Studies of Charmed Baryons at LHCb

CHARM 2013 Manchester

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on behalf of the LHCb collaboration

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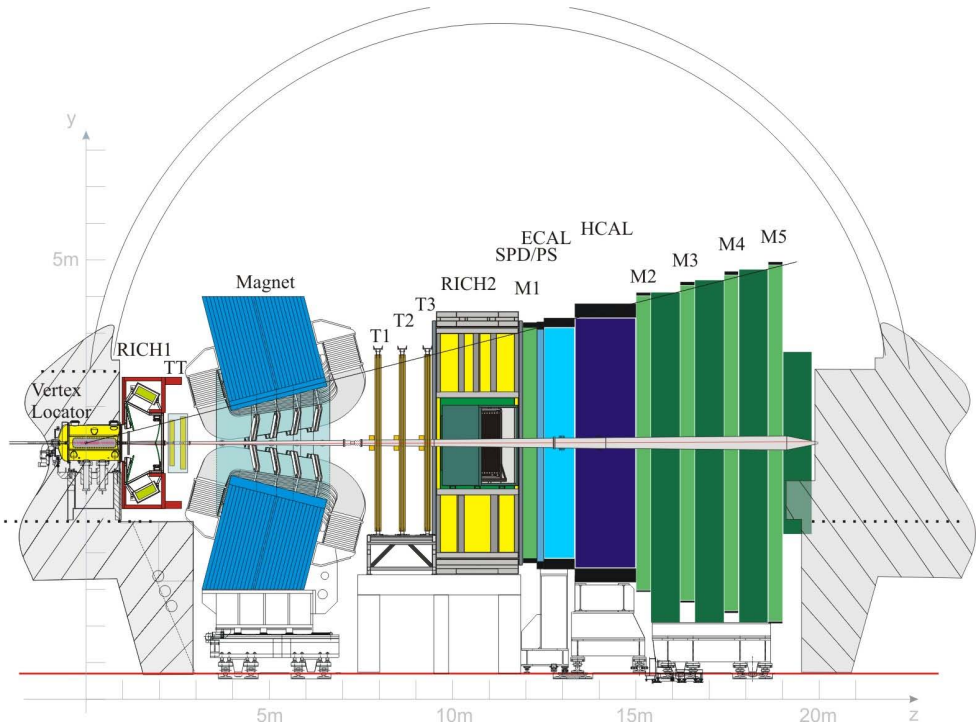
Overview

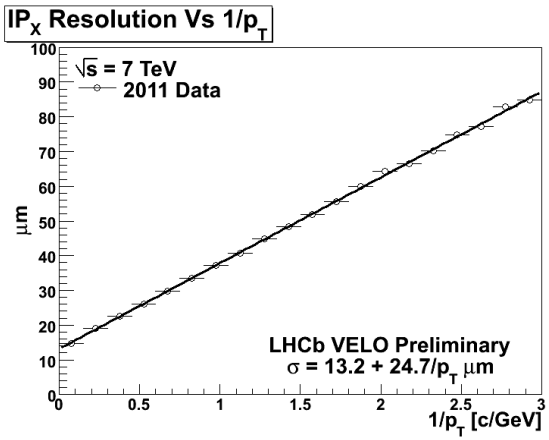
1. The LHCb Detector

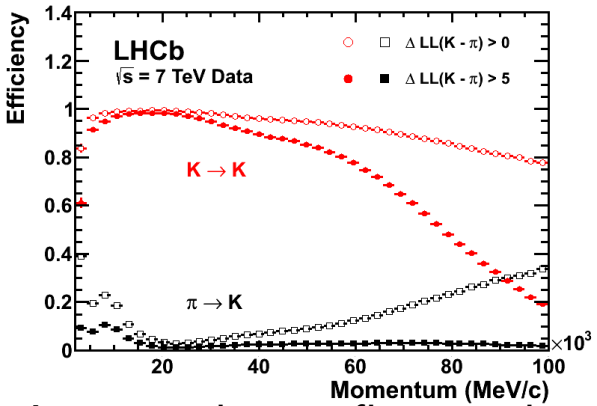
2. 2011 Ξ_{cc}^{+} Search
   - Double Charm Baryons
   - Candidate Selection and Yield Extraction
   - Statistical Significance and UL Calculations
   - Results and Future Prospects

The LHCb Detector

- Forward arm spectrometer designed for precision flavour measurements

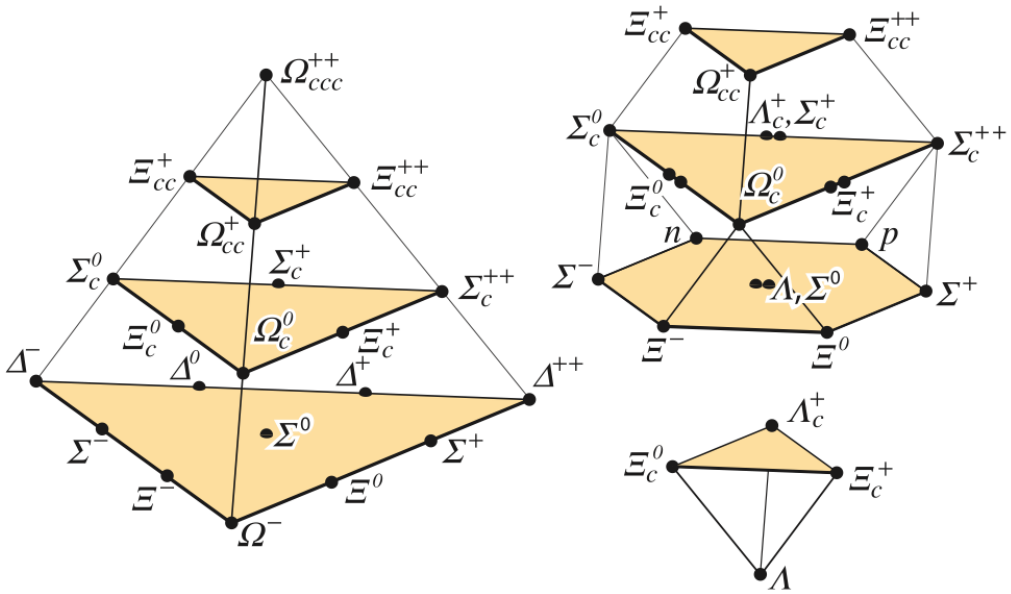






- VELO - powerful secondary vertex discrimination to trigger on heavy flavour decays
- Tracker momentum resolution: $\Delta p/p = 0.4\%$ at $5 GeV/c$ to 0.6% at $100 GeV/c$
- RICH - daughter particle discrimination:
  Kaon ID efficiency $\sim 95\%$ for $\sim 5\%$ $\pi \to K$ mis-id probability

Ξ_{cc}^{+} Search - Motivation I



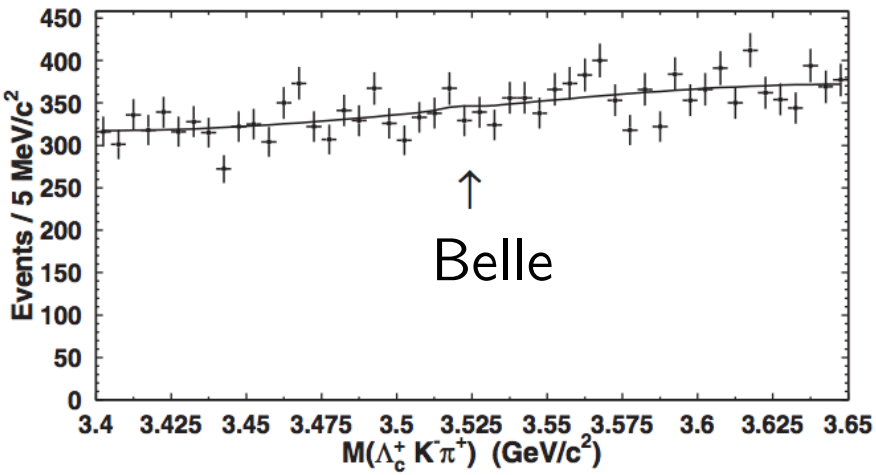
From PDG: Phys. Rev. D86, 010001 (2012)

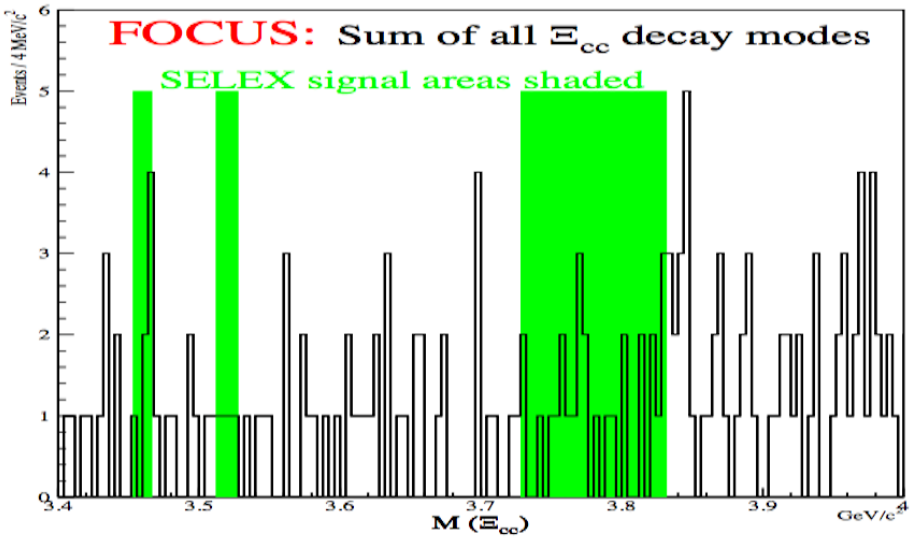
- Baryons with u,d,s,c form SU(4) multiplets
- Ground state baryons shown
- Three weakly decaying $C = 2, J^P = 1/2^+$ states:
  - Ξ_{cc} isodoublet (ccu, ccd)
  - Ω_{cc} singlet (ccs)

- Numerous predictions for masses and lifetimes:
  - $M\ (\Xi_{cc}^{+})$: $3500 - 3700 MeV/c^2$ - Phys. Rev. D70 (2004) 094004
  - $\tau\ (\Xi_{cc}^{+})$: $100 - 250 fs$ - Eur. Phys. J. A45 (2010) 267
- SELEX reported signals in $\Lambda_c^+ K^- \pi^+$ and $p^+ D^+ K^-$ final states
  - $M\ (\Xi_{cc}^{+})$: $3519 \pm 2 MeV/c^2$, $\tau\ (\Xi_{cc}^{+})$: $< 30 fs @ 90\% CL$
  - Phys. Rev. Lett. 89, 112001 (2002), Phys. Lett. B628 (2005) 18

Ξ_{cc}^{+} Search - Motivation - II

- SELEX calculate that 20% of their Λ_c^+ sample is produced from Ξ_{cc}^{+} decays
  - Theory predicts Ξ_{cc}^{+} production suppressed by several orders of magnitude over Λ_c^+ production - Physics-Uspekhi 45 (2002), no. 5 455
- Subsequent searches at Belle (left), FOCUS (right) and BaBar experiments show no evidence for Ξ_{cc}^{+} with SELEX reported properties
  - Phys. Rev. Lett. 97 (2006) 162001,
    Nuclear Physics-Section B-PS-Proceedings Supplements 115 (2003) 33,
    Phys. Rev. D74 (2006) 011103





- Might be explained by different production environments - SELEX is hyperon beam on fixed target, FOCUS photoproduction, Belle and BaBar e^+e^-

Ξ_{cc}^{+} Search - Analysis Outline

- Search for particle in decay $\Xi_{cc}^{+} \to (\Lambda_c^+ \to p^+ K^- \pi^+) K^- \pi^+$
- Using $0.65 fb^{-1}$ of 2011 data at $\sqrt{s} = 7$ TeV
  Relevant triggers only online for half the year
- Measure production ratio relative to control $\Lambda_c^+ \to p^+ K^- \pi^+$:

$$R \equiv \frac{\sigma(\Xi_{cc}^{+})\mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} = \frac{N_{signal}}{N_{control}} \frac{\epsilon_{control}}{\epsilon_{signal}}$$

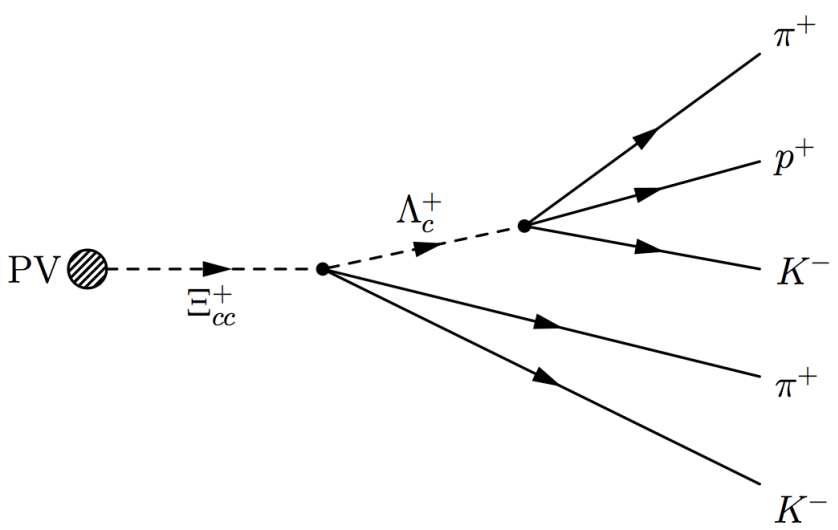
  - Measured LHCb Λ_c^+ cross-section at $\sqrt{s} = 7 TeV \approx 230 \mu b$
    NUCL.PHYS.B871,1-20
  - Predicted LHC Ξ_{cc}^{+} cross-section at $\sqrt{s} = 14 TeV \approx (60 - 1800) nb$.
    At $\sqrt{s} = 7$ TeV expected to be roughly half this
- Assuming the following:

$$\mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+) \approx \mathcal{B}(\Lambda_c^+ \to p^+ K^- \pi^+) \approx 5\%$$

  expected value of R at LHCb is of order 10^{-5} to 10^{-4}
- Analysis performed with a blind approach.

Ξ_{cc}^{+} Search - Candidate Selection

- Use same trigger requirements for control and signal based on $\Lambda_c^+ \to p^+ K^- \pi^+$ decay
  - One Λ_c^+ daughter track must fire calorimeter hardware trigger
  - One Λ_c^+ daughter track selected by inclusive software trigger
  - Λ_c^+ candidate reconstructed and accepted by dedicated $\Lambda_c^+ \to p^+ K^- \pi^+$ selection algorithm in software trigger - geometric and kinematic requirements, and using RICH PID info for proton.
- Offline reconstruction and selection based on PV displacement and particle identification requirements



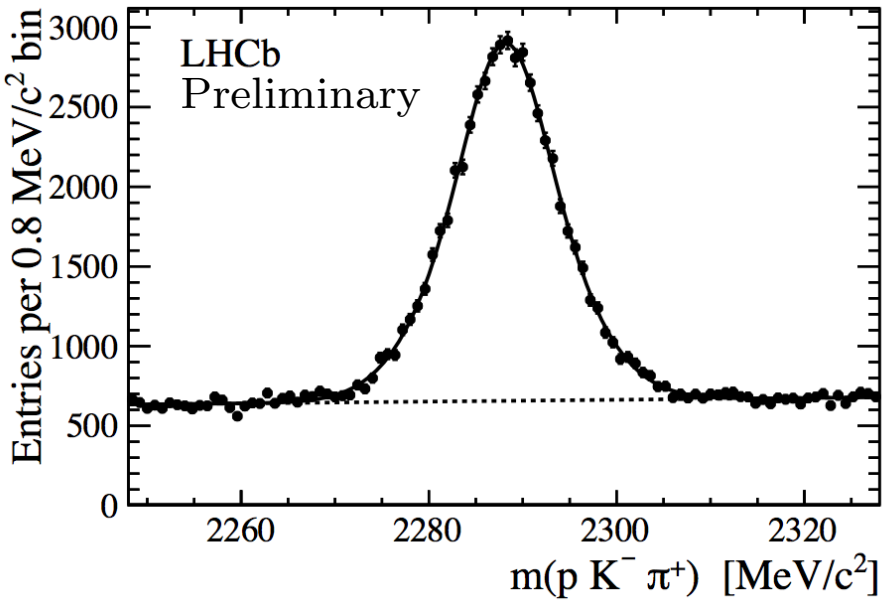
- To make Ξ_{cc}^{+} candidates:
  - Pair Λ_c^+ with K and π at common vertex displaced from PV
  - Displacement cut reduces sensitivity to SELEX-like Ξ_{cc}^{+}
    Can be relaxed in future analyses
  - Artificial Neural Network final selection. Input variables chosen for minimal Ξ_{cc}^{+} lifetime dependence

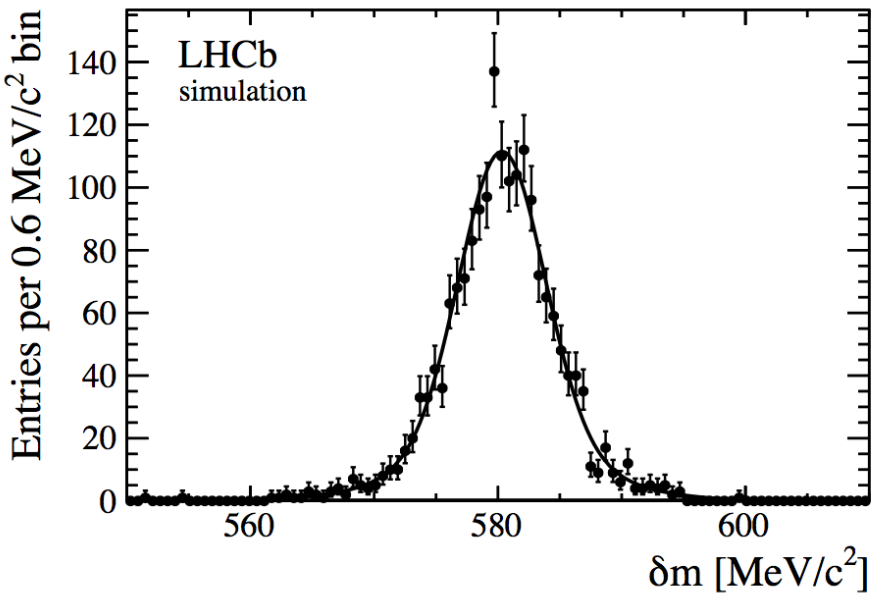
Ξ_{cc}^{+} Search - Yield Extraction I

- Fit performed to $p^+K^-\pi^+$ mass spectrum to extract Λ_c^+ yield
- Total yield $N_{con} = (818 \pm 7) \times 10^3$, resolution $\approx 6 MeV/c^2$ (5% total yield shown left)
- For signal yield construct δm quantity:

$$\delta m \equiv m(\Lambda_c^+ K^- \pi^+) - m_{meas}(\Lambda_c^+) - m(K^-) - m(\pi^+)$$

- Take signal resolution from MC, $\approx 4.4 MeV/c^2$ (right)
  - Dedicated generator, GENXICC v2.0, used to produce Ξ_{cc}^{+} MC





Ξ_{cc}^{+} Search - Yield Extraction II

- Define narrow 2D signal window requiring:
  - $2273 < m_{meas}(\Lambda_c^+) < 2303 MeV/c^2$
  - $|\delta m - \delta m_0| < 10 MeV/c^2$
- Number of events in window taken to be N_{S+B}
- Data outside window used to evaluate background inside window
- 5×5 array of tiles centred on signal region.
- Assume background is combinatoric, described by 2D quadratic
- Requires only mild assumptions about distributions
- Crosscheck: 1D fit to dm after tight cut on $m_{meas}(\Lambda_c^+)$

Ξ_{cc}^{+} Search - Efficiencies I

- Selection efficiencies calculated using data-driven techniques and MC
- MC derived effs strongly depend on generated Ξ_{cc}^{+} mass and lifetime
  - these are a priori unknown in data
- MC generated with $\tau_{\Xi_{cc}^{+}} = 333fs$, $m(\Xi_{cc}^{+}) = 3500 MeV/c^2$
- Vary mass and lifetime for different scenarios:
  - τ variations - re-weight lifetimes to different exponential distributions
  - m variations - generator-only MC at $m(\Xi_{cc}^{+}) = 3300, 3700 MeV/c^2$ used to re-weight Ξ_{cc}^{+} daughter p_T.
- Kinematic distribution of Ξ_{cc}^{+} at LHC also unknown, assume distributions produced by GENXICC model

Ξ_{cc}^{+} Search - Efficiencies II

- Define event sensitivity $\alpha \equiv \frac{\epsilon_{con}}{N_{con}\epsilon_{sig}}$
- Strong lifetime dependence observed.
- Left: $\tau = 333fs$. Right: $m(\Xi_{cc}^{+}) = 3500MeV/c^2$.

$m(\Xi_{cc}^{+})$	$\alpha\,[\times 10^{-5}]$
$3300\,\mathrm{MeV}/c^2$	2.29 ± 0.61
$3500\,\mathrm{MeV}/c^2$	2.38 ± 0.62
$3700\,\mathrm{MeV}/c^2$	2.36 ± 0.63

τ	$\alpha\,[\times 10^{-5}]$
100 fs	60 ± 30
150 fs	14 ± 5
250 fs	4.0 ± 1.1
333 fs	2.4 ± 0.6
400 fs	1.8 ± 0.5

Source of uncertainty	Size
Tracking efficiency	4.7%
IP Smearing	13.3%
PID calibration	11.8%
Trigger efficiency	3.3%
Simulated sample size	18.0%
Total uncertainty	26.0%

Ξ_{cc}^{+} Search - Statistical Significance and UL Calculations

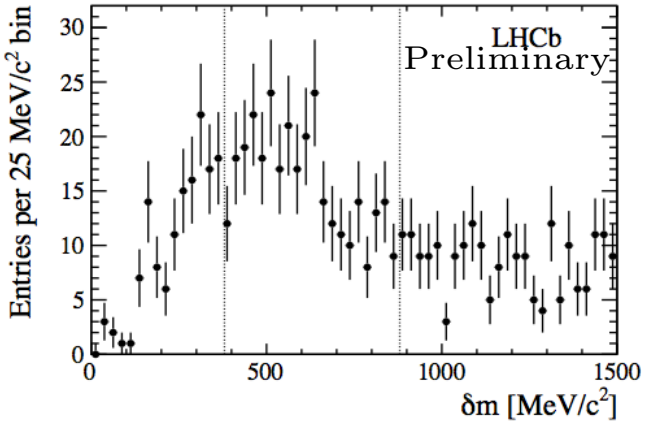
- As $m(\Xi_{cc}^{+})$ unknown, look for signal in $\delta m = 380 - 880 MeV/c^2$ in $1 MeV/c^2$ steps
- From these calculate local significances:

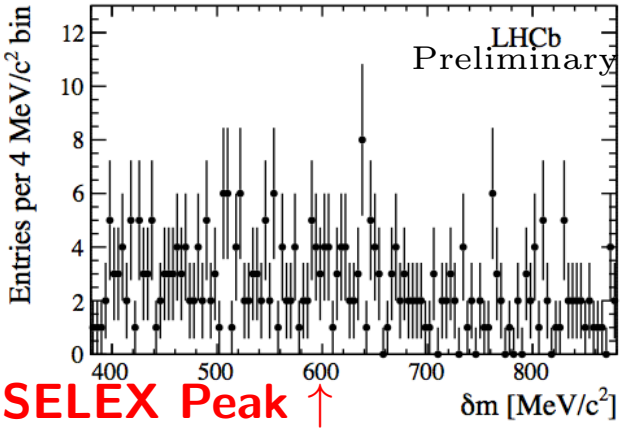
$$\mathcal{S}(\delta m) \equiv \frac{N_{S+B} - N_B}{\sqrt{\sigma_{S+B}^2 + \sigma_B^2}}$$

- Multiple points sampled, must take look elsewhere effect into account:
  - Generate large number of toys containing background only
  - Full analysis procedure applied to each, local significance measured at all values of δm
  - LEE-corrected p-value for given $\mathcal{S}$ is then the fraction of toys containing equal or larger local significance anywhere in δm
- If no significant signal seen upper limits quoted
- CL_s method applied to determine ULs on R for varying δm and lifetime hypotheses
- 95% CL upper limit taken as value of R for $CL_s = 0.05$

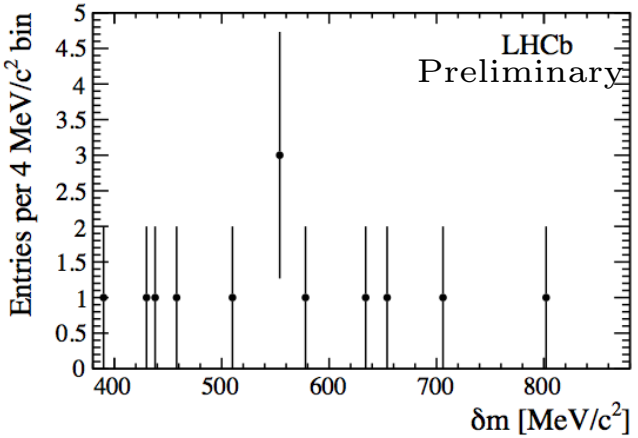
Ξ_{cc}^{+} Search - Results I

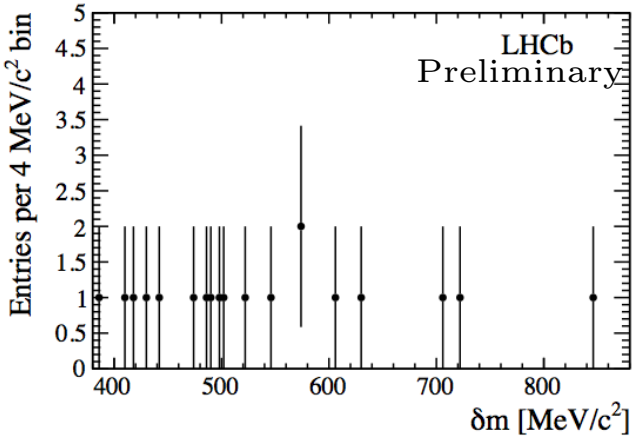
- δm spectrum in data shown. No observed excess.





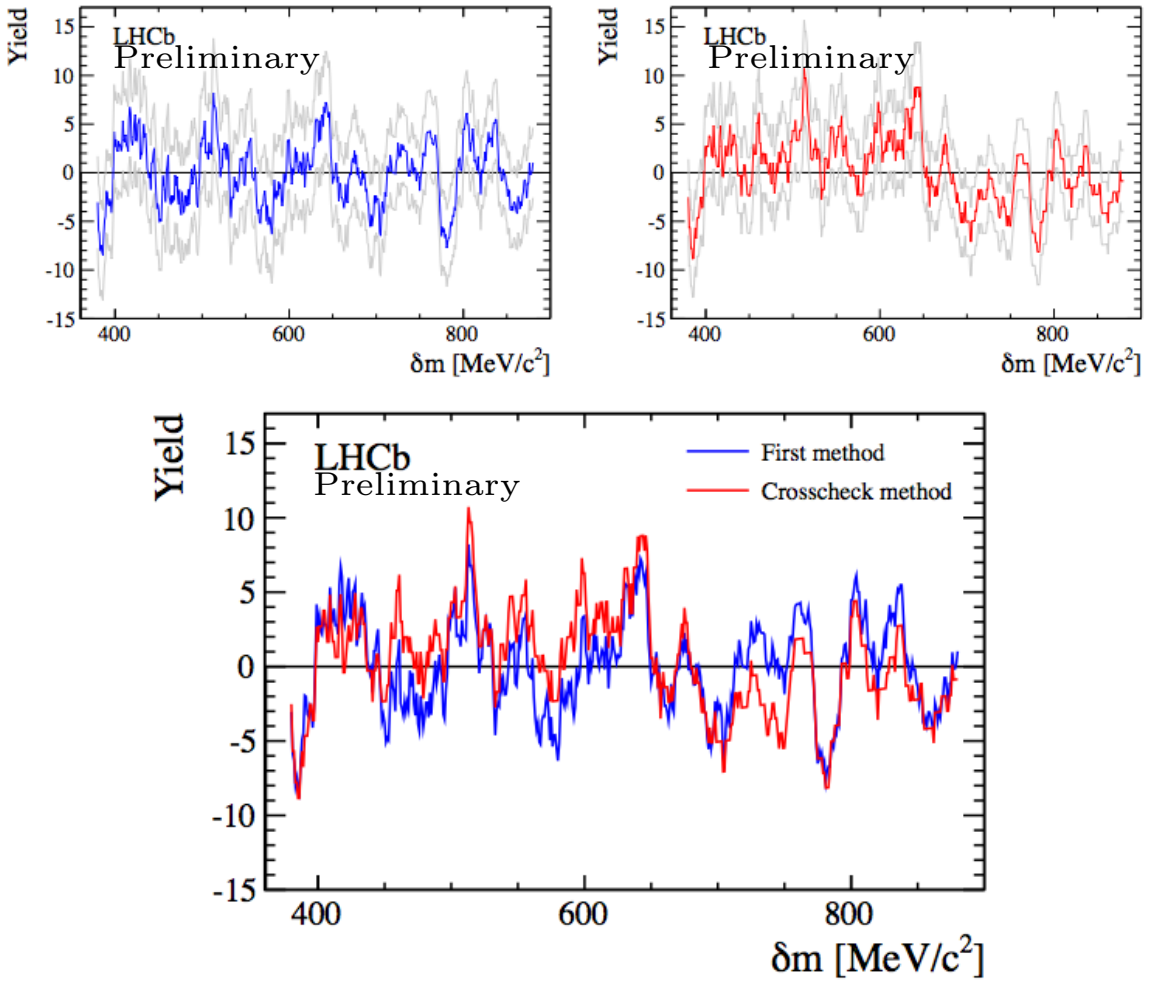
- Candidates after requiring $2273 < m_{meas}(\Lambda_c^+) < 2303 MeV/c^2$ and candidates consistent with:
  - left - intermediate $\Sigma_c(2455)^{++}$, right - intermediate $\Sigma_c(2520)^{++}$





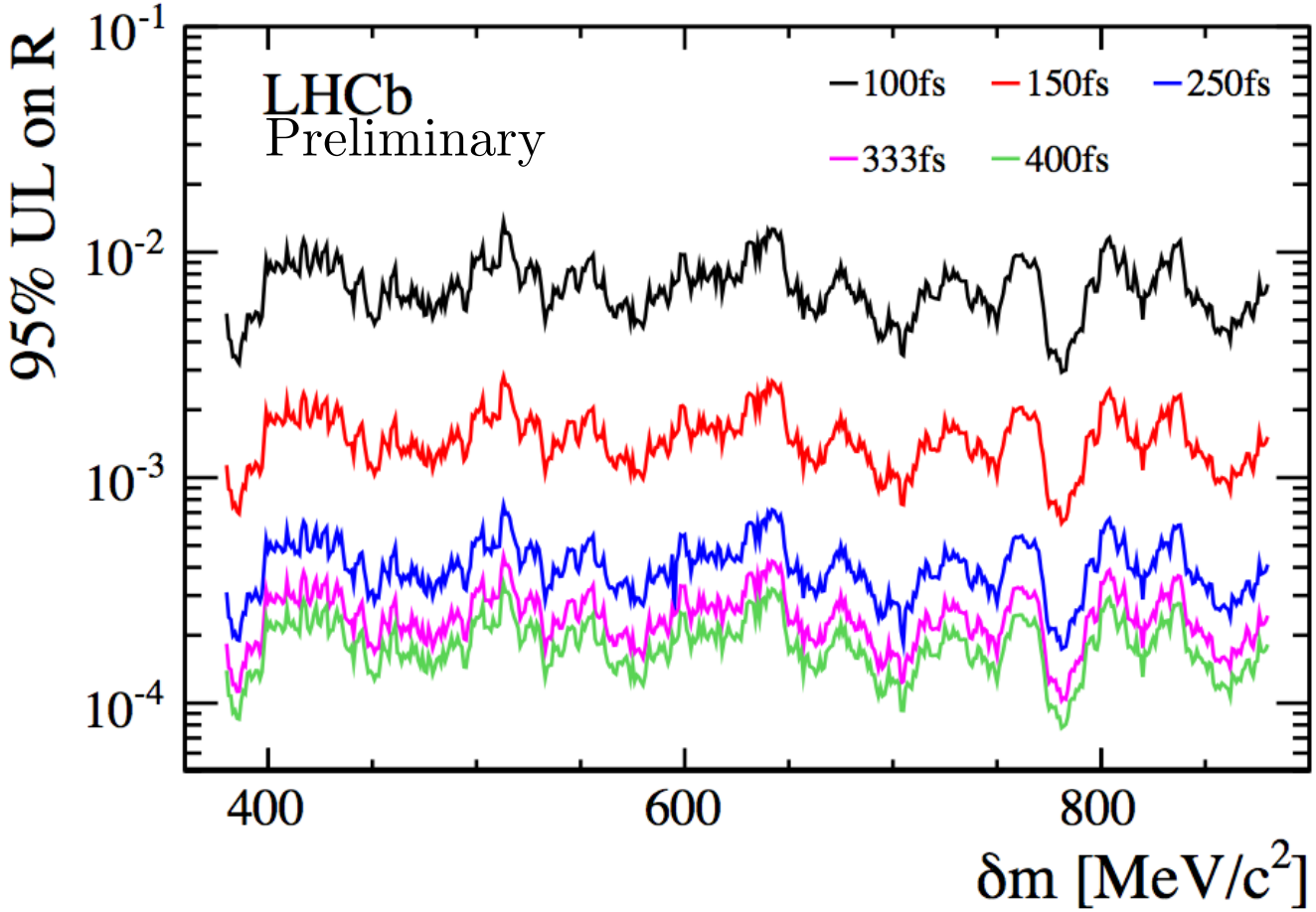
Ξ_{cc}^{+} Search - Results II

- Signal yields across δm. Estimated signal coloured bands, $\pm 1\sigma$ stat. error grey
- Compatibility check between different background subtraction methods bottom.
- Largest local significances: $\mathcal{S} = 1.5\sigma$ (primary method), $\mathcal{S} = 2.2\sigma$ (cross check).
- Applying LEE - p-values of 99% and 53% for null hypothesis.



Ξ_{cc}^{+} Search - Results III

- 95% CL_s ULs as function of δm for each lifetime hypothesis shown
- Predicted value of R at LHCb is 10^{-5} to 10^{-4}
  expected we don't observe Ξ_{cc}^{+}, especially under short lifetime hypotheses.



Ξ_{cc}^{+} Search - 2012 Dataset Outlook

- Now searching for Ξ_{cc}^{+} and Ξ_{cc}^{++} in multiple final states
- Notable inclusion: $\Xi_{cc}^{+} \to (D^{+} \to K^{-}\pi^{+}\pi^{+})p^{+}K^{-}$.
- High D lifetime $(1ps)$ cf. $\Lambda_{c}^{+}(0.2ps)$ - more efficient selections
- Full $2.08fb^{-1}$ at $\sqrt{s} = 8$ TeV available for analysis
- $\Lambda_{c}^{+} \to p^{+}K^{-}\pi^{+}$ trigger and selection performance improved for 2012
- 2012 analysis will have far greater sensitivity.

Final Words

- Results on our 2011 Ξ_{cc}^{+} search presented.
- No signal observed. ULs given for variety of Ξ_{cc}^{+} lifetime hypotheses.
- Prospects for Ξ_{cc}^{+} in 2012 at LHCb look great.
- Healthy charmed baryon program underway at LHCb.
- Many analyses underway or nearing completion.
- Expect more from us very soon!

BACKUP

Ξ_{cc}^{+} Search - Ξ_{cc}^{+} R Upper Limits

- 95% CL_s Upper limits in blocks of δm and lifetime. UL given is highest/worst in that region

δm (MeV/c^2)	100fs	150fs	250fs	333fs	400fs
380–429	1.1×10^{-2}	2.4×10^{-3}	6.4×10^{-4}	3.8×10^{-4}	2.9×10^{-4}
430–479	1.0×10^{-2}	2.1×10^{-3}	5.8×10^{-4}	3.4×10^{-4}	2.6×10^{-4}
480–529	1.4×10^{-2}	2.8×10^{-3}	7.5×10^{-4}	4.5×10^{-4}	3.4×10^{-4}
530–579	9.7×10^{-3}	2.0×10^{-3}	5.5×10^{-4}	3.3×10^{-4}	2.5×10^{-4}
580–629	9.8×10^{-3}	2.1×10^{-3}	5.6×10^{-4}	3.3×10^{-4}	2.5×10^{-4}
630–679	1.3×10^{-2}	2.7×10^{-3}	7.2×10^{-4}	4.3×10^{-4}	3.2×10^{-4}
680–729	8.5×10^{-3}	1.8×10^{-3}	4.9×10^{-4}	2.9×10^{-4}	2.2×10^{-4}
730–779	9.7×10^{-3}	2.0×10^{-3}	5.5×10^{-4}	3.3×10^{-4}	2.5×10^{-4}
780–829	1.2×10^{-2}	2.4×10^{-3}	6.6×10^{-4}	3.9×10^{-4}	2.9×10^{-4}
830–880	1.1×10^{-2}	2.3×10^{-3}	6.2×10^{-4}	3.7×10^{-4}	2.8×10^{-4}
380–880	1.4×10^{-2}	2.8×10^{-3}	7.5×10^{-4}	4.5×10^{-4}	3.4×10^{-4}