Beauty 2014, Edinburgh, Scotland, July 14-18, 2014

Beauty Baryon Decays @ LHCb

Steven Blusk
Syracuse University

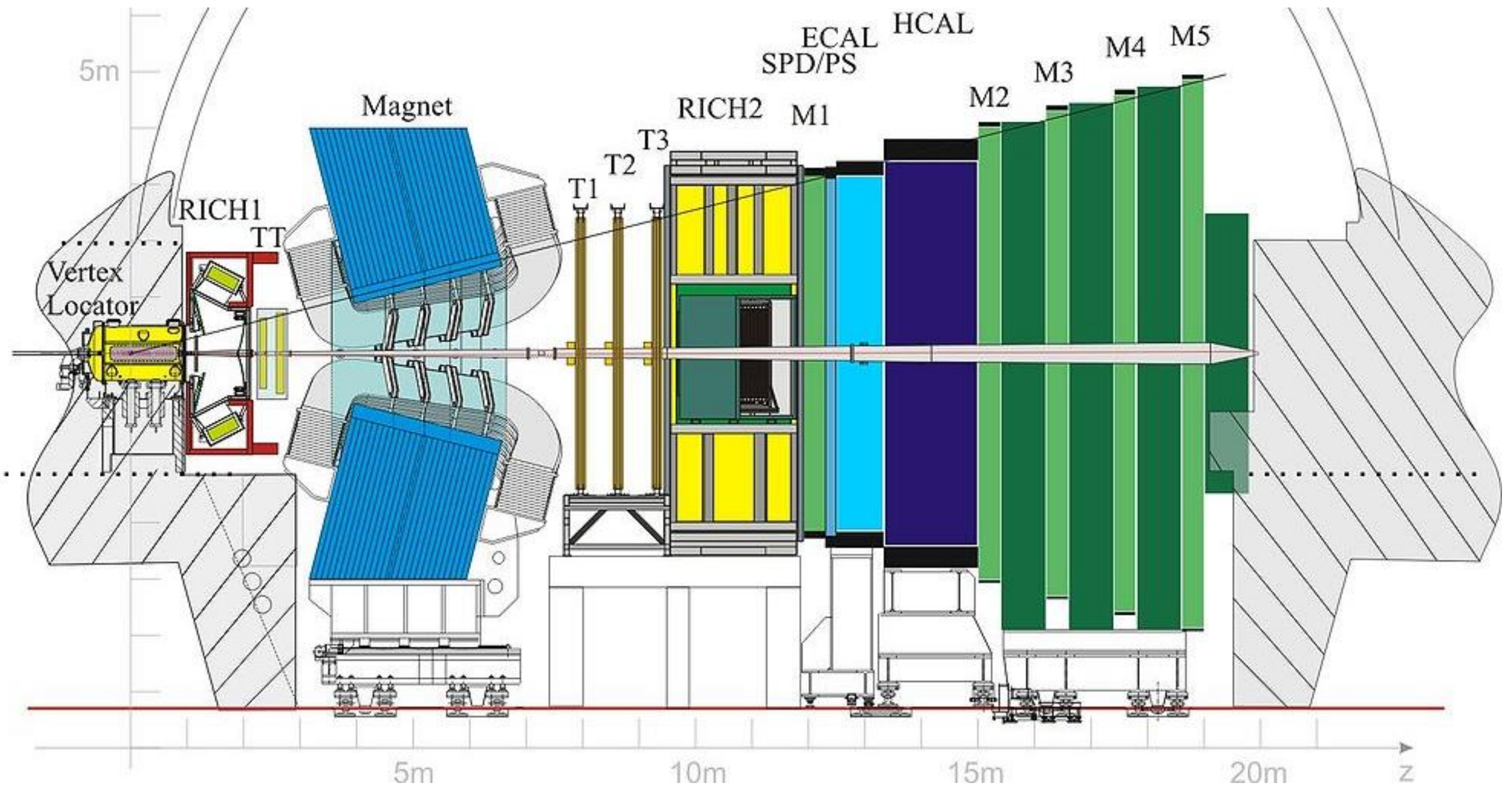
On behalf of the LHCb collaboration

Beauty baryons @ LHCb

- Beauty baryons are produced copiously in LHCb, opening up new avenues for study and improved precision of their properties and decays.
  - Production
  - Mass
  - Lifetime
  - New decay modes
  - CP asymmetries

  - Other studies, for a future BEAUTY meeting…
    - Rare decays, e.g. $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$.
      - 1 fb^{-1} result (PLB 725, 2013) being updated to 3 fb^{-1}.
    - Probe CKM elements V_{cb}, V_{ub} in $\Lambda_b \rightarrow \Lambda_c \ell \nu$ and $\Lambda_b \rightarrow p \ell \nu$ decays
    - Excited b-baryon states
    - bc-baryons

Detector & data sets

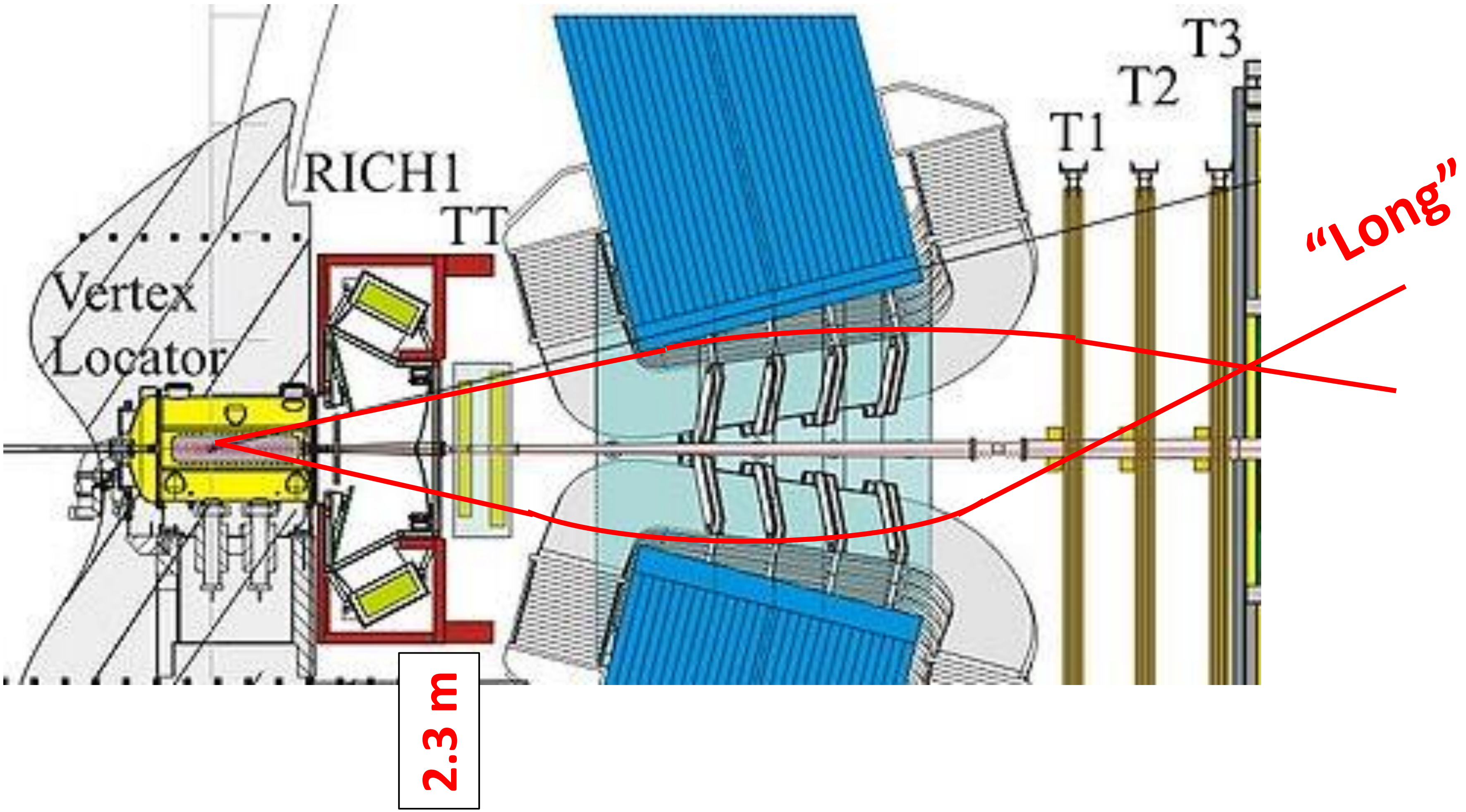


- Precision vertex detector (σ_{ip}~ 20 um), tracking $\sigma_p/p \approx 0.5\%$
- Excellent particle identification, including hadron separation to ~100 GeV
- High bandwidth trigger, ~2-5 kHz to tape, hadronic, EM and muonic final states.
  - Wide & flexible physics scope: b, c, quarkonia, W, Z's, exotics, jets, etc.
- Analyses based on:
  - 2011, 1 fb^{-1} @ 7 TeV
  - 2012, 2 fb^{-1} @ 8 TeV

Menu for this talk

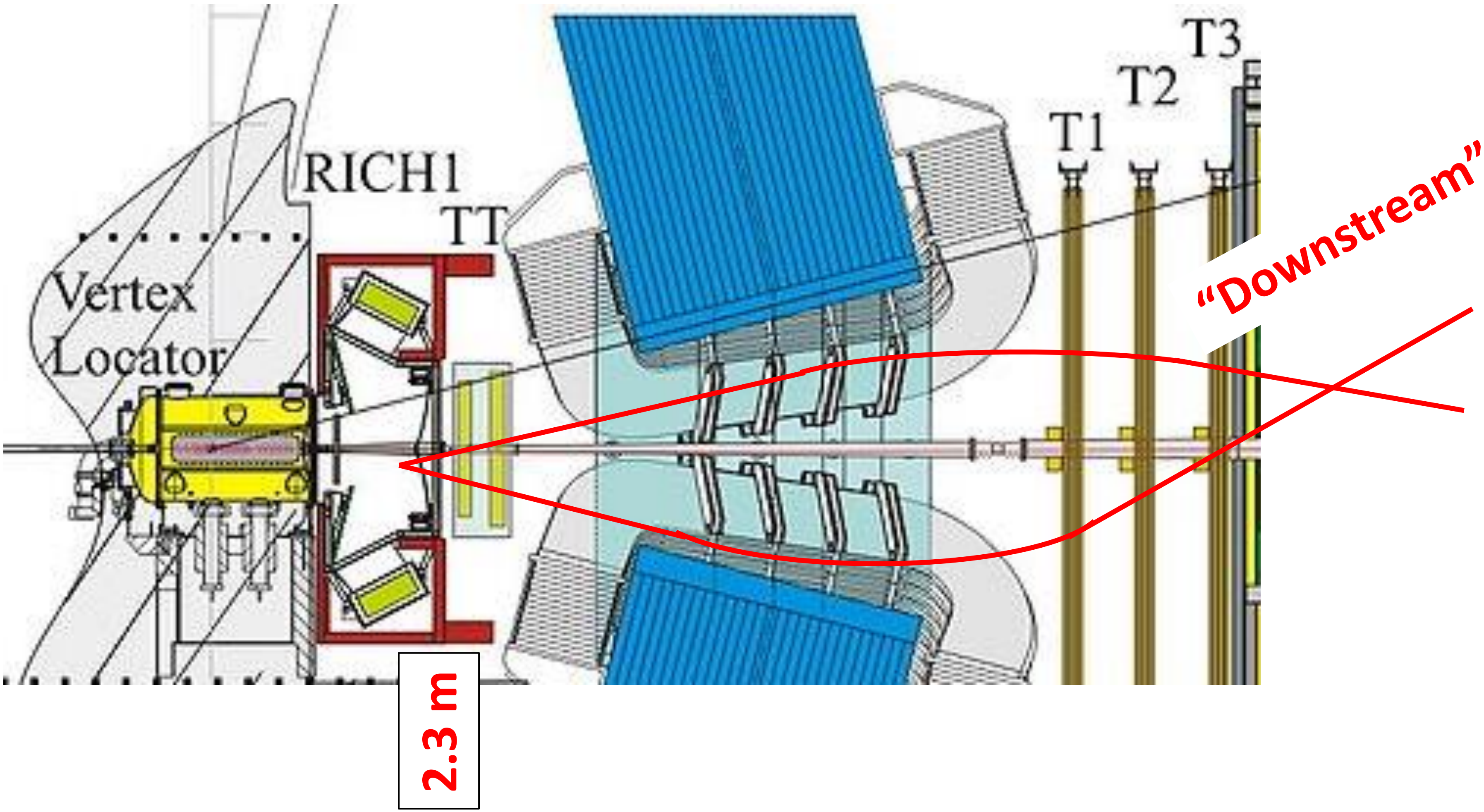
- $B(\Lambda_b \rightarrow \Lambda_c \pi)$ arXiv:1405.6842
- Ξ_b^- and Ω_b^- lifetimes arXiv:1405.1543
- Ξ_b^0 mass, lifetime & production properties arXiv:1405.7223
-
- $\Lambda_b/\Xi_b^0 \rightarrow D^0 p h^\pm$ decays arXiv:1311.4823
- $\Lambda_b \rightarrow J/\psi p K^-$ and $\Lambda_b \rightarrow J/\psi p \pi^-$ arXiv:1406.0755
- Search for $\Lambda_b/\Xi_b^0 \rightarrow K_S p h^\pm$ arXiv:1402.0770
- First observation of $\Lambda_b \rightarrow \Lambda_c^+ D_{(s)}^-$ arXiv:1403.3606

Reconstructing hyperons from b decay



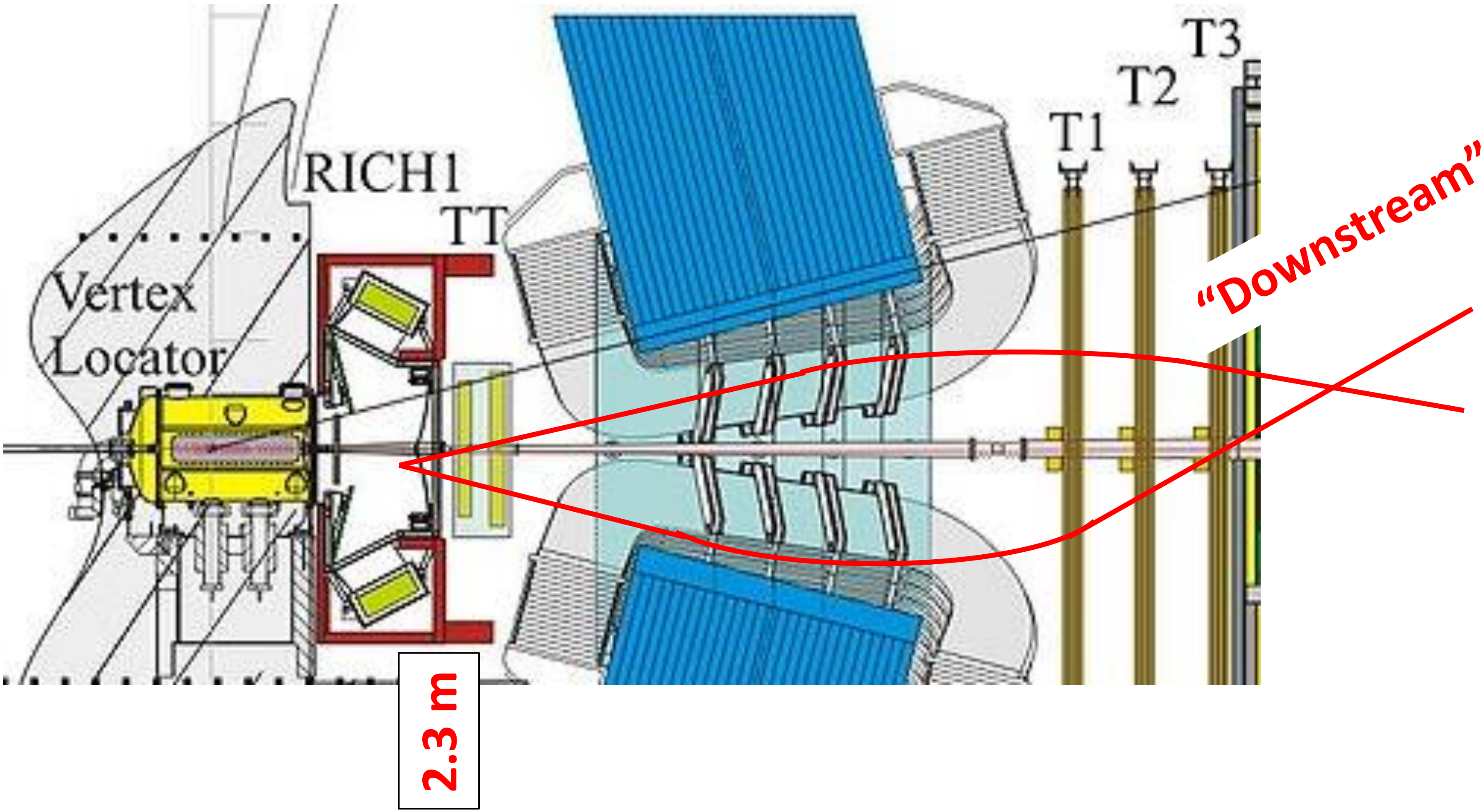
- Average b-momentum in LHCb ~ 100 GeV
  - E.g. $\Lambda_b \rightarrow J/\psi\Lambda$, 30 GeV $\Lambda \rightarrow \gamma\approx30 \rightarrow$ **<d> ≈ 2.5 m**

Reconstructing hyperons from b decay



- Average b-momentum in LHCb ~ 100 GeV
  - E.g. $\Lambda_b \rightarrow J/\psi\Lambda$, 30 GeV $\Lambda \rightarrow \gamma \approx 30 \rightarrow$ **<d> ≈ 2.5 m**
- Hyperons reconstructed if they decay **upstream of TT**.

Reconstructing hyperons from b decay



- Going beyond Λ_b ..
  - Example: $\Xi_b^- \rightarrow J/\psi \Xi^-$, $\Xi^- \rightarrow \Lambda \pi^-$
- Get hit 2X .... $\tau(\Xi^-)$~164 ps, $\tau(\Lambda)$~260 ps

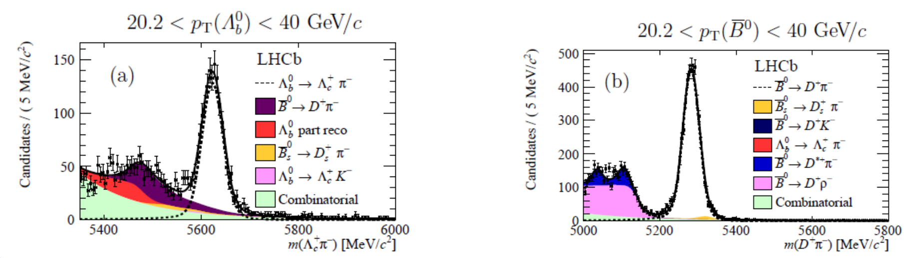
Production, BFs Mass and Lifetimes

$\Lambda_b \rightarrow \Lambda_c\pi$ BF

LHCb-PAPER-2014-004
arXiv:1405.6842
submitted to JHEP
1 fb^{-1}

- **State of affairs, pre-2014**: $B(\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-) = 5.7^{+4.0}_{-2.6} \times 10^{-3}$
  - "Golden mode" for Λ_b decays only known to ≈ 70% precision!

- Use **45,000** fully reco'd $\Lambda_b \rightarrow \Lambda_c\pi^+$ and **106,000** $B^0 \rightarrow D^-\pi^+$ decays.



$\Lambda_b \rightarrow \Lambda_c\pi$ BF

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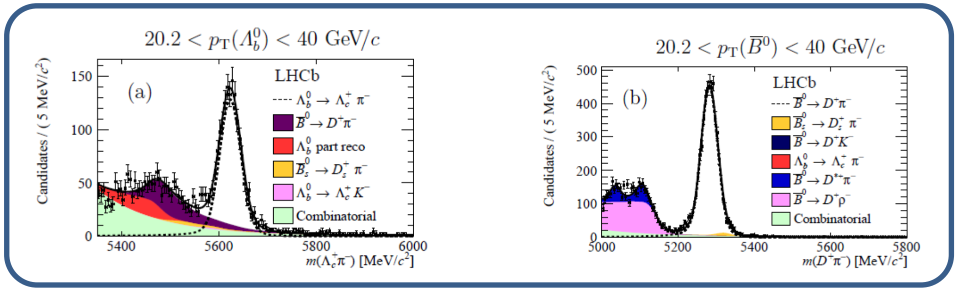
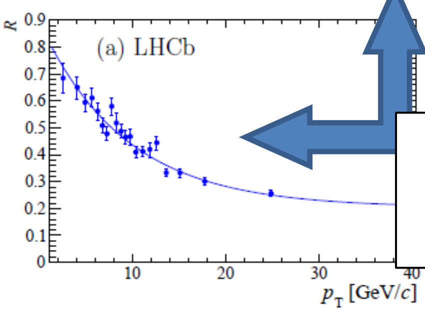


- **Anatomy:**

$$\frac{N^{\mathbf{cor}}_{\Lambda_b^0\rightarrow\Lambda_c^+\pi^-}(p_T)}{N^{\mathbf{cor}}_{\bar{B}^0\rightarrow D^+\pi^-}(p_T)} = \frac{\mathbf{B}(\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-)}{\mathbf{B}(\bar{B}^0 \rightarrow D^+\pi^-)} \cdot \frac{\mathbf{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)}{\mathbf{B}(D^+ \rightarrow K^-\pi^+\pi^+)} \cdot \frac{f_{\Lambda_b}}{f_d}(p_T)$$

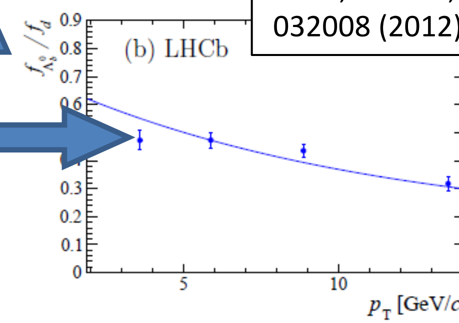


Measured here, in $\Lambda_b \rightarrow \Lambda_c\pi$ decays

Scale factor between the two analyses

Measured in semileptonic analysis

LHCb, PRD 85, 032008 (2012)



$\Lambda_b \rightarrow \Lambda_c \pi$ BF

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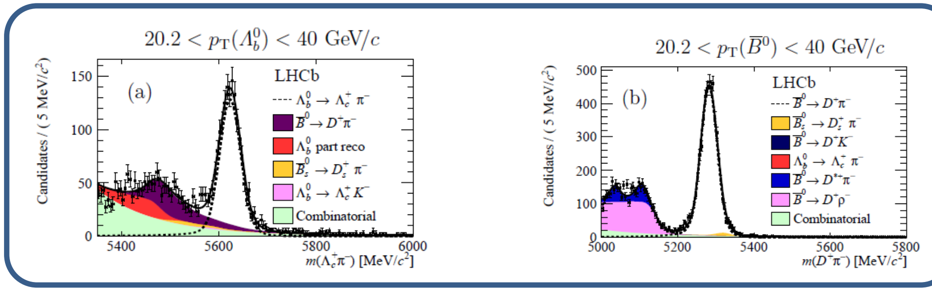

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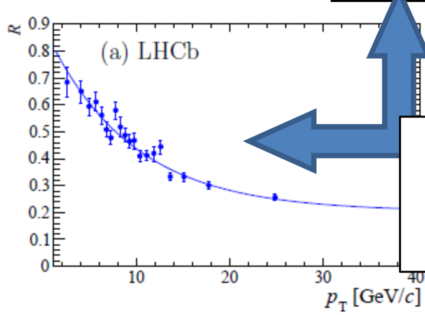

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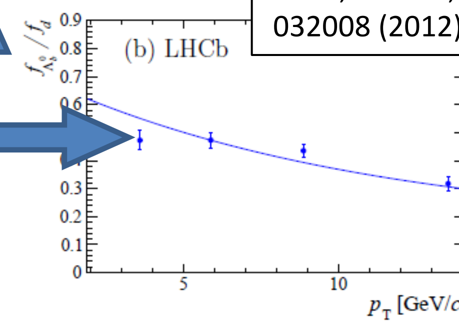


- **$B(\Lambda_c \rightarrow pK\pi)$ common to both analyses → cancelation of large syst. error**

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-) = \left(4.30 \pm 0.03 \; ^{+0.12}_{-0.11} \pm 0.26 \pm 0.21\right) \times 10^{-3}$$

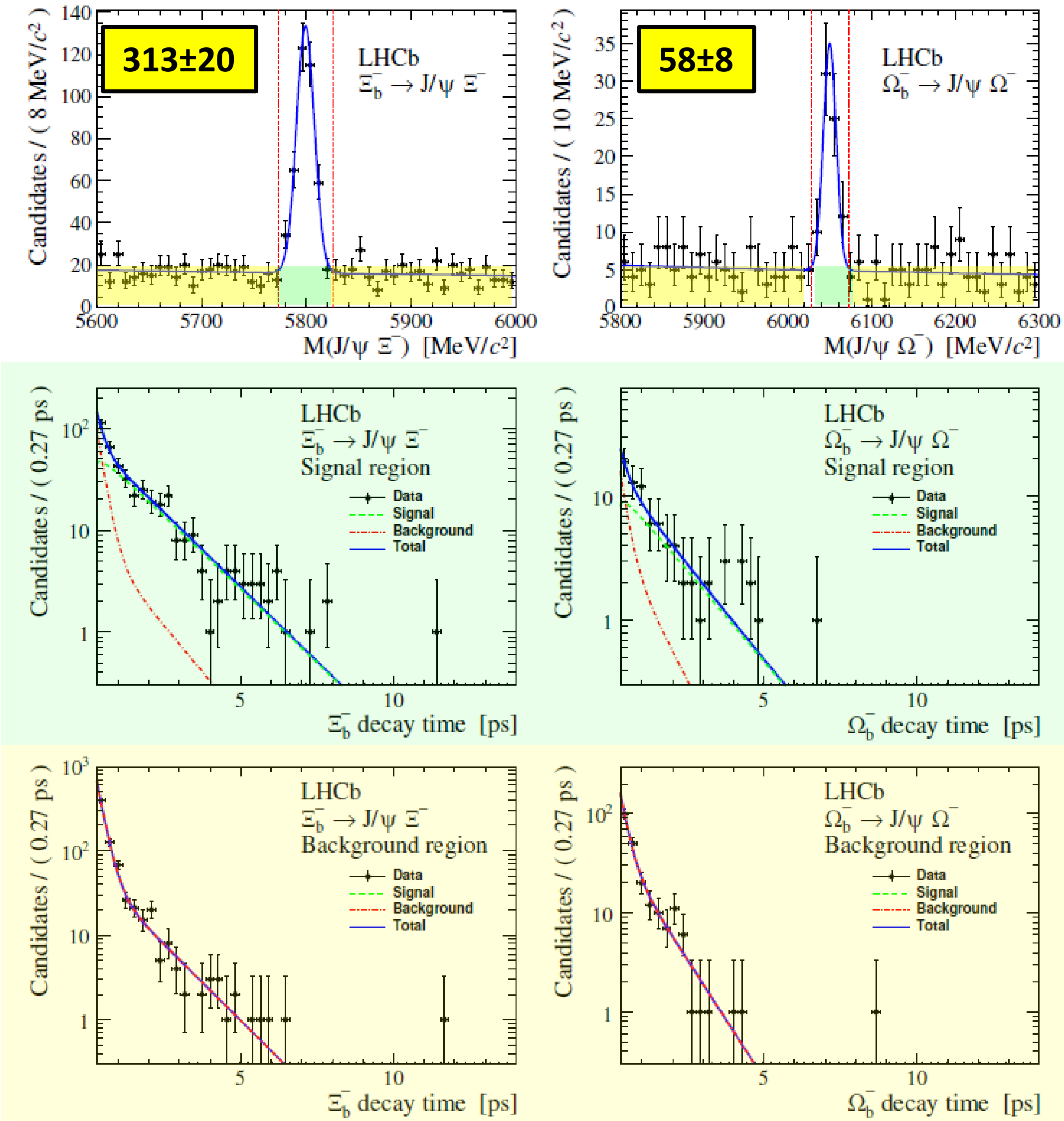
BF measured to 8% precision! Huge leap forward in precision!

Ξ_b^- and Ω_b^- lifetimes

LHCb-PAPER-2014-010
arXiv:1405.1543
submitted to PLB

3 fb^{-1}

- Reconstruct $\Xi_b^- \to J/\psi\Xi^-$, $\Xi^- \to \Lambda\pi^-$ and $\Omega_b^- \to J/\psi\Omega^-$, $\Omega^- \to \Lambda K^-$, with $\Lambda \to p\pi^-$.



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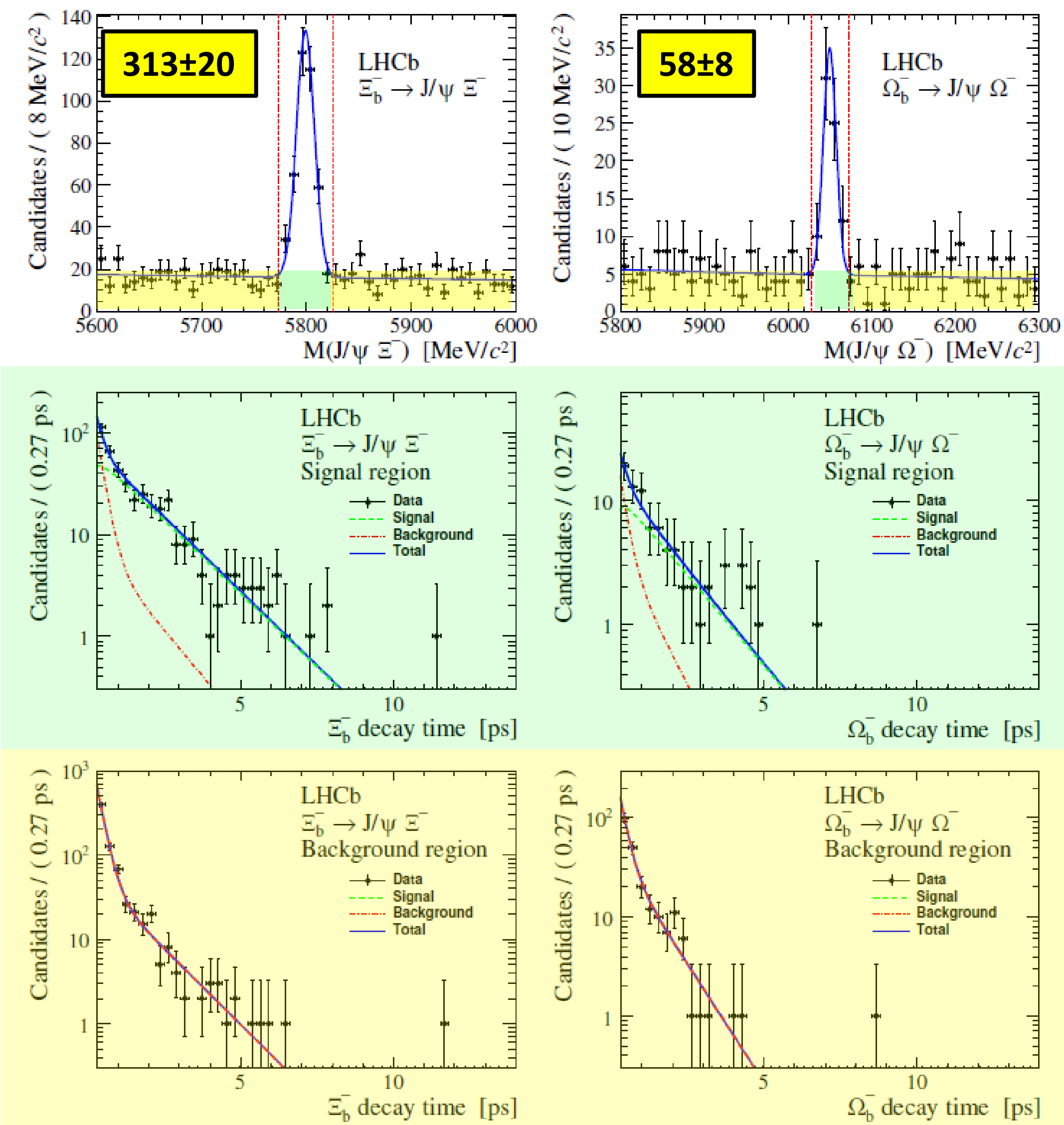

$$\tau(\Xi_b^-) = 1.55^{+0.10}_{-0.09} \pm 0.03 \text{ ps}$$
$$\tau(\Omega_b^-) = 1.54^{+0.26}_{-0.21} \pm 0.05 \text{ ps}$$

Source	$\Xi_b^- \to J/\psi\,\Xi^-$	$\Omega_b^- \to J/\psi\,\Omega^-$
Trigger efficiency	9.9	6.5
Reconstruction and selection efficiency	29.0	45.0
Signal modelling	5.9	11.4
Combinatorial background modelling	3.0	3.0
Cross-feed background	0.1	11.1
Detector length scale	0.3	0.3
Total	31.4	48.3

- ❑ Best precision to date.
- ❑ Consistent with the recent CDF results

CDF, PRD 89, 072014 (2014)

$$\tau(\Xi_b^-) = 1.32 \pm 0.14 \pm 0.02 \text{ ps}$$
$$\tau(\Omega_b^-) = 1.66\ ^{+0.53}_{-0.40} \pm 0.02 \text{ ps}$$

(See talk by J. Rosner)

Studies of the Ξ_b^0 baryon - 1

LHCb-PAPER-2014-021
arXiv:1405.7223
Accepted in PRL

3 fb^{-1}

- **Until recently, little known about the Ξ_b^0 baryon.**
  - Lifetime unmeasured
  - Mass only known to ~2.5 MeV (Λ_b mass known to ~0.3 MeV)
  - Relative production rates ? Are prod. properties (p_T, η) similar to Λ_b ?

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- **In Ξ_b, Ω_b studies, decays with J/ψ+hyperons have been 'the work horse'.**
  - Use CF decays, J/ψ for triggering, well-displaced vertices from hyperons with narrow widths. **Hadron ID helpful, but not crucial**.
  - In LHCb, large boosts, large $c\tau$ leads to a reduction in total efficiency for hyperon reco.

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- **To play into LHCb's strengths, use Cabibbo-suppressed decays … no hyperons!**

$$\Xi_b^0 \xrightarrow{\text{CF}} \Xi_c^+ \pi^-, \quad \Xi_c^+ \xrightarrow{\text{CS}} pK^-\pi^+ \qquad \frac{B(\Xi_c^+ \to pK^-\pi^+)}{B(\Xi_c^+ \to \Xi^-\pi^+\pi^+)B(\Xi^- \to \Lambda\pi^-)B(\Lambda \to p\pi^-)} \sim 0.34$$

- **Despite 3 X lower BF, still win big in total acceptance.**

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- **Despite 3 X lower BF, still win big in total acceptance.**
- **Excellent normalization mode (identical final state): $\Lambda_b \to \Lambda_c\pi$, $\Lambda_c \to pK\pi$!**
  - **Most systematics cancel at 1st order in relative measurements.**
  - **Small differences in momentum spectra and lifetime of Ξ_c vs $\Lambda_c \to pK\pi$**

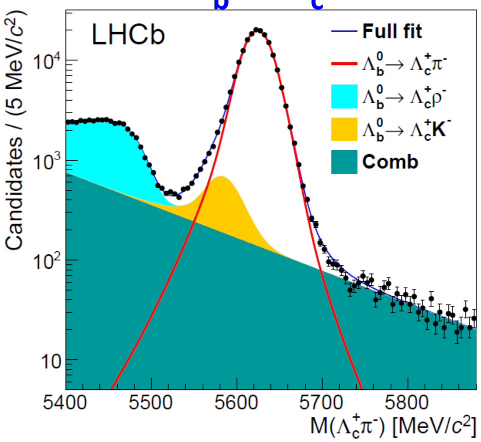
Studies of the Ξ_b^0 baryon - 2

LHCb-PAPER-2014-021
arXiv:1405.7223
Accepted in PRL

3 fb^{-1}

❑ Precision mass

$\Lambda_b \rightarrow \Lambda_c^+ \pi^-$



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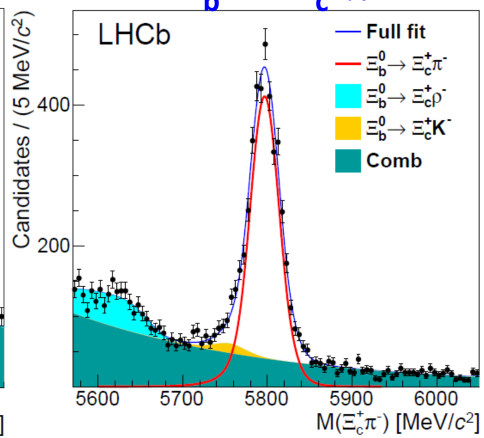

~188,000 $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$
~3,800 $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$

Mass of Ξ_b^0 ~5X more precise than prev. best from LHCb

$$\Delta M(\Xi_b^0 - \Lambda_b^0) = 172.44 \pm 0.39 \pm 0.17 \text{ MeV}$$

$$M(\Xi_b^0) = 5791.80 \pm 0.39 \pm 0.17 \pm 0.26_{\Lambda_b^0} \text{ MeV}$$

Studies of the Ξ_b^0 baryon - 2

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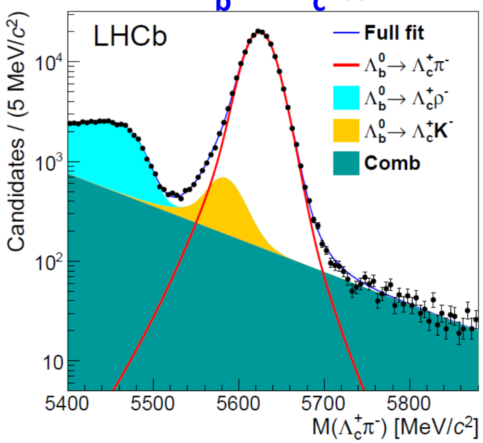

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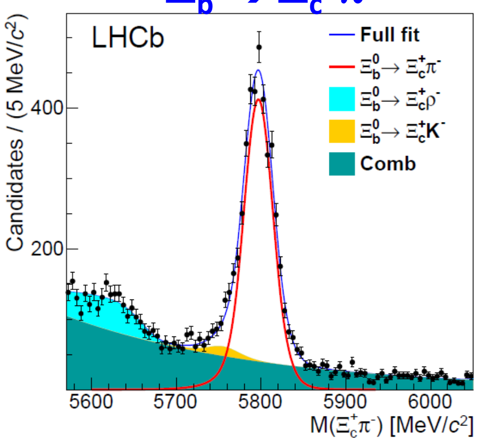

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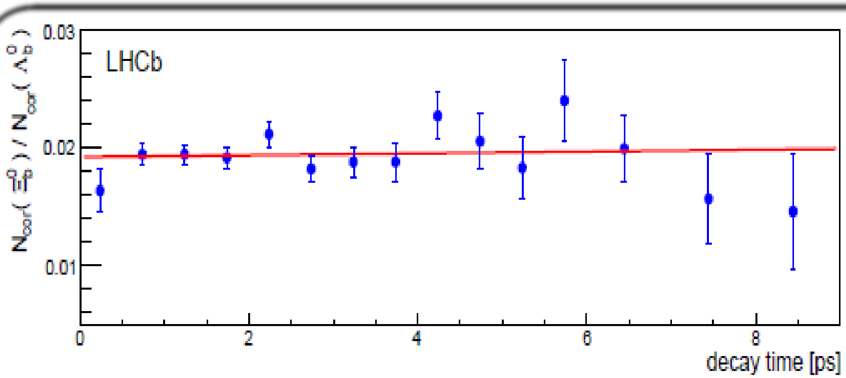
❑ Lifetime of Ξ_b^0 baryon measured relative to that of Λ_b.

- ❑ Λ_b lifetime now known to high precision (see talk by P. Gandini)
- ❑ Perform sim. fit in bins of decay time, correct by relative efficiency (from simulation)



$$\frac{N_{cor}(\Xi_b^0)}{N_{cor}(\Lambda_b^0)} \propto e^{\beta t} \qquad \beta = \frac{1}{\tau_{\Lambda_b^0}} - \frac{1}{\tau_{\Xi_b^0}}$$

1st measurement of Ξ_b^0 lifetime

$$\tau(\Xi_b^0)/\tau(\Lambda_b^0) = 1.006 \pm 0.018 \pm 0.010$$

$$\tau(\Xi_b^0) = 1.477 \pm 0.026 \pm 0.014 \pm 0.013_{\Lambda_b^0} \text{ ps}$$

- ❑ **Λ_b and Ξ_b^0 lifetimes equal to within 2%**
- ❑ **Consistent with expectations from HQE**

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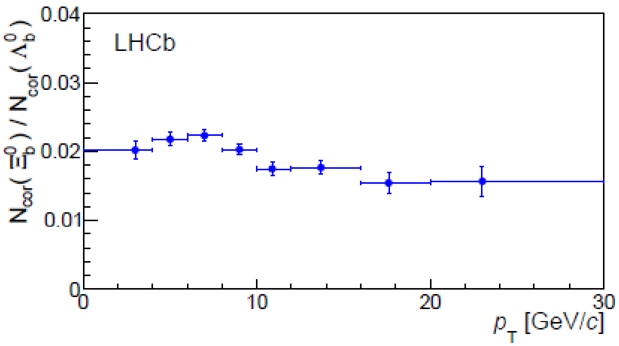
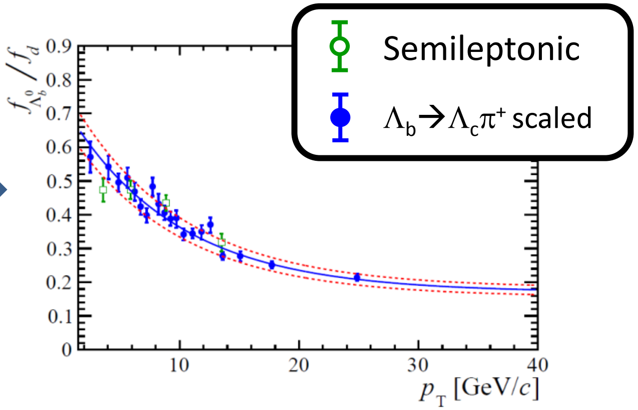
Studies of the Ξ_b^0 baryon - 3

3 fb^{-1}

- **Can also study the relative production rate vs (p_T, η)**



Steep p_T dependence of Λ_b/B^0 production also in Ξ_b^0!
(see talk by Maria Zangoli)



- **Relative production rate, integrated.**

$$\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \cdot \underbrace{\frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)}}_{\approx 1} \cdot \underbrace{\frac{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}}_{\approx 0.1} = (1.88 \pm 0.04 \pm 0.03) \times 10^{-2}.$$

Consistent with $f_{\Xi_b^0} / f_{\Lambda_b^0} \approx 0.2$ with above assumptions

Studies of the Ξ_b^0 baryon - 3

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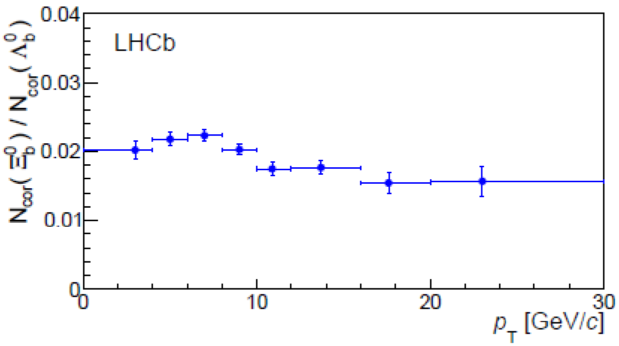

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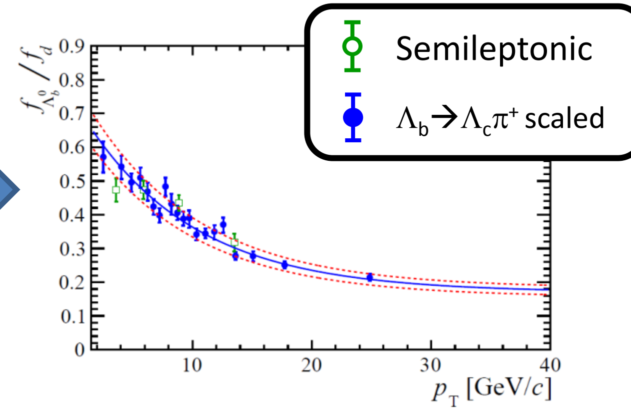

- Relative production rate, integrated.

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≈1 ≈0.1

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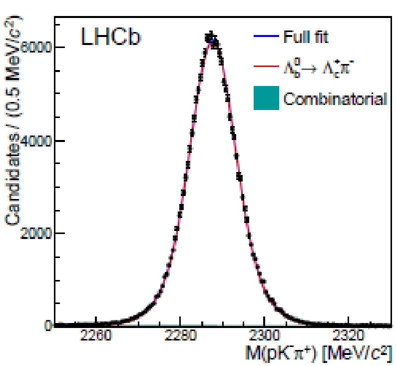
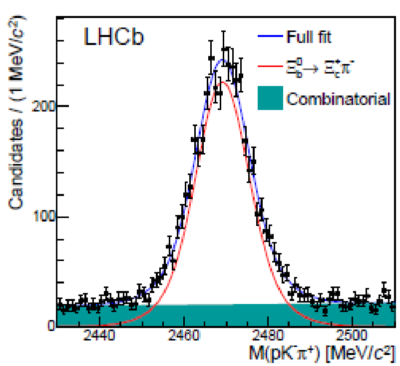
- We also have a VERY CLEAN sample of Ξ_c^+ decays





Mass of Ξ_c^+ ≈4X more precise than WA

$$\Delta M(\Xi_c^+ - \Lambda_c^+) = 181.51 \pm 0.14 \pm 0.10 \text{ MeV}$$

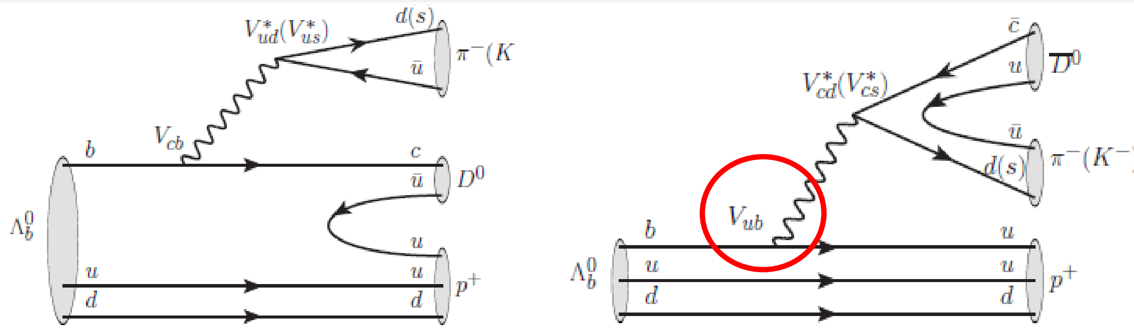
$$M(\Xi_c^+) = 2467.97 \pm 0.14 \pm 0.10 \pm 0.14_{\Lambda_c^+} \text{ MeV}$$

New decay modes & CPV studies

$\Lambda_b/\Xi_b^0 \rightarrow D^0ph^\pm$

LHCb-PAPER-2013-056
arXiv:1311.4823
PRD 89, 032001 (2014)
1 fb^{-1}

- **The $\Lambda_b \rightarrow D^0pK$ decay can be used to measure the weak phase γ, ala $B^0 \rightarrow D^0K^{*0}$.**



Usual trick..

- Both diagrams are $O(\lambda^3)$
- Exploit interference for final states common to $\overline{D}^0$ and D^0.

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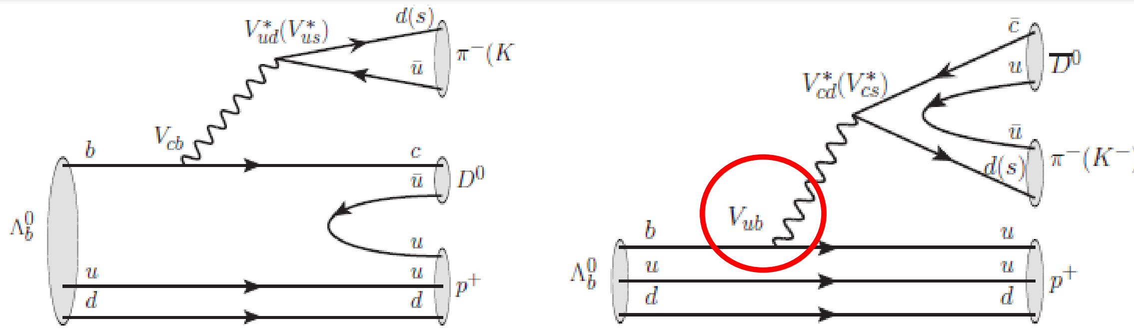
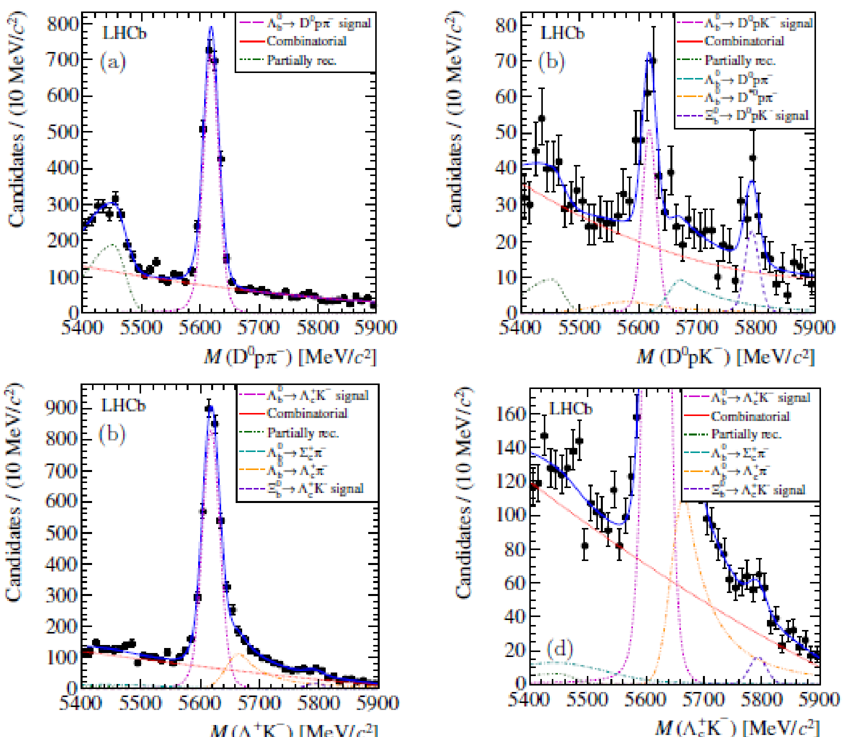


Usual trick..

- Both diagrams are $O(\lambda^3)$
- Exploit interference for final states common to $\overline{D}^0$ and D^0.

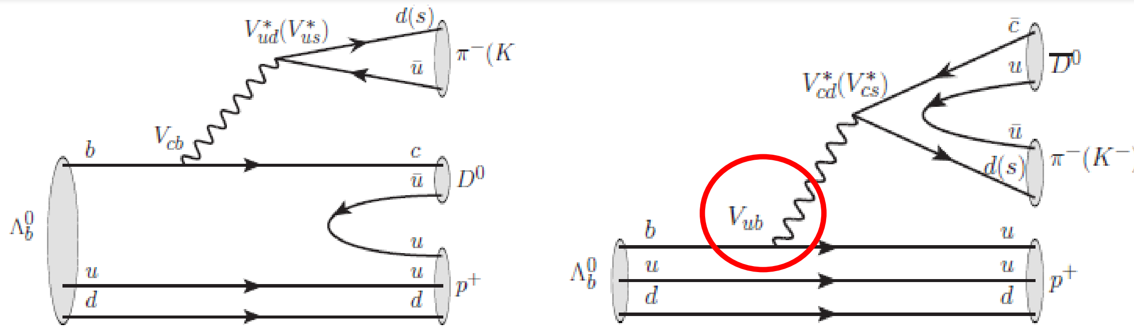
- Start with CF $D^0 \rightarrow K\pi$ decay, to first observe these decays.



$\Lambda_b/\Xi_b^0 \to D^0ph^\pm$

LHCb-PAPER-2013-056
arXiv:1311.4823
PRD 89, 032001 (2014)
1 fb^{-1}

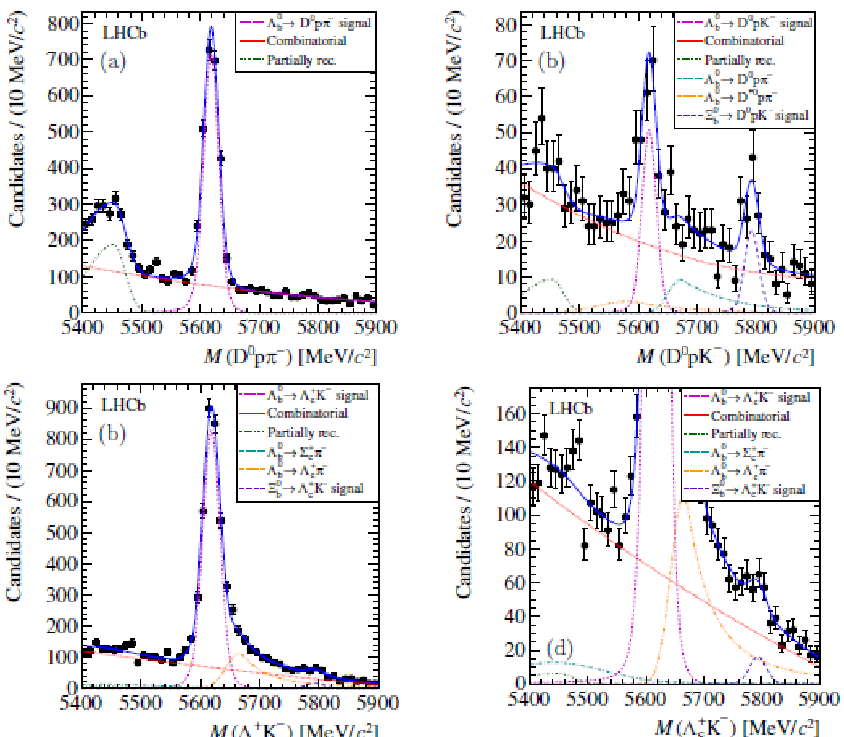
- **The $\Lambda_b \to D^0pK$ decay can be used to measure the weak phase γ, ala $B^0 \to D^0K^{*0}$.**



Usual trick..

- Both diagrams are $O(\lambda^3)$
- Exploit interference for final states common to $\overline{D}^0$ and D^0.

- **Start with CF $D^0 \to K\pi$ decay, to first observe these decays.**



- **Several first observations in Λ_b and Ξ_b^0 decays!**

$$R_{\Lambda_b^0\to D^0p\pi^-} \equiv \frac{\mathcal{B}(\Lambda_b^0\to D^0p\pi^-)\times\mathcal{B}(D^0\to K^-\pi^+)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\pi^-)\times\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)} = 0.0806\pm0.0023\pm0.0035,$$

$$R_{\Lambda_b^0\to D^0pK^-} \equiv \frac{\mathcal{B}(\Lambda_b^0\to D^0pK^-)}{\mathcal{B}(\Lambda_b^0\to D^0p\pi^-)} = 0.073\pm0.008\,^{+0.005}_{-0.006},$$

$$R_{\Lambda_b^0\to\Lambda_c^+K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+K^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\pi^-)} = 0.0731\pm0.0016\pm0.0016,$$

$$R_{\Xi_b^0\to D^0pK^-} \equiv \frac{f_{\Xi_b^0}\times\mathcal{B}(\Xi_b^0\to D^0pK^-)}{f_{\Lambda_b^0}\times\mathcal{B}(\Lambda_b^0\to D^0pK^-)} = 0.44\pm0.09\pm0.06,$$

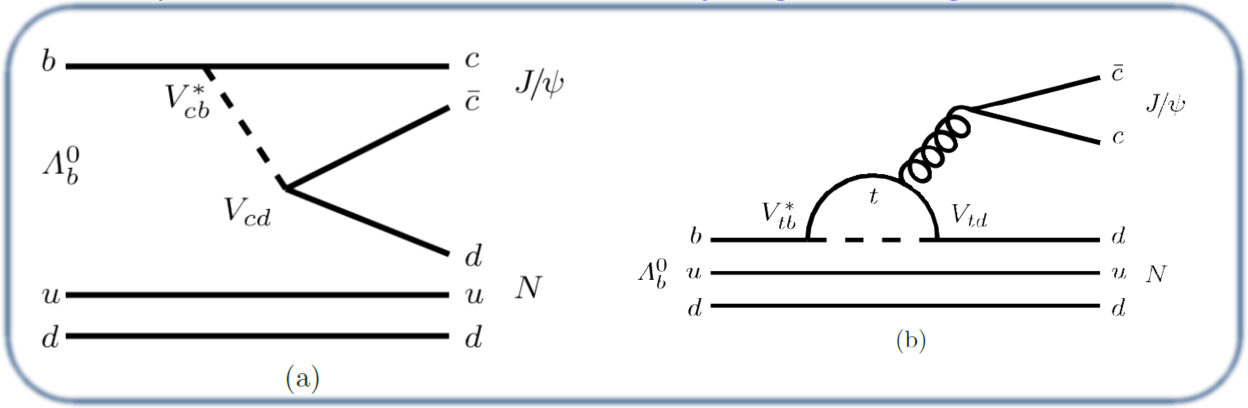
$$R_{\Xi_b^0\to\Lambda_c^+K^-} \equiv \frac{\mathcal{B}(\Xi_b^0\to\Lambda_c^+K^-)\times\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)}{\mathcal{B}(\Xi_b^0\to D^0pK^-)\times\mathcal{B}(D^0\to K^-\pi^+)} = 0.57\pm0.22\pm0.21,$$

- **Good prospects for γ with larger data set**

$\Lambda_b \rightarrow J/\psi p K^-$ and $\Lambda_b \rightarrow J/\psi p \pi^-$

LHCb-PAPER-2014-020
arXiv:1406.0755 |
Submitted to JHEP
3 fb^{-1}

- **CP violation not yet observed in the baryon sector.**
- The decay $\Lambda_b \rightarrow J/\psi pK$ recently observed by LHCb → most precise $\tau(\Lambda_b)$ (see P. Gandini talk).
- The CS decay, **$\Lambda_b \rightarrow J/\psi p \pi^-$,** unobserved prior to this analysis, has 2 amplitudes, tree & penguin with different weak phase → **NP can enter in the penguin and give rise to direct CPV**.



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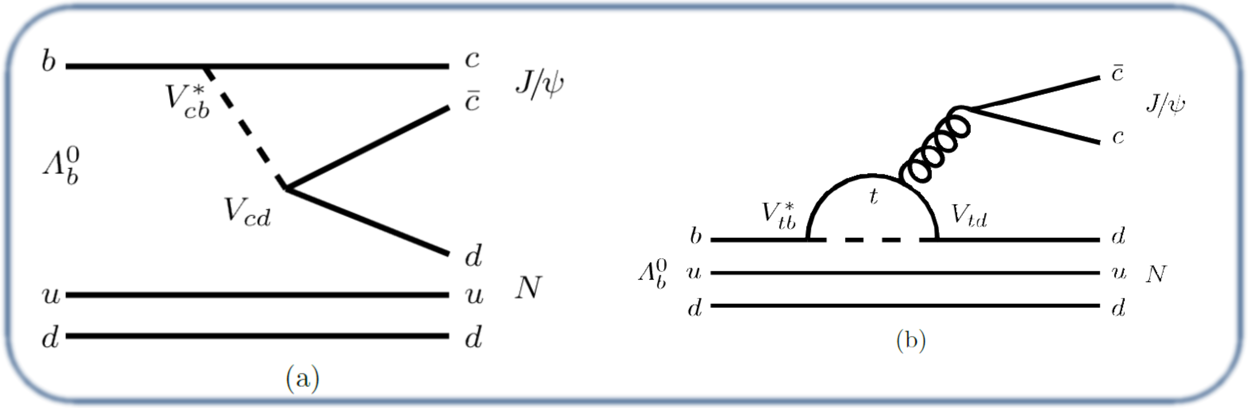
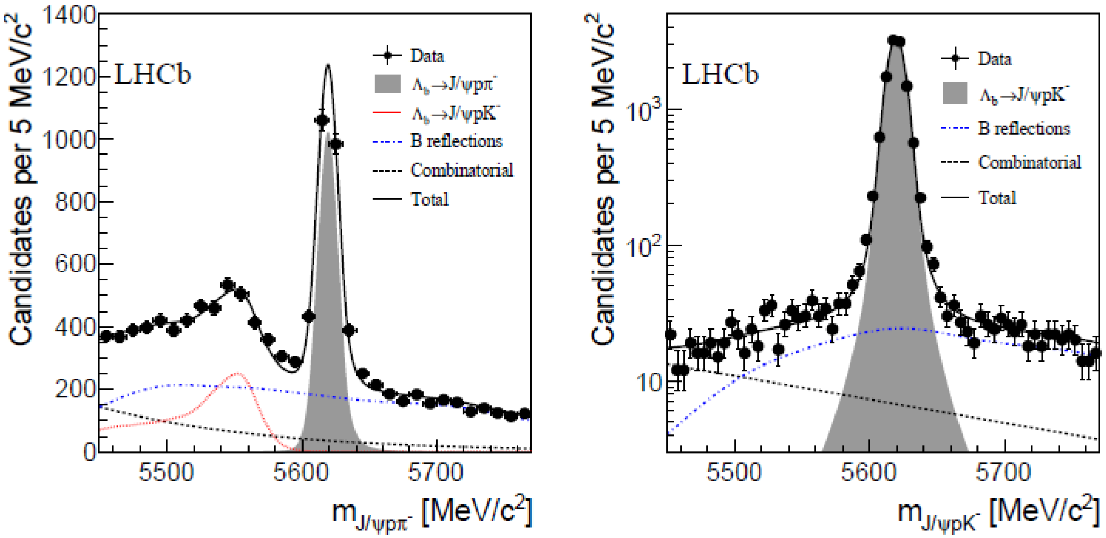




- First observation of $\Lambda_b \to J/\psi p\pi^-$

$$\frac{B(\Lambda^0_b \to J/\psi\, p\pi^-)}{B(\Lambda^0_b \to J/\psi\, pK^-)} = (8.24 \pm 0.25 \pm 0.42)\%$$

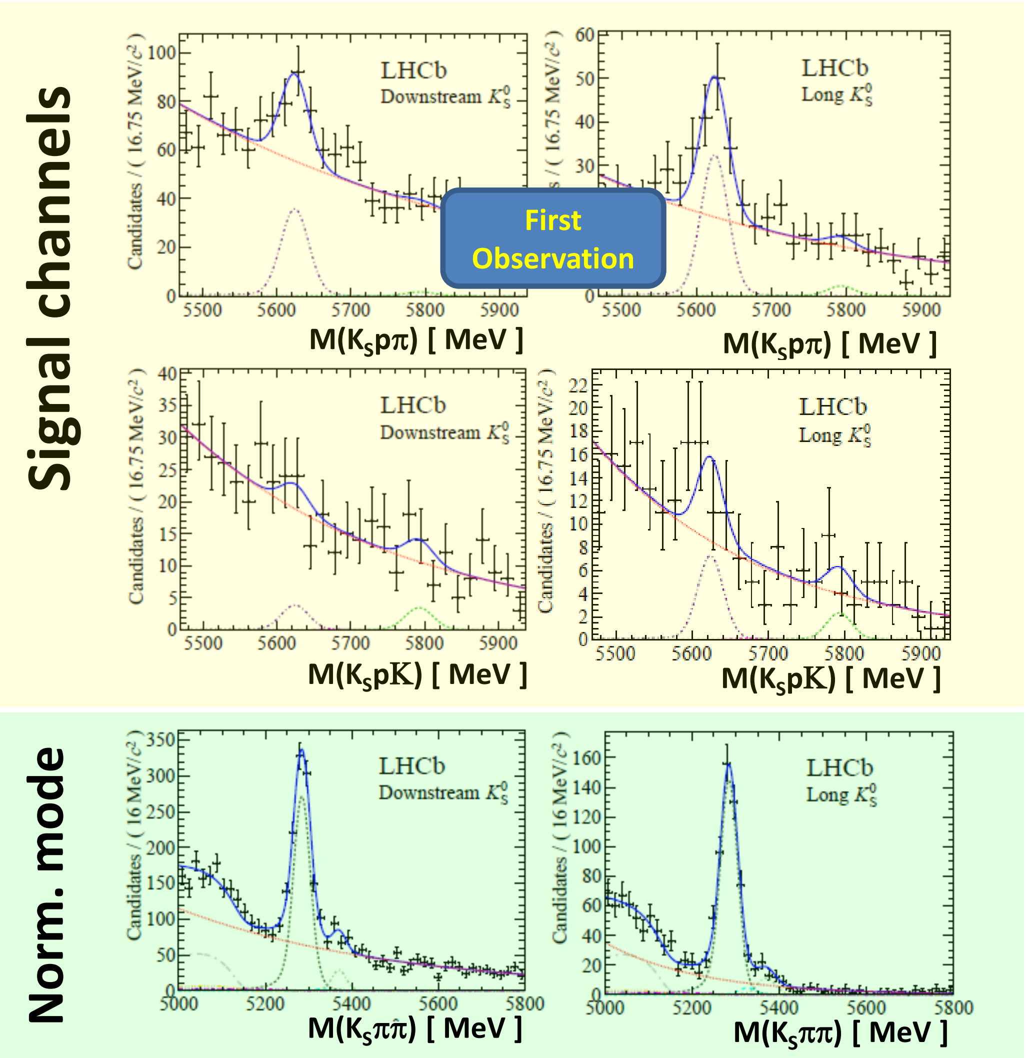
- Direct CPV wrt favored mode ($|P/T|_{SM} \ll 1$)

$$\Delta \mathbf{A}_{CP} \equiv \mathbf{A}(\Lambda^0_b \to J/\psi\, p\pi^-) - \mathbf{A}(\Lambda^0_b \to J/\psi\, pK^-) = (5.7 \pm 2.3 \pm 1.2)\%$$

Charmless: Search for $\Lambda_b/\Xi_b^0 \rightarrow K_S p h^{\pm}$

LHCb-PAPER-2013-061
arXiv:1402.0770
JHEP 04 (2014) 087
1 fb^{-1}

- Prior to this analysis, **no 3-body charmless decays of b-baryons had been observed**.
  Like B decays, 3-body charmless b-baryon decays contains penguin contributions → **NP can enter**.
- Opens up an interesting window to explore CPV in the b-baryon sector across the Dalitz plot.
- BFs normalized to the kinematically similar $B^0 \rightarrow K_S \pi^+ \pi^-$ decay.



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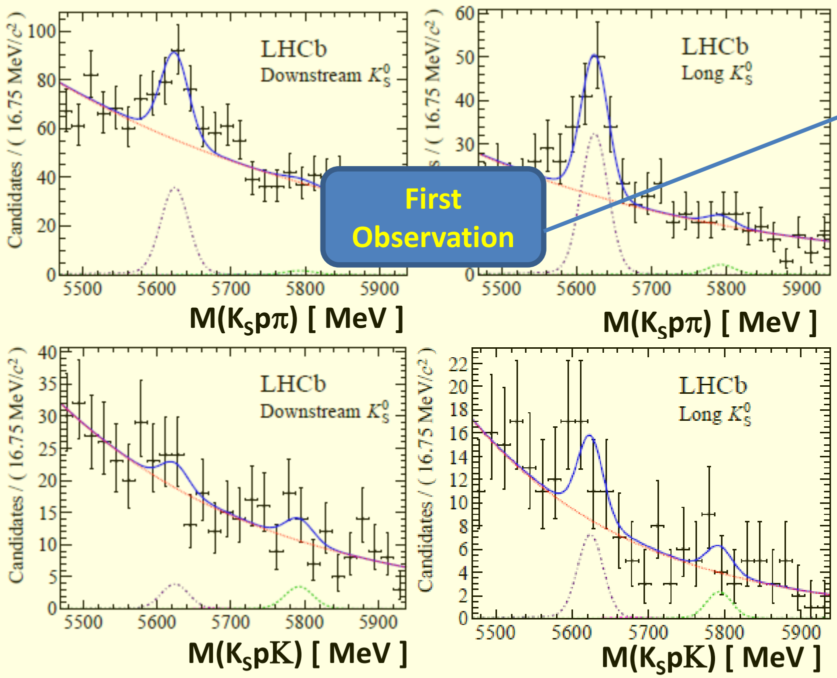
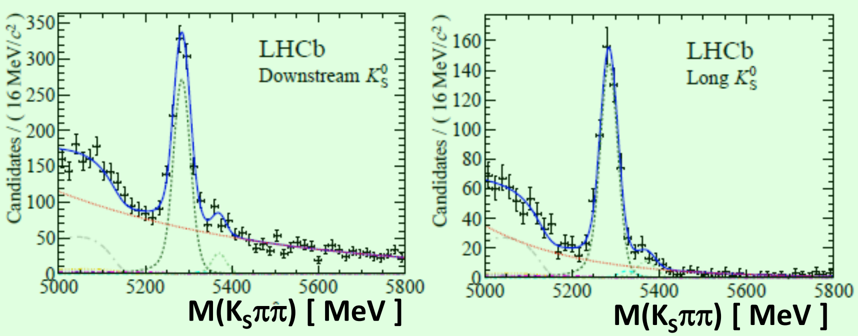
Signal channels



Norm. mode



$$\frac{B(\Lambda_b^0 \to K_S^0 p\pi^-)}{B(B^0 \to K_S^0\pi^+\pi^-)} = 0.25 \pm 0.04 \pm 0.02 \pm 0.02_{f_{\Lambda_b}/f_d}$$

$$\frac{B(\Lambda_b^0 \to K_S^0 pK^-)}{B(B^0 \to K_S^0\pi^+\pi^-)} < 0.07 \quad \text{@90\% CL}$$

$$\frac{f_{\Xi_b^0}}{f_d}\frac{B(\Xi_b^0 \to K_S^0 p\pi^-)}{B(B^0 \to K_S^0\pi^+\pi^-)} < 0.03 \quad \text{@90\% CL}$$

$$\frac{f_{\Xi_b^0}}{f_d}\frac{B(\Xi_b^0 \to K_S^0 pK^-)}{B(B^0 \to K_S^0\pi^+\pi^-)} < 0.02 \quad \text{@90\% CL}$$

See paper for additional Λ_b BFs

- ❑ Measure direct CPV relative to CF mode $\Lambda_b \to \Lambda_c(pK_S)\pi^-$ (penguins should be negligible)

$$\Delta\mathbf{A}_{CP} \equiv \mathbf{A}(\Lambda_b^0 \to K_S^0 p\pi^-) - \mathbf{A}(\Lambda_b^0 \to \Lambda_c^+(K_S^0 p)\pi^-)$$
$$= 0.22 \pm 0.13 \pm 0.03$$

Consistent with zero.

$\Lambda_b \rightarrow \Lambda_c^+ D_{(s)}^-$

LHCb-PAPER-2014-002
arXiv:1403.3606
PRL 112, 202001 (2014)
3 fb^{-1}

- **First observation of b-baryons decaying to double-charm final states**

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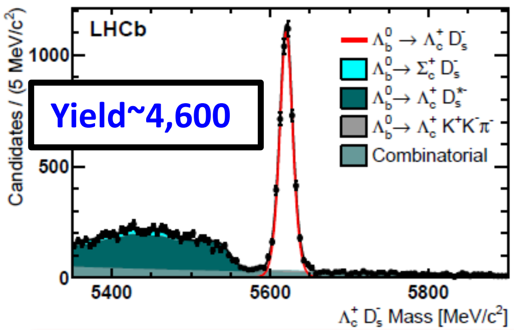

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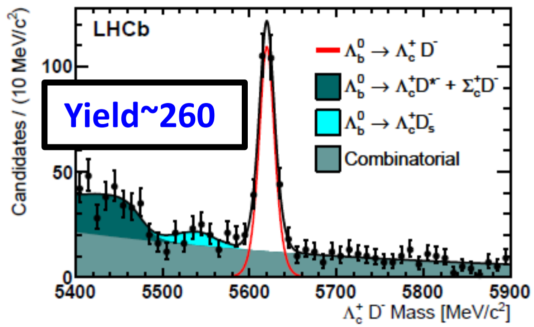

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D^-)/\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-) = 0.042 \pm 0.003\,(\mathrm{stat}) \pm 0.003\,(\mathrm{syst})$$

Consistent with expected Cabibbo suppression

Bonus: Get most precise Λ_b mass measurement from measured mass difference $M(\Lambda_b) - M(B^0)$:

$$M(\Lambda_b^0) = 5619.30 \pm 0.34\,\mathrm{MeV}/c^2,$$

LHCb-PAPER-2014-002
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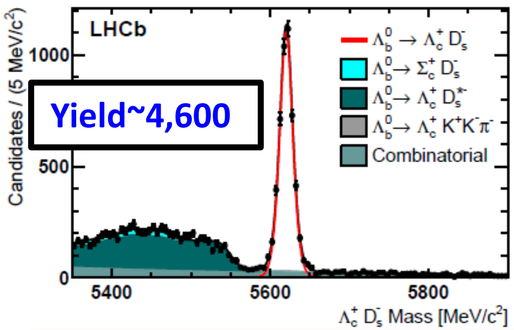

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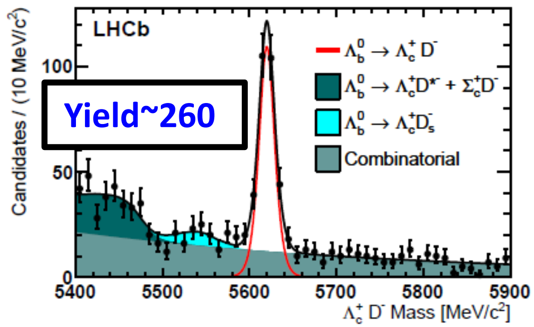

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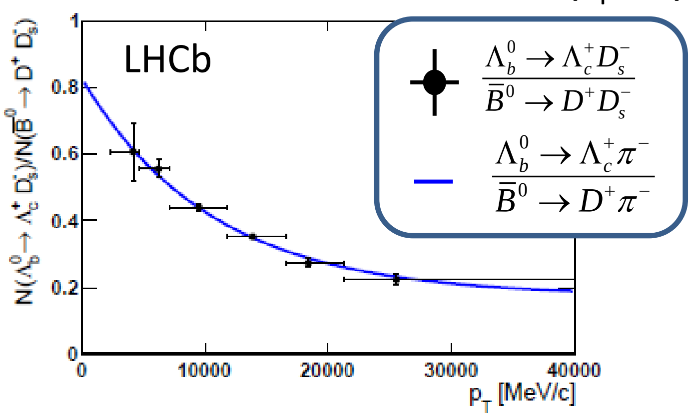
- **$B(\Lambda_b \rightarrow \Lambda_c D_s)$:** Normalize to $B(B^0 \rightarrow D^- D_s^+)$, **but** relative yield strong function of p_T.
- Measure double ratio, same p_T dependence, which cancels in ratio.



Several world best BF measurements

$$\begin{aligned}
\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-) &= (1.1 \pm 0.1) \times 10^{-2}, \\
\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D^-) &= (4.7 \pm 0.6) \times 10^{-4}, \\
\mathcal{B}(B_s^0 \to D^+ D_s^-) &= (2.7 \pm 0.5) \times 10^{-4}, \\
\mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \Lambda_c^-) &< 1.6 \times 10^{-5}\ [95\%\ \text{C.L.}], \\
\mathcal{B}(B_s^0 \to \Lambda_c^+ \Lambda_c^-) &< 8.0 \times 10^{-5}\ [95\%\ \text{C.L.}].
\end{aligned}$$

$$\left[\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}{\mathcal{B}(\overline{B}^0 \to D^+ D_s^-)}\right] \Big/ \left[\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)}{\mathcal{B}(\overline{B}^0 \to D^+ \pi^-)}\right] = 0.96 \pm 0.02\,(\text{stat}) \pm 0.06\,(\text{syst}),$$

Summary

- b-baryon rate at LHCb very large, **1 Λ_b for every 2 B^0**!
- Production, decays, b-baryon properties and CPV are beginning to be probed.
  - Lifetime of Ξ_b^0 went from unmeasured → 2% precision ($\tau(\Lambda_b)$ known to ~1%)
  - Mass of Ξ_b^0 went from ±2.5 MeV → ~0.4 MeV, almost on par with Λ_b!
- Other high yield modes of b-baryons are also being explored that exploit the excellent PID in LHCb.
- Expect more on rare decays, V_{cb}, V_{ub}, excited baryonic states soon..

The future is bright for b-baryon studies @ LHCb.