Hadron spectroscopy and exotics at LHCb

Yiming Li 李一鸣 Institute of High Energy Physics, CAS



The 19th HFCPV, Nanjing Normal University, 11 Dec 2022

Heavy flavour production at LHC



LHCb





Vertex res.	$\sigma_{\mathrm{IP}} = 20 \ \mathrm{\mu m}$
Time res.	$\sigma_{ au} = 45 \ { m fs} \qquad { m for} \ B^0_s o J/\psi \phi \ { m or} \ D^+_s \pi^-$
Momentum res.	$\Delta p/p = 0.4 \sim 0.6\% (5 - 100 \text{ GeV}/c)$
Mass	$\sigma_m = 8 \; { m MeV}/c^2$ for $B o J/\psi X$
Hadron ID	$\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$
Muon ID	$arepsilon(\mu ightarrow \mu) \sim 97\% $ mis-ID $arepsilon(\pi ightarrow \mu) \sim 1 - 3\%$
ECAL res.	$\Delta E/E = 1\% \oplus 10\%/\sqrt{E \text{ (GeV)}}$

Approaches of new particle search

- Particles produced promptly in pp collision
 - Fully exploiting the large crosssection at LHC
 - Large combinatorial background
 - Only mass & width/lifetime
 - Effective for long-lived particles
 - τ > ~ ps

- Particles produced in *b*-decays
 - Yield suppressed by *b*-decay BF
 - Background is generally clean due to effective *b*-selection
 - Mass, width and angular distribution (hence quantum numbers!)

Common features

- Most powerful for final states of all charged tracks:
 - excellent momentum resolution and PID
- Possible with K_S^0 or π^0 in the final state with reduced efficiency
- Partial reconstruction also effective with a soft γ or π^0 missing

New particles in a glance

60 new hadrons discovered at LHCb!



https://www.nikhef.nl/~pkoppenb/particles.html

Selected highlights



Full list: https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_all.html

Exotic hadron naming convention: arXiv:2206.15233

Ξ_c baryon in *B* decay

■ $E_c(2930)^0$ (*csd*) found in $B^- \to \overline{\Lambda}_c^- \Lambda_c^+ K^$ at BaBar, confirmed by Belle

- Resolved into $\mathcal{E}_c(2923)^0$ and $\mathcal{E}_c(2939)^0$ in prompt $\Lambda_c^+ K^-$ search at LHCb PHYS. REV. LETT. 124 (2020) 222001
- Confirmed by recent $B^- \rightarrow \bar{\Lambda}_c^- \Lambda_c^+ K^$ study at LHCb arXiv:2211.00812

State	Mass (MeV)	Width (MeV)
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.2 \pm 5.8$
$\Xi_{c}(2923)^{0}$	$2924.5 \pm 0.4 \pm 1.1$	$4.8\pm0.9\pm1.5$
$\Xi_{c}(2939)^{0}$	$2938.5 \pm 0.9 \pm 2.3$	$11.0\pm1.9\pm7.5$

$$R_{\mathcal{B}} = \frac{\mathcal{B}(B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-)}{\mathcal{B}(B^- \to D^- D^+ K^-)} = 2.36 \pm 0.11 \pm 0.22 \pm 0.25$$

arXiv:2211.00812 (submitted to PRD)





New decay mode of \mathcal{Z}_{cc}^{++}

LHCb opens a new era in doubly heavy baryon search where Chinese groups have been leading the efforts

- Starting with observation of Ξ_{cc}^{++} in $\Lambda_c^+ K^- \pi^+ \pi^+$
- Confirmed in $\Xi_{c}^{+}\pi^{+}$ decay PRL 121 (2018) 162002

Recently a new decay $\Xi_c^{\prime+}\pi^+$ found

•
$$\mathcal{Z}_{cc}^{++} \to \mathcal{Z}_{c}^{\prime+} (\to \mathcal{Z}_{c}^{+} \gamma) \pi^{+}$$

• $\frac{\mathcal{B}(\mathcal{Z}_{cc}^{++} \to \mathcal{Z}_{c}^{\prime+} \pi^{+})}{\mathcal{B}(\mathcal{Z}_{cc}^{++} \to \mathcal{Z}_{c}^{+} \pi^{+})} = 1.41 \pm 0.17 \pm 0.10$

tension with prediction



JHEP 05 (2022) 038

IHEP 05 (2022) 038

PRL 119 (2017) 112001

Search of *E*_{bc}

arXiv: 2204.09541(submitted to CPC)

- First search for Ξ_{bc}^{0} performed
 - $\Xi_{bc}^+ \rightarrow J/\psi \Xi_c^+$

	6571 MeV	6694 MeV
Local signficance	4.3 <i>σ</i>	4.1 <i>σ</i>
Global significance	2.8 σ	2.4 σ





B⁺_c decay BF measurement

arXiv:2210.12000 (submitted to JHEP)

 $\ \ \, B_c^+\to B_s^0\pi^+$

PRL 111 (2013) 181801

- First *B* weak decay to another beauty
- Branching fraction expected to be large, and contributes to more stringent limit on $B_c^+ \rightarrow \tau^+ \nu$ decay BF

•
$$\frac{\mathcal{B}(B_c^+ \to B_s^0 \pi^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 91 \pm 10 \pm 8 \pm 3$$







X(3960)

- First observation of $B^+ \rightarrow D_s^+ D_s^- K^+$
 - $\frac{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)}{\mathcal{B}(B^+ \to D^+ D^- K^+)} = 0.525 \pm 0.033 \pm 0.027 \pm 0.034$
- Near-threshold structure X(3960) ($c\bar{c}s\bar{s}$) observed in $D_s^+D_s^-$ system (>12 σ)
 - $m = 3956 \pm 5 \pm 10 \text{ MeV}$
 - $\Gamma = 43 \pm 13 \pm 8 \text{ MeV}$
 - $J^{PC} = 0^{++}$
 - Evidence of $X_0(4140)$: tetraquark? Cross-channel effect?
 - Evidence of $\psi(4260)$ and $\psi(4660)$



Tetraquark with open charm

arXiv: 2211.02716 (submitted to PRL) arXiv: 2211.02717 (submitted to PRD)

First observation of doubly charged $T^a_{c\bar{s}0}(2900)^{++}(cu\bar{s}\bar{d})$ and its isospin partner $T^a_{c\bar{s}0}(2900)^0(cu\bar{s}\bar{u})$ in $B^{+/0} \rightarrow \overline{D}^{-/0}D^+_s\pi^{+/-}$

- Amplitude analysis using the package TF-PWA
- Reminder: $T_{cs0}(2900)^0$ and $T_{cs1}(2900)^0$ with quark content $(cs\bar{u}\bar{d})$ with $J^P = 0^+$ and 1^- found in Dalitz analysis of the $B^+ \rightarrow D^+D^-K^+$ decay PRL 125 (2020) 242001
- $T_{c\bar{s}0}^{a}(2900)^{0}$ mass is consistent with $T_{cs0}(2900)^{0}$, but width and flavour differ

Assuming isospin symmetry: $m = 2908 \pm 11 \pm 20 \text{ MeV}$ $\Gamma = 136 \pm 23 \pm 13 \text{ MeV}$

 $m = 2886 \pm 7 \pm 2 \text{ MeV}$ $\Gamma = 57 \pm 12 \pm 4 \text{ MeV}$



Yiming Li, Hadron spectroscopy and exotics at LHCb @ HFCPV2022

Tetraquark with hidden charm

- $Z(4430)^+$ or $T^b_{\psi s}(4430)^+$, a charged state with minimum quark content ($c\bar{c}u\bar{d}$) and $J^P = 1^+$ was first observed in decay $B^0 \rightarrow \psi(2S)K^-\pi^+$ by Belle and confirmed by LHCb PRL 100 (2008) 142001, PRL 112 (2014) 222002, PRD 92 (2015) 112009
- $B^+ \rightarrow J/\psi \phi K^+$: a zoo of exotic states
 - Multiple exotic states found in $J/\psi\phi$ system
 - Two Z_{cs} states in $J/\psi K$ system

J^P	Contribution	Significance $[\times\sigma]$	$M_0[{ m MeV}]$	$\Gamma_0 [{ m MeV}]$
2^{-}	X(4150)	4.8 (8.7)	$4146\pm18\pm33$	$135\pm28{}^{+59}_{-30}$
1-	X(4630)	5.5(5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27 {}^{+ 134}_{- 73}$
0+	X(4500)	20(20)	$4474\pm3\pm3$	$77\pm6{}^{+10}_{-8}$
	X(4700)	17(18)	$4694 \pm 4 {}^{+ 16}_{- 3}$	$87\pm8{}^{+16}_{-6}$
	$\mathrm{NR}_{J/\psi\phi}$	4.8(5.7)		
1+	X(4140)	13 (16)	$4118 \pm 11 {}^{+ 19}_{- 36}$	$162\pm21{}^{+24}_{-49}$
	X(4274)	18 (18)	$4294 \pm 4 {}^{+ 3}_{- 6}$	$53\pm5\pm5$
	X(4685)	15(15)	$4684 \pm 7 {}^{+ 13}_{- 16}$	$126\pm15{}^{+37}_{-41}$
1+	$Z_{cs}(4000)$	15 (16)	$4003\pm6{}^{+}_{-}{}^{4}_{14}$	$131\pm15\pm26$
	$Z_{cs}(4220)$	5.9(8.4)	$4216 \pm 24 {}^{+ 43}_{- 30}$	$233 \pm 52 {}^{+ 97}_{- 73}$



PRL 127 (2021) 082001

Tetraquark with hidden charm

LHCb-PAPER-2022-040

- Combined fit to $B^+ \rightarrow J/\psi \phi K^+$ and $B^0 \rightarrow J/\psi \phi K_S^0$ find evidence (4.0 σ) of $Z_{cs}(4000)^0$ or $T_{\psi s1}^{\theta}(4000)^0$, with quark content $c\bar{c}s\bar{d}$
 - Assuming isospin asymmetry the significance is 5.4 sigma



Pentaquark

- A new pentaquark with strangeness $P^{\Lambda}_{\psi s}(4338)^0$ (*cc̄sud*) observed in the $B^- \rightarrow J/\psi \Lambda \bar{p}$ decay
 - At $\Xi_c^+ D^-$ threshold
 - $m = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$
 - $\Gamma=7.0\pm1.2\pm1.3~\text{MeV}$

•
$$J^P = \frac{1}{2}$$

- Most precise single measurement of B⁻ mass:
 - $5279.44 \pm 0.05 \pm 0.07 \text{ MeV}$



arXiv: 2210.10346 (submitted to PRI)

2022/12/11

Summary

- Thanks to the huge production rate at LHC and excellent detector performance, LHCb has greatly extended our knowledge on heavy hadron spectroscopy, both for conventional or exotic hadrons
- Chinese groups have been playing a crucial role, largely benefiting from active interaction with theoretical community
- This trend will continue as Upgrade I close to completion and much more data expected



BACKUP

Doubly charmed tetraquark

A narrow resonance T_{cc}^+ ($cc\bar{u}\bar{d}$) discovered in prompt $D^0D^0\pi^+$ spectrum, just below the $D^{*+}D^0$ mass



Nature Physics 18 (2022) 751 Nature Comm. 13 (2022) 3351

Fully charmed tetraquark

- Narrow resonance of X(6900) or $T_{\psi\psi}(6900)$ discovered with full LHCb Run 1+2 data in prompt $J/\psi J/\psi$ pair spectrum
 - First tetraquark with all-charm quark
 - Recently confirmed by CMS and ATLAS



Science Bulletin 65 (2020) 1983

Pentaquark

• Evidence of $P_{\psi}^{N}(4337)^{+}$ in the $B_{s}^{0} \rightarrow J/\psi p \bar{p}$ decay



First evidence of pentaquark with strangeness $P_{\psi s}^{\Lambda}(4459)^{0}$ (ccuds) discovered in $\Xi_{b}^{-} \rightarrow J/\psi \Lambda K^{-}$



PRL 128 (2022) 062001