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

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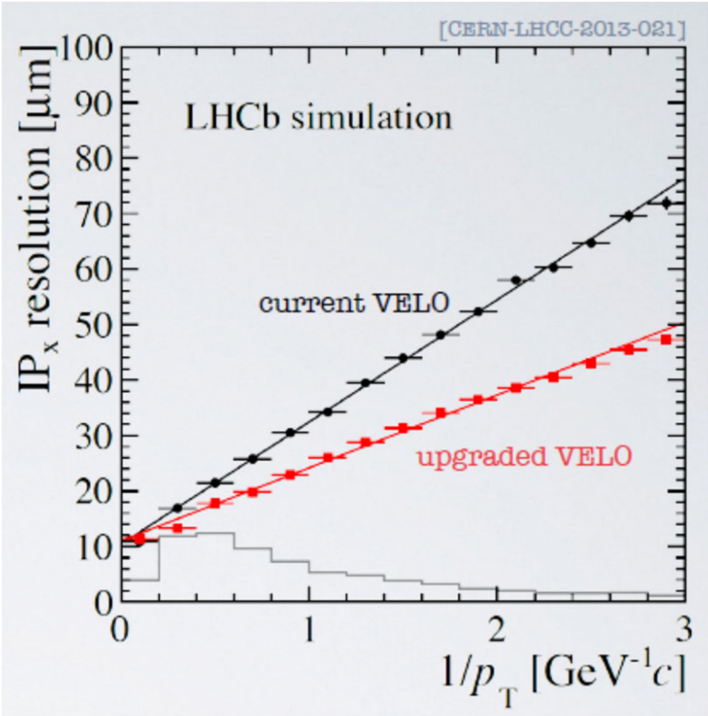
T_{cc} and beyond Workshop

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
  - **~40% of $\sigma(b\bar{b}, c\bar{c})$ in 4% of solid angle**
  - **~10×$\mathcal{L}_{int}$ compared to Run 2:** Run 3 (2022-2024) + Run 4 (2028-2030) → **50 fb^{-1}.**
  - **Full software trigger**: ~2-3x increase in trigger efficiency for b→fully-hadronic final states
  - **Improved IP resolution:** Vertex detector distance reduced from 5 mm to 3.5 mm from beam
    → Better discrimination of primary and secondary particles (O(20%)).



Double-heavy hadrons

- **cc: Lowest mass state is above DDπ threshold**
  - $T^{+}_{cc[\bar{u}\bar{d}]}$ discovered LHCb 2021 (arXiv:2109.01056, arXiv:2109.01038). Very close to threshold → Narrow. (see previous talk for details)

- **bc: Lowest mass $T^{0}_{bc[\bar{u}\bar{d}]}$ 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→c*** ($D^0D^+\pi^-$, $\Xi^{+}_{cc}\bar{p}$, etc) , ***c→s*** ($\bar{B}^0K^-\pi^+$, $\Xi^{0}_{b}\bar{p}\pi^+$)

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

$T^{-}_{bb[\bar{u}\bar{d}]}$	$T^{-}_{bb[\bar{u}\bar{s}]}$, $T^{0}_{bb[\bar{d}\bar{s}]}$	**Ref**	**Comments**
-121 MeV	-48 MeV	Eichten & Quigg, PRL119, 202002 (2017)	"Cornell" Coulomb + linear Potential model
-189 MeV	-98 MeV	Francis et al, PRL118, 142001 (2017)	LQCD
-90 MeV		Bicudo et al, PRD92 , 014507 (2015)	LQCD
-170 MeV	-52 MeV	Karliner & Rosner, PRL119, 202001 (2017)	Quark model + quarkonia and Ξ^{++}_{cc} data

- **Expect these 3 states to decay weakly!**

Prospects for double-heavy tetraquarks in LHCb

$$N_{signal} = \mathcal{L}_{int}\,\sigma_{signal}\,\mathcal{B}(signal)\,\mathcal{B}(daughters)\,\mathcal{E}_{tot}$$

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

$$\sigma_{signal}^{eff} = \sigma_{signal}\,\mathcal{B}(signal)\,\mathcal{B}(daughters)$$

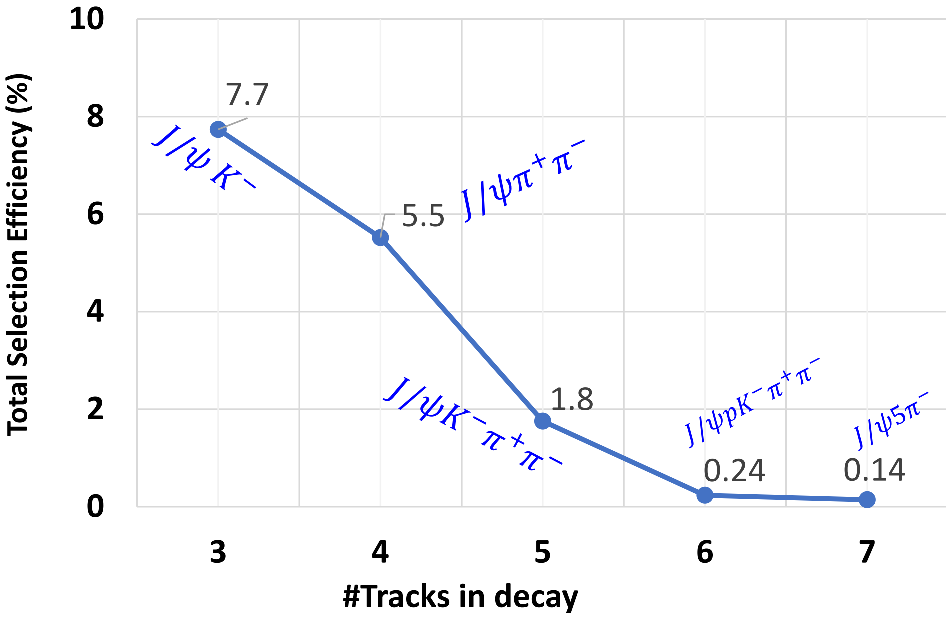
- ❑ **The branching ratios can easily combine to give 10^{-5} - 10^{-6} (or less)**
- ❑ **A 10 nb cross-section effectively becomes 0.01 - 0.1 pb** [$\sigma_{t\bar{t}} \sim 900$ pb]

- ❑ $\mathcal{E}_{tot}$ **quite dependent on final state track multiplicity, p_T & IP requirements, etc.**

What can we expect for $\mathcal{E}_{tot}$?

- ❑ **Let's consider b→ J/ψ X modes**
  (Using Run 2 data)

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



- ❑ **Very much analysis dependent, so just gives a rough idea.**
- ❑ **Roughly $\varepsilon_{tot}(B^-\to J/\psi h^-) \approx 0.10$**

- ❑ 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 **$\varepsilon(B^-) \sim 30\%$**

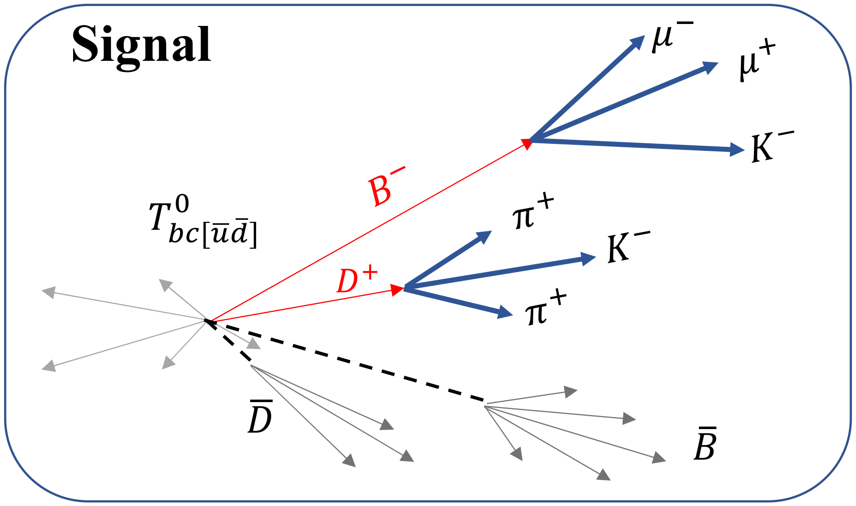
- ❑ For **D mesons** produced in association with the fully reconstructed B meson, assume 50% efficiency per final state hadron (LHCb Acc, p>2.5 GeV), and $\varepsilon_D \sim 70\%$ (displaced vertex, IP cuts, etc)
  - ❑ **$\varepsilon(D^+)$, $\varepsilon(D^{*+}) \sim 0.08$**
  - ❑ **$\varepsilon(D^0\to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

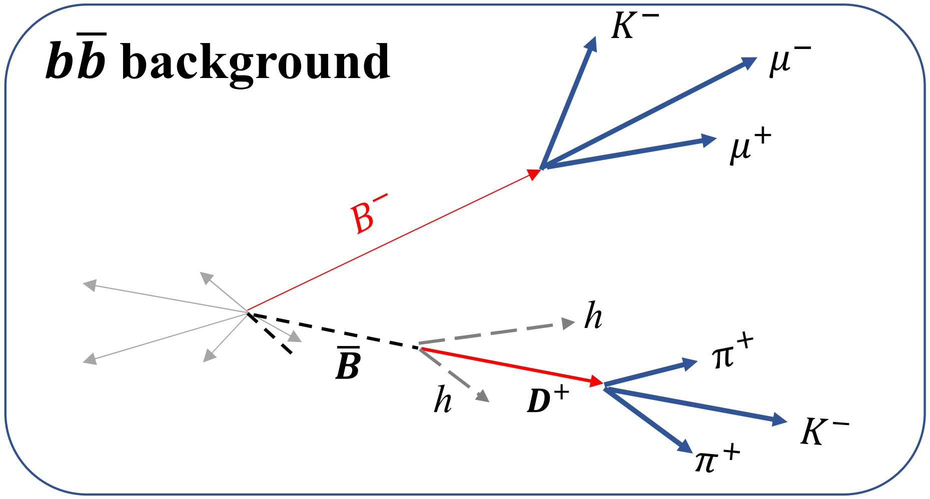
- ❑ **The D efficiencies are likely on the optimistic side.**

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

- Assume $\sigma(T^0_{bc[\bar{u}\bar{d}]})$ ~ **100 nb** at 13 TeV
  - See Ali, et al., Phys. Lett. B785 (2018) 605.
- Compare to σ(pp→B⁻ X) ~ **90 μb** **(900** $\sigma(T^0_{bc[\bar{u}\bar{d}]})$ **)**

Strong Decay: $T^0_{bc[\bar{u}\bar{d}]} \to B^- D^+$, $B^- \to J/\psi K^-, D^+ \to K^- \pi^+ \pi^+$





- Assume B($T^0_{bc[\bar{u}\bar{d}]} \to B^- D^+$) ~ 0.5

$$\Rightarrow \sigma^{eff}_{signal} \sim 0.3 \text{ pb}$$

- $\varepsilon_{tot} \approx 2.4\%$

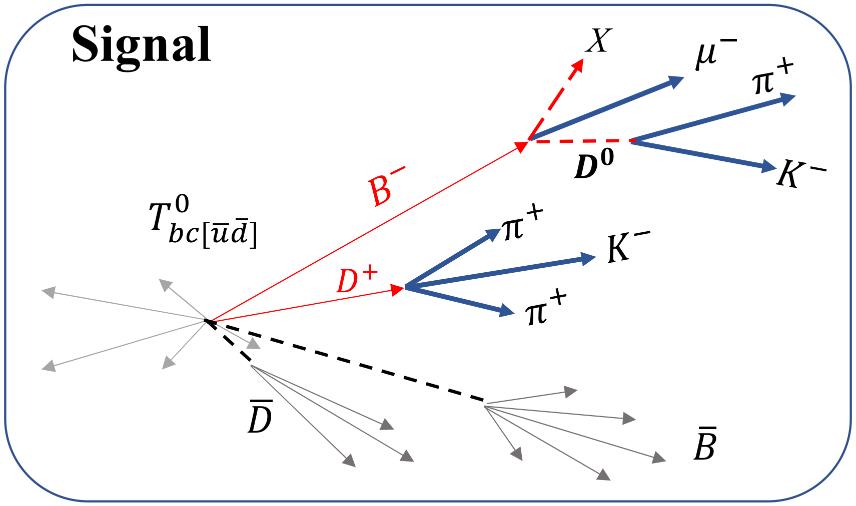
$$N_{signal}(50\, fb^{-1}) \sim \mathbf{350} \left(\frac{\sigma_{sig}}{100\, nb}\right)\left(\frac{B_{sig}}{0.5}\right)\left(\frac{\varepsilon_{tot}}{0.024}\right)$$

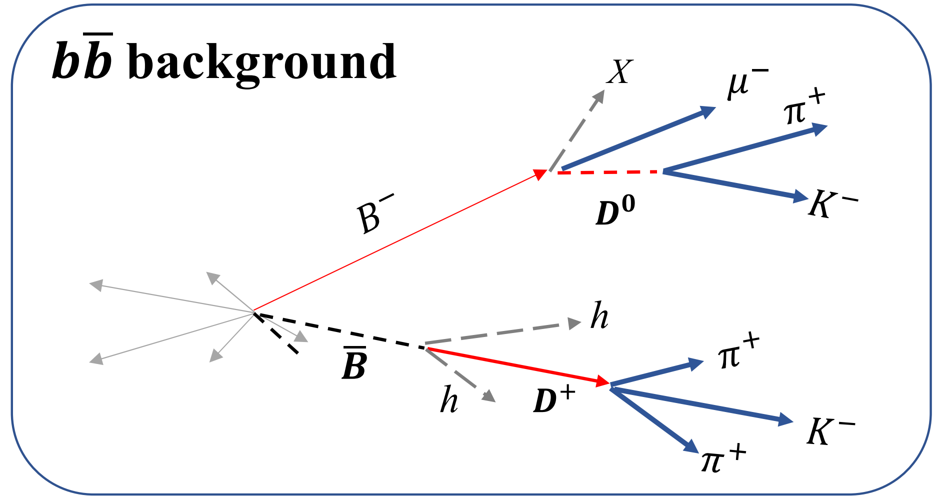
- **Perhaps × 1.5 − 2.0 for B^0D^0 final states**

- Main background likely, $pp \to b\bar{b} \to B^- D^+ X$, **BUT**:
  - D^+ is "wrong-sign", e.g. B($B^0 \to D^- X$) ≈ 37%, while B($B^0 \to D^+ X$) < 3.1%,
  - D^+ is from PV, not from a displaced vertex (should allow large suppression of $pp \to b\bar{b}$).
- 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: $T^0_{bc[\bar{u}\bar{d}]} \to B^- D^+$, $\boldsymbol{B^- \to D^0(K^-\pi^+)\mu^-\nu X}$, $D^+ \to K^-\pi^+\pi^+$





- ❑ Assume B($T^0_{bc[\bar{u}\bar{d}]} \to B^- D^+$)~0.5
- ❑ **B(B⁻ → D⁰ μ⁻X) ~ 10%**
  (Reconstruct $\vec{p}(\nu)$ using B mass and vertex constraints)

  $\Rightarrow \sigma^{eff}_{signal} \sim 20$ pb
- ❑ $\mathcal{E}_{tot} \approx 0.16\%$

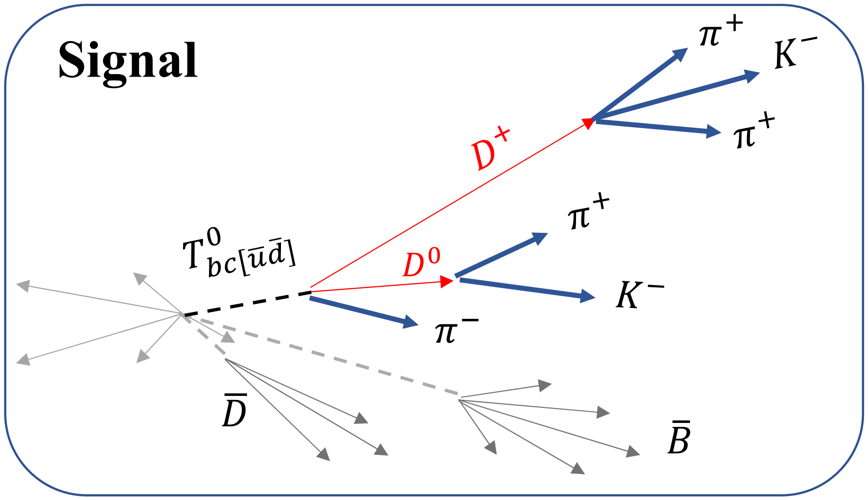
$$N_{signal}(50\,fb^{-1}) \sim \mathbf{1500}\left(\frac{\sigma_{sig}}{100\,nb}\right)\left(\frac{B_{sig}}{0.5}\right)\left(\frac{\varepsilon_{tot}}{0.0016}\right)$$

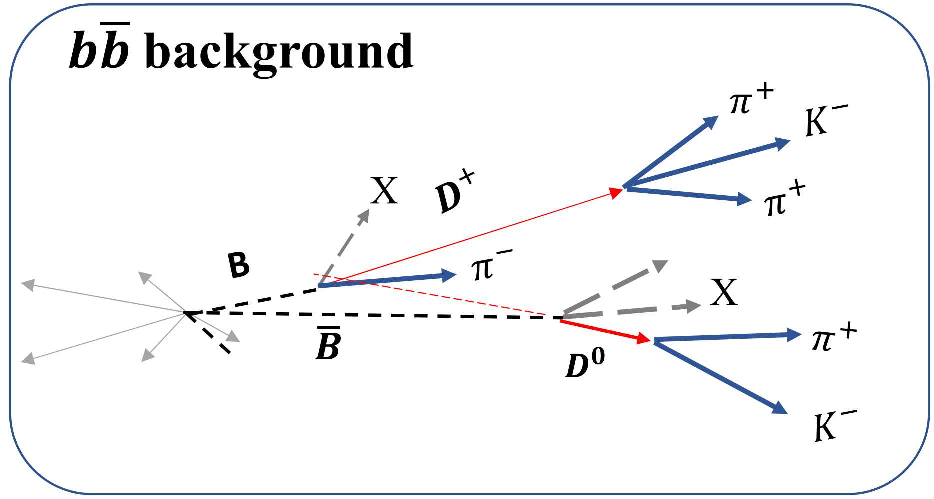
- ❑ **Perhaps $\times$ 1.5 – 2.0 for B^0D^0 final states**

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

- ❑ **Could be within reach with full Run 3 + Run 4 data set**

Weak Decay, $b \to c\bar{u}d$: $T^0_{bc[\bar{u}\bar{d}]} \to D^0 D^+ \pi^-$, $D^0 \to K^- \pi^+$, $D^+ \to K^- \pi^+ \pi^+$





- ❑ Assume B($T^0_{bc[\bar{u}\bar{d}]} \to D^0 D^+ \pi^-$)~0.01

$\Rightarrow \sigma^{eff}_{signal} \sim 3.7$ pb

- ❑ Estimate: $\mathcal{E}_{tot} \approx 0.7\%$

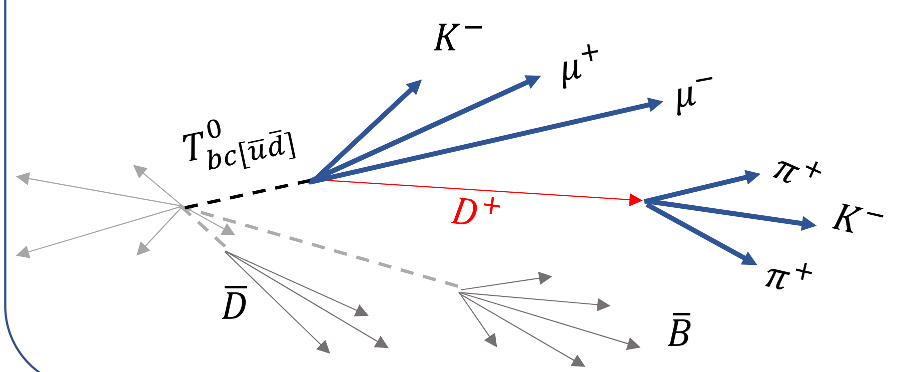
$$N_{signal}(50\ fb^{-1}) \sim \mathbf{1300} \left(\frac{\sigma_{sig}}{100\ nb}\right)\left(\frac{B_{sig}}{0.01}\right)\left(\frac{\varepsilon_{tot}}{0.007}\right)$$

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

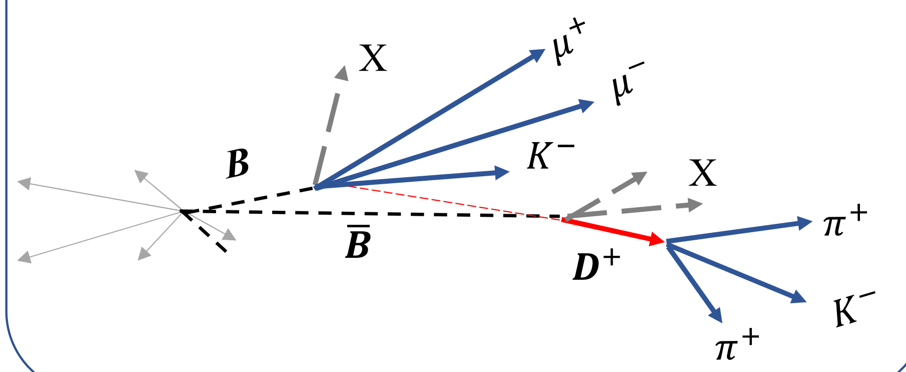
- ❑ **Could be within reach with full Run 3 + Run 4 data set**
  - ❑ Should select and save all possible B^-D^+ that form a good vertex with $\vec{p}(D^0 D^{(*)+} \pi^-)$ must point back to PV

Weak Decay, $b \to c\bar{c}s$: $T^0_{bc[\bar{u}\bar{d}]} \to J/\psi D^+ K^-$, $D^+ \to K^- \pi^+ \pi^+$

Signal



$b\bar{b}$ background



- ❑ Assume B($T^0_{bc[\bar{u}\bar{d}]} \to J/\psi K^- D^+$)~0.01

$\Rightarrow \sigma^{eff}_{signal} \sim 5.6$ pb

- ❑ Estimate: $\mathcal{E}_{tot} \approx 2.4\%$

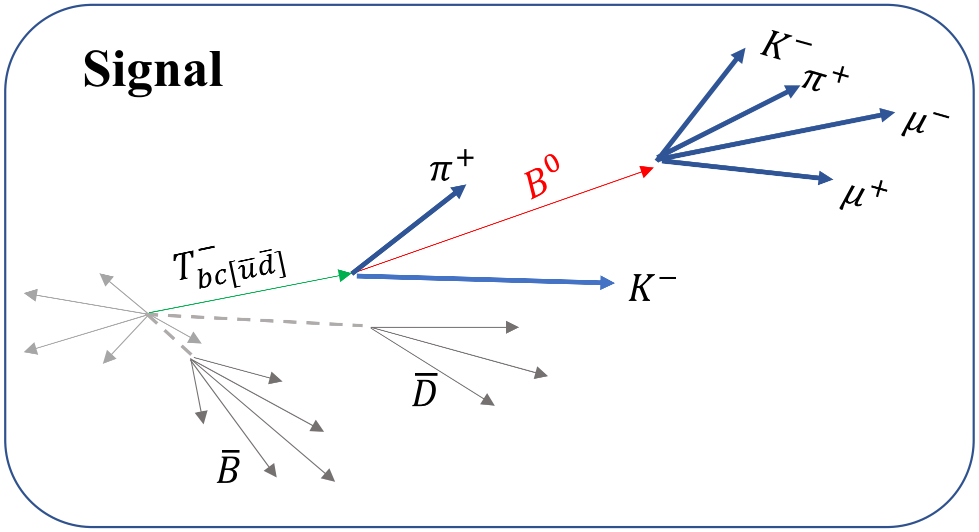
$$N_{signal}(50\ fb^{-1}) \sim \mathbf{6800} \left(\frac{\sigma_{sig}}{100\ nb}\right)\left(\frac{B_{sig}}{0.01}\right)\left(\frac{\varepsilon_{tot}}{0.024}\right)$$

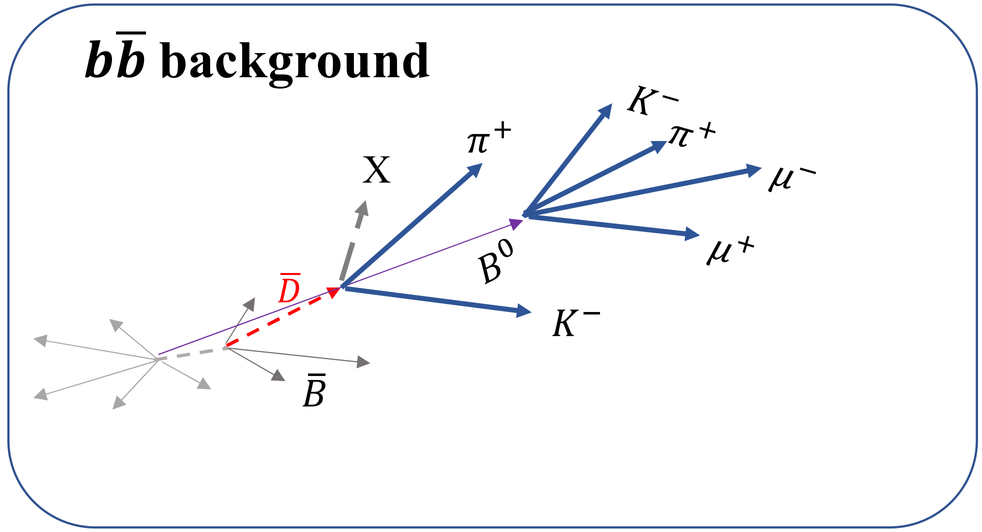
- ❑ Similarly: $T^0_{bc[\bar{u}\bar{d}]} \to J/\psi D^0 K^- \pi^+$

- ❑ Main background $pp \to b\ (B \to J/\psi X)\ \bar{b}\ (\bar{B} \to D^+ X)$ **BUT**:
  - ❑ WS D$^+$ suppressed by ~10X compared to RS
  - ❑ J/ψ 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, $c \to s u \bar{d}$: $T^0_{bc[\bar{u}\bar{d}]} \to B^0 K^- \pi^+$, $B^0 \to J/\psi K^- \pi^+$





- Assume B($T^0_{bc[\bar{u}\bar{d}]} \to B^0 K^- \pi^+) \sim 0.01$

$$\Rightarrow \sigma^{eff}_{signal} \sim 0.07 \text{ pb}$$

- Estimate: $\mathcal{E}_{tot} \approx 1.5\%$

$$N_{signal}(50\ fb^{-1}) \sim \mathbf{54} \left(\frac{\sigma_{sig}}{100\ nb}\right)\left(\frac{B_{sig}}{0.01}\right)\left(\frac{\varepsilon_{tot}}{0.015}\right)$$

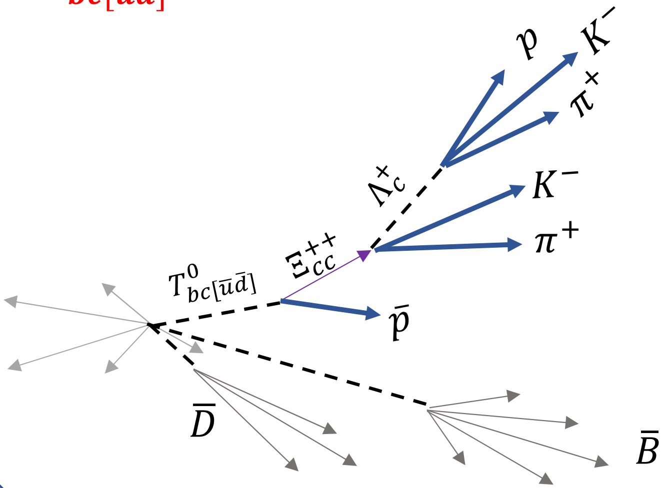
- Similarly: $T^0_{bc[\bar{u}\bar{d}]} \to B^- K^- \pi^+ \pi^+$, similar yields

- Main background $pp \to B^0$ ($\bar{B} \to \bar{D}(K\pi X)X$):
  - $\vec{p}(B^0 K^- \pi^+)$ 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: $T^0_{bc[\bar{u}\bar{d}]}$

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



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

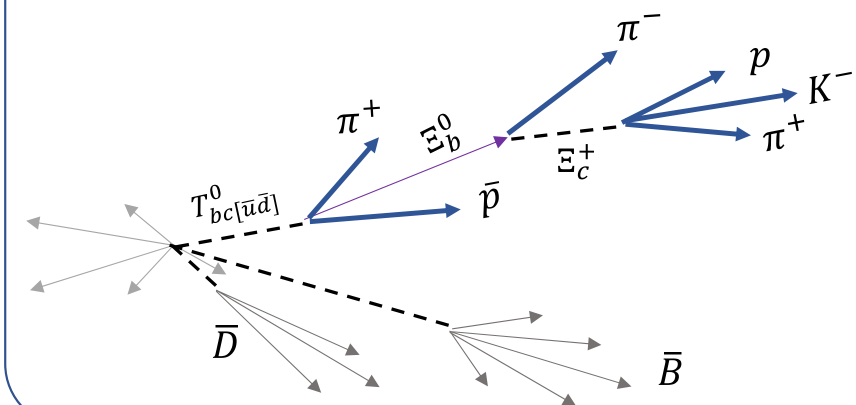
$\Rightarrow\ \sigma^{eff}_{signal}\ \sim$ 3.2 pb

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

- Estimate: $\mathcal{E}_{tot} \approx$ 0.5%

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

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



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

$\Rightarrow\ \sigma^{eff}_{signal}\ \sim$ 0.05 pb

- Estimate: $\mathcal{E}_{tot} \approx$ 1%

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

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

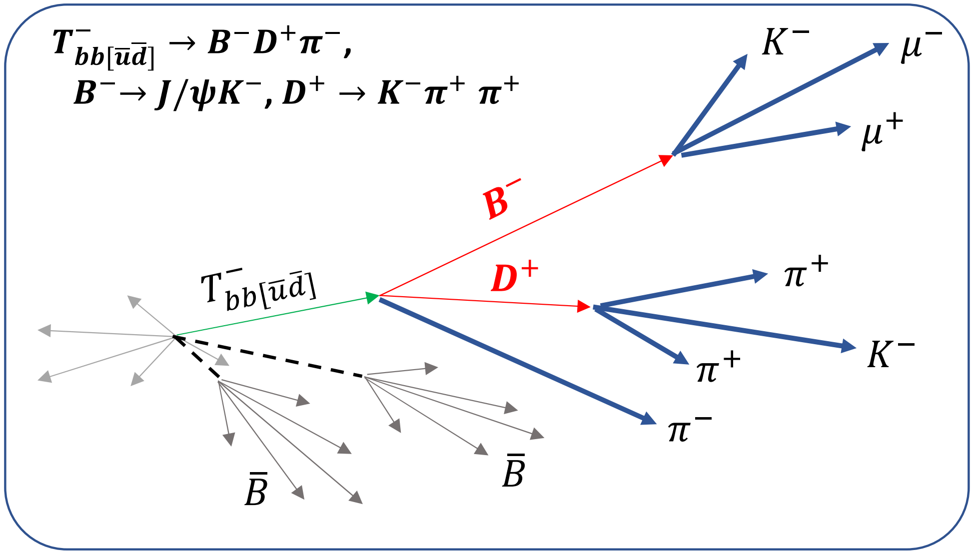
- **Strong decays to BD**
  - Involves known B, D BFs, so less guesstimating.
  - $b\bar{b}$ background suppressed, since signal D is “WS”
  - IP-related selections can suppress secondary D mesons from B decays
  - Double-parton scattering remains, but doesn’t peak in M(BD).

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

$T^{-}_{bb[\bar{u}\bar{d}]}$

- Expect σ($T^{-}_{bb[\bar{u}\bar{d}]}$) ~ 1 nb
- Expected to be below BB* threshold → **Weak decay**
  - Lifetime predicted to be ~ 0.6 ps [Agaev et al, EPJA 56, 177 (2020)], or maybe it's 7.6 ps(!) [Hernandez et al, PLB800, 135073 (2020)].

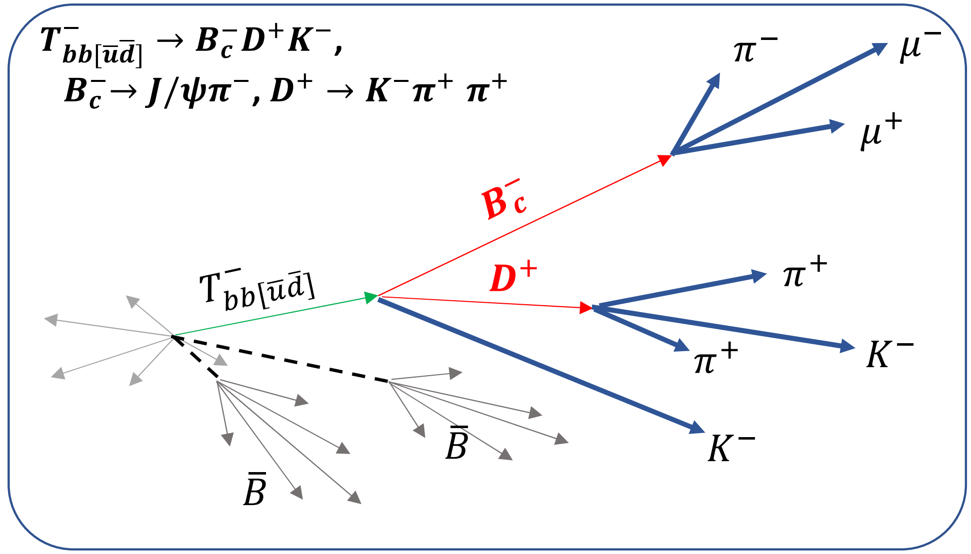
Weak decay: $T^{-}_{bb[\bar{u}\bar{d}]} \to B^{-}_{(c)} D^{+} h^{-},\ B_c^{-} \to J/\psi \pi^{-}, D^{+} \to K^{-}\pi^{+}\pi^{+}$



- ❑ Assume B($T^{0}_{bb[\bar{u}\bar{d}]} \to B^{-}D^{+}\pi^{-}$) ~ 0.02
- ❑ $\epsilon_{tot} \sim 0.8\%$

$\Rightarrow\ \sigma^{eff}_{signal} \sim 0.1$ fb

$N_{signal}(50\ fb^{-1}) \sim \mathbf{0.05} \left(\frac{\sigma_{sig}}{1\ nb}\right)\left(\frac{B_{sig}}{0.02}\right)\left(\frac{\varepsilon_{tot}}{0.008}\right)$



- ❑ Assume B($T^{0}_{bb[\bar{u}\bar{d}]} \to \boldsymbol{B_c^{-}D^{+}K^{-}}$) ~ 0.02
- ❑ Assume B($B_c \to J/\psi\ \pi^{+}$) = 5×10^{-3}
- ❑ $\epsilon_{tot} \sim 0.8\%$

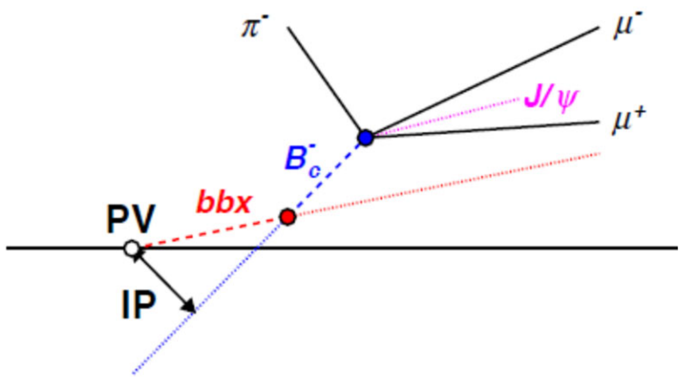
$\Rightarrow\ \sigma^{eff}_{signal} \sim 0.5$ fb

$N_{signal}(50\ fb^{-1}) \sim \mathbf{0.2} \left(\frac{\sigma_{sig}}{1\ nb}\right)\left(\frac{B_{sig}}{0.02}\right)\left(\frac{\varepsilon_{tot}}{0.008}\right)$

❑ Fully reconstructed final states seems difficult

$T^-_{bb[\bar{u}\bar{d}]} \to B^-_c X$

- ❑ Possibly look at **inclusive secondary B_c decays** (see Gershon & Poluektov, JHEP 2019)
  - ❑ Only need to reconstruct the $B_c^+ \to J/\psi\pi^+$
  - ❑ Only known contribution would be $T^-_{bb[\bar{q}\bar{q}']}$ tetraquarks and *bbq* baryons

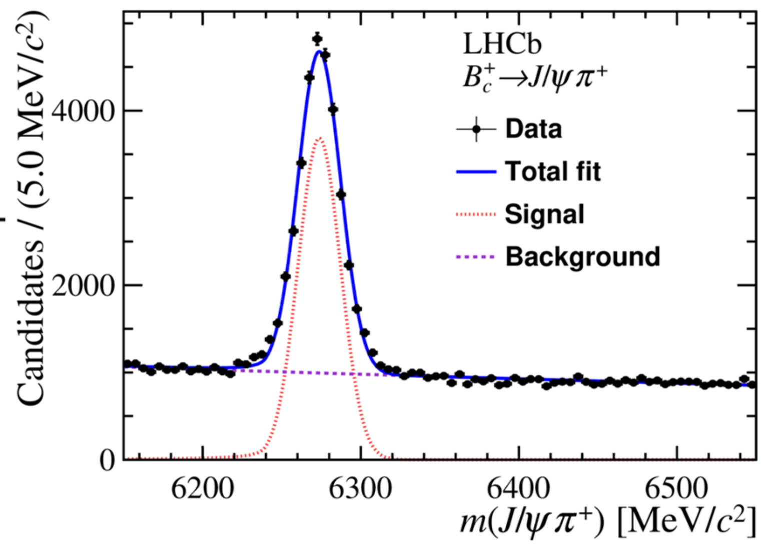


- ❑ Assume $B(T^0_{bb[\bar{u}\bar{d}]} \to \boldsymbol{B^-_c X}) \sim 0.10$
- ❑ $\epsilon_{tot} \sim 10\%$

$\Rightarrow \sigma^{eff}_{signal} \sim 30$ fb

$N_{signal}(50\ fb^{-1}) \sim \mathbf{150} \left(\frac{\sigma_{sig}}{1\ nb}\right)\left(\frac{B_{sig}}{0.10}\right)\left(\frac{\varepsilon_{tot}}{0.10}\right)$

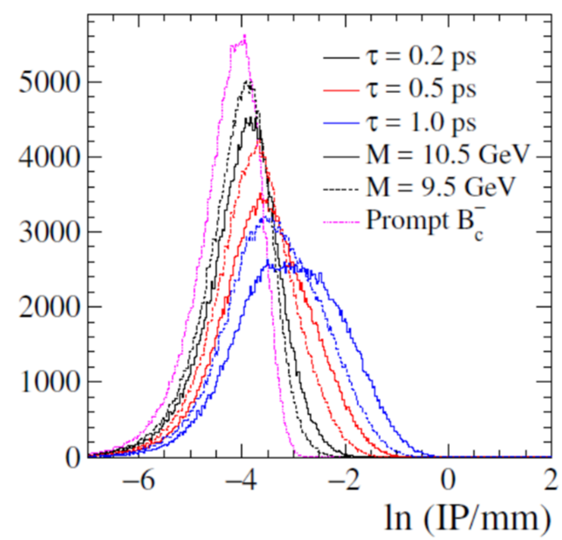
LHCb, JHEP 07 (2020) 123



- ❑ ~20,000 $B_c^+ \to J/\psi\pi^+$ in 6 fb^{-1} at 13 TeV

→~ 170,000 in 50 fb^{-1}

Gershon & Poluektov, JHEP 2019)



- ❑ IP distribution can discriminate prompt from secondary
- ❑ Could calibrate prompt IP component using $B_s^{**} \to B^+K^-$, $B^+ \to J/\psi\ K^-$

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 $T^{-}_{bb[\bar{u}\bar{d}]}$ vs Ξ_{bb} decays.

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 <u>and dominant backgrounds</u>
  - For weak decays, predictions for the branching fractions would be helpful.

- $T^-_{bb[\bar{u}\bar{d}]}$ tetraquarks seem much harder
  - Smaller cross-section expected (O(50-100) times less than $T^0_{bc[\bar{u}\bar{d}]}$)
  - 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 $\mathcal{O}(1000)$ 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