A LITTLE ABOUT HADRONS WITH TWO HEAVY b QUARKS: (i) FINITE DIQUARK SIZE EFFECTS, (ii) DETECTING THESE HADRONS

bbq & $bb\bar{q}\bar{q}$

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OUTLINE

Finite Diquark Size Effects

The Direct Coupling of Light Quarks to Heavy Di-quarks
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Discovery of Hadrons With two b quarks

An Estimate of the Inclusive Branching Ratio to B_c in Ξ_{bbq} Decay
Alexander K. Ridgway, Mark B. Wise (Caltech). Feb 12, 2019. 6 pp.
e-Print: arXiv:1902.04582 **[hep-ph] |** PDF

A Few References

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Finite Diquark Size Effects

Baryons and tetraquarks with two very heavy quarks Q have a large negative contribution to mass from Coulomb binding energy in anti-triplet channel

$$V(r) = -\frac{2}{3}\frac{\alpha_s(m_Q \mathrm{v}_{\rm rel})}{r}$$

Explanation of suppression of attraction in large N_c
At end of talk if time

Ground state tetraquarks with very heavy quarks decay weakly

$T_{QQ\bar{q}\bar{q}} \to M_{Q\bar{q}} + M_{Q\bar{q}}$ or $\Xi_{QQq} + \bar{B}_{\bar{q}\bar{q}\bar{q}}$ forbidden

Effective theory with heavy diquark (spin 1 ground state) spin symmetry,

$$m_Q > m_Q \mathrm{v}_{\rm rel} > m_Q \mathrm{v}_{\rm rel}^2 >> \Lambda_{QCD}$$

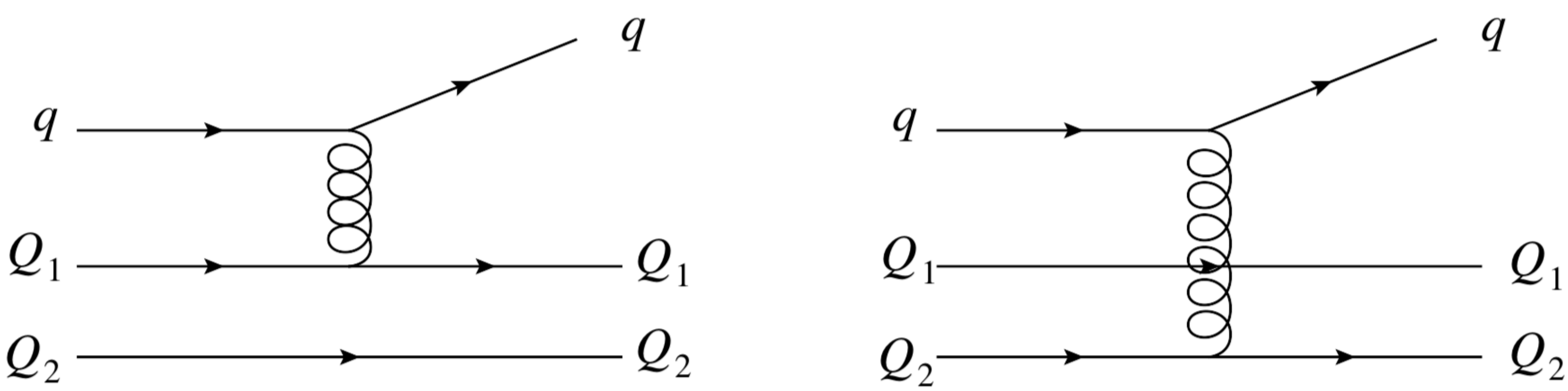
$$\mathscr{L} = \Phi_{\rm v}^{\dagger} i \mathrm{v}^{\mu} D_{\mu} \Phi_{\rm v} - \frac{1}{4} G^{A\mu\nu} G^{A}_{\mu\nu} + \sum_q \bar{q}(i\gamma^{\mu} D_{\mu} - m_q) q + \ldots$$

Match from full QCD to this effective theory in one step, relative velocity not very small.

In ellipsis terms suppressed by inverse powers of heavy quark mass including those that depend on size of diquark.

Compute coefficient of local operator in ellipsis that gives leading coupling of light quarks to diquark and coefficient arises from finite size of diquark.

Compute elastic light quark diquark scattering amplitude at tree level



Neglect effects suppressed by heavy quark mass in spinors

Three momentum transfer of light quark **k**. Expand in **k.** Leading term diquark charge

$$\mathcal{A} \simeq \frac{g^2}{2k^2}\left(2m_{Q_1} + 2m_{Q_2}\right)\bar{u}(k_f)T^A_{\beta'\beta}\gamma^0 u(k_i)\left(-T^A\right)_{\alpha\alpha'} \times$$
$$\int \frac{d^3p}{(2\pi)^3}\left(\tilde{\phi}^*\left(\mathbf{p} - \frac{m_{Q_2}}{m_{Q_1}+m_{Q_2}}\mathbf{k}\right) + \tilde{\phi}^*\left(\mathbf{p} + \frac{m_{Q_1}}{m_{Q_1}+m_{Q_2}}\mathbf{k}\right)\right)\tilde{\phi}(\mathbf{p})$$

Linear term vanishes because s-wave wave functions

Linear term vanishes because s-wave wave functions

$$\mathscr{A}_2 \simeq \frac{g^2}{2}\left(2m_{Q_1}+2m_{Q_2}\right)\bar{u}(k_f)T^A_{\beta'\beta}\gamma^0 u(k_i)\left(-T^A\right)_{\alpha\alpha'}\left(-\frac{\langle r^2\rangle}{6}\right)\frac{m_{Q_1}^2+m_{Q_2}^2}{(m_{Q_1}+m_{Q_2})^2},$$

Identify operator. Include anomalous dimension scaling

$$\Delta L = \left(\frac{\pi\alpha_s(m_Q \mathrm{v}_{\mathrm{rel}})\langle r^2\rangle}{18}\right)\left(\frac{m_{Q_2}^2+m_{Q_1}^2}{(m_{Q_1}+m_{Q_2})^2}\right)\left[\frac{\alpha_s(m_Q v)}{\alpha_s(\mu)}\right]^{\left(\frac{-\frac{9}{2}+\frac{2}{3}n_q}{11-\frac{2}{3}n_q}\right)} O_-(\mu)$$

$$O_- = \left(\Phi^\dagger_{\mathrm{v}\alpha}\Phi_{\mathrm{v}\alpha}\right)\sum_q\left(\bar{q}_\beta\gamma^\mu \mathrm{v}_\mu q_\beta\right) - 3\left(\Phi^\dagger_{\mathrm{v}\alpha}\Phi_{\mathrm{v}\beta}\right)\sum_q\left(\bar{q}_\alpha\gamma^\mu \mathrm{v}_\mu q_\beta\right).$$

Make familiar quark model estimate of matrix element in baryon case $\Xi_{bbq} \sim \Phi q$

Get light quark wave function at origin from B meson decay constant

Neglect anomalous scaling $\Delta m_{\Xi_{bbq}} \sim \left(\frac{\pi\alpha_s(m_b \mathrm{v}_{\mathrm{rel}})\langle r^2\rangle}{54}\right) f_B^2 m_B$

Estimate mass shift due to diquark finite size $\Delta m_{\Xi_{bbq}} = \left(\frac{\pi \alpha_s(m_b \mathrm{v}_{\mathrm{rel}}) \langle r^2 \rangle}{54} \right) f_B^2 m_B$

Cornell potential $V_{\Phi_{bb}}(r) = -\frac{2}{3}\left(\frac{0.3}{r}\right) + \frac{1}{2}(0.2\mathrm{GeV}^2)r$

Implies radius $\langle r^2 \rangle = 3.2\mathrm{GeV}^{-2}$

Mass shift of about 10 MeV due to finite diquark size. Probably ok to neglect such effects.

Detecting Hadrons with two b quarks at the LHC

Baryon with two heavy charm quarks discovered at LHCb in 2017 using mode
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

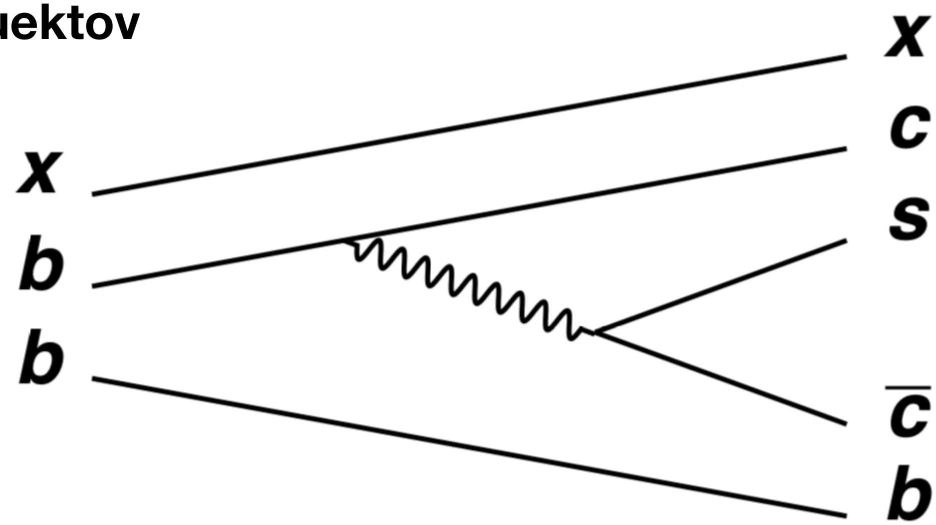
Harder to detect baryons with two heavy bottom quarks using exclusive modes

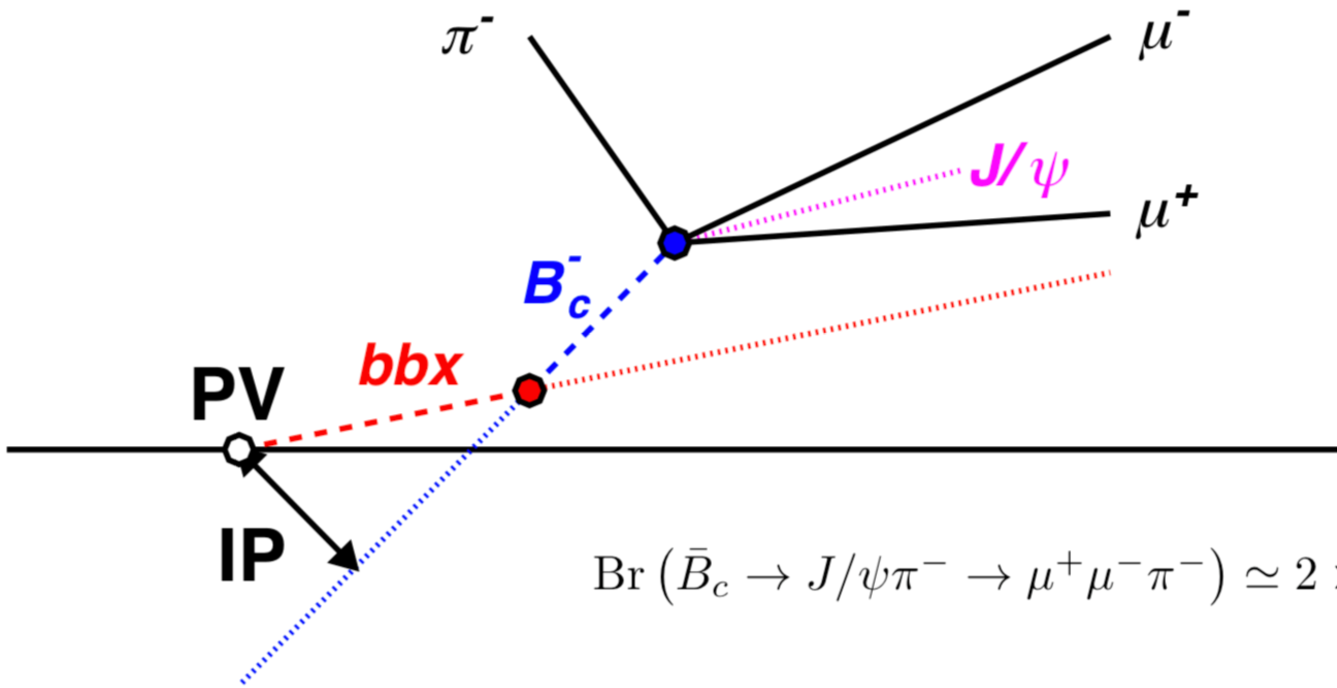
For example suppose use $\Xi_{bbu} \to B^- \Lambda_c^+$. Branching ratio guess $\sim 10^{-3}$

$Br(\Lambda_c^+ \to p K^- \pi^+) \sim 10^{-3}$ $Br(B^- \to J/\psi K^-) \sim 10^{-3}$ $Br(J/\psi \to \mu^+ \mu^-) \sim 10^{-1}$

Idea of Gershon and Poluektov

$x = q, \bar{q}\bar{q}$





$$\mathrm{Br}\left(\bar{B}_c \to J/\psi\pi^- \to \mu^+\mu^-\pi^-\right) \simeq 2 \times 10^{-4}.$$

$$H = \frac{4G_F}{\sqrt{2}} V_{cs}^* V_{cb} \left[C_1 O_1 + C_2 O_2\right]$$

$$O_1 = \left[\bar{c}_\alpha \gamma^\mu P_L b_\alpha\right]\left[\bar{s}_\beta \gamma_\mu P_L c_\beta\right] \quad O_2 = \left[\bar{c}_\beta \gamma^\mu P_L b_\alpha\right]\left[\bar{s}_\alpha \gamma_\mu P_L c_\beta\right]$$

$$\mathcal{M}(\Phi_{bb}(\mathbf{0}, \gamma) \to \bar{B}_c(\mathbf{k}) + c(\mathbf{p}_c, \alpha) + s(\mathbf{p}_s, \beta)),$$

$$\frac{d\Gamma(\Xi_{bbq} \to \bar{B}_c^{(*)}(k) + X_{c,s,q})}{dk} \simeq \left(\frac{G_F^2}{3\pi^3}\right)(C_1 - C_2)^2 |V_{cb} V_{cs}|^2 |\mathcal{I}\left(m_b k/(m_b + m_c)\right)|^2 \times k^2 \frac{(m_{\Phi_{bb}}^2 + m_{\bar{B}_c}^2 - m_c^2 - 2 m_{\Phi_{bb}} E_{\bar{B}_c}(k))^2}{(m_{\Phi_{bb}}^2 + m_{\bar{B}_c}^2 - 2 m_{\Phi_{bb}} E_{\bar{B}_c}(k))}$$

$$\mathcal{I}(k) = \int \frac{d^3 p}{(2\pi)^3} \tilde{\psi}_{\bar{B}_c}^* \left(|\mathbf{p} + \mathbf{k}|\right) \tilde{\psi}_{\Phi_{bb}}(p) = 4\pi \int dr r^2 \psi_{\bar{B}_c}^*(r) \psi_{\Phi_{bb}}(r) \frac{\sin(kr)}{kr}.$$

$$\mathcal{M} \sim \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{E_{\bar{B}_c}(k) m_{\Phi_{bb}}}}{\sqrt{E_c(|\mathbf{p}+\mathbf{k}|)E_b(p)}} \tilde{\psi}^*_{\bar{B}_c}(|\mathbf{p} + \frac{m_b}{m_b+m_c}\mathbf{k}|)\tilde{\psi}_{\Phi_{bb}}(p)$$

$$\times \left[\bar{u}^{(s)}(\mathbf{p_s})\gamma^\mu P_L v^{(c)}(\mathbf{p}+\mathbf{k})\right] \left[\bar{u}^{(c)}(\mathbf{p_c})\gamma_\mu P_L u^{(b)}(\mathbf{p})\right].$$

Wavefunctions restrict arguments to be small compared with heavy quark masses

$$|\mathbf{p} + \frac{m_b}{m_b+m_c}\mathbf{k}| << m_c$$

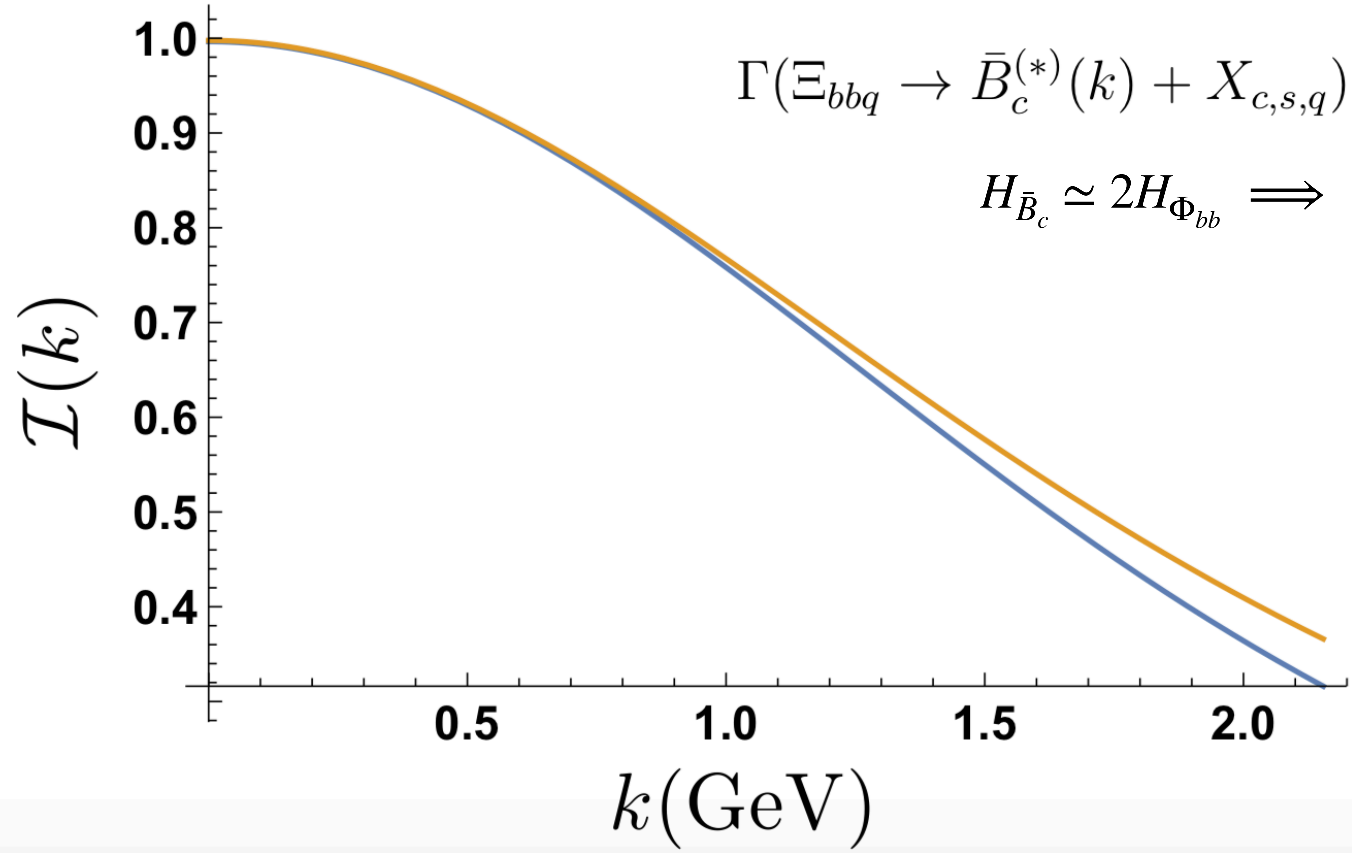
$$\mathbf{p}+\mathbf{k} \to (m_c/(m_b+m_c))\mathbf{k} \text{ in } E_c \text{ and } v^{(c)}$$

$$E_c((m_c/(m_b+m_c))k) = (m_c/(m_c+m_b))E_{\bar{B}_c}(k)$$

$$\mathcal{M} \sim \mathcal{I}\left(\frac{m_b}{m_b+m_c}k\right)[\bar{u}^{(s)}(\mathbf{p_s})\gamma^\mu P_L v^{(c)}(\frac{m_c}{m_b+m_c}\mathbf{k})]\sqrt{2}\left[\bar{u}^{(c)}(\mathbf{p_c})\gamma_\mu P_L u^{(b)}(\mathbf{0})\right]$$

$$\Gamma(\Xi_{bbq} \to \bar{B}_c^{(*)}(k) + X_{c,s,q}) = 1.5 \times 10^{10}\ \mathrm{s}^{-1}$$

$$H_{\bar{B}_c} \simeq 2H_{\Phi_{bb}} \implies I_{\bar{B}'_c}(0) = 0$$



Suppose sample of 10^8 Ξ_{bbq} and $T_{bb\bar{q}\bar{q}}$

Then about 10^6 $\bar{B}_c$ that don't point back to interaction point

About 100 end up in final state $J/\psi\pi^- \to \mu^-\mu^+\pi^-$

Tetraquarks with two heavy quarks in large N_c

Quarkonium interpolating field (just keep track of color) $Q_{1\alpha}\bar{Q}_{2\alpha}$

Short distance potential
$$V(r) = -\left(\frac{N_c^2 - 1}{2N_c}\right)\frac{\alpha_s}{r} \to -\frac{\hat{\alpha}_s}{r}$$

$$\hat{\alpha}_s = N_c \alpha_s$$

Tetraquark interpolating field $Q_{1\alpha}Q_{2\beta}\bar{q}_{1\alpha}\bar{q}_{2\beta} - Q_{1\alpha}Q_{2\beta}\bar{q}_{1\beta}\bar{q}_{2\alpha}$

Short distance potential between heavy quarks
$$V(r) = -\left(\frac{N_c + 1}{2N_c}\right)\frac{\alpha_s}{r} \to 0\frac{\hat{\alpha}_s}{r}$$

In large N_c limit $3 \times \bar{3} \to 1$ attractive channel but $3 \times 3 \to \bar{3}$ is not