Experimental aspects for discovering Ξ_{bc}

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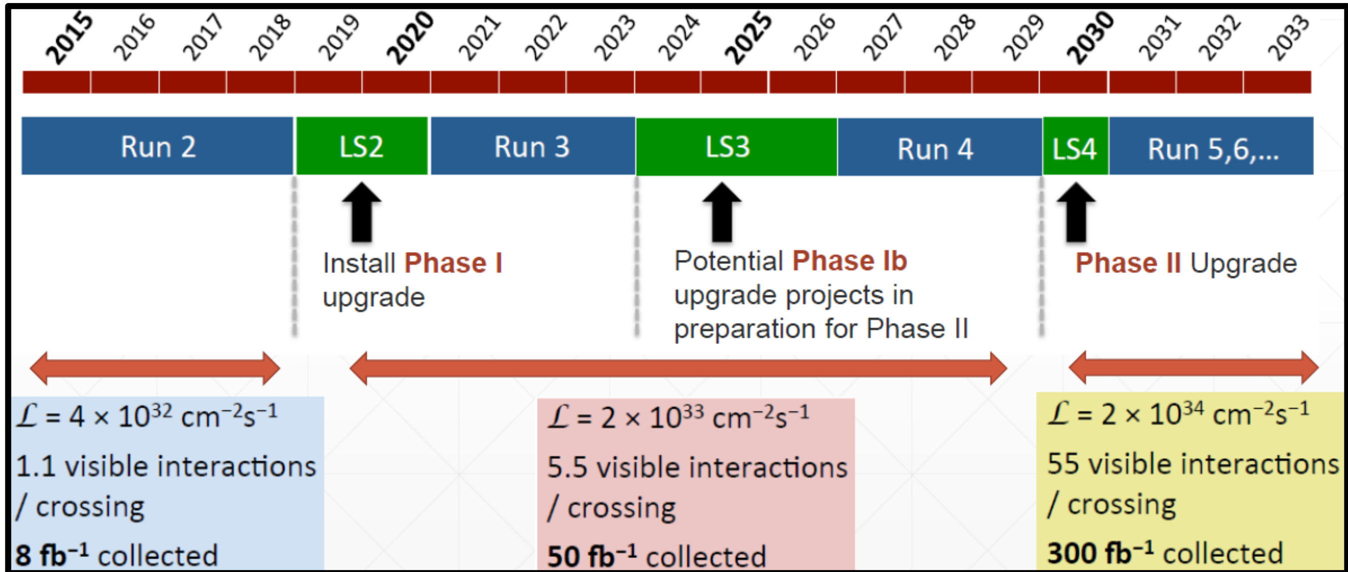
Introduction

- I won't spend time reviewing theory, please see talks by previous speakers.
- Here, I'd like to share what I see as the experimental issues & prospects (LHCb-centric, sorry)

- **LHCb strengths are:**
  - **VELO**: Excellent proper time resolution, ~50 fs for *b*-hadrons, ~100 fs for *c*-hadrons
  - **RICH:** Excellent separation of K, p from π (RICH)
  - **Trigger:** Highly flexible, now have "offline quality" at the trigger level.
    - Can do analysis directly on data coming out of the trigger (*e.g.* Ξ_{cc}^{++})
    - Physics groups slowly migrating (req. for the Phase 1(b) upgrade.)
  - **Spectrometer:** Excellent mass resolution.

- **LHCb – into the future**
  - L0 hardware trigger (1 MHz max) gone!
  - Full software trigger, with calibrated detector.
  - Large increase in eff, especially for hadronic modes!



Preliminaries (1)

All numbers here are unofficial!

$$N_{obs}(\Xi_{bc} \to f) = \left(\sigma_{pp\to\Xi_{bc}X}\ L_{\rm int}\right)\ \left(B_{tot}(\Xi_{bc} \to f)\right)\ \left(\mathrm{Acc(LHCb)}\right)\left(\ \varepsilon_{sel}\right)$$

- Theory expectation: $\sigma(\Xi_{bc}^{+}) \sim \sigma(\Xi_{bc}^{0}) \cong$ 20 nb at 14 TeV, ~10 nb each at 7 TeV
  - For reference σ(bb) ~ 70 ub (at least 1 b in LHCb acceptance).

J.-W. Zhang, et al., PRD 83 034026 (2011)

- In Run 1: L_{int} = 3 fb^{-1}, (2015+2016) L_{int} ~1.8 fb^{-1}.

$$N_{prod}(\Xi_{bc}^{+}) \approx N_{prod}(\Xi_{bc}^{0}) \cong \left[10\text{ nb } \times\ 3\text{ fb}^{-1} +\ 20\text{ nb } \times\ 1.8\text{ fb}^{-1}\right] \approx \mathbf{66\times 10^{6}}$$

- Cannot "afford" $B_{tot} < 10^{-5}$, until after LHCb Phase 1b upgrade (unless $\sigma(\Xi_{bc})$ is much larger than expected)

- Most Ξ_{bc} decays have 3 BFs involved: Assume all CF, and are **~5%** each: **B_{tot} = 1.25 x 10^{-4}** ➔ **After BFs**: ~ **8250**
- Geometric acceptance for 5 tracks within LHCb acceptance (10 < θ < 400 mrad): **Acc ~ 0.15** ➔ **After Acc(det):** ~ **1200**
- In this scenario, one would want to have ε_{tot} > ~1% to have a shot at discovery with 1 mode.

- To give a **VERY ROUGH** idea (from simulation of Ξ_{bc}, τ = 400 ps) in Run 1
  - J/ψ modes: $\varepsilon_{sel}(\Xi_{bc}\to J/\psi\Lambda_c,\ J/\psi\to\mu^-\mu^+,\ \Lambda_c^{+}\to pK^-\pi^+)$ **~ 3%**
  - Fully hadronic: $\varepsilon_{sel}(\Xi_{bc}\to\Lambda_c^{+}D^0,\ D^0\to K^-\pi^+,\ \Lambda_c^{+}\to pK^-\pi^+)$ **~ 0.6%**
  - Much of difference from L0 E_T thresholds for hadronic trigger (dimuons are golden!)

- **Probably need to combine many modes to increase our chances here..**

Preliminaries (2)

$$N_{obs}(\Xi_{bc} \to f) = \left(\sigma_{pp\to\Xi_{bc}X}\ L_{\text{int}}\right)\ \left(B_{tot}(\Xi_{bc} \to f)\right)\ \left(\text{Acc(LHCb)}\right)\left(\ \varepsilon_{sel}\right)$$

- Large number of possible final states, depending on whether the *b* or the *c* undergoes the weak decay first.

- **Experimental wish list:**
  - As large B_{tot} as possible
  - As few final state tracks as possible (lose ~ factor of 2–3 in Acc(det) x ε_{sel} for each extra track)
  - Largest possible IP (impact parameter) to PV (to suppress PV background).
    - Prefer most/all tracks from tertiary vertices

- **General challenges / issues**
  - Small production cross-section (and sizeable uncertainty on its value)
  - Large uncertainty / unknown absolute BRs for Ξ_{bc}, Ξ_{cc}, Ξ_c
  - Ξ_{bc} lifetime expected to be short, ~100–300 fs or so.

- Improved predictions on lifetime or BRs can be a big help for us to focus on most promising modes

- I will discuss a handful of modes that LHCb can pursue, along with their pros & cons

Classes of final states

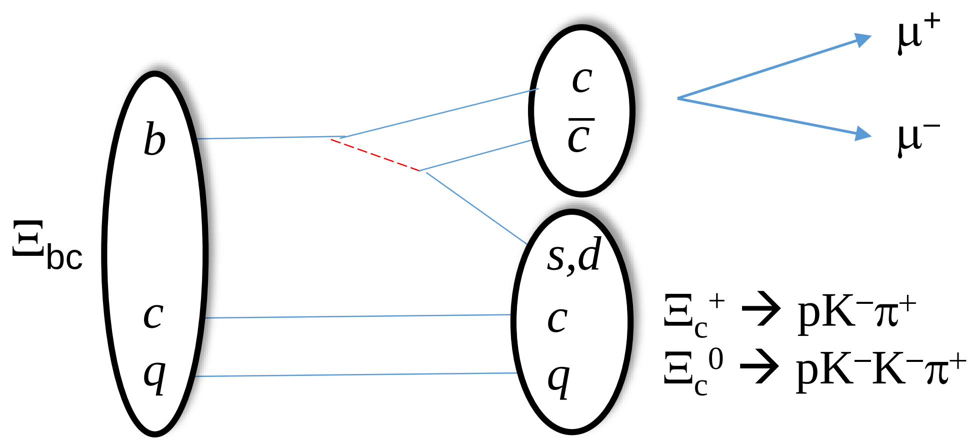
- **Fully reconstructed:** For a discovery, the most convincing evidence will be a narrow mass peak, consistent with the detector resolution, more or less in the expected mass range.
  - Seeing the peak in > 1 decay mode would be a bonus.

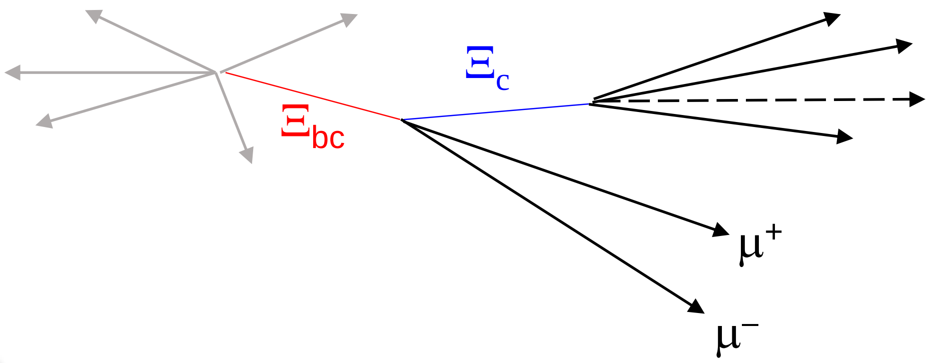
- **Partially reconstructed:** Semileptonic decays may provide larger signal rates, but one usually doesn't end up with a sharp mass peak.
  - Counting experiment, using a number of discriminating variables.
  - Data-driven methods for background determination required.
  - B_c was first discovered in $J/\psi\mu$ at CDF via counting expt.

- Ultimately, we'd want to also investigate the lifetime & production rates/properties, relative BRs as well.

Fully reconstructed decays

Modes with J/ψ





Pros

- $b \rightarrow cc s$ is CF
- High L0 efficiency for J/ψ, ~90%.
- Narrow charm resonances
- Normalization/control channel: $B_c \rightarrow J/\psi D_s^+$.
- p,K,π have *moderately large* IP due to $\tau(\Xi_c)$.

Issues

- BFs of $\Xi_c^{(+,0)}$ probably not too large, O(1-2%)*.
- Physics backgrounds from $b \rightarrow J/\psi X$, random J/ψ+charm, ..

BRs

- $B(\Xi_{bc} \rightarrow J/\psi X_c)\ B(J/\psi \rightarrow \mu\mu)\ B(\Xi_c \rightarrow pK\pi(K))$

Other modes:

- $J/\psi\Lambda_c$, Ξ_{bc} is CS, but larger Λ_c BF.
- $J/\psi\Lambda_c K$
- J/ψpK ($b \rightarrow u$, but don't have another charm BF)

Particle	BR (%)	Lifetime (ps)
J/ψ	6.0	-
Λ_c^+	5.5	~0.20
Ξ_c^+	1-2*	~0.45
Ξ_c^0	1-2†	~ 0.13

* e.g see: Yu et al, arXiv:1703.09086.
† My estimate

Rough estimate

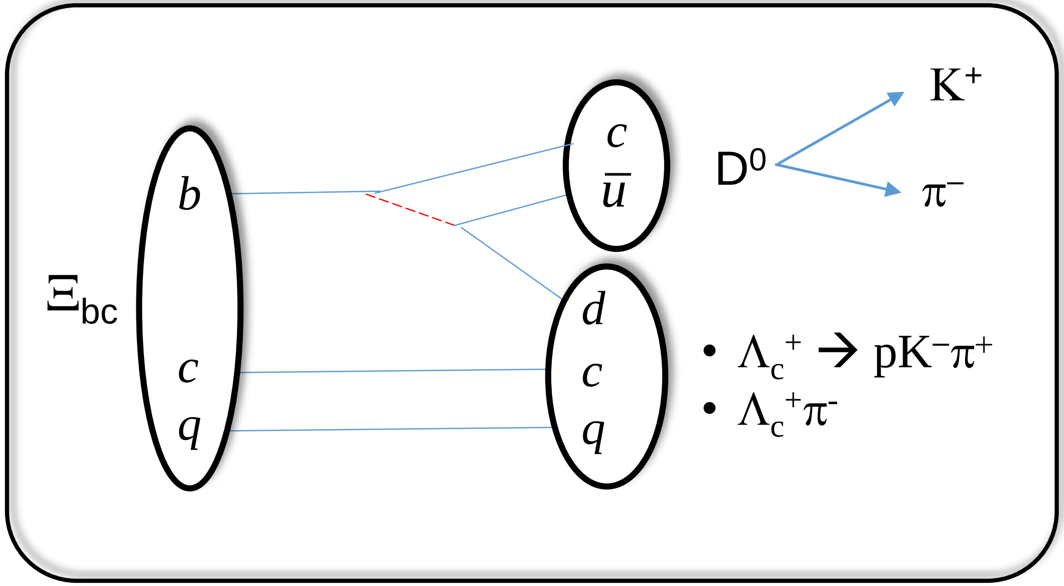
$$\frac{N(\Xi_{bc}^{+} \to J/\psi\ \Xi_{c}^{+})}{N(B_{c}^{+} \to J/\psi D_{s}^{+})} = \frac{f_{\Xi_{bc}^{+}}}{f_{B_{c}^{+}}} \bullet \frac{B(\Xi_{bc}^{+} \to J/\psi\ \Xi_{c}^{+})}{B(B_{c}^{+} \to J/\psi D_{s}^{+})} \bullet \frac{B(\Xi_{c}^{+} \to pK\pi)}{B(D_{s}^{+} \to KK\pi)} \bullet \varepsilon_{rel}$$

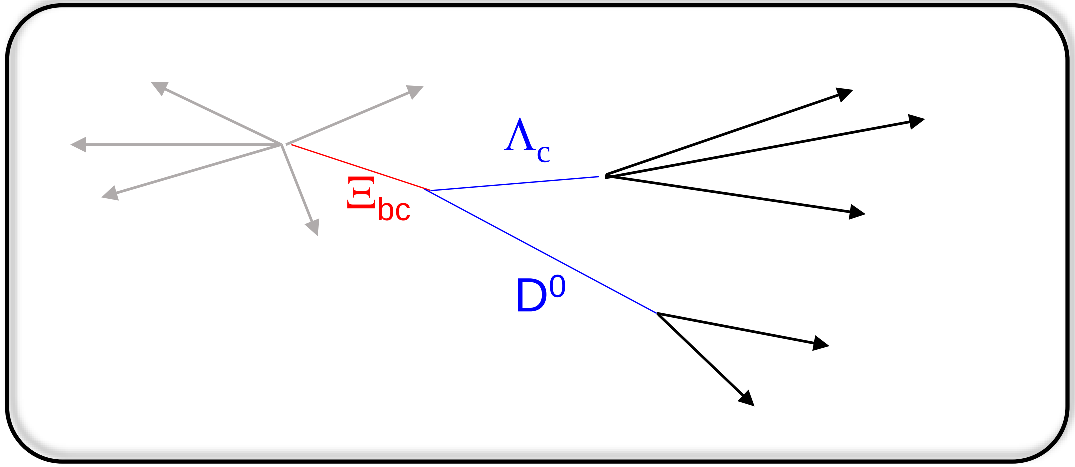
Guesses: (0.3) (~ 0.5 ?) (~0.3) (0.8) ~ 0.04

- In Run 1 + 2015 + 2016, we have/expect **ROUGHLY** 300 reco'd $B_c \to J/\psi D_s^+$.
  - ➔ Could expect: $N(\Xi_{bc} \to J/\psi \Xi_c^+) \sim$ **12**
- Clearly, large uncertainties here, but perhaps some reason for optimism.

- Much more comfortable with $N(B_c \to J/\psi D_s^+) = 3000$! ☺
  - LHCb upgrade stats!

Modes with 2 charm hadrons





Pros

- $b \rightarrow cud$ is CF
- Narrow charm resonances
- CF decays of charm hadrons
- Normalization/control channels: $B^+ \rightarrow D^0 D_s^+$,
- *Moderately large* IPs due to intermediate charm.

Issues

- Fully hadronic: ε(L0) ~ 25%.
- Internal tree (color suppressed)
- Physics backgrounds from pp→*cc*X, bb→*cc*X, …

BRs

- $B(\Xi_{bc} \rightarrow D^0 \Lambda_c)\ B(D^0 \rightarrow K\pi)\ B(\Lambda_c \rightarrow pK\pi)$

Other

- Could add $D^0 \rightarrow K\pi\pi\pi$, could provide ~50% more signal
- $\Lambda_c D^0 \pi$.

Particle	BR (%)	Lifetime (ps)
Λ_c^+	5.5	0.20
D^0	4.0	0.41

Rough estimate

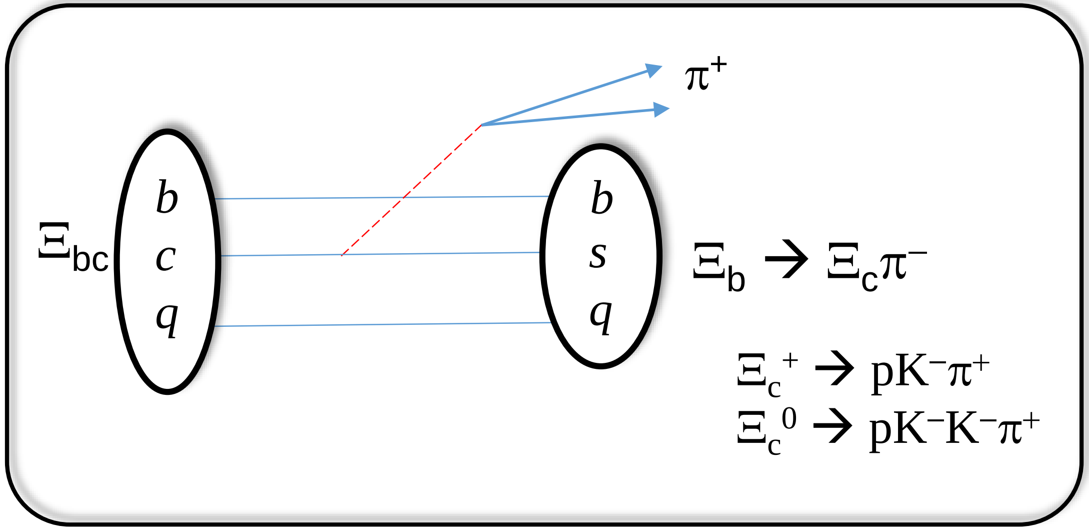
$$\frac{N(\Xi_{bc}^{+} \to D^{0}\Lambda_{c}^{+})}{N(B^{+} \to D^{0}D_{s}^{+})} = \frac{f_{\Xi_{bc}^{+}}}{f_{B^{+}}} \bullet \frac{B(\Xi_{bc}^{+} \to D^{0}\Lambda_{c}^{+})}{B(B_{c}^{+} \to D^{0}D_{s}^{+})} \bullet \frac{B(\Lambda_{c}^{+} \to pK\pi)}{B(D_{s}^{+} \to KK\pi)} \bullet \varepsilon_{rel}$$

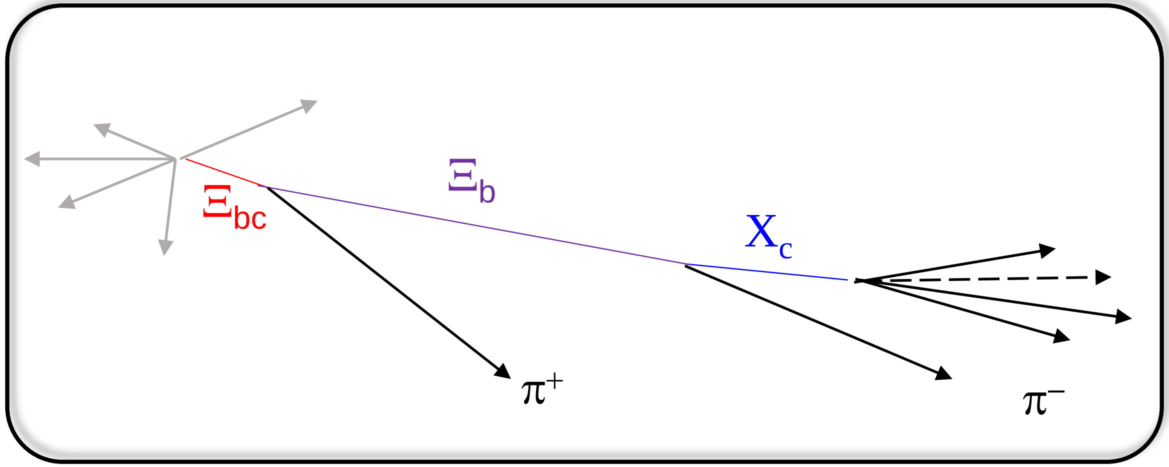
Guesses: (0.001) (~ 0.5 ?) (~1) (0.3) ~ 1.5×10^{-4}

[known]

- In Run 1, we reconstruct **ROUGHLY** 20,000 $B^{+}\to D^{0}D_{s}^{+}$. (LHCb-PAPER-2013-060)
- Could expect: $N(\Xi_{bc}\to D^{0}\Lambda_{c})$ ~ **7** (Run 1 + 2015 + 2016)
  - Perhaps ~10 with $D^{0}\to K\pi\pi\pi$.
- Again, large uncertainties here on BRs, $f_{\Xi bc}$.

Modes with a *b*-hadron





Pros

- ❑ $c \rightarrow sud$ is CF
- ❑ Narrow, clean Ξ_b signal in data
- ❑ Normalization to inclusive Ξ_b decay
- ❑ Daughter IPs are "large" due to $\tau(\Xi_b)$~1.5 ps, except for π^+ from Ξ_{bc}.

Issues

- ❑ Fully hadronic: ε(L0) ~ 25%
- ❑ Relatively low yield of fully-reco'd Ξ_b in data
  - ❑ Run 1: ~6000 $\Xi_b^{(0,-)}$ signal.
- ❑ backgrounds from Ξ_b + random π^+.

BRs

- ❑ $B(\Xi_{bc} \rightarrow \Xi_b\pi)$ $B(\Xi_b \rightarrow \Xi_c\pi)$ $B(\Xi_{c,} \rightarrow pK(K)\pi)$

Other modes with b-hadrons:

- ❑ $\Lambda_b\pi^+$: Larger Λ_c BF, but Ξ_{bc} is CS.
- ❑ $B^0\Lambda^0$, $\Lambda_b K_S$ Low $\varepsilon_{tot}(\Lambda^0)$, $\varepsilon_{tot}(K_S)$
- ❑ $\Lambda_b K\pi^+$: Phase space?
- ❑ B^0pK: phase space supp?
- ❑ B^0p: Ξ_{bc} is CS.

Rough estimate

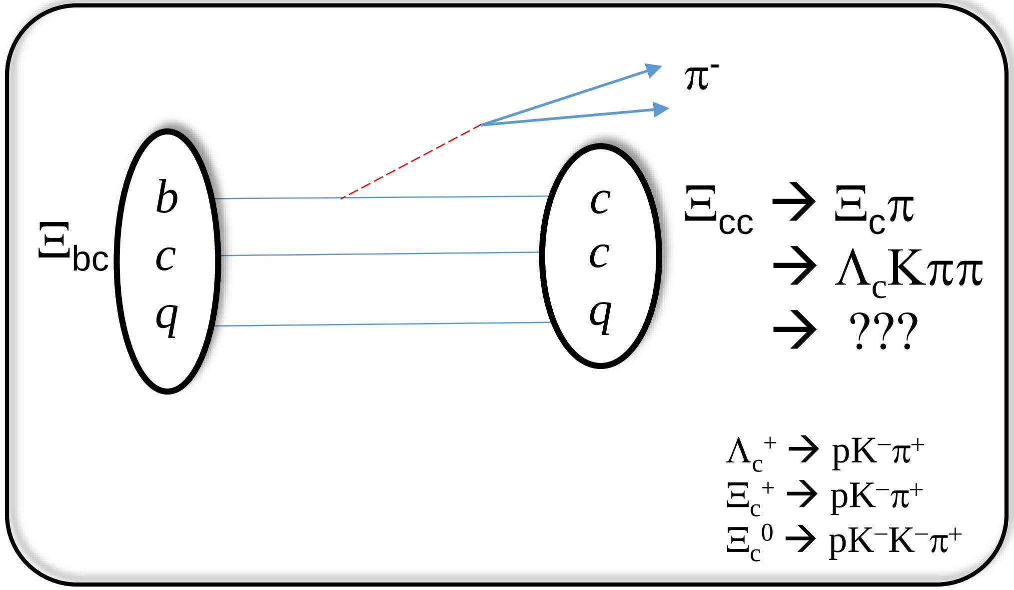
$$\frac{N(\Xi_{bc}^{+} \to \Xi_b \pi^{+})}{N(\Xi_b)} = \frac{f_{\Xi_{bc}^{+}}}{f_{\Xi_b}} \bullet B(\Xi_{bc}^{+} \to \Xi_b \pi^{+}) \bullet \varepsilon_{rel}$$

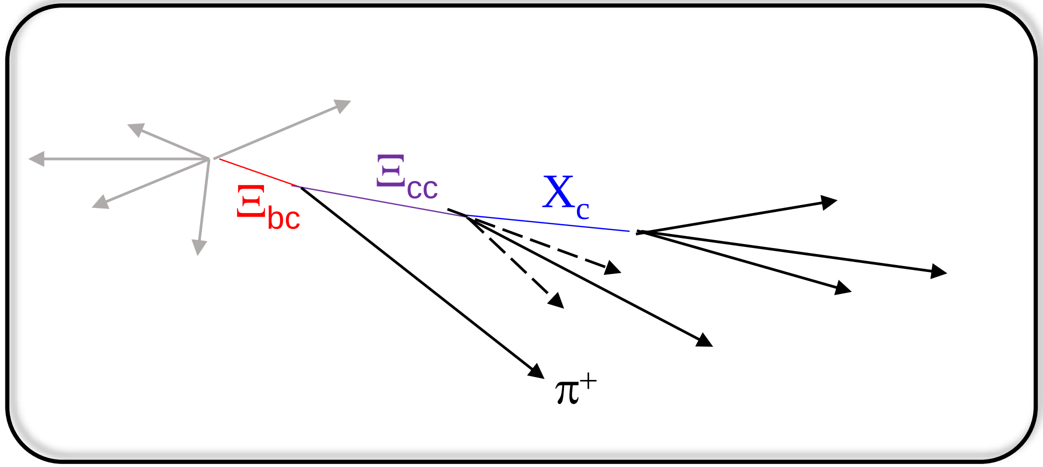
Guesses: (0.01) (~ 0.02) (0.5) ~ 10^{-4}

[arXiv:1707.028341]

- In Run 1, we have **ROUGHLY** 4000 $\Xi_b^0 \to \Xi_c^+ \pi^-$. (LHCb-PAPER-2014-021)
- Again, sizeable uncertainties..
- Not super-promising, until phase 1b upgrade, may be worth further exploration though.

Modes with a Ξ_{cc}–baryon





Pros

- ❑ $b \to cud$ is CF
- ❑ Know $m(\Xi_{cc})$ now – tight mass cut around Ξ_{cc} will provide very large BG suppression.
- ❑ Normalization to inclusive Ξ_{cc} signal
- ❑ π^- from Ξ_{bc} is high p_T.
- ❑ *Moderately large* IPs

Issues

- ❑ Fully hadronic: ε(L0) ~ 25%
- ❑ Expected signal yield may be too low (~500 "prompt" $\Xi_{cc}^{++} \to \Lambda_c K\pi\pi$)
- ❑ Exploration of other $\Xi_{cc}^{+(+)}$ modes very important.

BRs

- ❑ $B(\Xi_{bc} \to \Xi_{cc}\pi)\ B(\Xi_{cc} \to \Xi_c\pi, \Lambda_c K\pi\pi)\ B(\Lambda_c, \Xi_c, \to pK\pi)$

Other modes

- ❑ Any additional clean / high yield Ξ_{cc} modes
- ❑ $\Xi_{cc} \to \Xi_c\pi\pi\pi$ (similar ε to $\Lambda_c K\pi\pi$)

Rough estimate

$$\frac{N(\Xi_{bc}^{+} \to \Xi_{cc}^{++}\pi^{-})}{N(\Xi_{cc}^{++})} = \frac{f_{\Xi_{bc}^{+}}}{f_{\Xi_{cc}^{++}}} \bullet B(\Xi_{bc}^{+} \to \Xi_{cc}^{++}\pi^{-}) \bullet \varepsilon_{rel}$$

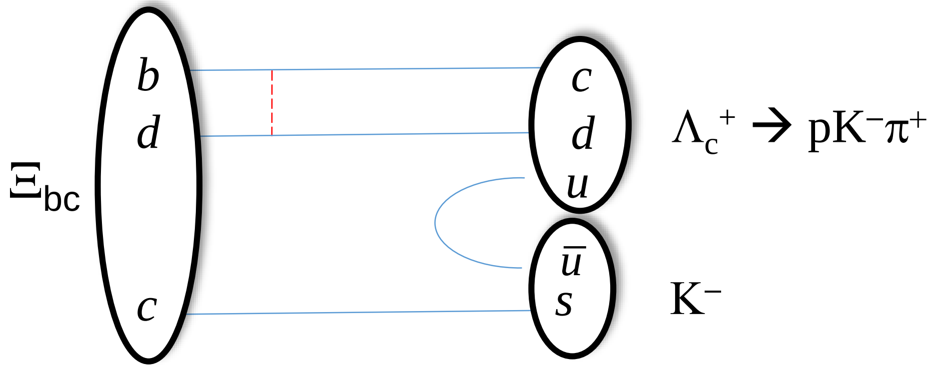
Guesses: (0.2) (~ 0.001) (0.5) ~ 10^{-4}

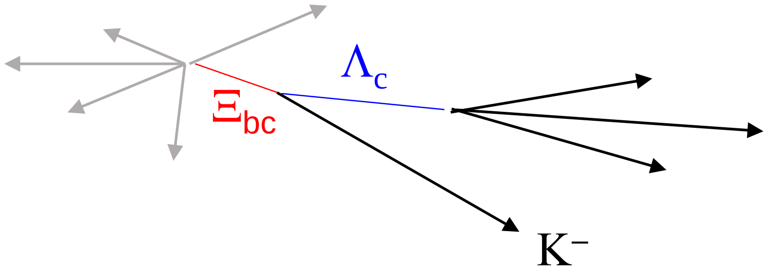
[arXiv:1707.028341]

- Scaling from LHCb-PAPER-2017-018, we expect **ROUGHLY 500** $\Xi_{cc}^{++} \to \Lambda_c K\pi\pi$ signal in Run 1 + 2015 + 2016 data sets.
- Additional Ξ_{cc} modes would help here, if they bring with them large signal yields.
- Would need sizeable gains in Ξ_{cc} signal yields to make such modes viable (unless above estimates are way off)
  - Perhaps with LHCb upgrade + more Ξ_{cc} modes..

Modes with one charm hadron

- **W-exchange processes, b→u, or penguin decays**





Pros

- Only 1 charm BF (20 –100 X less reduction)
- Narrow charm resonance.
- *Moderately large* IPs
- Hadron from Ξ_{bc} vertex high p_T.

Issues

- Fully hadronic: ε(L0) ~ 25%
- Combinatorial backgrounds.
- **Could BR for such decays be $O(10^{-4})$ [or larger]?**

BRs

- $B(\Xi_{bc} \to \Lambda_c K)\ B(\Lambda_c \to pK\pi)$ [**not 3 !**]

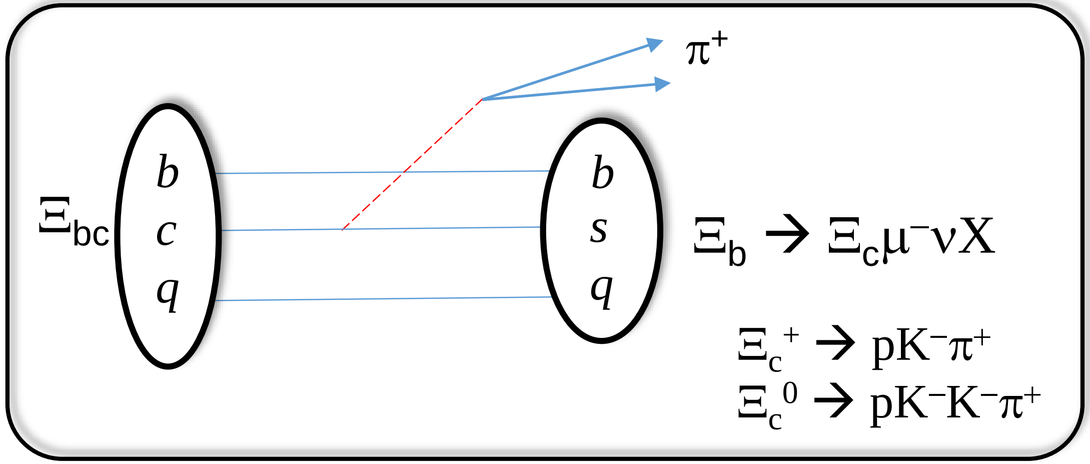
Some other modes with 1 *c*-hadron:

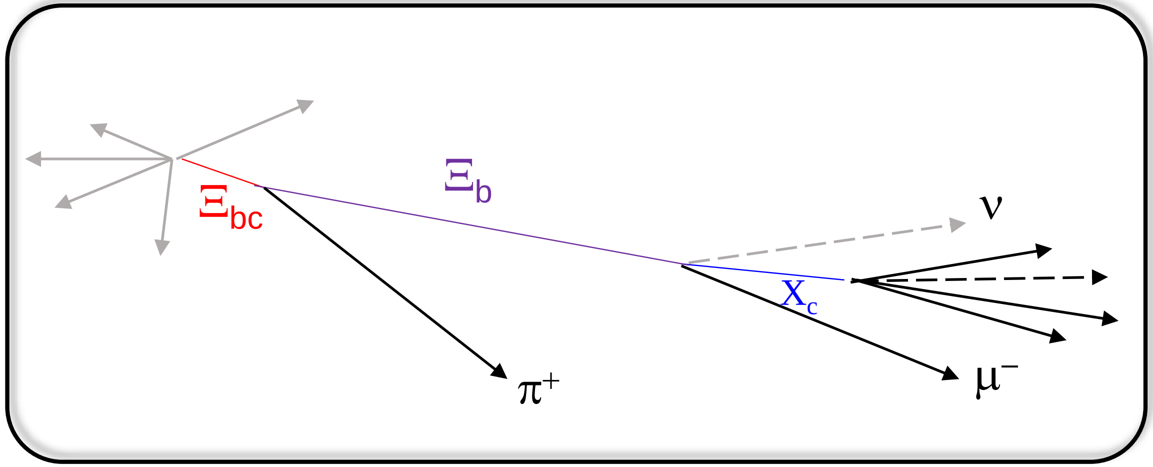
- $\Xi_c^+\pi^-$: but smaller BR for Ξ_c+.
- $\Xi_c^0\pi^+$: 1 extra track, maybe longer[?] $\tau(\Xi_{bc}^+)$ compensates.
- $\Xi_c\pi\pi$, $\Lambda_c K\pi$: Two tracks with small IP, instead of one.
- $\Lambda_c^+\pi(\pi)$: CS, but $B(\Lambda_c^+) > B(\Xi_c^+)$
- D^0pK: 4% BF for D^0, tight PID on "pK" to suppress BG.
- **D^0p:** CS, 4% BF for D^0, tight PID on proton, **only 3 tracks**.
- D^+pK: 9% BF for D^+, $\tau(D^+)$ ~1 ps, tight PID on "pK"
- $\Xi_c\phi$: Narrow ϕ resonance (Penguin)

Semileptonic decays

Semileptonic decays

Can get very large gain by considering SL b - decays





Pros

- ❑ **$N(\Xi_b \rightarrow \Xi_c \mu\nu X) \sim 15 \times N(\Xi_b \rightarrow \Xi_c \pi)$**
- ❑ Daughter IPs are "large" due to $\tau(\Xi_b)$~1.5 ps, except for π^+ from Ξ_{bc}.
- ❑ Normalization to inclusive Ξ_b decay

Issues

- ❑ No sharp Ξ_b mass peak.
- ❑ Backgrounds from Ξ_b + random π^+.

BRs

- ❑ $B(\Xi_{bc} \rightarrow \Xi_b \pi)\ B(\Xi_b \rightarrow \Xi_c \mu\nu X)\ B(\Xi_{c,} \rightarrow pK(K)\pi)$

- ❑ Can do "neutrino reconstruction" for Ξ_b, but generally assume Ξ_b comes from PV.
  - ❑ How much is p(ν) resolution degraded ? (needs study)
  - ❑ May still get narrow peak in $\delta m = m(\Xi_c \mu\nu\pi) - m(\Xi_c \mu\nu)$
- ❑ MVA critical to distinguish backgrounds from signal.
- ❑ Modes with 2 tracks from Ξ_{bc} vertex to pin down Ξ_{bc} vertex? *e.g.* $\Xi_{bc} \rightarrow \Lambda_b K^- \pi^+$, where $\Lambda_b \rightarrow \Lambda_c \mu\nu X$

Other modes under discussion.

- There are quite a few other ideas for modes to investigate within LHCb.
  - Two-body charmless modes: very small BF, but only 1 BF enters. Also higher selection efficiency.
  - $D^0 D^0 p$
  - $J/\psi D^0 p$
  - $\Xi_{bc} \rightarrow \Xi_b \mu^+ \nu\ X$, $\Xi_b \rightarrow \Xi_c \pi^-$
  - $\Xi_{bc} \rightarrow \Xi_b \mu^+ \nu\ X$, $\Xi_b \rightarrow \Xi_c \mu^- \nu$ → Signature: $\Xi_c \mu^+ \mu^-$

  - Bright ideas very welcome for new modes to consider!
    - Few tracks as possible
    - Large IP
    - Large BF

☺

Summary

- With discovery of Ξ_{cc}, we need to ramp up our efforts on Ξ_{bc}.
- Challenging: B_{tot} x ε_{tot} mustn't exceed ~10^{-7}, to have a shot with Run 1 + Run 2 data.
  - Many possible modes, a few appear more promising than others.
  - We have a chance, but probably need to combine several of the most promising modes.
  - We should be careful in "writing off" modes. Some predictions come with large uncertainties, and m'ment sometimes challenges prediction(s). Case in point:

Penguin/Annihilation diagrams → numerator; CF Tree diagram → denominator

$$\frac{B(B_c^+ \to D^0 K^+)}{B(B_c^+ \to J/\psi \pi^+)} = 0.13 \pm 0.04$$

LHCb-PAPER-2016-058

- I have not discussed other double-heavies, e.g. Ω_{bc}, or Ξ_{bb}, as these are even more difficult (although no less interesting!)

- If we do not discover Ξ_{bc} in Run1 + Run 2, it should certainly be well within reach with Phase 1(b) upgrade of LHCb.