Discovery potential of doubly-heavy tetraquarks at the LHCb and the CEPC

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A.Ali, Parkhomenko, **QQ**, W. Wang, arXiv:1805.02535
A.Ali, **QQ**, W. Wang, arXiv:1806.09288
QQ, F.S.Yu, arXiv:2008.08026

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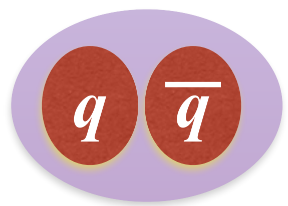
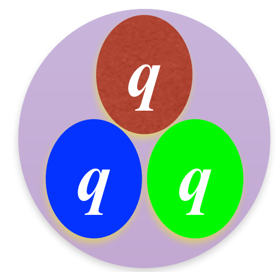
Exotic hadronic states

- 1950-1960s, an era of new mesons and baryons ➡ Quark model

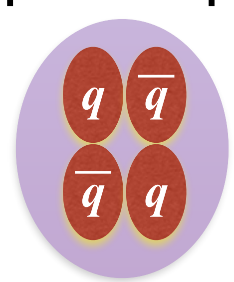




[Gell-Mann,Phys.Lett.8(1964)214]

- Living with mesons and baryons for a long time, until half a century later…

- Tetraquark states (and also later pentaquarks) were found, XYZs



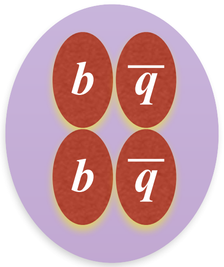
Their nature is still unclear

Chen, Chen, Liu, Zhu, ’16; Esposito, Pilloni, Polosa, ’16; Lebed, Mitchell, Swanson, ’16; Guo, Hanhart, Meissner, Wang, Zhao, Zou, ’17; Ali, Lange, Stone, ’17; Olsen, Skwarnicki, Zieminska, ’18 …

- Exploring physics of hadronic spectrum:
  ➡ test of quark model
  ➡ understanding nonperturbative QCD: a mysterious area within the SM

Doubly-heavy tetraquarks

- An era of exotic hadronic states
- Recently, a new type —— singly-heavy tetraquarks: $X_{0,1}(2900)\ (cs\bar{u}\bar{d})$ [LHCb,2009.00025,2009.00026]
- Less recently, doubly-heavy baryons: $\Xi_{cc}^{++}\ (ccu)$ [LHCb,1707.07621]
- Next, more doubly heavy baryons and also doubly-heavy tetraquarks?
- A unique nice feature —— weakly decaying (at least $T_{[qq']}^{\{bb\}}$) [Eichten,Quigg,1707.09575]

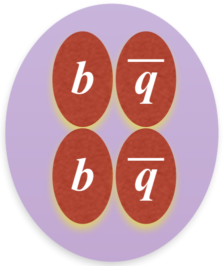


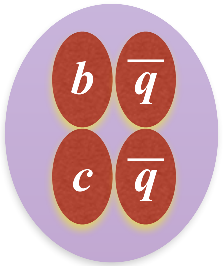
A new window to tetraquark nature

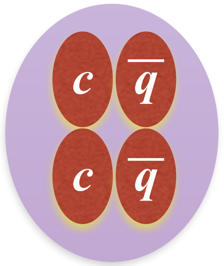
- But first, are they there?

Doubly-heavy tetraquarks

- Two possibilities: yes or no.
- If no, a big problem to theorists.
- If yes, we need to find them first.
- Two questions:
  ✓ Can we?
  ✓ How can we?
- Two key issues to answer:
  ✓ Production
  ✓ Detection



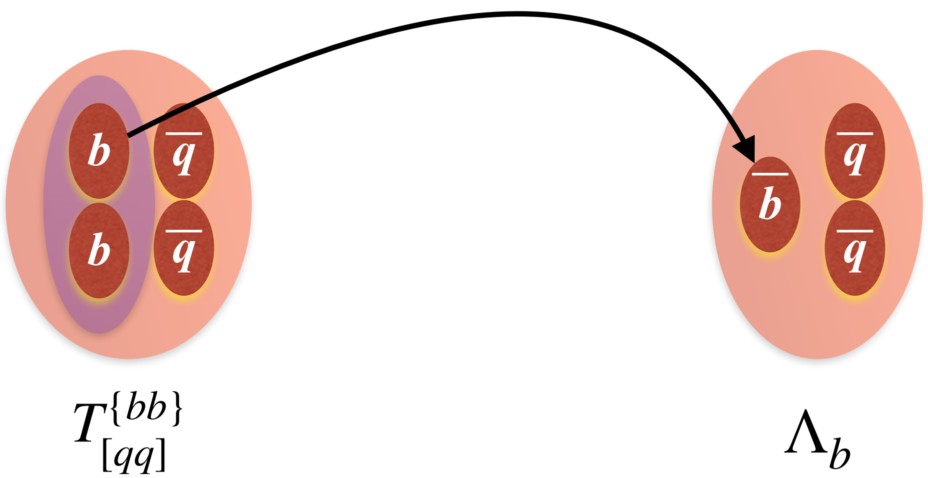




Production

- Heavy quark symmetry ➡ two heavy quarks form a heavy diquark

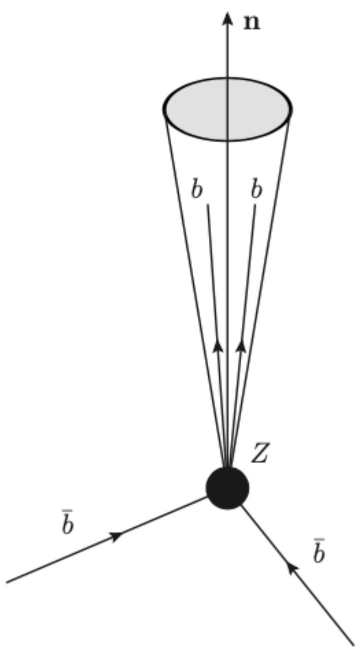
[Eichten,Quigg,1707.09575]



- Hadronization from a heavy diquark jet as a heavy baryon: two steps

1. Collinear bb quarks → diquark jet

2. Diquark jet → fragmentation into hadrons



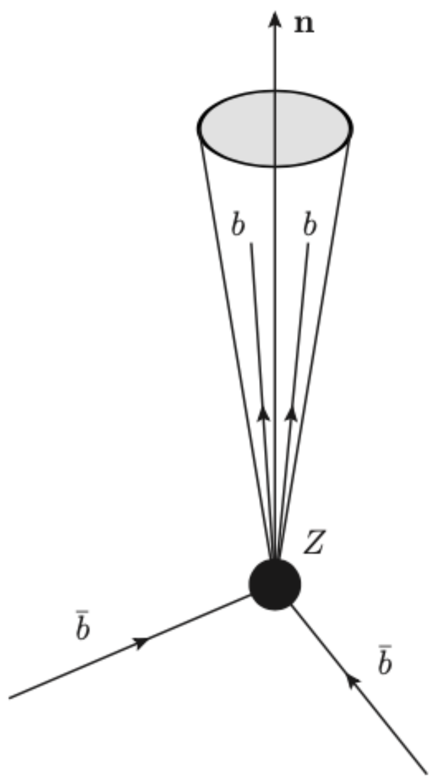
- Key issue: how to identify a diquark jet

[A.Ali, Parkhomenko, **QQ**, W. Wang,1805.02535]

Production: diquark jet

- To form a diquark jet: bb quarks produced collinearly.
- To quantify how collinear, we use the invariant mass

$$M_{bb-\text{jet}} < 2m_b + \Delta M$$



- The diquark jet resolution parameter ΔM is determined by B_c meson production at LHCb and at Z factories

$$\Delta M = \begin{cases} \left(2.0^{+0.5}_{-0.4}\right) \text{GeV, for LHCb,} \\ \left(2.7^{+1.3}_{-0.5}\right) \text{GeV, for Z factories.} \end{cases}$$

- The results for production rates

$$\sigma(H_{cc}, H_{bc}, H_{bb}) \approx 2.2 \times 10^2,\ 2.7 \times 10^2,\ 15 \text{ nb}$$ at LHCb

$$B(Z \to H_{cc}, H_{bb} + X) \approx 3.0 \times 10^{-5},\ 1.6 \times 10^{-5}$$ at CEPC

[A.Ali, Parkhomenko, **QQ**, W. Wang,1805.02535]
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Production: fragmentation

- For bb and bc tetraquarks (stable):

$$f(T^{\{bb\}})/f(\Xi_{bb}) \approx f(\Lambda_b)/f(B)$$

$$\frac{f_{\Lambda_b^0}}{f_u + f_d}(p_T) = (1 \pm 0.061)\Big[(0.0793 \pm 0.0141) + e^{(-1.022\pm0.047)+(-0.107\pm0.002)\times p_T}\Big]$$

[LHCb, 1902.06794]

$B(Z \to T^{\{bb\}}_{[\bar{u}\bar{d}]} + X) \approx 1.2 \times 10^{-6}$ at CEPC

$\sigma(T^{\{bb\}}_{[\bar{u}\bar{d}]}, T^{\{bc\}}_{[\bar{u}\bar{d}]}) \approx 2.4,\ 88$ nb at LHCb

- For cc tetraquarks (unstable), we still need the excitation-ground rate

$$\frac{f_{\Lambda_c}}{f_{\Lambda_c+\Sigma_c+\Lambda_c^*}} = 0.48 \pm 0.08$$

[Belle, arXiv:1706.06791]

$B(Z \to T^{\{cc\}}_{[\bar{u}\bar{d}]} + X) \approx 1.1 \times 10^{-6}$ at CEPC

$\sigma(T^{\{cc\}}_{[\bar{u}\bar{d}]}) \approx 15$ nb at LHCb

[A.Ali, Parkhomenko, **QQ**, W. Wang,1805.02535]
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[**QQ**, F.S.Yu, arXiv:2008.08026]

Production: results

- Crosscheck with LHCb and NRQCD (Ξ_{cc}^{++} production at LHC)

$\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+}) \approx 47$ nb ⟷ 30 ~ 130 nb (LHCb) [LHCb, 1902.06794]
62 nb (NRQCD) [Chang, Qiao, Wang, Wu, '06]

- A brief summary

No. of events	$T^{\{cc\}}_{[\bar{u}\bar{d}]}$	$T^{\{bc\}}_{[\bar{u}\bar{d}]}$	$T^{\{bb\}}_{[\bar{u}\bar{d}]}$	Ξ_{bc}^{+}	Ξ_{bb}^{0}
LHCb ($10\,\mathrm{fb}^{-1}$)	1.5×10^{8}	8.8×10^{8}	2.4×10^{7}	1.4×10^{9}	3.8×10^{7}
CEPC (Tera-Z)	10^{6}		10^{6}		1.6×10^{6}

[A.Ali, Parkhomenko, **QQ**, W. Wang,1805.02535]
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Detection: $T^{\{cc\}}$

- Its gold channels (possible discovery channels), highly depend on its mass

Reference	[26]	[27]	[29]	[28]	[30]	[31]	[20]	[22]	[14]	[24]
$T^{\{cc\}}_{\bar{n}\bar{n}'}$	-79	-96	-150	+53	+166	+60	-	AT	+102	+88
$T^{\{cc\}}_{\bar{n}\bar{s}}$	-9	-56	+94	+128	+255	+166	+143	AT	+179	+181
Reference	[32]	[23]	[33]	[34]	[13]	[35]	[21]	[11]	[25]	
$T^{\{cc\}}_{\bar{n}\bar{n}'}$	BT	-215	-149	-182	+7	+98	+91	+125	AT	

compared to DD^* threshold

- For different masses, we suggest

mass	most favored channel
1. Above DD* threshold (strong decay)	$T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^0 D^{*+}$
2. Between DD* and DD threshold (EM decay)	$T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^0 D^+ \gamma$
3. Below DD threshold (weak decay)	$T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^+ K^- \pi^+$

[**QQ**, F.S.Yu, arXiv:2008.08026]

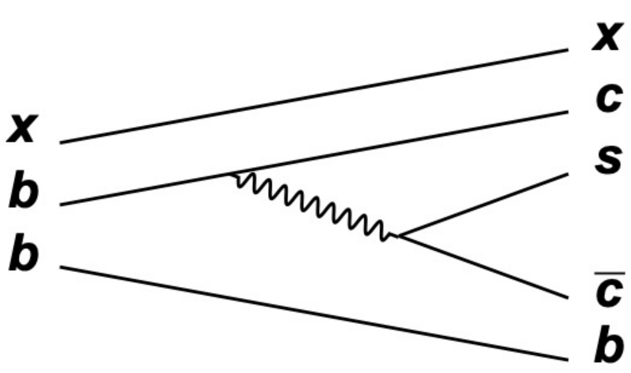
Detection: $\mathrm{T}^{\{bb\}}$ (H_{bb})

- In contrary to cc, H_{bb} has much lower exclusive branching ratios ($\sim 10^{-6}$)
- Go inclusive!
- Weakly decaying H_{bb} are the only sources for displaced B_c mesons
  ➡ $b \to \bar{c}$ transition is required

[Gershon,Poluektov,1810.06657]

- The branching ratio

$$B(\Xi_{bbq} \to \bar{B}_c + X) \approx 0.8\,\%$$



- With the $\bar{B}_c$ detection efficiency $B(\bar{B}_c \to J\psi + \pi^- \to \mu^+\mu^-\pi^-) \approx 2 \times 10^{-4}$ and 10 fb^{-1} data at LHCb, $\mathcal{O}(10^2)$ events are expected.

[Ridgway,Wise,1902.04582]

Detection: $\mathbf{T^{\{bc\}}}$ ($\mathbf{H_{bc}}$)

- Some suggestions in the literature:

➡ $B(\Xi_{bc}^0 \to pK^-) = \mathcal{O}(10^{-8} - 10^{-7})$ [Li,Lu,Wang,Yu,Zou,1701.03284]

➡ $B(\Xi_{bc}^+ \to \Sigma_b^+ \bar{K}^{*0}, \Xi_{bc}^0 \to \Lambda_b^0 \bar{K}^{*0}, \Omega_{bc} \to \Xi_b^0 \bar{K}^{*0}) = \mathcal{O}(1\% - 10\%)$

Small branching ratio or low detection efficiency.

- A new idea. (come out soon)

Summary

- Come back to the two questions:
  - ✓ Can we?

    Yes, if not too weird. For each doubly-heavy hadrons, **millions** will be produced at CEPC, and **more by 1 to 2 orders** at LHCb.
  - ✓ How can we?

- For $T^{\{cc\}}_{[\bar{q}\bar{q}]}$

mass	most favored channel
1. Above DD* threshold (strong decay)	$T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^0 D^{*+}$
2. Between DD* and DD threshold (EM decay)	$T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^0 D^+ \gamma$
3. Below DD threshold (weak decay)	$T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^+ K^- \pi^+$

- For H_{bb}, a displaced B_c meson should be searched.

$$B(\Xi_{bbq} \to \bar{B}_c + X) \approx 0.8\,\%$$

Thank you!