Baryon Spectroscopy at LHCb

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on behalf of the LHCb collaboration

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1. **INTRODUCTION**
   - LHCb
   - Data collection

2. **Λ^0_b PRODUCTION**
   - Λ^0_b cross-sections
   - Λ^0_b-Λ̅^0_b asymmetry
   - Absolute branching fraction of Λ^0_b → J/ψ pK^−

3. **Beauty Baryon Spectroscopy**
   - Excited Λ^0_b baryons
   - Ξ^0_b baryon spectroscopy
   - Ξ^−_b baryon spectroscopy

4. **SUMMARY**
LHCb at LHC

Overall view of the LHC experiments.
LHCb: a single-arm forward spectrometer at the LHC,

- Optimized for heavy flavor physics with LHC proton-proton collisions,
- Large production cross-sections for heavy hadrons,
- Precise vertexing,
- Excellent charged hadron identification.

Flexible two-stage trigger,

- L0 hardware trigger — high $p_t$ particles,
- High Level Trigger (HLT) in software
  - Software trigger running in event farm,
  - Real-time calibration for physics-quality reconstruction,
  - Full event reconstruction,
  - Two stages running asynchronously to optimize usage of computing resources.
Pseudorapidity of $b$ and $\bar{b}$ produced in $pp$ collisions for LHCb simulation.

LHCb acceptance

- ALICE
  - central
  - forward muon coverage

- ATLAS & CMS
  - central detectors

- LHCb
  - forward detector
  - tracking, particle-ID and calorimetry in full acceptance

Pseudorapidity range:
- $\eta$ from $-8$ to $8$
High rate heavy flavor production into LHCb acceptance

Cross-sections at \( pp \sqrt{s} = 7 \) TeV:

\[ \sigma_{\text{vis}}^{pp} = 58.8 \pm 0.2 \text{ mb} \]

[\text{JINST 7 (2012) P01010}]

\[ \sigma_{b\bar{b}, \text{acc}} = 49.1 \pm 6.9 \mu\text{b} \]

\( \Rightarrow 20 \text{ kHz of } b\bar{b} \)


\[ \sigma_{c\bar{c}, \text{acc}} = 1419 \pm 134 \mu\text{b} \]

\( \Rightarrow 600 \text{ kHz of } c\bar{c} \)

[\text{Nucl.Phys.B 871, 1-20}]
Data collection in 2015 (LHC Run 2)

Exceeding design specifications to maximize physics reach

<table>
<thead>
<tr>
<th></th>
<th>Design</th>
<th>2012 (Run1)</th>
<th>Run2 nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp collision energy (TeV)</td>
<td>14</td>
<td>7-8</td>
<td>13</td>
</tr>
<tr>
<td>Instantaneous luminosity, $\mathcal{L}_{\text{inst}}$ (cm$^{-2}$ s$^{-1}$)</td>
<td>$2 \times 10^{32}$</td>
<td>$4 \times 10^{32}$</td>
<td>$4 \times 10^{32}$</td>
</tr>
<tr>
<td>Mean visible $p$-$p$ interactions/crossing, $\mu$</td>
<td>0.4</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>HLT output rate to tape (kHz)</td>
<td>2</td>
<td>5</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Cross-sections at $pp \sqrt{s} = 13$ TeV:

$\sigma_{b\bar{b},\text{acc}} = 100.9 \pm 10.3 \mu$b

$\Rightarrow$ 40 kHz of $b\bar{b}$ production

[JHEP 1510 (2015) 172]

$\sigma_{c\bar{c},\text{acc}} = 2940 \pm 3 \pm 240 \mu$b

$\Rightarrow$ 1.2 MHz of $c\bar{c}$ production

[JHEP 1603 (2016) 159]
Production measurements of heavy flavor hadrons can be vital to improved understanding of QCD,

- Test precise cross-section predictions,
- Provide empirical fragmentation functions,
- Probe proton structure.

Necessary for MC generator tuning,

- Simulation inputs to precision flavor physics measurements,
- Long term program planning,
- New experiment design.

Standard Model backgrounds for New Physics searches,

- Absolute rates of SM processes must be known precisely.
Differential production cross-sections of $\Lambda_b^0$ multiplied by branching fraction from $\Lambda_b^0 \rightarrow J/\psi pK^-$, $J/\psi \rightarrow \mu^+ \mu^-$ decays,

$$\frac{d^2\sigma_i(\Lambda_b^0)}{dp_T dy} B(\Lambda_b^0 \rightarrow J/\psi pK^-) = \frac{1}{\Delta p_T \Delta y} \frac{N_i(\Lambda_b^0 \rightarrow J/\psi (\mu^+ \mu^-)pK^- + \text{c.c.})}{\varepsilon_{i,\text{tot}} L_{\text{int}} B(J/\psi \rightarrow \mu^+ \mu^-)}$$

in bins of $p_T$ and $y$ with respect to the collision axis.

- $B(\Lambda_b^0 \rightarrow J/\psi pK^-)$ not previously measurable,
- $N_i(\Lambda_b^0 \rightarrow J/\psi (\mu^+ \mu^-)pK^- + \text{c.c.})$: signal yield in bin $i$,
- $\varepsilon_{i,\text{tot}}$: total signal efficiency
  - Components evaluated in independent data samples where possible,
- $L_{\text{int}}$: integrated luminosity of sample,
  - $1.019 \pm 0.017 \text{ fb}^{-1}$ for $\sqrt{s} = 7 \text{ TeV}$ sample,
  - $2.056 \pm 0.023 \text{ fb}^{-1}$ for $\sqrt{s} = 8 \text{ TeV}$ sample.
Differential cross-sections multiplied by branching fraction

$$\frac{d^2\sigma_i(\Lambda^0_b)}{dp_T dy} B(\Lambda^0_b \rightarrow J/\psi pK^-)$$

measured in $pp$ collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.

Data sets partitioned into $(p_T, y)$ bins

- 5 bins in $y \in [2.0, 4.5]$,
- 10 bins in $p_T \in [0, 20]$ GeV for $\sqrt{s} = 7$ TeV,
- 12 bins in $p_T \in [0, 20]$ GeV for $\sqrt{s} = 8$ TeV.

Signal yields in each bin measured with a fit to the reconstructed $\Lambda^0_b$ mass distribution.

Example of fit to determine signal yield in bin $p_T \in [6, 7]$ and $y \in [3.0, 3.5]$ for $\sqrt{s} = 8$ TeV sample.
$\Lambda^0_b$ CROSS-SECTIONS

$(d^2\sigma(\Lambda^0_b)/d\eta dy) B$ for the $\sqrt{s} = 7$ TeV sample.

Integrated cross-section in $p_T < 20$ GeV and $2.0 < y < 4.5$:

$\sigma(\Lambda^0_b;\sqrt{s} = 7$ TeV $) B = 6.12 \pm 0.10$(stat) $\pm 0.25$(syst) nb.

$(d^2\sigma(\Lambda^0_b)/d\eta dy) B$ for the $\sqrt{s} = 8$ TeV sample.

Integrated cross-section in $p_T < 20$ GeV and $2.0 < y < 4.5$:

$\sigma(\Lambda^0_b;\sqrt{s} = 8$ TeV $) B = 7.51 \pm 0.08$(stat) $\pm 0.31$(syst) nb.
Ratios of cross-sections at the two collision energies, \( \sigma(\Lambda^0_b; 8 \text{ TeV})/\sigma(\Lambda^0_b; 7 \text{ TeV}) \):

- \( \mathcal{B}(\Lambda^0_b \rightarrow J/\psi pK^-) \) cancels,
- Correlated measurement uncertainties also cancel.

Theoretical predictions of the cross-section ratios also benefit from cancellation of large uncertainties,

- Fixed order with next-to-leading-log resummation (FONLL) predictions superposed (JHEP 1210 (2012) 137).

Integrated cross-section ratio in \( p_T < 20 \text{ MeV} \) and \( 2.0 < y < 4.5 \):

\[
\frac{\sigma(\Lambda^0_b; 8 \text{ TeV})}{\sigma(\Lambda^0_b; 7 \text{ TeV})} = 1.23 \pm 0.02 \pm 0.04.
\]
Signal yields determined separately for $\Lambda_b^0 \rightarrow J/ψ pK^−$ and $\bar{\Lambda}_b^0 \rightarrow J/ψ \bar{p}K^+$.

Raw asymmetries

$$A_{\text{raw},i} = \frac{N_i(\Lambda_b^0)-N_i(\bar{\Lambda}_b^0)}{N_i(\Lambda_b^0)+N_i(\bar{\Lambda}_b^0)}$$
corrected for asymmetries in detector response to measure combined production and decay asymmetry, $a_{p+d}$.

Linear fits to the trends,

- Slopes of $p_T$ consistent with 0,
- Non-zero slope of trend in $y$:

$$a_{p+d}(y) = (-0.001 \pm 0.007) + (0.058 \pm 0.014)(y - \langle y \rangle)$$

where \( \langle y \rangle = 3.1 \).
**Absolute BF of $\Lambda_b^0 \rightarrow J/\psi pK^-$**

Cross-sections used to determine absolute branching fraction of $\Lambda_b^0 \rightarrow J/\psi pK^-$. Parallel analysis of $B^0 \rightarrow J/\psi K^{*0}$ to measure

$$R_{\Lambda_b^0/B^0} \equiv \frac{\sigma(\Lambda_b^0) \mathcal{B}(\Lambda_b^0 \rightarrow J/\psi pK^-)}{\sigma(B^0) \mathcal{B}(B^0 \rightarrow J/\psi K^{*0})}$$

$R_{\Lambda_b^0/B^0}$ is related to $b$ fragmentation ratio

$$R_{\Lambda_b^0/B^0}(p_T) = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi pK^-)}{\mathcal{B}(B^0 \rightarrow J/\psi K^{*0})} \frac{f_{\Lambda_b^0}}{f_d}(p_T)$$

Use previously measured dependence of $f_{\Lambda_b^0}/f_d(p_T)$ (JHEP 1408 (2014) 143) to fit for the constant $\frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi pK^-)}{\mathcal{B}(B^0 \rightarrow J/\psi K^{*0})} = 0.2458 \pm 0.0030$.

Then with externally measured $\mathcal{B}(B^0 \rightarrow J/\psi K^{*0})$ (Belle, Phys.Lett. B538 11-20),

$$\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi pK^-) = \left(3.17 \pm 0.04^{\text{(stat)}} \pm 0.07^{\text{(syst)}} \pm 0.34(B^0 \text{ BF})^{+0.45}_{-0.28}^{\text{(frag)}}\right) \times 10^{-4}$$
Observation of excited $\Lambda_b^0$ states

Searches for excited states with large samples of high purity ground state decays.

Sample of $70,540 \pm 330 \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \text{ decays in 1.0 fb}^{-1} \text{ of data.}$

Two narrow states observed in the $\Lambda_b^0 \pi^+ \pi^-$ mass spectrum.

$\Lambda_b^*0(5912)$: $5.2\sigma$ significance,

$N_{\Lambda_b^*0(5912)} = 17.6 \pm 4.8,$

$M_{\Lambda_b^*0(5912)} = 5911.97 \pm 0.12 \pm 0.66 \text{ MeV},$

$\Delta M_{\Lambda_b^*0(5912)} = 292.60 \pm 0.12 \pm 0.04 \text{ MeV},$

$\Gamma_{\Lambda_b^*0(5912)} < 0.66 \text{ MeV at 90% C.L.}$

$\Lambda_b^*0(5920)$: $10.2\sigma$ significance,

$N_{\Lambda_b^*0(5920)} = 52.5 \pm 8.1,$

$M_{\Lambda_b^*0(5920)} = 5919.77 \pm 0.08 \pm 0.66 \text{ MeV},$

$\Delta M_{\Lambda_b^*0(5920)} = 300.40 \pm 0.08 \pm 0.04 \text{ MeV},$

$\Gamma_{\Lambda_b^*0(5920)} < 0.63 \text{ MeV at 90% C.L.}$
Lowest-lying $\Xi_b$ baryons in the quark model,

- Ground state $J^P = \frac{1}{2}^+$ $\Xi_b^0$ and $\Xi_b^-$, decay weakly,
- $J^P = \frac{1}{2}^+$ isodoublet $\Xi_b'^0$ and $\Xi_b'^-$,
- $J^P = \frac{3}{2}^+$ isodoublet $\Xi_b^*0$ and $\Xi_b^*-$. 

In 2012, CMS identified a new $\Xi_b^0$ state decaying to $\Xi_b^− \pi^+$, most likely $\Xi_b^*0$,

- Mass difference
  \[ \delta m \equiv m(\Xi_b^- \pi^+) - m(\Xi_b^-) - m(\pi^+) = 14.84 \pm 0.74 \pm 0.28 \text{ MeV}. \]
- No evidence for a second peak,
  - Expectation that the $\Xi_b'^0$ mass is below the $\Xi_b^- \pi^+$ threshold.

SU(3) flavor multiplets of heavy baryons; $\alpha (\pm n)$ denotes the electric charge. Image from Liu, et al., PRD 77, 014031.
LHCb recently examined the $\Xi_b^-\pi^+$ mass spectrum

- $\Xi_b^-$ reconstructed in the decay $\Xi_b^- \rightarrow \Xi_c^0\pi^-$, $\Xi_c^0 \rightarrow pK^-K^-\pi^+$,
- High purity sample of $\Xi_b^-$.
- Full Run 1 data set, 3 fb$^{-1}$.

One resonant structure observed near threshold, confirming the CMS observation.

Mass and width of the state measured.

Relative production cross-section determined with respect to that of $\Xi_b^-$:

$$\frac{\sigma (pp \rightarrow \Xi_{b}^{*0} X) \beta (\Xi_{b}^{*0} \rightarrow \Xi_{b}^-\pi^+)}{\sigma (pp \rightarrow \Xi_{b}^- X)}$$
One narrow resonant feature observed in the mass spectrum
\[ \delta m \equiv m(\Xi_b^- \pi^+) - m(\Xi_b^0) - m(\pi^+) \]

Fit for mass and width:
- \(P\)-wave relativistic Breit-Wigner convolved with resolution function.

Consistent with CMS with an order of magnitude improvement in precision.

\[ m(\Xi_b^{*0}) - m(\Xi_b^0) - m(\pi^+) = 15.727 \pm 0.068 \pm 0.023 \text{ MeV}. \]

\[ \Gamma(\Xi_b^{*0}) = 0.90 \pm 0.16 \pm 0.08 \text{ MeV}. \]
Production cross-section of $\Xi^*_b{}^0$ into the LHCb acceptance measured relative to that of $\Xi^-_b$,

- $\Xi^-_b$ selection common to both,
- Cancellation of efficiencies and branching fractions related to $\Xi^-_b$.

$$\frac{N(\Xi^*_b{}^0)}{N(\Xi^-_b)} = \frac{\frac{\sigma(pp \to \Xi^*_b{}^0 X)\mathcal{B}(\Xi^*_b{}^0 \to \Xi^-_b \pi^+)}{\sigma(pp \to \Xi^-_b X)}\epsilon_{\Xi^*_b}^{rel}}{\sigma(pp \to \Xi^-_b X)}$$

where $\epsilon_{\Xi^*_b}^{rel}$ is the residual selection efficiency of $\Xi^*_b{}^0$ related to the additional $\pi^-$. 

Result: $\frac{\sigma(pp \to \Xi^*_b{}^0 X)\mathcal{B}(\Xi^*_b{}^0 \to \Xi^-_b \pi^+)}{\sigma(pp \to \Xi^-_b X)} = 0.27 \pm 0.03 \pm 0.01$
Search for new $\Xi_b^-$ states in the $\Xi_b^0\pi^-$ mass spectrum.

$\Xi_b^0$ reconstructed in mode $\Xi_b^0 \rightarrow \Xi_c^+\pi^-$, $\Xi_c^+ \rightarrow pK^-\pi^+$,

- $\Xi_c^+ \rightarrow pK^-\pi^+$ is a suppressed decay, but very efficiently detected.

Two new resonances observed.

Mass and width of the state measured.

Relative production cross-section determined with respect to that of $\Xi_b^0$:

$$\frac{\sigma(pp \rightarrow \Xi_b^{(*)-}X) \mathcal{B}(\Xi_b^{(*)-} \rightarrow \Xi_b^0\pi^-)}{\sigma(pp \rightarrow \Xi_b^0X)}$$
Masses of new states

Fits to $P$-wave relativistic Breit-Wigner line shapes convolved with a resolution function.

$\delta m(\Xi_b^-) = 3.653 \pm 0.018 \pm 0.006 \text{ MeV}$

$\Gamma(\Xi_b^-) < 0.08 \text{ MeV} \text{ at 95\% C.L.}$

$m(\Xi_b^-) = 5935.02 \pm 0.02 \pm 0.01 \pm 0.50 \text{ MeV}$

$\delta m(\Xi_b^*) = 23.96 \pm 0.12 \pm 0.06 \text{ MeV}$

$\Gamma(\Xi_b^*) = 1.65 \pm 0.31 \pm 0.10 \text{ MeV}$

$m(\Xi_b^*) = 5955.33 \pm 0.12 \pm 0.06 \pm 0.50 \text{ MeV}$
CONFIRMATION WITH ADDITIONAL $\Xi^0_b$ MODE

Checked search with independent sample of $\Xi^0_b$ reconstructed from $\Xi^0_b \to \Lambda_c^+ K^- \pi^+ \pi^-$, $\Lambda_c^+ \to pK^- \pi^+$ decays.

Both peaks present in the $\delta m$ distribution.

Peak significance:
- $6.4\sigma$ for $\Xi^{'-}_b$,
- $4.7\sigma$ for $\Xi^{*-}_b$,

(peak masses and widths fixed to values determined in primary analysis.)

Fits to the $\Xi^0_b \pi^-$ $\delta m$ spectrum where $\Xi^0_b$ is reconstructed in the mode $\Xi^0_b \to \Lambda_c^+ K^- \pi^+ \pi^-$. 
Examined helicity angles of the two states.

Both have flat distributions,

- Fits to quadratic function
  \[ f(\cos \theta_h) = \frac{1}{2} \left[ a + 3(1 - a) \cos^2 \theta_h \right] \]
  
  \[ a_{\Xi_b^-} = 0.89 \pm 0.11 \]
  
  \[ a_{\Xi_b^*^-} = 0.88 \pm 0.11 \]

Indicative of \( J = 1/2 \) or \( J > 1/2 \) with no polarization,

- Other values of \( J \) cannot be excluded.

Feed-down from \( \Xi_b^{**-} \)?

- Cannot be ruled out, but contrived scenario.
**Summary of new \( \Xi_b \) state properties**

<table>
<thead>
<tr>
<th>( \Xi_b )</th>
<th>( \Xi_b^* )</th>
<th>( \Xi_b^{*0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta m ) (MeV)</td>
<td>3.653 ± 0.018 ± 0.006</td>
<td>23.96 ± 0.12 ± 0.06</td>
</tr>
<tr>
<td>( \Gamma ) (MeV)</td>
<td>&lt; 0.08 at 95% C.L.</td>
<td>1.65 ± 0.31 ± 0.10</td>
</tr>
<tr>
<td>( M ) (MeV)</td>
<td>5935.02 ± 0.02 ± 0.50</td>
<td>5955.33 ± 0.12 ± 0.50</td>
</tr>
<tr>
<td>( \frac{\sigma(\Xi_b^{(*)})}{\sigma(\Xi_b)} B )</td>
<td>0.118 ± 0.017 ± 0.007</td>
<td>0.207 ± 0.032 ± 0.015</td>
</tr>
</tbody>
</table>

**Isospin splitting of \( \Xi_b^* \):**

\[
m(\Xi_b^{*-}) - m(\Xi_b^{*0}) = \delta m(\Xi_b^{*-}) - \delta m(\Xi_b^{*0}) - \left[ m(\Xi_b^{-}) - m(\Xi_b^{0}) \right] = 2.31 ± 0.62 ± 0.24 \text{ MeV}.
\]

**Production ratio of new \( \Xi_b^- \) states:**

\[
\frac{\sigma(pp \to \Xi_b^{*-} X) \times B(\Xi_b^{*-} \to \Xi_b^{0} \pi^-)}{\sigma(pp \to \Xi_b^{*-} X) \times B(\Xi_b^{*-} \to \Xi_b^{0} \pi^-)} = 1.74 ± 0.30 ± 0.12.
\]
LHCb is collecting the world’s largest samples of heavy flavored hadrons with a detector that is designed for their study.

Exploiting the large production of heavy baryons in the LHC’s $pp$ collisions to precisely measure their properties.

Confirmation of CMS’s observation of $\Xi^*_b$ with an order of magnitude improvement in its mass difference determination

$$M(\Xi^*_b) = 5953.02 \pm 0.07 \text{(stat)} \pm 0.02 \text{(syst)} \pm 0.55(m(\Xi^-_b))$$

Two new $\Xi^-_b$ states

$$M(\Xi'_b^-) = 5935.02 \pm 0.02 \text{(stat)} \pm 0.01 \text{(syst)} \pm 0.50(m(\Xi^0_b))$$
$$M(\Xi^*_b^-) = 5955.33 \pm 0.12 \text{(stat)} \pm 0.06 \text{(syst)} \pm 0.50(m(\Xi^0_b))$$

Many more measurements in progress with an ever-increasing data set

- Including spectroscopy of charmed baryons!
Backup
Suites of open charm cross-sections in 15 nb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV,

- $D^0 \to K^−\pi^+$
- $D_s^+ \to \phi(K^−K^+)\pi^+$
- $D^*+ \to D^0\pi^+$
- $\Lambda_c^+ \to p^+K^−\pi^+$
- $D^+ \to K^−\pi^+\pi^+$

Dedicated data sample

- Low pile-up, simple trigger.

Binned in $p_T$ and $y$, differential $d\sigma/dp_T$

- $p_T < 8$ GeV/$c$, $2 < y < 4.5$,
- 15 nb$^{-1}$ of 2010 data.

Includes measurements of

- Differential cross-sections,
- Charm species production ratios,
- Total $c\bar{c}$ cross-section.
Differential cross-sections: $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$

Differential cross-section of $\Lambda_c^+$ as functions of $p_T$ (shown at left) and $y$.

Production ratios integrated over $p_T < 8 \text{ GeV}/c$, $2 < y < 4.5$:

$$\frac{\sigma(\Lambda_c^+)}{\sigma(D^0)} = 0.140 \pm 0.045$$

$$\frac{\sigma(\Lambda_c^+)}{\sigma(D^+)} = 0.361 \pm 0.116$$

$$\frac{\sigma(\Lambda_c^+)}{\sigma(D^{*+})} = 0.344 \pm 0.111$$

$$\frac{\sigma(\Lambda_c^+)}{\sigma(D_s^+)} = 1.183 \pm 0.402$$

$d\sigma/dp_T$ compared to predictions from GMVFNS

DOUBLE CHARM HADRONS, $\Xi_{cc}^+$

Constituent-quark model predicts three weakly decaying $C = 2$, $J^P = \frac{1}{2}^+$ states:
- $\Xi_{cc}^+$ (ccd),
- $\Xi_{cc}^{++}$ (ccu),
- $\Omega_{cc}^+$ (ccs).

SELEX claims first evidence for $\Xi_{cc}^+$, unexpectedly
- Short lifetime, $\tau < 33$ fs,
- 20% of $\Lambda_c^+$ production with baryon beams.

SELEX evidence in $\Lambda_c^+K^-\pi^+$ and $pD^+K^-$ final states.
Searches at BaBar, FOCUS, and Belle failed to find evidence for it.
SEARCH FOR $\Xi_{cc}^+$

Initial search at LHCb in $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$:

- No evidence of $\Xi_{cc}^+$ production.
- Set upper limits on production
  \[ R \equiv \frac{\sigma(\Xi_{cc}^+) B(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} \]

Improved search in progress,

- Full Run 1 data set ($3 \times$ larger),
- Search for $\Xi_{cc}^+$ and $\Xi_{cc}^{++}$,
- Search in more than just one decay mode, some of which were triggered more efficiently than $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$.

LHC Run 2 promises to be even better,

- Increased collision energy $\Rightarrow$ greater production cross-section,
- Further trigger improvements.