization effects are not important.[2]

The situation with the meson doublet, T and T^*, is more complicated. In the following we estimate Δm and $\Delta \Gamma$. The idea is to use D and B data and Heavy Quark Effective Theory (HQET) to predict these quantities for a heavy top.

We start with the calculation of Δm. It is determined by the HQET λ_2 parameter [7]

$$\Delta m = \frac{2\lambda_2}{m}. \tag{3.2}$$

B meson data implies $\lambda_2(\mu = m_b) \approx 0.12 \, \text{GeV}$. Using leading log running [13], we get

$$\Delta m = \Delta m_B \left(\frac{m_B}{m_T}\right) \left(\frac{\alpha_s(m_T)}{\alpha_s(m_B)}\right)^{3/(11-2n_f/3)}. \tag{3.3}$$

Once the new particle mass is determined, we can therefore calculate Δm. For example, using $m_t = 170$ GeV, $n_f = 5$ and $\alpha_s(m_t)/\alpha_s(m_B) \approx 3.5$ we get

$$\Delta m \approx 1 \, \text{MeV}. \tag{3.4}$$

While this is only a rough estimate it serves two purposes. First, we learn that Δm is in the range that is of interest to us. Second, we see that in principle we can get quite an accurate determination of Δm. If needed, higher order corrections can be included.

Next we move to the calculation of Γ_γ. We can use heavy quark symmetry and D^* decay data to get Γ_γ for much heavier mesons. Following [14] and [15] the decay rate can be parameterized as

$$\Gamma_\gamma^a = \frac{\alpha}{3}|\mu^a|^2|k_\gamma|^3, \tag{3.5}$$

where $a = u, d, s$ is the light quark index, α is the fine structure constant, k_γ is the photon momentum, and μ^a is a coupling constant of dimension -1. We have basically two unknowns in eq. (3.5), $|k_\gamma|$ and $|\mu^a|$. For a very heavy quark the photon momentum is given by $|k_\gamma| = \Delta m_T$, a quantity we already discussed, see eq. (3.3). The calculation of $|\mu^a|$ is more complicated. Both the light and heavy quarks contribute to μ^a, but their contributions scale like $1/m_q$. For the D case, where $1/m_c$ is not very small, the charm contribution is important. In our case, however, since the top is very heavy, we can neglect its contribution to μ^a. We only need the contributions of the light quarks in order to calculate μ^a.

To calculate μ^a we use the approximate flavor SU(3) symmetry. In the SU(3) symmetry limit μ^a is proportional to one reduced matrix element [14]

$$\mu^a = q_a \beta, \tag{3.6}$$

where q_a is the electric charge of the light quark, and β is the reduced matrix element. When SU(3) breaking effects are included, the simple ratio of $2:1:1$ is not maintained.

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[2]For the B case there is a subtlety related to the Σ_b that can actually affect the initial polarization. This issue is discussed in [5], where it is shown that the effects are important for the case of $m \sim 5 \, \text{GeV}$ but can be safely neglected for heavy quarks with $m \gtrsim 100 \, \text{GeV}$.

To get a rough estimate we use here the simple quark model prediction [14]

$$\mu_u = \frac{2}{3}\beta - \frac{g^2}{4\pi}\left(\frac{m_K}{f_K^2} - \frac{m_\pi}{f_\pi^2}\right),$$
$$\mu_d = -\frac{1}{3}\beta - \frac{g^2}{4\pi}\frac{m_\pi}{f_\pi^2},$$
$$\mu_s = -\frac{1}{3}\beta - \frac{g^2}{4\pi}\frac{m_K}{f_K^2}, \tag{3.7}$$

where g is the effective $T^*T\pi$ coupling. While at present our knowledge of the values of β and g is limited, if needed in the future much more precise values can be obtained using the lattice or updating the analysis of [15]. For us it is enough to use rough values for these parameters. We use the following representative values

$$\beta \sim 3\,\text{GeV}^{-1}, \qquad g \sim 0.5. \tag{3.8}$$

(The above values are different from those found in [15]. The reason for it is that the data changed. The above values are roughly the best fit values using current data [16].) For $m_t = 170\,\text{GeV}$ and $\Delta m = 1\,\text{MeV}$ we obtain

$$\Gamma_\gamma^u \approx 1.0 \times 10^{-2}\,\text{eV}, \qquad \Gamma_\gamma^d \approx 2.5 \times 10^{-3}\,\text{eV}, \qquad \Gamma_\gamma^s \approx 2.5 \times 10^{-3}\,\text{eV}. \tag{3.9}$$

We learn that we can expect $\Delta\Gamma$ of order of $10^{-2}\,\text{eV}$. This value correspond to lifetimes that are within the problematic region.

We conclude this section with two comments. First we mention that Δm and $\Delta\Gamma$ scale differently as a function of the heavy quark. The leading order scaling is

$$\Delta m \propto m_t^{-1}, \qquad \Delta\Gamma \propto m_t^{-3}. \tag{3.10}$$

The strong dependence of y on the heavy quark mass make it such that for very heavy quarks $\Delta\Gamma$ may be very small.

Second we note that $\Delta\Gamma$ is not flavor universal. This is since the width scales like the square of the light quark electric charge. The fact that the width is not flavor universal can help us to get more precise information about the heavy quark lifetime. The point is that we know the hadronization flavor ratio, and therefore we have several time scales that control the depolarization. We obtain

$$r = P(\Lambda_t) + \frac{1}{2}\left[\frac{1 - P(\Lambda_t)}{1 + x^2} + \frac{P(T_u)}{1 + y_u} + \frac{P(T_d)}{1 + y_d} + \frac{P(T_s)}{1 + y_s}\right]. \tag{3.11}$$

where $y_a \equiv (\Gamma_\gamma^a/2\Gamma)$ and $P(X)$, the hadronization probability into hadron X, are assumed to be known, see eq. (3.1). We also used $P(\Lambda_t) + P(T_u) + P(T_d) + P(T_s) = 1$. Eq. (3.11) is an improvement over its simplified version, eq. (2.10). We see that it involves several time scales and thus a refined way to probe Γ if it happened to be of the order of Γ_γ.

4. Discussions and conclusions

We discussed only a top like heavy particle, that is, a color triplet spin half heavy fermion. Our method can be extended to other representation. Clearly, it can work only for particles that are charged under the strong interaction and are not scalars. For such cases, however, it is harder to calculate Δm and $\Delta\Gamma$ since we do not have similar systems that we can use to extrapolate like we did with the b and c quarks. Yet, we do not see a fundamental obstacle to calculate it using models for QCD or on the lattice.

There are several issues that have to be under control before our method can be used:

1. We must know the spin and the $\mathrm{SU}(3)_C$ representation of the new particle.

2. We must have a reliable way to calculate its initial polarization.

3. We need a way to measure the polarization when the heavy particle decays.

We do not discuss these issues in detail here. We mention that we would like to know all that independently of our motivation. We do, however, show that in some cases there are ways around some of the above requirements.

If we work within a given model, we can calculate the first two items. That is, once all the model parameters are given, we can check if the apparent measurement of the lifetime using our method agrees with the model prediction.

There is, in principle, a model independent way to avoid the need to know the initial polarization. Consider a situation where we can experimentally separate events where the top hadronizes into a baryon or a meson. As we discussed, baryonic events have negligible depolarization, and therefore their final polarization is the same as the initial polarization of the mesonic events. Thus, the baryonic events can be used to measure the initial polarization.

We did not discuss the possibility of spectator decay $s \to u e^- \overline{\nu}$. This decay introduces a new time scale which could in principle add an additional probe on the lifetime by changing the polarization in the case of the spectator is an s-quark. We did not study this decay in detail, and only comment that it can be relevant for heavy particles where Γ_γ is very small.

To conclude, we show that hadronization can be used to probe lifetimes of particles with intermediate width. The basic idea is that the depolarization time depends on known QCD dynamics. For particles with weak scale masses, the depolarization time happen to be in the region that corresponds to intermediate lifetimes. Therefore, a measurement of the amount of depolarization can be used to determine the lifetime of such a particle.

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