Experimental review of baryons with two heavy quarks (including $P_c$)

Liming Zhang (Tsinghua University)
Outline

- Doubly-charmed baryon at LHCb
  - Observation of $E_{cc}^{++}$ with $\Lambda_c^+ K^- \pi^+ \pi^+$ and $E_c^+ \pi^+$ decays
  - Search for $E_{cc}^{++} \rightarrow D^+ p K^- \pi^+$ decays
  - Prospects for other doubly-charmed baryons

- Hidden-charm pentaquarks
  - Recall of 2015 observation at LHCb
  - Recent pentaquark results at LHCb
  - Pentaquark search at GlueX
The LHCb Experiment

- LHCb is a dedicated flavour physics experiment at the LHC
  - $>10^4 \times$ larger $b$ production rate than the B factories @ Y(4S)
  - Access to all $b$-hadrons: $B^+, B^0, B^+_S, B^+_c$, $b$-baryons
- Can also study hadron spectroscopy and exotic states
- Acceptance optimised for forward $b\bar{b}$ production

- $\Theta^{++}$ results based on 2016 1.7fb$^{-1}$ data
- Pentaquark results based on full dataset

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Two methods for spectroscopy at LHCb

- Direct production in $pp$ collisions
  - Combine a heavy flavour (HF) hadron with one or more light particles
  - Pros: high statistics
  - Cons: large background

- Production by a heavier particle decay, usually with amplitude analysis
  - Pros: low background, better determination of $J^P$
  - Cons: less statistics

\[ \Xi^{++}_{cc} \to K^-\pi^+\pi^+ \Lambda_c^+ (\to pK^-\pi^+) \]

\[ \Lambda_b^0 \to K^-\Lambda_c^+ (\to J/\psi p) \]
In 1964, Gell-Mann and Zweig proposed a way to construct the numerous hadrons using three fundamental particles: quarks. Successfully predicted $\Omega^-(sss)$.

Three quarks ($u, d, s$) can explain all observed particles at that time, called flavor SU(3) multiplets.

Quark model (QM)
1964-1974 was a barren time for particle physics

The QM had some striking successes, but was in an uncomfortable situation

- No discovery of free quarks (explained by quark confinement)

What rescued the QM was completely unexpected: the discovery of $J/\psi$ meson and the fourth quark charm

- Announced on Nov. 11 1974 independently by S. Ting (BNL) and B. Richter (SLAC)

The fifth quark bottom was discovered 3 years later in 1977
Quark model (QM)

Multiquark objects were predicted in the birth of Quark model - now called exotic

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

...
Doubly-charmed baryon
The doubly-charmed baryons

- 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: $\Xi^{++}_{cc}(dcc)$, $\Xi^{++}_{cc}(ucc)$, $\Omega^{++}_{cc}(scc)$

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

- $J^P = \frac{1}{2}^+$ states decay weakly with a $c$ quark transformed to lighter quarks
Doubly charmed baryons: motivation

- Doubly charmed baryons are not all established

- Baryons with two heavy quarks provide a unique system to test QCD [hep-ph/9811212]
  - The heavy quarks are nearly static and act as a center of gravity for the hadron
  - HQET: two charm quarks considered as a heavy diquark, doubly heavy baryon similar to a heavy meson $\bar{Q}q$
  - Such diquark can naturally extend to $\bar{Q}q\bar{q}q = ccq\bar{q}q$ exotic system
  - Doubly heavy baryons’ mass and decay width to test QCD motivated models
SELEX results on $E_{cc}^+$

- SELEX (Fermilab E781) collides high energy hyperon beams ($\Sigma^-$) with nuclear targets ($p$)
- Observation of $E_{cc}^+(dcc)$ reported by SELEX
  - Mass: $3518.7 \pm 1.7$ MeV
  - Short lifetime: $\tau(E_{cc}^+) < 33$ fs @90% CL, but not zero
  - Large production: $R = \frac{\sigma(E_{cc}^+) \times BF(E_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} \sim 20\%$

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

$E_{cc}^+ \to pD^+\pi^-$ PLB 628 (2005) 18

$N_{\text{sig}} = 15.9 \quad 6.3\sigma$

SELEX

$N_{\text{sig}} = 5.6 \quad 4.8\sigma$

SELEX

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SELEX results not confirmed


- However, these experiments have different production environments than that of SELEX
Observation of $E_{cc}^{++}$ from two decay modes

- Expect $E_{cc}^{++}$ (ucc) has higher sensitivity at LHCb due to longer lifetime [larger $B$ and higher efficiency] [Yu et al., arXiv:1703.09086, CPC 42 (2018) 051001]

- Observed two suggested decay modes
  - Reconstruct $\Lambda_c^+$ and $E_c^+$ (singly Cabibbo-suppressed) by decay $pK^-\pi^+$
  - $\epsilon(\Lambda_c^+K^-\pi^+\pi^+)/\epsilon(E_c^+\pi^+) = 0.110$ due to two more tracks in former decay

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Observation of new decay mode $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$

- Ratio of branching fractions

$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+; \Xi_c^+ \rightarrow pK^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+; \Lambda_c^+ \rightarrow pK^- \pi^+)} = (3.5 \pm 0.9 \pm 0.3) \times 10^{-2}$$

- $\mathcal{B}(\Lambda_c^+ \rightarrow pK^- \pi^+) = (6.28 \pm 0.32)\%$ [PDG] and $\mathcal{B}(\Xi_c^+ \rightarrow pK^- \pi^+) = (0.45 \pm 0.21 \pm 0.07)\%$

  [1st absolute measurement, Belle, arXiv:1904.12093]

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)} = 0.49 \pm 0.13(\mathcal{R}) \pm 0.24(\mathcal{B}_{\Xi_c^+}) \quad [\text{my computation}]$$

- $\Xi_c^0 \pi^+$ would be a good mode to search for $\Xi_{cc}^{++}$, but the most efficient decay $\Xi_c^0 \rightarrow pK^- K^- \pi^+$ suffers low $\mathcal{B}(\Xi_c^0 \rightarrow pK^- K^- \pi^+) = (0.58 \pm 0.23 \pm 0.05)\%$

  [Belle, PRL 122 (2019) 082001]
Observation of new decay mode $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$

- **Consistent mass measurements**

  $3621.40 \pm 0.72 \pm 0.27 \pm 0.14(\Lambda_c^+) \text{ MeV}$

  $3620.56 \pm 1.5 \pm 0.4 \pm 0.3(\Xi_c^+) \text{ MeV}$

  $3621.24 \pm 0.65 \pm 0.31 \text{ MeV}$

- Mass difference: $m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_{cc}^+)_{\text{SELEX}} = 103 \pm 2 \text{ MeV}$

  - Inconsistent with being isospin partners
Search for $\Xi_{cc}^{++} \rightarrow D^+ p K^- \pi^+$

- Decay diagram is similar to that of $\Lambda_c^+ K^- \pi^+ \pi^+$, but smaller phase space
  - Just swap $u$ and $c$ quarks
- Efficiency is similar
- No evident signal
- Very stringent upper limit is obtained

$$R = \frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow D^+ p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)} < 0.021 @ 95\% \text{ C.L.}$$

arXiv:1905.02421

More details see "Baryon spectroscopy at LHCb" on 20/8 (Tues.) at S2 by Ao Xu
First measurement of $\Xi_{cc}^{++}$ lifetime

Using $\Xi_{cc}^{++} \rightarrow \Lambda_{c}^{+} K^{-} \pi^{+} \pi^{+}$ decays

$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_{b}^{0}}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_{b}^{0}}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_{b}^{0}}}\right)}$$

PRL 121 (2018) 052002

$$\tau_{\Xi_{cc}^{++}} = 256^{+24}_{-22} \pm 14 \text{ fs}$$

Precision 10.5%

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal and background mass models</td>
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</tr>
<tr>
<td>Correlation of mass and decay-time</td>
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</tr>
<tr>
<td>Binning</td>
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<tr>
<td>Data-simulation differences</td>
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<tr>
<td>Resonant structure of decays</td>
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<tr>
<td>Hardware trigger threshold</td>
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<tr>
<td>Simulated $\Xi_{cc}^{++}$ lifetime</td>
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<tr>
<td>$\Lambda_{b}^{0}$ lifetime uncertainty</td>
<td>0.001</td>
</tr>
<tr>
<td>Sum in quadrature</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Confirmed it is weakly decaying $J = \frac{1}{2}$ ground state
Mass and lifetime predictions vs measurements

- Predicted $\Xi_{cc}^{++}$ masses in range $3.5 - 3.7$ GeV
- Mass splitting between $\Xi_{cc}^+$ and $\Xi_{cc}^{++}$ only a few MeV due to $u, d$ symmetry
- Expectation: $\tau(\Xi_{cc}^{++}) \approx 3 \times \tau(\Xi_{cc}^+)$
- Calculations give $\tau(\Xi_{cc}^{++}) \in [200 - 1550]$ fs

\[ \text{LHCb } \Xi_{cc}^{++} \]

\[ \text{SELEX } \Xi_{cc}^+ \]

Measured lifetime at low side of predictions
Prospects on $\Xi_{cc}^+$ and $\Omega_{cc}^+$ searches at LHCb

- **Mass**
  
  \[ m(\Xi_{cc}^+) \approx m(\Xi_{cc}^{+*}) = 3621.24 \pm 0.72 \text{ MeV} \]
  
  \[ m(\Omega_{cc}^+) \approx m(\Xi_{cc}^{+*}) + 100 \text{ MeV} \]

- **Lifetime**
  
  \[ 3\tau(\Xi_{cc}^+) \approx 3\tau(\Omega_{cc}^+) \approx \tau(\Xi_{cc}^{+*}) = 0.256 \pm 0.027 \text{ ps} \]

- **Production**
  
  \[ \sigma(\Xi_{cc}^{+*}) : \sigma(\Xi_{cc}^+) : \sigma(\Omega_{cc}^+) \approx 1 : 1 : 0.3 \]

- **Shorter lifetime in $\Xi_{cc}^+$ and $\Omega_{cc}^+$ makes numbers of drawbacks**
  - Smaller $\mathcal{B}$, lower efficiency and larger background
  - $\Xi_{cc}^+$: uncertain with current full LHCb data
    - Expect ~200 reconstructed $\Xi_{cc}^+ \rightarrow \Lambda_{c}^+ K^- \pi^+$ with full LHCb data, but how about the background level? exponentially increases? assuming $\mathcal{R}_\tau = \frac{\tau(\Xi_{cc}^{+*})}{\tau(\Xi_{cc}^+)} = \frac{1}{3}$
  - $\Omega_{cc}^+$: More challenge

- **Estimation of golden mode $\Xi_{cc}^+ \rightarrow \Lambda_{c}^+ K^- \pi^+$**
  
  \[ \frac{\mathcal{B}(\Xi_{cc}^+ \rightarrow \Lambda_{c}^+ K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{+*} \rightarrow \Lambda_{c}^+ K^- \pi^+ \pi^+)} = \left( \frac{\mathcal{R}_\tau}{0.3} \right) \times 0.22 \text{ [Fu et. al.]} \]

Compared to $\Xi_{cc}^{+*} \rightarrow \Lambda_{c}^+ K^- \pi^+ \pi^+$

- BR a factor of 1/5
- Similar efficiency: a factor of 1/3 due to $\tau$ & a factor of 2 larger due to one less track
- Production cross-section is the same
- Full luminosity is a factor of 4 as 2016 data
Hidden-charm pentaquarks
LHCb observation in 2015

- Two $J/\psi p$ resonant structures are revealed by a full 6D amplitude analysis
  - $P_c(4450)^+$ $\Leftarrow$ the prominent peak
  - $P_c(4380)^+$ $\Leftarrow$ required to obtain a good fit to the data
  - Consistent with pentaquarks with minimal quark content of $uudcc\bar{c}$

\[
P_c(4450)^+ \quad M = 4450 \pm 2 \pm 3 \text{ MeV} \quad \Gamma = 39 \pm 5 \pm 19 \text{ MeV} \quad F.F. = 4.1 \pm 0.5 \pm 1.1 \%
\]

\[
P_c(4380)^+ \quad M = 4380 \pm 8 \pm 29 \text{ MeV} \quad \Gamma = 205 \pm 18 \pm 86 \text{ MeV} \quad F.F. = 8.4 \pm 0.7 \pm 4.2 \%
\]
Limited knowledge of $P_c$

- Observation of LHCb opens a gate to study pentaquarks
- To interpret the nature of $P_c$, more studies are needed
  - $J^P$, spectroscopy, decay modes and production mechanism?

Tightly-bound pentaquark?

Loosely-bound pentaquark?

Kinematical effect: triangle diagram?

Maiani, Polosa, Riquer, PLB 749 (2015) 289
Lebed, PLB 749 (2015) 454
Anisovich, Matveev, Nyiri, Sarantsev PLB 749 (2015) 454 and others

$M_{P_c^+} = M_{J/ψ} + M_p + \sim 400$ MeV

$M_{P_c^0} = M_{B^0} + M_{Σ_c^0} = \sim \text{few MeV}$

Kinematical effect: triangle diagram?

Guo, Meissner, Wang, Yang, PRD 92 (2015) 071502
Liu, Wang, Zhao, PLB 757 (2016) 231
Mikhasenko, arXiv:1507.06552
Szczepaniak, PLB 757 (2016) 61 and others

$P_c(4450)^+ = X_{c1}p$ threshold?
An order of magnitude increases in signal yield

- Inclusion of Run 2 data (x 5)
- Improved data selection (x 2)
Consistency check

- We can reproduce the results in the previous publication, when fitting the new data with 2015 amplitude model.
- But the fit is only considered as a cross-check.
Confirms the peaking structure at ~4450 MeV, which is resolved into two narrower pentaquark states with nearly identical masses

- Unable to resolve in earlier smaller data set because mass split is small, and comparable to natural widths of the two states

A new narrow peak at lower mass is also uncovered

- Size too small to have been detected in earlier smaller data set
How to fit the data

- **Simplified approach** fits to 1D $m_{J/\psi p}$ distribution
  - Narrow signals:
    - three Breit-Wigner (BW) functions $\otimes$ resolution (2-3 MeV)
  - Background of $\Lambda^+$ + non-$\Lambda^0_b$ + possible broad $P_c^+$: two models compared
    - higher-order polynomial or
    - low-order polynomial + broad BW

- It can robustly determine $M$ and $\Gamma$ of narrow structures
  - Shown by studies of toy simulations
  - But not sensitive to $J^P$
  - Not sensitive to broad peaks, like $P_c(4380)^+$

- Several $m_{J/\psi p}$ distributions with different selection or weighting for systematic evaluation
Fit-1: all candidates

- Fit inclusive $m_{J/\psi p}$ distribution
- Clear narrow structures, but background is high
Fit-2: $P_c^+$ dominated region

- Fit $m_{Kp} > 1.9$ GeV events, $\sim 80\% \Lambda^*$ bkg removed
- Significances: $P_c(4312)^+, 7.3\sigma$; $P_c(4440)^+, 5.4\sigma$
  - Evaluated with toy simulations from 6D amplitude model
  - Have taken account of look elsewhere effect

LHCb

- $m_{Kp} > 1.9$ GeV data
- total fit
- polynomial

Yield:

$\begin{align*}
795^{+150}_{-140} & \quad \text{PRL 122 (2019) 222001} \\
657^{+153}_{-128} & \quad \text{LHCb}
\end{align*}$
Fit-3: Novel method

- Candidates weighted by $w(\cos\theta_{P_c}) = \frac{1}{\sigma_{\text{stat.}}^2} \approx \frac{1}{S+B}$
  - $w$ is inverse of $\cos\theta_{P_c}$ distribution of $A_0^0$ candidates with $m_{J/\psi p} \in [4.2, 4.6]$ GeV
- Most statistically sensitive method

Nominal fit for $M&\Gamma$ measurements

- $\theta_{P_c}$ is $P_c$ helicity angle, correlated with $m_{KP}$
Results

- Masses and widths are shown
- Relative $P_c^+$ production rates are determined

$$\mathcal{R} = \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-) \mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

- Fit inclusive $m_{J/\psi p}$ with efficiency correction
- The fit is not sensitive to broad peaks, like $P_c(4380)^+$

<table>
<thead>
<tr>
<th>State</th>
<th>$M$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
<th>(95% CL)</th>
<th>$\mathcal{R}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4312)^+$</td>
<td>4311.9±0.7$^{+6.8}_{-0.6}$</td>
<td>9.8±2.7$^{+3.7}_{-4.5}$</td>
<td>(&lt;27)</td>
<td>0.30±0.07$^{+0.34}_{-0.09}$</td>
</tr>
<tr>
<td>$P_c(4440)^+$</td>
<td>4440.3±1.3$^{+4.1}_{-4.7}$</td>
<td>20.6±4.9$^{+8.7}_{-10.1}$</td>
<td>(&lt;49)</td>
<td>1.11±0.33$^{+0.22}_{-0.10}$</td>
</tr>
<tr>
<td>$P_c(4457)^+$</td>
<td>4457.3±0.6$^{+4.1}_{-1.7}$</td>
<td>6.4±2.0$^{+5.7}_{-1.9}$</td>
<td>(&lt;20)</td>
<td>0.53±0.16$^{+0.15}_{-0.13}$</td>
</tr>
</tbody>
</table>
Plausible interpretation

- The near-threshold masses of $P_c(4312)^+$, $P(4440)^+$, $P_c(4457)^+$ favour "molecular" pentaquarks with meson-baryon substructure, but other hypotheses are not ruled out

- The 1D fit provides limited information. More work needed
  - $J^P$ measures and information of $P_c(4380)^+$ require amplitude analysis
  - To find isospin partners, and other decay modes

- Regardless of the binding mechanism, the new pentaquarks suggest the existence of a whole new family of such particles
Predictions with molecular picture

- Several theoretical predictions for $\Sigma_c^+ D(\ast)^0$ bound states before 2015
- Some are in good agreement with the LHCb data
  - Wu,Molina,Oset,Zou, PRL 105 (2010) 232001
  - Wang,Huang,Zhang,Zou, PR C84 (2011) 015203
  - Wu, Lee, Zou, PR C85 (2012) 044002
- $J^P$ and more states at $\Sigma_c^* D(\ast)$ thresholds are predicted

M. Z. Liu et al., PRL 122 (2019) 242001

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Molecule</th>
<th>$J^P$</th>
<th>$B$ (MeV)</th>
<th>$M$ (MeV)</th>
</tr>
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<tbody>
<tr>
<td>$B$</td>
<td>$\bar{D}\Sigma_c$</td>
<td>$1^-_3$</td>
<td>7.8 – 9.0</td>
<td>4311.8 – 4313.0</td>
</tr>
<tr>
<td>$B$</td>
<td>$\bar{D}\Sigma_c'$</td>
<td>$3^-_1$</td>
<td>8.3 – 9.2</td>
<td>4376.1 – 4377.0</td>
</tr>
<tr>
<td>$B$</td>
<td>$\bar{D}^*\Sigma_c$</td>
<td>$3^-_2$</td>
<td>Input</td>
<td>4440.3</td>
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<tr>
<td>$B$</td>
<td>$\bar{D}^*\Sigma_c'$</td>
<td>$5^-_2$</td>
<td>Input</td>
<td>4457.3</td>
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<tr>
<td>$B$</td>
<td>$\bar{D}^<em>\Sigma_c^</em>$</td>
<td>$1^-_2$</td>
<td>25.7 – 26.5</td>
<td>4500.2 – 4501.0</td>
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<tr>
<td>$B$</td>
<td>$\bar{D}^<em>\Sigma_c^</em>$</td>
<td>$1^-_2$</td>
<td>15.9 – 16.1</td>
<td>4510.6 – 4510.8</td>
</tr>
<tr>
<td>$B$</td>
<td>$\bar{D}^<em>\Sigma_c^</em>$</td>
<td>$1^-_2$</td>
<td>3.2 – 3.5</td>
<td>4523.3 – 4523.6</td>
</tr>
</tbody>
</table>
Triangle diagrams?

- Can produce peaking structure at or above mass threshold, but not below
- Cannot rule out $P_c(4457)^+$ as a triangle effect

$P_c(4312)^+, P_c(4440)^+$ are too far from any rescattering thresholds

$P_c(4457)^+$ is right at the $\Lambda_c(2595)^+\bar{D}^0$ threshold

3 triangle-diagram amplitudes + polynomial

2BW + 1 triangle-diagram amplitudes + polynomial

$LHCb$ weighted candidates/(2 MeV) $\Gamma_0 = 159$ MeV [PDG]

Liming Zhang
Very recent GlueX results

“First measurement of near-threshold J/ψ exclusive photoproduction off the proton”

A less model-dependent limit at 90% C.L.:

$$\sigma_{\max}(\gamma p \rightarrow P_c^+) \times B(P_c^+ \rightarrow J/ψ p) < 4.6, 1.8, 3.9 \text{ nb for } P_c(4312)^+, P_c(4440)^+, P_c(4457)^+,$$

respectively.

at the resonance maximum
Summary

- $\Xi^{++}_{cc}$ has been firmly established by LHCb
  - Observed by two decay modes
  - Properties are first measured
- Searches for the other doubly-heavy baryons are underway at LHCb

- Recent pentaquark result at LHCb is presented
  - An order of magnitude increases in signal yield is achieved with respect to 2015 result
  - $P_c(4450)^+$ peak structure is an overlap of two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$.
  - A new narrow state $P_c(4312)^+$ is also observed
  - The mass thresholds play an important role in the dynamics of these states
  - The analysis is not sensitive to broad $P_c^+$, so confirmation of the broad $P_c^+$ seen before will need detailed amplitude analysis
  - To further decipher their nature, the $J^P$ measurement will be essential

$m(\Xi^{++}_{cc}) = 3621.24 \pm 0.65 \pm 0.31$ MeV

$\tau_{\Xi^{++}_{cc}} = 256^{+24}_{-22} \pm 14$ fs
Upgrade I: installation ongoing

- Almost a new detector for factor 5 luminosity increase
- Remove the hardware trigger → all detector read out at 40 MHz
- Expect to have data of $23 \text{ fb}^{-1}$ by 2023 and of $50 \text{ fb}^{-1}$ by 2029
Upgrade II: started to investigate
- Aim to collect > $300 \text{ fb}^{-1}$
- Instantaneous $\mathcal{L} = 2 \times 10^{34}$, x10 with respect to Upgrade I
- Expression of Interest issued in 2017 [CERN-LHCC-2017-003]
- Physics case document released [CERN-LHCC-2018-027]
- Green light from LHCC to proceed to TDRs (expected ~late 2020)
Expected yields in future

- LHCb is now boosting the data to a new level
  - Expect to \(7\times\) more data (\(14\times\) more hadronic events) by 2029 than current data
  - Could have another factor of \(6\) increase from Upgrade II

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^+ \rightarrow X(3872)(\rightarrow J/\psi \pi^+ \pi^-)K^+)</td>
<td>14k 30k 180k</td>
</tr>
<tr>
<td>(B^+ \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^+)</td>
<td>500 1k 7k</td>
</tr>
<tr>
<td>(B^0 \rightarrow \psi(2S)K^-\pi^+)</td>
<td>340k 700k 4M</td>
</tr>
<tr>
<td>(B^+_c \rightarrow D^+_s D^0\bar{D}^0)</td>
<td>10 20 100</td>
</tr>
<tr>
<td>(\Lambda^0_b \rightarrow J/\psi pK^-) [*]</td>
<td>680k 1.4M 8M</td>
</tr>
<tr>
<td>(\Xi^-_b \rightarrow J/\psi \Lambda K^-)</td>
<td>4k 10k 55k</td>
</tr>
<tr>
<td>(\Xi^{++}_c \rightarrow \Lambda^+_c K^-\pi^+\pi^+)</td>
<td>7k 15k 90k</td>
</tr>
<tr>
<td>(\Xi^+_bc \rightarrow J/\psi \Xi^+_c)</td>
<td>50 100 600</td>
</tr>
</tbody>
</table>

[*] updated according to the latest result

BES3, Belle2, JLab, PANDA, EIC… also contribute important knowledge to hadron spectroscopy
Backup
Past claimed pentaquark

- Search for pentaquark states has been performed by many experiments in the last 50 years
  - Example: Θ$^+$ [uudd$\bar{s}$] reported by many experiments in early 2000s was concluded to be just a fluctuation
Improved selection

- Selection uses the feature of $B$-hadron decays
  - High $p_T$
  - Detached from primary vertex
  - Hadron ID information

- Selection improved with better uses of hadron ID
  - Hadron ID requirements are put into a multivariate (MVA) based selection. A much powerful MVA is achieved.
  - Use hadron ID to help vetoing $B^0 \rightarrow J/\psi K^-\pi^+$, $B_s^0 \rightarrow J/\psi K^+K^-$ and other mis-ID backgrounds.

- Efficiency is doubled while maintaining similar background fraction, compared to the previous publication
Display in smaller bin size

- More narrow structures emerge, shown in a 2 MeV (≈ mass resolution) bin size

![Graphs showing the distribution of particles](image)

PRL 122, 222001 (2019)
Search for $X_{bb\bar{b}b\bar{b}} \rightarrow \Upsilon(1S)\mu^+\mu^-$

- Binding of double-heavy $b\bar{b}$ pairs quite different to $c\bar{c}$+light meson cloud
- Ground state bound $b\bar{b}b\bar{b}$ tetraquark $\sim 18 - 19$ GeV in many phenomenological models.
- Typically below $\eta_b\eta_b$ threshold. Can decay to $\Upsilon(1S)\mu^+\mu^-$
- No hint of a structure in LHCb search with 2011-2016 data. Upper limits placed.
Prospects

Analyses to update

- $\Lambda_b^0 \rightarrow J/\psi p K^-$ amplitude analysis
  - $J^P$ and $P_c(4380)^+$?
- $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ amplitude analysis
  - To study the production of observed $P_c^+$
  - Find evidence of exotic hadron contribution in Run-1 data [PRL 117 (2016) 082003]

More interesting ideas

- Decay modes to other charmonium states than $J/\psi$?
- Hidden-charmonium pentaquarks with strangeness?
- Open charm baryon meson final state, eg. $\Lambda_b^0 \rightarrow \Lambda_c^+\bar{D}^0 K^-$?
Observation of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$

- Search for $P_c(4450)^+$ in $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$ decays
  $\Rightarrow$ Test hypothesis of kinematic rescattering effect
- First step: observe the decays, measure $\mathcal{B}$
- Use $\chi_{c(1,2)} \to J/\psi \gamma$, constrain $J/\psi \gamma$ mass to known $\chi_{c1}$ mass

\begin{align*}
\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} &= 0.242 \pm 0.014 \pm 0.013 \pm 0.009 \\
\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} &= \mathcal{B}(\chi_{cJ}) \\
&= 0.248 \pm 0.020 \pm 0.014 \pm 0.009
\end{align*}

Next step: full amplitude analysis with more data
Observation of $\Xi_b^- \rightarrow J/\psi \Lambda K^-$

- Strange pentaquark ($udsc\bar{c}$) predicted in [PRL 105 (2010) 232001]
- Can be searched for in the $\Xi_b^-$ decay [PRC 93 (2016) 065203]

\[
N_{\text{sig}} = 308 \pm 21 \ (21\sigma)
\]

\[
\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{B(\Xi_b^- \rightarrow J/\psi \Lambda K^-)}{B(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = (4.19 \pm 0.29 \pm 0.15) \times 10^{-2}
\]

Expect ~1500 signals after 2018 for amplitude analysis
Correlation of $\cos \theta_{P_c}$ and $m_{pK}$

- For events with $m_{J/\psi p} \in [4.2, 4.6]$ GeV
Systematic uncertainty

- The largest ones are due to interference effect

<table>
<thead>
<tr>
<th></th>
<th>$P_c(4312)^+$</th>
<th>$P_c(4400)^+$</th>
<th>$P_c(4457)^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$ MeV</td>
<td>$\Gamma$ MeV</td>
<td>$M$ MeV</td>
</tr>
<tr>
<td>value ± statistical error</td>
<td>4311.9 ± 0.7</td>
<td>9.8 ± 2.7</td>
<td>4440.3 ± 1.3</td>
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<tr>
<td>bkg.subtr. &amp; cut variation</td>
<td>+0.8 -0.6</td>
<td>+3.7 -4.5</td>
<td>+0.1 -1.1</td>
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<tr>
<td>including interferences</td>
<td>+6.8 -0.6</td>
<td>+3.7 -4.5</td>
<td>+4.1 -4.7</td>
</tr>
<tr>
<td>mass resolution</td>
<td>&lt; 0.1 -0.5</td>
<td>&lt; 0.1 -0.5</td>
<td>&lt; 0.1 -0.0</td>
</tr>
<tr>
<td>mass scale</td>
<td>&lt; 0.2 —</td>
<td>&lt; 0.2 —</td>
<td>&lt; 0.2 —</td>
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<tr>
<td>Blatt-Weisskopf factors</td>
<td>&lt; 0.1 +0.0 -0.1</td>
<td>&lt; 0.1 &lt; 0.1</td>
<td>&lt; 0.1 &lt; 0.1</td>
</tr>
<tr>
<td>efficiency in fit function</td>
<td>&lt; 0.1 +0.0 -0.1</td>
<td>&lt; 0.1 +0.0 -0.2</td>
<td>&lt; 0.1 &lt; 0.1</td>
</tr>
</tbody>
</table>

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Requirements:

- All the intermediate states are on shell
- The proton emitted from the decay of the $\Lambda^*$ moves along the same direction as the $\chi_{c1}$ and can catch up with it to rescatter
- Can only happen on the red line of the Dalitz-plot boundary
### Future

<table>
<thead>
<tr>
<th>Year</th>
<th>2018</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
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</thead>
<tbody>
<tr>
<td><strong>Belle II</strong></td>
<td></td>
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<td>50 ab⁻¹</td>
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<td></td>
<td></td>
<td></td>
<td>≈ 55×10⁹ BB pairs</td>
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<tr>
<td><strong>LHCb</strong></td>
<td>9 fb⁻¹</td>
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<td></td>
<td></td>
<td>300 fb⁻¹</td>
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<td><strong>Phase I</strong></td>
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<tr>
<td><strong>LHCb Upgrade 1</strong></td>
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<tr>
<td><strong>Phase 1b</strong></td>
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<tr>
<td><strong>Phase 1b Upgrade</strong></td>
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<tr>
<td><strong>Phase 2</strong></td>
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<tr>
<td><strong>Phase 2 Upgrade</strong></td>
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<tr>
<td><strong>BES III</strong></td>
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<tr>
<td><strong>Continue to run for 8-10 years</strong></td>
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<tr>
<td><strong>Increase E_{cm} =&gt; 4.9 GeV</strong></td>
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</tbody>
</table>

Liming Zhang
Introduction

- QCD describing strong interaction between quarks and gluons is not well understood due to its non-perturbative nature at low energy scale.
- Hadron spectroscopy provides opportunities to test QCD and its effective models:
  - e.g. lattice QCD, diquark model, potential model …
- Exotic hadrons provide unique probe to QCD:
  - Predicted in quark model
  - Recent results show strong evidence for their existence

- mesonic molecule ?
- tetraquark ?
- pentaquark ?
- hybrid ?
Quark model (QM)

- Extended to SU(4) and SU(5) to include new quarks: charm (c), bottom (b)

👉 16 mesons of SU(4) were all discovered
👉 Double-charmed baryons remain to discover/confirm
Why pentaquarks?

- Interest in pentaquarks arises from the fact that they would be new type of particles beyond the simplest quark combination. Could teach us a lot about strong force and QCD.

- There is no reason they should not exist
  - Predicted by Gell-Mann (64), Zweig (64), others later in context of specific QCD models: Jaffe (76), Högaasen & Sorba (78), Strottman (79)

- Name of “pentaquark” is coined by Lipkin (87), who proposed existence of a $D_s^- p$ bound state