Double-bottom Tetraquarks - Production, Decays, and Lifetimes

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- Introduction
- Spectroscopy of doubly-heavy Tetraquarks
- Production cross sections of double-bottom hadrons at the LHC
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- Exclusive weak decays of $T^{\{bb\}}_{[\bar{q}\bar{q}']}$
- Detached B_c-vertices as a signature of double-bottom hadrons
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Introduction

- Stable (w.r.t. strong decays) heavy multiquark states were predicted a long time ago [J. P. Ader et al., PRD 25 (1982) 2370; A. V. Manohar & M. B. Wise, NPB 399 (1993) 17, D. Ebert *et al.*, PRD 76 (2007), 114015]

- Discovery of the double-charmed baryon $\Xi_{cc}^{++} = (ccu)$ [R. Aaij *et al.* (LHCb), PRL 119 (2017) 112001] , and more recently, of the double-charmed tetraquark $T_{cc}^{+} = (cc\bar{u}\bar{d})$ [R. Aaij *et al.* (LHCb), arxiv:2109.01038] has evoked a lot of theoretical and phenomenological interest in the double-bottom baryons and double-bottom tetraquarks $T_{[\bar{q}\bar{q}']}^{\{bb\}}$, where $[\bar{q}\bar{q}'] = [\bar{u}\bar{d}], [\bar{u}\bar{s}], [\bar{d}\bar{s}]$

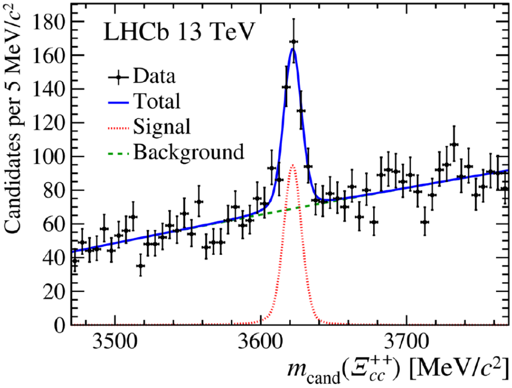
- Heavy Quark - Heavy Diquark Symmetry relates singly heavy mesons, anti-baryons and doubly-heavy baryons and tetraquarks [T. Mehen; E. Eichten & C. Quigg;....]

Discovery of Double-Charm Baryon

R. Aaij *et al.*, PRL 119 (2017) 112001

$$M(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}$$

$$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.012}(\text{stat.}) \pm 0.014(\text{syst.})\ \text{ps}$$

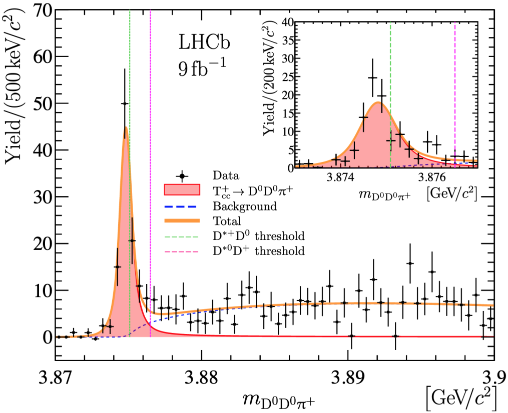


Observation of an exotic doubly charmed tetraquark

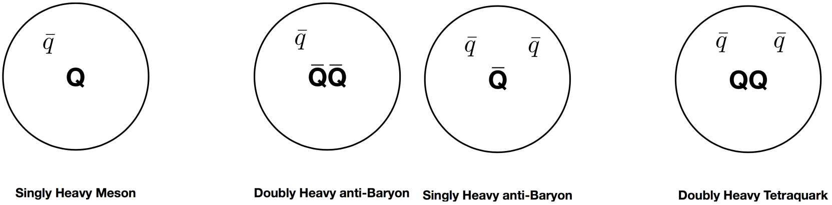
R. Aaij *et al.*, arxiv:2109.01038 & CERN-EP-2021-65

$$\delta m_{\rm BW} = M(T_{cc}^+) - (M_{D^{*+}} - M_{D^0}) = -273 \pm 61(\text{stat.}) \pm 5(\text{syst.})^{+11}_{-14}(J^P)\ \text{keV}$$

$$\Gamma_{\rm BW}(T_{cc}^+) = 410 \pm 165(\text{stat.}) \pm 43(\text{syst.})^{+18}_{-38}(J^P)\ \text{keV}$$



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 $QQ\bar{q}\bar{q}$

Spectroscopy of Doubly-Heavy Tetraquarks

- Constituent quark-diquark model based estimates

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

- Estimates from Heavy Quark Symmetry and corrections

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

  Including diquark-size mass corrections

  Haipeng An, Mark B. Wise, PL B788 (2019), 131

- Estimates based on Born-Oppenheimer approximation and Lattice QCD

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

- Lattice QCD estimates

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

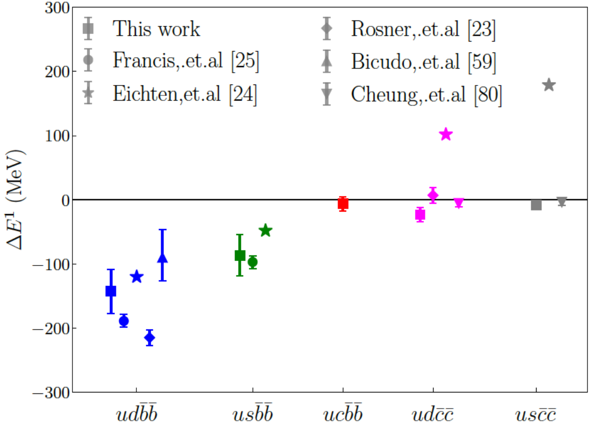
  P. Junnarkar, N. Mathur, M. Padmanath, PR D99 (2019) 034507

  L. Leskovec et al., PR D100 (2019) 014503

  Hadron Spectrum Coll.

Global results for the binding energy ΔE on spin-1 doubly-heavy tetraquarks

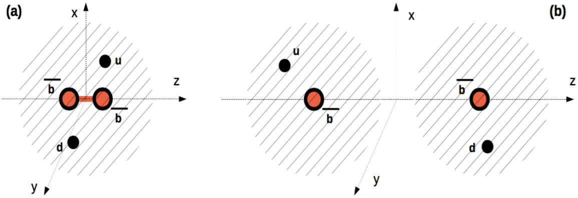
[P. Junnarkar, N. Mathur, M. Padmanath, PR D99 (2019) 034507]



- Consensus that $J^P = 1^+$ doubly-bottom tetraquarks lie below their resp. strong thresholds

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.

PHYSICAL REVIEW D **103,** 114506 (2021)

Importance of meson-meson and of diquark-antidiquark creation operators for a $\bar{b}\bar{b}ud$ tetraquark

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In recent years, the existence of a hadronically stable $\bar{b}\bar{b}ud$ tetraquark with quantum numbers $I(J^P) = 0(1^+)$ was confirmed by first principles lattice QCD computations. In this work we use lattice QCD to compare two frequently discussed competing structures for this tetraquark by considering meson-meson as well as diquark-antidiquark creation operators. We use the static-light approximation, where the two $\bar{b}$ quarks are assumed to be infinitely heavy with frozen positions, while the light u and d quarks are fully relativistic. By minimizing effective energies and by solving generalized eigenvalue problems we determine the importance of the meson-meson and the diquark-antidiquark creation operators with respect to the ground state. It turns out, that the diquark-antidiquark structure dominates for $\bar{b}\bar{b}$ separations $r \lesssim 0.25$ fm, whereas it becomes increasingly more irrelevant for larger separations, where the $I(J^P) = 0(1^+)$ tetraquark is mostly a meson-meson state. We also estimate the meson-meson to diquark-antidiquark ratio of this tetraquark and find around 60%/40%.

DOI: 10.1103/PhysRevD.103.114506

Numerical Results

[P. Bicudo et al., Phys. Rev. D103, 114506 (2021)]

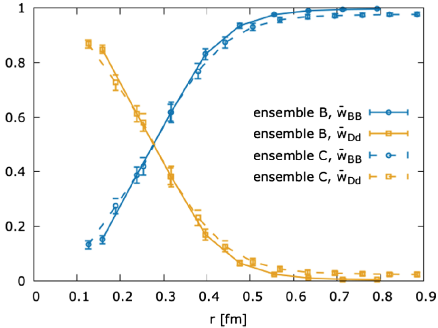
- Creation operators, which excite two B-mesons

$$\mathcal{O}_{BB,\Gamma} \sim (C\Gamma)_{AB}\ (C\tilde{\Gamma})_{CD}\ \left(\bar{Q}^a_C(r_1)\psi^{(f)a}_A(r_1)\right)\ \left(\bar{Q}^b_D(r_2)\psi^{(f)b}_B(r_2)\right)$$

- Diquark-Antidiquark pair with heavy quarks separated by r & connected with a gluonic string

$$\mathcal{O}_{Dd,\Gamma} \sim \epsilon^{abc}\left(\psi^{(f)b}_A(\vec{z})(C\Gamma)_{AB}\psi^{(f')c}_B(\vec{z})\right)\epsilon^{ade}\left(\bar{Q}^f_C(\vec{r}_1)U^{fd}(\vec{r}_1,\vec{z})(C\tilde{\Gamma})_{CD}\ \bar{Q}^g_D(\vec{r}_2)U^{ge}(\vec{r}_2,\vec{z})\right)$$

- Trial states $|\phi_{b,d}\rangle = b|\phi_{BB,(1+\gamma_0)\gamma_5}\rangle + d|\phi_{Dd,(1+\gamma_0)\gamma_5}\rangle$
- $w_{BB} = \frac{|b|^2}{|b|^2+|d|^2}$; $\quad w_{Dd} = \frac{|d|^2}{|b|^2+|d|^2}$
- $\Longrightarrow$ Diquark-configuration dominates over the Meson-meson for $r \lesssim 0.25$ fm



Spectroscopic Expectations

- Masses of the mixed charm-beauty tetraquarks $T^{\{cc\}}_{[\bar{q}\bar{q}']}$, $T^{\{bc\}}_{[\bar{q}\bar{q}']}$, and $T^{[bc]}_{\{\bar{q}\bar{q}'\}}$ are either close to the thresholds or larger; will decay strongly in a pair of mesons

- Masses of the ground state double-bottom tetraquarks are estimated to be below the corresponding BB^* thresholds; hence, they are expected to decay weakly

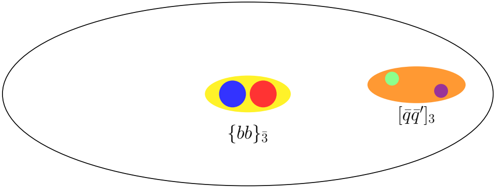
- The Fock space of the double-bottom tetraquarks is expected to consists of a significant fraction of the diquatk-antidiquark configuration

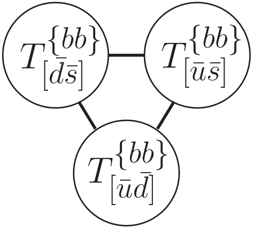
- Experimental Target: Establish the diquark configurations unambiguously through production and characteristic decays

Objects of Interest

$SU(3)_F$-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: $J^P = 1^+$





Experimental Topologies

- Requires production of a large $b\bar{b}b\bar{b}$ data set
- Possible only at LHC and a Tera-Z Factory (FCC, CEPC)
- Topology of interest: (bb)-jet with a small Jet-radius:
  $\Delta R = \sqrt{\Delta\phi(b,b)^2 + \Delta\eta(b,b)^2}$
  An unchartered experimental setup so far
- Typical toplogy: Doubly-b-tagged, 3-jet events
- First studies of $g \to b\bar{b}$-jets with a small jet-radius undertaken by ATLAS at LHC [ATLAS Coll., Phys. Rev. D99, 052004 (2019)]

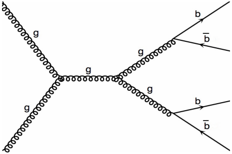
Prospects of observing Double-bottom Tetraquarks at the LHC

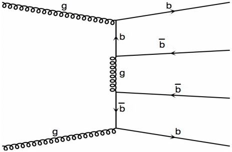
[AA, Qin Qin, Wei Wang, Phys. Lett. B785, 605 (2018).]

- Dominant partonic processes at the LHC:

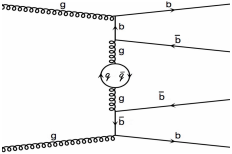
$$gg \to b\bar{b}b\bar{b} + X; \qquad q\bar{q} \to b\bar{b}b\bar{b} + X$$

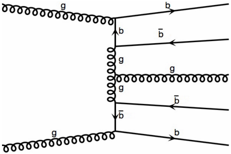
  - LO Diagrams ($gg \to b\bar{b}b\bar{b}$)





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



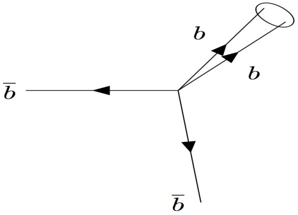


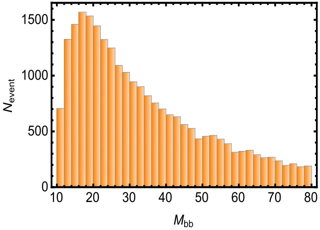
Production cross sections of double-bottom hadrons at the LHC

[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

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

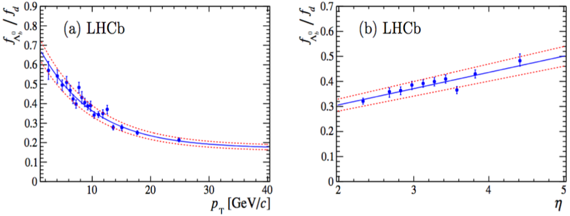
Estimates of the $(bb)_{\mathrm{Jet}}$-parameter ΔM

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

- $H_{\{bb\}}$ includes mainly the double-bottom 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
- The relative probabilities are measured differently at LEP and LHC

$\left[\frac{f_{\Lambda_b}}{f_{B_u}+f_{B_d}}\right](p_T)$ Distribution at LHC

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

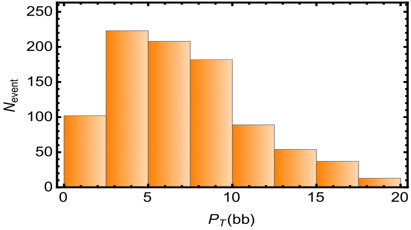


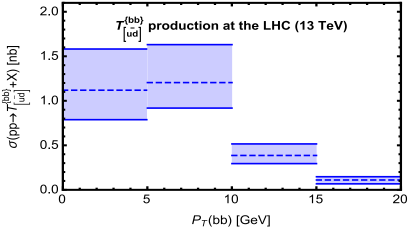
[R. Aaij *et al.* [LHCb Collaboration], JHEP **1408**, 143 (2014)]

- Need $(bb)_{\text{jet}}(p_T)$-distribution in $pp \to (bb)_{\text{jet}} + \bar{b} + \bar{b} + X$ to 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

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

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





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

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

- Using $f_s/f_d = 0.256 \pm 0.020$ in the $b \to B_q$ fragmentation [LHCb] $\Longrightarrow$
- $\sigma(pp \to T^{\{bb\}}_{[\bar{u}\bar{s}]} + X) = \sigma(pp \to T^{\{bb\}}_{[\bar{d}\bar{s}]} + X) \simeq 1/4\sigma(pp \to T^{\{bb\}}_{[\bar{u}\bar{d}]} + X)$
- $\sigma(pp \to (\Xi^0_{bb}, \Xi^-_{bb}, \Omega^-_{bb}) + X)/\sigma(pp \to T^{\{bb\}}_{[\bar{q}\bar{q}']} + X) \approx 2.4$

Inclusive decay widths

- Concentrating on hadrons with a b quark, the starting point is the transition operator $\mathcal{T}(b \to f \to b)$, describing the forward scattering amplitude of b quarks via an intermediate state f

$$\Gamma(H_b) = \frac{1}{2M_{H_b}} \langle H_b | \mathcal{T}(b \to f \to b) | H_b \rangle$$

- To second order in the weak interaction,

$$\mathcal{T}(b \to f \to b) = i \,\mathrm{Im} \int \{\mathcal{L}_W(x)\mathcal{L}_W(0)\}_T$$

  $\mathcal{L}_W(x) = \frac{G_F}{\sqrt{2}}[J_\mu J^{\mu\dagger} + h.c.]$ denotes the effective weak Lagrangian, and $\{.\}_T$ denotes the time-ordered product

- Treating m_b as a large parameter, a Wilson OPE allows to express the non-local operator $\mathcal{T}$ as an infinite sum of local operators with increasing dimensions of $1/m_b$

$$\mathcal{T}(b \to f \to b) = \sum_n C_n(\mu)\mathcal{O}_n(\mu)$$

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:

$$\Gamma(T^{\{bb\}}_{[\bar{q}\bar{q}']}) = \frac{G_F m_b^5}{192\pi^3}|V_{CKM}|^2 c_{3,b}\frac{1}{3}\sum_\lambda \frac{\langle T^{\{bb\}}_{[\bar{q}\bar{q}']}|\bar{b}b|T^{\{bb\}}_{[\bar{q}\bar{q}']}\rangle}{2m_{T^{\{bb\}}_{[\bar{q}\bar{q}']}}}$$

- $\frac{\langle T^{\{bb\}}_{[\bar{q}\bar{q}']}|\bar{b}b|T^{\{bb\}}_{[\bar{q}\bar{q}']}\rangle}{2m_{T^{\{bb\}}_{[\bar{q}\bar{q}']}}}$ 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 $\tau(T^{\{bb\}}_{[\bar{u}\bar{d}]}) \simeq 1/2\tau(B)$:

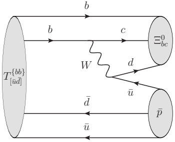
$$\tau(T^{\{bb\}}_{[\bar{q}\bar{q}']}) \sim \frac{1}{2} \times 1.6 \times 10^{-12}s = 800 \times 10^{-15}s$$

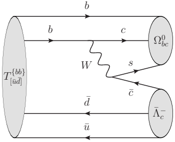
Exclsuive weak Decays of $T^{\{bb\}}_{[\bar{q}\bar{q}']}$

- Tell-Tale signatures: Decays into "wrong-sign" heavy mesons
  [A. Esposito *et al.* , Phys. Rev. D88, 054029 (2013); S.Q. Luo *et al.* , EPJC 77, 709 (2017)]
- Effective Weak Hamiltonian

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

- Two-Body Baryonic Decays from $b \to c + d + \bar{u}$ and $b \to c + s + \bar{c}$





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

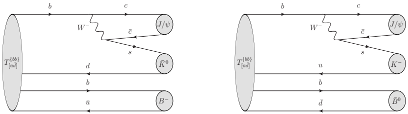
$$\begin{aligned}\mathcal{B}(\overline{B}^0 \to D^+\pi^-) &= (2.52 \pm 0.13) \times 10^{-3} \\ \mathcal{B}(\overline{B}^0 \to D^+D_s^-) &= (7.2 \pm 0.8) \times 10^{-3}\end{aligned}$$

- 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}

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 $\mathcal{B}(B \to J/\psi K)$:

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

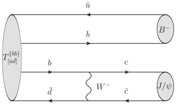
- Expect that the product branching ratios to establish $T^{\{bb\}-}_{[\bar{u}\bar{d}]}$ are at most of $O(10^{-6})$

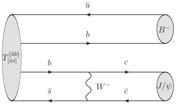
Weak Annihilation Decays of Stable DHTQs

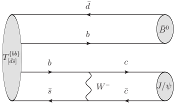
[AA, A. Parkhomenko, Qin Qin, Wei Wang, Phys.Lett. B782, 412 (2018).]

- 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

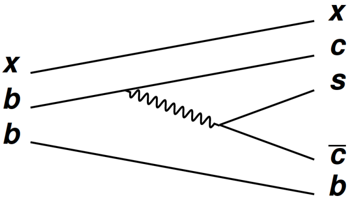
$$\mathcal{M}(T^{\{bb\}-}_{[\bar{u}\bar{s}]} \to B^- \, J/\psi) = \frac{G_F}{\sqrt{2}} \, V_{cb} V^*_{cs} \, a_2^{\rm eff} m_\psi f_\psi \, \varepsilon^{*\mu}_\psi \langle B^- \left| \bar{s} \gamma_\mu \, (1 - \gamma_5) \, b \right| T^{\{bb\}-}_{[\bar{u}\bar{s}]} \rangle$$

- 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 a factor of 25

Detached B_c-vertices as a signature of double-bottom hadrons

[T. Gershon, A. Poluektov, JHEP, 1901 (2019) 019]

- Exclusive approaches appear formidable
- Therefore, go inclusive
- Key observation
  Weakly decaying double beauty hadrons are the only possible source of displaced B_c mesons
- Require $b \to c$ transitions



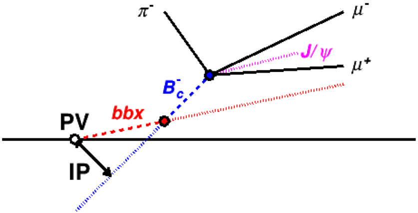
Detached B_c-vertices as a sign of double-bottom hadrons

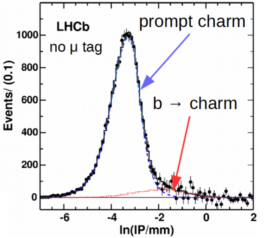
[T. Gershon, A. Poluektov, JHEP, 1901 (2019) 019]

Working example: Displaced charm

Signature of displaced charm used to measure inclusive pp→$b\bar{b}$X production cross-section
LHCb-PAPER-2010-002

Muon tag from semileptonic decay helps to suppress background from prompt charm
→ not possible for displaced B_c analysis
→ (b→$\bar{c}$) instead of (b→c)





signal:background ~ 1:20

still able to distinguish displaced charm with 2.9 nb^{-1}

IP resolution since improved

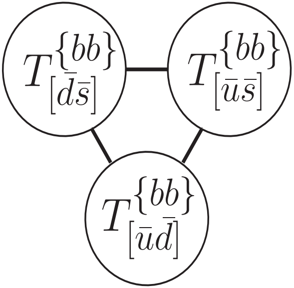
7

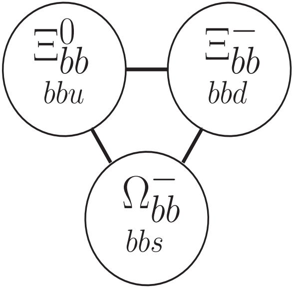
Rate Estimates for Detached B_c-vertices

- $\mathcal{B}(\Xi_{bbq} \to \bar{B}_c^{(*)} + X) = 0.8 \times 10^{-3}$
- $\mathcal{B}(T_{[\bar{q}\bar{q}']}^{\{bb\}-} \to \bar{B}_c^{(*)} + X) \simeq \mathcal{B}(\Xi_{bbq} \to \bar{B}_c^{(*)} + X)$ [Ridgway, Wise, PL B793 (2019) 181]
- $\mathcal{B}(\bar{B}_c \to J/\psi \pi^- \to \mu^+\mu^-\pi^-) \simeq 2 \times 10^{-4}$ [C.F. Qiao et al., , PRD 89 (2014) 034008]
- $\sigma(pp \to H_{\{bb\}} + X) \simeq 15$ nb [AA, Qin, Wang; PL B785 (2018) 605]
- With 9 $(\mathrm{fb})^{-1}$ yield $\sim 10^2$ detached $\mu^+\mu^-\pi^-$ events at LHCb
- Yield an order of magnitude higher for the ATLAS & CMS; worth an attempt with current data!

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 and Tera-Z!





- Hope: Will establish heavy-heavy (Coulomb) diquarks as fundamental constituents of hadronic matter!!