CHARMED MESON AND BARYON SPECTROSCOPY

SELECTED RECENT EXPERIMENTAL RESULTS

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on behalf of the LHCb collaboration
with input from representatives of Belle and BESIII

University of Glasgow | Experimental Particle Physics

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OUTLINE

1. NEW BARYON RESONANCES
   - Evidence for a new state decaying to $\Sigma_c^{++(0)}\pi^{-(+)}$ at Belle: Phys.Rev.Lett. 130 (2023) 3, 031901 (arXiv:2206.08822 [hep-ex])
   - More $\Omega_c(X)^0$ states at LHCb: LHCb-PAPER-2022-043 (arXiv:2302.04733 [hep-ex])
2. PARTICLE PROPERTIES
   - $\Lambda_c(2625)^+$ properties at Belle: Phys.Rev.D 107 (2023) 3, 032008 (arXiv:2212.04062 [hep-ex])
   - Spin and parity of $D^*_{(s)}$ at BESIII: arXiv:2305.14631 [hep-ex]
3. STRONG AND EM DECAYS
   - Observation of $D^{*0} \to D^0 e^+ e^-$ at BESIII: Phys.Rev.D 104 (2021) 11, 112012 (arXiv:2111.06598 [hep-ex])
   - Branching fraction of $D_s^{*+} \to D_s^+ \pi^0$ at BESIII: Phys.Rev.D 107 (2023) 3, 032011 (arXiv:2212.13361 [hep-ex])
4. DOUBLY-CHARMED BARYONS
   - Observation of $\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+$ at LHCb: JHEP 05 (2022) 038 (arXiv:2202.05648 [hep-ex])
   - Continuing search for Ξ_{cc}^+ at LHCb: JHEP 12 (2021) 107 (arXiv:2109.07292 [hep-ex])

New baryon resonances

ANALYSIS OF $\Sigma_c^{++(0)}\pi^{-(+)}$ IN $\bar{B}^0$ DECAYS

BELLE: PHYS.REV.LETT. 130 (2023) 3, 031901 (ARXIV:2206.08822 [HEP-EX])

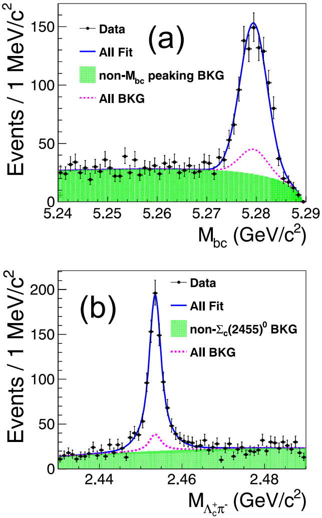
Part of an analysis of $\bar{B}^0 \to \Lambda_c^+\pi^+\pi^-\bar{p}$

- Full Belle $\Upsilon(4S)$ dataset,
- Includes Λ_c^+ reconstructed as $pK^-\pi^+$, pK_S^0, and $\Lambda\pi^+$.

Subdecay $\bar{B}^0 \to \Sigma_c^0(\Lambda_c^+\pi^-)\pi^+\bar{p}$

- Yield from simultaneous fit to
  - Beam-constrained $\bar{B}^0$ mass, M_{bc},
  - $M(\Lambda_c^+\pi^-)$.
- Subset used in subsequent quasi-3-body analysis: $|M(\Lambda_c^+\pi^-) - m_{\mathrm{PDG}}(\Sigma_c^0)| < 14\,\mathrm{MeV}$.

Similarly for $\bar{B}^0 \to \Sigma_c^{++}(\Lambda_c^+\pi^+)\pi^-\bar{p}$.



Evidence for a new baryon state

Belle: Phys.Rev.Lett. 130 (2023) 3, 031901 (arXiv:2206.08822 [hep-ex])

Coincident peaking features in

- $M(\Sigma_c^0(\Lambda_c^+\pi^-)\pi^+)$, and
- $M(\Sigma_c^{++}(\Lambda_c^+\pi^+)\pi^-)$.

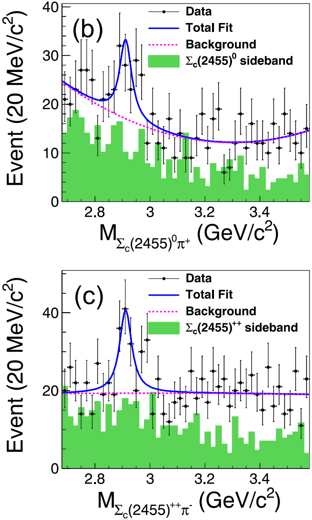
Not observed in $\bar{B}^0$ and $\Sigma_c^{++(0)}$ mass sidebands.

Provisionally assumed to be a new state,

- Tentatively named $\Lambda_c(2910)^+$.

Fits to combined $M\left(\Sigma_c^{++(0)}(\Lambda_c^+\pi^{-(+)})\pi^{+(-)}\right)$

- 4.2σ total yield significance,
- $M(\Lambda_c(2910)^+) = 2913.8 \pm 5.6 \pm 3.8\,\mathrm{MeV}$,
- $\Gamma(\Lambda_c(2910)^+) = 51.8 \pm 20.0 \pm 18.8\,\mathrm{MeV}$.



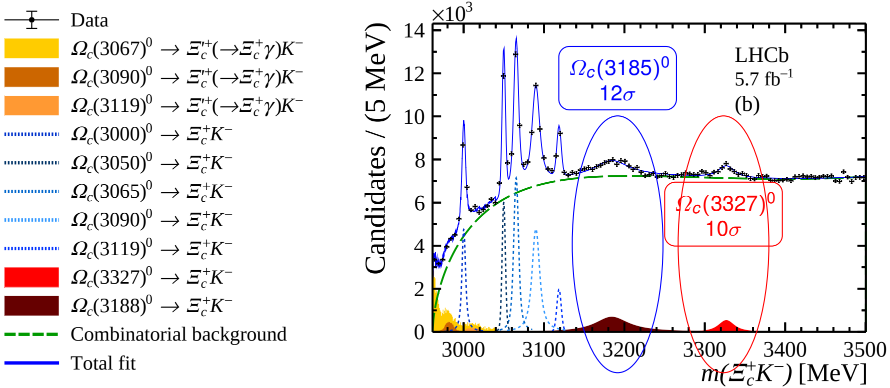
More $\Omega_c(X)^0$ states!

LHCb: LHCb-PAPER-2022-043 (arXiv:2302.04733 [hep-ex])

Updates Phys.Rev.Lett. 118 (2017) 18, 182001, the analysis of the $M(\Xi_c^+ K^-)$ spectrum, to the full Run 1 + Run 2 data set.

- Approximately 5× more signal due to Run 2 $\sqrt{s}$ and trigger.

Two additional observed peaks!



MASSES AND WIDTHS OF $\Omega_c(X)^0$ STATES

LHCb: LHCb-PAPER-2022-043 (ARXIV:2302.04733 [HEP-EX])

Masses and widths measured with improved precision over previous measurements.

Resonance	m (MeV)	Γ (MeV)	Also seen
$\Omega_c(3000)^0$	$3000.44 \pm 0.07\ ^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23\ ^{+1.59}_{-0.29}$	[1],[2]
$\Omega_c(3050)^0$	$3050.18 \pm 0.04\ ^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17\ ^{+0.64}_{-0.72}$ < 1.8 MeV, 95% C.L.	[1],[2]
$\Omega_c(3065)^0$	$3065.63 \pm 0.06\ ^{+0.06}_{-0.06} \pm 0.23$	$3.79 \pm 0.20\ ^{+0.38}_{-0.47}$	[1],[2]
$\Omega_c(3090)^0$	$3090.16 \pm 0.11\ ^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44\ ^{+0.61}_{-1.62}$	[1],[2]
$\Omega_c(3119)^0$	$3118.98 \pm 0.12\ ^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63\ ^{+0.90}_{-1.05}$ < 2.5 MeV, 95% C.L.	
$\Omega_c(3185)^0$	$3185.1 \pm 1.7\ ^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7\ ^{+10}_{-20}$	
$\Omega_c(3327)^0$	$3327.1 \pm 1.2\ ^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5\ ^{+13}_{-1}$	

[1] Belle $e^+e^- \to \Xi_c^+ K^- X$, Phys.Rev.D 97 (2018) 5, 051102
[2] LHCb $\Omega_b^- \to \Xi_c^+ K^- \pi^+$, Phys.Rev.D 104 (2021) 9, L091102

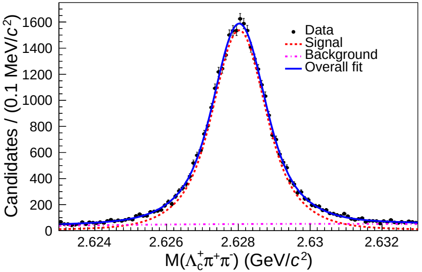
Particle properties

MASS AND WIDTH OF $\Lambda_c(2625)^+$

BELLE: PHYS.REV.D 107 (2023) 3, 032008 (ARXIV:2212.04062 [HEP-EX])

Analysis of $\Lambda_c(2625)^+ \to \Lambda_c^+ \pi^- \pi^+$ in full Belle dataset

- $\mathcal{L}_{\text{int}} = 980\,\text{fb}^{-1}$,
- Λ_c^+ subdecay to $p^+ K^- \pi^+$,
- Approximately 30k signal decays.



Mass and width of $\Lambda_c(2625)^+$ measured with $M(\Lambda_c^+ \pi^- \pi^+)$ distribution

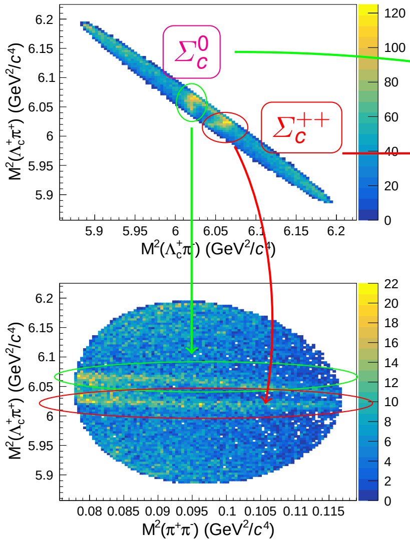
- Kinematic fit of the decay with Λ_c^+ constrained to world average,
- Width consistent with experimental resolution.

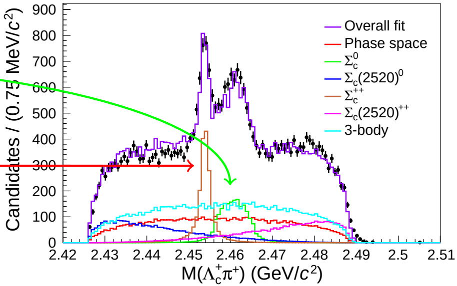
	$m(\Lambda_c(2625)^+) - m(\Lambda_c^+)$ (MeV)	$\Gamma(\Lambda_c(2625)^+)$ (MeV)
This result	$341.518 \pm 0.006 \pm 0.049$	< 0.52
PDG 2022[1]	341.65 ± 0.13	< 0.97

[1] PDG 2022 WA dominated by CDF: Phys.Rev.D 84 (2011) 012003

AMPLITUDE ANALYSIS OF $\Lambda_c(2625)^+ \to \Lambda_c^+ \pi^- \pi^+$

BELLE: PHYS.REV.D 107 (2023) 3, 032008 (ARXIV:2212.04062 [HEP-EX])





Amplitude fit with 5 signal comp.

- $\Sigma_c^{++(0)}\pi^{-(+)}$,
- Off-shell $\Sigma_c(2520)^{++(0)}\pi^{-(+)}$,
- Non-resonant $\Lambda_c^+\pi^-\pi^+$.

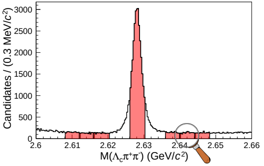
Used to measure relative BR of $\Sigma_c^{++(0)}\pi^{-(+)}$.

SIDEBAND ANALYSIS OF $\Lambda_c(2625)^+ \to \Lambda_c^+\pi^-\pi^+$

BELLE: PHYS.REV.D 107 (2023) 3, 032008 (ARXIV:2212.04062 [HEP-EX])

Non-$\Lambda_c(2625)^+$ contributions to $\Sigma_c^{++(0)}\pi^{-(+)}$ estimated by analysis of $M(\Lambda_c^+\pi^-\pi^+)$ sidebands,

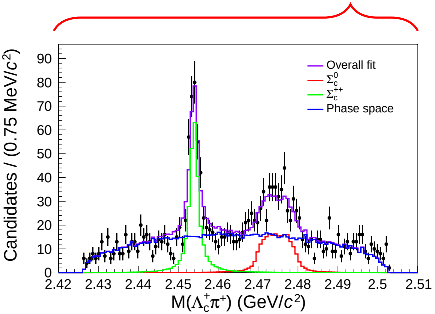
- 6 sidebands (3 on each side),
- Linear extrapolation to $\Lambda_c(2625)^+$ signal region.



$$\frac{\mathcal{B}(\Lambda_c(2625)^+\to\Sigma_c^{++(0)}\pi^{-(+)})}{\mathcal{B}(\Lambda_c(2625)^+\to\Lambda_c^+\pi^-\pi^+)} = \frac{N_{\rm sig}(\Sigma_c^{++(0)})-N_{\rm bkg}(\Sigma_c^{++(0)})}{N_{\rm sig}(\Lambda_c(2625)^+)}$$

$$\frac{\mathcal{B}(\Lambda_c(2625)^+\to\Sigma_c^{++}\pi^{-})}{\mathcal{B}(\Lambda_c(2625)^+\to\Lambda_c^+\pi^-\pi^+)} = (5.13\pm0.26\pm0.32)\%$$

$$\frac{\mathcal{B}(\Lambda_c(2625)^+\to\Sigma_c^{0}\pi^{+})}{\mathcal{B}(\Lambda_c(2625)^+\to\Lambda_c^+\pi^-\pi^+)} = (5.19\pm0.23\pm0.40)\%$$

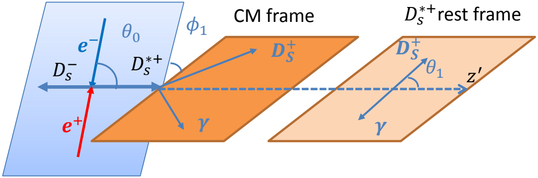


SPIN AND PARITY OF $D^*_{(s)}$

BESIII: ARXIV:2305.14631 [HEP-EX]

Helicity amplitude analysis in 3.19 fb^{-1} of e^+e^- at $\sqrt{s} = 4.178\,\text{GeV}$

1. $e^+e^- \to \gamma^* \to D^{*0}\bar{D}^0$, $D^{*0} \to D^0\pi^0$
2. $e^+e^- \to \gamma^* \to D^{*+}D^-$, $D^{*+} \to D^+\pi^0$
3. $e^+e^- \to \gamma^* \to D_s^{*+}D_s^-$, $D_s^{*+} \to D_s^+\gamma$



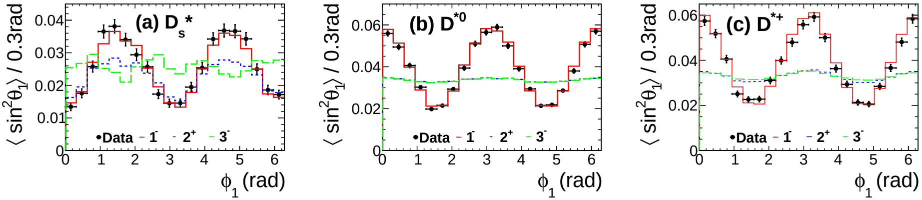
Likelihoods for each natural J^P in $\{1^-, 2^+, 3^-\}$ constructed from helicity amplitudes,

$$\mathcal{L}^{J^P} = \prod_{i=1}^{N_{\text{evts}}} \frac{1}{\mathcal{C}} \mathcal{W}^{J^P}(\theta_0^i, \theta_1^i, \phi_1^i, m_{12}) = \prod_{i=1}^{N_{\text{evts}}} \frac{1}{\mathcal{C}} \overline{\sum_{m,\lambda_i}} \left| A(m, \lambda_1, \theta_0^i, \theta_1^i, \phi_1^i, m_{12}) \right|^2$$

where m is the helicity of γ^* and λ_1 the helicity of the γ or π^0 from the D^*.

SPIN AND PARITY OF $D^*_{(s)}$

BESIII: ARXIV:2305.14631 [HEP-EX]



For each of D_s^{*+}, D^{*0}, and D^{*+}, $J^P = 1^-$ fits well.

$J^P = 2^+$ and 3^- tested as 'null hypotheses'

- Likelihood compared to that of a linear combination of $J^P = 1^-$ and the 'null' J^P.

Process	Hypothesis	$\Delta(-2\ln\mathcal{L})$
$D_s^{*+}D_s^-$	1^- over 2^+	1102
	1^- over 3^-	2104
$D^{*0}\bar{D}^0$	1^- over 2^+	12134
	1^- over 3^-	12096
$D^{*+}D^-$	1^- over 2^+	11308
	1^- over 3^-	11222

In all cases, the bare 'null' $J^P = 2^+$ and 3^- disfavored by $> 10\sigma$.

Strong and EM decays

OBSERVATION AND BR OF $D^{*0} \to D^0 e^+ e^-$

BESIII: PHYS.REV.D 104 (2021) 11, 112012 (ARXIV:2111.06598 [HEP-EX])

Analysis in $e^+e^- \to D^{*0}\bar{D}^{*0}$ events from $3.19\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 4.178\,\mathrm{GeV}$.

D^0 reconstructed in decay modes $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^-\pi^+$.

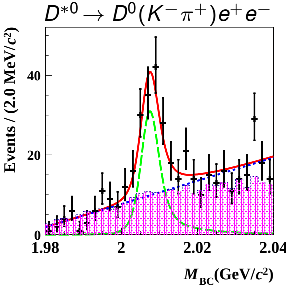
Backgrounds from $D^{*0} \to D^0\gamma$ via $\gamma \to e^+e^-$ material conversions suppressed by e^+e^- vertex cut.

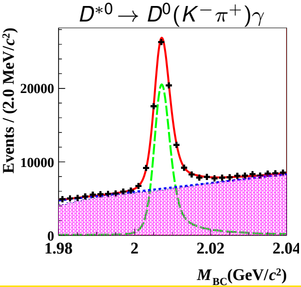
Clear $D^{*0} \to D^0 e^+e^-$ peak in each D^0 mode,

- 13.2σ total statistical significance.

Branching ratio measured relative to $D^{*0} \to D^0\gamma$:

$$\frac{\mathcal{B}(D^{*0}\to D^0 e^+e^-)}{\mathcal{B}(D^{*0}\to D^0\gamma)} = (11.08 \pm 0.76 \pm 0.49) \times 10^{-3}$$





BRANCHING FRACTION OF $D_s^{*+} \to D_s^+ \pi^0$

BESIII: PHYS.REV.D 107 (2023) 3, 032011 (ARXIV:2212.13361 [HEP-EX])

Analysis of $e^+e^- \to D_s^{*+} D_s^-$ events from $7.33\,\text{fb}^{-1}$ at $\sqrt{s} = 4.128$ to $4.226\,\text{GeV}$.

Reconstruct both D_s^+ and D_s^- in each event,

- In decays to either $K^\pm K^\mp \pi^\pm$ or $K_S^0 K^\pm$

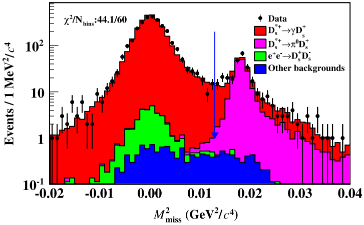
Spectrum of squared missing mass,

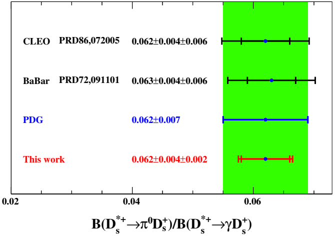
$$M^2_{\text{miss}} \equiv (\sqrt{s} - E_{D_s^+} - E_{D_s^-})^2 - |\vec{p}_{D_s^+} + \vec{p}_{D_s^-}|^2,$$

- Peaks at 0 for $D_s^{*\pm} \to D_s^\pm \gamma$,
- Peaks at $m^2_{\pi^0}$ for $D_s^{*\pm} \to D_s^\pm \pi^0$.

Cut-and-count methodology,

- Partition into γ and π^0 regions,
- Unfold with an efficiency matrix.



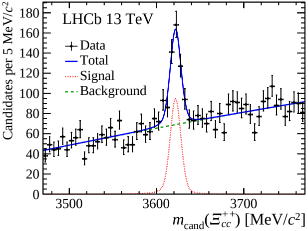


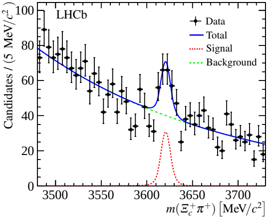
$$\frac{D_s^{*+} \to D_s^+ \pi^0}{D_s^{*+} \to D_s^+ \gamma} = (6.16 \pm 0.43 \pm 0.18)\%$$

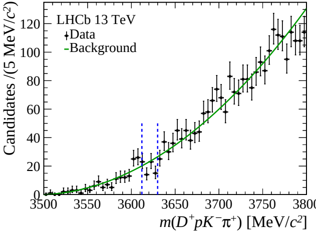
Doubly-charmed baryons

Ξ_{cc} AT LHCb SO FAR

Ξ_{cc}^{++} (*ccu*) baryon observed in two decay modes:







$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ — Phys.Rev.Lett. 119 (2017) 11, 112001

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ — Phys.Rev.Lett. 121 (2018) 16, 162002

$\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ — JHEP 10 (2019) 124

With properties:

- Mass $m = 3621.55 \pm 0.23 \pm 0.30\,\mathrm{MeV}$ (JHEP 02 (2020) 049)
- Lifetime $\tau = 0.256^{+0.024}_{-0.022} \pm 0.014\,\mathrm{ps}$ (Phys.Rev.Lett. 121 (2018) 5, 052002)
- $\left(\frac{\sigma(\Xi_{cc}^{++})\mathcal{B}(\Xi_{cc}^{++}\to\Lambda_c^+K^-\pi^+\pi^+)}{\sigma\Lambda_c^+}\right)_{\rm fid} = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$ (Chin.Phys.C 44 (2020) 2, 022001)

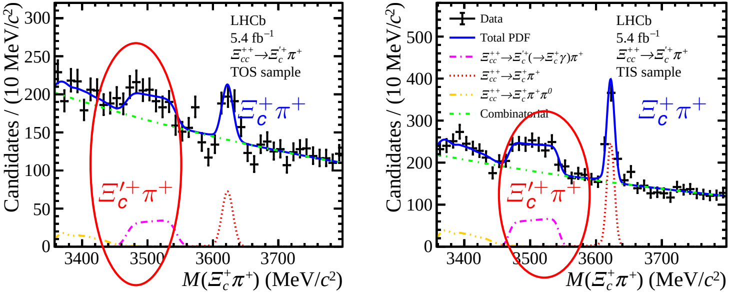
Observation of $\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$

LHCb:JHEP 05 (2022) 038 (arXiv:2202.05648 [hep-ex])

Search in the $\Xi_c^+\pi^+$ mass spectrum (with $\Xi_c^+ \to pK^-\pi^+$),

- Signature of $\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$, $\Xi_c^{\prime +} \to \Xi_c^+\gamma$ with unreconstructed γ,
- Appears as a peaking structure at a lower mass than the previously observed $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$ signal.

Analyzed in two statistically independent subsets



$> 9\sigma$ significance with $\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\pi^+)} = 1.41 \pm 0.17 \pm 0.10$

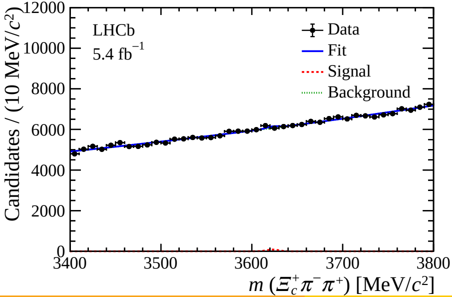
SEARCH FOR $\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{-}\pi^{+}$

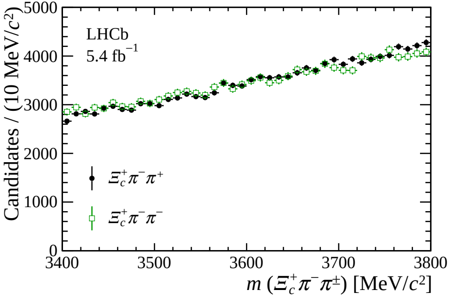
LHCb: JHEP 12 (2021) 107 (ARXIV:2109.07292 [HEP-EX])

Search with a two-tiered selection.

Most restrictive: *default trigger* set,

- Selection and trigger requirements matched to $\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+}$,
- Best precision/upper limits of production $\times$ branching ratio.





Superset: *extended trigger* set.

- More inclusive set of triggers.

Best chance of detecting a signal.

Full analysis, including decision tree of how to present results in all scenarios, fully defined before unblinding.

COMBINATION OF $\Xi_c^+\pi^-\pi^+$ AND $\Lambda_c^+K^-\pi^+$

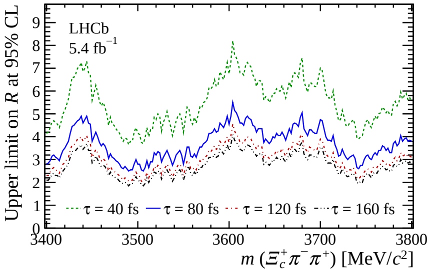
LHCb: JHEP 12 (2021) 107 (ARXIV:2109.07292 [HEP-EX])

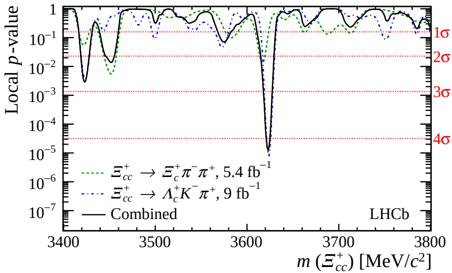
No evidence for $\Xi_{cc}^+ \to \Xi_c^+\pi^-\pi^+$.

Determination of mass-dependent upper limit for

$$R \equiv \frac{\sigma(\Xi_{cc}^+)\times\mathcal{B}(\Xi_{cc}^+\to\Xi_c^+\pi^-\pi^+)}{\sigma(\Xi_{cc}^{++})\times\mathcal{B}(\Xi_{cc}^{++}\to\Xi_c^+\pi^+)}$$

R estimated for several hypothetical lifetimes.





Statistical combination with $\Xi_{cc}^+ \to \Lambda_c^+K^-\pi^+$ search

Sci.China Phys.Mech.Astron. 63 (2020) 2, 221062

Joint fit to the mass spectra.

No evidence for Ξ_{cc}^+

- Largest deviation: 2.9σ after systematics and look-elsewhere.

WRAP-UP AND ACKNOWLEDGMENTS

Our experimental understanding of charm spectroscopy continues to benefit from complementary experiments,

- Direct production in both e^+e^- and pp collisions,
- Production in decay of large b-hadron samples.

The continuously increasing sample sizes are furthering both the precision and comprehensiveness of our knowledge.

Large-sample flavor experiments continue to discover new and interesting behaviors of charmed hadrons.

I thank the following for recommending results to include in this talk:
Federico Betti (LHCb), Wolfgang Gradi (BESIII), Alexander Lenz,
Dominik Mitzel (LHCb), Diego Tonelli (Belle).