Search for T_{bc}: Prospects for Run3

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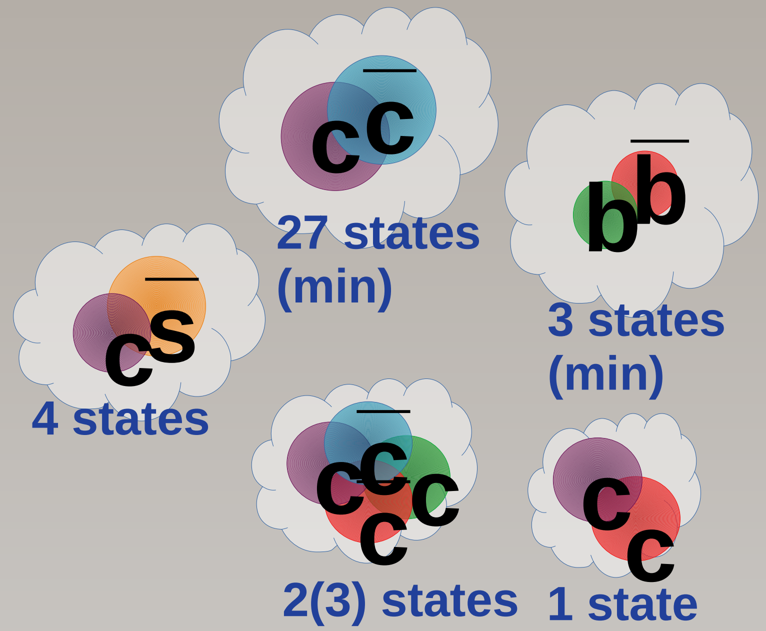
T_{bc} at LHCb mini-workshop

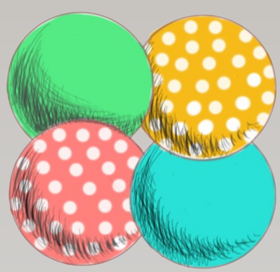
5 October 2023

Motivation

- >35 different states discovered since 2003



- Still can’t understand their nature



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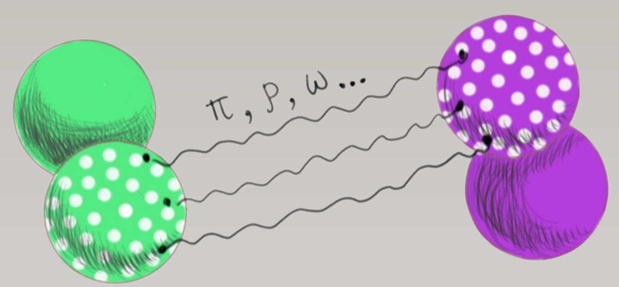
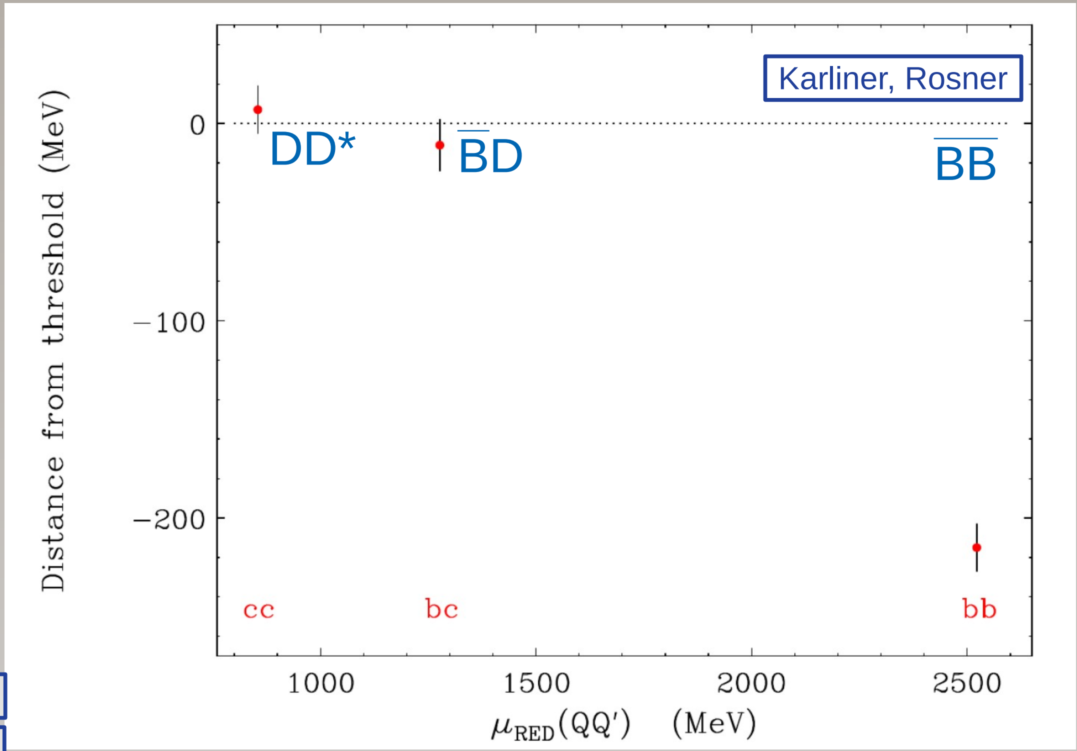


- Unambiguous experimental input is needed
  - T_{cc} is the best example so far (δm=-360±40 keV)

Other doubly-heavy states, $[QQ\bar{u}\bar{d}]$

- The T_{bb} ***$[bb][\bar{u}\bar{d}]$*** is likely long-lived...
  … but yields are suppressed due to x-section and BR(b → Dπ/μ) → expect only ~10^{-3} events in Run3&4



- T_{bc} ***$[bc][\bar{u}\bar{d}]$*** may be below B̄D threshold by O(10) MeV

Karliner, Rosner, 2017 | Semay, SIlvestre-Brac, 1994 | Caramés, Vijande, Valcarce, 2019 | Meng et al., 2021

- Opposite expectations in some molecular models Li, Sun, Liu, Zhu, 2012 | Liu et al., 2019 | Hudspith et al., 2020

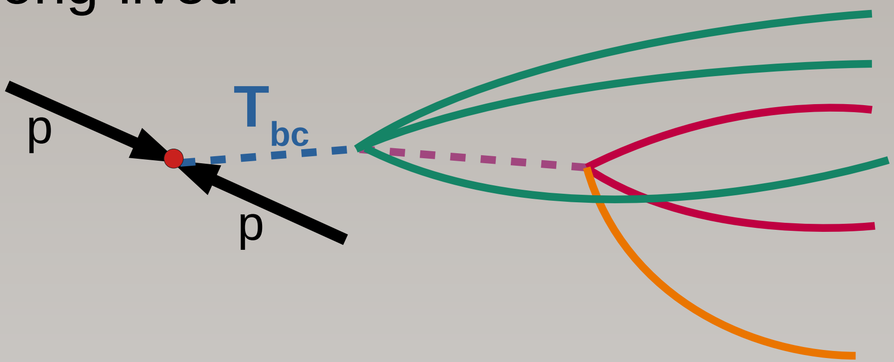
what your model predicts?

Much more interesting!

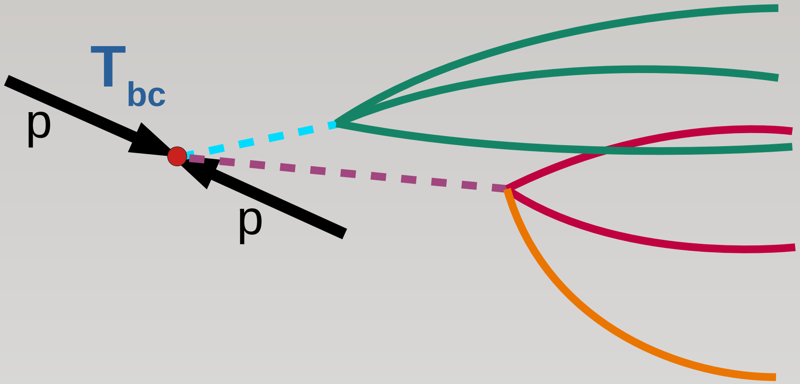
Question to theory:
Can we say T_{bc} is within ±25MeV of B̄D threshold?

The two cases

- Having mass below/above $\bar{B}D$ threshold means very different signatures
  - $\delta m<0$: only weakly decaying, long-lived



  - $\delta m>0$: strongly decaying to $\bar{B}^0D^0$ & B^-D^+, short-lived



Question to theory:
Does it unambiguosly tells about the nature of binding mechanisms?

Estimations of sensitivity in Run3

- Compare to Steven Blusk's presentation at
  LHCb mini-workshop: Tcc and beyond, Sept 2021

Summary

- $T^0_{bc[\bar{u}\bar{d}]}$ 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.

- My estimations are factor ~100 more pessimistic
  (to be discussed in following)

- LHCb in Run3 vs. Run1&2
  - 20 fb^{-1} at 14 TeV vs. 5+3fb^{-1} at 13 TeV +8/7TeV
  - efficiency higher by factor 1-2x
  - overall gain up to 5x

T_{bc} production cross-section

- Various predictions can be found in literature:
  - **103^{+39}_{-25} nb** for pp at 13 TeV [Ali, Qin, Wang, 2018]
  - **0.3-0.4 nb** for pp at 14 TeV [Chen, Wu, 2011]

- Can estimate via T_{cc} cross-section [Zhang et al., 2011]
  & assuming $\sigma(T_{bc})/\sigma(T_{cc}) \sim \sigma(\Xi_{bc})/\sigma(\Xi_{cc}) \sim 0.4$

$$\frac{\sigma(pp \to T_{cc}^{+})}{\sigma(pp \to \chi_{c1}(3872))} \sim 0.05$$

$$\sigma(pp \to \chi_{c1}(3872)) \sim 0.9\ \mu\text{b}$$

Steve's number: **100 nb**

→ $\sigma(pp \to T_{cc}+X) = (45\pm20)$ nb

→ **$\sigma(pp \to T_{bc}+X) = (20\pm9)$ nb**

for $2<p_T<20$ GeV/c and $2<y<4.5$

Question to theory:
How reasonable this is?

Weakly-decaying T_{bc}: Lifetime

- Expect lifetime similar to Ξ_{bc} (0.28-0.33 ps) Kiselev, Likhoded, 2002
- In same spirit estimate decay widths to be:
  - **b→c**: Γ_b = 0.63 ps^{-1}
    with possible correction due to Pauli interference of $\Gamma_{b,corr}$ = (0.2±0.2) ps^{-1}
  - **c→s**: Γ_c = (1.2±0.2) ps^{-1}
    with correction due to Pauli interference & weak-scattering effects $\Gamma_{c,corr}$ = (1.5±0.5) ps^{-1}
  - **W exchange in b→c & c→s**: Γ_W = (0.20±0.15) ps^{-1}
- Summing altogether get

$$\tau(T_{bc}) = (0.27 \pm 0.04)\ \text{ps}$$

and following probabilities:

f_b = 0.22±0.04,
f_c = 0.72±0.04,
f_W = 0.06±0.04,

Question to theory:
Should the uncertainties be reduced/increased?

Weakly-decaying T_{bc}. Branching fractions

T^0_{bc} decay	$\mathcal{B}$ estimation	analogous B-decays	$\mathcal{B}$, exp
	$b \to D$ + hadrons decay modes		
$D^0 D^0$	$10^{-3} \times f_b$ or $10^{-3} \times f_W$	—	—
$D^0 D^+ \pi^-$	$(2.5-5.0) \times 10^{-3} \times f_b$	$B^- \to D^0 \pi^-$	$(4.61 \pm 0.10) \times 10^{-3}$
		$\overline{B}^0 \to D^+ \pi^-$	$(2.51 \pm 0.08) \times 10^{-3}$
		$B^0_s \to D^+_s \pi^-$	$(2.98 \pm 0.14) \times 10^{-3}$
		$\Lambda^0_b \to \Lambda^+_c \pi^-$	$(4.9 \pm 0.4) \times 10^{-3}$
$D^{*0} D^+ \pi^-$	$(5.2 \pm 0.5) \times 10^{-3} \times f_b$	$B^- \to D^{*0} \pi^-$	$(5.17 \pm 0.15) \times 10^{-3}$
$D^{*+} D^0 \pi^-$	$(2.7 \pm 0.3) \times 10^{-3} \times f_b$	$\overline{B}^0 \to D^{*+} \pi^-$	$(2.74 \pm 0.13) \times 10^{-3}$
$D^+ D^+ \pi^- \pi^-$	$(1-8) \times 10^{-3} \times f_b$	$B^- \to D^+ \pi^- \pi^-$	$(1.07 \pm 0.05) \times 10^{-3}$
		$\overline{B}^0 \to D^+ \rho^-{}_{[\pi^- \pi^0]}$	$(7.6 \pm 1.2) \times 10^{-3}$
		$B^0_s \to D^-_s \rho^+{}_{[\pi^+ \pi^0]}$	$(6.8 \pm 1.4) \times 10^{-3}$
$D^0 D^0 \pi^+ \pi^-{}_{NR}$	$(0.9 \pm 0.4) \times 10^{-3} \times f_b$	$\overline{B}^0 \to D^0 \pi^+ \pi^-$	$(0.88 \pm 0.05) \times 10^{-3}$
$D^0 D^+ \pi^- \pi^0{}_{NR}$	$(1.0 \pm 0.3)\% \times f_b$	$B^- \to D^0 \rho^-{}_{\pi^- \pi^0}$	$(1.34 \pm 0.18) \times 10^{-2}$
		$\overline{B}^0 \to D^+ \rho^-{}_{\pi^- \pi^0}$	$(0.76 \pm 0.12) \times 10^{-2}$
	$b \to D + \mu X$ decay modes		
$D^0 D^+ \mu^- \nu$	$(2.3 \pm 0.1)\% \times f_b$	$B^- \to D^0 \mu^- \nu$	$(2.30 \pm 0.09)\%$
		$\overline{B}^0 \to D^+ \mu^- \nu$	$(2.24 \pm 0.09)\%$
$D^{*0} D^+ \mu^- \nu$	$(5.1 \pm 0.2)\% \times f_b$	$B^- \to D^{*0} \mu^- \nu$	$(5.30 \pm 0.09)\%$
$D^0 D^{*+} \mu^- \nu$	$(5.1 \pm 0.2)\% \times f_b$	$\overline{B}^0 \to D^{*+} \mu^- \nu$	$(4.97 \pm 0.12)\%$
$D^0 D^+ \mu^- X$	$(2-8)\% \times f_b$	$B^{+/0}_{mix} \to D^+ \mu^- X$	$(2.6 \pm 0.5)\%$
		$B^{+/0}_{mix} \to D^0 \mu^- X$	$(7.3 \pm 1.5)\%$
		$B^+ \to D \mu^- X$	$(9.6 \pm 0.7)\%$
		$\overline{B}^0 \to D \mu^- X$	$(9.3 \pm 0.8)\%$
	$b \to J/\psi$ + hadrons decay modes		
$J/\psi D^+ K^-$	$(1.0 \pm 0.1) \times 10^{-3} \times f_b$	$B^- \to J/\psi K^-$	$(1.02 \pm 0.02) \times 10^{-3}$
$J/\psi D^0 K^0_S$	$(0.45 \pm 0.05) \times 10^{-3} \times f_b$	$\overline{B}^0 \to J/\psi K^0_S$	$(0.89 \pm 0.02)/2 \times 10^{-3}$
$J/\psi D^0 K^{*-}$	$(1.3 \pm 0.2) \times 10^{-3} \times f_b$	$B^- \to J/\psi K^{*-}$	$(1.43 \pm 0.08) \times 10^{-3}$
		$\overline{B}^0 \to J/\psi K^{*0}$	$(1.27 \pm 0.05) \times 10^{-3}$
		$B^0_s \to J/\psi \phi$	$(1.04 \pm 0.04) \times 10^{-3}$
		$\Lambda^0_b \to J/\psi \Lambda(1520)$	$(0.32 \pm 0.06) \times (0.19 \pm$
$J/\psi D^0 K^- \pi^+{}_{NR}$	$(0.3-1.2) \times 10^{-3} \times f_b$	$\overline{B}^0 \to J/\psi K^- \pi^+{}_{NR}$	$(1.15 \pm 0.05) \times 10^{-3}$
		$B^0_s \to J/\psi K^+ K^-{}_{NR}$	$(0.79 \pm 0.07) \times 10^{-3}$
		$\Lambda^0_b \to J/\psi p K^-{}_{sum}$	$(0.32 \pm 0.06) \times 10^{-3}$

f_b = 0.22±0.04, f_c = 0.72±0.04, f_W = 0.06±0.04,

T^0_{bc} decay	$\mathcal{B}$ estimation	analogous B/D-decays	$\mathcal{B}$, exp
	$c \to s$ transition		
$\overline{B}^0 K^- \pi^+$	$(4 \pm 1)\% \times f_c$	$D^0 \to K^- \pi^+$	$(3.95 \pm 0.03)\%$
$B^- K^- \pi^+ \pi^+$	$(7.5 \pm 2.5)\% \times f_c$	$D^+ \to K^- \pi^+ \pi^+$	$(9.38 \pm 0.16)\%$
		$D^+_s \to K^+ K^- \pi^+$	$(5.39 \pm 0.15)\%$
		$\Lambda^+_c \to p K^- \pi^+$	$(6.28 \pm 0.32)\%$
$\overline{B}^0 K^- \pi^+ \pi^+ \pi^-$	$(8 \pm 2)\% \times f_c$	$D^0 \to K^- \pi^+ \pi^+ \pi^-$	$(8.22 \pm 0.14)\%$
$\overline{B}^0 K^- \mu^+ \nu$	$(3 \pm 1)\% \times f_c$	$D^0 \to K^- \mu^+ \nu$	$(3.41 \pm 0.04)\%$
$\overline{B}^0 K^- \mu^+ X$	$(2 \pm 1)\% \times f_c$	$D^0 \to K^{*-} \mu^+ \nu$	$(1.89 \pm 0.24)\%$
		$D^0 \to K^- \pi^0 e^+ \nu$	$(1.6^{+1.3}_{-0.5})\%$
$B^- K^- \pi^+ \mu^+ \nu$	$(3.5 \pm 1.5)\% \times f_c$	$D^+ \to K^- \pi^+ \mu^+ \nu_{sum}$	$(3.65 \pm 0.34)\%$
	W exchange in $bc \to cs$		
$D^0 K^- \pi^+$	$(5 \pm 4) \times 10^{-4} \times f_W$	—	—
$D^+ K^-$	$(5 \pm 4) \times 10^{-4} \times f_W$	—	—
$D^0 K^0_S$	$(5 \pm 4) \times 10^{-4} \times f_W$	—	—
	$b \to u$ transition		
$D^0 \pi^+ \pi^+$	$(3 \pm 2) \times 10^{-5} \times f_b$	$B^+ \to \pi^+ \pi^0$	5.5×10^{-6}
$D^+ \pi^-$	$(3 \pm 2) \times 10^{-5} \times f_b$	$B^+ \to \pi^+ \pi^+ \pi^-$	1.5×10^{-5}
$D^+ \pi^+ \pi^- \pi^-$	$(3 \pm 2) \times 10^{-5} \times f_b$	$B^0 \to \rho^+ \pi^-$	2.3×10^{-5}

Channel	My estimation	Steve's number
DD+h	(0.02-0.2)%	1%
J/ψD+h	(0.01-0.03)%	1%
B+h	(3-6)%	1%
Dh	$\sim 10^{-5}$	

Question to theory:

Can you provide us with better estimates?

Efficiencies

- Use toy formula:
  $\varepsilon = \varepsilon_{trig} \times \varepsilon_{tau} \times \varepsilon_{base} \times \varepsilon_{tracks}$
- trig: 90% for J/ψ+X final state
  & 60(30)% for D+X final state for Run3(2)
- tau: 1 – exp(-τ / 0.4 ps) *(53% for T_{bc}, 71% for B_c, 97% for B)*
- base: 50%
- tracks: $\Pi_i \varepsilon_{tr,i}$, where for every charged tracks $\varepsilon_{tr,i}$ is
  - 40% if directly from H_{bc} hadron
  - 40% if directly from B_c meson
  - 50% if from B/D meson

Efficiencies

- Use toy formula:

  $\varepsilon = \varepsilon_{trig} \times \varepsilon_{tau} \times \varepsilon_{base} \times \varepsilon_{tracks}$

- trig: 90% for J/ψ+X final state
  & 60(30)% for D+X final state for Run3(2)

* here ε includes ε_{acc} = 27% which corresponds to probability of having b-quark in LHCb acceptance

1% for B_c, 97% for B)

Decay	$\varepsilon_{est}[10^{-4}]$	$\varepsilon_{MC}[10^{-4}]$	ratio
$B_c^+ \to J/\psi K^+$	55	45 [31]	1.2
$B_c^+ \to J/\psi \pi^+\pi^+\pi^-$	8.9	7.8 [32]	1.1
$B_c^+ \to J/\psi K^+K^-\pi^+$	8.9	10 [32]	0.9
$B_c^+ \to J/\psi K^+\pi^+\pi^-$	8.9	6.8 [32]	1.3
$B_c^+ \to J/\psi 5\pi$	1.4	1.4 [33]	1.0
$B_c^+ \to J/\psi 2K3\pi$	1.4	1.1 [33]	1.3
$B_c^+ \to J/\psi 7\pi$	0.23	0.31 [33]	0.7
$B_c^+ \to J/\psi D_s^+$	17.3	20 [34]	0.9
$\Xi_{bc} \to \Lambda_c^+\pi^+$	10.7	14.9 [35]	0.7
$\Xi_{bc} \to \Xi_c\pi^+$	10.7	20.8 [35]	0.5
$\Xi_{bc} \to D^0pK^-$	8.6	8.1 [36]	1.1

Channel	this estimation	Steve's number
$T_{bc} \to D^0D^+\pi^-$	0.2%	0.7%
$T_{bc} \to J/\psi D^+K^-$	0.2%	2.4%
$T_{bc} \to B^0K^-\pi^+$, $B^0 \to J/\psi K^-\pi^+$	0.24%	2.4%

Good up to ±25%

Expected yields

- Expected yields:
  $$N = \sigma \times \mathcal{L} \times \mathcal{B} \times \mathcal{B}_{B,D,J/\psi} \times \varepsilon$$

- σ = 20 nb
- L = 20 fb^{-1} (Run3)

- O(1-10) signal events in individual modes
  → expect O(100) in 20-40 channels combined + O(100) in SL

- Reality may differ a lot, by factor 0.3-3x easily
  → all classes are important

- Gain a lot from many modes like
  $D^0 \to K\pi$ & $K3\pi$,
  $B \to J/\psi K$, $D\pi$, $D\pi$ modes

decay channel	$\varepsilon_{tot} \times \mathcal{B}$ $[10^{-9}]$	Expected yield
fully reconstructed channels		
$D^0 D^0$	7.8	3.1
$D^0 D^+ \pi^-$	9.2	3.7
$D^0 D^0 \pi^+ \pi^-$	3.4	1.4
$D^+ D^+ \pi^- \pi^-$	3.5	1.4
sum		10
$J/\psi D^+ K^-$	2.3	0.9
$J/\psi D^0 K^- \pi^+$	3.1	1.2
sum		2.1
$\overline{B}^0 K^- \pi^+$	32.9	13.2
$B^- K^- \pi^+ \pi^+$	33.6	13.4
$\overline{B}^0 K^- \pi^+ \pi^+ \pi^-$	6.7	2.7
sum		29
$\overline{B}^0{}_{SL} K^- \pi^+$	188	75
$B^-{}_{SL} K^- \pi^+ \pi^+$	94	38
$\overline{B}^0{}_{SL} K^- \pi^+ \pi^+ \pi^-$	61	24
sum		137
$D^0 D^+ \mu^- \nu$	56	22
$D^0 D^0 \pi^+ \mu^- \nu$	43	17
$D^0 D^+ \mu^- + X$	163	65
$D^0 D^0 \mu^- + X$	108	43
sum		147
$\overline{B}^0 K^- \mu^+ \nu$	24	9.5
$B^- K^- \pi^+ \mu^+ \nu$	16	6.5
sum		16
$D^0 K^- \pi^+$	68	27
$D^+ K^-$	134	54
$D^0 \pi^+ \pi^-$	2.5	1
$D^+ \pi^-$	4.9	2
sum		84

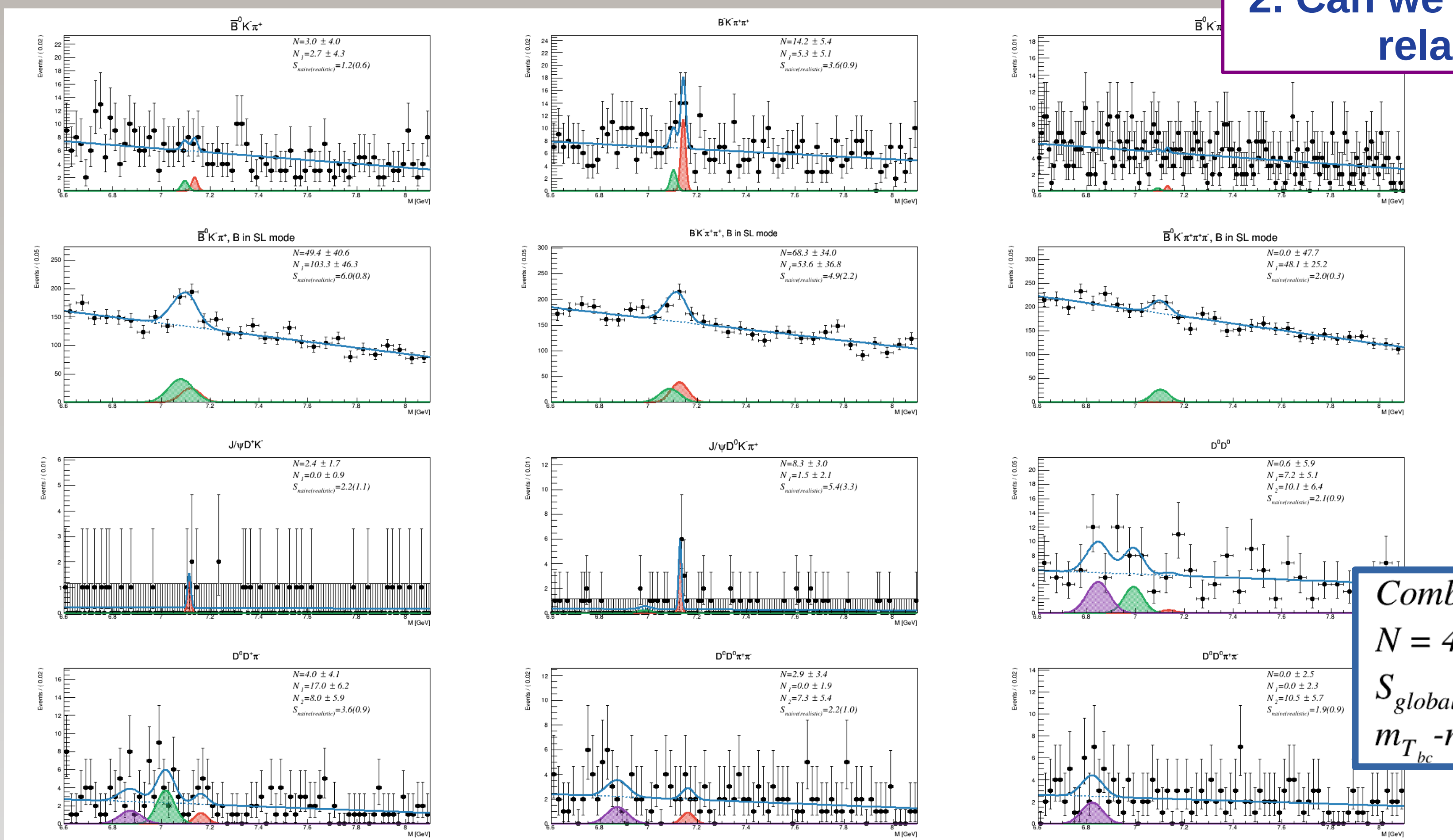
Combining channels together

- Simultaneous mass fit for 20-40 channels
- All shapes are fixed, yields are free (can one use constraints?)
- Scan common $m(T_{bc})$ in [-25;0] MeV within $\overline{B}^0 D^0$ threshold

Question to theory:

1. Is this range enough?

2. Can we put constrains on relative yields?



Combined:

$N = 428 \pm 98$

$S_{global,naive(realistic)} = 11.5(7.2)$

$m_{T_{bc}} - m_{\overline{B}^0 D^0, thr} = -6.0 \pm 6.3$ MeV

Strongly-decaying T_{bc}

- Decaying to $\overline{B}^0D^0$ & B^-D^+ with BRs=50%
- Estimate expected yields in the same manner
- Signal peaks are likely within ~1MeV of threshold → even 40 events could give >5σ significance

decay channel	$\varepsilon_{tot} \times \mathcal{B}$ $[10^{-9}]$	Expected yield
B in fully reconstructed modes		
$\overline{B}^0 D^0$	90	36
$B^- D^+$	108	43
sum		79
B in semi-leptonic modes		
$\overline{B}^0 D^0$	560	225
$B^- D^+$	300	120
sum		345

Control channels

- Natural choice to use decays of B_c mesons:
  - J/ψDX: $B_c \to J/\psi D_s$ (4k), $B_c \to J/\psi D^{(*)0} K^+$ (1.1k)
  - BX: $B_c \to B_s \pi^+$ (1.8k), $B_c \to B^{(*)+} K^+ \pi^+$ (900)
  - DDX: $B_c \to \overline{D}^0 D^+$ (?), $B_c \to \overline{D}^0 D^0 \pi^+$ (?)
  - DX: $B_c \to D^0 K^+$ (250), $B_c \to D^+ K^+ \pi^-$ (600)

- Possibly also (not-yet-discovered) Ξ_{bc}
  - Larger x-section.
  - Lower BRs of baryon decays

  → expect O(10) of events in Run3 (see backup)

my estimation:
***$\sigma(pp \to \Xi_{bc}+X)$ ~ 100 nb** in p_T>4 GeV*
[Zhang et al]: ~37nb for p_T>4 GeV

- For strongly-decaying states:
  - $B^- D^0$ & $\overline{B}^0 D^+$ from DPS or B_c^{**} (0.5-5k)

see *Quan Zou, B&Q meeting, Nov 2022*

Common framework

Simplifying and automatizing analysis steps as much as possible

- Merging decay modes in simulation and ntuple production
- Training MVA for selection and optimising final cut
- Signal shapes (mass resolution & reflections) from MC
- Efficiencies from MC
- Simultaneous fits for various combinations of decay modes
  → dedicated toyMC to estimate significances
- Setting upper limits while accounting for variations in
  - efficiency, T_{bc} lifetime, expected BRs

Preparations

- Most of Hlt2/Sprucing lines already prepared (in B&Q and B2OC), few Sprucing lines to be added

- Forming a group of interested people to join the efforts:
  - Steve (Syracuse),
  - Yiming, Mingjie, ... (IHEP),
  - Paolo (Milano)

  Let me know if you're interested

- Roadmap document is in progress

LHCb-INT-2023-YYY
October 2, 2023

Search for T^0_{bc} tetraquark (Roadmap)

Ivan Polyakov[1].

[1] *CERN, Switzerland*

Abstract

In this note a strategy for search of a T^0_{bc} tetraquak in Run3 of LHCb is presented. Both cases of weakly-decaying (and thus long-lived) and strongly-decaying T^0_{bc} are considered.

Contents

Other T_{bc} states

- The ground $[bc\bar{u}\bar{d}]$ state mass is around $\bar{B}^0 D^0$ threshold if it's difference to $\bar{B}^0 D^0$ is <4.5 MeV
  → should decay predominantly to $\mathbf{\bar{B}^0 D^0}$

- If there is also a $\mathbf{\bar{B}^* D}$ molecule, it's mass is ~0.1-1 MeV below $\bar{B}^{*0} D^0$ threshold
  → should decay predominantly to $\mathbf{[\bar{B}^0 \gamma]_{B^*} D^0}$

- If there is also a $\mathbf{\bar{B} D^*}$ molecule, ...
  → should decay predominantly to $\mathbf{\bar{B}^0 [D^0 \pi^0/\gamma]_{D^*}}$

- If there is also a $\mathbf{\bar{B}^* D^*}$ molecule, …
  → should decay predominantly as
  $[\bar{B}^0\gamma]_{B^*} D^{*0}$ or $\bar{B}^{*0}[D^0\pi^0/\gamma]_{D^*}$ → $\mathbf{[\bar{B}^0\gamma]_{B^*}[D^0\pi^0/\gamma]_{D^*}}$

- We can't reconstruct π^0/γ → all give peak in $\bar{B}^0 D^0$

	$m_{th}(B^{(*)-}D^{(*)+})$ - $m_{th}(\bar{B}^{(*)0}D^{(*)0})$
$\bar{B}D$	4.50±0.05 MeV
$\bar{B}^*D$	3.91±0.26 MeV
$\bar{B}D^*$	3.09±0.06 MeV
$\bar{B}^*D^*$	2.50±0.26 MeV

	Γ
D^{*0}	55 keV
D^{*+}	83 keV
B^*	<10 keV ?

Question to theory:
Can they all co-exist?

Prospects of CMS

- CMS/ATLAS sometimes appears to be very competitive to LHCb: $B_c(2S)$, $X \to J/\psi J/\psi$, $\chi_b(3P)$, $\Xi_b(5945)^0$, $\Xi_b(6100)^-$

- Contr's:
  - only modes with J/ψ
  - in general efficiency lower by ~20x
  - no hadron PID

- Pro's:
  - $150 fb^{-1}$ (Run2) + $250 fb^{-1}$ (Run3)
  - 49% of b-quarks are within CMS acceptance vs 27% for LHCb
  - good efficiency for tracks additional to reconstructed B-meson
  - good efficiency for K_s^0

- Expected yields for Run2&3: ~36 events in 5 modes + 47 in modes with B*/D*

decay channel	$\varepsilon_{tot} \times \mathcal{B}$ $[10^{-9}]$	Expected yield
fully reconstructed channels		
$\overline{B}^0 K^- \pi^+$	0.10	1.4
$B^- K^- \pi^+ \pi^+$	0.26	3.7
$\overline{B}^0 K^- \pi^+ \pi^+ \pi^-$	0.13	1.9
$J/\psi D^+ K^-$	0.54	7.8
$J/\psi D^0 K^- \pi^+$	1.45	21
sum		36

Conclusion

- Feasible in Run3, but only if many modes (20-40) are combined
- A group is forming, preparation work started
- Should not ignore CMS/ATLAS

- Questions to theory:
  1. Will observing $\delta m(T_{bc})<0$ or >0 unambiguously tell about the nature of binding mechanism?
  2. Is searching in range $-25<\delta m(T_{bc})<25$ MeV enough?
  3. How well we can predict
     a) x-section,
     b) lifetime,
     c) BRs?
  4. Can we have states near $\bar{B}D$, $\bar{B}^*D$, $\bar{B}D^*$ and $\bar{B}^*D^*$ thresholds all at once?

Backup

Expected yields

- Expected yields:

$$N = \sigma \times \mathcal{L} \times \mathcal{B} \times \mathcal{B}_{B,D,J/\psi} \times \varepsilon$$

- σ = 20 nb
- $\mathcal{L}$ = 20 fb^{-1} (Run3)
-

decay channel	$\varepsilon_{tot} \times \mathcal{B}$ [10^{-9}]	Expected yield
fully reconstructed channels		
${D^0}_{K\pi}{D^0}_{K\pi}$	3.4	
${D^0}_{K\pi}{D^0}_{K3\pi}$	3.5	
${D^0}_{K3\pi}{D^0}_{K3\pi}$	0.9	
sum	7.8	3.1
${D^0}_{K\pi}D^+\pi^-$	6.0	
${D^0}_{K3\pi}D^+\pi^-$	3.2	
sum	9.2	3.7
$D^0[D^0\pi^+]_{D^{*+}}\pi^-$	2.3	
$D^0D^0\pi^+{\pi^-}_{NR}$	1.1	
sum	3.4	1.4
$D^+D^+\pi^-\pi^-$	3.5	1.4
$J/\psi D^+K^-$	2.3	0.9
$J/\psi[D^0\pi^+]_{D^{*+}}K^-$	2.4	
$J/\psi D^0K^-{\pi^+}_{NR}$	0.9	
sum	3.1	1.2
${\overline{B}^0}_{J/\psi K\pi}K^-\pi^+$	4.7	
${\overline{B}^0}_{D^+\pi^-}K^-\pi^+$	11	
${\overline{B}^0}_{D^0\pi^+\pi^-}K^-\pi^+$	2.4	
${\overline{B}^0}_{[D^0\pi^+]_{D^{*+}}\pi^-}K^-\pi^+$	5.1	
${\overline{B}^0}_{D^+3\pi}K^-\pi^+$	6.4	
${\overline{B}^0}_{D^04\pi}K^-\pi^+$	3.3	
sum	32.9	13.2
${B^-}_{J/\psi K}K^-\pi^+\pi^+$	6.2	
${B^-}_{J/\psi K\pi\pi}K^-\pi^+\pi^+$	1.2	
${B^-}_{D^0\pi^-}K^-\pi^+\pi^+$	18.9	
${B^-}_{D^03\pi}K^-\pi^+\pi^+$	5.6	
${B^-}_{D^+\pi^-\pi^-}K^-\pi^+\pi^+$	1.7	
sum	33.6	13.4
${\overline{B}^0}_{J/\psi K\pi}K^-\pi^+\pi^+\pi^-$	1.5	
${\overline{B}^0}_{D^+\pi}K^-\pi^+\pi^+\pi^-$	3.4	
${\overline{B}^0}_{D^0\pi^+\pi^-}K^-\pi^+\pi^+\pi^-$	1.8	
sum	6.7	2.7
$D^0K^-\pi^+$	68	27 (1-60)
D^+K^-	134	54 (2-125)
$D^0\pi^+\pi^-$	2.5	1.0 (0.3-2.0)
$D^+\pi^-$	4.9	2.0 (0.5-4.0)
sum		84

decay channel	$\varepsilon_{tot} \times \mathcal{B}$ [10^{-9}]	Expected yield
channels with γ from $B^* \to B\gamma$ not reconstructed		
$\overline{B}^{*0}K^-\pi^+$	32.9	13.2
$B^{*-}K^-\pi^+\pi^+$	33.6	13.4
$\overline{B}^{*0}K^-\pi^+\pi^+\pi^-$	6.7	2.7
sum		29
channels with π/γ from $D^* \to D\pi/\gamma$ not reconstructed		
${D^{*0}}_{D^0\pi^0}D^+\pi^-$	8.2	
${D^{*0}}_{D^0\gamma}D^+\pi^-$	4.5	
$D^0{D^{*+}}_{D^+\pi^0}\pi^-$	2.0	
sum	14.7	5.9
$D^0{D^{*+}}_{D^0\pi^+}\pi^-$	5.7	2.3
$J/\psi {D^{*+}}_{D^+\pi^0}K^-$	2.2	0.9
$J/\psi {D^{*+}}_{D^0\pi^+}K^-$	6.1	2.4
$J/\psi {D^{*0}}_{D^0\pi^0}K^-\pi^+$	1.5	
$J/\psi {D^{*0}}_{D^0\gamma}K^-\pi^+$	0.8	
sum	2.3	0.9
channels with B meson partially reconstructed in SL decay mode		
${\overline{B}^0}_{D^+\mu^-\nu}K^-\pi^+$	96	38
${\overline{B}^0}_{D^0\pi^+\mu^-\nu}K^-\pi^+$	92	37
${B^-}_{D^0\mu^-\nu}K^-\pi^+\pi^+$	94	38
${\overline{B}^0}_{D^+\mu^-\nu}K^-\pi^+\pi^+\pi^-$	31	12
${\overline{B}^0}_{D^0\pi^+\mu^-\nu}K^-\pi^+\pi^+\pi^-$	30	12
sum		137
channels with T^0_{bc} partially reconstructed in SL decay mode		
$D^0D^+\mu^-\nu$	56	22 (15-32)
${D^{*0}}_{D^0\pi^0}D^+\mu^-\nu$	81	32 (22-45)
${D^{*0}}_{D^0\gamma}D^+\mu^-\nu$	44	18 (11-25)
$D^0[D^0\pi^+]_{D^{*+}}\mu^-\nu$	43	17 (11-26)
$D^0{D^{*+}}_{D^0\pi^+}\mu^-\nu$	108	43 (28-65)
$D^0{D^{*+}}_{D^+\pi^0}\mu^-\nu$	38	15 (10-22)
sum		150 (95-215)
${\overline{B}^0}_{J/\psi K\pi}K^-\mu^+\nu$	3.5	1.4 (0.7-2.5)
${\overline{B}^0}_{D^+\pi^-}K^-\mu^+\nu$	8.1	3.2 (1.5-5)
${\overline{B}^0}_{all}K^-\mu^+\nu$	24	9.5 (5-15)
${B^-}_{J/\psi K}K^-\pi^+\mu^+\nu$	2.9	1.2 (0.5-2)
${B^-}_{D^0\pi^-}K^-\pi^+\mu^+\nu$	8.8	3.5 (1.5-6)
${B^-}_{all}K^-\pi^+\mu^+\nu$	16	6.5 (2.5-11)

Sensitivity to Ξ_{bc}

$\sigma(pp \to T_{bc}+X)$ ~ (20±9) nb in p_T>2 GeV,
$\sigma(pp \to B_c+X)$ ~ (0.2-1.0) μb,
$\sigma(pp \to \Xi_{cc}+X)$ ~ (0.25-1.3) μb in p_T>4 GeV,
→ **$\sigma(pp \to \Xi_{bc}+X)$ ~ 100 nb in p_T>4 GeV?**

[Zhang et al]:
$\sigma(pp \to \Xi_{cc}+X)$~92nb for p_T>4 GeV
$\sigma(pp \to \Xi_{bc}+X)$~37nb for p_T>4 GeV

Table 11: Estimation of $\varepsilon_{tot} \times BR$ for various Ξ_{bc} decay modes for LHCb and expected yields with integrated luminosity of 8 fb^{-1} (Run 1&2) and 20 fb^{-1} (Run 3) and Ξ_{bc} cross-section of 100 nb in LHCb acceptance at 13/14 TeV.

decay channel	ε_{tot} $[10^{-3}]$	$\mathcal{B}$ $[10^{-6}]$	$\varepsilon_{tot} \times \mathcal{B}$ $[10^{-9}]$	Expected yield Run 1&2	Expected yield Run 3
fully reconstructed channels					
$J/\psi \Lambda_c^+$	4.8	0.02 ± 0.01	0.1	0.07 (0-0.2)	0.2 (0.1-0.3)
$J/\psi \Xi_c$	4.8	0.04 ± 0.02	0.2	0.1 (0.05-0.2)	0.4 (0.2-0.6)
$\Lambda_c^+ \pi^-$	4.0	0.21 ± 0.14	0.8	0.5 (0.2-1)	3 (1.5-6)
$\Xi_c \pi^-$	4.0	0.56 ± 0.50	2.2	1.4 (0.1-5)	9 (0.5-25)
$D^0 p K^-$	3.2	3.6 ± 3.3	11	7 (1-15)	44 (3-80)
$\Lambda^0_{b\,J/\psi pK} K^- \pi^+$	2.4	0.27 ± 0.15	0.65	0.4 (0.2-1)	1.3 (0.5-3)
$\Lambda^0_{b\,\Lambda_c^+ \pi^-} K^- \pi^+$	0.8	4.4 ± 2.3	3.5	2 (1-3)	14 (7-30)
$B^0{}_{J/\psi K \pi} p K^- \pi^+$	0.95	1.0 ± 0.5	0.9	0.6 (0.3-1)	1.8 (1-3)
$B^0{}_{D^+ \pi^-} p K^- \pi^+$	0.32	3.4 ± 1.7	1.1	0.7 (0.3-1)	4.5 (2-7)
$\Lambda_c^+ D^0 \pi^-$	1.0	0.8 ± 0.6	0.8	0.5 (0.1-1)	3.2 (0.5-6)

Simulation

- Only few decay descriptors with many modes combined:
  - weakly-decaying (long-lived)
  - strongly-decaying (short-lived)
  - (additional) $\bar{B}^*D^*$ molecule decaying to $(\bar{B}^0\gamma)(D\pi^0/\gamma)$ via off-shell B^*/D^*

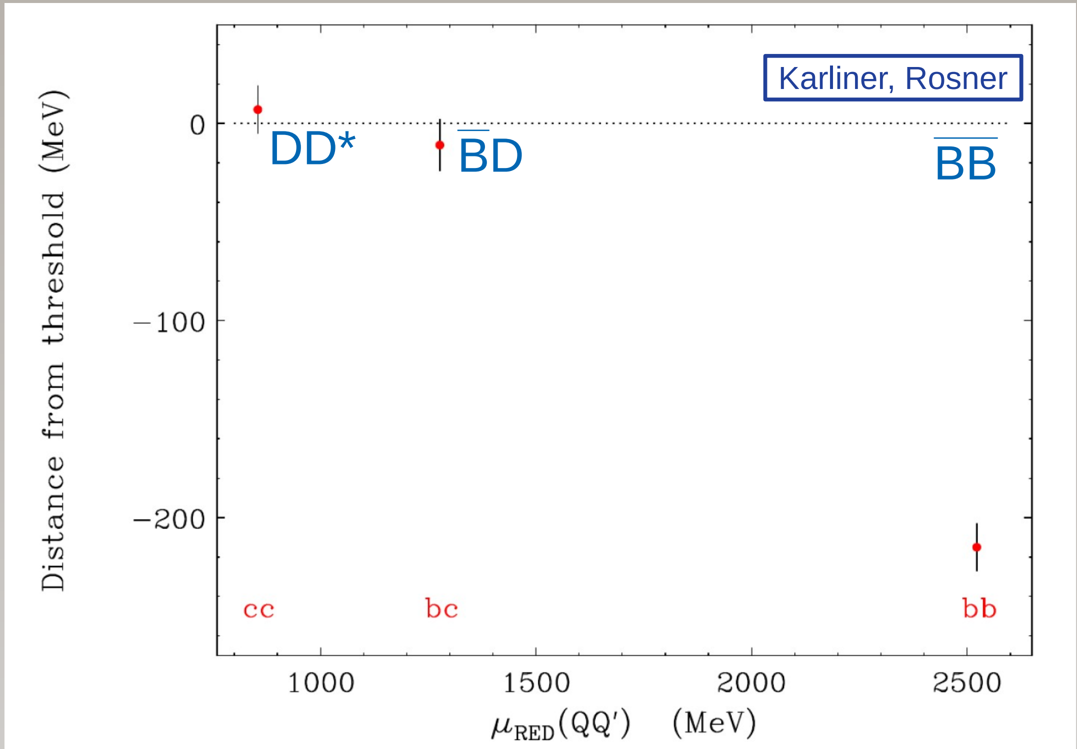
- Parameters fixed
  - Long-lived:
    - $m(T_{bc}) = m(B^0)+m(D^0) - 10\,\text{MeV} = 7134.5\,\text{MeV}$ *(expected range [-25;0] MeV)*
    - $\tau(T_{bc}) = 300\,\text{ps}$ *(expected range [230;310] ps)*
  - Short-lived:
    - $m(T_{bc}) = m(B^0)+m(D^0) + 2\,\text{MeV} = 7146.5\,\text{MeV}$
    - $\Gamma(T_{bc}) = 5\,\text{MeV}$

Other doubly-heavy states, [$bb\overline{ud}$]

- The T_{cc} below DD* threshold supports predictions for long-lived T_{bb} ***[bb][$\overline{ud}$]***

  - Semay, SIlvestre-Brac, 1994
  - Janc, Rosina, 2003
  - Bicudo et al, 2015
  - Karliner, Rosner, 2017
  - Francis et al., 2017
  - Junnarkar, Mathur, Padmanath, 2018

  … and many more



- Suppressed wrt to T_{cc} (150 events):
  - $b\bar{b}b\bar{b}$ production: 1.5%
  - BR($b \rightarrow D\pi/\mu$): $(0.1\text{-}1\%)^2$

  → expect yields of only ~10^{-4} in Run1&2
  or ~10^{-2}-10^{-1} in HL-LHC

The narrowest one - T_{cc} $[cc\bar{u}\bar{d}]$

- 2021: signal in $D^0D^0\pi^+$ just below D^0D^{*+} threshold

- Model as $T_{cc}^{+} \to D^0D^{*+}(\to D\pi)$ for $I(J^P)$ of T_{cc} as $0(1^+)$

  in this model width defined by $\Gamma(D^{*+})$ and δm

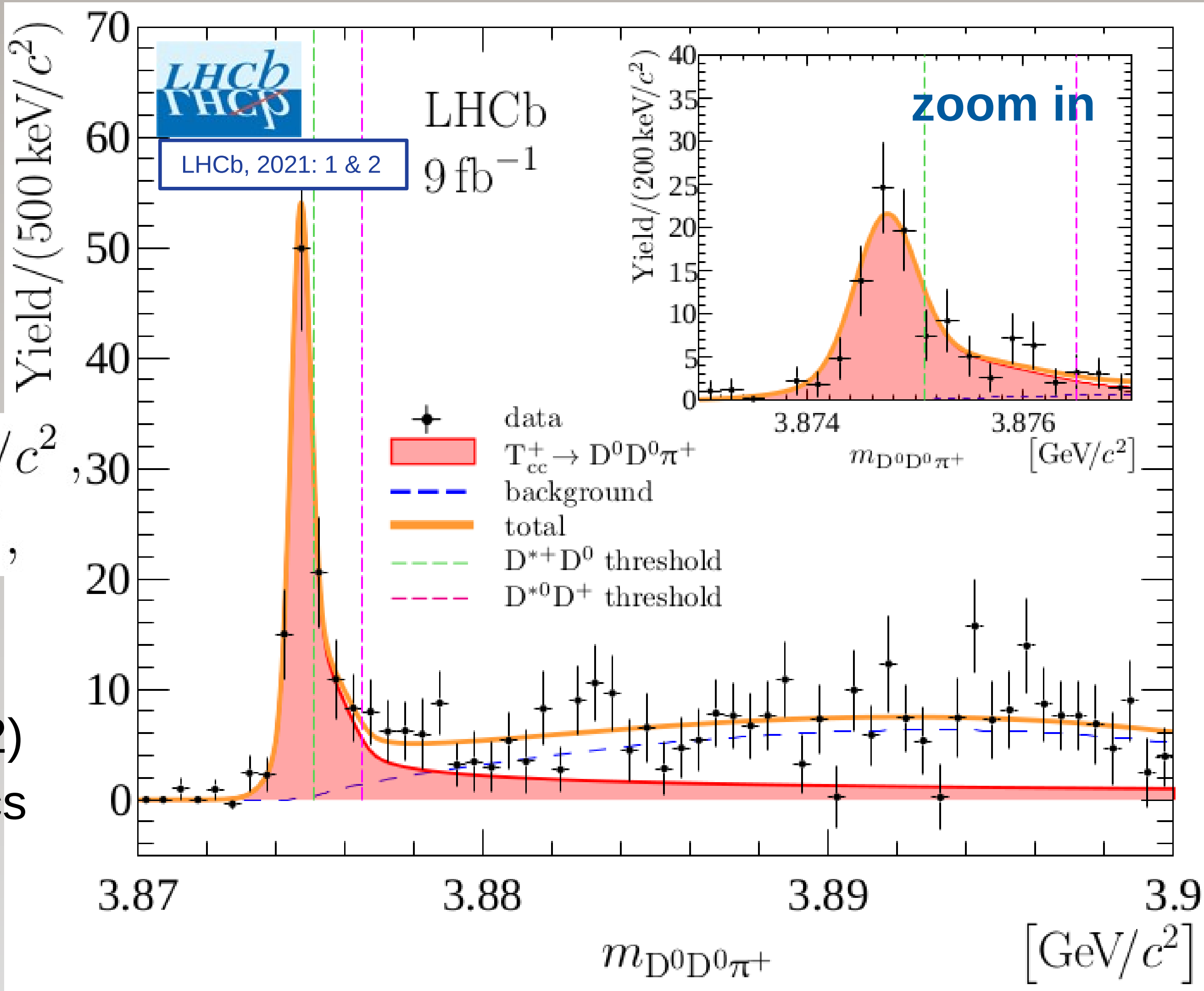
- Results:

$$\delta m_{\rm pole} = -360 \pm 40 ^{+4}_{-0} \ \mathrm{keV}/c^2 ,$$
$$\Gamma_{\rm pole} = 48 \pm 2 ^{+0}_{-14} \ \mathrm{keV} ,$$

- 20x more narrow than $\chi_{c1}(3872)$ and 1000x than all other exotics

Nature Phys. 18 (2022) 751

Nature Commun. 13 (2022) 3351



T_{cc}: Summary of Results

- A narrow peak in $D^0D^0\pi^+$ below D^0D^{*+} threshold is observed with S>20σ
- Naive BW parameters:
$$\begin{aligned}\delta m_{BW} &= -273 \pm 61 \pm 5\,^{+11}_{-14}\,\mathrm{keV}/c^2\,,\\ \Gamma_{BW} &= 410 \pm 165 \pm 43\,^{+18}_{-38}\,\mathrm{keV}\,,\end{aligned}$$
- Consistent with $[cc\overline{ud}]$ isoscalar tetraquark T_{cc}^+ with $J^P=1^+$ for which
$$\delta' m_0 = -359 \pm 40\,^{+9}_{-6}\,\mathrm{keV}/c^2$$
is determined using dedicated model
- A lower limit is set on $T_{cc}^+ \to DD^*$ coupling: $|g| > 5.1\,(4.3)\,\mathrm{GeV}$ at $90\,(95)\,\%$ CL
- Threshold structures observed in D^0D^0 and D^0D^+ are found to be consistent with $T_{cc}^+ \to D^0D^{0/+}\pi^{+/0}/\gamma$ decays via off-shell D^* mesons
- Matching to low-energy DD^* scattering amplitude we get
- Pole position:
$$\begin{aligned}\delta' m_{pole} &= -360 \pm 40\,^{+4}_{-0}\,\mathrm{keV}/c^2\,,\\ \Gamma_{pole} &= 48 \pm 2\,^{+0}_{-14}\,\mathrm{keV}\,,\end{aligned}$$

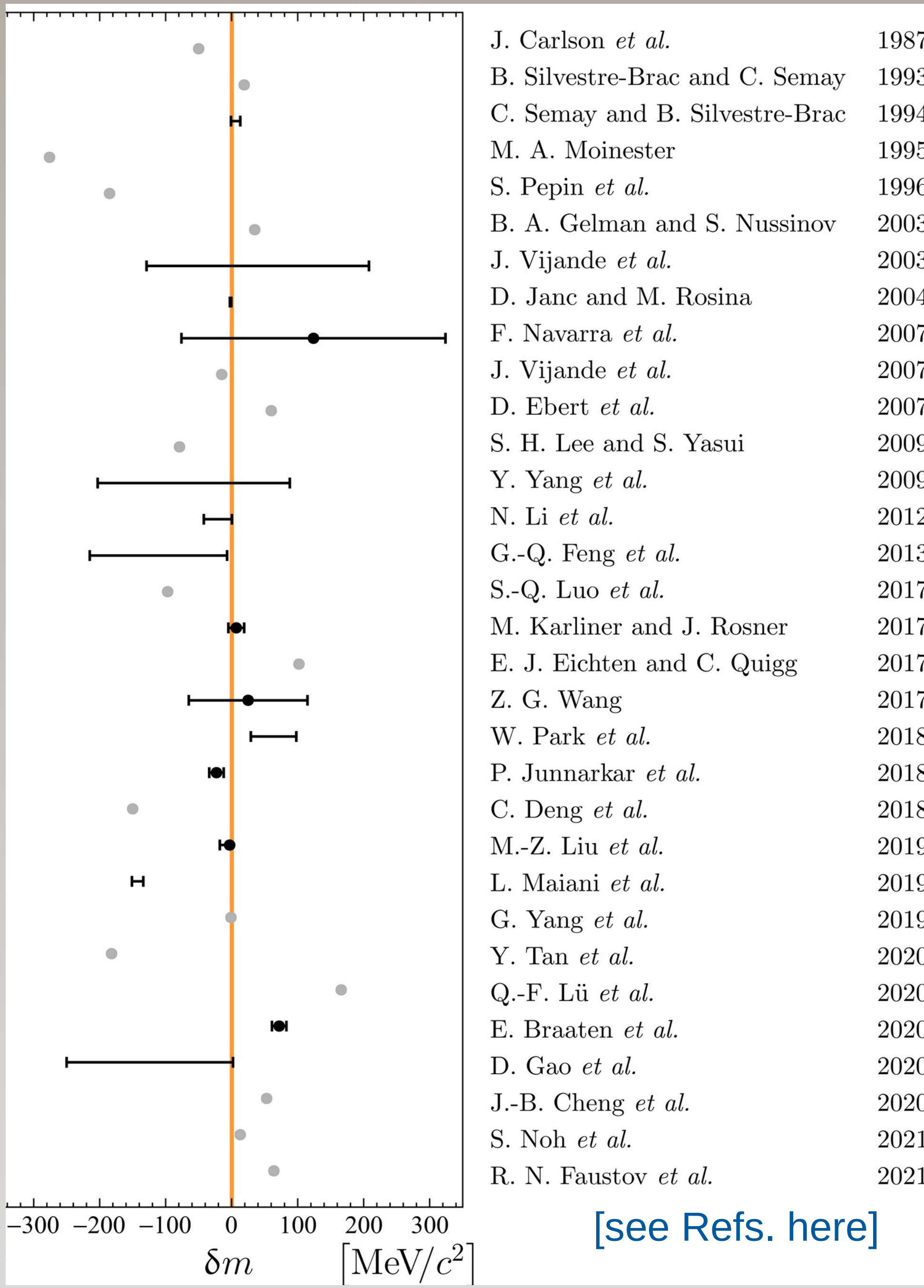
Measured mass, notable matches

- The measured mass difference

$$\delta m_{\mathrm{U}} = -359 \pm 40^{+9}_{-6}\,\mathrm{keV}/c^2$$

is consistent with some of predictions.

- Few notable matches for δm predictions:
  - **[-1,+13] MeV** Semay, SIlvestre-Brac, 1994
    (NR quark-quark potential model)
    false prediction (1993) for spin-0&1 $cc\bar{q}\bar{q}$ states with masses ~3300-3400 MeV
  - **[-2.7,-0.6] MeV** Janc, Rosina, 2003
    (NR quark-quark potential model)
    -0.6 MeV corresponds to Bhaduri potential
  - **[-42.1;+0.3] or [-18;+1] MeV**
    (OME exchange in DD molecula)*
    Li, Sun, Liu, Zhu, 2012 Liu, Wu, Valderrama, Xie, Geng, 2019
  - **1±12 MeV** Karliner, Rosner, 2017
    (phenomenology model for compact tetraquark)
  - **-23±11 MeV** Junnarkar, Mathur, Padmanath, 2018
    (Lattice QCD)



[see Refs. here]

Notable match 1

- The measured mass difference

$$\delta m_{\mathrm{U}} = -359 \pm 40\,^{+\,9}_{-\,6}\,\mathrm{keV}/c^2$$

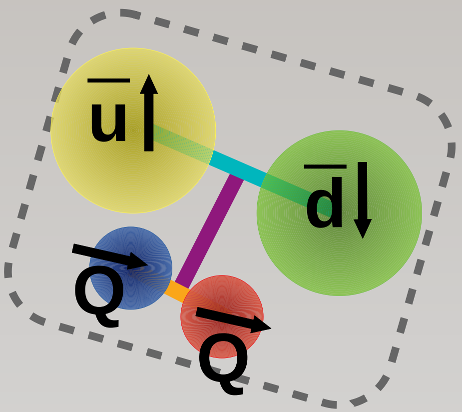
- Phenomenology model for compact tetraquark [cc]-[$\overline{\mathrm{ud}}$]
  - **1±12 MeV**

    - using measured Ξ_{cc} mass to calibrate cc binding

    (δm = 7±12 MeV → 1±12 MeV)

    Karliner, Rosner, 2017

Contribution	Value (MeV)
$2m_c^b$	3421.0
$2m_q^b$	726.0
$a_{cc}/(m_c^b)^2$	14.2
$-3a/(m_q^b)^2$	−150.0
cc binding	−129.0
Total	3882.2 ± 12



Notable match 2

- The measured mass difference

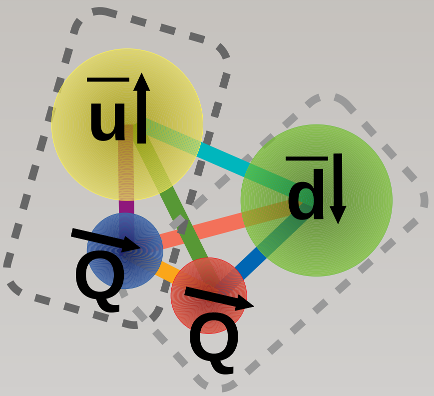
$$\delta m_{\rm U} = -359 \pm 40\,^{+\,9}_{-\,6}\,{\rm keV}/c^2$$

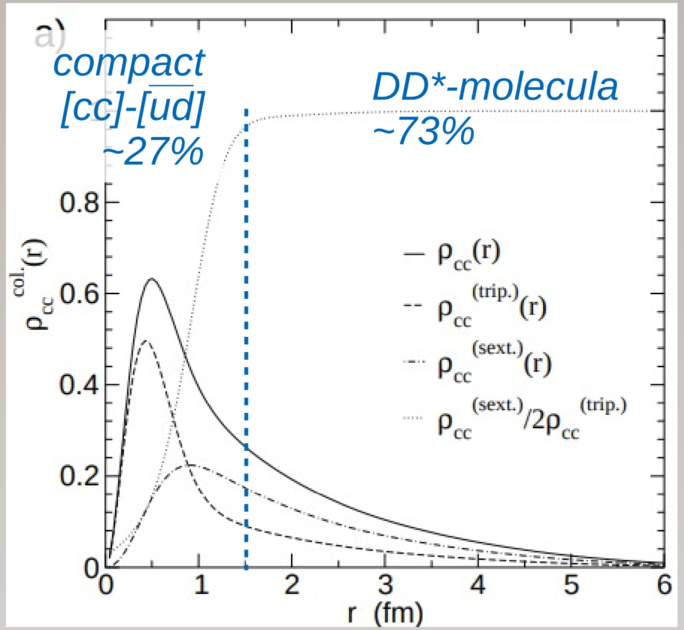
- NR quark-quark potential model
  - **[-2.7,-0.6] MeV**

    with Bhaduri potential

  - gives insight into wave function: spatial & color configuration → dominated by DD* component

    Janc, Rosina, 2003





Would love to see a refined calculation