Prospects for the Discovery of Stable Doubly-Bottom Tetraquarks at the LHC

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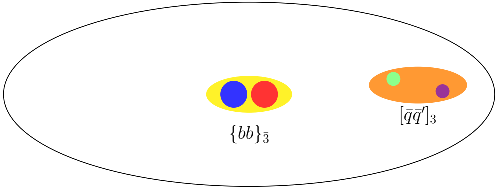
- Introduction
- Spectroscopy of Doubly-Heavy Tetraquarks
- Production at the LHC
- Lifetimes and Decays
- Outlook

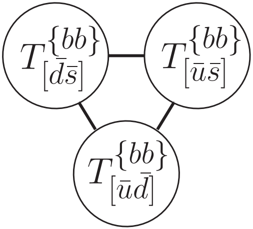
Stable Double-Heavy Tetraquarks

- Possibility of stable multiquark states was pointed out a long time ago [J. P. Ader et al., PRD 25 (1982) 2370; A. V. Manohar & M. B. Wise, NPB 399 (1993) 17]
- Discovery of the double-charmed baryon $\Xi_{cc}^{++} = (ccu)$ by the LHCb Collab. last year has evoked a lot of theoretical and phenomenological interest in the double-bottom baryons and double-bottom tetraquarks $T^{\{bb\}}_{[\bar{q}\bar{q}']}$, where $[\bar{q}\bar{q}'] = [\bar{u}\bar{d}], [\bar{u}\bar{s}], [\bar{d}\bar{s}]$
- Masses of the ground state tetraquarks are estimated to be below the corresponding BB^* thresholds; hence, they are expected to decay weakly
- Their experimental observation would herald a new era in multiquark physics
- Masses of their partners $T^{\{cc\}}_{[\bar{q}\bar{q}']}$, $T^{\{bc\}}_{[\bar{q}\bar{q}']}$, and $T^{[bc]}_{\{\bar{q}\bar{q}'\}}$ are either close to the thresholds or larger; most likely they will decay strongly in a pair of mesons

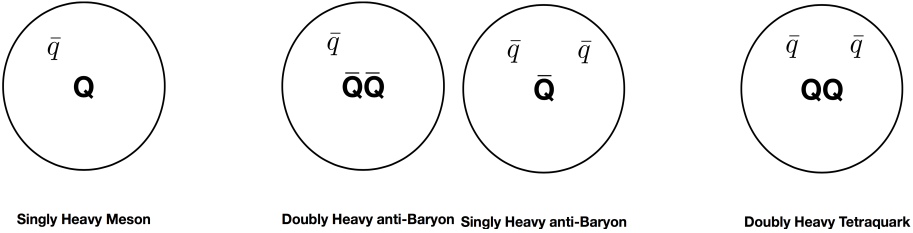
$SU(3)_F$-Triplet of Stable Double-Bottom Tetraquarks

- Double-heavy diquark: color $\bar{3}$, spin $S_{\{bb\}} = 1$
- Light antidiquark: color 3, spin $S_{[\bar{q}\bar{q}']} = 0$
- Ground DHTQ states: $L = 0$
- Spin-parity of DHTQ: $J^P = 1^+$





HQ Symmetry relations involving heavy Mesons, Baryons and Tetraquarks

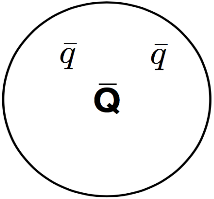


- Heavy quark symmetry relates a singly heavy meson $Q\bar{q}$ and a doubly heavy antibaryon $\bar{Q}\bar{Q}\bar{q}$
- Likewise, it relates a singly heavy antibaryon $\bar{Q}\bar{q}\bar{q}$ and a doubly heavy tetraquark $QQ\bar{q}\bar{q}$

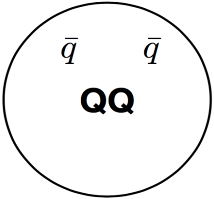
Stable Heavy Tetraquarks $T(QQ\bar{q}\bar{q}')$, $(QQ = cc, cb, bb)$

Heavy Quark-Diquark Symmetry (HQDQS)

$m_Q \to \infty$ **QQ is compact object in color $\bar{\mathbf{3}}$**



Singly Heavy anti-Baryon



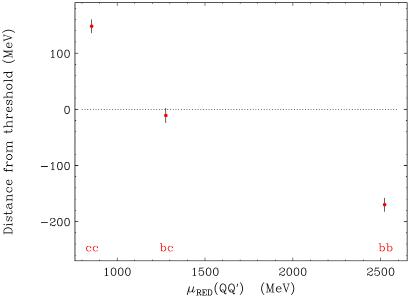
Doubly Heavy Tetraquark

l.d.o.f are the same in these hadrons

Distance from Thresholds for DHTQs

[M. Karliner & J. L. Rosner, PRL 119 (2017) 202001]

- Distance from threshold (in MeV) for the lowest-mass DHTQs $T^{\{cc\}}_{[\bar{u}\bar{d}]}$, $T^{[bc]}_{[\bar{u}\bar{d}]}$, and $T^{\{bb\}}_{[\bar{u}\bar{d}]}$ with spin-parity $J^P = 1^+, 0^+, 1^+$
- Corresponding thresholds are $D^0 D^+ \gamma$, $\bar{B}^0 D^0$, and $\bar{B}^0 B^- \gamma$



- $M\left(T^{\{cc\}}_{[\bar{u}\bar{d}]}\right) = (3882 \pm 12)$ MeV, $\quad Q = +148$ MeV
- $M\left(T^{[bc]}_{[\bar{u}\bar{d}]}\right) = (7134 \pm 13)$ MeV, $\quad Q = -11$ MeV
- $M\left(T^{\{bb\}}_{[\bar{u}\bar{d}]}\right) = (10389 \pm 12)$ MeV, $\quad Q = -170$ MeV

Heavy Quark Symmetry involving Heavy Mesons, Baryons and Tetraquarks

[A. Manohar, M. Wise (1993); E. Eichten, C. Quigg, PRL 119, 202002 (2017)]

- In the HQS limit, following relations hold among the masses

$$
\begin{aligned}
m(\{Q_iQ_j\}\{\bar{q}_k\bar{q}_l\}) - m(\{Q_iQ_j\}q_y) &= m(Q_x\{q_kq_l\}) - m(Q_x\bar{q}_y) \\
m(\{Q_iQ_j\}[\bar{q}_k\bar{q}_l]) - m(\{Q_iQ_j\}q_y) &= m(Q_x[q_kq_l]) - m(Q_x\bar{q}_y) \\
m([Q_iQ_j]\{\bar{q}_k\bar{q}_l\}) - m([Q_iQ_j]q_y) &= m(Q_x\{q_kq_l\}) - m(Q_x\bar{q}_y) \\
m([Q_iQ_j][\bar{q}_k\bar{q}_l]) - m([Q_iQ_j]q_y) &= m(Q_x[q_kq_l]) - m(Q_x\bar{q}_y)
\end{aligned}
$$

  $\{Q_iQ_j\}$ and $[Q_iQ_j]$ denote symmetric or antisymmetric flavors

- The dissociation $Q_iQ_j\bar{q}_k\bar{q}_l \to Q_i\bar{q}_k + Q_j\bar{q}_l$ is kinematically forbidden for sufficiently heavy quarks. Follows from the $\mathcal{Q}$ value for the decay

$$
\begin{aligned}
\mathcal{Q} &\equiv m(Q_iQ_j\bar{q}_k\bar{q}_l) - [m(Q_i\bar{q}_k) + m(Q_j\bar{q}_l)] \\
&= \Delta(q_k, q_l) - \tfrac{1}{2}\left(\tfrac{2}{3}\alpha_s\right)^2 [1 + O(v^2)]\overline{M} + O(1/\overline{M}) \, ,
\end{aligned}
$$

  $\Delta(q_k, q_l)$ is independent of the heavy-quark masses, α_s is the strong coupling, and $\overline{M} \equiv (1/m_{Q_i} + 1/m_{Q_j})^{-1}$ is the reduced mass; the middle term dominates, which is negative, so the tetraquark is stable against decay into two heavy-light mesons

Heavy Quark Symmetry Relations

[A. Manohar, M. Wise (1993); E. Eichten, C. Quigg, PRL 119, 202002 (2017)]

- Decay channel to a doubly heavy baryon and a light antibaryon

$$(Q_i Q_j \bar{q}_k \bar{q}_l) \to (Q_i Q_j q_m) + (\bar{q}_k \bar{q}_l \bar{q}_m)$$

  In the HQS limit,

$$m(Q_i Q_j \bar{q}_k \bar{q}_l) - m(Q_i Q_j q_m) = m(Q_x q_k q_l) - m(Q_x \bar{q}_m)$$

- It has the generic form $\Delta_0 + \Delta_1 / M_{Q_x}$. Using $m(\Lambda_c) - m(D) = 416.87$ MeV, $m(\Lambda_b) - m(B) = 340.26$ MeV, $m_c \equiv m(J/\psi)/2 = 1.55$ GeV, $m_b \equiv m(\Upsilon)/2 = 4.73$ GeV, one finds $\Delta_0 = 303$ MeV, $\Delta_1 = 176.6$ MeV^2
- All these mass differences are smaller than the mass of the lightest antibaryon, $m(\bar{p}) = 938.27$ MeV, and hence decay to a doubly heavy baryon and a light antibaryon is kinematically not allowed
- Thus, in HQS limit, stable $Q_i Q_j \bar{q}_k \bar{q}_l$ mesons must exist

Beyond the Heavy-Quark Limit

[E. Eichten, C. Quigg, PRL 119, 202002 (2017)]

- LO corrections to HQS come from the spin-dependent and K.E. shifts

$$\delta m = \mathcal{S}\frac{\vec{S}\cdot\vec{j}_\ell}{2\mathcal{M}} + \frac{\mathcal{K}}{2\mathcal{M}}$$

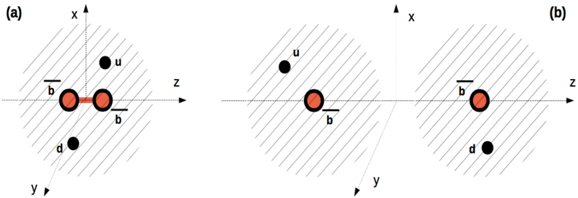
- $\mathcal{M} = m_{Q_i}$ or $m_{Q_i} + m_{Q_j}$, $\vec{j}_\ell$ the spin current of lights quarks and the coefficients $\mathcal{S}$ and $\mathcal{K}$ are determined from experiment

Expectations for ground-state tetraquark masses

State	J^P	$m(Q_iQ_j\bar{q}_k\bar{q}_l)$	Decay Channel	$\mathcal{Q}$ [MeV]
$\{cc\}[\bar{u}\bar{d}]$	1^+	3978	D^+D^{*0} 3876	102
$\{cc\}[\bar{q}_k\bar{s}]$	1^+	4156	$D^+D_s^{*-}$ 3977	179
$\{cc\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	4146, 4167, 4210	D^+D^0, D^+D^{*0} 3734, 3876	412, 292, 476
$[bc][\bar{u}\bar{d}]$	0^+	7229	B^-D^+/B^0D^0 7146	83
$[bc][\bar{q}_k\bar{s}]$	0^+	7406	B_sD 7236	170
$[bc]\{\bar{q}_k\bar{q}_l\}$	1^+	7439	B^*D/BD^* 7190/7290	249
$\{bc\}[\bar{u}\bar{d}]$	1^+	7272	B^*D/BD^* 7190/7290	82
$\{bc\}[\bar{q}_k\bar{s}]$	1^+	7445	DB_s^* 7282	163
$\{bc\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	7461, 7472, 7493	BD/B^*D 7146/7190	317, 282, 349
$\{bb\}[\bar{u}\bar{d}]$	1^+	10482	$B^-\bar{B}^{*0}$ 10603	−121
$\{bb\}[\bar{q}_k\bar{s}]$	1^+	10643	$\bar{B}\bar{B}_s^*/\bar{B}_s\bar{B}^*$ 10695/10691	−48
$\{bb\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	10674, 10681, 10695	B^-B^0, B^-B^{*0} 10559, 10603	115, 78, 136

QCD dynamics of a doubly heavy tetraquarks $T(QQ\bar{q}\bar{q}')$, $(QQ = cc, cb, bb)$

[P. Bicudo et al., Phys.Rev. D95, 142001 (2017)]

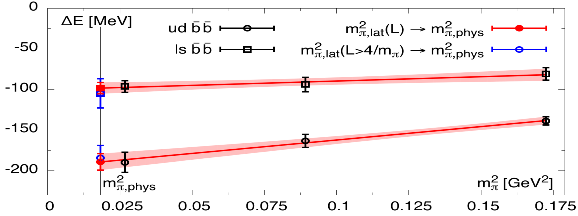


- At very short $\bar{b}\bar{b}$ distances, the interaction is Coulomb-like, given by one-gluon exchange (a)
- At large $\bar{b}\bar{b}$ separations, the light quarks ud screen the interaction, and the four quarks form two rather weakly interacting $B\, B^*$ mesons (b)
- Using this (Born-Oppenheimer) potential, a coupled-channel Schrödinger equation is solved, leading to a bound state, whose mass is estimated as $M(\mathcal{T}^{\{bb\}-}_{[\bar{u}\bar{d}]}) = 10545^{+38}_{-30}$ MeV.

Lattice QCD estimates of $bb\bar{u}\bar{d}$ tetraquark mass using NRQCD

[A. Francis et al., PRL 118, 142001 (2017)]

- Chiral extrapolations of the $ud\bar{b}\bar{b}$ and $qs\bar{b}\bar{b}$ binding energies
- $M(\mathcal{T}^{\{bb\}-}_{[\bar{u}\bar{d}]}) = 10415 \pm 10\,\mathrm{MeV}$
- $M(\mathcal{T}^{\{bb\}-}_{[\bar{q}\bar{s}]}) = 10549 \pm 8\,\mathrm{MeV}$
- Both lie below their respective thresholds



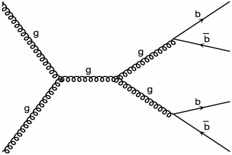
Prospects of observing Double-bottom Tetraquarks at the LHC

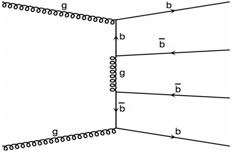
[AA, Qin Qin, Wei Wang, Phys. Lett. B785, 605 (2018).]

- Dominant partonic process at the LHC:

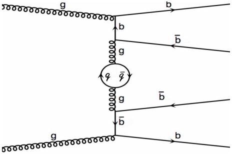
$$gg \to b\bar{b}b\bar{b} + X; q\bar{q} \to b\bar{b}b\bar{b} + X$$

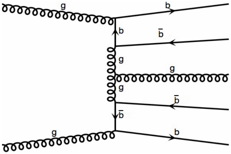
  - LO Diagrams ($gg \to b\bar{b}b\bar{b}$)





  - NLO Diagrams ($gg \to b\bar{b}b\bar{b} + (g)$)



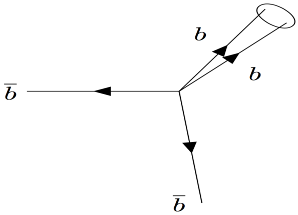


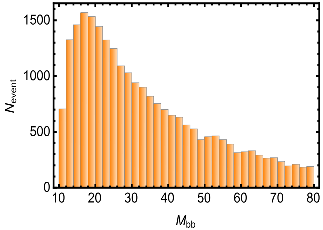
Prospects of observing Stable Tetraquarks at the LHC

[AA, Qin Qin, Wei Wang, Phys. Lett. B785, 605 (2018).]

- Using the CT14 NNLO PDF, MadGraph, and Pythia, at $\sqrt{s} = 13$ TeV:

$$\sigma(pp \to b\bar{b}b\bar{b} + X) = (463 \pm 4 \text{ nb})$$





- Double-b-hadrons, such as the tetraquark $T^{\{bb\}}_{[\bar{u}\bar{d}]}$ and double-b baryons Ξ^{q}_{bb}, are the fragmentation products of the $(bb)_{\text{Jet}}$
- They are anticipated to populate low-M_{bb} invariant mass region

Estimates of the $(bb)_{\rm Jet}$-parameter ΔM

[AA, Qin Qin, Wei Wang, Phys. Lett. B785, 605 (2018).]

- From $pp \to b\bar{b}b\bar{b} + ...$, calculate $pp \to T^{\{bb\}}_{[\bar{u}\bar{d}]}\bar{b}\bar{b} + ...$ using the invariant mass cut $M(T^{\{bb\}}_{[\bar{u}\bar{d}]})^2 \leq M(bb)^2_{\rm Jet} \leq (2m_b + \Delta M)^2$
- To determine ΔM, use $pp \to b\bar{b}c\bar{c} + ... \to B_c^{\pm} + X$ as a bench-mark
- At $\sqrt{s} = 8$ TeV, $0 < p_{\rm T} < 20$ GeV, and $2.0 < y < 4.5$
  [R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **114**, 132001 (2015)]

$$R \equiv \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)} = (0.683 \pm 0.018 \pm 0.009)$$

- With $\sigma(B^+)$ and $\mathcal{B}(B^+ \to J/\psi K^+)$ measured by LHCb, this yields

$$\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+) = (0.36 \pm 0.03)\ \text{nb}$$

- To extract $\sigma(B_c^+)$, need to know $\mathcal{B}(B_c^+ \to J/\psi\pi^+)$, for which we use estimates from pQCD [Z. Rui *et al.*, Eur. Phys. J. C **76**, 564 (2016)] and NRQCD [C. F. Qiao *et al.*, Phys. Rev. D **89**, 034008 (2014)]
- This yields: $\sigma(pp \to B_c^+ X) = (139^{+34}_{-41})$ nb (pQCD),
  $\sigma(pp \to B_c^+ X) = (124^{+28}_{-19})$ nb (NRQCD)

Estimates of the $(bb)_{\rm Jet}$-parameter ΔM

[AA, Qin Qin, Wei Wang, Phys. Lett. B785, 605 (2018).]

- Next, we use MadGraph [J. Alwall *et al.*, JHEP **1407**, 079 (2014)] to calculate the cross section for the process $pp \to \bar{b}b\bar{c}c + X$ at $\sqrt{s} = 8$ TeV,

$$\sigma(pp \to \bar{b}b\bar{c}c + X) = (4.79 \pm 0.08) \times 10^3 \text{ nb}$$

- $\Longrightarrow$ fragm. fraction ($p_{\rm T}(B_c^+) < 20$ GeV, $2.0 < y(B_c^+) < 4.5$):

$$f(c\bar{b} \to B_c^+) = (2.9^{+0.7}_{-0.8})\% \text{ (pQCD)},$$
$$f(c\bar{b} \to B_c^+) = (2.6^{+0.5}_{-0.3})\% \text{ (NRQCD)}$$

- This, in turn, leads to an estimate of the jet-cone invariant mass $\Delta M_{c\bar{b}}$

$$\Delta M_{c\bar{b}} = (2.0^{+0.5}_{-0.4}) \text{ GeV (pQCD)},$$
$$\Delta M_{c\bar{b}} = (1.9^{+0.3}_{-0.3}) \text{ GeV (NRQCD)},$$

- We assume $\Delta M_{bb} = \Delta M_{c\bar{b}} = (2.0^{+0.5}_{-0.4})$ GeV(pQCD) to calculate

$$\sigma(pp \to H_{\{bb\}} + X) = (14.8^{+5.4}_{-3.7}) \text{ nb}$$

Estimates of the $(bb)_{\text{Jet}}$-parameter ΔM

[AA, Qin Qin, Wei Wang, Phys. Lett. B785, 605 (2018).]

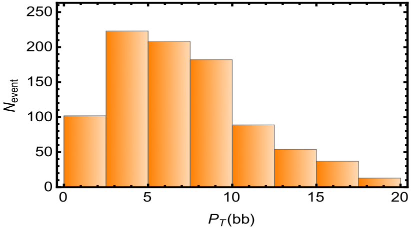
- $H_{\{bb\}}$ includes mainly the double-bottm tetraquarks $T^{\{bb\}}_{[\bar{q}\bar{q}']}$, bb-baryons $\Xi^0_{bb}(bbu)$, $\Xi^-_{bb}(bbd)$, and $\Omega^-_{bb}(bbs)$, and their excited states
- Fragmentation of a (bb)-jet: The fractions $f(H_{\{bb\}} \to T^{\{bb\}}_{[\bar{q}\bar{q}']})$, $f(H_{\{bb\}} \to \Xi_{bb}(bbq))$ and $f(H_{\{bb\}} \to \Omega^-_{bb}(bbs))$ are not known
- Involve a light anti-diquark pair excitation $(\bar{q}\bar{q}')$ to form $T^{\{bb\}}_{[\bar{q}\bar{q}']}$, and of a light $(q\bar{q})$ pair to form the baryons $\Xi_{bb}(bbq)$ and $\Omega^-_{bb}(bbs)$
- Assume, appealing to the heavy quark - heavy diquark symmetry, that they are similar to the measured ones in a single b-quark jet
  [R. Aaij *et al.* [LHCb Collaboration], JHEP **1408**, 143 (2014)]

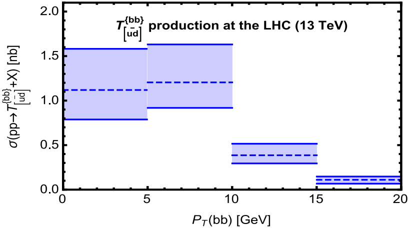
$$\left[\frac{f_{\Lambda_b}}{f_{B_u} + f_{B_d}}\right](p_T) = (0.404 \pm 0.036) \times [1 - (0.031 \pm 0.005) p_T(\text{GeV})]$$

Estimates of $\sigma(pp \to T^{\{bb\}}_{[\bar{q}\bar{q}']} + X)$ and $T^{\{bb\}}_{[\bar{q}\bar{q}']}(p_T)$-Distribution at LHC

[AA, Qin Qin, Wei Wang, Phys. Lett. B785, 605 (2018).]

- Need $(bb)_{\text{jet}}(p_T)$-distribution in $pp \to (bb)_{\text{jet}} + \bar{b} + \bar{b} + X$
- Convolute with the $\left[\frac{f_{\Lambda_b}}{f_{B_u}+f_{B_d}}\right](p_T)$ to get $T^{\{bb\}}_{[\bar{q}\bar{q}']}(p_T)$-Distribution





- X-sections $(T^{\{bb\}}_{[\bar{q}\bar{q}']}(p_T) \leq 20\text{ GeV},\ 2.0 \leq y(T^{\{bb\}}_{[\bar{q}\bar{q}']}) \leq 4.5,\ \sqrt{s} = 13\text{TeV})$

$$\sigma(pp \to T^{\{bb\}}_{[\bar{u}\bar{d}]} + X) = (2.8^{+1.0}_{-0.7})\text{ nb}$$

- $\sigma(pp \to T^{\{bb\}}_{[\bar{u}\bar{s}]} + X) = \sigma(pp \to T^{\{bb\}}_{[\bar{d}\bar{s}]} + X) \simeq 1/4\sigma(pp \to T^{\{bb\}}_{[\bar{u}\bar{d}]} + X)$
- $\sigma(pp \to (\Xi^0_{bb}, \Xi^-_{bb}, \Omega^-_{bb}) + X) : \sigma(pp \to T^{\{bb\}}_{[\bar{q}\bar{q}']} + X) \approx 2.4$

Estimates of the lifetime for $T^{\{bb\}}_{[\bar{u}\bar{d}]}$ using heavy quark expansion

[AA, A. Parkhomenko, Qin Qin, Wei Wang, Phys.Lett. B782, 412 (2018).]

- HQE simplifies the inclusive decay widths. Up to dimension 6 :

$$\mathcal{T} = \frac{G_F^2 m_b^5}{192\pi^3}|V_{CKM}|^2\Big[c_{3,b}\bar{b}b + \frac{c_{5,b}}{m_b^2}\bar{b}g_s\sigma_{\mu\nu}G^{\mu\nu}b + 2\frac{c_{6,b}}{m_b^3}(\bar{b}q)_\Gamma(\bar{q}b)_\Gamma + ...\Big]$$

- At leading order in $1/m_b$, only the $\bar{b}b$ operator contributes:

$$\Gamma(T^{\{bb\}}_{[\bar{q}\bar{q}']}) = \frac{G_F m_b^5}{192\pi^3}|V_{CKM}|^2 c_{3,b}\frac{\langle T^{\{bb\}}_{[\bar{q}\bar{q}']}|\bar{b}b|T^{\{bb\}}_{[\bar{q}\bar{q}']}\rangle}{2m_{T^{\{bb\}}_{[\bar{q}\bar{q}']}}}$$

- $\frac{\langle T^{\{bb\}}_{[\bar{q}\bar{q}']}|\bar{b}b|T^{\{bb\}}_{[\bar{q}\bar{q}']}\rangle}{2m_{T^{\{bb\}}_{[\bar{q}\bar{q}']}}}$ corresponds to the bottom-quark number in $T^{\{bb\}}_{[\bar{q}\bar{q}']}$, and is twice the matrix element for B meson and Λ_b baryon
- Hence, expect $\tau(T^{\{bb\}}_{[\bar{u}\bar{d}]}) \simeq 1/2\tau(B)$:

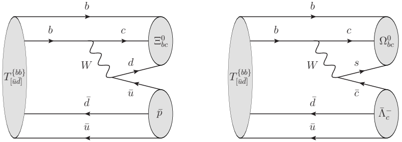
$$\tau(T^{\{bb\}}_{[\bar{q}\bar{q}']}) \sim \frac{1}{2}\times 1.6\times 10^{-12}s = 800\times 10^{-15}s$$

Weak Decays of $T^{\{bb\}}_{[\bar{u}\bar{d}]}$

- Effective Weak Hamiltonian

$$
\begin{aligned}
\mathcal{H}_{\text{eff}}^{(cc)} &= \frac{4G_F}{\sqrt{2}} V_{cb}V_{ud}^* \Big\{ C_1 \left[\bar{c}_\alpha \gamma_\mu P_L b^\alpha\right] \left[\bar{d}_\beta \gamma^\mu P_L u^\beta\right] \\
&\qquad + C_2 \left[\bar{c}_\beta \gamma_\mu P_L b^\alpha\right] \left[\bar{d}_\alpha \gamma^\mu P_L u^\beta\right] \Big\} \\
&+ \frac{4G_F}{\sqrt{2}} V_{cb}V_{cs}^* \Big\{ C_1 \left[\bar{c}_\alpha \gamma_\mu P_L b^\alpha\right] \left[\bar{s}_\beta \gamma^\mu P_L c^\beta\right] \\
&\qquad + C_2 \left[\bar{c}_\beta \gamma_\mu P_L b^\alpha\right] \left[\bar{s}_\alpha \gamma^\mu P_L c^\beta\right] \Big\} + \text{h. c.}
\end{aligned}
$$

- Two-Body Baryonic Decays from $b \to c + d + \bar{u}$ (left panel) and $b \to c + s + \bar{c}$ (right panel)



An order of magnitude estimate

- Involve non-factorizable Amplitudes . For the $J^P = 1^+$ tetraquark, the general form of the decay amplitude is:

$$\begin{aligned}\mathcal{M}(T^{\{bb\}-}_{[\bar{u}\bar{d}]} \to \Xi^0_{bc}\,\bar{p}) = \bar{v}(p_p)\Big[&f_1^{\Xi_{bc}\bar{p}}\,q_\mu + f_2^{\Xi_{bc}\bar{p}}\,\gamma_\mu \\ &+ f_3^{\Xi_{bc}\bar{p}}\,\sigma_{\mu\nu}\,\frac{q^\nu}{M_T} + g_1^{\Xi_{bc}\bar{p}}\,\gamma_5\,q_\mu + g_2^{\Xi_{bc}\bar{p}}\,\gamma_\mu\gamma_5 \\ &+ g_3^{\Xi_{bc}\bar{p}}\,\sigma_{\mu\nu}\gamma_5\,\frac{q^\nu}{M_T}\Big]\,u(p_{\Xi_{bc}})\,\varepsilon^\mu_T(p_T)\end{aligned}$$

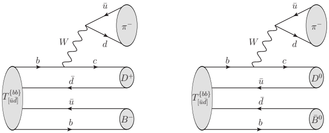
- Inspired by the B meson decay data

$$\begin{aligned}\mathcal{B}(\overline{B}^0 \to D^+\pi^-) &= (2.52 \pm 0.13) \times 10^{-3} \\ \mathcal{B}(\overline{B}^0 \to D^+ D_s^-) &= (7.2 \pm 0.8) \times 10^{-3}\end{aligned}$$

- Infer that $\mathcal{B}(T^{\{bb\}-}_{[\bar{u}\bar{d}]} \to \Xi^0_{bc}\,\bar{p})$ and $\mathcal{B}(T^{\{bb\}-}_{[\bar{u}\bar{d}]} \to \Omega^0_{bc}\,\bar{\Lambda}_c^-)$ are of $O(10^{-3})$
- Needs reconstructing the doubly heavy baryons Ξ^0_{bc} and Ω^0_{bc}, such as through $\Xi^0_{bc} \to \Lambda_b K^- \pi^+$, expect the two-body baryonic decay modes of $T^{\{bb\}-}_{[\bar{u}\bar{d}]}$ can have branching fractions of order 10^{-6}

Three-body Mesonic Decay Modes of $T^{\{bb\}-}_{[\bar{u}\bar{d}]}$

- Feynman diagrams due to the b-quark decay $b \to c + d + \bar{u}$



- The factorizable amplitudes of these decays can be written as:

$$\mathcal{M}(T^{\{bb\}-}_{[\bar{u}\bar{d}]} \to B^- \, D^+ \, \pi^-) = i \, \frac{G_F}{\sqrt{2}} \, V_{cb} V^*_{ud} \, a_1^{\text{eff}} f_\pi \, p_\pi^\mu$$

$$\times \langle (BD)^0_{J_{BD}} (p_{BD}) \left| \bar{d} \gamma_\mu \, (1 - \gamma_5) \, u \right| T^{\{bb\}-}_{[\bar{u}\bar{d}]} (p_T) \rangle,$$

$$\mathcal{M}(T^{\{bb\}-}_{[\bar{u}\bar{d}]} \to \bar{B}^0 \, D^0 \, \pi^-) = i \, \frac{G_F}{\sqrt{2}} \, V_{cb} V^*_{ud} \, a_1^{\text{eff}} f_\pi \, p_\pi^\mu$$

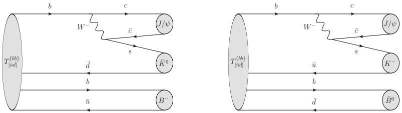
$$\times \langle (BD)^0_{J_{BD}} (p_{BD}) \left| \bar{s} \gamma_\mu \, (1 - \gamma_5) \, c \right| T^{\{bb\}-}_{[\bar{u}\bar{d}]} (p_T) \rangle$$

$$\mathcal{B}(T^{\{bb\}}_{[\bar{u}\bar{d}]} \to B^- D^+ \pi^-) = \mathcal{B}(T^{\{bb\}}_{[\bar{u}\bar{d}]} \to \bar{B}^0 D^0 \pi^-) \sim 0.5 \times 10^{-3}$$

Hidden-Charm final states in $T^{\{bb\}-}_{[\bar{u}\bar{d}]}$ decays

- In some decays hidden-charm mesons, such as J/ψ, ψ', can be produced

$$T^{\{bb\}}_{[\bar{u}\bar{d}]} \to J/\psi \overline{K}^0 B^-,$$
$$T^{\{bb\}}_{[\bar{u}\bar{d}]} \to J/\psi K^- \overline{B}^0$$



- Their decay branching ratios can be comparable with the $\mathcal{B}(B \to J/\psi K)$:

$$\mathcal{B}(\overline{B}^0 \to J/\psi \overline{K}^0) \quad = \quad (8.73 \pm 0.32) \times 10^{-4}$$

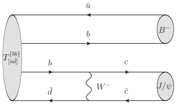
- Expect that the product branching ratios to measure the mass of $T^{\{bb\}-}_{[\bar{u}\bar{d}]}$ are at most of $O(10^{-5})$

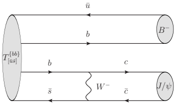
Weak Annihilation Decays of Stable DHTQs

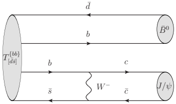
[AA, A. Parkhomenko, Qin Qin, Wei Wang, Phys.Lett. B782, 412 (2018).]

- Weak annihilation decays are determined by W-exchange diagrams
- Of interest for LHC are modes with J/ψ-meson production

$$T^{\{bb\}-}_{[\bar{u}\bar{d}]} \to B^- J/\psi, \qquad T^{\{bb\}-}_{[\bar{u}\bar{s}]} \to B^- J/\psi, \qquad T^{\{bb\}0}_{[\bar{d}\bar{s}]} \to \bar{B}^0 J/\psi$$







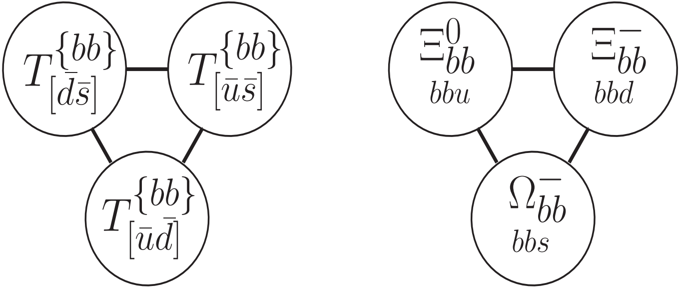
- Described by factorizable amplitudes

$$\mathcal{M}(T^{\{bb\}-}_{[\bar{u}\bar{s}]} \to B^- J/\psi) = \frac{G_F}{\sqrt{2}} V_{cb} V^*_{cs} a_2^{\text{eff}} m_\psi f_\psi \, \varepsilon^{*\mu}_\psi \langle B^- | \bar{s}\gamma_\mu (1-\gamma_5) b | T^{\{bb\}-}_{[\bar{u}\bar{s}]} \rangle$$

- The general decomposition of $T^{\{bb\}-}_{[\bar{u}\bar{s}]} \to B$ transition is similar to $B \to A$ transition matrix element; one needs to know form factors
- Decay $T^{\{bb\}-}_{[\bar{u}\bar{d}]} \to B^- J/\psi$ is suppressed due to the CKM factor V^*_{cd} by approximately the factor 25

Outlook

- Great potential of discovering double-bottom tetraquarks $T^{\{bb\}}_{[\bar{q}\bar{q}']}$ and double-bottom baryons Ξ^0_{bb}, Ξ^-_{bb}, Ω^-_{bb} at the LHC!



- Will establish diquarks as fundamental constituents of hadronic matter!!