Angular distributions as lifetime probes

A new way to measure particle lifetime in a problematic region

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Jeff Asaf Dror

(in collaboration with Yuval Grossman)

Cornell University

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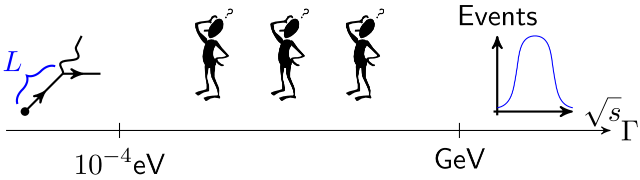
The problem of a lifetime

- At the LHC we can measure lifetimes using two techniques:
  - $\Gamma \gtrsim$ GeV ($\tau \lesssim 10^{-24}$s): Scanning over width
  - $\Gamma \lesssim 10^{-4}$eV ($\tau \gtrsim 10^{-12}$s): Use a displaced vertex
- In 2008 Grossman and Nachshon presented new way to measure Γ

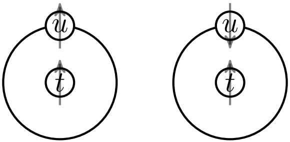
How we currently measure lifetimes:



The model

- Consider a hypothetical "top-like" quark particle with
  - Spin $1/2$
  - Heavy: $m_t \gg \Lambda_{QCD}$.
  - Charged under $SU(3)_c$
  - **but lifetime in the problematic region!**
- Basic idea: collection of spin up tops undergo a three step process:
  1. Tops hadronize mostly into mesons
  2. Top spin and light quark spin interact → depolarizing the tops
  3. Spin of tops at time of decay depends on lifetime and depolarization scales

Heavy quark hadronization - surprisingly simple



- The energy splitting between the triplet and singlet states, $\Delta m \equiv m_{s=1} - m_{s=0} \ll \Lambda_{QCD} \Rightarrow$ **incoherent mix:**

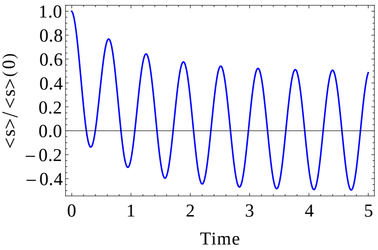
$$50\% \; |\overbrace{\;+\;}^{\text{top spin}} \underbrace{\;+\;}_{\text{light quark}}\rangle \qquad 50\% \; |+-\rangle \quad ,$$

$$|++\rangle = |1,1\rangle , \qquad |+-\rangle = \frac{|1,0\rangle + |0,0\rangle}{\sqrt{2}} \, .$$

Depolarization - a flip flop top

- $|++\rangle$: Second order decay with rate Γ_γ to $|00\rangle$.
- $|+-\rangle$: Oscillates between $|+-\rangle$ and $|-+\rangle$ with rate,
  $\Delta m \equiv m_{s=1} - m_{s=0}$.

$$\text{Normalized angular mom.} = \frac{\langle s\rangle (t)}{\langle s\rangle (0)} = \frac{1}{2}\left(e^{-\Gamma_\gamma t} + \cos \Delta m t\right)$$



Including top weak decay

- Thus far we have ignored particle decay
- To account for that we have the angular momentum per unit time.

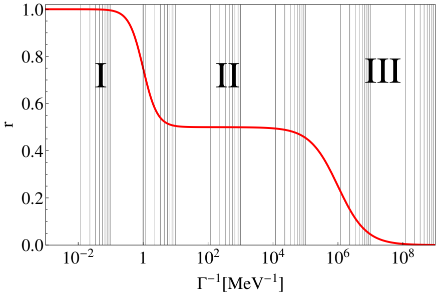
$$\frac{\langle s\rangle(t)}{\langle s\rangle(0)} \to \Gamma e^{-\Gamma t}\frac{1}{2}\left(e^{-\Gamma_\gamma t} + \cos\Delta m t\right)$$

- Can only measure time-average,

$$\boldsymbol{r} \equiv \int \langle s\rangle(t)\,dt = \frac{1}{2}\left(\frac{1}{1+x^2} + \frac{1}{1+y}\right)$$

where $x \equiv \frac{\Delta m}{2\Gamma}$ and $y \equiv \frac{\Gamma_\gamma}{\Gamma}$.

The lifetime staircase

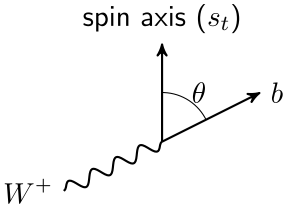


- By measuring r we can find Γ.
- 3 timescales: $\Delta m, \Gamma_\gamma$, and Γ with $\Delta m \gg \Gamma_\gamma$.
- Depending on value of Γ relative to Δm, Γ_γ particle lives in different region.

- r is really only split up into three regions.

What about the LHC?

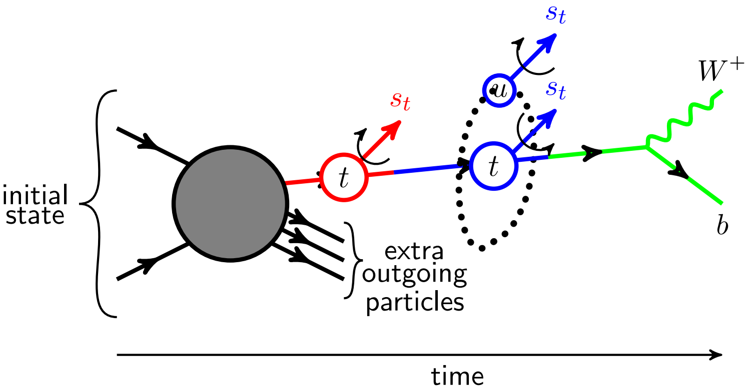
- Can't trap, polarize, and measure angular momentum
  - But we can almost do it!
- **Polarize particles:** By choosing clever spin axis ⇒ almost 100% polarized tops.



- **Spin Measurement:** Angular distributions depend on top spin

Process Breakdown

- Proton execution to b quark distribution:



- **Angular distributions will depend on r!**

Adding in hadronization

- **Without hadronization** (interference terms are small):

$$d\sigma \approx \sigma_{\uparrow}\frac{d\Gamma_{\uparrow}}{\Gamma} + \sigma_{\downarrow}\frac{d\Gamma_{\downarrow}}{\Gamma} \quad (1)$$

  - $\sigma_\lambda \rightarrow$ production cross-section
  - $d\Gamma_\lambda \rightarrow$ decay distribution

- Decay distributions gets modified ($P(t) \equiv$ Prob($\uparrow \xrightarrow{had} \uparrow$)):

$$\frac{d\Gamma_{\uparrow}}{\Gamma} \xrightarrow{had} P(t)\frac{d\Gamma_{\uparrow}}{\Gamma} + (1 - P(t))\frac{d\Gamma_{\downarrow}}{\Gamma}$$

The final product

- So we have

$$\frac{d\sigma}{dt} = \Gamma e^{-\Gamma t}\sigma_{\uparrow}\left(P(t)\frac{d\Gamma_{\uparrow}}{\Gamma} + (1 - P(t))\frac{d\Gamma_{\downarrow}}{\Gamma}\right) + \sigma_{\downarrow}\left((1 - P(t))\frac{d\Gamma_{\uparrow}}{\Gamma} + P(t)\frac{d\Gamma_{\downarrow}}{\Gamma}\right)$$

- $r = \int \Gamma e^{-\Gamma t}(2P(t) - 1)\, dt$
- We need to calculate three different things:
  1. $P(t)$ (essentially done above)
  2. Production cross-sections
  3. Differential rates

Example

- Consider s channel production and $t \to bW$ decay,

$$\frac{d\sigma(t)}{d\cos\theta dt} = \Gamma e^{-\Gamma t}\left\{\left(\sigma_\uparrow P(t) + \sigma_\downarrow(1 - P(t))\right)\frac{d\Gamma_\uparrow}{d\cos\theta} + \left(\sigma_\downarrow P(t) + \sigma_\downarrow(1 - P(t))\right)\frac{d\Gamma_\downarrow}{d\cos\theta}\right\}$$

  where θ is the angle between the top spin axis and the b quark.

- After calculating $\sigma_\uparrow$ and $\sigma_\downarrow$ and integrating,

$$a_{fb} = \left\{\frac{2M_W^2 - m^2}{2M_W^2 + m^2}\right\} \times r$$

Conclusion

- Currently we can't measure lifetimes for GeV $\lesssim \Gamma \lesssim 10^{-4}$eV
- New technique to measure lifetime of top-like particles
- Understanding the depolarization can give access to lifetime
- Angular distributions are dependent on the amount of depolarization (hence depend on r)
- Could be extended to different colored particles (gluino?)
- Lifetime gap isn't solved but maybe one step in the right direction

Thank you for listening!