LHCb-FIGURE-2021-001
March 3, 2021

List of hadrons observed at the LHC

LHCb collaboration

Abstract

In ten years of operation the LHC has uncovered 59 new hadrons [1–32]. This note provides a full list of states observed by the ATLAS, CMS and LHCb collaborations.

An up-to-date list is maintained at `https://www.nikhef.nl/~pkoppenb/particles.html`.

1 Introduction

While the LHC is best known for the observation of the first fundamental scalar particle, the Higgs Boson [33, 34], it has also yielded many observations of yet unknown hadrons. Hadrons are composed of quarks and are thus not fundamental particles of the Standard Model. However, their properties follow from yet unsolved mysteries of the strong interaction.

Although the QCD Lagrangian is expected to completely describe the spectrum of hadrons and all of their properties, there is no rigorous first-principle way of expressing this mathematically. The quark confinement conjecture is experimentally well tested, but mathematically still unproven. And it is still unknown which combinations of quarks may or may not form hadrons. Experimental guidance is needed to help improving theoretical models. These models are then in turn needed to constrain hadronic uncertainties which affect searches for New Physics phenomena.

The huge luminosity of the LHC combined with a large heavy-flavour cross-section provides an ideal environment to search for unknown hadrons containing heavy quarks. These can either be produced directly in the pp collisions, or appear in decays of heavier known states. The unprecedented b-hadron sample permits high-yield amplitude analyses, which have allowed the LHC experiments to uncover new particles containing c quarks. Unflavoured and strange hadrons have been extensively scrutinised by fixed-target experiments and there is thus little left for the LHC to discover at low mass. The new states are thus all heavy hadrons with masses between 2.5 and 11 GeV/c^2. The new-states counter now indicates 59.

The most prominent observation is certainly that of pentaquarks [10], but many other exotic hadrons that do not fit the conventional $q\overline{q}$ or qqq picture have been found. The LHC has also uncovered many excited conventional hadrons that were just waiting to be searched for — the comb-like Ω_c^0 plot in Fig. 3q [14] is the most spectacular example — as well as multi-heavy baryons like the Ξ_{cc}^{++} ground state [15]. The LHC has also yielded interesting null results in searches for controversial states. Searches for the $X(5568)^\pm$ meson reported by the D0 experiment at the Tevatron [35, 36] did only yield upper limits on the cross-section [37–39]. Similarly the Ξ_{cc}^+ baryon reported by SELEX [40, 41] does not appear in LHCb data [42].

Only states observed with high significance are listed in this note, but many are still of uncertain nature. For instance the narrow $P_c(4450)^+$ pentaquark reported in Ref. [10] was later split into two even narrower states dubbed $P_c(4440)^+$ and $P_c(4457)^+$ [21]. It is to be expected that some of the states presented here will later be reassessed as a combination of several states.

While amplitude analyses provide a measurement of all quantum numbers, bump-hunting does not. Information from the mass, width, decay modes and cross-section will point to an identity hypothesis, but this will always be under the assumption of the quark model. It should be reminded here that many heavy baryons lack a measured spin-parity assignment, as for instance the Λ_b^0 baryon, the lightest with a b quark.

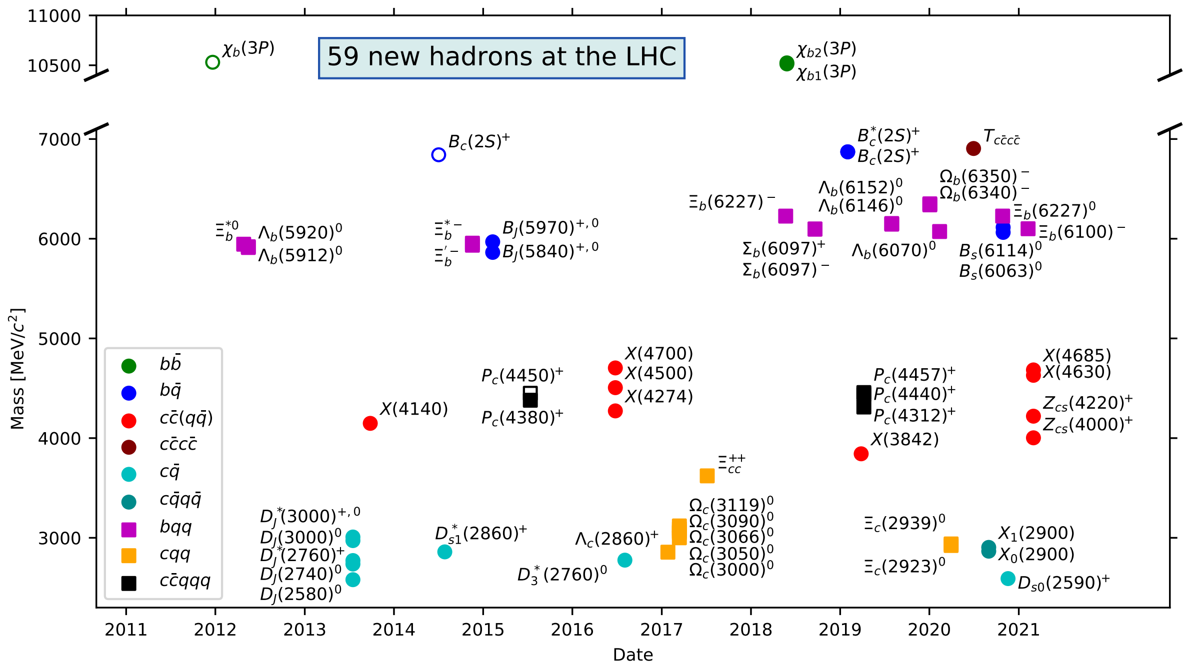

Figure 1: All states in Table 1 plotted as mass versus preprint submission date. Hollow markers indicate superseded states.

2 List

The list of observed hadrons is tabulated in Tab. 1 and graphically shown in Fig. 1. Only states that exceed the background-only hypothesis by 5σ (including systematic uncertainties) are reported here. Charge-conjugate states are implied. Isospin partners are counted separately as they are usually observed in separate analyses. Hence the $\Sigma_b(6097)^-$ and $\Sigma_b(6097)^+$ baryons [18] appear in different entries while the missing member of the triplet, $\Sigma_b(6097)^0$, is yet to be observed. However, the $B_J(5840)$ and $B_J(5970)$ mesons are counted as two states each (a neutral and a charged one), following the conclusions of Ref. [9], although some peaks fall short of 5σ when searched for in individual fits.

Table 1: Chronologically ordered list of hadrons observed at the LHC. The date refers to the arXiv submission date.

№	Experiment	State	Mass [MeV/c^2]	Quarks	Submission	Ref.
1.	ATLAS	$\chi_b(3P)$	10530 ± 10	$b\bar{b}$	21 Dec 2011	[1][1]
2.	CMS	Ξ_b^{*0}	5945 ± 3	bsu	26 Apr 2012	[2]
3.	LHCb	$\Lambda_b(5920)^0$	5919.8 ± 0.7	bud	15 May 2012	[3]
4.	LHCb	$\Lambda_b(5912)^0$	5912.0 ± 0.7	bud		[3]
5–6.	LHCb	$D_J^*(3000)^{+,0}$	3008 ± 4	$c\bar{q}$	17 Jul 2013	[4][2]
7.	LHCb	$D_J(3000)^0$	2972 ± 9	$c\bar{u}$		[4]
8.	LHCb	$D_J^*(2760)^+$	2772 ± 4	$c\bar{d}$		[4]
9.	LHCb	$D_J(2740)^0$	2737 ± 12	$c\bar{u}$		[4]

[1]Later resolved into $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ [17].
[2]The mass of the $D_J^*(3000)^+$ state is fixed to that of $D_J^*(3000)^0$ in the fit.

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10.	LHCb	$D_J(2580)^0$	2580 ± 6	$c\bar{u}$		[4]
11.	CMS	$X(4140)$	4148 ± 7	$c\bar{c}s\bar{s}$	26 Sep 2013	[5][3]
12.	ATLAS	$B_c(2S)^+$	6842 ± 6	$\bar{b}c$	03 Jul 2014	[6][4]
13.	LHCb	$D_{s1}^*(2860)^+$	2859 ± 27	$c\bar{s}$	28 Jul 2014	[7][5]
14.	LHCb	Ξ_b^{*-}	5955.3 ± 0.5	bsd	18 Nov 2014	[8]
15.	LHCb	$\Xi_b^{\prime -}$	5935.0 ± 0.5	bsd		[8]
16–17.	LHCb	$B_J(5970)^{+,0}$	5969 ± 6	$\bar{b}q$	09 Feb 2015	[9][6]
18–19.	LHCb	$B_J(5840)^{+,0}$	5863 ± 9	$\bar{b}q$		[9][7]
20.	LHCb	$P_c(4380)^+$	4380 ± 30	$c\bar{c}uud$	13 Jul 2015	[10]
21.	LHCb	$P_c(4450)^+$	4449.8 ± 3.0	$c\bar{c}uud$		[10][8]
22.	LHCb	$X(4700)$	$4704\,^{+17}_{-26}$	$c\bar{c}s\bar{s}$	25 Jun 2016	[11][9]
23.	LHCb	$X(4500)$	$4506\,^{+16}_{-19}$	$c\bar{c}s\bar{s}$		[11]
24.	LHCb	$X(4274)$	$4273\,^{+19}_{-9}$	$c\bar{c}s\bar{s}$		[11]
25.	LHCb	$D_3^*(2760)^0$	2776 ± 8	$c\bar{u}$	03 Aug 2016	[12]
26.	LHCb	$\Lambda_c(2860)^+$	$2856\,^{+2}_{-6}$	cud	26 Jan 2017	[13]
27.	LHCb	$\Omega_c(3119)^0$	$3119.1\,^{+1.0}_{-1.1}$	css	14 Mar 2017	[14]
28.	LHCb	$\Omega_c(3090)^0$	$3090.2\,^{+0.7}_{-0.8}$	css		[14]
29.	LHCb	$\Omega_c(3066)^0$	$3065.6\,^{+0.4}_{-0.6}$	css		[14]
30.	LHCb	$\Omega_c(3050)^0$	$3050.2\,^{+0.3}_{-0.5}$	css		[14]
31.	LHCb	$\Omega_c(3000)^0$	$3000.4\,^{+0.4}_{-0.5}$	css		[14]
32.	LHCb	Ξ_{cc}^{++}	3621.4 ± 0.8	ccu	06 Jul 2017	[15]
33.	LHCb	$\Xi_b(6227)^-$	6226.9 ± 2.0	bsd	23 May 2018	[16]
	CMS	$\chi_{b2}(3P)$	10524.0 ± 0.6	$b\bar{b}$	28 May 2018	[17]
34.	CMS	$\chi_{b1}(3P)$	10513.4 ± 0.4	$b\bar{b}$		[17][10]
35.	LHCb	$\Sigma_b(6097)^-$	6095.8 ± 1.8	bdd	20 Sep 2018	[18]
36.	LHCb	$\Sigma_b(6097)^+$	6098.0 ± 1.8	buu		[18]
37.	CMS	$B_c^*(2S)^+$	Undetermined	$\bar{b}c$	01 Feb 2019	[19][11]
	CMS	$B_c(2S)^+$	6871.0 ± 1.6	$\bar{b}c$		[19]
38.	LHCb	$X(3842)$	3842.7 ± 0.2	$c\bar{c}(q\bar{q}?)$	28 Mar 2019	[20]
	LHCb	$P_c(4457)^+$	$4457\,^{+4}_{-2}$	$c\bar{c}uud$	08 Apr 2019	[21]
39.	LHCb	$P_c(4440)^+$	$4440\,^{+4}_{-5}$	$c\bar{c}uud$		[21][12]
40.	LHCb	$P_c(4312)^+$	$4312\,^{+7}_{-1}$	$c\bar{c}uud$		[21]
41.	LHCb	$\Lambda_b(6152)^0$	6152.5 ± 0.4	bud	31 Jul 2019	[22]

[3] First reported by CDF in a 2011 preprint [43] that was however only published in 2017.

[4] Later resolved into two states [19].

[5] The previously known narrow $D_{sJ}(2860)^+$ state [44] is resolved into a narrow spin-3 and a wide spin-1 state. We therefore consider the $D_{s1}^*(2860)^+$ meson to be a new observation while for the $D_{s3}^*(2860)^+$ meson the spin is measured. See Ref. [45] for details.

[6] Mass of the neutral state. Could be the $B(5970)$ meson reported by CDF [46].

[7] Mass of the neutral state.

[8] Later resolved into $P_c(4440)^+$ and $P_c(4457)^+$ [21].

[9] A state dubbed $X(4740)$ was later reported in Ref. [47] with properties that are consistent with those of the $X(4700)$ state. It is therefore left out of this table.

[10] Resolves $\chi_b(3P)$ [1].

[11] The mass of the $B_c^*(2S)^+$ is determined to be $m(B_c^*(2S)^+) - m(B_c^{*+}) = 567.0 \pm 1.0\,\mathrm{MeV}/c^2$. Resolves the state reported by ATLAS [6].

[12] Resolves $P_c(4450)^+$ [10].

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42.	LHCb	$\Lambda_b(6146)^0$	6146.2 ± 0.4	bud		[22]
43.	LHCb	$\Omega_b(6350)^-$	6349.9 ± 0.6	bss	03 Jan 2020	[23]
44.	LHCb	$\Omega_b(6340)^-$	6339.7 ± 0.6	bss		[23]
45.	LHCb	$\Lambda_b(6070)^0$	6072.3 ± 3.0	bud	12 Feb 2020	[24]
46.	LHCb	$\Xi_c(2939)^0$	2938.55 ± 0.30	csd	30 Mar 2020	[25][13]
47.	LHCb	$\Xi_c(2923)^0$	2923.04 ± 0.35	csd		[25]
48.	LHCb	$T_{c\bar{c}c\bar{c}}$	6905 ± 13	$c\bar{c}c\bar{c}$	30 Jun 2020	[26]
49.	LHCb	$X_1(2900)$	2904 ± 5	$\bar{c}d\bar{s}u$	31 Aug 2020	[27]
50.	LHCb	$X_0(2900)$	2866 ± 7	$\bar{c}d\bar{s}u$		[27]
51.	LHCb	$\Xi_b(6227)^0$	$6227.1\,^{+1.5}_{-1.6}$	bsu	27 Oct 2020	[28]
52.	LHCb	$B_s(6114)^0$	6114 ± 6	$\bar{b}s$	29 Oct 2020	[29]
53.	LHCb	$B_s(6063)^0$	6063.5 ± 1.4	$\bar{b}s$		[29]
54.	LHCb	$D_{s0}(2590)^+$	2591 ± 9	$c\bar{s}$	18 Nov 2020	[30]
55.	CMS	$\Xi_b(6100)^-$	6100.3 ± 0.6	bsd	08 Feb 2021	[31]
56.	LHCb	$Z_{cs}(4000)^+$	$4003\,^{+7}_{-15}$	$c\bar{c}u\bar{s}$	02 Mar 2021	[32][14]
57.	LHCb	$Z_{cs}(4220)^+$	$4220\,^{+50}_{-40}$	$c\bar{c}u\bar{s}$		[32]
58.	LHCb	$X(4630)$	$4630\,^{+20}_{-110}$	$c\bar{c}s\bar{s}$		[32]
59.	LHCb	$X(4685)$	$4684\,^{+15}_{-17}$	$c\bar{c}s\bar{s}$		[32]

As mentioned in the introduction, more data permits more fine-grained analyses which uncover new states. The $B_c(2S)^+$ state found ATLAS [6] was later resolved into two by CMS [19] and then LHCb [49], and thus only one of the two states seen by CMS counts toward the number of observed hadrons. The same applies to the $\chi_b(3P)$ states [1, 17]. Similarly, the $P_c(4450)^+$ pentaquark [10] was later found to be a superposition of the $P_c(4440)^+$ and $P_c(4457)^+$ [21] states.

The situation in charmed-meson spectroscopy is complicated. In Ref. [4] seven new states are reported, from which we exclude the $D_J^*(2650)^0$ meson which may be identical to the $D(2600)^0$ state reported earlier by BaBar [50]. It could also be the same state appearing as $D_1^*(2680)^0$ in Ref. [12], which is therefore also excluded from the list. The latter paper also reports a $D_2^*(3000)^0$ state that could be the same as the $D_J^*(3000)^0$ resonance from Ref. [4]. The BaBar paper [50] reports a $D_J^*(2760)^0$ state later confirmed in prompt production [4] and in $B^- \to D^+K^-\pi^-$ decays [51] with spin-parity determined to be 1^-. Ref. [12] then confirms it in $B^- \to D^+\pi^-\pi^-$ decays but sees another spin-3 state, $D_3^*(2760)^0$, at the same mass. The latter is listed a new state in the table. Similar ambiguities are mentioned in the footnotes.

Figure 2 shows how the harvest has increased versus time. For convenience, all relevant mass distributions are copied in Fig. 3. Several observations are the result of multidimensional amplitude fits, and thus rely on more information than what is visible in the mass distribution only.

[13] A third state, $\Xi_c(2965)^0$, is observed, but it is not yet clear if it differs from the known $\Xi_c(2970)^0$ baryon.

[14] The mass of the $Z_{cs}(4000)^+$ state is consistent with that of the $Z_{cs}(3985)^+$ reported by BESIII [48] in another decay channel, but its width is significantly larger.

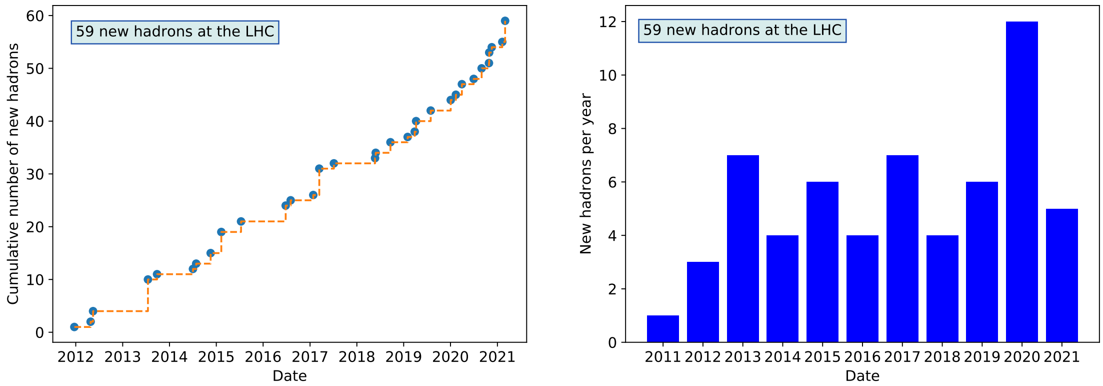
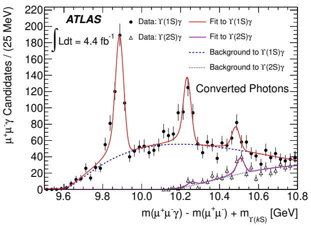
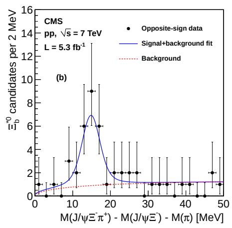


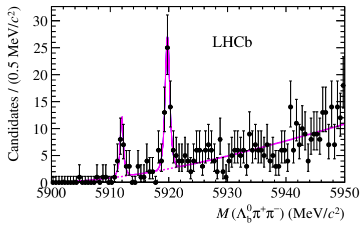
Figure 2: Number of found states (left) versus date and (right) per year.



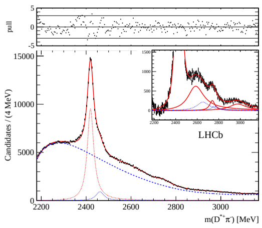
(a) $\chi_b(3P)$ [1]



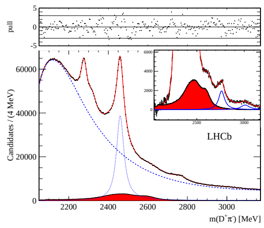
(b) Ξ_b^{*0} [2]



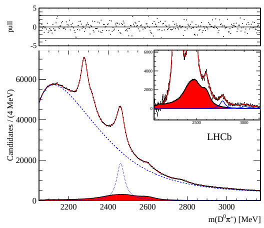
(c) $\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$ [3]



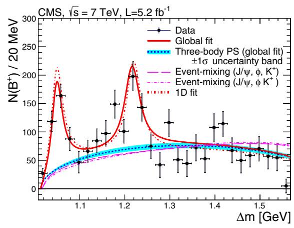
(d) $D_J(2580)^0$, $D_J(2740)^0$, $D_J(3000)^0$ [4]



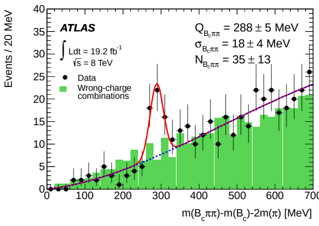
(e) $D_J^*(3000)^0$ [4]



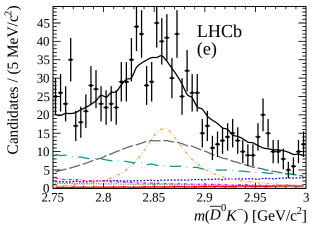
(f) $D_J^*(2760)^0$, $D_J^*(3000)^+$ [4]



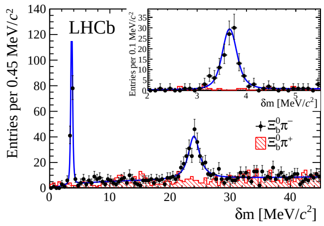
(g) $X(4140)$ [5]



(h) $B_c(2S)^+$ [6]



(i) $D_{s1}^*(2860)^-$ [7]

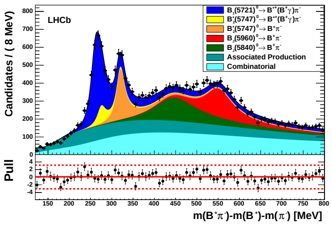


(j) Ξ_b^{*-}, $\Xi_b^{\prime -}$ [8]

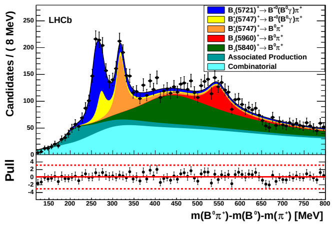
Figure 3: All mass plots.

3 Conclusion

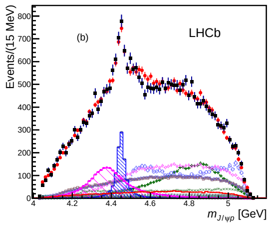
In ten years of operation, the LHC has uncovered 59 new hadrons. The harvest is certainly far from finished. More states are presumably hiding in Run 2 data and more are waiting to be discovered with the upcoming Run 3 data. At the present rate, it should take much less than 10 years to reach the 100-hadrons mark.



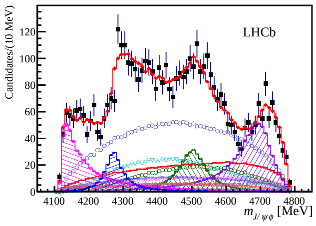
(k) $B_J(5840)^0$, $B_J(5970)^0$ [9]



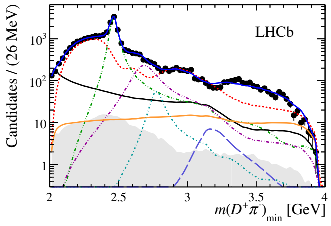
(l) $B_J(5840)^+$, $B_J(5970)^+$ [9]



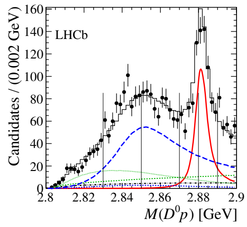
(m) $P_c(4380)^+$, $P_c(4450)^+$ [10]



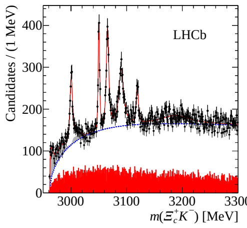
(n) $X(4274)$, $X(4500)$, $X(4700)$ [11]



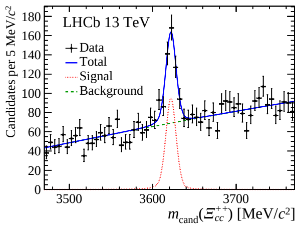
(o) $D_3^*(2760)^0$ [12]



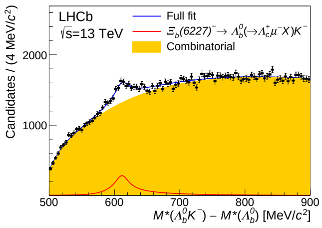
(p) $\Lambda_c(2860)^+$ [13]



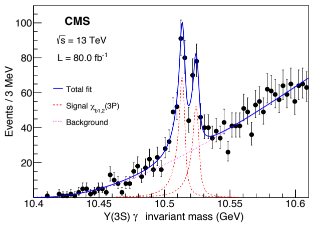
(q) Five Ω_c^0 [14]



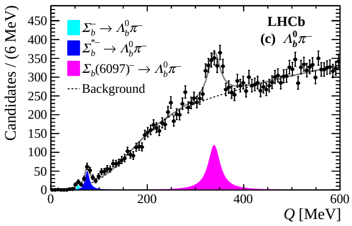
(r) Ξ_{cc}^{++} [15]



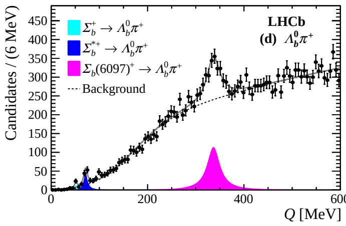
(s) $\Xi_b(6227)^-$ [16]



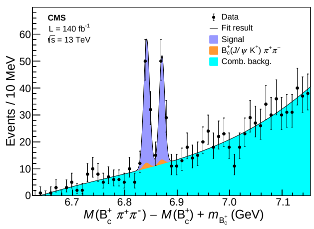
(t) $\chi_{b1}(3P)$, $\chi_{b2}(3P)$ [17]



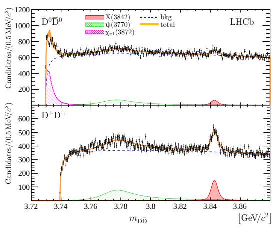
(u) $\Sigma_b(6097)^-$ [18]



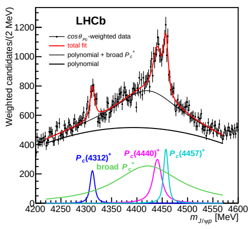
(v) $\Sigma_b(6097)^+$ [18]



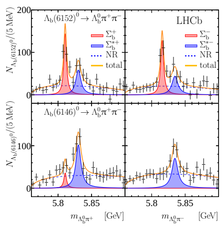
(w) $B_c(2S)^+$, $B_c^*(2S)^+$ [19]



(x) $X(3842)$ [20]

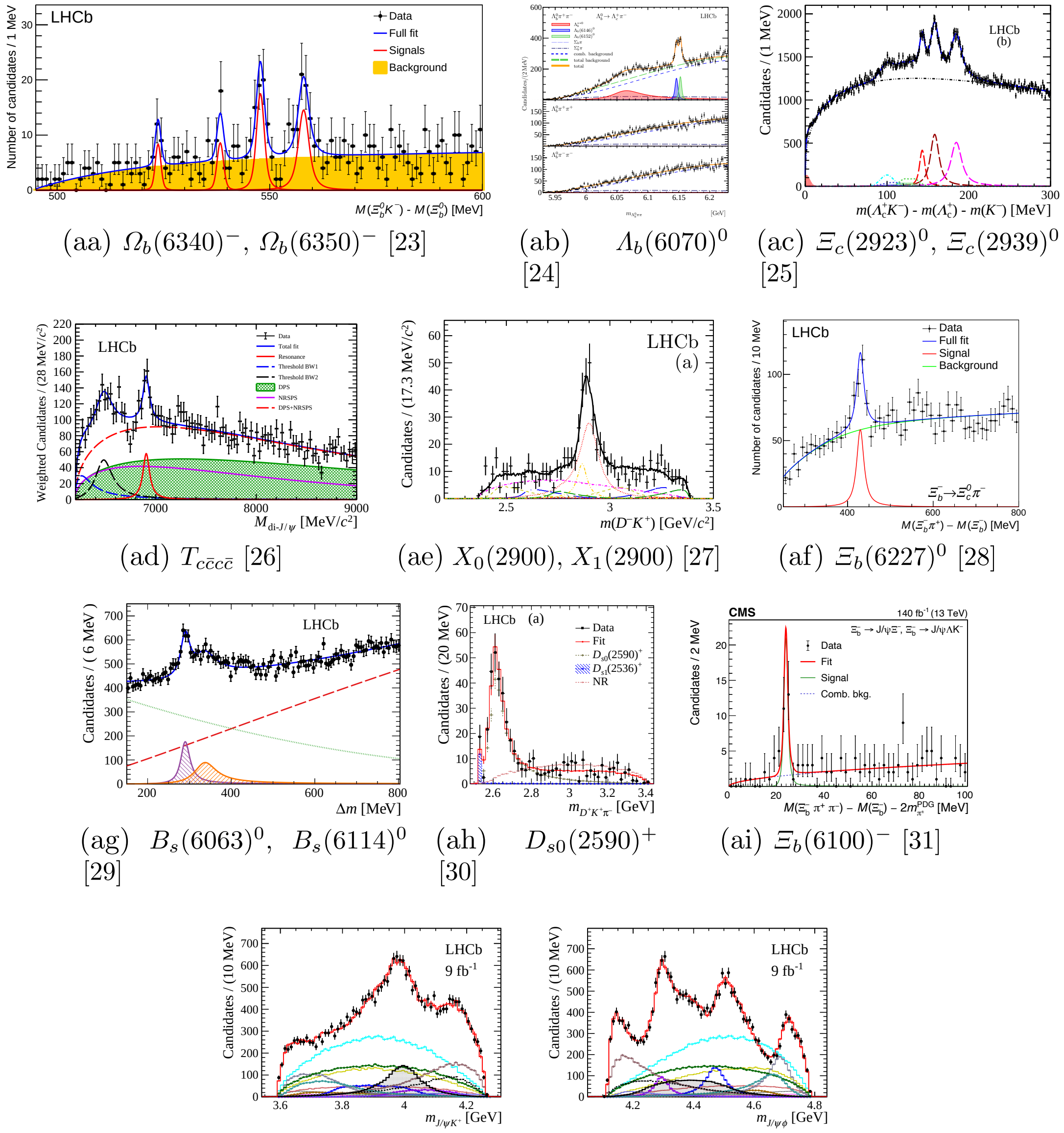


(y) $P_c(4440)^+$, $P_c(4457)^+$ [21]



(z) $\Lambda_b(6146)^0$, $\Lambda_b(6152)^0$ [22]

Figure 3: All mass plots (cont.).



(aa) $\Omega_b(6340)^-$, $\Omega_b(6350)^-$ [23]
(ab) $\Lambda_b(6070)^0$ [24]
(ac) $\Xi_c(2923)^0$, $\Xi_c(2939)^0$ [25]

(ad) $T_{c\bar{c}c\bar{c}}$ [26]
(ae) $X_0(2900)$, $X_1(2900)$ [27]
(af) $\Xi_b(6227)^0$ [28]

(ag) $B_s(6063)^0$, $B_s(6114)^0$ [29]
(ah) $D_{s0}(2590)^+$ [30]
(ai) $\Xi_b(6100)^-$ [31]

(aj) $Z_{cs}(4000)^+$, $Z_{cs}(4220)^+$ [32]
(ak) $X(4630)$, $X(4685)$ [32]

Figure 3: All mass plots (cont.).

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