Recent LHCb results on heavy hadron spectroscopy

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Outline

Introduction

Conventional spectroscopy:

- observation of new excited Ω_c^0 states;
- observation of new excited Ξ_b^0 states;
- observation of the decay $\Xi_b^- \to \Lambda_b^0 \pi^-$;
- charmonia decays into $K_s^0 K^\pm \pi^\mp$;
- study of the new B_c^+ meson decays;

Exotic spectroscopy:

- evidence for the $T_{\psi s1}^{\theta}(4000)^0$ state;
- observation of $T_{c\bar{s}0}^{a}(2900)^{++}$ and $T_{c\bar{s}0}^{a}(2900)^0$ states;
- study of the $B^+ \to D_s^+ D_s^- K^+$ decay;
- observation of $P_{\psi s}^{\Lambda}(4338)^0$ state;

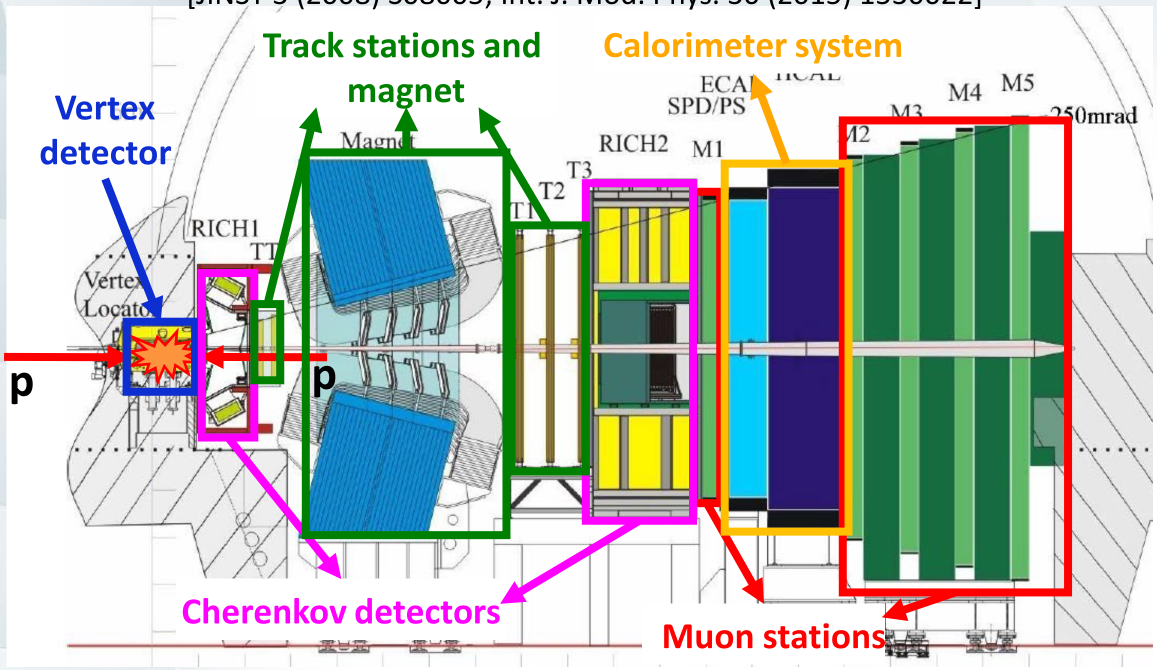
Summary and prospects

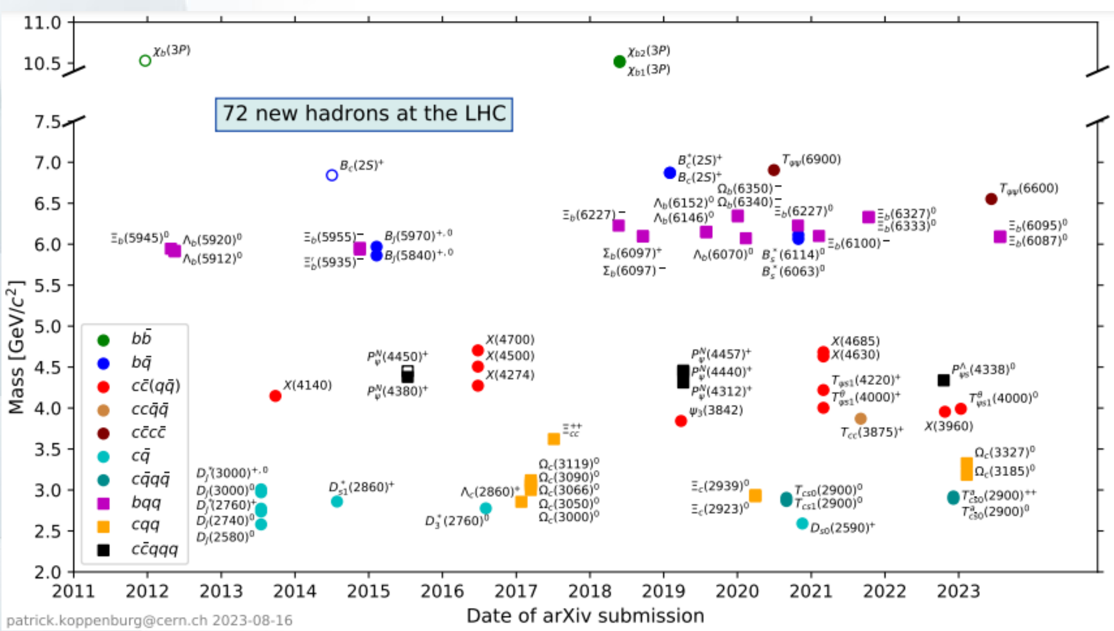
Introduction

- LHCb detector;
- motivation of heavy hadron spectroscopy;
- event reconstruction and selection.

LHCb detector

[JINST 3 (2008) S08005; Int. J. Mod. Phys. 30 (2015) 1530022]





Features:

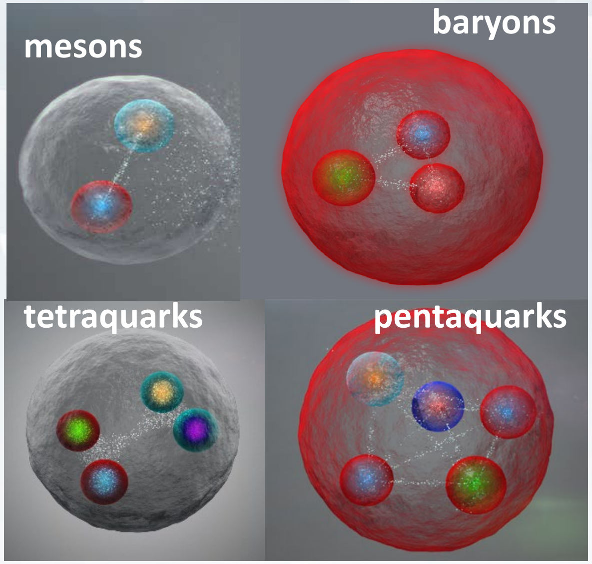
- high b-quark **production cross-section** at the Large Hadron Collider energies;
- rapidity range between $2 < y < 4.5$;
- allows to study all kinds of B-mesons: $B^{\pm}$, B^{0}, B_s^0, $B_c^{\pm}$, beauty baryons (their excitations), exotic states;
- high track-multipilicty ⇒ effective multi-level trigger system;
- proton-proton collision energies and collected luminosities:
  - 2011-2012 (Run 1): $\sqrt{s}$ = 7, 8 TeV, $\mathcal{L}$ ~ 3 fb^{-1}; $\boldsymbol{\sigma_{b\bar{b}} \approx 280}$**μb;**
  - 2015-2018 (Run 2): $\sqrt{s}$ = 13 TeV, $\mathcal{L}$ ~ 6 fb^{-1}; $\boldsymbol{\sigma_{b\bar{b}} \approx 500}$**μb.**

LHCb experiment is **a very powerful tool** for heavy hadron spectroscopy ⇒ contribute to major part of hadrons discovered at LHC (**64 new hadrons**).

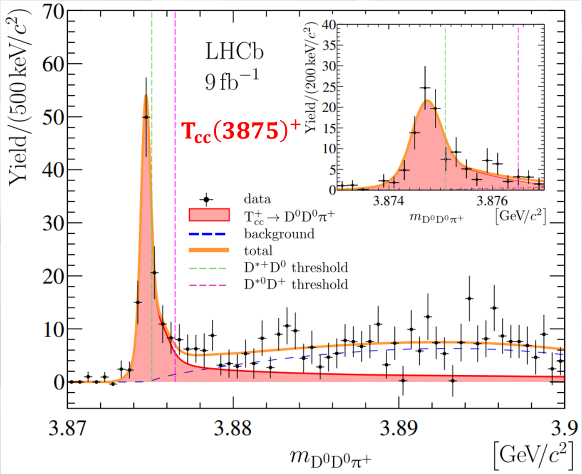
[https://www.nikhef.nl/~pkoppenb/particles.html]

Motivation

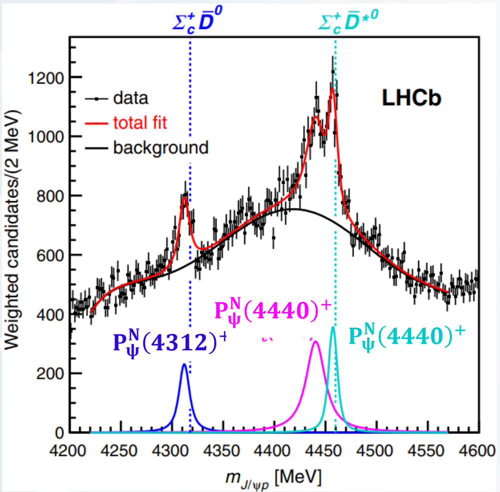
- Study of hadron production provides information for:
  - ✓ quark production mechanisms;
  - ✓ hadron formation from quarks (hadronisation);
  - ✓ hadron internal structure.
- Important measurements for quantum chromodynamics (QCD):
  - ✓ discrimination among predictions obtained in different QCD approaches.
- Detailed study of hadron properties and decays possible at LHCb:
  - ✓ search for new states;
  - ✓ spin-parity assignments;
  - ✓ polarisation;
  - ✓ amplitude analyses;
  - ✓ branching fractions, lifetimes, masses, widths.



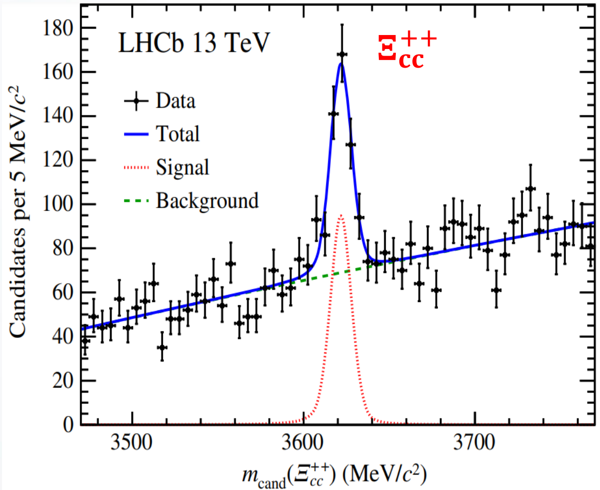
[Nature Phys. 18 (2022) 751; Nature Commun. 13 (2022) 3351]



[Phys. Rev. Lett. 122 (2019) 222001]

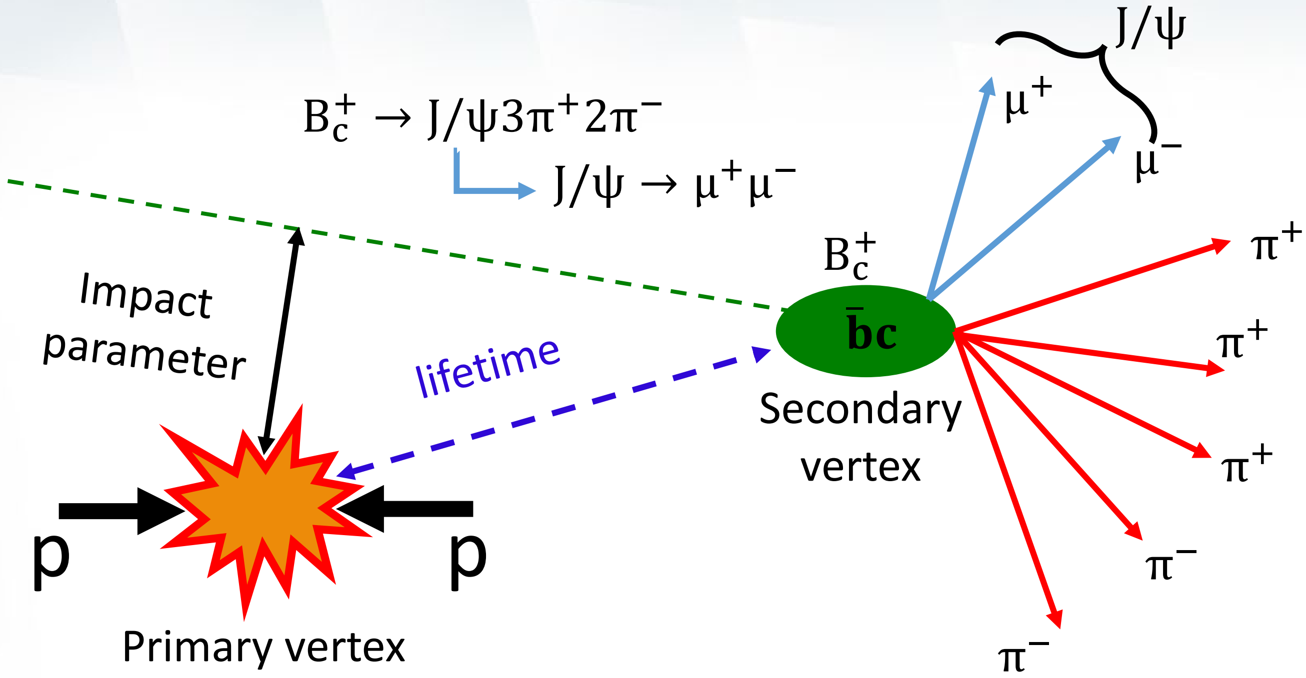


[Phys. Rev. Lett. 119 (2017) 112001]



Event reconstruction and selection

Based on search for detached secondary vertex



- well reconstructed and identified tracks;
- primary and secondary vertices separation (requirements on flavour hadron lifetimes);
- daughter tracks originating from the secondary vertex (impact parameter);
- requirements on kinematic parameters;
- background suppression by using multivariate analysis techniques (neural networks, decision trees).

Conventional spectroscopy

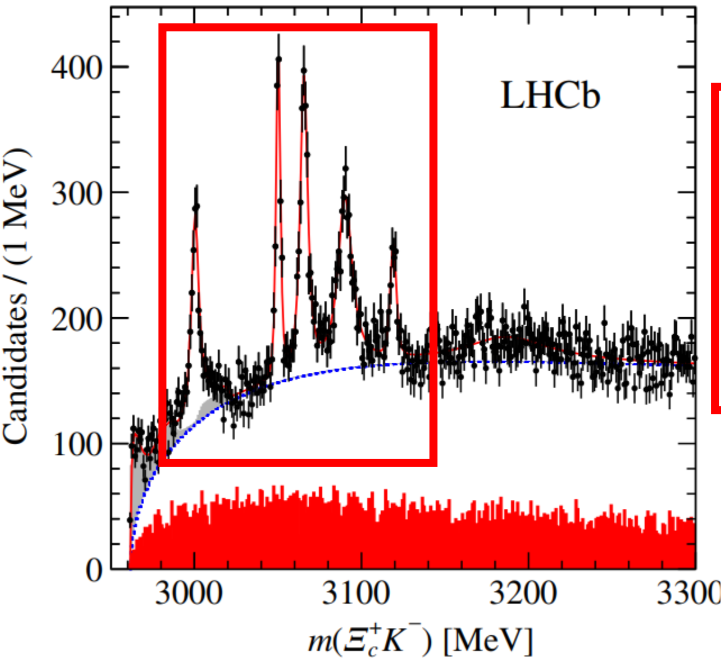
- observation of new excited Ω_c^0 states; [Phys. Rev. Lett. 131 (2023) 131902]
- observation of new baryons in $\Xi_b^- \pi^+ \pi^-$ and $\Xi_b^0 \pi^+ \pi^-$ systems; [Phys Rev. Lett. 131 (2023) 171901]
- observation of the decay $\Xi_b^- \to \Lambda_b^0 \pi^-$; [Phys. Rev. D 108 (2023) 072002]
- charmonia decays into $K_s^0 K^\pm \pi^\mp$ [Phys. Rev. D 108 (2023) 032010]
- study of the new B_c^+ meson decays. [JHEP 07 (2023) 198]

Observation of new excited Ω_c^0 states

Singly charmed baryons consist of one charm quark and two lighter quarks. Such systems provides an ideal testing ground for theories of the strong force provides important insights into the fundamental nature of hadronic matter.

The **five narrow excited Ω_c^0 (ssc) states** were observed for the first time in Run 1 data in the $\Xi_c^+(usc)(\to pK^-\pi^+)K^-$ system.

[Phys. Rev. Lett. 118 (2017) 182001]

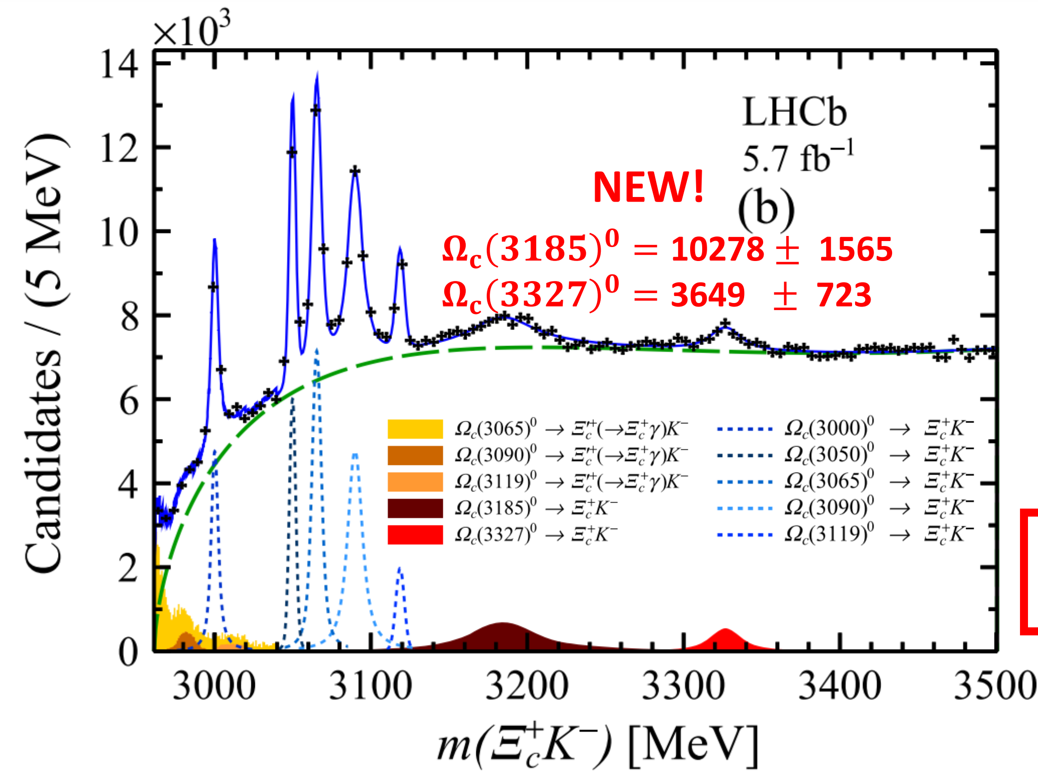


Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		<1.2 MeV, 95% C.L.		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		<2.6 MeV, 95% C.L.		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{fd}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{fd}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{fd}$			$190 \pm 70 \pm 20$	

Based on larger Run 2 data sample ($\sqrt{s}$ = 13 TeV, $\mathcal{L}$ ~ 6 fb^{-1}) analysis was repeated

Observation of new excited Ω_c^0 states

[Phys. Rev. Lett. 131 (2023) 131902]



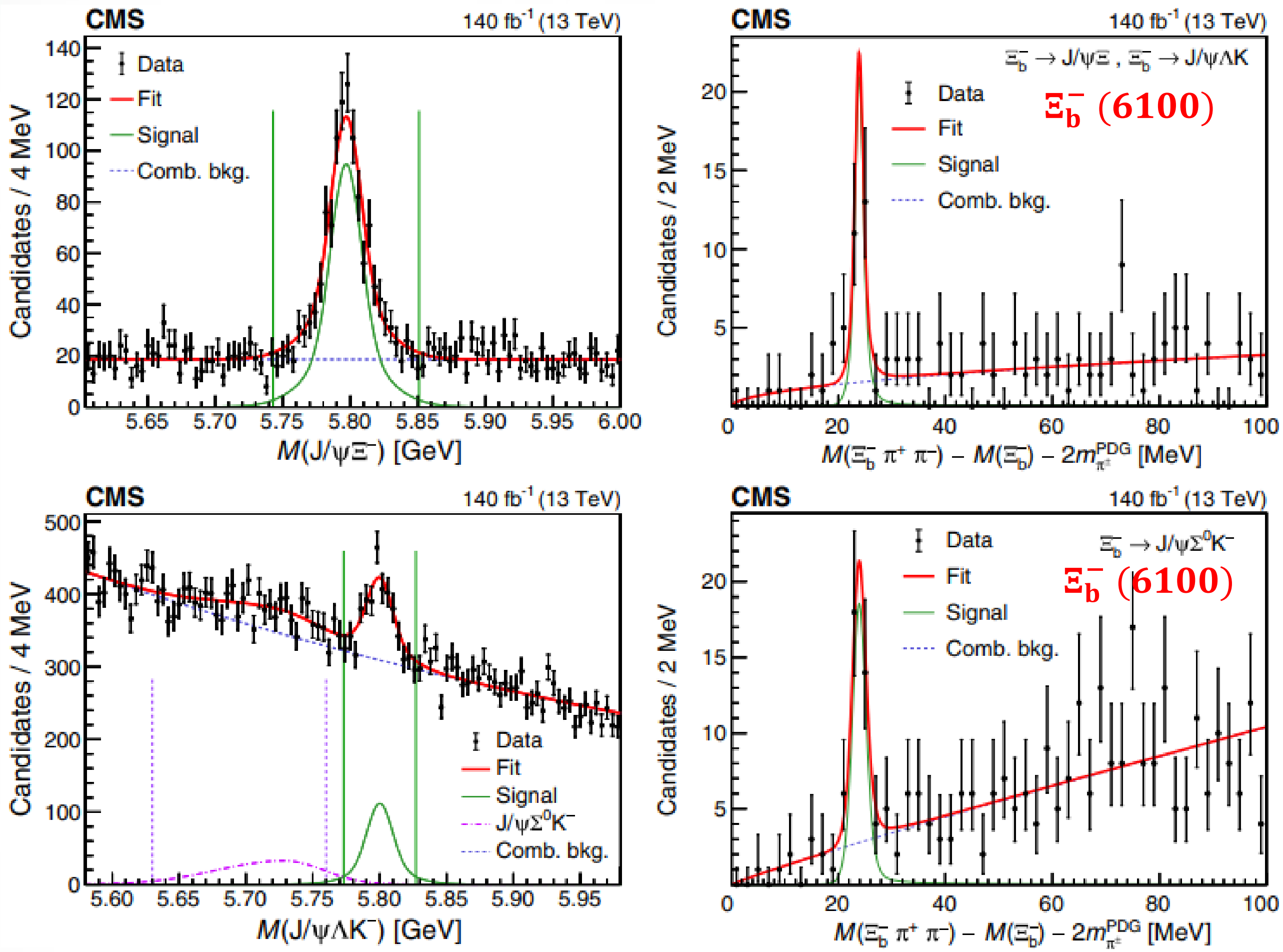
Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17^{+0.64}_{-0.72}$
		< 1.8 MeV, 95% CL
$\Omega_c(3065)^0$	$3065.63 \pm 0.06^{+0.06}_{-0.06} \pm 0.23$	$3.79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

- confirm Run 1 results;
- two new broad resonances $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$ are observed for **the first time**;
- their masses and widths **are measured**;
- quantum numbers remain to be determined.

Observation of new excited Ξ_b^0 states

Investigation of the $\Xi_b^{0,\pm}\,\pi^+\pi^-$ is very interesting since contain still missing unobserved states. The CMS collaboration has reported the observation of the new Ξ_b^- (6100) state in 2021.

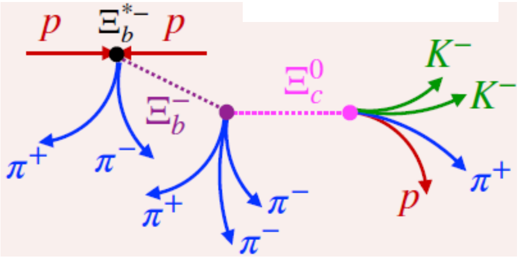
[Phys. Rev. Lett. 126 (2021) 252003]



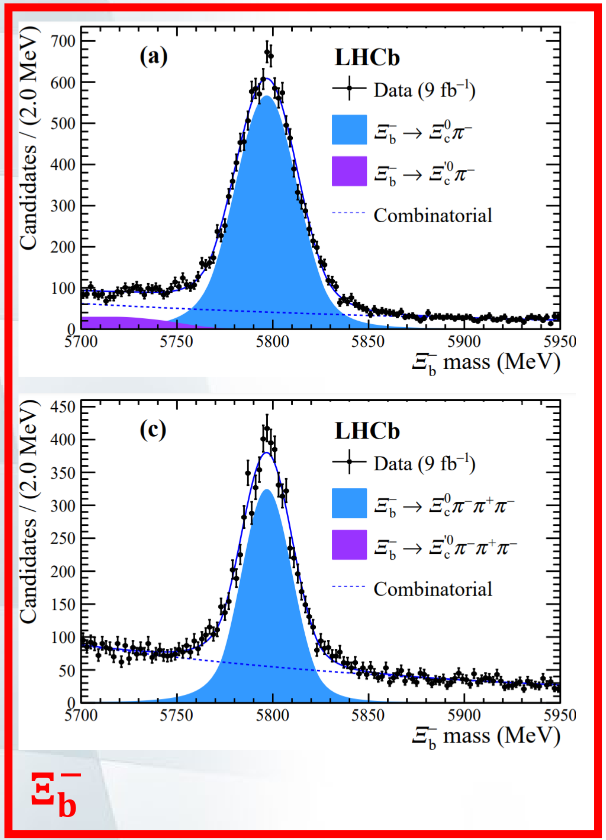
The LHCb has performed study of **both**, neutral $\Xi_b^0(usb)$ and charged $\Xi_b^-(dsb)/\,\Xi_b^+(\bar{d}\bar{s}\bar{b})$: $\Xi_b^{0,\pm}\,\pi^+\pi^-$ systems

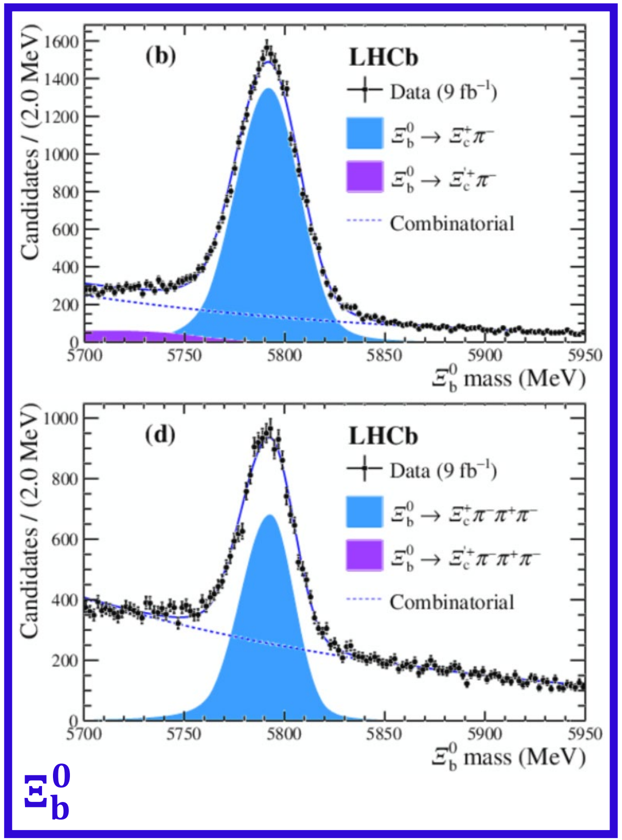
Observation of new excited Ξ_b^0 states

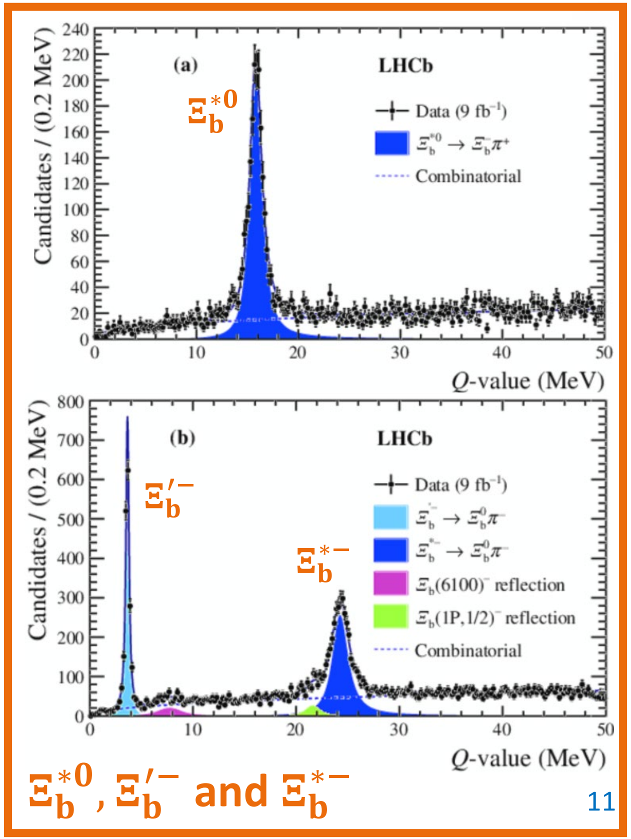
- the Ξ_b^- (Ξ_b^0) candidates are formed from $\Xi_c^0\pi^-$ ($\Xi_c^+\pi^-$) and $\Xi_c^0\pi^-\pi^+\pi^-$ ($\Xi_c^+\pi^-\pi^+\pi^-$) combinations;
- Ξ_c^0 and Ξ_c^+ baryons are reconstructed in the $pK^-K^-\pi^+$ and $pK^-\pi^+$ final state;
- then $\Xi_b^{-,0}$ candidates are combined with another pion to form Ξ_b^{*0}, $\Xi_b'^-$ and Ξ_b^{*-} candidates.



[Phys Rev. Lett. 131 (2023) 171901]



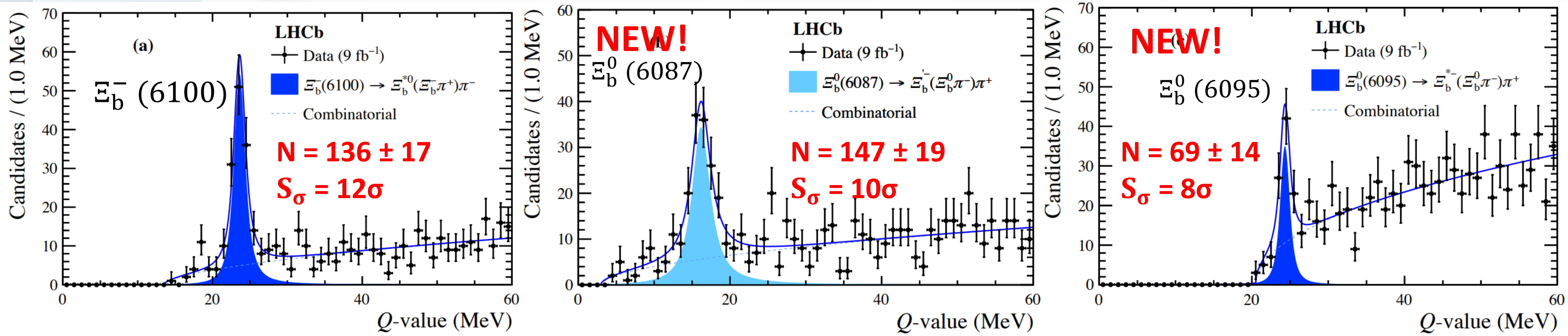




Observation of new excited Ξ_b^0 states

The selected Ξ_b^{*0}, $\Xi_b^{\prime -}$ and Ξ_b^{*-} candidates then finally combined with the second opposite-charged pion.

[Phys Rev. Lett. 131 (2023) 171901]



State	Observ.	Value (MeV)	
$\Xi_b(6100)^-$	Q_0	$23.6 \pm 0.11 \pm 0.02$	**Confirmed!**
	Γ	$0.94 \pm 0.30 \pm 0.08$	
	m_0	$6099.74 \pm 0.11 \pm 0.02 \ \pm 0.6\ (\Xi_b^-)$	
$\Xi_b(6087)^0$	Q_0	$16.20 \pm 0.20 \pm 0.06$	**NEW!**
	Γ	$2.43 \pm 0.51 \pm 0.10$	
	m_0	$6087.24 \pm 0.20 \pm 0.06 \ \pm 0.5\ (\Xi_b^0)$	
$\Xi_b(6095)^0$	Q_0	$24.32 \pm 0.15 \pm 0.03$	**NEW!**
	Γ	$0.50 \pm 0.33 \pm 0.11$	
	m_0	$6095.36 \pm 0.15 \pm 0.03 \ \pm 0.5\ (\Xi_b^0)$	

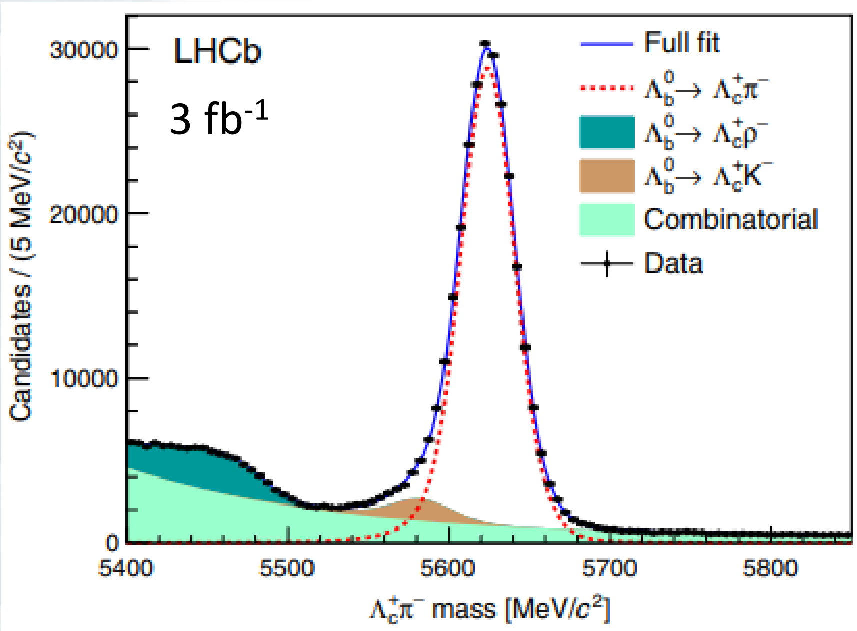
State	Observ.	Value (MeV)
Ξ_b^{*0}	Q_0	$15.80 \pm 0.02 \pm 0.01$
	Γ	$0.87 \pm 0.06 \pm 0.05$
	m_0	$5952.37 \pm 0.02 \pm 0.01 \ \pm 0.6\ (\Xi_b^-)$
$\Xi_b^{\prime -}$	Q_0	$3.66 \pm 0.01 \pm 0.00$
	Γ	$0.03 \pm 0.01 \pm 0.03$
	m_0	$5935.13 \pm 0.01 \pm 0.00 \ \pm 0.5\ (\Xi_b^0)$
Ξ_b^{*-}	Q_0	$24.27 \pm 0.03 \pm 0.01$
	Γ	$1.43 \pm 0.08 \pm 0.08$
	m_0	$5955.74 \pm 0.03 \pm 0.01 \ \pm 0.5\ (\Xi_b^0)$

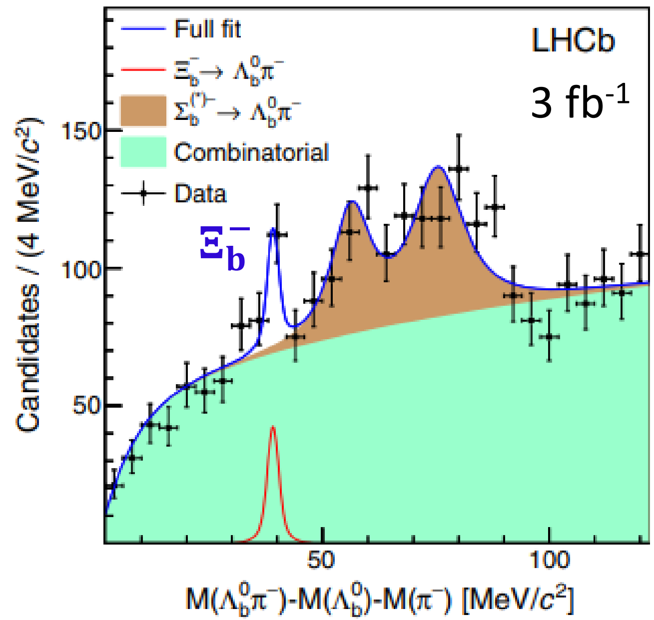
- the Ξ_b^- (6100) **confirms** previous CMS observation [Phys. Rev. Lett. 126 (2021) 252003];
- new Ξ_b^0 (6087) and Ξ_b^0 (6095) states **are observed**;
- similarity of decay pattern with *c*-baryon system suggests P-wave states;
- properties of the Ξ_b^{*0}, $\Xi_b^{\prime -}$ and Ξ_b^{*-} baryons are **measured with best precision**;
- additional studies with more data are required to measure quantum numbers.

Observation of the decay $\Xi_b^- \to \Lambda_b^0 \pi^-$

A previous LHCb study based on Run 1 data showed and evidence (3.2σ) for the strangeness-changing weak $\Xi_b^- \to \Lambda_b^0(\to \Lambda_c^+(\to pK^-\pi^+)\pi^-)\pi^-$ decay ⇒ updated with Run 2 sample.

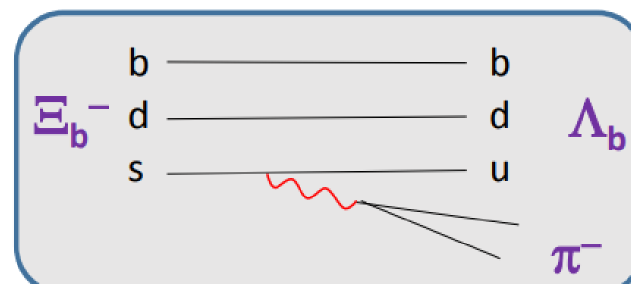
[Phys. Rev. Lett. 115 (2015) 241801]





Branching fraction determined as

$$r_s \equiv \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \mathcal{B}(\Xi_b^- \to \Lambda_b^0 \pi^-)$$

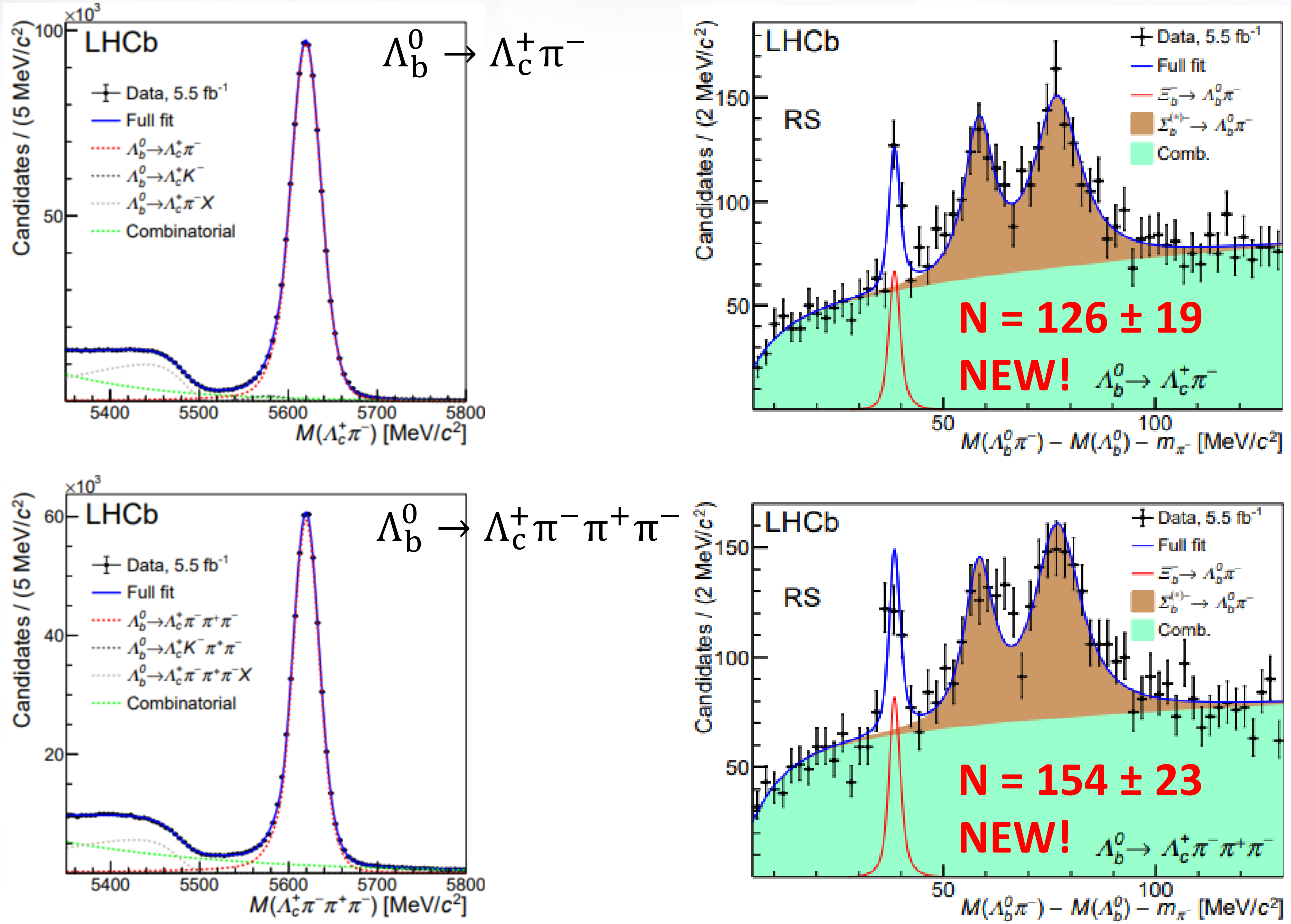


The fragmentation fractions ratio (f) measured by

LHCb to be $\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (8.2 \pm 0.7 \pm 0.6 \pm 2.5)\%$ [Phys. Rev. D 99 (2019) 052006]

Observation of the decay $\Xi_b^- \to \Lambda_b^0 \pi^-$

In the updated study Λ_b^0 baryons are reconstructed by using two decay modes and then combined with additional π^- candidate to form Ξ_b^- baryon [Phys. Rev. D 108 (2023) 072002]



Consistent with theory predictions based on papers:

- [JHEP 03 (2016) 028];
- [Phys. Rev. D 105 (2022) 094011];
- [Phys. Lett. B750 (2015) 653];
- [Phys. Rev. D 106 (2022) 093005];
- [Phys. Rev. D 93 (2016) 034020].

$$\mathcal{B}(\Xi_b^- \to \Lambda_b^0 \pi^-) = (0.89 \pm 0.10 \pm 0.07 \pm 0.29)\%,$$

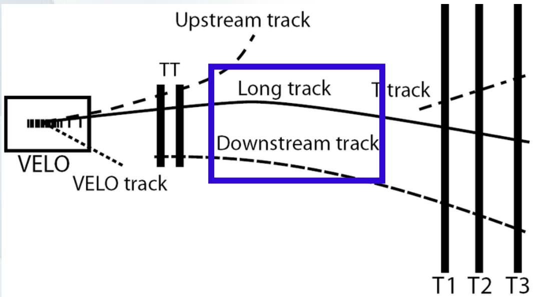
Due to $f_{\Xi_b^-} / f_{\Lambda_b^0}$ determination

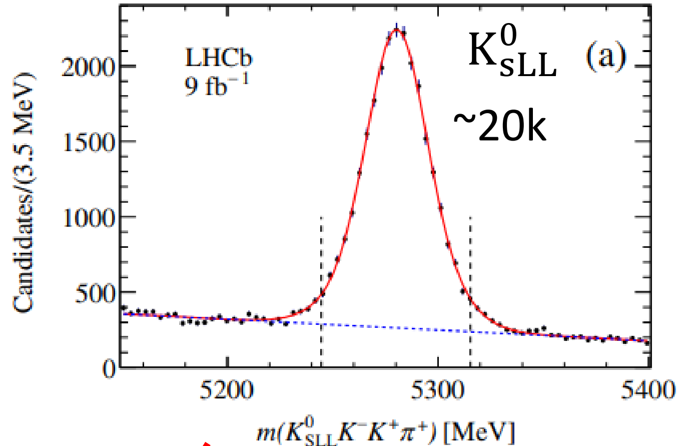
Charmonia decays into $K_s^0 K^{\pm}\pi^{\mp}$

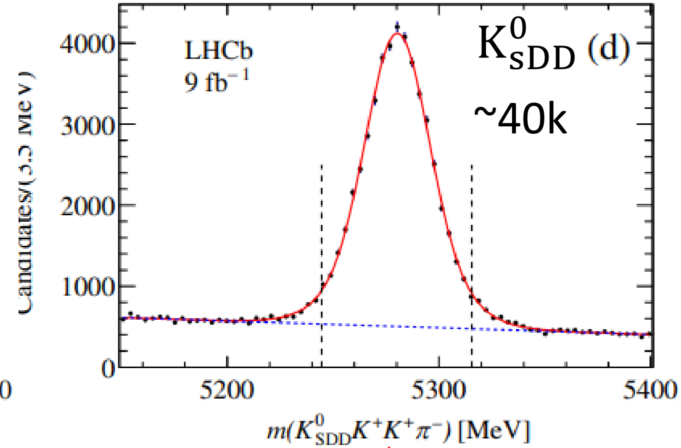
A study of the high statistic $B^+ \to K_s^0 K^+ K^- \pi^+$ and $B^+ \to K_s^0 K^+ K^+ \pi^-$ is performed. The K_s^0 mesons are reconstructed for two categories:

[Phys. Rev. D 108 (2023) 032010]

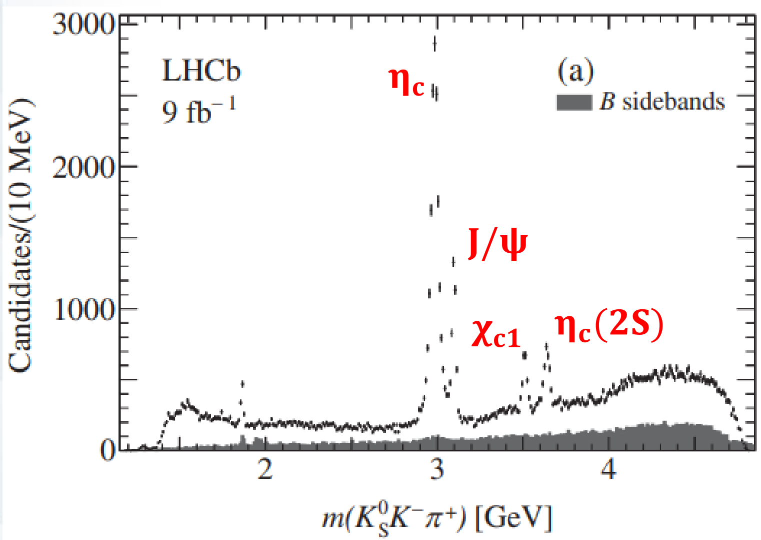
- K_s^0 decaying **inside** vertex detector (K^0_{sLL});
- K_s^0 decaying **outside** vertex detector (K^0_{sDD});

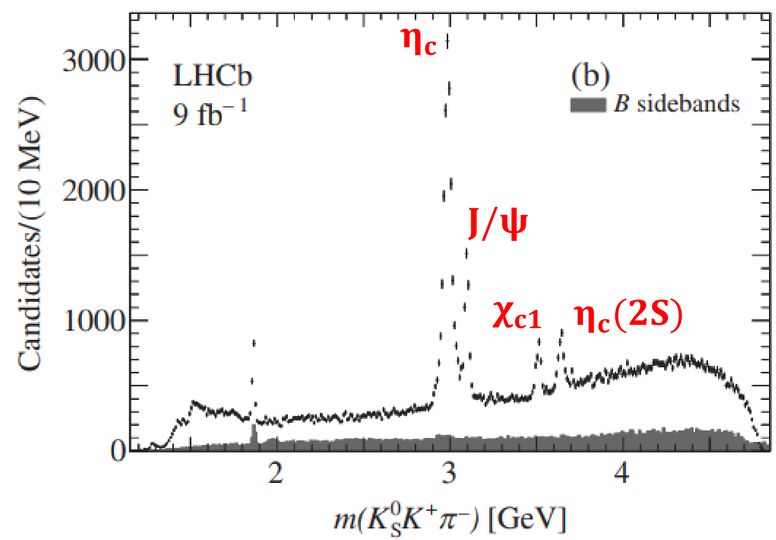






Two entries per event



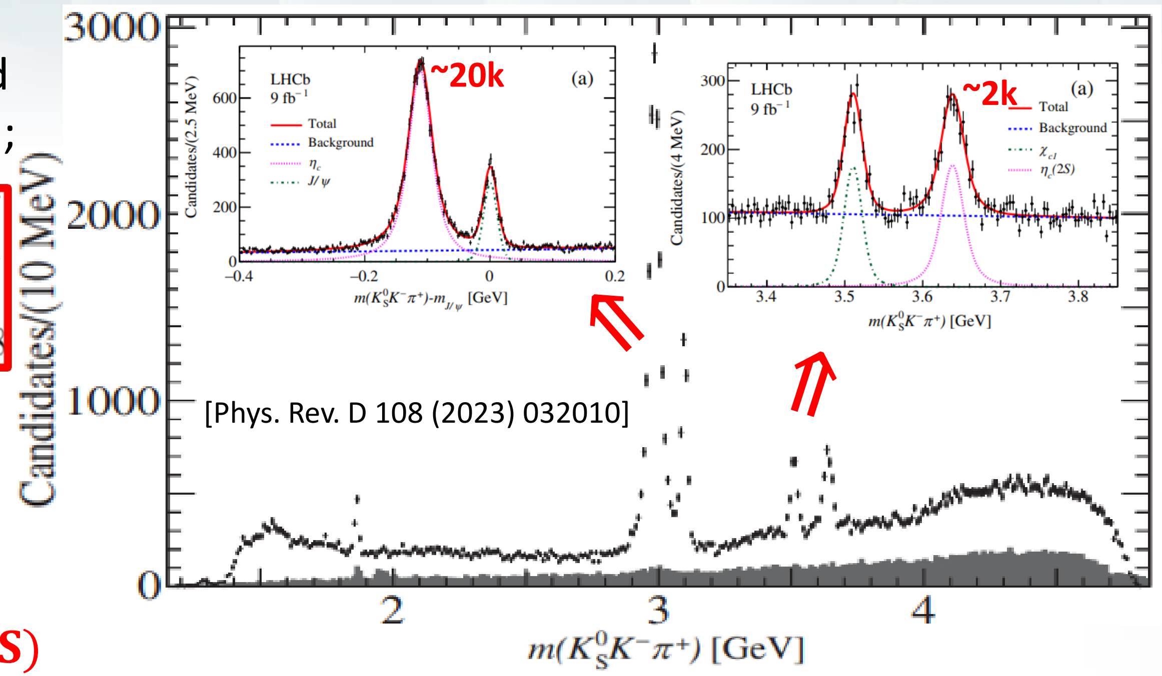


- prominent signals of η_c, J/ψ, χ_{c1}, $\eta_c(2S)$ are observed.

Charmonia decays into $K^0_S K^{\pm}\pi^{\mp}$

- most precise measurement of η_c and $\eta_c(2S)$ Breit-Wigner mass and width;

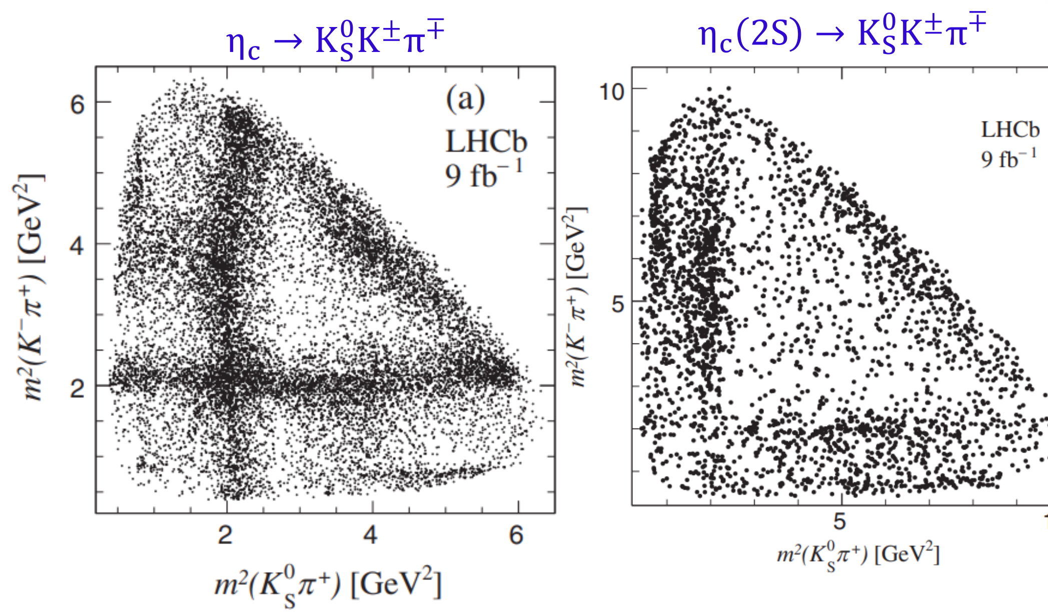
	Mass [MeV]	Width [MeV]
η_c	$2985.01 \pm 0.17 \pm 0.89$	$29.7 \pm 0.5 \pm 0.2$
$\eta_c(2S)$	$3637.90 \pm 0.54 \pm 1.40$	$10.77 \pm 1.62 \pm 1.08$



- Dalitz plot analysis of η_c and $\eta_c(2S)$ states is performed, provide a lot of experimental information on **kaon spectroscopy**;

Breit-Wigner masses and widths

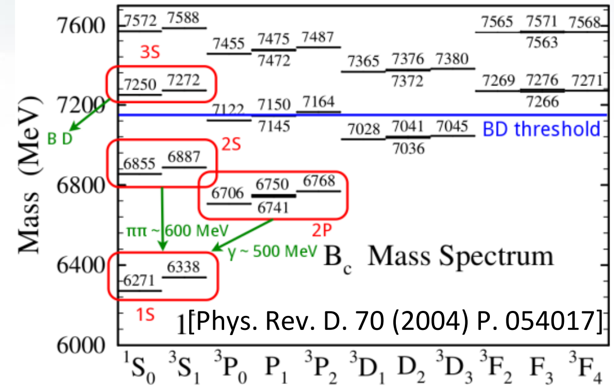
Resonance	Mass [MeV]	Γ [MeV]
$K^*_0(1430)$	$1493 \pm 4 \pm 7$	$215 \pm 7 \pm 4$
$K^*_0(1950)$	$1980 \pm 14 \pm 19$	$229 \pm 26 \pm 16$
$a_0(1700)$	$1736 \pm 10 \pm 12$	$134 \pm 17 \pm 61$
$\kappa(2600)$	$2662 \pm 59 \pm 201$	$480 \pm 47 \pm 72$



Study of the new B_c^+ meson decays

The B_c^+ meson is a bound state of $\bar{b}c$ quarks, firstly observed by the CDF collaboration in 1998

Unique system:



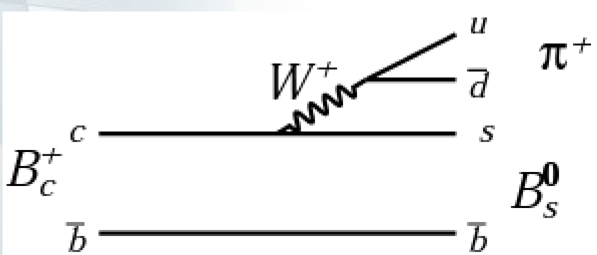
- only one meson with two heavy quarks of different flavours;
- nonrelativistic system ⇒ quarkonium spectrum;
- cannot be produced on B-factories;
- lifetime in 3 times lower in comparison with B^+ meson ⇒ important role of c-quark in decay mechanism;

B_c^+ MEAN LIFE [PDG live] $B^\pm$ MEAN LIFE

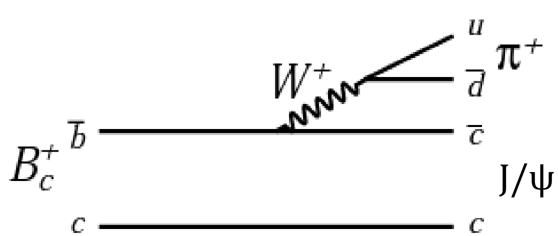
$(0.510 \pm 0.009) \times 10^{-12}$ s $(1638 \pm 4) \times 10^{-15}$ s

- heaviest meson that decays via weak mechanism;
- a lot of decay modes are expected.

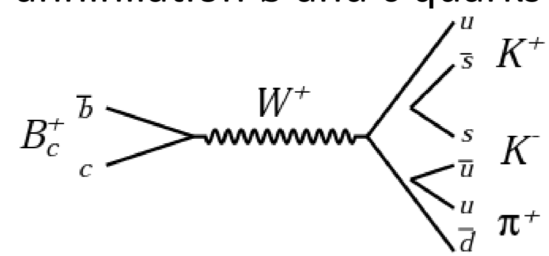
$\bar{b}$ quark-spectator



c quark-spectator



annihilation $\bar{b}$ and c quarks



B_c^+ meson spectroscopy provide significant information about the dynamics of heavy quarks and contribute to the development of theories to describe the strong interaction.

Study of the new B_c^+ meson decays

The B_c^+ meson was discovered 25 years ago, but still poorly studied and only **few decay modes were observed**.

[Prog. Theor. Exp. Phys. (2020) 083C01]

The B_c^+ spectroscopy aimed on:

- study of production mechanism;
- measurement of properties (lifetime, mass);
- searching for new decay channels.

B_c^+ $I(J^P) = 0(0^-)$

I, J, P need confirmation.

Quantum numbers shown are quark-model predictions.

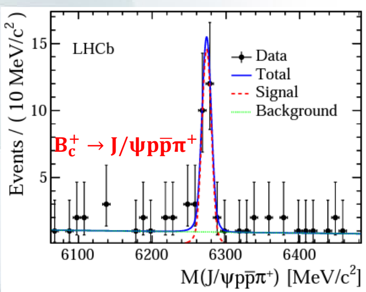
Mass $m = 6274.47 \pm 0.32$ MeV

$m_{B_c^+} - m_{B_s^0} = 907.8 \pm 0.5$ MeV

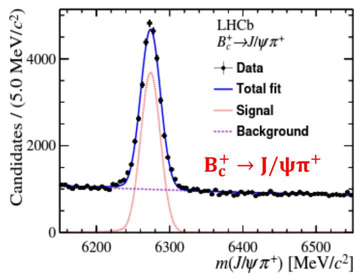
Mean life $\tau = (0.510 \pm 0.009) \times 10^{-12}$ s

B_c^- modes are charge conjugates of the modes below.

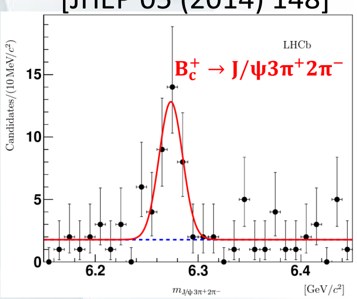
[Phys. Rev. Lett. 113 (2014) 152003]



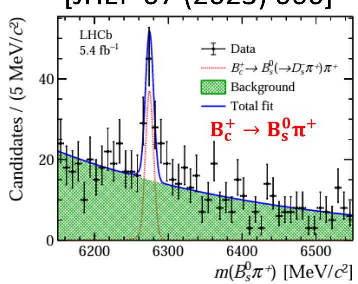
[JHEP 07 (2020) 123]



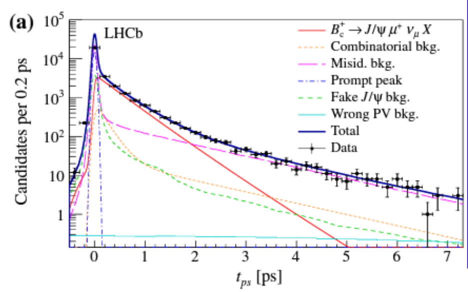
[JHEP 05 (2014) 148]



[JHEP 07 (2023) 066]



[Eur. Phys. J. C (2014) 74:2839]



B_c^+ DECAY MODES × B($\bar{b} \to B_c$)	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$J/\psi(1S)\ell^+\nu_\ell$ anything	seen		–
$J/\psi(1S)\mu^+\nu_\mu$	seen		2372
$J/\psi(1S)\tau^+\nu_\tau$	seen		1932
$J/\psi(1S)\pi^+$	seen		2370
$J/\psi(1S)K^+$	seen		2341
$J/\psi(1S)\pi^+\pi^+\pi^-$	seen		2350
$J/\psi(1S)a_1(1260)$	not seen		2169
$J/\psi(1S)K^+K^-\pi^+$	seen		2203
$J/\psi(1S)\pi^+\pi^+\pi^+\pi^-\pi^-$	seen		2309
$\psi(2S)\pi^+$	seen		2051
$J/\psi(1S)D^0K^+$	seen		1539
$J/\psi(1S)D^*(2007)^0K^+$	seen		1411
$J/\psi(1S)D^*(2010)^+K^{*0}$	seen		919
$J/\psi(1S)D^+K^{*0}$	seen		1122
$J/\psi(1S)D_s^+$	seen		1821
$J/\psi(1S)D_s^{*+}$	seen		1727
$J/\psi(1S)p\bar{p}\pi^+$	seen		1791
$\chi_c^0\pi^+$	$(2.4^{+0.9}_{-0.8}) \times 10^{-5}$		2205
$p\bar{p}\pi^+$	not seen		2970
D^0K^+	seen		2837

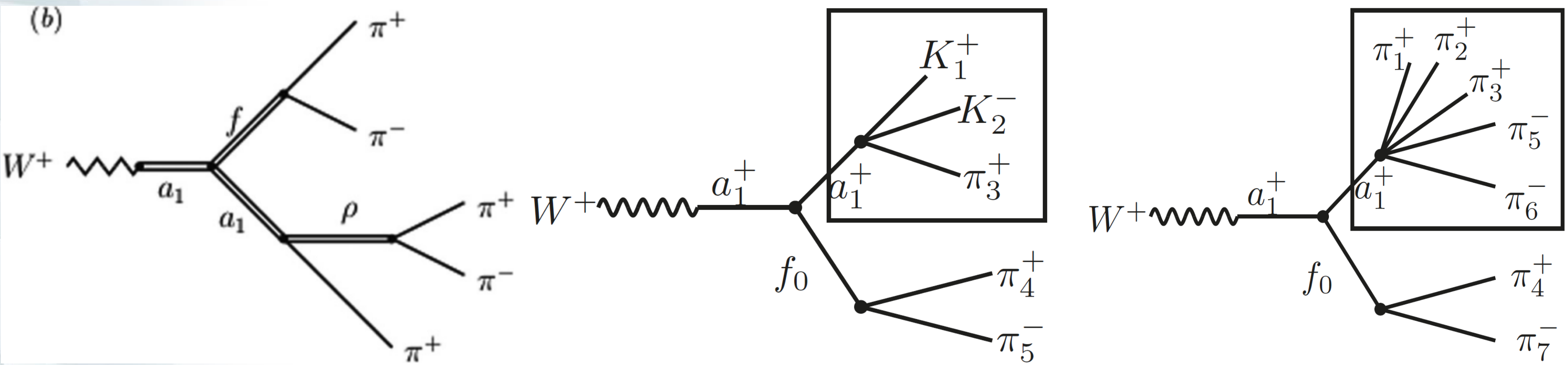
~90% B_c^+ meson decays discovered by the LHCb. Moreover, the experiment **provides record precision** measurements of the masses and lifetimes of heavy hadrons.

Study of the new B_c^+ meson decays

Multihadron $B_c^\pm$ decays into charmonium (ψ) and light hadrons ($h^\pm = \pi^\pm, K^\pm$), according to the factorisation approach, can be described by the $B_c^\pm \to \psi W^\pm$ process, with following $W^\pm$ boson transition into light hadrons.

[Z. Phys. C34 (1987) 103; Prog. Part. Nucl. Phys. 21 (1988) 33; Phys. Usp. 38 (1995) 1]

Decay diagrams of studied channels



[Phys. Lett. B832 (2022) 137269]

The model, based on factrorisation approach for the description of studied channels proposed by A. Berezhnoy, A. Luchinsky and A. Likhoded (BLL model).

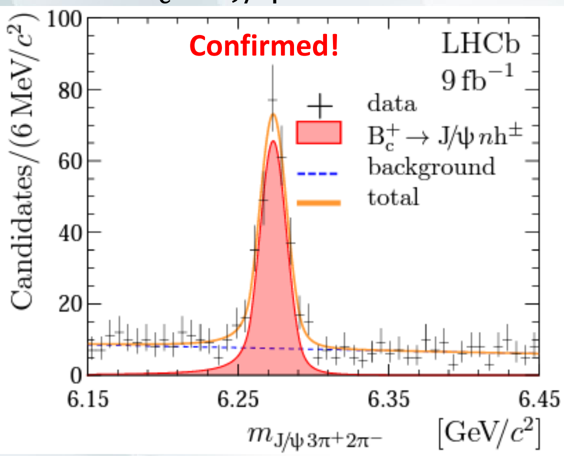
The model well predicted **branching fractions** and **contributions of intermediate resonances** from previous LHCb study of $B_c^\pm \to \psi 3h^\pm$ decays. [JHEP 01 (2022) 065]

The prediction power of the BLL model was tested on B_c^+ decays with five ($3\pi^+2\pi^-, K^+K^-\pi^+\pi^-\pi^+$) and seven ($4\pi^+3\pi^-$) light hadrons in the final state

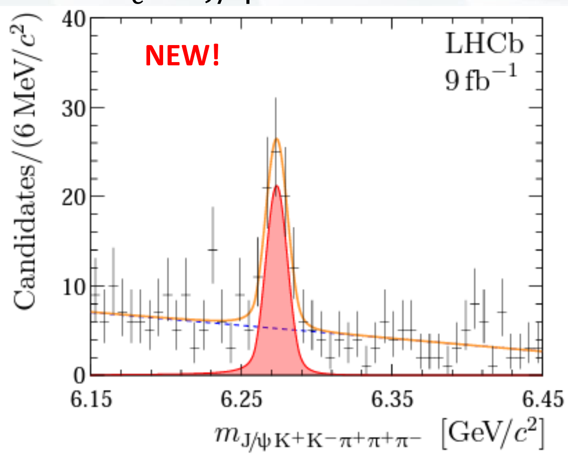
Study of the new B_c^+ meson decays

[JHEP 07 (2023) 198]

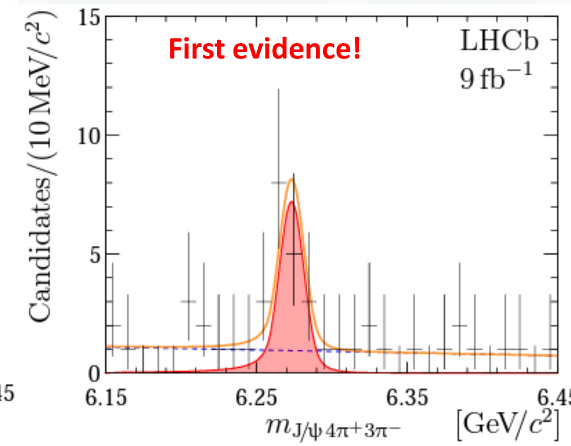
$B_c^+ \to J/\psi 3\pi^+ 2\pi^-$



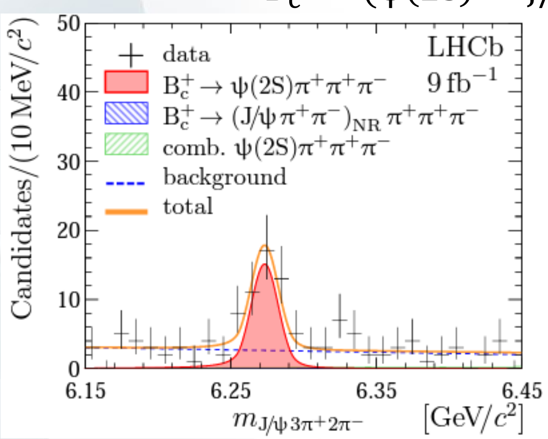
$B_c^+ \to J/\psi K^+ K^- \pi^+ \pi^- \pi^+$

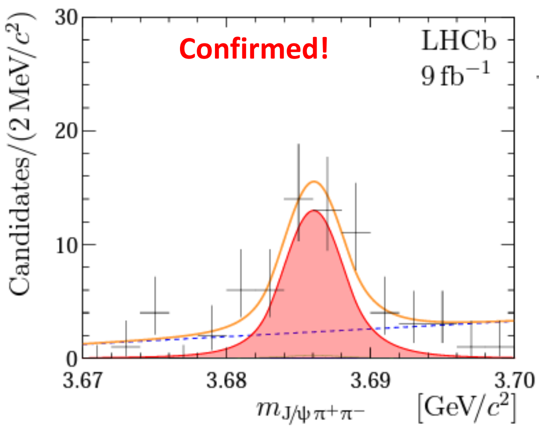


$B_c^+ \to J/\psi 4\pi^+ 3\pi^-$



$B_c^+ \to (\psi(2S) \to J/\psi \pi^+ \pi^-) \pi^+ \pi^- \pi^+$





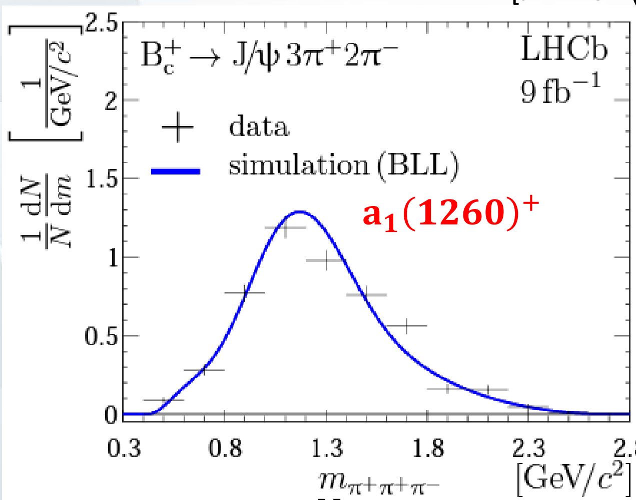
Decay	Yield	$\mathcal{S}$ [σ]
$B_c^+ \to J/\psi\, 3\pi^+ 2\pi^-$	268 ± 20	21.0
$B_c^+ \to J/\psi\, K^+ K^- \pi^+ \pi^+ \pi^-$	69 ± 11	9.0
$B_c^+ \to J/\psi\, 4\pi^+ 3\pi^-$	16 ± 5	4.7
$B_c^+ \to (\psi(2S) \to J/\psi\, \pi^+ \pi^-) \pi^+ \pi^+ \pi^-$	40 ± 8	5.2

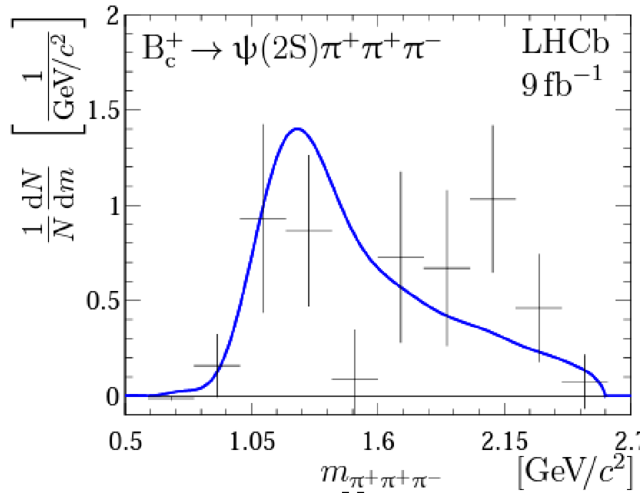
- the $B_c^+ \to J/\psi K^+ K^- \pi^+ \pi^- \pi^+$ decay is observed for **the first time**;
- **the first evidence** of the $B_c^+ \to J/\psi 4\pi^+ 3\pi^-$ decay (**secondary vertex with 9 tracks!**);
- the $B_c^+ \to \psi(2S) \pi^+ \pi^- \pi^+$ decay **is confirmed** with $\psi(2S) \to J/\psi \pi^+ \pi^-$ mode;
- the $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$ decay **is confirmed** .

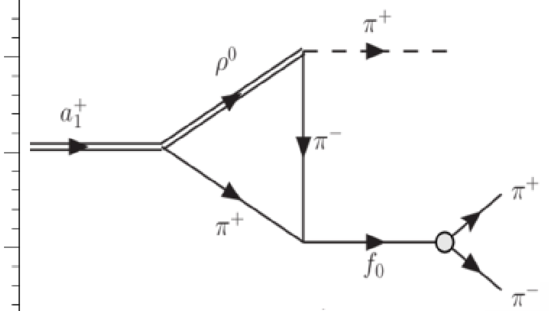
Study of the new B_c^+ meson decays

To test the BLL model the light hadron systems were investigated

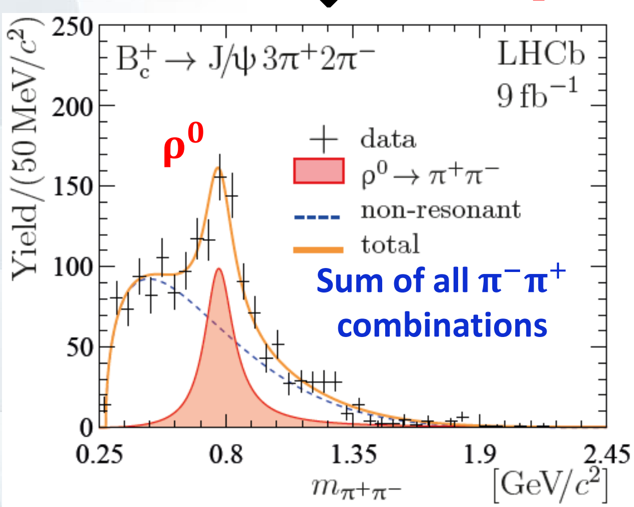
[JHEP 07 (2023) 198]

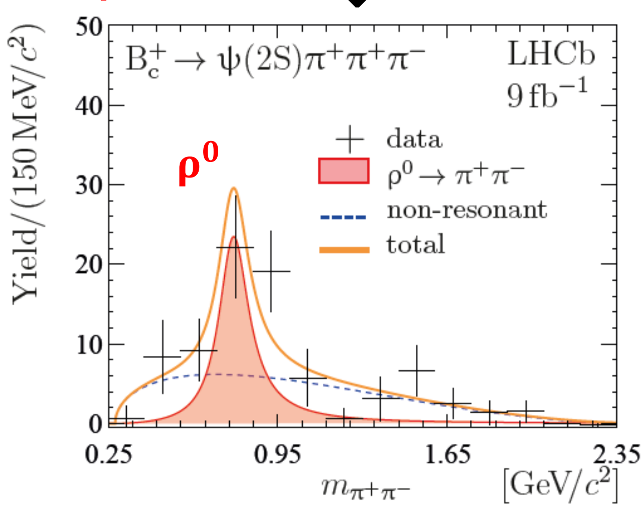






$a_1(1260)^+ \to \rho^0\pi^+$





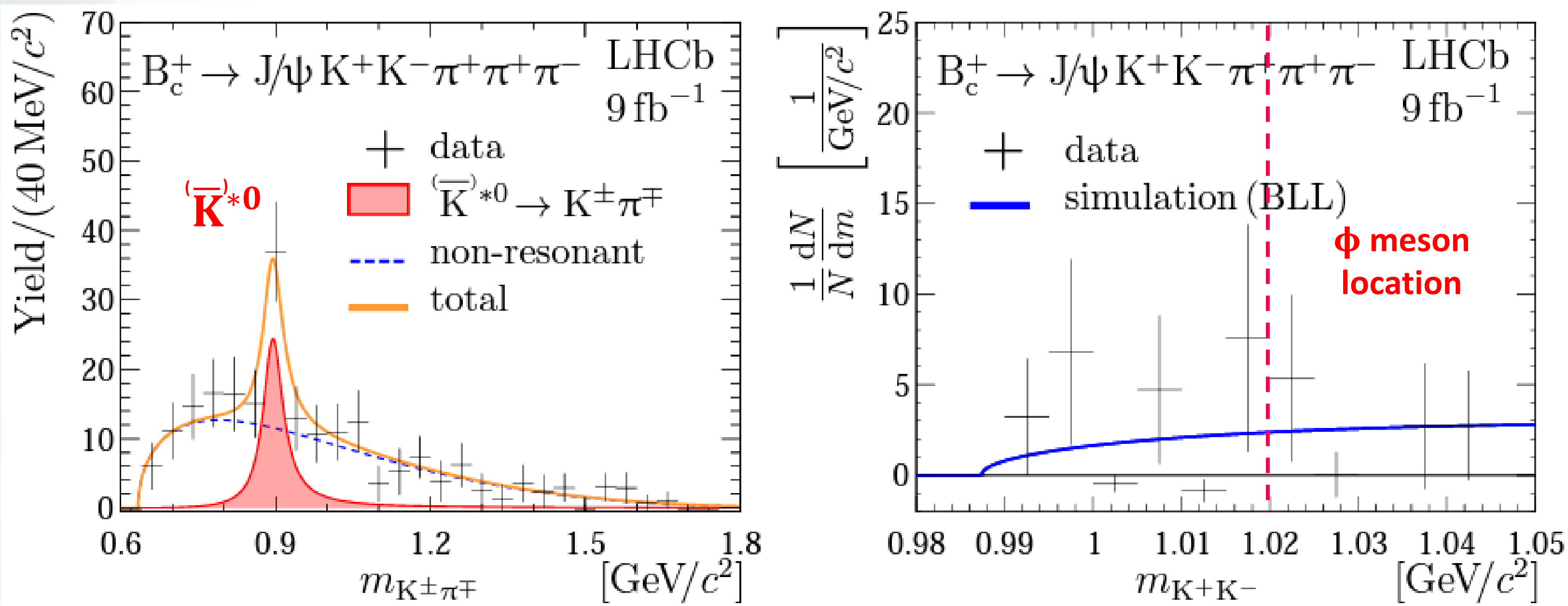
The dominating contributions from ρ^0 state (**agrees with BLL model**).

[Phys. Lett. B832 (2022) 137269]

Study of the new B_c^+ meson decays

In the $B_c^+ \to J/\psi K^+K^-\pi^+\pi^-\pi^+$ channel the mass combinations of $K^\pm\pi^\mp$ and K^+K^- systems were studied.

[JHEP 07 (2023) 198]



- fit results shows large contributions from intermediate process $B_c^+ \to J/\psi\bar{K}^{*0}K^+\pi^-\pi^+$ and $B_c^+ \to J/\psi K^{*0}K^-\pi^+\pi^+$ processes;
- the contributions from $B_c^+ \to J/\psi\phi\pi^+\pi^-\pi^+$ decays is not seen (**agrees with BLL model)**; [Phys. Lett. B832 (2022) 137269]
- the same effects were seen in the $B_c^+ \to J/\psi K^+K^-\pi^+$ channel from previous LHCb studies.

[JHEP 11 (2013) 94; JHEP 01 (2022) 065]

Exotic spectroscopy

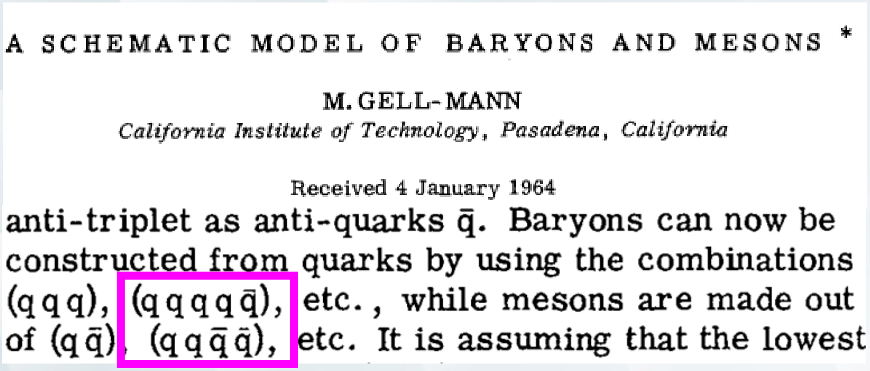
- evidence for the $T^{\theta}_{\psi s1}(4000)^0$ state; [Phys. Rev. Lett. 131 (2023) 131901]
- observation of $T^{a}_{c\bar{s}0}(2900)^{++}$ and $T^{a}_{c\bar{s}0}(2900)^0$ states; [Phys. Rev. Lett. 131 (2023) 041902; Phys. Rev. D 108 (2023) 012017]
- study of the $B^+ \to D_s^+ D_s^- K^+$ decay; [Phys. Rev. D 108 (2023) 034012; Phys. Rev. Lett. 131 (2023) 071901]
- observation of $P^{\Lambda}_{\psi s}(4338)^0$ state. [Phys. Rev. Lett. 131 (2023) 031901]

Quark model of hadrons

According to the quark model, all conventional hadrons (**mesons** and **baryons**) consist of particles with fractional electric charges - quarks and their corresponding antiparticles (antiquarks).

M. Gell-Mann

[Phys. Lett. 8 (1964) 214]



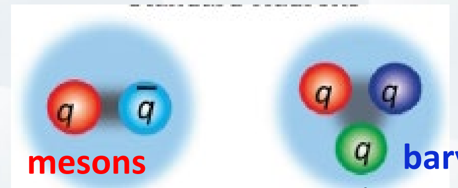
A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

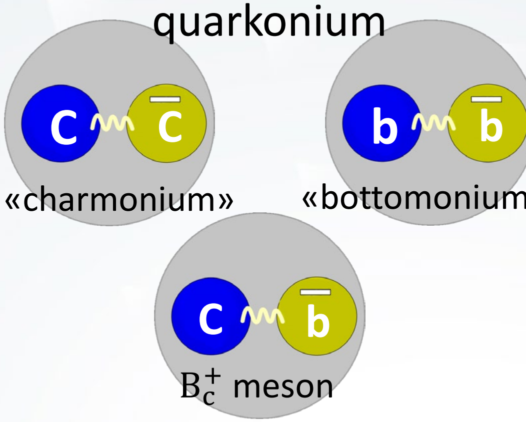
anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

conventional hadrons



(quark-antiquark pair) (three quarks)

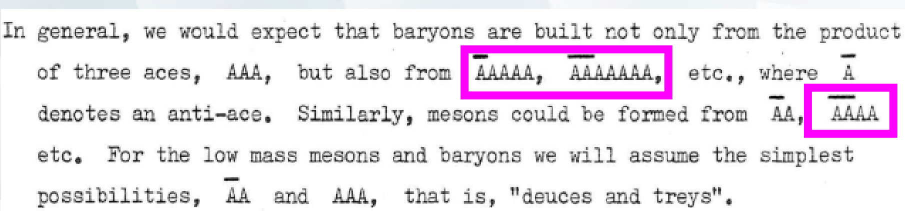
quarkonium



Exotic hadrons – everything beyond $q\bar{q}$-meson and qqq-baryon scheme. Could be various multiquark states, hadron molecules, hybrids, etc. First predicted in 1964 by M.Gell-Mann and G. Zweig

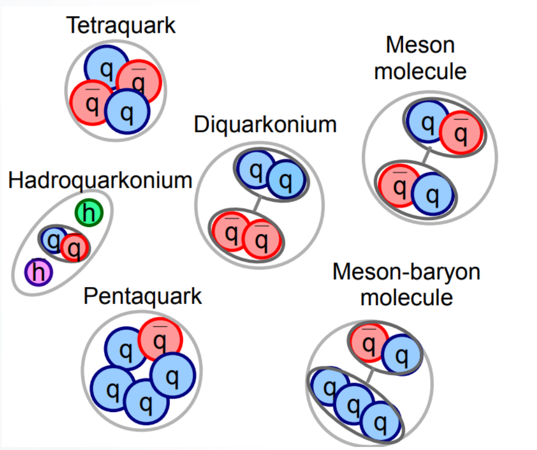
G. Zweig

[CERN-TH-412]



In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $A\bar{A}AAA$, $AA\bar{A}\bar{A}AAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $A\bar{A}A\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $A\bar{A}$ and AAA, that is, "deuces and treys".

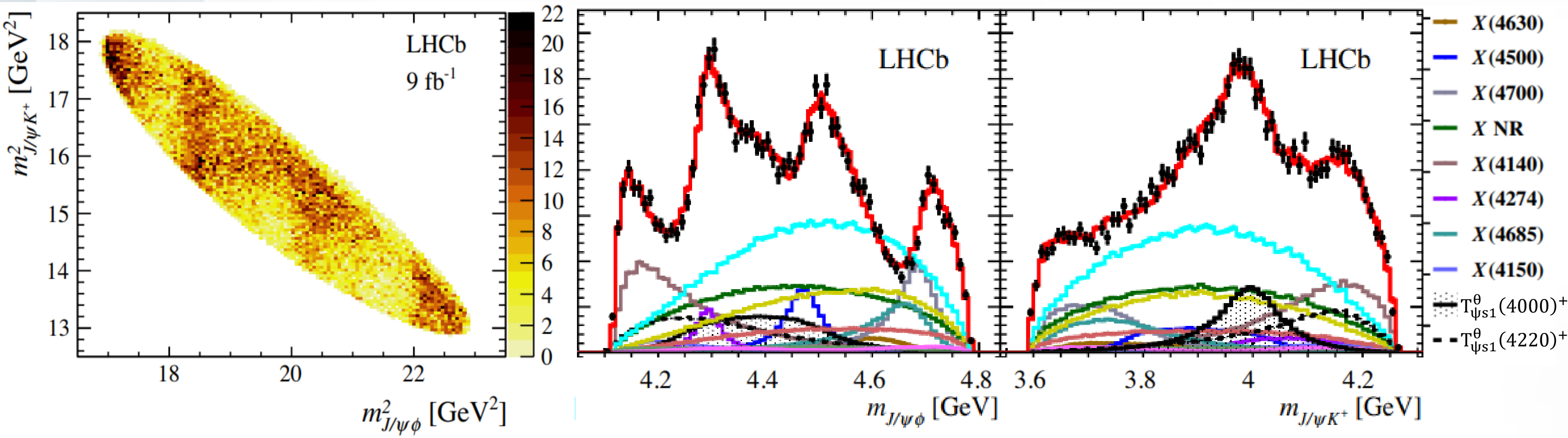
Exotic hadrons



Evidence for the $T^{\theta}_{\psi s1}(4000)^0$ state

- $T^{\theta}_{\psi s1}(4000)^+$ and $T^{\theta}_{\psi s1}(4220)^+$ $(c\bar{c}u\bar{s})$ are observed in $B^+ \to J/\psi\phi K^+$ decays:

[Phys. Rev. Lett. 127 (2021) 082001]

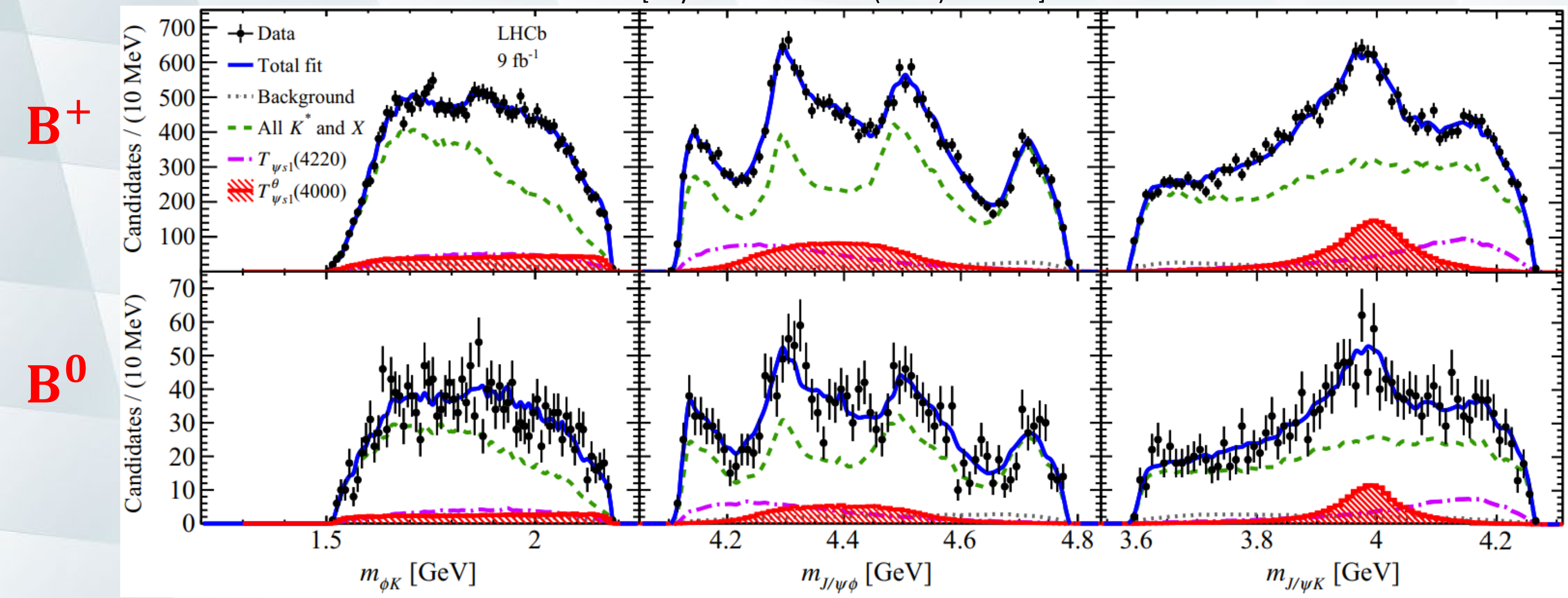


J^P	Contribution	Significance (σ)	M_0 (MeV)	Γ_0 (MeV)	FF (%)
1^+	$T^{\theta}_{\psi s1}(4000)^+$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
	$T^{\theta}_{\psi s1}(4220)^+$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

- searching for their isospin partners;
- an ideal process for such search is $B^0 \to J/\psi\phi K^0_S$ decay due to isospin symmetry;
- simultaneous fit is performed to $B^0 \to J/\psi\phi K^0_S$ and the $B^+ \to J/\psi\phi K^+$ samples.

Evidence for the $T^{\theta}_{\psi s1}(4000)^0$ state

[Phys. Rev. Lett. 131 (2023) 131901]



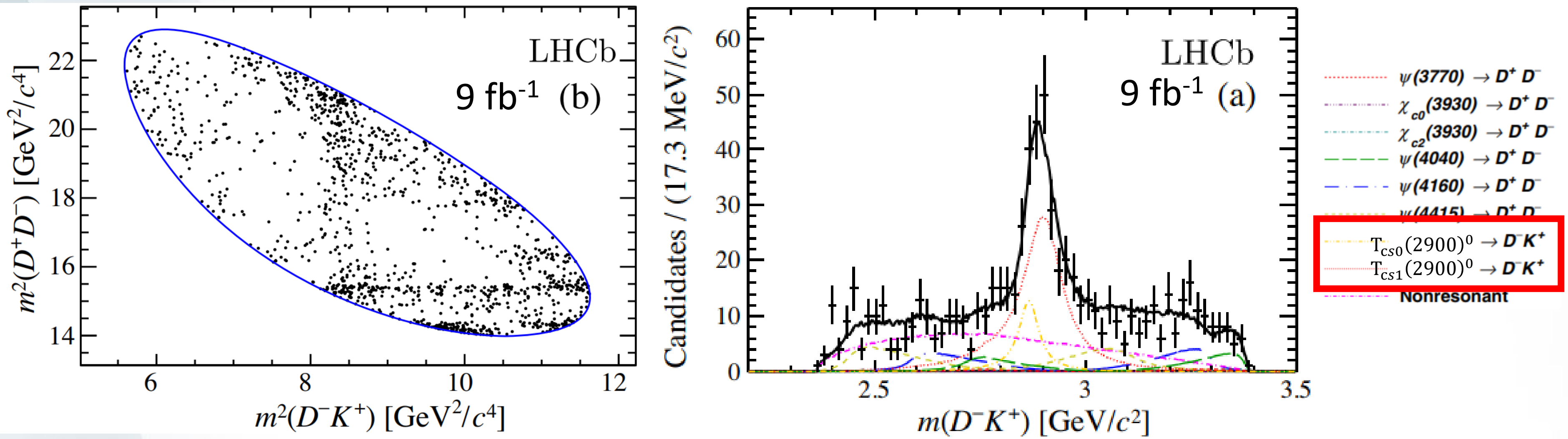
- evidence of a $J/\psi K^0_S$ structure with a significance of 4σ is performed;
- denoted as $T^{\theta}_{\psi s1}(4000)^0$ ($c\bar{c}d\bar{s}$), which likely to be the isospin partner of $T^{\theta}_{\psi s1}(4000)^+$($c\bar{c}u\bar{s}$);
- determined parameters:

State	Mass (MeV)	Width (MeV)	Fit fraction (%)	ΔM (MeV)
$T^{\theta}_{\psi s1}(4000)^0$	$3991^{+12}_{-10}{}^{+9}_{-17}$	$105^{+29}_{-25}{}^{+17}_{-23}$	$7.9 \pm 2.5^{+3.0}_{-2.8}$	$-12^{+11}_{-10}{}^{+6}_{-4}$

Observation of $T^{a}_{c\bar{s}0}(2900)^{++}$ and $T^{a}_{c\bar{s}0}(2900)^{0}$ states

First evidence of open-charm tetraquark candidates with four different flavors ($cs\bar{u}\bar{d}$) was done in $B^+ \to D^+D^-K^+$ channel

[Phys. Rev. D 102 (2020) 112003; Phys. Rev. Lett. 125 (2020) 242001]



$T_{cs0}(2900)^0$: $M = 2.866 \pm 0.007 \pm 0.002\ \mathrm{GeV}/c^2,\ \Gamma = 57 \pm 12 \pm 4\ \mathrm{MeV}$

$T_{cs1}(2900)^0$: $M = 2.904 \pm 0.005 \pm 0.001\ \mathrm{GeV}/c^2,\ \Gamma = 110 \pm 11 \pm 4\ \mathrm{MeV}$

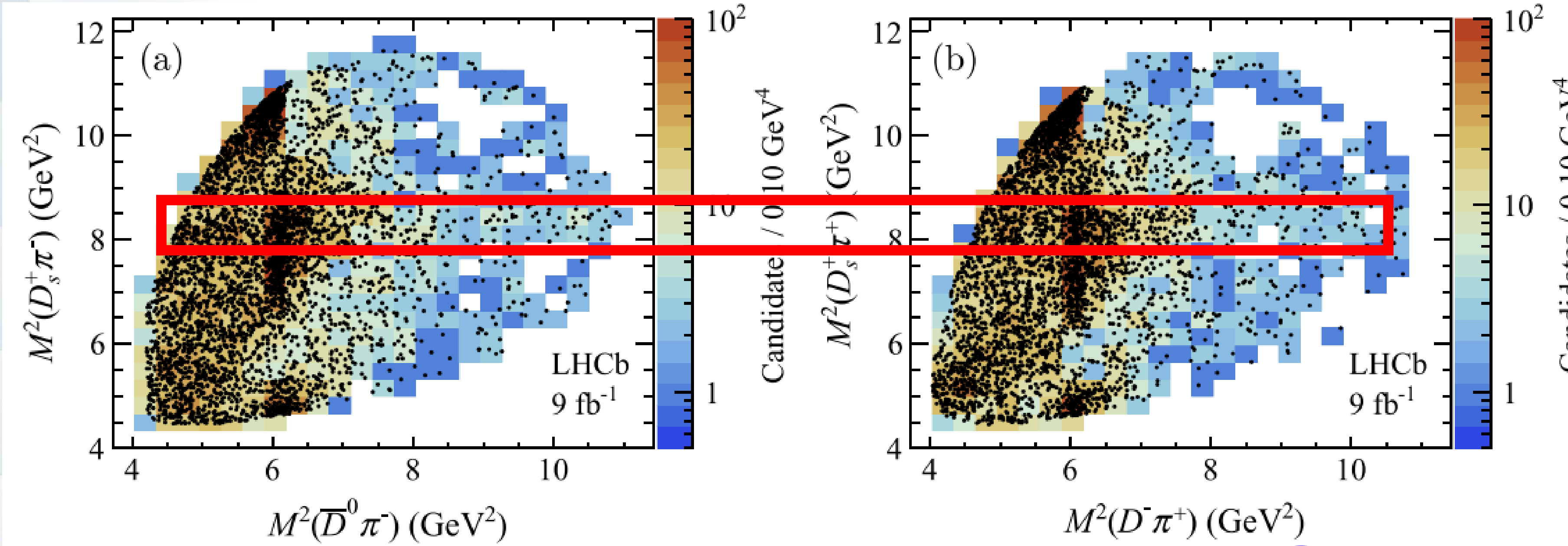
- search for tetraquark candidates, with quark component ($c\bar{s}u\bar{d}$) or ($c\bar{s}\bar{u}d$) can be performed in $B^+ \to D^-D_s^+\pi^+$ and $B^0 \to \bar{D}^0D_s^+\pi^-$ decays;
- a combined amplitude analysis of the $B^+ \to D^-D_s^+\pi^+$ and $B^0 \to \bar{D}^0D_s^+\pi^-$ decays is performed.

Observation of $T^{a}_{c\bar{s}0}(2900)^{++}$ and $T^{a}_{c\bar{s}0}(2900)^{0}$ states

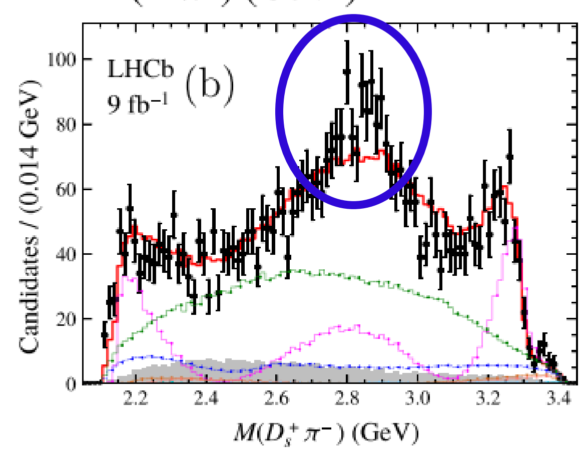
- Full LHCb data:
  - **4009** $B^0 \to \bar{D}^0 D_s^+ \pi^-$ candidates;
  - **3750** $B^+ \to D^- D_s^+ \pi^+$ candidates;

Signal purity > 90%

[Phys. Rev. Lett. 131 (2023) 041902; Phys. Rev. D 108 (2023) 012017]



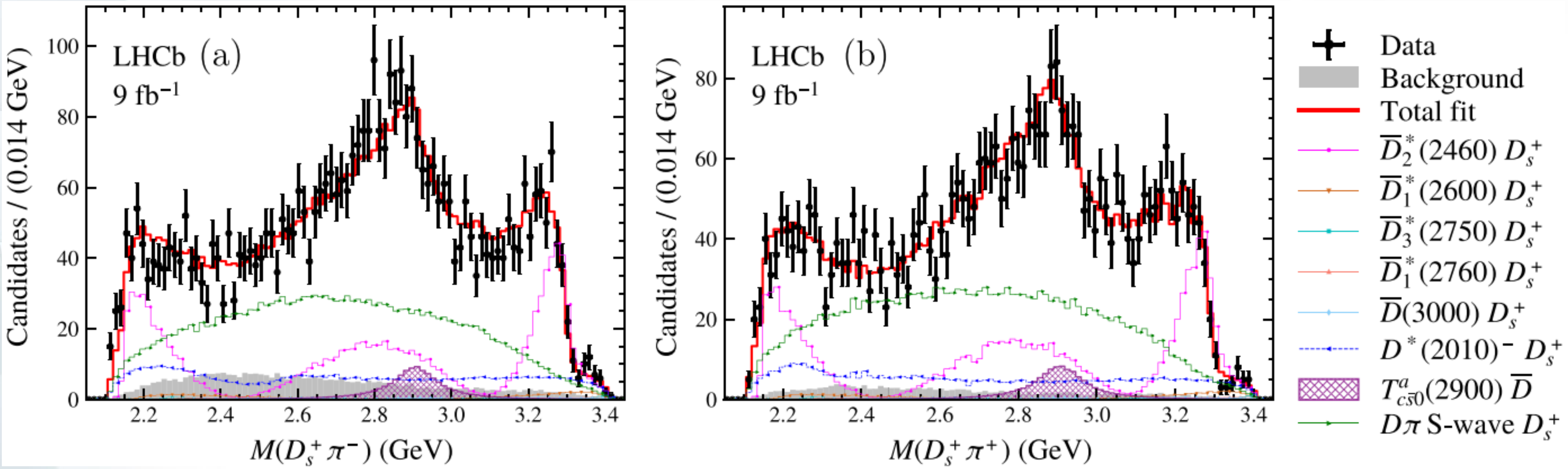
- structure at 2.9 GeV in $D_s^+\pi^\pm$ spectra **cannot be well described** by any known or new $D_s^{*+,0} \to \bar{D}^{0,-}\pi^+$ resonances;
- two new $D_s^+\pi^\pm$ exotic resonances are included in the fit model.



Observation of $T^a_{c\bar{s}0}(2900)^{++}$ and $T^a_{c\bar{s}0}(2900)^0$ states

With two additional $D_s^+\pi^\pm$ components, the data is better described

[Phys. Rev. Lett. 131 (2023) 041902; Phys. Rev. D 108 (2023) 012017]



- both states prefer $J^P = 0^+$ (1^- rejected by > 7σ);
- separated fit parameters (mass and width in great agreement);

$$T^a_{c\bar{s}0}(2900)^0: \; M = 2.892 \pm 0.014 \pm 0.015 \text{ GeV}, \quad \Gamma = 0.119 \pm 0.026 \pm 0.013 \text{ GeV},$$

8σ

$$T^a_{c\bar{s}0}(2900)^{++}: \; M = 2.921 \pm 0.017 \pm 0.020 \text{ GeV}, \quad \Gamma = 0.137 \pm 0.032 \pm 0.017 \text{ GeV},$$

6.5σ

$T^a_{c\bar{s}0}(2900)^{++}(c\bar{s}u\bar{d})$ is the first **doubly-charged** tetraquark candidate!

- Combined fit parameters (assume both belong to the same isospin triplet)

$$M = 2.908 \pm 0.011 \pm 0.020 \text{ GeV}, \quad \Gamma = 0.136 \pm 0.023 \pm 0.013 \text{ GeV},$$

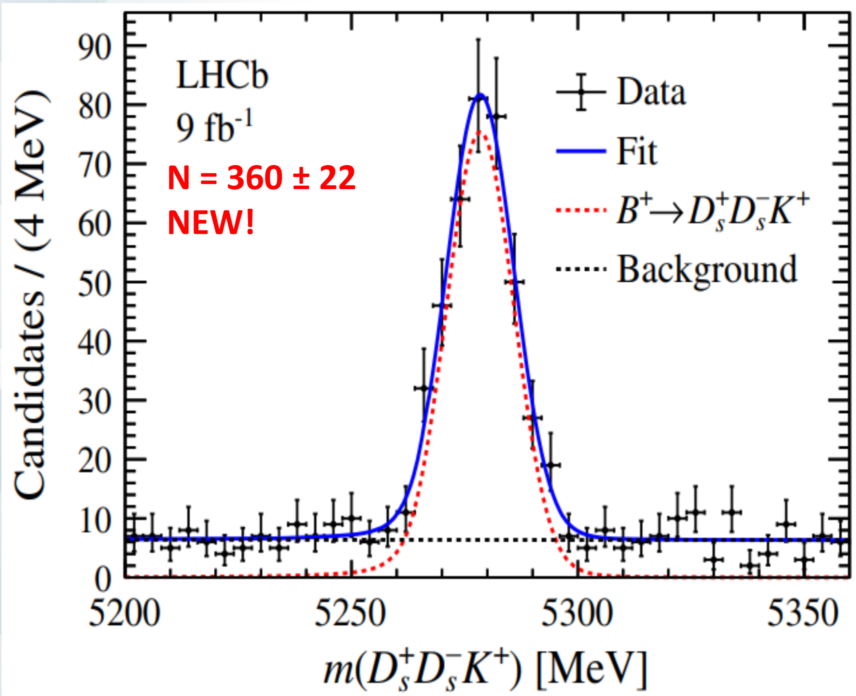
Combined significance >9σ

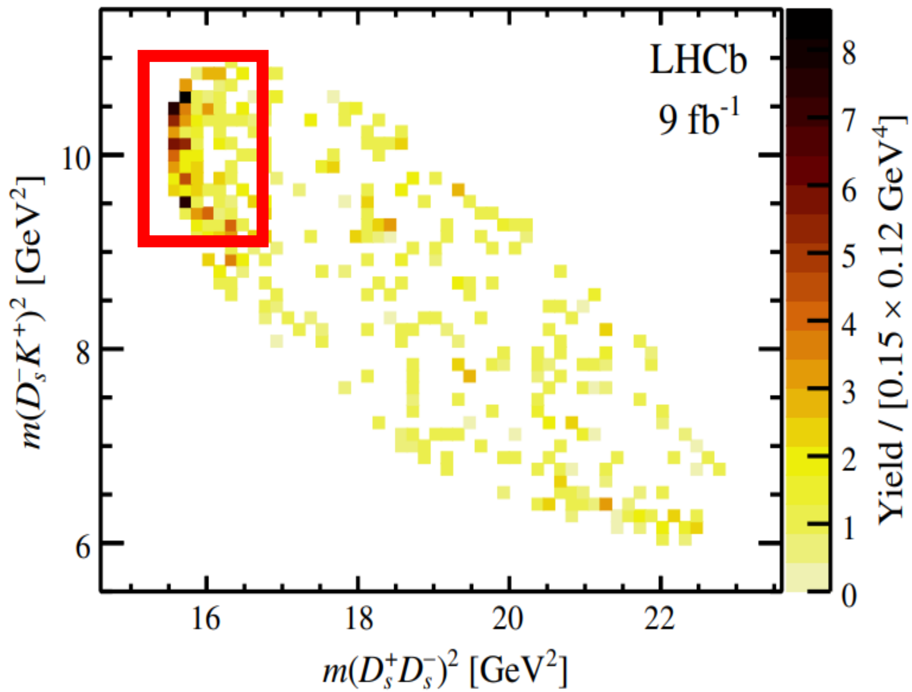
Study of the $B^+ \to D_s^+ D_s^- K^+$ decay

The family of $B \to D_{(s)}^{(*)} \overline{D}_{(s)}^{(*)} K^{(*)}$ decays proceeds at the quark level via the Cabibbo-favored $\bar{b} \to c\bar{c}\bar{s}$ transition. Such decays provide an excellent laboratory for investigations of open- and hidden-charm meson spectroscopy, covering both conventional and **exotic states**.

Near threshold enhancement in $D_s^+ D_s^-$ mass spectra ⇒ amplitude analysis is performed

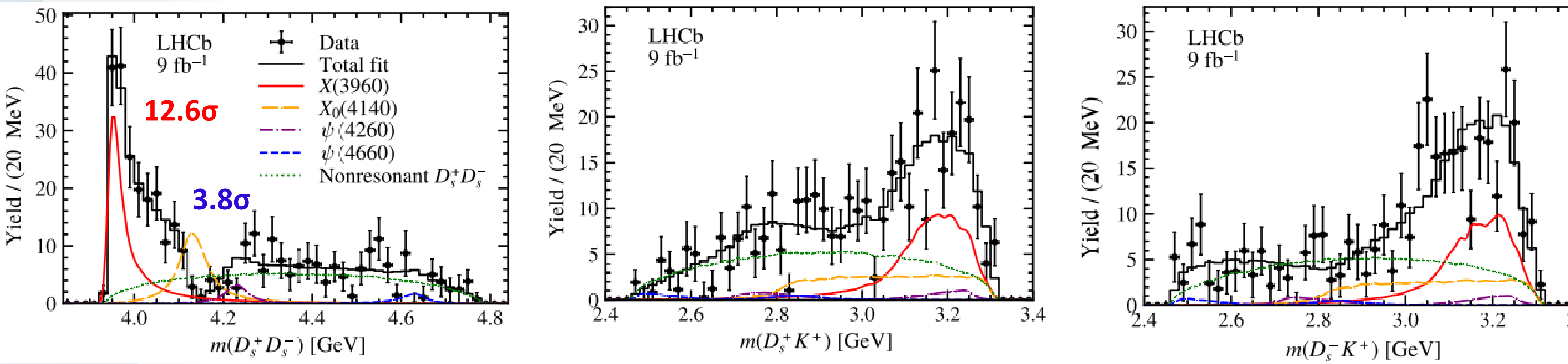
[Phys. Rev. D 108 (2023) 034012; Phys. Rev. Lett. 131 (2023) 071901]





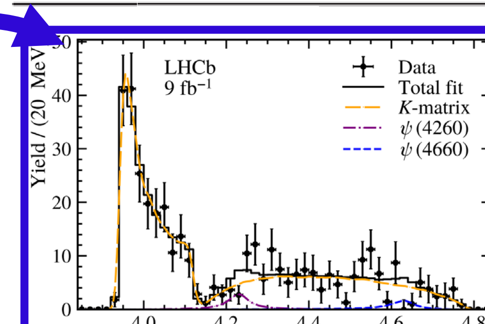
Study of the $B^+ \to D_s^+ D_s^- K^+$ decay

- Baseline model: [Phys. Rev. D 108 (2023) 034012; Phys. Rev. Lett. 131 (2023) 071901]
  - $X_0(4140)$ (to describe **the dip** at 4.14 GeV via interference);
  - non-resonant;
  - new X(3960) state (to describe the **near-threshold enhancement**);
  - $\psi(4260), \psi(4660)$.



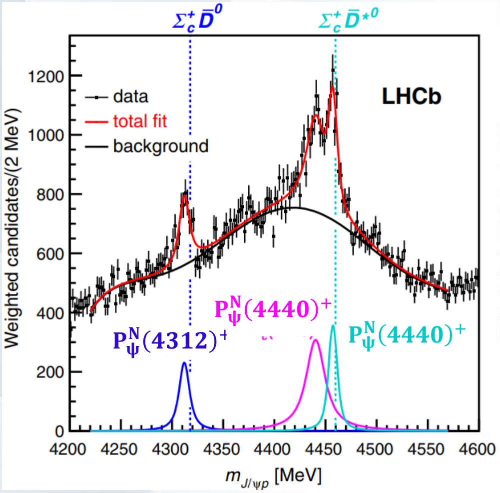
- X(3960) state threshold enhancement:
  - $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 9.3σ and 12.3σ;
- $X_0(4140)$ dip at 4.14 GeV via interference:
  - $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 3.5σ and 4.2σ;
  - the dip can be also described by **$J/\psi\phi \leftrightarrow D_s^+ D_s^-$ scattering**;
- X(3960) state could be the same as $\chi_{c0}(3930)$ observed in D^+D^-?
  - $\dfrac{\Gamma(X \to D^+D^-)}{\Gamma(X \to D_s^+ D_s^-)} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$;
  - incompatible with the suppression of $s\bar{s}$ pair from vacuum (w.r.t $u\bar{u}$ or $d\bar{d}$) and the smaller phase-space volume of $D_s^+ D_s^-$;
  - possible exotic candidate with minimal quark content ($c\bar{c}s\bar{s}$).

Component	M_0 (MeV)	Γ_0 (MeV)
$X(3960)$	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$
$X_0(4140)$	$4133 \pm 6 \pm 6$	$67 \pm 17 \pm 7$
$\psi(4260)$	4230 [60]	55 [60]
$\psi(4660)$	4633 [32]	64 [32]
NR	...	...



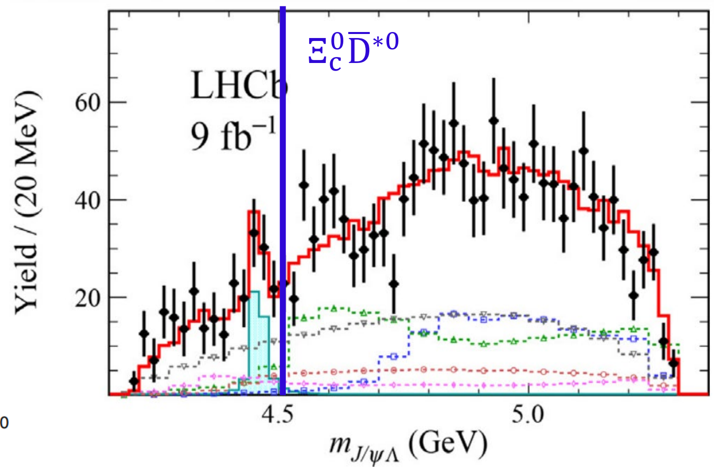
Observation of $P_{\psi s}^{\Lambda}(4338)^0$ state

The mass of pentaquarks is found to be close to charm-baryon and charm-meson threshold. Their interpretation as hadronic molecular-state is one of the popular theories.



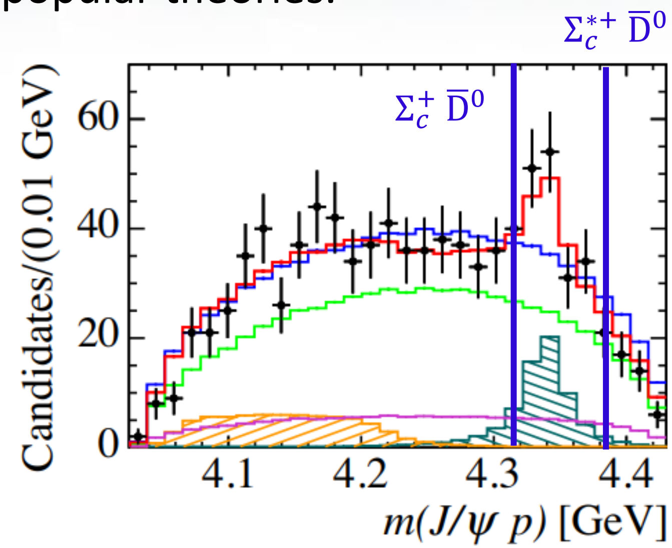
[Phys. Rev. Lett. 122 (2019) 222001]

Observation of P_ψ^N in $\Lambda_b^0 \to J/\psi p K^-$ ($c\bar{c}uud$)



[Sci. Bull. 66 (2021) 1278]

Evidence of $P_{\psi s}^{\Lambda}$ in $\Xi_b^- \to J/\psi \Lambda K^-$ ($c\bar{c}uds$)

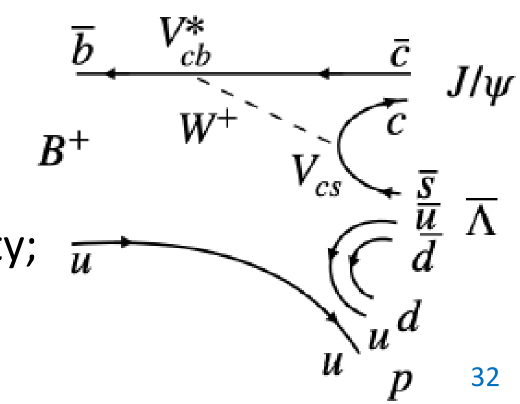


[Phys. Rev. Lett. 128 (2022) 062001]

Evidence of P_ψ^N in $B_s^0 \to J/\psi p\bar{p}$ ($c\bar{c}uud$)

- the $B^+ \to J/\psi \Lambda p$ is an ideal channel to search pentaquark candidates related to the thresholds of: $\Xi_c^+ D^-$, $\Lambda_c^+ D_s^-$ and $\Lambda_c^+\bar{D}^0$, $\Sigma_c \bar{D}^{(*)}$ at the same time;

$J/\psi\Lambda$ **$J/\psi p$**

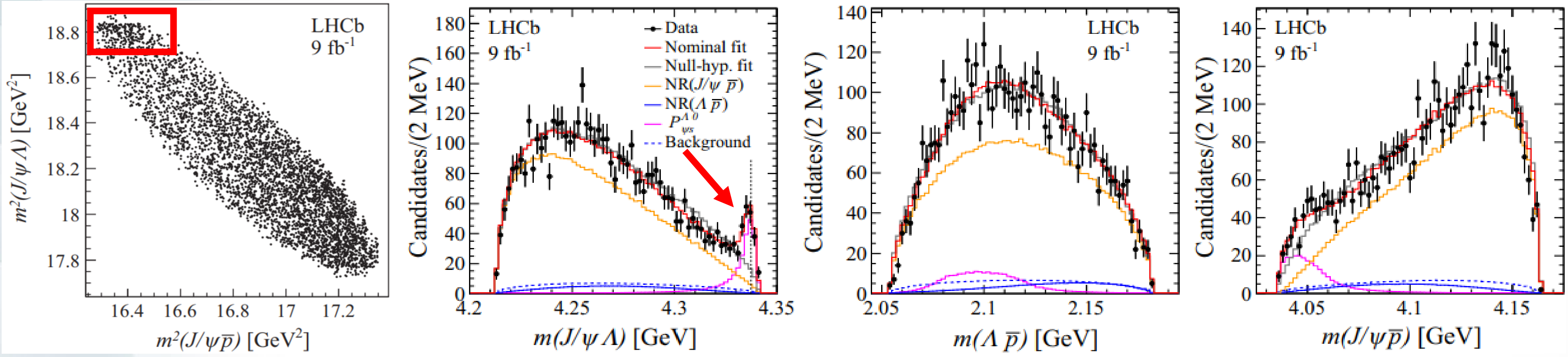


- large statistic ~4400 events (full Run 1 and Run 2 data) with 93% purity;
- six-dimensional fit is performed.

Observation of $P_{\psi s}^{\Lambda}(4338)^0$ state

- start from the K^* model: $K^*_{2,3,4}$ can't describe the data well;
- nominal model with non-resonant $\Lambda\bar{p}$, $J/\psi\bar{p}$ and $P_{\psi s}^{\Lambda}$ component significantly improved the fit.

[Phys. Rev. Lett. 131 (2023) 031901]



The $P_{\psi s}^{\Lambda}(4338)^0$ state is **observed for the first time** (significance > 10σ w.r.t. null hypo):

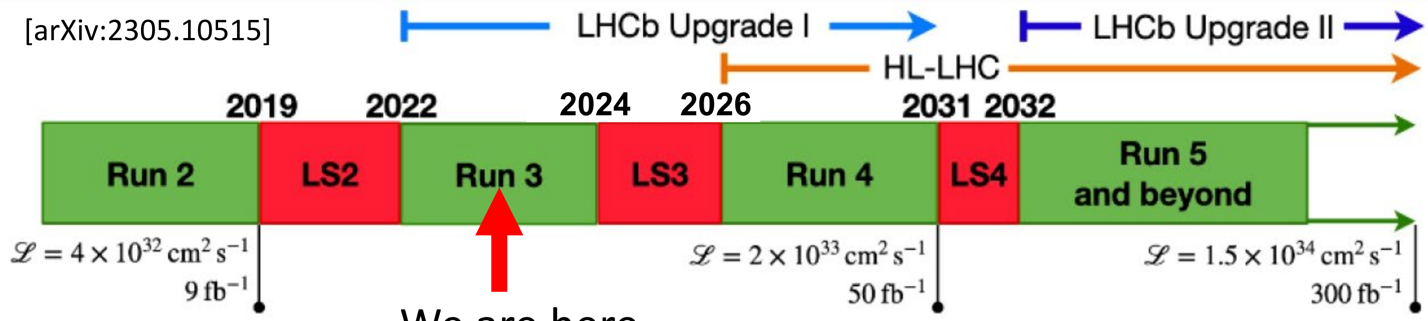
- quark component: ($c\bar{c}uds$);
- first observation of a hidden-charm pentaquark candidate with strangeness
- $J^P = 1/2^-$ is preferred;
- Breit-Wigner mass and width are determined;

$$M_{P_{\psi s}^{\Lambda}} = 4338.2 \pm 0.7 \pm 0.4\ \text{MeV}$$
$$\Gamma_{P_{\psi s}^{\Lambda}} = 7.0 \pm 1.2 \pm 1.3\ \text{MeV}$$

- close to $\Xi_c^+ D^-$ threshold and J^P consistent with S-wave $\Xi_c\bar{D}$ molecular state;
- most precise single measurement to date of the B^- mass. $M_{B^-} = 5279.44 \pm 0.05 \pm 0.07$ MeV

Summary and prospects

[arXiv:2305.10515]



The most recent interesting results are presented:

- new conventional hadrons are observed: $\Omega_c(3185)^0$, $\Omega_c(3327)^0$, $\Xi_b^0(6087)$, $\Xi_b^0(6095)$;
- first observation of the $\Xi_b^- \to \Lambda_b^0 \pi^-$ decay;
- charmonia decays into $K_S^0 K^\pm \pi^\mp$ final state are studied;
- four B_c^+ meson decays into charmonia and multihadron final states are studied;
- new tetraquark candidates: $T_{\psi s1}^{\theta}(4000)^0$, $T_{c\bar{s}0}^{a}(2900)^{++}$, $T_{c\bar{s}0}^{a}(2900)^0$, X(3960);
- new pentaquark candidate: $P_{\psi s}^{\Lambda}(4338)^0$.

Higher statistics in upgrade and improved trigger efficiency for all-hadronic final states boosts hadron spectroscopy studies at LHCb:

- search for more conventional excited states;
- *evidence* ⇒ *observation* of some hadrons/decay modes;
- search for new decay modes of observed exotic hadrons;
- determine J^P and other properties of multiquark states;
- precise measurements of properties of heavy flavour hadrons;
- …….and many other unique studies.

Stay tuned and follow for the news on the LHCb website
https://lhcb.web.cern.ch/

Thank you!

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