FERMILAB-SLIDES-19-067-T

Narrow $(c\bar{c})$ above Flavor Threshold

B_c excited states

(Stable) Doubly Heavy Tetraquarks

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Fermilab & TUM

Deciphering strong interactions . . . · MIAPP / Garching · October 25, 2019

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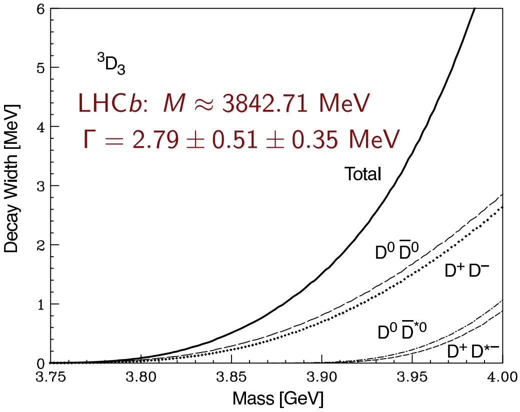
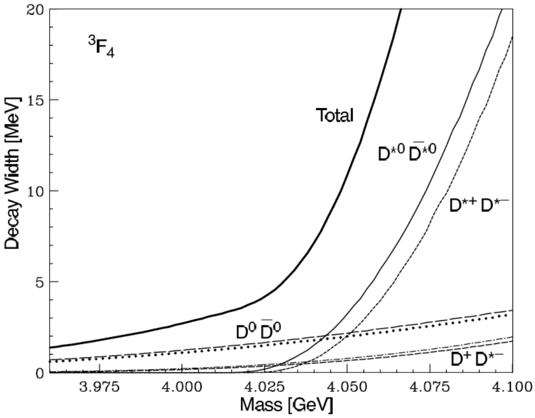
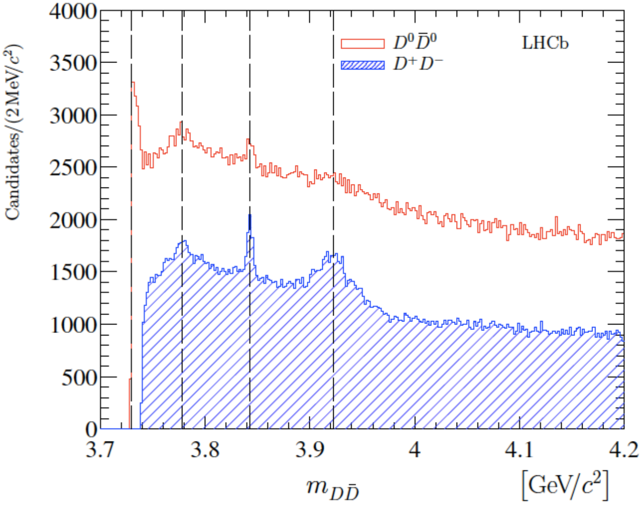
Narrow $(c\bar{c})$ states above flavor threshold





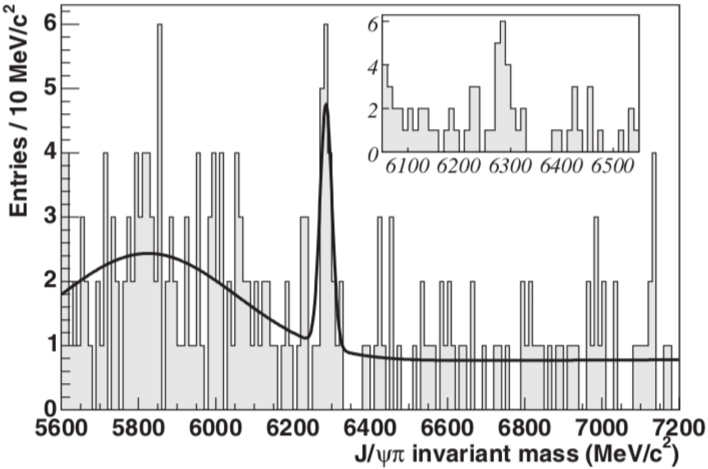
Eichten, Lane, Quigg, Phys. Rev. D **69**, 094019 (2004) / hep-ph/0401210.

LHCb observation of $^3D_3$ candidate



Can we find $^3F_4$, perhaps near 4054 MeV?

Reconstruction of B_c meson (CDF, 2006)



$M(B_c) = 6274.9 \pm 0.8$ MeV (Test of lattice QCD prediction)

Mesons with beauty and charm: stress test for NRQM, LQCD

B_c: weak decays only

$b \to c \qquad c \to s \qquad b\bar{c} \to W^-$

$B_c \to J/\psi\pi$: $(Q\bar{Q})$ transmutation

Rich $(b\bar{c})$ excitation spectrum; interpolates $J/\psi, \Upsilon$ ($\neq$ masses)

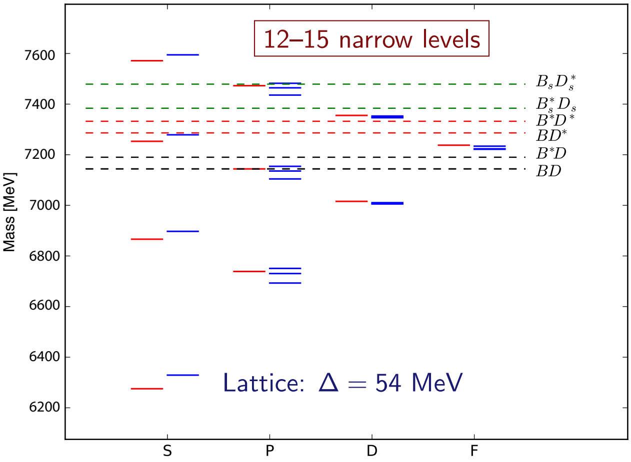
Excited states below $BD \to B_c + \ldots$

$B_c(2S) \to B_c(1S) + \pi\pi$

P states: γ transitions

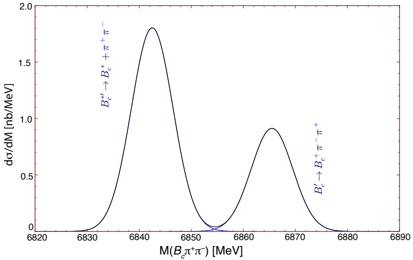
Many states observable at LHC, Tera$Z$

Update: Eichten & CQ (2019) using "frozen-α_s" potential, new approach to spin splittings



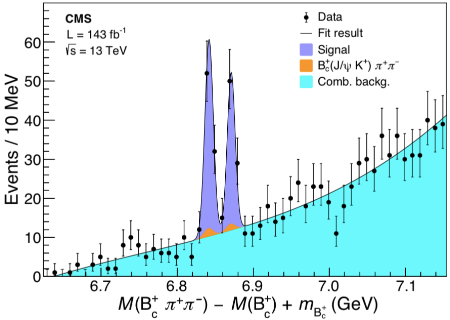
Observing the B_c spectrum: $\pi\pi$ transitions

Combine predicted production rates (BCVEGPY2.2) with calculated branching fractions to obtain expectations for $\pi\pi$ transition rates
$\leadsto$ *peak heights:* $B_c^{*\prime}/B_c^{\prime} \approx 2.5$



M1 $B_c^* \to \not\gamma B_c$ unobserved

$[M(B_c^{*\prime}) - M(B_c^{\prime})] - [M(B_c^*) - M(B_c)]$
≈ -23 MeV: $B_c^{*\prime}$ lower peak



2S $\to \pi\pi +$ 1S transitions observed by ATLAS, CMS, LHC*b*

CMS separation: -29 MeV
LHC*b*: -31 MeV

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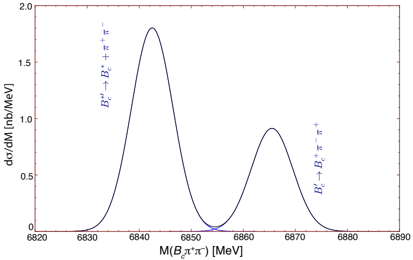

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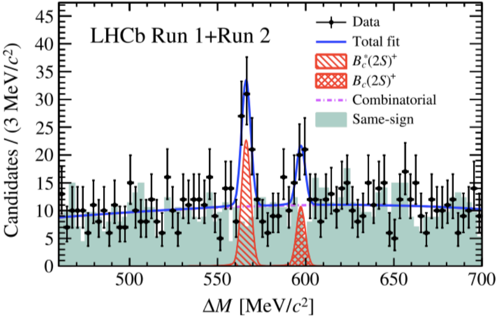

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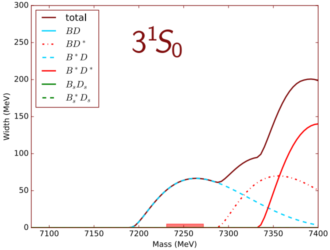
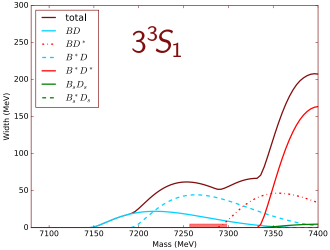
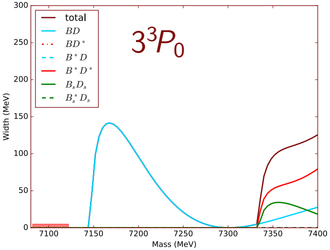
Mesons with beauty and charm: states near flavor threshold

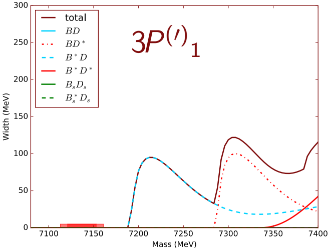
$3S$ states above threshold have significant decay widths

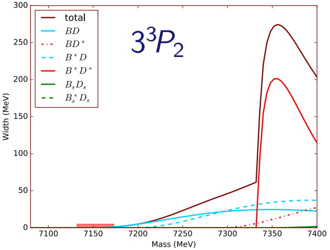




$3P$ states just below threshold; $J = 1$ may have significant mixing







Observing the B_c spectrum: E1 transitions

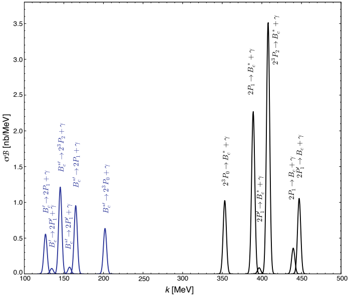
E1 spectroscopy in the $(b\bar{b})$ family:
LHC experiments discovered χ''_{b1}, χ''_{b2}.

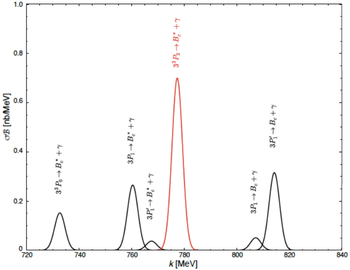
Incentive for the search: $2S \to 2P$ and $2P \to 1S$ transitions, assuming missing $B_c^* \to B_c \not\gamma$ in the reconstruction.

$3S, 3P$ yields $\approx \frac{1}{4} \times$ $2P \to 1S$ lines, but higher γ energies may aid detection.

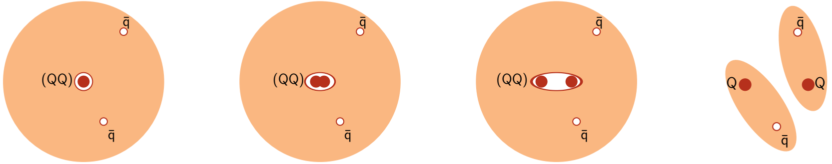
$3^3P_2(7154) \to B_c^* \gamma(777\ \text{MeV})$

Encourage search for $(3,2)P(b\bar{c})$.





Heavy quark symmetry $\Rightarrow$ stable heavy tetraquarks $Q_iQ_j\bar{q}_k\bar{q}_l$



HQS relates DHTQ mass to masses of QQq, Qqq, $Q\bar{q}$.

Lightest $bb\bar{u}\bar{d}$, $bb\bar{u}\bar{s}$, $bb\bar{d}\bar{s}$ states: (likely) no strong decays.

Heavier $bb\bar{q}_k\bar{q}_l$, $cc\bar{q}_k\bar{q}_l$, $bc\bar{q}_k\bar{q}_l \to Q\bar{q} + Q\bar{q}$ might be seen as "double-flavor" resonances near threshold.

Observing a weakly decaying double-beauty state would establish the existence of tetraquarks and illuminate the role of heavy color-$\bar{\mathbf{3}}$ diquarks as hadron constituents.

Eichten & CQ 1707.09575

Stability in the heavy-quark limit

1) *Dissociation into two heavy-light mesons is kinematically forbidden.*

$$\mathcal{Q} \equiv m(Q_i Q_j \bar{q}_k \bar{q}_l) - [m(Q_i \bar{q}_k) + m(Q_j \bar{q}_l)] =$$

$$\underbrace{\Delta(q_k, q_l)}_{\text{light d.o.f.}} - \tfrac{1}{2}\left(\tfrac{2}{3}\alpha_s\right)^2 [1 + O(v^2)]\overline{M} + O(1/\overline{M}) \,,$$

$$\overline{M} \equiv (1/m_{Q_i} + 1/m_{Q_j})^{-1}\text{: reduced mass of } Q_i \text{ and } Q_j$$

$$\Delta(q_k, q_l) \xrightarrow{\overline{M}\to\infty} \text{independent of heavy-quark masses}$$

For large enough $\overline{M}$, QQ Coulomb binding dominates, $\boxed{\mathcal{Q} < 0}$

Stability in the heavy-quark limit

2) *Decay to doubly heavy baryon and light antibaryon?*

$$(Q_iQ_j\bar{q}_k\bar{q}_l) \to (Q_iQ_jq_m) + (\bar{q}_k\bar{q}_l\bar{q}_m)$$

Core Q_iQ_j is color-$\mathbf{\bar{3}}$, same as $\bar{Q}_x$. Up to contributions from Q motion and spin interactions,

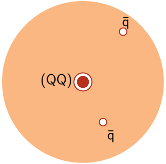
$$m(Q_iQ_j\bar{q}_k\bar{q}_l) - m(Q_iQ_jq_m) = m(Q_xq_kq_l) - m(Q_x\bar{q}_m)$$

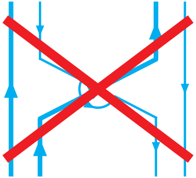
(spin configurations matter) RHS has generic form $\Delta_0 + \Delta_1/M_{Q_x}$

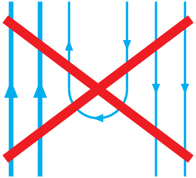
Using $m(\Lambda_c) - m(D) = 416.87$ MeV and $m(\Lambda_b) - m(B) = 340.26$ MeV, we estimate $\Delta_0 \approx 330$ MeV (asymptotic mass difference).

$$\boxed{\text{All} < m(\bar{p}) = 938\text{ MeV}}$$

No open strong decay channels in the heavy-quark limit!

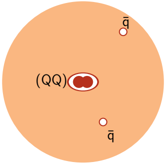






As $\overline{M} \to \infty$, stable $Q_i Q_j \bar{q}_k \bar{q}_l$ mesons must exist

Implications for the real world?



$$\langle r^2 \rangle^{1/2} = 0.28\ \text{fm}(cc), 0.24\ \text{fm}(bc), 0.19\ \text{fm}(bb)$$

HQS relations for ground-state tetraquark masses

Assumed: compact diquark, light degrees of freedom "same" for all (QQ)

$$m(Q_iQ_j\bar{q}_k\bar{q}_l) - m(Q_iQ_jq_m) = m(Q_xq_kq_l) - m(Q_x\bar{q}_m)$$

$+$ finite-mass corrections

RHS is determined from data

One doubly heavy baryon observed, Ξ_{cc}; others from model calculations*

$$\text{LHC}b\text{: } M(\Xi_{cc}^{++}) = 3621.40 \pm 0.78 \text{ MeV}$$

*We adopt Karliner & Rosner, *PRD* **90**, 094007 (2014)

Strong decays $(Q_iQ_j\bar{q}_k\bar{q}_l) \not\to (Q_iQ_jq_m) + (\bar{q}_k\bar{q}_l\bar{q}_m)$ $\forall$ ground states

Consider decays to pairs of heavy–light mesons case-by-case

Expectations for ground-state tetraquark masses, in MeV

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

Cf. M. Karliner & J. L. Rosner model, Phys. Rev. Lett. **119**, 202001 (2017) [arXiv:1707.07666].
Estimate deeper binding, so additional *bc* and *cc* candidates.

Real-world candidates for stable tetraquarks

$J^P = 1^+ \; \{bb\}[\bar{u}\bar{d}]$ meson, bound by 121 MeV

(77 MeV below $B^-\bar{B}^0\gamma$)

$$\mathcal{T}^{\{bb\}}_{[\bar{u}\bar{d}]}(10482)^- \to \Xi^0_{bc}\bar{p},\; B^-D^+\pi^-, \text{ and } \underbrace{B^-D^+\ell^-\bar{\nu}}_{\text{manifestly weak!}}$$

$J^P = 1^+ \; \{bb\}[\bar{u}\bar{s}]$ and $\{bb\}[\bar{d}\bar{s}]$ mesons, bound (?) by 48 MeV

(3 MeV below $BB_s\gamma$)

$$\mathcal{T}^{\{bb\}}_{[\bar{u}\bar{s}]}(10643)^- \to \Xi^0_{bc}\overline{\Sigma}^- \qquad \mathcal{T}^{\{bb\}}_{[\bar{d}\bar{s}]}(10643)^0 \to \Xi^0_{bc}(\bar{\Lambda}, \overline{\Sigma}^0)$$

Unstable doubly heavy tetraquarks

Resonances in "wrong-sign" (double flavor) combinations DD, DB, BB?

$J^P = 1^+ \; \mathcal{T}^{\{cc\}++}_{[\bar{d}\bar{s}]}(4156) \to D^+ D_s^{*+}$: *prima facie evidence* for non-$q\bar{q}$ level

Double charge / double charm

(New kind of resonance: no attractive force at the meson–meson level.)

Also, $1^+ \; \mathcal{T}^{\{bb\}}_{\{\bar{q}_k\bar{q}_l\}}(10681)^{0,-,--}$, $\mathcal{Q} = +78$ MeV $\quad 1^+ \; \mathcal{T}^{\{bc\}}_{[\bar{u}\bar{d}]}(7272)^0$, $\mathcal{Q} = +82$ MeV

$0^+ \; \mathcal{T}^{[bc]}_{[\bar{u}\bar{d}]}(7229)^0$, $\mathcal{Q} = +83$ MeV $\quad 1^+ \; \mathcal{T}^{\{cc\}}_{[\bar{u}\bar{d}]}(3978)^+$, $\mathcal{Q} = +102$ MeV

Homework for experiment

1. Look for double-flavor resonances near threshold.

2. Discover and determine masses of doubly-heavy baryons.
   needed to implement HQS calculation of tetraquark masses
   intrinsic interest in these states:
   compare heavy–light mesons, possible core excitations

   Resolve Ξ_{cc}^{+} uncertainty (SELEX/LHCb)

3. Measure cross sections for final states containing 4 heavies:
   B_c, QQq baryons, $Q_i\bar{Q}_iQ_j\bar{Q}_j$.

4. Find stable tetraquarks through weak decays. Lifetime: $\sim$ ps ??

Homework for theory

1. Develop expectations for production. A. Ali talk

2. Refine lifetime estimates for stable states.

3. Understand how color configurations evolve with QQ (and $\bar{q}\bar{q}$) masses. J.-M. Richard, et al., Phys. Rev. C **97**, 035211 (2018) [1803.06155];
   A. Czarnecki, B. Leng and M. B. Voloshin, Phys. Lett. B **778**, 233 (2018) [1708.04594];
   C. Hughes, E. Eichten and C. T. H. Davies, Phys. Rev. D **97**, 054505 (2018) [1710.03236];
   + ongoing lattice QCD studies (Marc Wagner talk).

4. Investigate stability of different body plans in the heavy-quark limit.
   ...up to $(Q_iQ_j)(Q_kQ_l)(Q_mQ_n)$: $B = 2$, but $Q_pQ_qQ_r$ color structure?