First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

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For the LHCb collaboration

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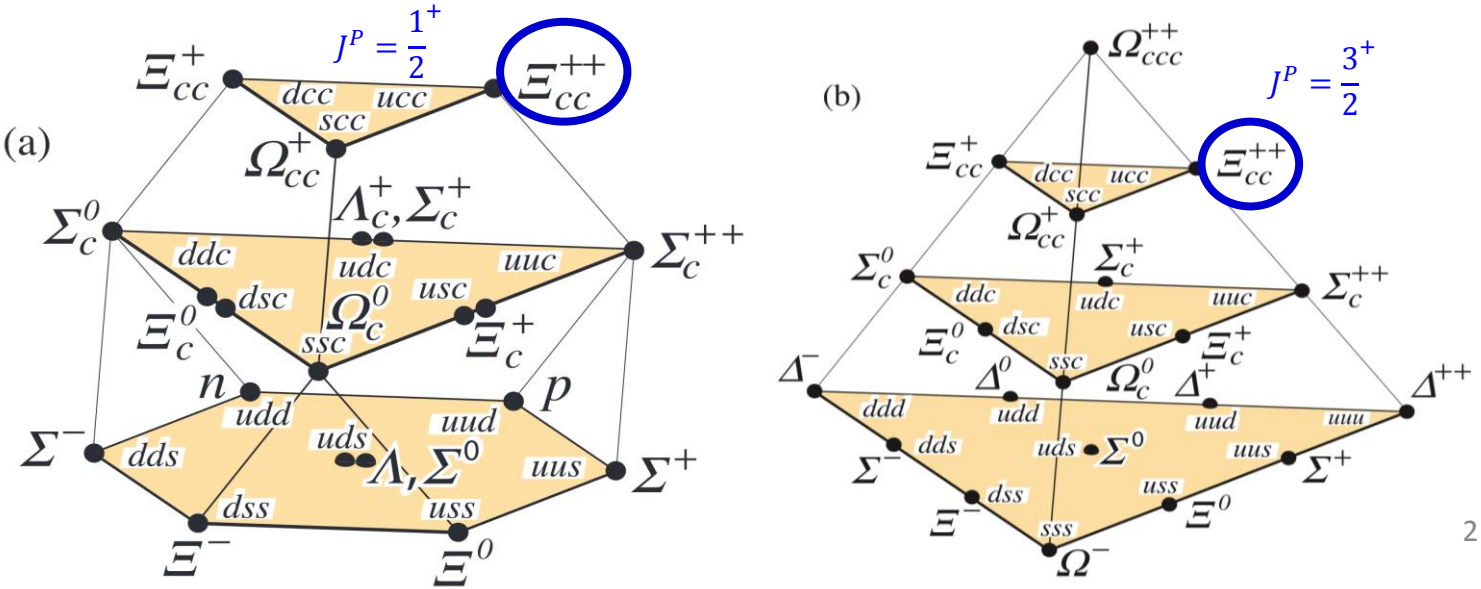
The 4th China Physics collaboration, 17 Dec 2018

Success of the constituent quark model

- **Two SU(4) baryon 20-plets with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$, each contains a SU(3) triplet with two charm quarks: $\Xi_{cc}^+(ccd), \Xi_{cc}^{++}(ccu), \Omega_{cc}^+(ccs)$**

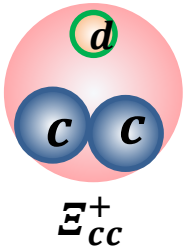
✓ $J^P = \frac{3}{2}^+$ states expected to decay to $\frac{1}{2}^+$ states via strong/electromagnetic interaction

✓ $J^P = \frac{1}{2}^+$ states decay weakly with a c quark transformed to lighter quarks



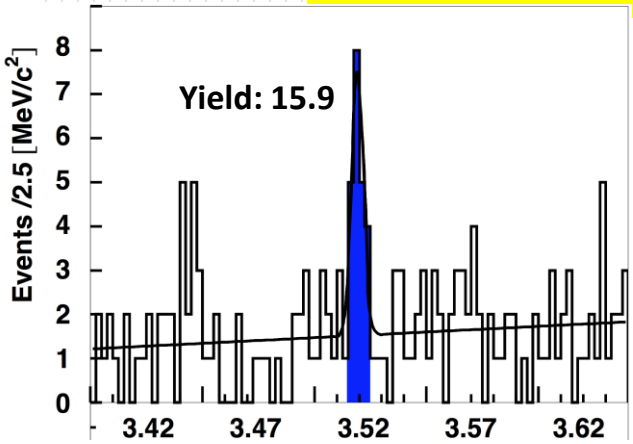
Studies of Ξ_{cc} by SELEX experiment

- **SELEX** (Fermilab E781) claimed observation of $\boldsymbol{\Xi_{cc}^{+}(ccd)}$ in $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ and $\Xi_{cc}^{+} \to p D^{+} K^{-}$ decays
  - ✓ **Short lifetime**: $\tau(\Xi_{cc}^{+}) < 33$ fs @90% CL, but not zero
  - ✓ **Large production**: $R = \dfrac{\sigma(\Xi_{cc}^{+}) \times \mathrm{BF}(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+})}{\sigma(\Lambda_c^{+})} \sim 20\%$
  - ✓ Mass (combined): 3518.7 ± 1.7 MeV

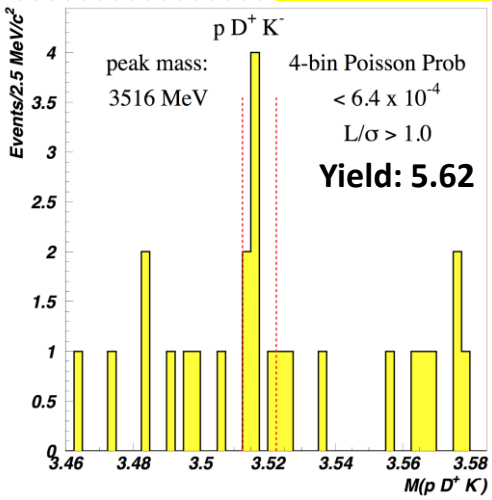


Ξ_{cc}^{+}

$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ **PRL 89 (2002) 112001**



$\Xi_{cc}^{+} \to p D^{+} K^{-}$ **PLB 628 (2005) 18**



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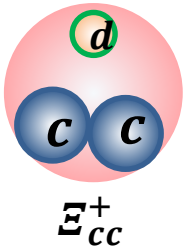
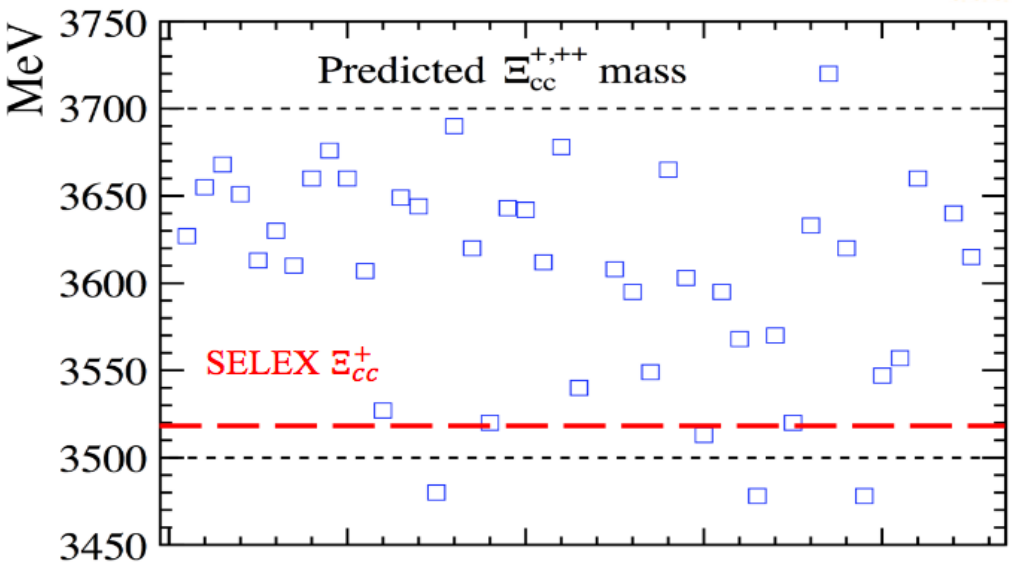
  - ✓ No confirmation from other experiments

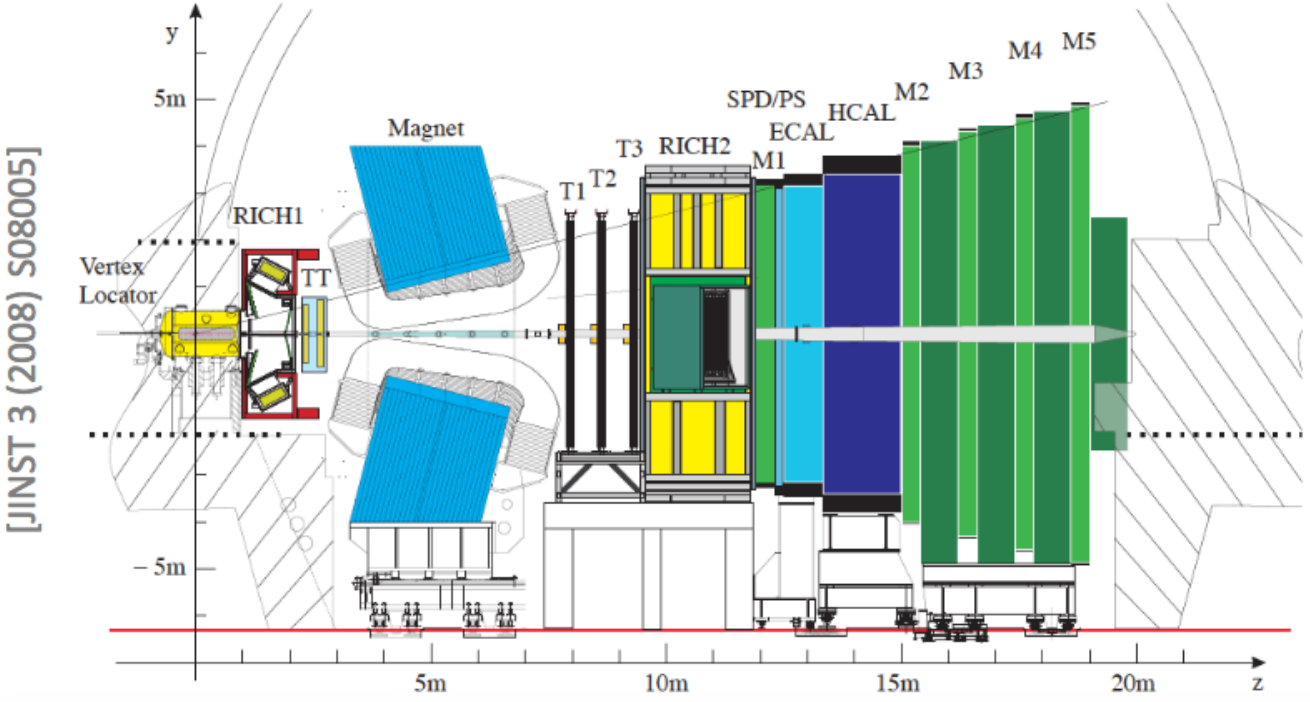


Ξ_{cc}^{+}



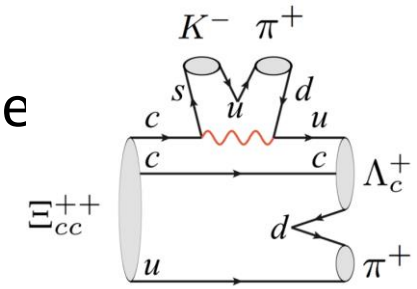
LHCb detector

- LHCb is a forward spectrometer : $2 < \eta < 5$
- Dedicated to precision study of b, c hadrons
- Momentum resolution: 0.5% at 5 GeV, 1.0% at 200 GeV
- Excellent track and vertex reconstruction
- Good PID separation



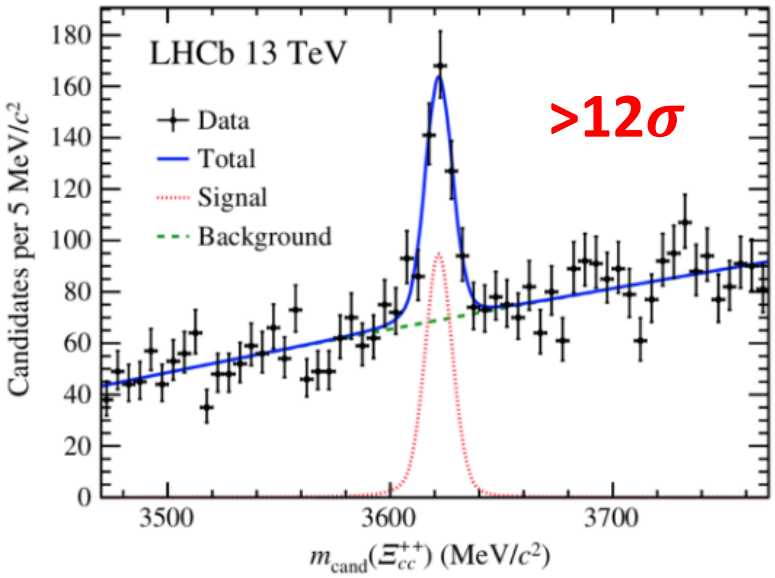
First Observation of Ξ_{cc}^{++}

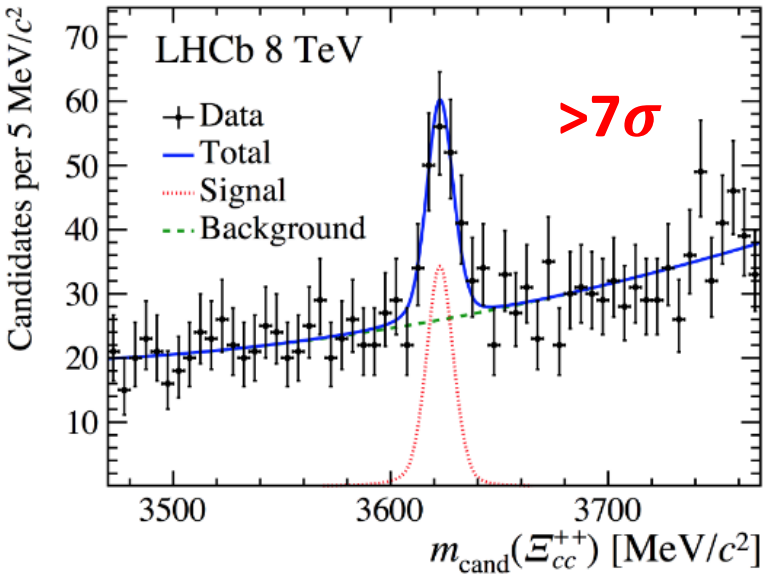
- $\Lambda_c^+ K^- \pi^+ \pi^+$ identified as the most promising channe
- First observed by **LHCb** CPC 42 (2018) 051001



  - ✓ Ξ_{cc}^{++} **mass measured:**
    $\mathbf{3621.40 \pm 0.72(stat) \pm 0.27(syst) \pm 0.14(\Lambda_c^+)\ MeV/c^2}$
  - ✓ Decaying only via weak interaction, mass peak remains after lifetime cut, $t > 5\sigma_t$

PRL 119 (2017) 112001





Searching for $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

- $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ expected to have large BR, one of the best channels to confirm Ξ_{cc}^{++}

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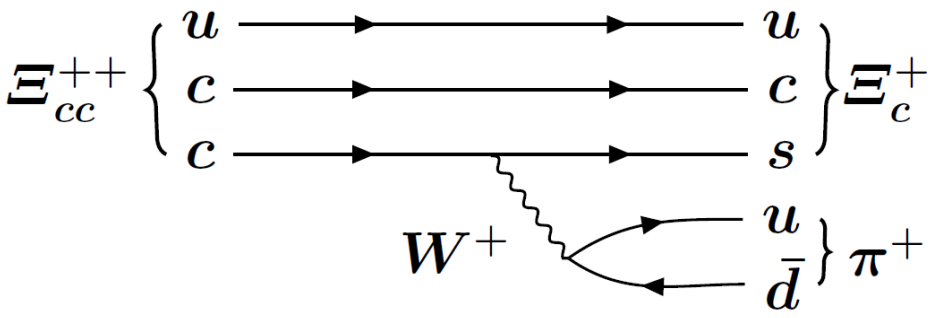
  - ✓ $BR(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \sim \mathcal{O}(1\%)$ **Prediction**
  - ✓ $BR(\Lambda_c^+ \to p^+ K^- \pi^+)$ −(6.23±0.33%) **Measurement**
  - ✓ $BR(\Xi_c^+ \to p^+ K^- \pi^+)$~(2%) **Prediction**
  - ✓ Fewer tracks (4 tracks) → higher efficiency

- Data sample: LHCb runII at $\sqrt{s} = 13\text{TeV}$, $\sim 1.7\text{fb}^{-1}$
  - ✓ Dedicated exclusive trigger ensuring high efficiency, full event reconstruction at trigger level



Analysis strategy

- Blinded analysis
- Event selection of $\Xi_c^+\pi^+$ candidates, 2016 data
- Multivariate selector to suppress combinatorial background
  - ✓ Simulation as signal, data upper sideband as background
- Open signal window
  - ✓ $> 3\sigma$ signal: mass measurement, ratio of branching fraction
  - ✓ Otherwise: upper limit setting

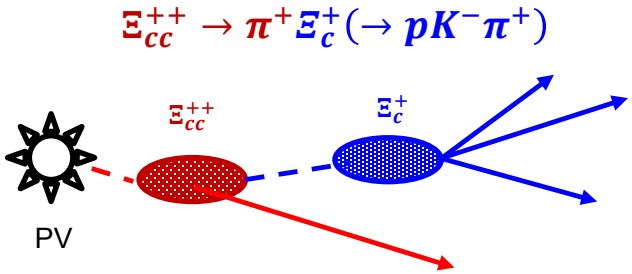
Candidate selection

- $\boldsymbol{\Xi_{cc}}$ cross-section much smaller(~$\times\ \boldsymbol{10^{-5}}$) in pp collisions, expecting large hadronic backgrounds

- $\boldsymbol{\Xi_c^+ \to pK^-\pi^+}$:
  - ✓ $\boldsymbol{p, K^-, \pi^+}$ tracks: particle ID, not produced from primary vertex
  - ✓ $\boldsymbol{\Xi_c^+}$: good vertex quality, separated from primary vertices
  - ✓ $\boldsymbol{p, K^-, \pi^+}$ and $\boldsymbol{\Xi_c^+}$ have large $\boldsymbol{p_T}$

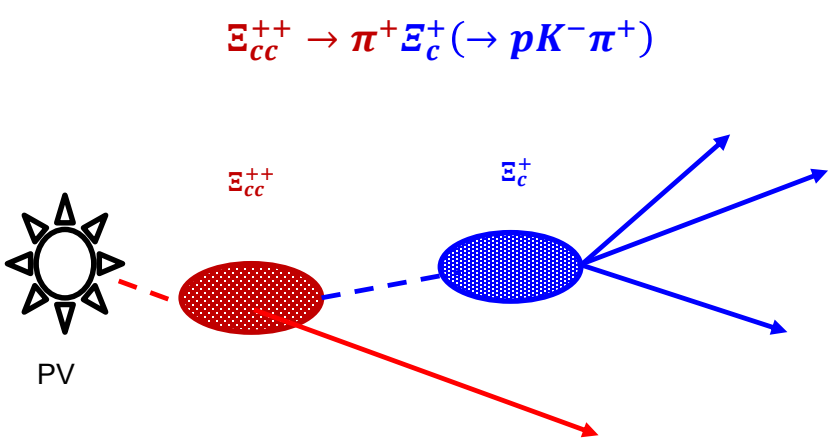
  Strongly suppressing the backgrounds

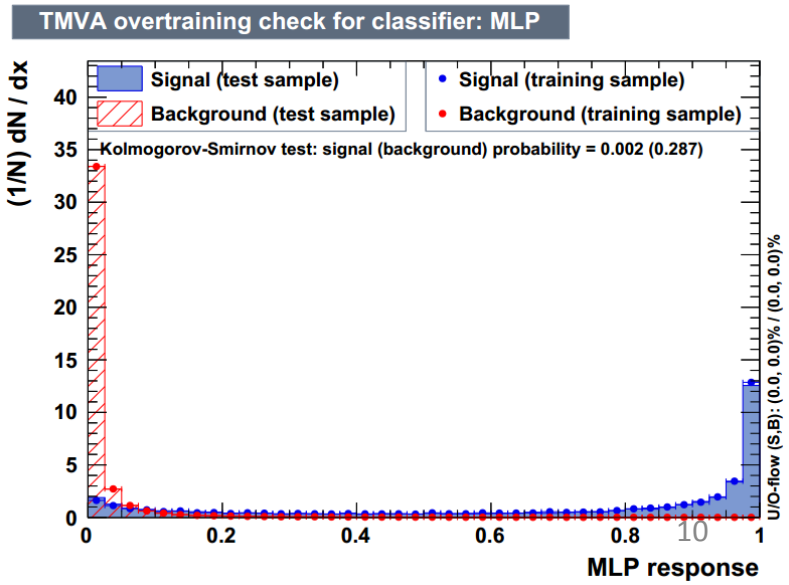
As a follow-up analysis of $\boldsymbol{\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+}$, $\boldsymbol{\Xi_{cc}^{++} \to \Xi_c^+\pi^+}$ has similar selection cuts as in previous analysis.



Machine learning

- Ξ_c^+ combined with PID-selected π^+ tracks to form Ξ_{cc}^{++} candidates
- Multivariate selector is used to further suppress the backgrounds
  - ✓ Decay fit quality（Vertex fitting quality）
  - ✓ Ξ_{cc}^{++} vertex separation from PV
  - ✓ Kinematics of final states
- More sensitive to **long lived** particles





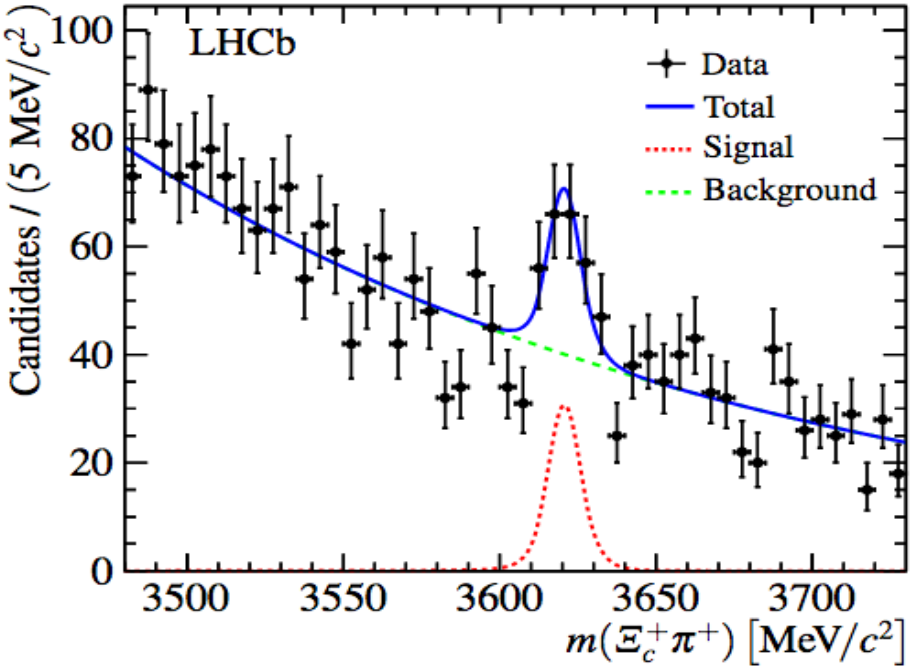
Signal yield

- Significant peak structure around $\mathbf{3620}\ \mathrm{MeV/c^2}$ observed
- Studying Ξ_c^+ mass corrected mass:

$$\mathrm{M_{cand}}(\Xi_{cc}^{++}) = \mathrm{M}(\Xi_c^+\pi^+) - \mathrm{M}(\Xi_c^+) + \mathrm{M}_{PDG}(\Xi_c^+)$$

  - ✓ Signal yields: $\mathbf{91 \pm 20}$
  - ✓ Resolution: 6.45±0.1MeV, consistent with simulated value
  - ✓ Local significance ~**6σ**

PRL 121 (2018) 162002



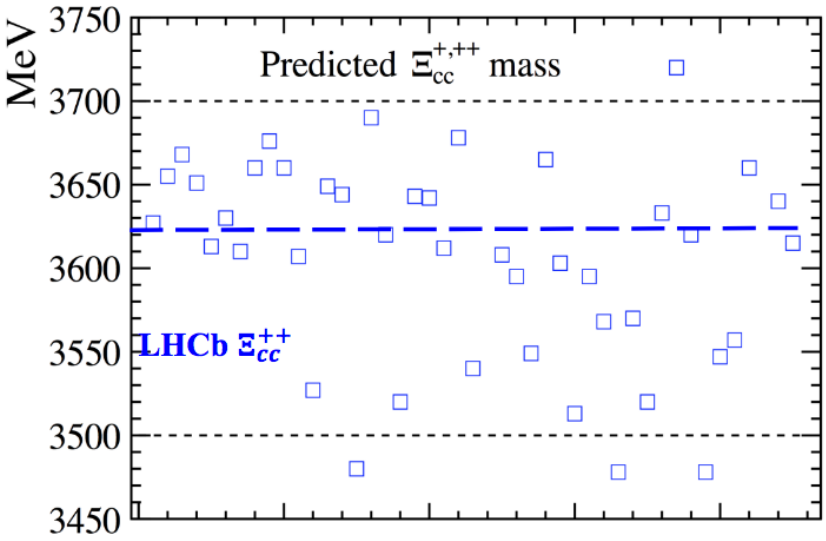
Mass measurement

- Systematic uncertainties studied
- The mass is measured to be

$$m(\Xi_{cc}^{++}) = 3620.56 \pm 1.45\ (\text{stat}) \pm 0.49\ (\text{syst})\ \text{MeV}/c^2$$

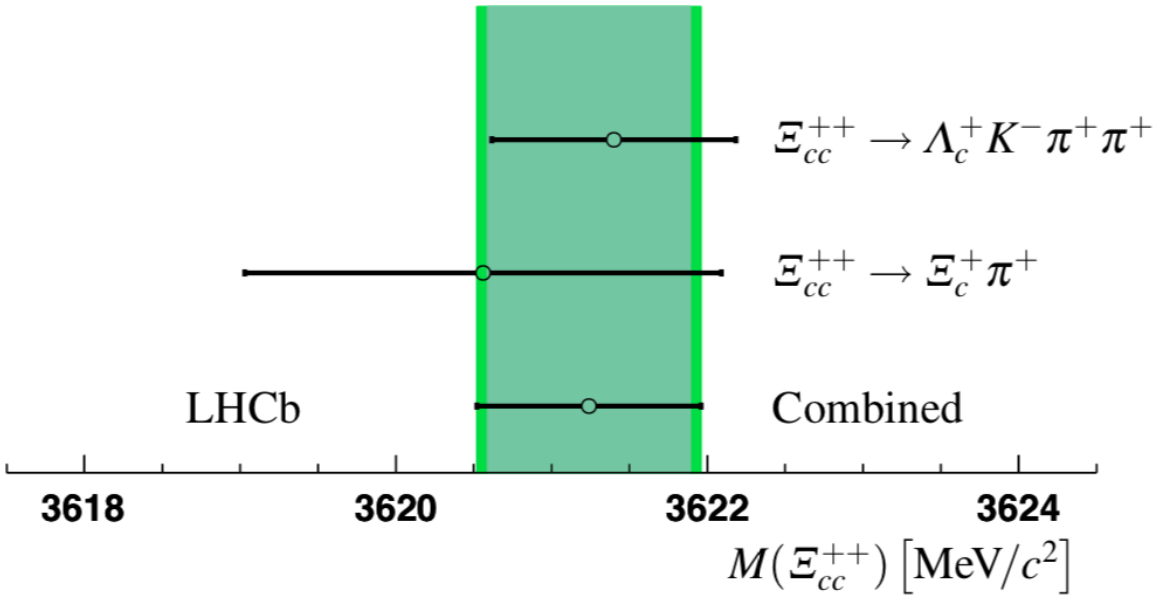
Value consistent with most of theoretical calculations

Source	Value(MeV/c^2)
Momentum-scale calibration	0.38
Ξ_c^+ bias due to selections	0.01
Ξ_{cc}^{++} bias due to selections	0.08
Ξ_{cc}^{++} unknown lifetime	0.03
FSR	0.03
Uncertainty of Ξ_c^+ mass	0.30
Mass fit model	0.05
Total	0.49



Mass Combination

- Consistent with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ result:
  $3621.40 \pm 0.72\,(stat) \pm 0.27\,(\mathrm{syst}) \pm 0.14\,(\Lambda_c^+)\ \mathrm{MeV/c^2}$
- Combined result: $3621.25 \pm 0.65\,(\mathrm{stat}) \pm 0.31\,(\mathrm{syst})\ \mathrm{MeV/c^2}$
  - ✓ Using BLUE method **EPJC 74 (2014) 3004**
  - ✓ Momentum scale and lifetime systematic uncertainties are 100% correlated between two channels
  - ✓ Other systematic uncertainties are uncorrelated



BR fraction measurement

- The ratio of total BR fraction ($\mathcal{R}$):

No direct branching fraction measurement of $\Xi_c^+ \to pK^-\pi^+$ from experiments.

$$\begin{aligned}\mathcal{R} &= \frac{\mathcal{B}\left(\Xi_{cc}^{++} \to \Xi_c^+(\to p^+K^-\pi^+)\pi^+\right)}{\mathcal{B}\left(\Xi_{cc}^{++} \to \Lambda_c^+(\to p^+K^-\pi^+)K^-\pi^+\pi^+\right)} \\ &= \frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+)} \times \frac{\mathcal{B}(\Xi_c^+ \to p^+K^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to p^+K^-\pi^+)} \\ &= \frac{N(\Xi_c^+\pi^+)}{N(\Lambda_c^+K^-\pi^+\pi^+)} \cdot \frac{\varepsilon(\Lambda_c^+K^-\pi^+\pi^+)}{\varepsilon(\Xi_c^+\pi^+)}\end{aligned}$$

- Measure the signal yields and efficiency for each channel:

$$\mathcal{R} = 0.035 \pm 0.009\,(stat) \pm 0.003\,(syst)$$

Consistent with prediction

CPC 42 (2018) 051001

Summary

- $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ is observed in the 2016 data sample
  - ✓ Signal yield: 91 ± 20
  - ✓ Significance is about $\boldsymbol{6\sigma}$
- The measured mass result is:

$$\mathbf{3620.56 \pm 1.45\ (stat) \pm 0.49\ (syst)\ MeV/c^2}$$

  - ✓ Good agreement with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ result

$$\mathbf{3621.4 \pm 0.72\ (stat) \pm 0.27\ (syst)\ MeV/c^2}$$

- The measured relative BR fraction is :

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

$$= \mathbf{0.035 \pm 0.009\ (stat) \pm 0.003\ (syst)}$$

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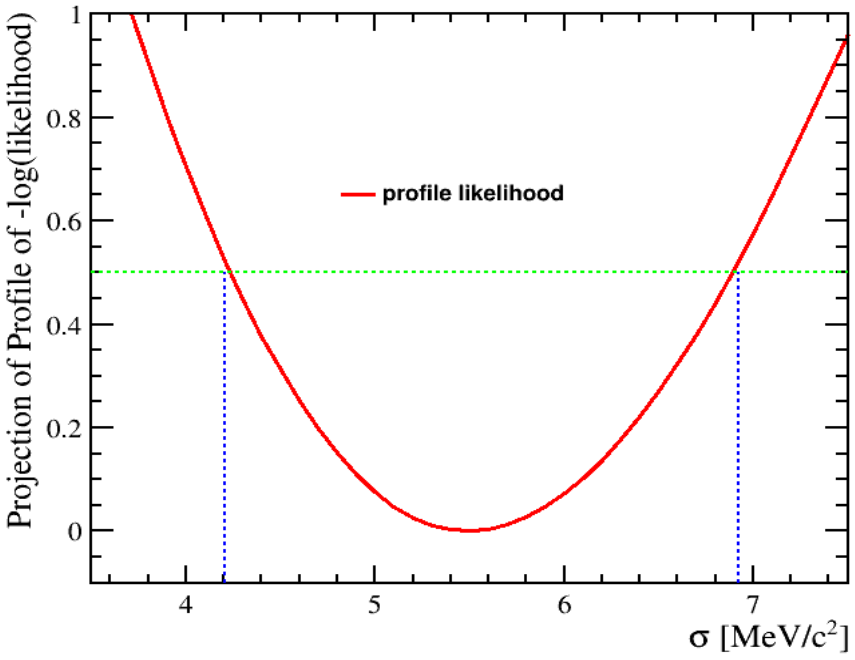
Back Up

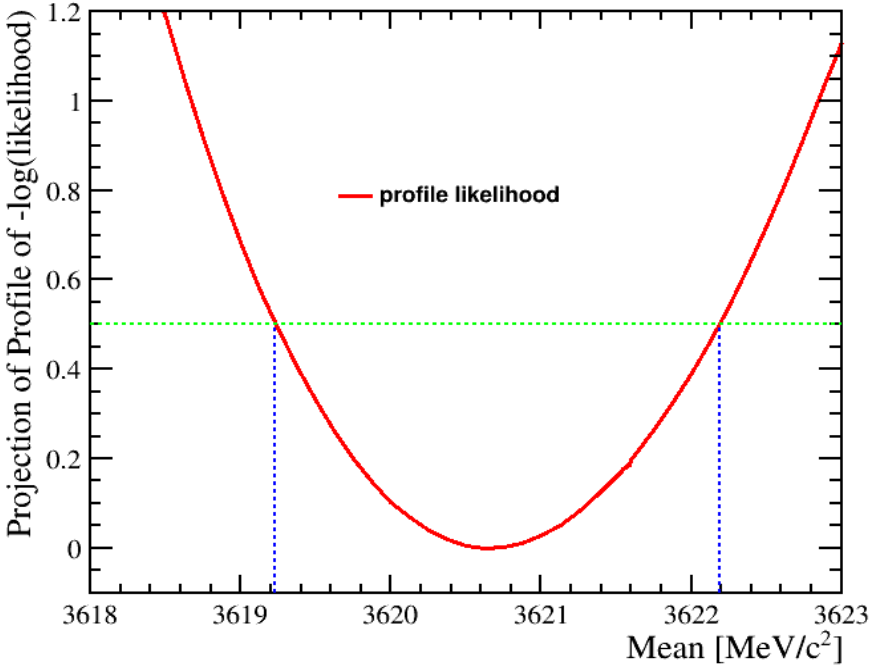
Profile likelihood scan

- $m(\Xi_{cc}^{++}) = 3620.66 \pm 1.45\ (\text{stat})\ \text{MeV/c}^2$

$\boldsymbol{\mu}$



$\boldsymbol{\sigma}$



Uncertainty

Source	Mass [MeV/c^2]	$\mathcal{R}(\mathcal{B})$ [%]
Momentum calibration	0.38	—
Selection bias correction	0.10	—
Fit model	0.05	5.2
Relative efficiency	—	6.5
Simulation modelling	—	1.2
Selection	—	0.7
Sum in quadrature	0.40	8.5

- With limited statistics of both signal and control samples, the dominated uncertainty is statistical uncertainty (1.5 MeV, 0.009)