Beyond $T_{cc}: T_{bc} & T_{bb}$

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$T_{cc}$ and beyond Workshop
Introduction

• With the discovery of a doubly-charmed tetraquark, we can begin to think about future discoveries of other double-heavy tetraquarks, namely $T_{bc}$ and $T_{bb}$.

• LHCb has a proven track record. Clearly in a good position to carry out such searches
  
  • $\sim 40\%$ of $\sigma(b\bar{b}, c\bar{c})$ in 4% of solid angle
  
  • $\sim 10 \times \mathcal{L}_{\text{int}}$ compared to Run 2: Run 3 (2022-2024) + Run 4 (2028-2030) $\rightarrow$ 50 fb$^{-1}$.

• Full software trigger: $\sim 2$-3x increase in trigger efficiency for $b\rightarrow$ fully-hadronic final states

• Improved IP resolution: Vertex detector distance reduced from 5 mm to 3.5 mm from beam $\rightarrow$ Better discrimination of primary and secondary particles (O(20%)).
Double-heavy hadrons

- **cc:** Lowest mass state is above DD$_\pi$ threshold
  - $T^+_\text{cc}[\bar{u}\bar{d}]$ discovered LHCb 2021 ([arXiv:2109.01056](https://arxiv.org/abs/2109.01056), [arXiv:2109.01038](https://arxiv.org/abs/2109.01038)). Very close to threshold $\rightarrow$ Narrow. (see previous talk for details)

- **bc:** Lowest mass $T^0_{\text{bc}[\bar{u}\bar{d}]}$ state close to BD threshold (e.g. see Karliner & Rosner, PRL119, 202001 (2017))
  - Above threshold: Strong decay to $BD$ mesons.
  - Below threshold: Weak decays: $b \rightarrow c$ ($D^0D^+\pi^-$, $\Xi^+_cc\bar{p}$, etc), $c \rightarrow s$ ($\bar{B}^0K^-\pi^+$, $\Xi^0_b\bar{p}\pi^+$)

- **bb:** Lowest mass states expected to be below threshold
  - Some recent predictions..

<table>
<thead>
<tr>
<th>$T^-_{bb[\bar{u}\bar{d}]}$</th>
<th>$T^-<em>{bb[\bar{u}\bar{s}]}$, $T^0</em>{bb[\bar{d}\bar{s}]}$</th>
<th>Ref</th>
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<tr>
<td>-189 MeV</td>
<td>-98 MeV</td>
<td>Francis et al, PRL118, 142001 (2017)</td>
<td>LQCD</td>
</tr>
<tr>
<td>-170 MeV</td>
<td>-52 MeV</td>
<td>Karliner &amp; Rosner, PRL119, 202001 (2017)</td>
<td>Quark model + quarkonia and $\Xi^0_{cc}$ data</td>
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- Expect these 3 states to decay weakly!
Prospects for double-heavy tetraquarks in LHCb

\[ N_{\text{signal}} = \mathcal{L}_{\text{int}} \sigma_{\text{signal}} \mathcal{B}(\text{signal}) \mathcal{B}(\text{daughters}) \varepsilon_{\text{tot}} \]

- \( \mathcal{L}_{\text{int}} \) = integrated luminosity
- \( \sigma_{\text{signal}} \) = cross section for producing the signal
- \( \mathcal{B}(\text{signal}) \) = branching fraction for the tetraquark decay mode
- \( \mathcal{B}(\text{daughters}) \) = branching fraction for daughter decay products, e.g. \( \mathcal{B}(D^0 \to K^-\pi^+) = 3.95\% \)
- \( \varepsilon_{\text{tot}} \) = Total efficiency to select the final state (LHCb acceptance, \( \varepsilon_{\text{trig}}, \varepsilon_{\text{rec}}, \varepsilon_{\text{sel}} \))

\[ \sigma_{\text{signal}}^{\text{eff}} = \sigma_{\text{signal}} \mathcal{B}(\text{signal}) \mathcal{B}(\text{daughters}) \]

- The branching ratios can easily combine to give \( 10^{-5} \) - \( 10^{-6} \) (or less)
- A 10 nb cross-section effectively becomes 0.01 - 0.1 pb \( [ \sigma_{t\bar{t}} \sim 900 \text{ pb} ] \)

- \( \varepsilon_{\text{tot}} \) quite dependent on final state track multiplicity, \( p_T \) & IP requirements, etc.
What can we expect for $\mathcal{E}_{\text{tot}}$?

Let’s consider $b \to J/\psi \times X$ modes

(Using Run 2 data)

$$\mathcal{E}_{\text{tot}} = \frac{N_{\text{sig}}}{\sigma(H_b) \mathcal{L}_{\text{int}} \mathcal{B}}$$

- Can get a factor of 3X more $B^-$ signal from $B^- \to D^0 \pi^-$, $B^- \to J/\psi K^- \pi^+ \pi^-$ + other modes (including improvements due to removal of high $E_T$ “L0” trigger for hadronic modes)
- Effectively $\mathcal{E}(B^-) \sim 30\%$

- For $D$ mesons produced in association with the fully reconstructed $B$ meson, assume 50% efficiency per final state hadron (LHCb Acc, p>2.5 GeV), and $\mathcal{E}_D \sim 70\%$ (displaced vertex, IP cuts, etc)
  - $\mathcal{E}(D^+), \mathcal{E}(D^{*+}) \sim 0.08$
  - $\mathcal{E}(D^0 \to K\pi) \sim 0.17$
  - Could also include $D^0 \to K\pi\pi\pi$ ($\sim$50% extra $D^0$)

- The $D$ efficiencies are likely on the optimistic side.

- Very much analysis dependent, so just gives a rough idea.
- Roughly $\mathcal{E}_{\text{tot}}(B^- \to J/\psi h^-) \approx 0.10$
Assume $\sigma(T_{bc[\bar{u}\bar{d}]}^0) \sim 100 \text{ nb}$ at 13 TeV


- Compare to $\sigma(pp \rightarrow B^- X) \sim 90 \mu b \left( 900 \sigma(T_{bc[\bar{u}\bar{d}]}^0) \right)$
**Strong Decay:** \( T_{bc[\bar{u}\bar{d}]}^0 \rightarrow B^- D^+ \), \( B^- \rightarrow J/\psi K^- \), \( D^+ \rightarrow K^- \pi^+ \pi^+ \)

**Signal**

- Assume \( B(T_{bc[\bar{u}\bar{d}]}^0 \rightarrow B^- D^+) \approx 0.5 \)
  
  \[ \Rightarrow \sigma_{signal}^{eff} \approx 0.3 \text{ pb} \]

- \( \varepsilon_{tot} \approx 2.4\% \)

**\( b\bar{b} \) background**

- Main background likely, \( pp \rightarrow b\bar{b} \rightarrow B^- D^+ X \), **BUT:**
  - \( D^+ \) is “wrong-sign”, e.g. \( B(B^0 \rightarrow D^- X) \approx 37\% \), while \( B(B^0 \rightarrow D^+ X) < 3.1\% \),
  - \( D^+ \) is from PV, not from a displaced vertex (should allow large suppression of \( pp \rightarrow b\bar{b} \)).
- DPS, Combinatorial BG

**Could be within reach with full Run 3 + Run 4 data set**
- Should select and save all possible \( B^-D^+ (B^0D^0) \) that form a good vertex & B, D consistent with coming from PV.
**Strong Decay:** $T_{bc[\bar{u}\bar{d}]}^0 \rightarrow B^- D^+$, $B^- \rightarrow D^0(K^- \pi^+) \mu^- \nu X$, $D^+ \rightarrow K^- \pi^+ \pi^+$

**Signal**

- Assume $B(T_{bc[\bar{u}\bar{d}]}^0 \rightarrow B^- D^+) \sim 0.5$
- $B(B^- \rightarrow D^0 \mu^- X) \sim 10\%$
- (Reconstruct $\vec{p}(v)$ using B mass and vertex constraints)
- $\Rightarrow \sigma_{signal}^{eff} \sim 20 \text{ pb}$
- $\varepsilon_{tot} = 0.16\%$

$N_{signal}(50 \text{ fb}^{-1}) \sim 1500 \left( \frac{\sigma_{sig}}{100 \text{ nb}} \right) \left( \frac{B_{sig}}{0.5} \right) \left( \frac{\varepsilon_{tot}}{0.0016} \right)$

- Perhaps $\times 1.5 - 2.0$ for $B^0 D^0$ final states

**$b\bar{b}$ background**

- Main background likely, $pp \rightarrow b\bar{b} \rightarrow B^- D^+ X$, **BUT:**
  - $D^+$ is “wrong-sign” and $D^+$ is from PV
  - DPS, Combinatorial BG
- Cons:
  - Cannot require BD form a vertex due to missing $\nu X$
  - Worse mass resolution than fully reco’d decays.

- Could be within reach with full Run 3 + Run 4 data set
Weak Decay, $b \to c\bar{u}d$:  $T_{bc[\bar{u}\bar{d}]}^0 \to D^0 D^+ \pi^-, D^0 \to K^- \pi^+, D^+ \to K^- \pi^+ \pi^+$

**Signal**

- Assume $B(T_{bc[\bar{u}\bar{d}]}^0 \to D^0 D^+ \pi^-) \sim 0.01$
  
  $\Rightarrow \sigma_{signal}^{eff} \sim 3.7 \text{ pb}$

- Estimate: $\varepsilon_{tot} \approx 0.7\%$

**$b\bar{b}$ background**

- Main background $pp \to b \ (B \to D^+X) \bar{b} \ (\bar{B} \to D^0X)$ BUT:
  - WS $D^0$ suppressed by $\sim 6X$ compared to RS
  - $D^0$ and $D^+$ from different $b$-hadrons have to form vertex
  - Resulting $p(D^0 D^+ \pi^-)$ must point back to PV.

- Combinatorial BG

- Could be within reach with full Run 3 + Run 4 data set
  - Should select and save all possible $B^-D^+$ that form a good vertex with $p(D^0 D^{(*)^+} \pi^-)$ must point back to PV

\[ N_{Signal}(50 \text{ fb}^{-1}) \sim 1300 \left( \frac{\sigma_{sig}}{100 \text{ nb}} \right) \left( B_{sig} \right) \left( \varepsilon_{tot} \right) \]
Weak Decay, \( b \to c\bar{c}s \): \( T_{bc[\bar{u}\bar{d}]}^0 \rightarrow J/\psi D^+ K^- \), \( D^+ \rightarrow K^- \pi^+ \pi^+ \)

Signal

- Assume \( B(T_{bc[\bar{u}\bar{d}]}^0 \rightarrow J/\psi K^- D^+) \sim 0.01 \)
  \[ \Rightarrow \sigma_{signal}^{eff} \sim 5.6 \text{ pb} \]
- Estimate: \( \varepsilon_{tot} \approx 2.4\% \)

\[ N_{Signal}(50 \text{ fb}^{-1}) \sim 6800 \left( \frac{\sigma_{sig}}{100 \text{ nb}} \right) \left( \frac{B_{sig}}{0.01} \right) \left( \frac{\varepsilon_{tot}}{0.024} \right) \]

- Similarly: \( T_{bc[\bar{u}\bar{d}]}^0 \rightarrow J/\psi D^0 K^- \pi^+ \)

\( b\bar{b} \) background

- Main background \( pp \rightarrow b \ (B \rightarrow J/\psi X) \ \bar{b} \ (\bar{B} \rightarrow D^+ X) \) BUT:
  - WS D$^+$ suppressed by \( \sim 10X \) compared to RS
  - \( J/\psi \) and D$^+$ from different b-hadrons have to form vertex
  - Resulting \( \vec{p}(J/\psi D^+ K^-) \) must point back to PV.
- Combinatorial BG

- Promising mode with Run 3 + Run 4 data set
Weak decay, $c \to s u \bar{d}$: $T_{bc[\bar{u}d]}^0 \to B^0 K^- \pi^+$, $B^0 \to J/\psi K^- \pi^+$

**Signal**

- Assume $B(T_{bc[\bar{u}d]}^0 \to B^0 K^- \pi^+) \sim 0.01$
- Estimate: $\mathcal{E}_{tot} \approx 1.5\%$
- $N_{signal}(50 fb^{-1}) \sim 54 \left( \frac{\sigma_{sig}}{100 nb} \right) \left( \frac{B_{sig}}{0.01} \right) \left( \frac{\mathcal{E}_{tot}}{0.015} \right)$
- Similarly: $T_{bc[\bar{u}d]}^0 \to B^- K^- \pi^+ \pi^+$, similar yields

**$b\bar{b}$ background**

- Main background $pp \to B^0 (\bar{B} \to \bar{D} (K\pi X) X)$:
  - $\hat{p}(B^0 K^- \pi^+)$ must point back to PV
  - Can suppress $b\bar{b}$ by requiring $B^0$ has large IP, but will cost efficiency.
  - Also, combinatorial BG

**Such modes will be difficult IMHO**
Weak decays with baryons: $T^{0}_{bc[\bar{u}\bar{d}]}$

- $T^{0}_{bc[\bar{u}\bar{d}]} \to \Xi^{+}_{cc} \bar{p}$, $\Xi^{+}_{cc} \to \Lambda^{+}_{c} K^{-} \pi^{+}$

- $T^{0}_{bc[\bar{u}\bar{d}]} \to \Xi^{0}_{b} p \pi^{+}$, $\Xi^{0}_{b} \to \Xi^{+}_{c} (pK^{-} \pi^{+}) \pi^{-}$

- Assume $B(T^{0}_{bc[\bar{u}\bar{d}]} \to \Xi^{+}_{cc} \bar{p}) \sim 0.01$
- Assume $B(\Xi^{+}_{cc} \to \Lambda^{+}_{c} K^{-} \pi^{+}) = 0.03$

- Estimate: $\epsilon_{tot} \approx 0.5\%$

$$N_{signal}(50 \text{ } fb^{-1}) \sim 950 \left( \frac{\sigma_{sig}}{100 \text{ } nb} \right) \left( \frac{B_{sig}}{0.01} \right) \left( \frac{\epsilon_{tot}}{0.005} \right)$$

- Assume $B(T^{0}_{bc[\bar{u}\bar{d}]} \to \Xi^{0}_{b} p \pi^{+}) \sim 0.01$
- Assume $B(\Xi^{0}_{b} \to \Xi^{+}_{c} \pi^{-}) = 0.005$
- Assume $B(\Xi^{+}_{c} \to pK^{-} \pi^{+}) = 0.01$

- Estimate: $\epsilon_{tot} \approx 1\%$

$$N_{signal}(50 \text{ } fb^{-1}) \sim 25 \left( \frac{\sigma_{sig}}{100 \text{ } nb} \right) \left( \frac{B_{sig}}{0.01} \right) \left( \frac{\epsilon_{tot}}{0.01} \right)$$

- Can also use $T^{0}_{bc[\bar{u}\bar{d}]} \to \Xi^{+}_{cc} \bar{p} \pi^{-}$

- $\Rightarrow \sigma^{eff}_{signal} \sim 3.2 \text{ } pb$

- $\Rightarrow \sigma^{eff}_{signal} \sim 0.05 \text{ } pb$
$T_{bc[\bar{u}\bar{d}]}^0$ summary

- There is potential for discovery of such states in Run 3 & 4 in various modes
  - Possibly $\mathcal{O}(100-1000)$ signal decays in 50 fb$^{-1}$ in various modes.
  - Based on very rough efficiency estimates (requires Run 3 simulation for better estimate)

- Strong decays to BD
  - Involves known B, D BF$s$, so less guesstimating.
  - $b\bar{b}$ background suppressed, since signal D is “WS”
  - IP-related selections can suppress secondary D mesons from B decays
  - Double-parton scattering remains, but doesn’t peak in M(BD).

- Weak decays
  - BF$s$ largely unknown, but likely O(1%) or less in most cases (ala B, D decays)
  - Significant $b\bar{b}$ background as both $T_{bc[\bar{u}\bar{d}]}^0$ and $b\bar{b}$ involve secondary tracks
  - $D^0D^+\pi^-$ in $b \to \bar{c}ud$ in $T_{bc[\bar{u}\bar{d}]}^0$ could be significant
  - $J/\psi D^+K^-$ looks potentially promising if BR is not too small.
  - Secondary $\Xi_{cc}$ could also prove fruitful
• Expect $\sigma(T_{bb[\bar{u}\bar{d}]}^-) \sim 1$ nb

• Expected to be below BB* threshold $\rightarrow$ Weak decay
  • Lifetime predicted to be $\sim 0.6$ ps [Agaev et al, EPJA 56, 177 (2020)], or maybe it’s 7.6 ps(!) [Hernandez et al, PLB800, 135073 (2020)].
Weak decay: $T_{bb[\bar{u}\bar{d}]}^- \rightarrow B^- D^+ h^-$, $B_c^- \rightarrow J/\psi \pi^-$, $D^+ \rightarrow K^- \pi^+ \pi^+$

- Assume $B(T_{bb[\bar{u}\bar{d}]}^0 \rightarrow B^- D^+ \pi^-) \sim 0.02$
- $\epsilon_{tot} \sim 0.8\%$

\[ \Rightarrow \sigma_{signal}^{eff} \sim 0.1 \text{ fb} \]

- $N_{signal}(50 fb^{-1}) \sim 0.05 \left( \frac{\sigma_{sig}}{1 nb} \right) \left( B_{sig} \right) \left( \epsilon_{tot} \right) \]

- Fully reconstructed final states seems difficult

- Assume $B(T_{bb[\bar{u}\bar{d}]}^0 \rightarrow B_c^- D^+ K^-) \sim 0.02$
- $\epsilon_{tot} \sim 0.8\%$

\[ \Rightarrow \sigma_{signal}^{eff} \sim 0.5 \text{ fb} \]

- $N_{signal}(50 fb^{-1}) \sim 0.2 \left( \frac{\sigma_{sig}}{1 nb} \right) \left( B_{sig} \right) \left( \epsilon_{tot} \right) \]
\( T_{bb[ar{u}d]} \rightarrow B_c^- X \)

- Possibly look at **inclusive secondary B_c decays** (see Gershon & Poluektov, JHEP 2019)
  - Only need to reconstruct the \( B_c^+ \rightarrow J/\psi \pi^+ \)
  - Only known contribution would be \( T_{bb[q\bar{q}]} \) tetraquarks and \( bbq \) baryons

- Assume \( B(T_{bb[u\bar{d}]} \rightarrow B_c^- X) \approx 0.10 \)
- \( \epsilon_{tot} \approx 10\% \)

\[ \Rightarrow \sigma_{signal}^{eff} \approx 30 \text{ fb} \]

\( N_{signal}(50 \text{ fb}^{-1}) \approx 150 \left( \frac{\sigma_{sig}}{1 \text{ nb}} \right) \left( \frac{B_{sig}}{0.10} \right) \left( \frac{\epsilon_{tot}}{0.10} \right) \)

- \( \approx 20,000 B_c^+ \rightarrow J/\psi \pi^+ \) in 6 fb\(^{-1}\) at 13 TeV
  \[ \Rightarrow \approx 170,000 \text{ in } 50 \text{ fb}^{-1} \]

- IP distribution can discriminate prompt from secondary
- Could calibrate prompt IP component using \( B_s^{**} \rightarrow B^+K^- \), \( B^+ \rightarrow J/\psi K^- \)
T_{bb} prospects

• Exclusive modes seem challenging due to small cross-section, BFs.
• Inclusive $B_c$ search could signal $bb$ hadron, but would need more to separate $T_{bb[\bar{u}d]}$ vs $\Xi_{bb}$ decays.
Summary

- $T_{bc[\bar{u}d]}^0$ tetraquarks could be within reach for Run 3 + 4 of LHCb.
  - Strong or weak decays, $O(100$ or even $1000+)$ signal potential
  - Could begin to lay the groundwork with Run 2 data (maybe get lucky!)

- A more definitive statement requires:
  - A full simulation of the signal and dominant backgrounds
  - For weak decays, predictions for the branching fractions would be helpful.

- $T_{bb[\bar{u}d]}^-$ tetraquarks seem much harder
  - Smaller cross-section expected ( $O(50-100)$ times less than $T_{bc[\bar{u}d]}^0$ )
  - Fully exclusive final states seem ‘out of reach’ in Run 3 + 4, with cross-sections of order 1 nb.
  - Perhaps some luck with detached $B_c$ searches. Requires excellent understanding of tails of IP resolution as there are $O(1000)$ times more prompt $B_c$ than secondary.

- Detector upgrades should improve our chances, e.g. magnet side chambers (> Run 4) will increase low momentum particle acceptance