# Displaced $B_c^-$ mesons as an inclusive signature of weakly decaying double beauty hadrons

Tim Gershon & Anton Poluektov

Snowmass Hadron Spectroscopy Topical Meeting

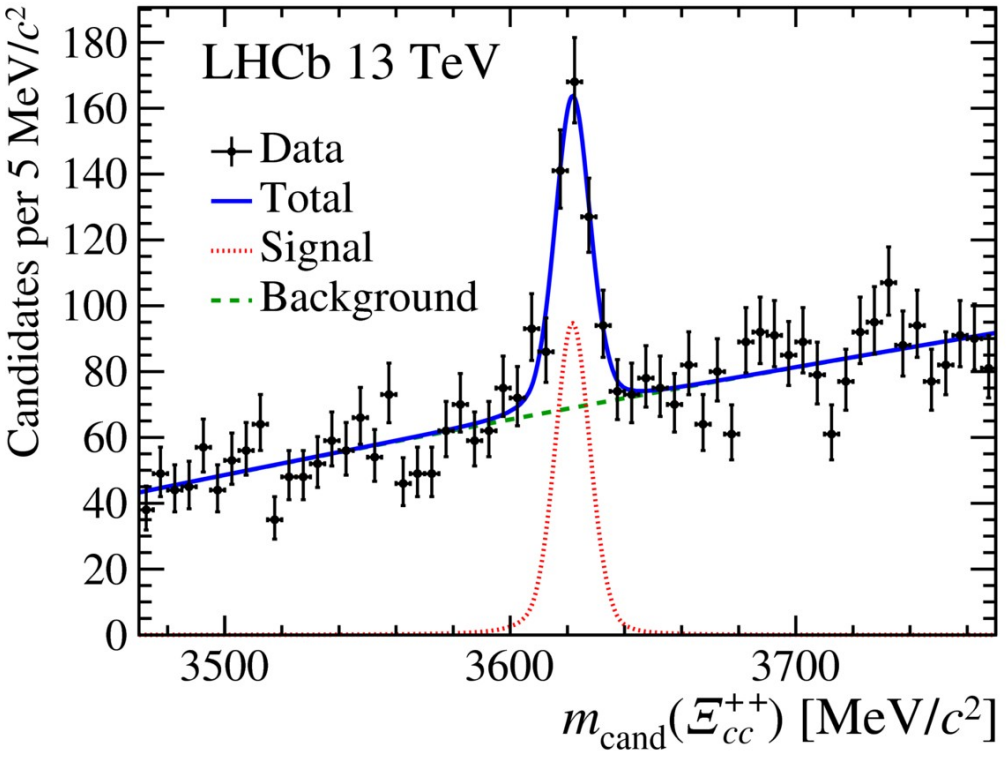
Heavy-Quark Exotic Hadrons

16 September 2020

arXiv:1810.06657
JHEP 01 (2019) 019

# $\Xi_{cc}^{++}$ discovered

PRL 119 (2017) 112001




How about other double heavies?

- Searches ongoing for $\Xi_{cc}^{+}$, $\Omega_{cc}^{+}$
- Lots of work for $\Xi_{bc}$ states
- Prospects for $\Xi_{bb}$ in exclusive decay modes less promising
  - Curse of product BFs: 2 x (b → c) x (c → s) x efficiency … low yields

# Proposed double beauty tetraquarks

## Discovery of doubly-charmed $\Xi_{cc}$ baryon implies a stable $bb\bar{u}\bar{d}$ tetraquark

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## Heavy-Quark Symmetry Implies Stable Heavy Tetraquark Mesons $Q_iQ_j\bar{q}_k\bar{q}_l$

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(Dated: November 29, 2017)

For very heavy quarks $Q$, relations derived from heavy-quark symmetry predict the existence of novel narrow doubly heavy tetraquark states of the form $Q_iQ_j\bar{q}_k\bar{q}_l$ (subscripts label flavors), where $q$ designates a light quark. By evaluating finite-mass corrections, we predict that double-beauty states composed of $bb\bar{u}\bar{d}$, $bb\bar{u}\bar{s}$, and $bb\bar{d}\bar{s}$ will be stable against strong decays, whereas the double-charm states $cc\bar{q}_k\bar{q}_l$, mixed beauty+charm states $bc\bar{q}_k\bar{q}_l$, and heavier $bb\bar{q}_k\bar{q}_l$ states will dissociate into pairs of heavy-light mesons. Observation of a new double-beauty state through its weak decays would establish the existence of tetraquarks and illuminate the role of heavy color-antitriplet diquarks as hadron constituents.

## Evidence for the existence of $ud\bar{b}\bar{b}$ and the non-existence of $ss\bar{b}\bar{b}$ and $cc\bar{b}\bar{b}$ tetraquarks from lattice QCD

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[(2)] *Johann Wolfgang Goethe-Universität Frankfurt am Main, Institut für Theoretische Physik, Max-von-Laue-Straße 1, D-60438 Frankfurt am Main, Germany and*

[(3)] *Adam Mickiewicz University, Faculty of Physics, Umultowska 85, 61-614 Poznan, Poland*

We combine lattice QCD results for the potential of two static antiquarks in the presence of two quarks $qq$ of finite mass and quark model techniques to study possibly existing $qq\bar{b}\bar{b}$ tetraquarks. While there is strong indication for a bound four-quark state for $qq = (ud - du)/\sqrt{2}$, i.e. isospin $I = 0$, we find clear evidence against the existence of corresponding tetraquarks with $qq \in \{uu, (ud + du)/\sqrt{2}, dd\}$, i.e. isospin $I = 1$, $qq = ss$ and $qq = cc$.

## Lattice Prediction for Deeply Bound Doubly Heavy Tetraquarks

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[c] *CSSM, University of Adelaide, Adelaide SA 5005, Australia*

(Dated: May 10, 2017)

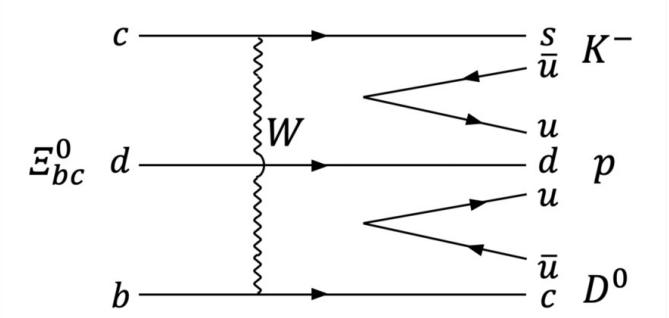
We investigate the possibility of $qq'\bar{b}\bar{b}$ tetraquark bound states using $n_f = 2 + 1$ lattice QCD ensembles with pion masses $\simeq$ 164, 299, and 415 MeV. Motivated by observations from heavy baryon phenomenology, we consider two lattice interpolating operators both of which are expected to couple efficiently to tetraquark states: one with diquark-antidiquark and one with a meson-meson structure. Using nonrelativistic QCD to simulate the bottom quarks, we study the $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$ channels with $\ell = u, d$, and find unambiguous signals for strong-interaction-stable $J^P = 1^+$ tetraquarks. These states are found to lie 189(10) and 98(7) MeV below the corresponding free two-meson thresholds.

See other talks in this meeting

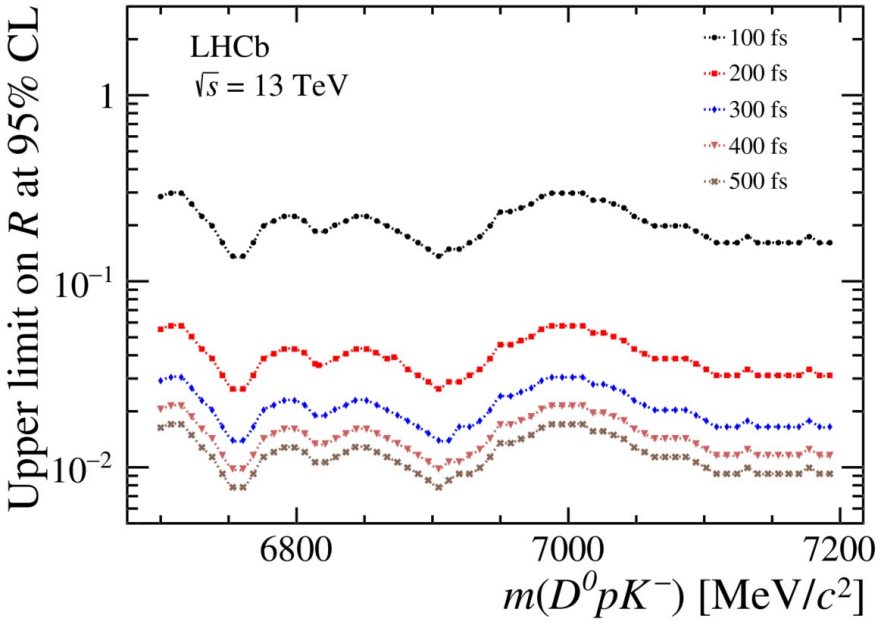
Many new theory papers prompted by $\Xi_{cc}^{++}$ discovery; also older literature

# How to search for double beauty?

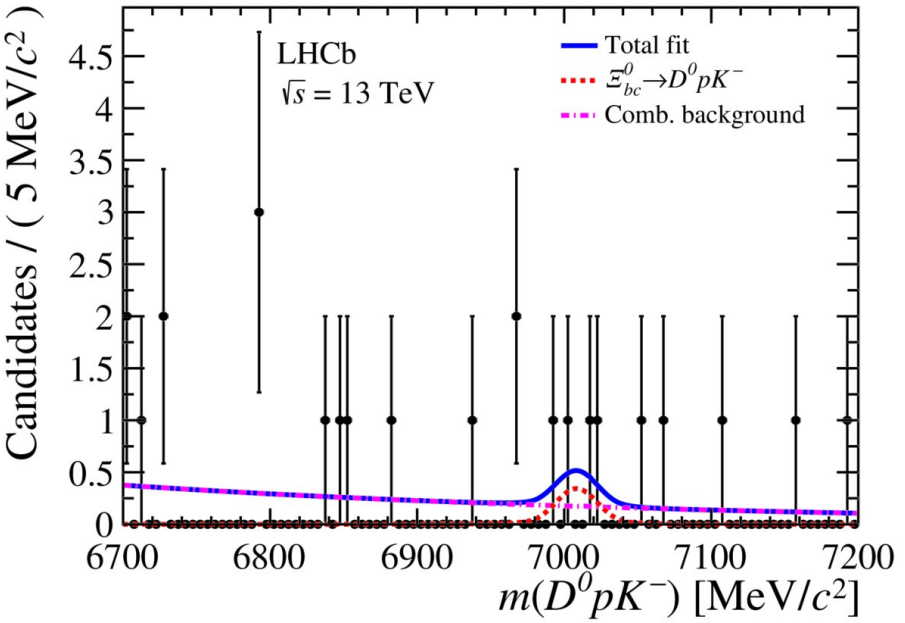
- Exclusive approaches appear unattractive
  - curse of product branching fractions




$$R \equiv \frac{\sigma(\Xi_{bc}^0)\mathcal{B}(\Xi_{bc}^0 \to D^0 p K^-)}{\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^0 \to D^0 p K^-)}$$

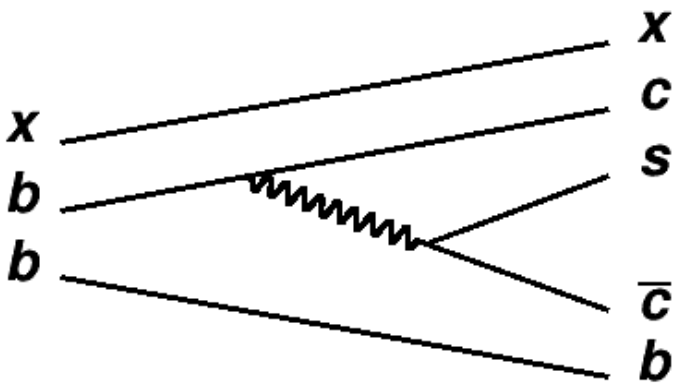



Example from
LHCb-PAPER-2020-014



# How to search for double beauty?

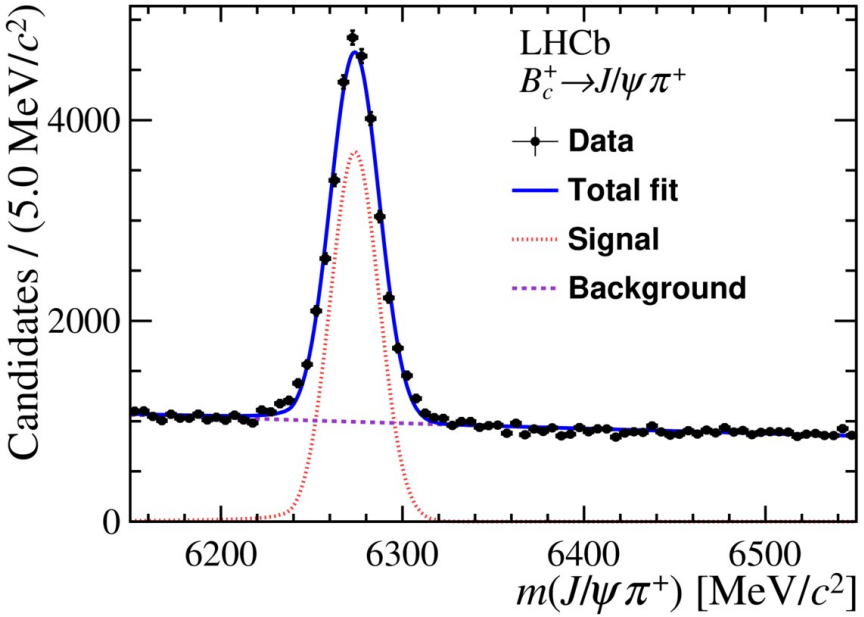
- Exclusive approaches appear unattractive
  - therefore go inclusive
    - see also Ali et al. PL B785 (2018) 605, arXiv:1806.09288 proposing search for double beauty jets
- Key observation:
  - Weakly decaying double beauty hadrons are the only(*) possible source of displaced $B_c^-$ mesons
    - requires $b \to \bar{c}$ transition, e.g.




(*) loophole for $bq\bar{c}\bar{c}$ tetraquark, if stable, but negligible impact

# Displaced $B_c^-$ mesons @ LHCb

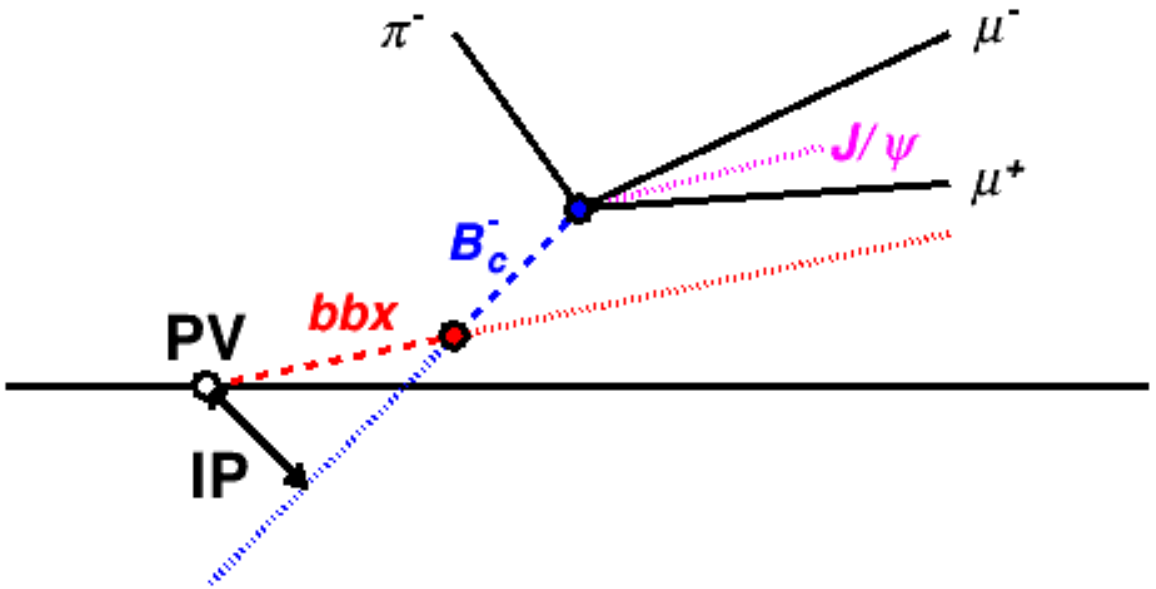
- Inclusive signature of displaced $B_c^-$ mesons is well suited for LHCb
  - use $B_c^- \to J/\psi\pi^-$, with $J/\psi \to \mu^+\mu^-$
    - largest yields as only 3 tracks to reconstruct
    - $B_c^- \to J/\psi\pi^-\pi^+\pi^-$ may also be worth including eventually
      - 25,180 ± 220 $B_c^- \to J/\psi\pi^-$ cf. 9,500 ± 140 $B_c^- \to J/\psi\pi^-\pi^+\pi^-$ in 9/fb




LHCb-PAPER-2020-003
($B_c$ mass)

# Displaced $B_c^-$ mesons @ LHCb

- Inclusive signature of displaced $B_c^-$ mesons is well suited for LHCb
  - benefit from excellent vertex & hence IP resolution
    - Already good now, and expect better in Run 3 (VELOPIX)



# Working example: Displaced charm

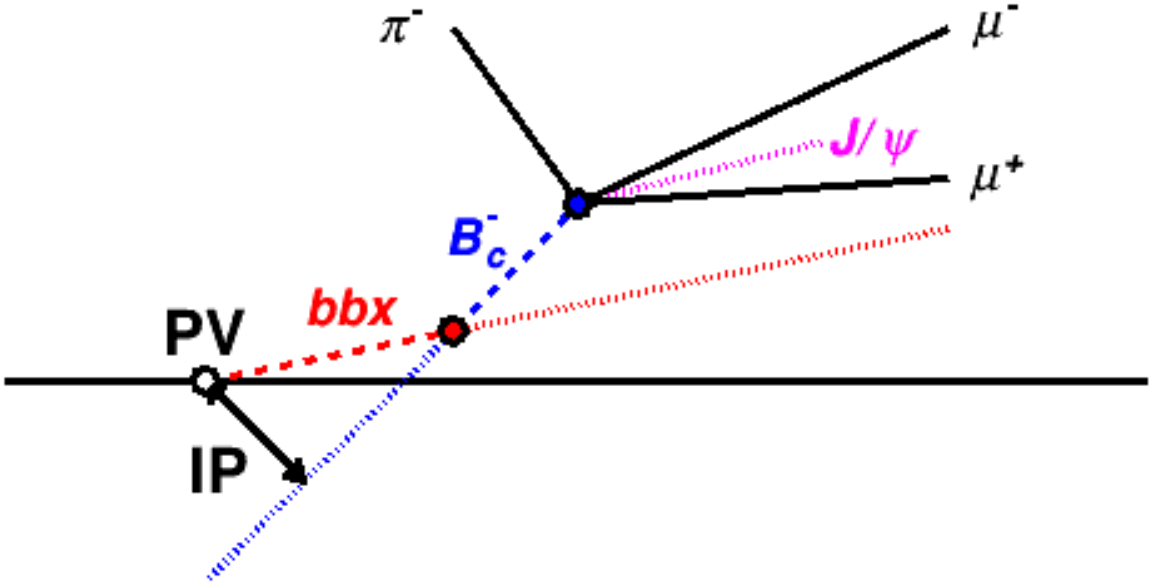
Signature of displaced charm used to measure inclusive $pp \to b\bar{b}X$ production cross-section

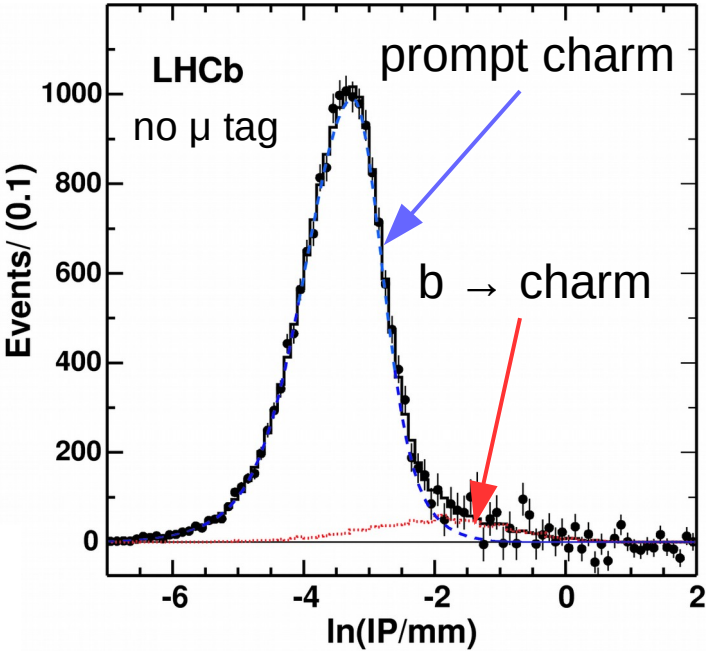
LHCb-PAPER-2010-002

Muon tag from semileptonic decay helps to suppress background from prompt charm

→ not possible for displaced $B_c$ analysis

→ $(b \to \bar{c})$ instead of $(b \to c)$




signal:background ~ 1:20

still able to distinguish displaced charm with 2.9 $nb^{-1}$

IP resolution since improved

# Is it feasible?

- How large are the potential yields?
  - Product of the following (with estimated/known values)
    - integrated luminosity
    - bbx hadron production cross-section (1 nb; arXiv:1806.09288)
    - branching fractions for inclusive $bbx \to B_c^- X$ (10%) ...
    - … and for $B_c^- \to J/\psi\pi^-$ (2%) and $J/\psi \to \mu^+\mu^-$ (6%) transitions
    - detection efficiency (10%)
  - Leads to around 10 displaced $B_c^-$ mesons per $fb^{-1}$
    - around 1% of prompt $B_c^-$ yield
  - But some of these estimates have large uncertainties

# Is it feasible?

arXiv:1902.04582
PL B793 (2019) 181

- branching fractions for inclusive bbx → $B_c^-$X (10%) ...

**An Estimate of the Inclusive Branching Ratio to $\bar{B}_c$ in $\Xi_{bbq}$ Decay**

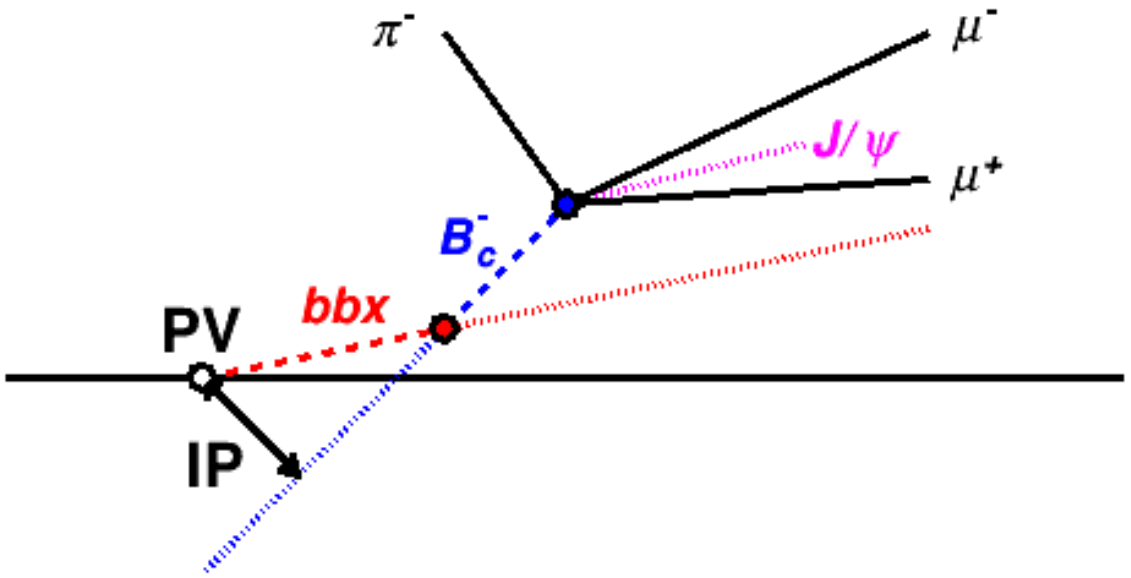
Alexander K. Ridgway and Mark B. Wise[1]

We calculated the inclusive decay rate for $\Xi_{bbq} \to \bar{B}_c + X_{c,s,q}$ to be $1.5 \times 10^{10}$ s$^{-1}$ (which implies $\mathrm{Br}(\Xi_{bbq} \to \bar{B}_c^{(*)}(k) + X_{c,s,q}) \simeq 8 \times 10^{-3}$).

Could easily be out by an order of magnitude
Require high luminosity, excellent detection capability and favourable properties

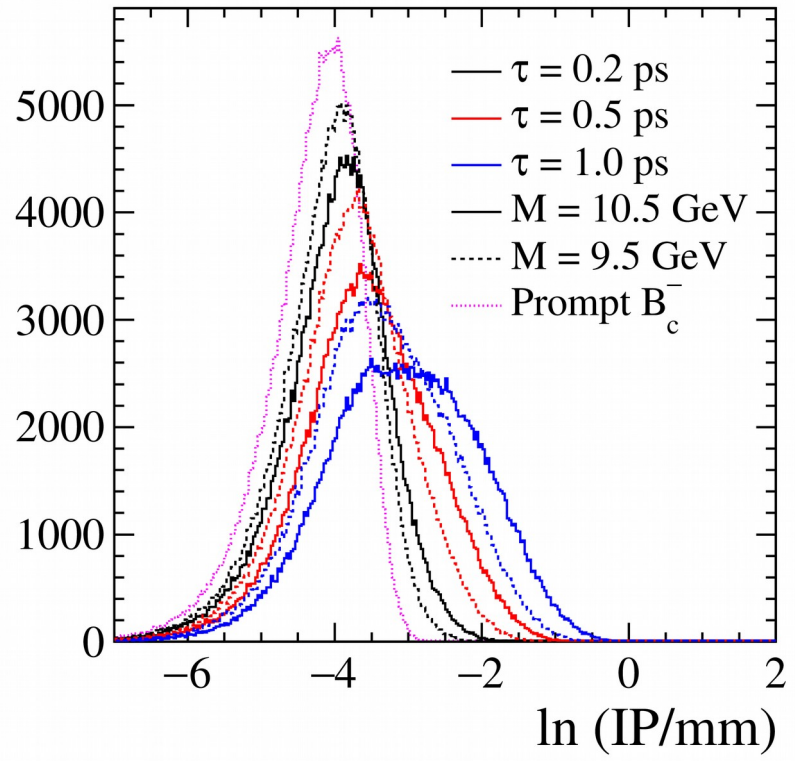
# Is it feasible?

- How good is signal/background separation?
  - IP distribution depends on properties of signal
    - flight distance (hence momentum & lifetime)
    - Q value of bbx $\rightarrow B_c^- X$ decay (hence mass)



# Simple toy study

- Assume bbx kinematics same as B mesons
  - ~flat in η, ~exponential in $p_T$ with mean 5 GeV
- Obtain approximate $B_c^-$ IP
  - weighted mean of IP of 3 final state tracks
  - full vertex fit not possible
  - **likely to underestimate tails**
- Assume track IP resolution measured in 2012
  - $\sigma_{IP}$ [μm] = 11.6 + 23.4/$p_T$ [GeV]
  - will be improved in upgraded detector (Run 3)
- Reasonable separation from prompt $B_c^-$ mesons
  - expect M ~ 10.5 GeV, τ ~ 0.4 - 0.8 ps
- **Control of tails will be essential**
  - $\overline{B}_s^{**}$ tagged $B^- \to J/\psi K^-$ control sample will help




Tails will be much trickier in real analysis

# What could be measured?

- Optimistically assume that a significant yield can be obtained, and its shape measured
  - Yield is related to
    - Production cross-section times $B(\mathrm{bbx} \rightarrow \mathrm{B_c^-X})$
    - Summed over all weakly decaying bbx hadrons
    - With improved theory predictions, could indicate whether only bb baryons or also bb tetraquarks are being produced
  - Shape is related to
    - Mass and lifetime
    - Averaged over all weakly decaying bbx hadrons
    - With prediction for mass could infer average bbx lifetime (or vice versa)
- Observation could also provide insight into future strategies for exclusive measurements

# How to distinguish bb tetraquarks?

- Inclusive approach could demonstrate bb hadron production
  - but no direct information if they are baryons or tetraquarks
  - theoretical uncertainties likely to be too large to make strong conclusions from inclusive properties
- Require exclusive reconstruction to be sure?
  - worth considering if semi-inclusive approaches could be useful
  - “baryon tagger” concept could be explored

    (like flavour tagging for decay-time-dependent CP violation measurements of $B^0$ and $B_s^0$ mesons)
  - would require excellent low momentum p identification
    - e.g. TORCH detector for LHCb Upgrade II
    - a big challenge for a long-term programme

# Summary

- Have presented an inclusive strategy to search for double beauty hadron production at the LHC through the signature of displaced $B_c^-$ mesons
  - Well suited for search at LHCb
  - Still highly challenging, but seems to have better potential than exclusive searches
- More detailed study needed to understand LHCb sensitivity
  - Depends on bbx production cross-sections, inclusive branching fractions to final states containing $B_c^-$ mesons, masses and lifetimes
  - More theory work on these would be welcome

arXiv:1810.06657
JHEP 01 (2019) 019