Weak decay of the double-beauty tetraquark

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Introduction

- $QQ\bar{q}\bar{q}$ bound below $(Q\bar{q}) + (Q\bar{q})$ if $M \gg m$ by chromoelectric effect
- Ader et al. (1981), often rediscovered and/or refined (Heller et al, Rosina et al., Valcarce et al., ...)
- $QQ\bar{u}\bar{d}$ also benefits from a favorable chromomagnetic effect
- $cc\bar{u}\bar{d}$ perhaps below DD^*. Pionic or γ decay
- $bc\bar{u}\bar{d}$ probably stable
- $bb\bar{u}\bar{d}$ almost certainly stable
- Confirmed in the "molecular" approach (Manohar & Wise, ...), QCD SR (Narison, Nielsen, ...)
- And several lattice QCD studies

Rough estimate of the lifetime of T_{bb}

- Unlike charm, beauty decays with an almost constant lifetime
- $\tau(B^\pm) \sim \tau(B^0) \sim \tau(B_s) \sim \tau(\Lambda_b) \sim 1.5\,\text{ps}$
- More delicate $\tau(B_c) \sim 0.5\,\text{ps}$
- One could naively expect $\tau(T_{bb}) \sim 1.5\,\text{ps}$
- Faster? Two b quarks
- Longer τ?
  - Average PS for $T \to B + c + X$ less than for $B \to c + X$
  - After W emission, $c\bar{q}$ not always color singlet
- KR estimated $\tau \sim 0.4\,\text{ps}$
- Ali et al. $\tau \sim 0.8\,\text{ps}$
- Xing & Zhu: many “gold” channels identified
- A paper (accepted in PRD!!!!): purely SL decay!!! $\tau \sim 0.009\,\text{ps}$

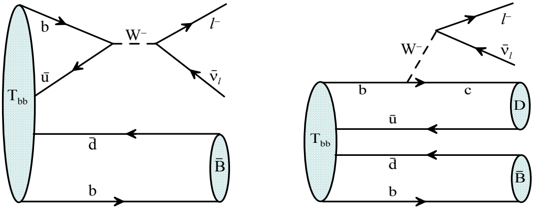
Framework

- Constituent quark model for T_{bb} and hadrons in final state
- Usual assumptions for SL and NL decays
- 4-body problem for T_{bb}: coupled-channel with in each channel

$$\Psi = \sum_i \gamma_i \{\exp[-a_i\,\boldsymbol{x}^2 - b_i\,\boldsymbol{y}^2 - \cdots + 2\,d_i\,\boldsymbol{x}.\boldsymbol{y} + \cdots] \pm (\boldsymbol{x} \leftrightarrow -\boldsymbol{x}) \pm (\boldsymbol{y} \leftrightarrow -\boldsymbol{y})\}$$

- $\pm$ according to spin-color-isospin
- where $\boldsymbol{x} = \boldsymbol{r}_2 - \boldsymbol{r}_1$, $\boldsymbol{y} = \boldsymbol{r}_4 - \boldsymbol{r}_3$, and $\boldsymbol{z} \propto \boldsymbol{r}_3 + \boldsymbol{r}_4 - \boldsymbol{r}_1 - \boldsymbol{r}_2$
- Diagonal and non-diagonal terms to achieve convergence
- Or (Nakamura et al) use diagonal terms in $\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{z}$
- and diagonal Gaussians in $\boldsymbol{x}'$, $\boldsymbol{y}'$ and $\boldsymbol{z}'$ and in $\boldsymbol{x}''$, $\boldsymbol{y}''$ and $\boldsymbol{z}''$
- where $\boldsymbol{x}' = \boldsymbol{r}_3 - r_1, \ldots$ and $\boldsymbol{x}'' = \boldsymbol{r}_4 - \boldsymbol{r}_1, \ldots$
- Color mixing $\bar{3}3$ and $6\bar{6}$ unless $m_Q \gg m_q$
- Diquark approximation not accurate

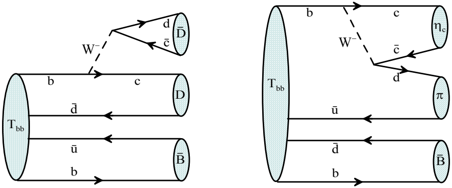
Semi-leptonic modes



Final state	$\Gamma\,[10^{-15}\,\mathrm{GeV}]$
$\bar{B}^{*0}\, e^-\, \bar{\nu}_e$	0.0365 ± 0.0004
$\bar{B}^0\, e^-\, \bar{\nu}_e$	0.0394 ± 0.0006
$\bar{B}^{*0}\, \mu^-\, \bar{\nu}_\mu$	0.0355 ± 0.0004
$\bar{B}^0\, \mu^-\, \bar{\nu}_\mu$	0.0396 ± 0.0006
$\bar{B}^{*0}\, \tau^-\, \bar{\nu}_\tau$	0.0355 ± 0.0004
$\bar{B}^0\, \tau^-\, \bar{\nu}_\tau$	0.0396 ± 0.0006

Final state	$\Gamma\,[10^{-15}\,\mathrm{GeV}]$	Final state	$\Gamma\,[10^{-15}\,\mathrm{GeV}]$
$B^{*-}\,D^{*+}\,\ell^-\,\bar{\nu}_\ell$ $\bar{B}^{*0}\,D^{*0}\,\ell^-\,\bar{\nu}_\ell$	9.02 ± 0.07	$B^{*-}\,D^{*+}\,\tau^-\,\bar{\nu}_\tau$ $\bar{B}^{*0}\,D^{*0}\,\tau^-\,\bar{\nu}_\tau$	1.55 ± 0.01
$B^{*-}\,D^{+}\,\ell^-\,\bar{\nu}_\ell$ $\bar{B}^{*0}\,D^{0}\,\ell^-\,\bar{\nu}_\ell$	3.59 ± 0.03	$B^{*-}\,D^{+}\,\tau^-\,\bar{\nu}_\tau$ $\bar{B}^{*0}\,D^{0}\,\tau^-\,\bar{\nu}_\tau$	0.727 ± 0.005
$B^{-}\,D^{*+}\,\ell^-\,\bar{\nu}_\ell$ $\bar{B}^{0}\,D^{*0}\,\ell^-\,\bar{\nu}_\ell$	4.63 ± 0.05	$B^{-}\,D^{*+}\,\tau^-\,\bar{\nu}_\tau$ $\bar{B}^{0}\,D^{*0}\,\tau^-\,\bar{\nu}_\tau$	0.86 ± 0.007
$B^{-}\,D^{+}\,l^-\,\bar{\nu}_l$ $\bar{B}^{0}\,D^{0}\,\ell^-\,\bar{\nu}_\ell$	1.92 ± 0.02	$B^{-}\,D^{+}\,\tau^-\,\bar{\nu}_\tau$ $\bar{B}^{0}\,D^{0}\,\tau^-\,\bar{\nu}_\tau$	0.409 ± 0.003

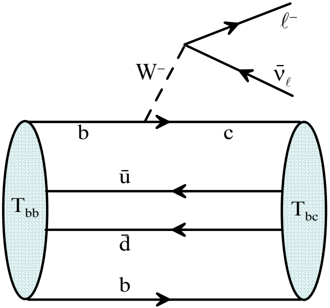
Non leptonic decays



Final state	$\Gamma\,[10^{-15}\,\mathrm{GeV}]$	Final state	$\Gamma\,[10^{-15}\,\mathrm{GeV}]$
$B^{*-}\ D^{*+}\ D_s^-$	4.00 ± 0.06	$B^-\ D^{*+}\ D_s^{*-}$	3.15 ± 0.05
$\bar{B}^{*0}\ D^{*0}\ D_s^-$		$\bar{B}^0\ D^{*0}\ D_s^{*-}$	
$B^{*-}\ D^{*+}\ D_s^{*-}$	6.50 ± 0.09	$B^-\ D^+\ D_s^{*-}$	1.20 ± 0.02
$\bar{B}^{*0}\ D^{*0}\ D_s^{*-}$		$\bar{B}^0\ D^0\ D_s^{*-}$	
$B^{*-}\ D^+\ D_s^-$	2.57 ± 0.04	$B^{*-}\ D^{*+}\ \rho^-$	3.57 ± 0.09
$\bar{B}^{*0}\ D^0\ D_s^-$		$B^{*-}\ D^{*+}\ \pi^-$	1.28 ± 0.03
$B^{*-}\ D^+\ D_s^{*-}$	2.32 ± 0.03	$B^{*-}\ D^+\ \rho^-$	1.70 ± 0.04
$\bar{B}^{*0}\ D^0\ D_s^{*-}$		$B^{*-}\ D^+\ \pi^-$	0.70 ± 0.02
$B^-\ D^{*+}\ D_s^-$	2.78 ± 0.05	$B^-\ D^{*+}\ \rho^-$	2.01 ± 0.05
$\bar{B}^0\ D^{*0}\ D_s^-$		$B^-\ D^{*+}\ \pi^-$	0.77 ± 0.03

$T_{bb} \to T_{bc}$ transitions

For completeness (as sometimes considered as possibly important)
Namely $T_{bb}(1^+)$ decaying with $T_{bc}(J^P = 0^+)$ in the final state.



Final state	$\Gamma\,[10^{-15}\,\mathrm{GeV}]$
$T^0_{bc}\, e^-\, \nu_e$	3.06 ± 0.03
$T^0_{bc}\, \mu^-\, \nu_\mu$	3.02 ± 0.02
$T^0_{bc}\, \tau^-\, \nu_\tau$	1.40 ± 0.01

Summary

- Fist comprehensive study of the decay of the T_{bb}^{-} tetraquark beyond simple guess-by-analogy estimations.
- Total width $\Gamma \approx 87 \times 10^{-15}$ GeV,
- Lifetime $\tau \approx 7.6$ ps
- The promising final states are, for SL
  - $\bar{B}^{*-}\, D^{*+}\, l^{-}\, \bar{\nu}_\ell$
  - $\bar{B}^{*0}\, D^{*0}\, \ell^{-}\, \bar{\nu}_\ell$
- and, for NL
  - $\bar{B}^{*-}\, D^{*+}\, D_s^{*-}$,
  - $\bar{B}^{*0}\, D^{*0}\, D_s^{*-}$,
  - $B^{*-}\, D^{*+}\, \rho^{-}$
- SL mode $T_{bc}^{0}\, \ell^{-} \nu_\ell$ relevant but not dominant
- Hopefully will help for experimental tracking
- Some rare but trigger friendly modes: $J/\psi BK$ or baryon-antibaryon stressed in the literature