Title: Spin, hadronization, and lifetimes

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Abstract: TBA

Hadronization, spin, and lifetimes

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Based on Y. Grossman and I. Nachshon, arXiv:0803.1787

The LHC is coming

Hopefully, soon, the LHC will find new particles. We then would like to measure their

- mass: “simple”
- spin: “possible”
- charge: “probably”
- SU(3) charge: “easy”
- lifetime: ?

The more we can determine, the better we are...

Lifetime

Basically two ways

- Measure the width. Works for $\Gamma \gtrsim 1\ \mathrm{GeV}$
- Measure displaced vertex. Works for $\Gamma \lesssim 10^{-4}\ \mathrm{eV}$
- There is a large “window” that we cannot cover

$$10^{-4}\ \mathrm{eV} \lesssim \Gamma \lesssim 1\ \mathrm{GeV}$$

Q: Can we do anything about this window?

A: In some cases we can do something

Is it a problematic region?

- In most "weak scale" models, the new particles are not in the problematic region
- The naive decay rate is $\Gamma \sim \alpha M \gg 1\,\mathrm{GeV}$
- Other particles are stable
- Yet, there are two reasons why we do care
  - We like to probe lifetimes independent of what any specific theory tells us
  - There are still many models with such lifetimes: split susy, some RS models, Z' susy breaking

Time scales

Time scales

- We need a time scale that is in the problematic region
- Consider some "approximate" QN. It is conserved over a time scale t_r. Compare to the lifetime

$$t_r \gg \tau \quad \Rightarrow \quad \text{QN is conserved}$$
$$t_r \ll \tau \quad \Rightarrow \quad \text{QN is not conserved}$$

- More generally, the integrated relaxation probability scales like

$$P = \exp\left(-\frac{\tau}{t_r}\right)$$

Idea: Measure P and calculate t_r so we can get Γ

Meson mixing

Consider a hypothetical world where

- We could not measure the B lifetime, Γ
- We could calculate the mixing, Δm
- We could measure the integrated oscillation probability (same sign dileptons) that is, $x = \Delta m/\Gamma$
- The theoretical Δm and experimental $x = \Delta m/\Gamma$ can be used to extract the B lifetime

The approximate QN is the b-flavor, and its relaxation time is the oscillation time

Back to the LHC

- The approximate QN is polarization
- In the problematic region $\Gamma \lesssim \Lambda_{QCD}$, thus all colored particles hadronized
- The relaxation time is due to hadronization and the QCD analog of the hyperfine splitting
- There are two times scales: The oscillation between the two hyperfine states and decay from the heavy to the light one
- It turns out these two time scales are in the problematic region for weak scale colored particles. Lucky us!

Back to first grade: Hydrogen atom

Hyperfine splitting

Using the fact that $m_P \gg m_e$ we know that

- The ground state splitting is much smaller compared to the other levels, so we can only consider the ground state
- The two spin halves combined to a triplet and a singlet

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

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

- The splitting, $\Delta E = E(H^*) - E(H)$, is small
- $\Gamma(H^* \to H\gamma)$ is tiny

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Hydrogen evolution

Consider the initial state, $H(t=0) = |+-\rangle$

- We care about the evolution of the proton's spin in time
- The initial state is not an energy eigenstates, thus, it oscillates with frequency ΔE
- At very short times, $t \ll 1/\Delta E$, it is still in a $|+-\rangle$ state. No proton depolarization.
- At long times, $t \gg 1/\Delta E$, we can average over the oscillation. The final state is an equal decoherance sum of T and S. Thus, the proton is depolarized
- Consider $H(t=0) = |++\rangle$. Then, there are no oscillations, and the polarization is lost only after time of order the triple's lifetime

Back to the LHC

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Back to the LHC

Hyperfine splitting of mesons

We consider a "top like" new particle we call top (it can even be the real top). Our aim is to measure its lifetime, Γ

- We assume that m_t is known
- We denote the ground states of the meson as T and T^* (the analog of B and B^*)
- The relevant new time scale are much smaller than $1/\Lambda_{QCD}$. The scaling is

$$\Delta m \equiv m(T^*) - m(T) \sim m_t^{-1}$$
$$\Gamma_\gamma \equiv \Gamma(T^* \to T\gamma) \sim m_t^{-3}$$

- We assume that we can calculate Δm and Γ_γ

The three time scales

- Λ_{QCD}: At that scale the meson set into its ground state
- $\Delta m \equiv M(T^*) - M(T)$: The oscillation between the two hyperfine states. It is the time it takes the spin of the heavy quark to rotate
- $\Gamma(T^* \to T\gamma)$: The decay of the heavy hyperfine state to the light one. At that scale all polarization is lost

Initial state

- Consider a situation where the top is produced with known polarization, say up
- We assume that we can measure the final top polarization
- Since QCD is parity conserving, after hadronization the initial state is an incoherent sum of $|++\rangle$ and $|+-\rangle$

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

Time evolution

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

- The top in $|++\rangle$ depolarizes at $t \sim 1/\Gamma_\gamma$
- The top in $|+-\rangle$ depolarizes much before, at $t \sim 1/\Delta m$
- Overall, depolarization at two time scales

$$\frac{\langle s_Z\rangle(t)}{\langle s_Z\rangle(t=0)} = \frac{e^{-\Gamma t}}{2}\left(\cos(\Delta m t) + e^{-\Gamma_\gamma t}\right)$$

Time integration

- Of course, we must integrate over time
- After integration, the depolarization fraction is

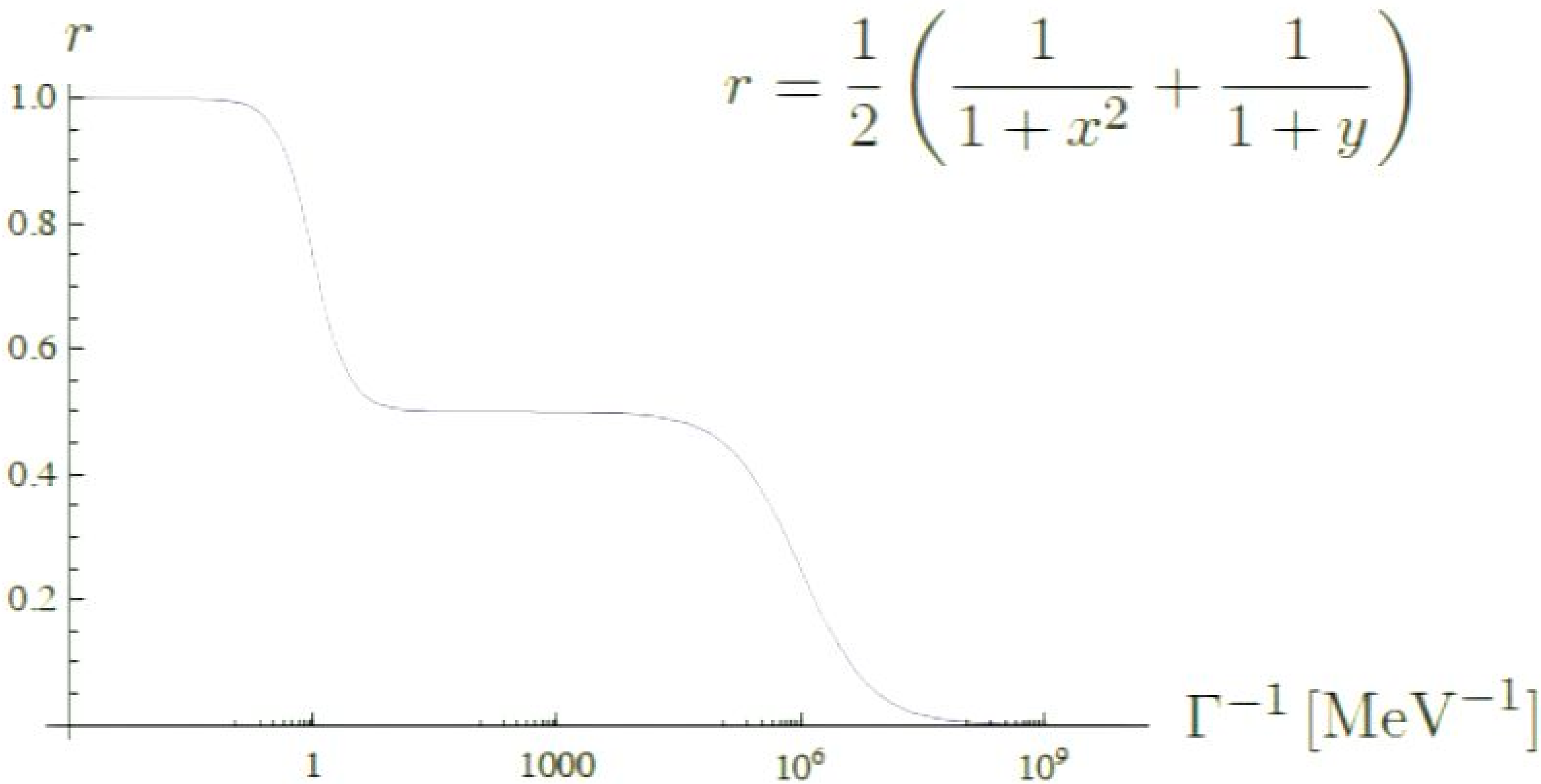
$$r = \frac{1}{2}\left(\frac{1}{1+x^2} + \frac{1}{1+y}\right)$$

where

$$x \equiv \frac{\Delta m}{\Gamma}, \qquad y \equiv \frac{\Gamma_\gamma}{2\Gamma}$$

- Measuring r and knowing Δm and Γ_γ enable us to determined Γ

Depolarization plot



- We used $\Delta m = 1\ \mathrm{MeV}$ and $\Gamma_\gamma = 1\ \mathrm{eV}$.
  $x = \Delta m/\Gamma \qquad y = \Gamma_\gamma/2\Gamma.$

Calculating Δm

- We use HQET to relate the measured Δm in the B system to that in the top

$$\Delta m_b \equiv m(B^*) - m(B) = \frac{2\lambda_2}{m_b} \qquad \lambda_2(\mu = m_b) \approx 0.12\,\mathrm{GeV}^2$$

- We know how λ_2 runs
- The fact that we can used data and HQET makes the error negligible
- Here we used the assumption that the new particle is color triplet

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Calculating Γ_γ

- For Γ_γ we use HQET, but need a hadronic model
- The decay rate depend on the spectator. HQET just tells us that we can forget about the heavy quark.
- We have only D data. For the B the width cannot be measured
- The reason we can do it for charm is that we have $D^* \to D\gamma$ and $D^* \to D\pi$.
- But the charm is not really heavy. We need a model to "subtract" the effect of the charm.

Numbers

- For $m_t \approx 170$ GeV

$$\Delta m \approx 1\,\mathrm{MeV} \quad \Gamma_\gamma^u \approx 1.0 \times 10^{-2}\,\mathrm{eV} \quad \Gamma_\gamma^d \approx 2.5 \times 10^{-3}\,\mathrm{eV}$$

- The two time scales are in the problematic region
- Γ_γ depends on the spectator. Good!
- The theoretical errors are still small compared to the accuracy we need

Baryons

- The top can hadronized into a Λ_t baryon
- The top in Λ_t keeps its polarization
- We know the hadronization fraction from B data

$$B_u : B_d : B_s : \Lambda_b \sim 4 : 4 : 1 : 1$$

- Overall we then have

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

  - $P(X)$ is the probability to hadronize into X
  - y_q is y for T_q
- We get even more control over the lifetime

Challenges

Spin and $SU(3)_C$

- We must know the spin and the $SU(3)_C$ representation of the new particle
- When the ground state is a singlet the whole method does not work
- If the ground state is not a singlet, we need to calculate Δm and $\Delta\Gamma$
- We cannot use data like for the quark case, but we may still use lattice QCD
- If we will need it, probably we will be able to get a rather accurate numbers

The Initial polarization

- We must have a reliable way to calculate its initial polarization
- Within a specific model we can do it
- Not easy model independently, but maybe possible
- We can also use correlations between the two quarks. This can help

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Measure the polarization

- We need a way to measure the polarization when the heavy particle decays
- Many ideas had been studied, and we can hope it will be done
- The basic idea is to look for some angular correlation of the decay products

Other time scales

- The method works only for particles with color and spin
- Can we find some other "time scale" that we can use?
- In some models we may be able to. For example, in susy if we know flavor or lepton number oscillation time

conclusion

- Using polarization measurements we can get some information on lifetimes of new particles
- As always, we need luck

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