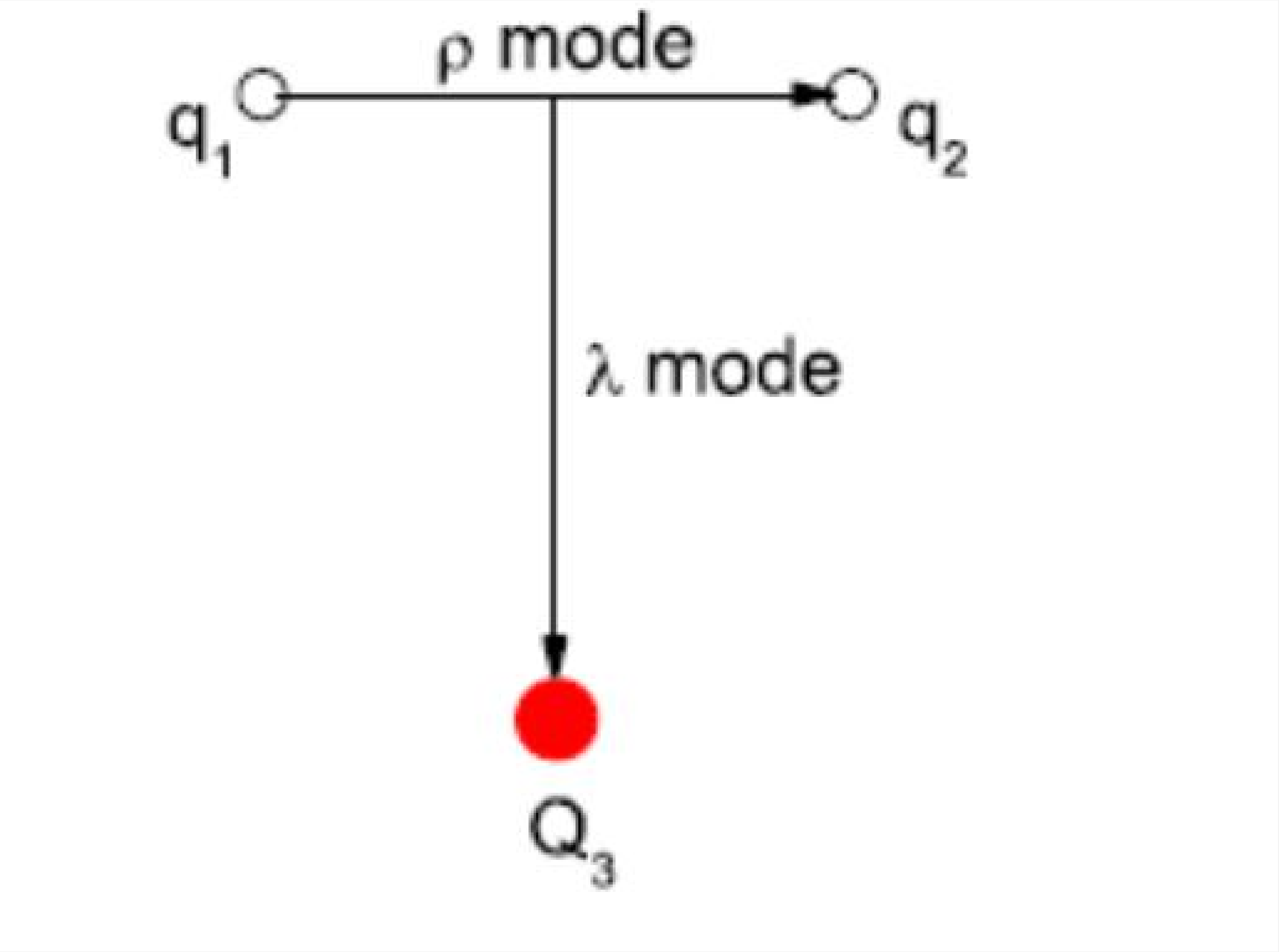
Singly-heavy baryon spectrum

Xian-Hui Zhong (钟显辉)

Hunan Normal University

第二届LHCb前沿物理研讨会
2020年12月12-13日

Simple structure



Classification (flavor)

Charmed baryon

$$\phi^c_{\bar{3}} = \begin{cases} \frac{1}{\sqrt{2}}(ud - du)c & \text{for } \Lambda_c^+, \\ \frac{1}{\sqrt{2}}(us - su)c & \text{for } \Xi_c^+, \\ \frac{1}{\sqrt{2}}(ds - sd)c & \text{for } \Xi_c^0; \end{cases}$$

$$\phi^c_{6} = \begin{cases} uuc & \text{for } \Sigma_c^{++}, \\ \frac{1}{\sqrt{2}}(ud + du)c & \text{for } \Sigma_c^+, \\ ddc & \text{for } \Sigma_c^0, \\ \frac{1}{\sqrt{2}}(us + su)c & \text{for } \Xi_c^{\prime +}, \\ \frac{1}{\sqrt{2}}(ds + sd)c & \text{for } \Xi_c^{\prime 0}, \\ ssc & \text{for } \Omega_c^0; \end{cases}$$

Bottom baryon

$$\phi^b_{\bar{3}} = \begin{cases} \frac{1}{\sqrt{2}}(ud - du)b & \text{for } \Lambda_b^0, \\ \frac{1}{\sqrt{2}}(us - su)b & \text{for } \Xi_b^0, \\ \frac{1}{\sqrt{2}}(ds - sd)b & \text{for } \Xi_b^-. \end{cases}$$

$$\phi^b_{6} = \begin{cases} uub & \text{for } \Sigma_b^+, \\ \frac{1}{\sqrt{2}}(ud + du)b & \text{for } \Sigma_b^0, \\ ddb & \text{for } \Sigma_b^-, \\ \frac{1}{\sqrt{2}}(us + su)b & \text{for } \Xi_b^{\prime 0}, \\ \frac{1}{\sqrt{2}}(ds + sd)b & \text{for } \Xi_b^{\prime -}, \\ ssb & \text{for } \Omega_b^-. \end{cases}$$

Antisymmetric antitriplet

$\underline{3}_F$ states

Λ_c and Λ_b states

YX Yao, KL Wang, XH, PRD98,076015(2018)

TABLE I. Mass spectra of the singly heavy baryons of $\bar{3}_F$ up to D wave from various quark models [21,22,27,33] compared with the data from the RPP [24].

	Λ_c				Λ_b		
State	RQM [21]	NQM [27]	NQM [33]	PDG [24]	RQM [21]	NQM [27]	PDG [24]
$1^2S_{\frac{1}{2}}^{\frac{1}{2}+}$	2286	2285	2286	2286	5620	5618	5620
$1^2P_{\lambda\frac{1}{2}}^{\frac{1}{2}-}$	2598	2628	2614	2592	5930	5938	5912
$1^2P_{\lambda\frac{3}{2}}^{\frac{3}{2}-}$	2627	2630	2639	2628	5942	5939	5920
$1^2D_{\lambda\lambda\frac{3}{2}}^{\frac{3}{2}+}$	2874	2920	2843	2860?	6190	6211	?
$1^2D_{\lambda\lambda\frac{5}{2}}^{\frac{5}{2}+}$	2880	2922	2851	2880?	6196	6212	?

How to establish the D-wave states?

Evidence of D-wave Λ_c states

$\Lambda_c(2860)^+$

$I(J^P) = 0(\frac{3}{2}^+)$

M =2856 MeV,
Γ =68 MeV

Only seen in D^0p channel

JHEP 1705 030 R. Aaij *et al.*

$\Lambda_c(2880)^+$

$I(J^P) = 0(\frac{5}{2}^+)$

M =2882 MeV,
Γ =5.6 MeV

Decay modes:

Γ_1	$\Lambda_c^+ \pi^+ \pi^-$
Γ_2	$\Sigma_c(2455)^{0,++} \pi^\pm$
Γ_3	$\Sigma_c(2520)^{0,++} \pi^\pm$
Γ_4	$p D^0$

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

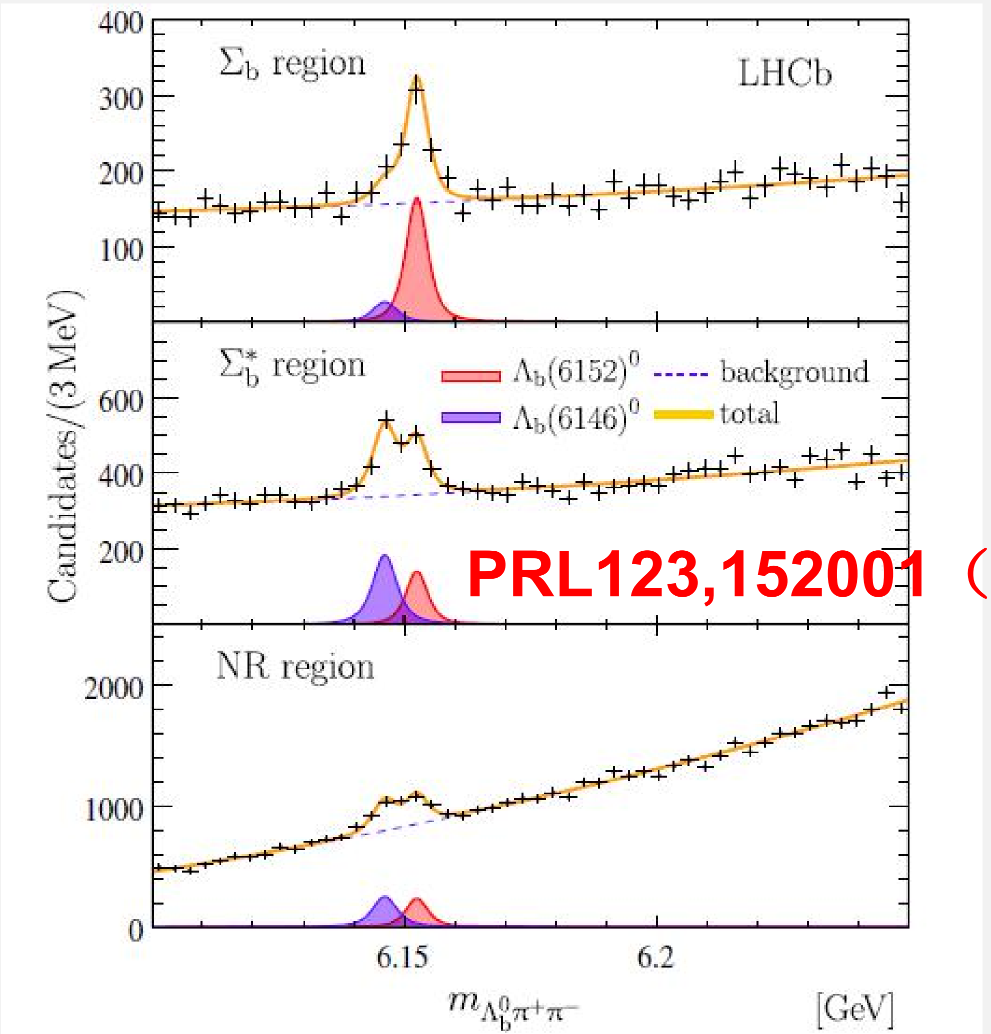
Our explaination

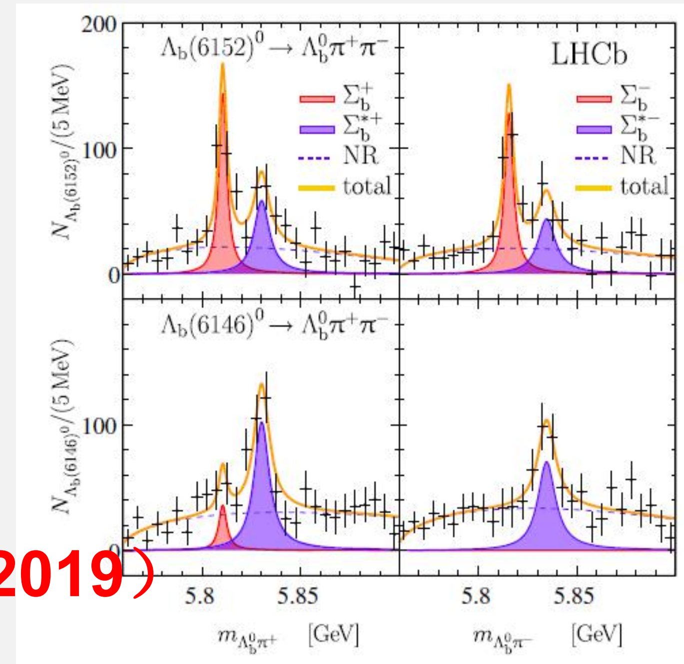
	$\vert\Lambda_c\,{}^2D_{\lambda\lambda}\frac{3}{2}^+\rangle(2856)$	$\vert\Lambda_c\,{}^2D_{\lambda\lambda}\frac{5}{2}^+\rangle(2881)$
Decay mode	Γ_i (MeV)	Γ_i (MeV)
$\Sigma_c\pi$	$4.57^{+1.09}_{-1.20}$	$1.33^{-0.35}_{+0.50}$
$\Sigma_c^*\pi$	$0.95^{-0.03}_{+0.09}$	$4.38^{+0.67}_{-0.74}$
Sum	$5.52^{+1.06}_{-1.11}$	$5.71^{+0.32}_{-0.24}$

- Λ_c (2860) and Λ_c (2880) most likely corresponds to the two D-wave Λ_c states.
- To confirm the Λ_c (2860), look for the $\Sigma_c\,\pi$ mode.
- M[Λ_c (2880)5/2$^+$)]>M[Λ_c (2860)3/2$^+$]

YX Yao, KL Wang, XH, PRD98,076015(2018)

Evidence of D-wave Λ_b states





PRL123,152001（2019）

$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \text{ MeV},$$
$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \text{ MeV},$$
$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \text{ MeV},$$
$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \text{ MeV},$$

Our explaination

PHYSICAL REVIEW D **100**, 114035 (2019)

TABLE IV. Partial widths (MeV) of strong decays for the λ-mode $1D$-wave Λ_b baryons.

	$\|J^P=\frac{3}{2}^+,2\rangle$		$\|J^P=\frac{5}{2}^+,2\rangle$	
Decay mode	$\Lambda_b(6146)$	$\Lambda_b(6152)$	$\Lambda_b(6146)$	$\Lambda_b(6152)$
$\Sigma_b\pi$	4.41	4.67	0.64	0.73
$\Sigma_b^*\pi$	1.26	1.41	4.26	4.60
Sum	5.67	6.08	4.90	5.33

Λ_b (6146) mainly decays into $\Sigma_b^*\pi$, $J^P=5/2^+$

Λ_b (6152) mainly decays into $\Sigma_b\pi$, $J^P=3/2^+$

However, we meet a serious problem of mass reverse!

$M[\Lambda_b\ (5/2^+)\ ]<M[\Lambda_b\ (3/2^+)\ ]$??? One or two resonances? ??

$M[\Lambda_c\ (2880)5/2^+)\ ]>M[\Lambda_c\ (2860)3/2^+\ ]$

Looking for higher Λ_c states

Can one find two 2P-wave states with masses around 3.0 GeV?

Qi-Fang Lv and XH, PRD101 (2020) no.1, 014017

TABLE IV. Decay widths of the $\Lambda_c(2P)$ states in MeV.

Mode	$\Lambda_{c1}(\frac{1}{2}^-, 2P)$	$\Lambda_{c1}(\frac{3}{2}^-, 2P)$
$\Sigma_c^{++}\pi^-$	0.49	0.52
$\Sigma_c^{+}\pi^0$	0.48	0.53
$\Sigma_c^{0}\pi^+$	0.49	0.52
$\Sigma_c^{*++}\pi^-$	0.50	0.97
$\Sigma_c^{*+}\pi^0$	0.51	0.97
$\Sigma_c^{*0}\pi^+$	0.50	0.97
$D^0 p$	1.19	19.54
$D^+ n$	1.68	18.80
$D^{*0} p$	17.31	55.25
$D^{*+} n$	16.67	56.59
Total width	39.84	154.67

Λ_c (2940) may be the 2P state with $J^P=3/2^-$.

QF, LY, ZY, XH, Eur. Phys. J. C (2018)78:599

Looking for higher Λ_b states

Can one find two 2P-wave states with masses around 6.3 GeV?

TABLE V. Decay widths of the $\Lambda_b(2P)$ states in MeV.

Mode	$\Lambda_{b1}(\frac{1}{2}^-, 2P)$	$\Lambda_{b1}(\frac{3}{2}^-, 2P)$
$\Sigma_b^+\pi^-$	0.76	0.60
$\Sigma_b^0\pi^0$	0.75	0.61
$\Sigma_b^-\pi^+$	0.78	0.58
$\Sigma_b^{*+}\pi^-$	0.94	1.34
$\Sigma_b^{*0}\pi^0$	0.95	1.34
$\Sigma_b^{*-}\pi^+$	0.92	1.35
B^-p	12.47	17.42
B^0n	13.07	17.04
$B^{*-}p$	30.33	60.76
$B^{*0}n$	29.91	61.37
Total width	90.90	162.42

Qi-Fang Lv and XH, PRD101 (2020) no.1, 014017

Ξ_c and Ξ_b states

State	Ξ_c RQM [21]	Ξ_c NQM [22]	Ξ_c NQM [33]	Ξ_c PDG [24]	Ξ_b RQM [21]	Ξ_b NQM [22]	Ξ_b PDG [24]
$1^2S\frac{1}{2}^+$	2476	2466	2470	2468	5803	5806	5795
$1^2P_{\lambda}\frac{1}{2}^-$	2792	2773	2793	2792	6120	6090	?
$1^2P_{\lambda}\frac{3}{2}^-$	2819	2783	2820	2817	6130	6093	?
$1^2D_{\lambda\lambda}\frac{3}{2}^+$	3059	3012	3033	3055?	6366	6311	?
$1^2D_{\lambda\lambda}\frac{5}{2}^+$	3076	3004	3040	3080?	6373	6300	?

YX Yao, KL Wang, XH, PRD98,076015(2018)

How to establish the missing P and D-wave states?

The 1P Ξ_c state may be established.

$\Xi_c(2790)$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$

M =2792 MeV,
Γ =8.9 MeV

Seen in the $\Xi_c' \pi$ channel

$\Xi_c(2815)$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$

M =2817 MeV,
Γ =2.43 MeV

	Mode
Γ_1	$\Xi'_c \pi$
Γ_2	$\Xi_c(2645)\pi$

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Our explaination with 1P states

$\vert{}^{2S+1}L_\lambda J^P\rangle$	State	Channel	Γ_i (MeV)	$\mathcal{B}_i$
$\vert{}^2P_{\lambda}\frac{1}{2}^-\rangle$	$\Xi_c(2790)$	$\Xi_c'\pi$	3.61	100%
		$\Xi_c'^*\pi$	3.9×10^{-4}	≃0.0%
		total	3.61	
$\vert{}^2P_{\lambda}\frac{3}{2}^-\rangle$	$\Xi_c(2815)$	$\Xi_c'\pi$	0.31	14.69%
		$\Xi_c^*\pi$	1.80	85.31%
		total	2.11	

The mass and decay of Ξ_c (2815) can be well understood.

The decay width of Ξ_c (2790) is a factor 3 smaller than our prediction.

Lei-Hua Liu, Li-Ye Xiao, XH, PRD86,034024(2012)

KL Wang, YX Yao, XH, QZ, PRD96,116016(2017)

Candidates of the D-wave Ξ_c states

$\Xi_c(3055)$	$\Xi_c(3080)$
M =3056 MeV, Γ =7.8 MeV	M =3077 MeV, Γ =3.6 MeV

$\Xi_c(3055)$:

	Mode
Γ_1	$\Sigma^{++} K^-$
Γ_2	ΛD^+

$\Gamma(\Lambda D^+)/\Gamma(\Sigma^{++} K^-)$

VALUE
5.09±1.01±0.76

$\Xi_c(3080)$:

	Mode
Γ_1	$\Lambda_c^+ \overline{K} \pi$
Γ_2	$\Sigma_c(2455) \overline{K}$
Γ_3	$\Sigma_c(2455)^{++} K^-$
Γ_4	$\Sigma_c(2520)^{++} K^-$
Γ_5	$\Sigma_c(2455) \overline{K} + \Sigma_c(2520) \overline{K}$
Γ_8	ΛD^+

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Our explaination with 1D states

Decay mode	M_f	$\vert\Xi_c\, ^2D_{\lambda\lambda}\frac{3}{2}^+\rangle(3055)$ Γ_i (MeV)	$\vert\Xi_c\, ^2D_{\lambda\lambda}\frac{5}{2}^+\rangle(3080)$ Γ_i (MeV)
$\Xi_c'\pi$	2575	$1.93^{+0.57}_{-0.61}$	$0.75^{-0.18}_{+0.27}$
$\Xi_c'^*\pi$	2645	$0.60^{-0.04}_{+0.07}$	$2.08^{+0.38}_{-0.40}$
$\Sigma_c K$	2455	$2.49^{+0.38}_{-0.29}$	$0.22^{<-0.01}_{+0.10}$
$\Sigma_c^* K$	2520	$0.14^{<-0.01}_{<+0.01}$	$1.68^{+0.11}_{-0.14}$
$\vert\Xi_c' 1^4P_{\lambda}\frac{1}{2}^-\rangle\pi$	2854	< 0.01	$1.42^{+0.39}_{-0.34}$
$\vert\Xi_c' 1^4P_{\lambda}\frac{3}{2}^-\rangle\pi$	2912	0.04	$0.20^{+0.04}_{-0.03}$
$\vert\Xi_c' 1^4P_{\lambda}\frac{5}{2}^-\rangle\pi$	2929	...	$0.54^{+0.10}_{-0.10}$
Sum		$5.20^{+0.91}_{-0.83}$	$6.90^{+0.84}_{-0.64}$

- **The predicted decay widths and main decay modes are consistent with the observations.**
- **To be further confirmed, for some main decay modes are still missing.**

YX Yao, KL Wang, XH, PRD98,076015(2018)

Looking for the missing 1P Ξ_b states

Can one find two 1P-wave states with masses around 6.1 GeV?

$\vert ^{2S+1}L_\lambda J^P\rangle$	State	Channel	Γ_i (MeV)	$\mathcal{B}_i$
$\vert ^2P_{\lambda}\frac{1}{2}^-\rangle$	$\Xi_b(6120)$	$\Xi_b'\pi$	2.84	98.61%
		$\Xi_b'^*\pi$	0.04	1.39%
		total	2.88	
$\vert ^2P_{\lambda}\frac{3}{2}^-\rangle$	$\Xi_b(6130)$	$\Xi_b'\pi$	0.07	2.37%
		$\Xi_b'^*\pi$	2.88	97.63%
		total	2.95	

- The $J^P=1/2^-$ state mainly decays into $\Xi'_b\pi$.
- The $J^P=3/2^-$ state mainly decays into $\Xi'_b{}^*\pi$.
- Very narrow states with a width of 3 MeV!

KL Wang, YX Yao, XH, QZ, PRD96,116016(2017)

Looking for the missing 1D Ξ_b states

Can one find two 1D-wave states with masses around 6.37 GeV?

		$\lvert \Xi_b\, {}^2D_{\lambda\lambda\frac{3}{2}^+} \rangle$(6366)	$\lvert \Xi_b\, {}^2D_{\lambda\lambda\frac{5}{2}^+} \rangle$(6373)
Decay mode	M_f	Γ_i (MeV)	Γ_i (MeV)
$\Xi_b'\pi$	5935	$2.41^{+0.79}_{-0.81}$	$0.90^{-0.22}_{+0.30}$
$\Xi_b'^*\pi$	5955	$1.45^{-0.13}_{+0.25}$	$3.22^{+0.68}_{-0.68}$
$\Sigma_b K$	5811	$2.47^{+0.20}_{-0.27}$	0.07
$\Sigma_b^* K$	5832	$0.30^{+0.04}_{-0.01}$	$2.10^{+0.12}_{-0.16}$
$\lvert \Xi_b' 1^4P_{\lambda\frac{1}{2}^-} \rangle \pi$	6227	< 0.01	$0.28^{+0.06}_{-0.06}$
$\lvert \Xi_b' 1^4P_{\lambda\frac{3}{2}^-} \rangle \pi$	6224	$0.11^{+0.02}_{-0.02}$	$0.10^{+0.02}_{-0.02}$
$\lvert \Xi_b' 1^4P_{\lambda\frac{5}{2}^-} \rangle \pi$	6226	0.06	$0.45^{+0.09}_{-0.09}$
Sum		$6.8^{+0.92}_{-0.02}$	$7.11^{+0.75}_{-0.71}$

◆ **Very narrow states with a width of about 7 MeV!**

YX Yao, KL Wang, XH, PRD98,076015(2018)

Symmetric sextet

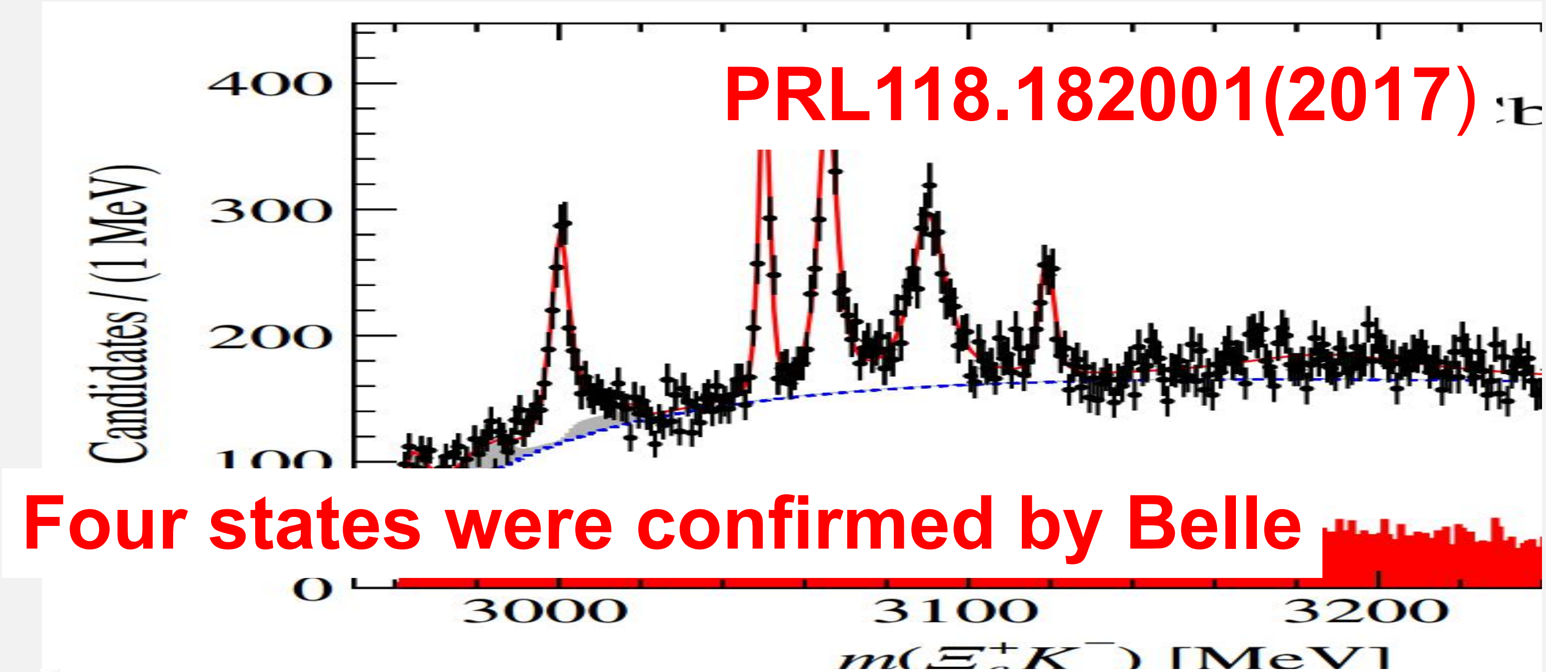
6_F states

Ω_c and Ω_b states

State	Ω_c RQM [21]	Ω_c NQM [27]	Ω_c NQM [22]	Ω_c PDG [24]	Ω_b RQM [21]	Ω_b NQM [27]	Ω_b PDG [24]
$1^2S\frac{1}{2}^+$	2698	2731	2718	2695	6064	6076	6046
$1^4S\frac{3}{2}^+$	2768	2779	2776	2770	6088	6094	?
$1^2P_\lambda\frac{1}{2}^-$	2966	3030	2977	?	6330	6333	?
$1^2P_\lambda\frac{3}{2}^-$	3029	3033	2986	?	6331	6336	?
$1^4P_\lambda\frac{1}{2}^-$	3055	3048	2990	?	6339	6340	?
$1^4P_\lambda\frac{3}{2}^-$	3054	3056	2994	?	6340	6344	?
$1^4P_\lambda\frac{5}{2}^-$	3051	3057	3014	?	6334	6345	?
$1^2D_{\lambda\lambda}\frac{3}{2}^+$	3282	3257	3262	?	6530	6528	?
$1^2D_{\lambda\lambda}\frac{5}{2}^+$	3286	3288	3273	?	6520	6561	?
$1^4D_{\lambda\lambda}\frac{1}{2}^+$	3287	3292	3275	?	6540	6561	?
$1^4D_{\lambda\lambda}\frac{3}{2}^+$	3298	3285	3280	?	6549	6559	?
$1^4D_{\lambda\lambda}\frac{5}{2}^+$	3297	3299	...	?	6529	6566	?
$1^4D_{\lambda\lambda}\frac{7}{2}^+$	3283	...	3327	?	6517	...	?

LHCb and Belle provide good oppertunities.

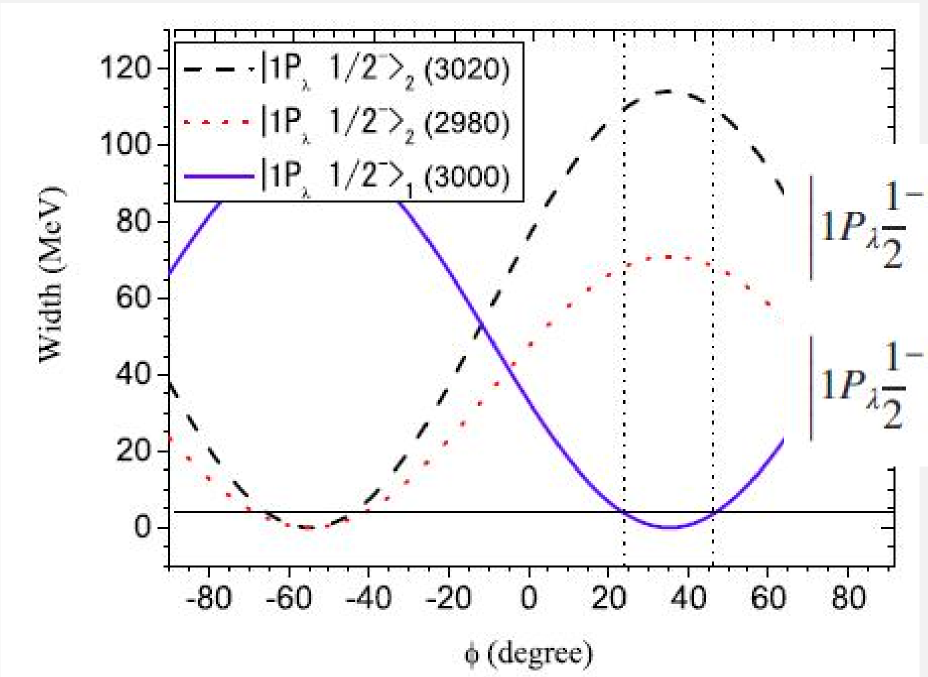
LHCb observed five excited Ω_c states!



Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		<1.2 MeV, 95% C.L.
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$

Our explaination

PRD95,116010 (2017)



$$\left|1P_{\lambda}\frac{1}{2}^{-}\right\rangle_1 = +\cos(\phi)\left|1^2P_{\lambda}\frac{1}{2}^{-}\right\rangle + \sin(\phi)\left|1^4P_{\lambda}\frac{1}{2}^{-}\right\rangle,$$

$$\left|1P_{\lambda}\frac{1}{2}^{-}\right\rangle_2 = -\sin(\phi)\left|1^2P_{\lambda}\frac{1}{2}^{-}\right\rangle + \cos(\phi)\left|1^4P_{\lambda}\frac{1}{2}^{-}\right\rangle,$$

State	Mass	$\Gamma(\Xi_c\bar{K})$	$\Gamma(\Xi_c'\bar{K})$	$\Gamma[\Omega_c(2695)\gamma]$	$\Gamma[\Omega_c(2770)\gamma]$	$\Gamma^{\rm th}_{\rm total}$	$\Gamma^{\rm exp}_{\rm total}$	Possible assignment
$\vert 1P_{\lambda}\frac{1}{2}^{-}\rangle_1$	3000	4.0	⋯	0.36/0.20	0.02/0.08	4.38/4.28	4.5 ± 0.9	$\Omega_c(3000)$
$\vert 1^4P_{\lambda}\frac{3}{2}^{-}\rangle$	3050	0.61	⋯	1.12×10^{-3}	0.33	0.94	0.8 ± 0.3	$\Omega_c(3050)$
$\vert 1^2P_{\lambda}\frac{3}{2}^{-}\rangle$	3066	4.61	⋯	0.35	5.68×10^{-4}	4.96	3.5 ± 0.4	$\Omega_c(3066)$
$\vert 1^4P_{\lambda}\frac{5}{2}^{-}\rangle$	3090	9.32	0.03	1.00×10^{-4}	0.18	9.53	8.7 ± 1.8	$\Omega_c(3090)$

Conslusion

- Ω_c (3000,3050,3066,3090) may be P-wave states with very narrow width.
- Ω_c(3119) may be the 2S state.
- A broad P wave state is waiting to be found!
- Radiative decay is worth observing.

Looking for D-wave Ω_c states @ 3.3 GeV

Decay mode	M_f	$\lvert\Omega_c\,{}^2D_{\lambda\lambda}\frac{3}{2}^+\rangle(3282)$		$\lvert\Omega_c\,{}^2D_{\lambda\lambda}\frac{5}{2}^+\rangle(3286)$		$\lvert\Omega_c\,{}^4D_{\lambda\lambda}\frac{1}{2}^+\rangle(3287)$		$\lvert\Omega_c\,{}^4D_{\lambda\lambda}\frac{3}{2}^+\rangle(3298)$		$\lvert\Omega_c\,{}^4D_{\lambda\lambda}\frac{5}{2}^+\rangle(3297)$		$\lvert\Omega_c\,{}^4D_{\lambda\lambda}\frac{7}{2}^+\rangle(3283)$	
		Γ_i	$\mathcal{B}_i$ (%)	Γ_i	$\mathcal{B}_i$ (%)	Γ_i	$\mathcal{B}_i$ (%)	Γ	$\mathcal{B}_i$ (%)	Γ_i	$\mathcal{B}_i$ (%)	Γ_i	$\mathcal{B}_i$ (%)
$\Xi_c K$	2470	$7.97^{+3.85}_{-3.61}$	44.7	$5.16^{-1.13}_{+1.42}$	57.3	$15.9^{+7.8}_{-7.2}$	71.4	$7.90^{+4.08}_{-3.73}$	48.2	$1.65^{-0.35}_{+0.44}$	19.8	$6.43^{-1.43}_{+1.77}$	81.7
$\Xi_c' K$	2575	$9.26^{+2.34}_{-2.55}$	51.9	$1.77^{-0.45}_{+0.64}$	19.7	$4.71^{+1.22}_{-1.34}$	20.8	$2.44^{+0.68}_{-0.73}$	14.8	$0.15^{-0.04}_{+0.05}$	1.79	$0.54^{-0.14}_{+0.20}$	6.73
$\Xi_c'^* K$	2645	$0.50^{-0.01}_{+0.02}$	2.8	$2.05^{+0.28}_{-0.32}$	22.8	$1.65^{+0.25}_{-0.31}$	7.4	$5.97^{+0.90}_{-1.03}$	36.4	$6.61^{-0.60}_{+0.64}$	79.2	$0.88^{+0.11}_{-0.12}$	11.2
$\lvert\Omega_c 1^2P_{\lambda}\frac{1}{2}^-\rangle\gamma$	3000	$91.8^{-14.5}_{+18.8}$	0.51	$9.79^{-1.60}_{+2.12}$	0.11	0.03	< 0.01	$0.49^{-0.05}_{+0.06}$	< 0.01	$0.19^{-0.02}_{+0.02}$	< 0.01	$\simeq 0.0$	< 0.01
$\lvert\Omega_c 1^2P_{\lambda}\frac{3}{2}^-\rangle\gamma$	3066	$18.4^{-3.1}_{+4.0}$	0.10	$39.7^{-6.7}_{+8.9}$	0.44	0.04	< 0.01	0.02	< 0.01	$0.17^{-0.02}_{+0.02}$	< 0.01	$0.13^{-0.02}_{+0.02}$	< 0.01
$\lvert\Omega_c 1^4P_{\lambda}\frac{1}{2}^-\rangle\gamma$	3050	$0.13^{-0.02}_{+0.01}$	< 0.01	0.008	< 0.01	$70.3^{-11.3}_{+14.8}$	0.32	$34.7^{-5.6}_{+7.3}$	0.21	$5.56^{-0.91}_{+1.20}$	0.07	$1.07^{-0.21}_{+0.30}$	0.01
$\lvert\Omega_c 1^4P_{\lambda}\frac{3}{2}^-\rangle\gamma$	3050	$0.2^{-0.03}_{+0.03}$	< 0.01	0.09	< 0.01	$27.5^{-4.5}_{+5.9}$	0.12	$54.1^{-8.8}_{+11.4}$	0.33	$39.8^{-6.6}_{+8.6}$	0.47	$5.62^{-0.94}_{+1.23}$	0.07
$\lvert\Omega_c 1^4P_{\lambda}\frac{5}{2}^-\rangle\gamma$	3090	0.03	< 0.01	$0.14^{-0.02}_{+0.03}$	< 0.01	$2.44^{-0.45}_{+0.62}$	< 0.10	$7.95^{-1.36}_{+1.82}$	0.05	$19.6^{-3.3}_{+4.3}$	0.24	$23.1^{-3.9}_{+5.3}$	0.29
Sum		$17.84^{+6.16}_{-6.16}$		$9.03^{-1.30}_{+1.73}$		$22.33^{+9.25}_{-8.83}$		$16.21^{+5.64}_{-5.47}$		$8.34^{-0.98}_{+1.11}$		$7.82^{-1.46}_{+1.85}$	

Decay widths are relatively narrow (about 10-20 MeV).

Decay modes $\Xi_c K$, $\Xi'_c K$, $\Xi'_c{}^* K$ are worth observing!

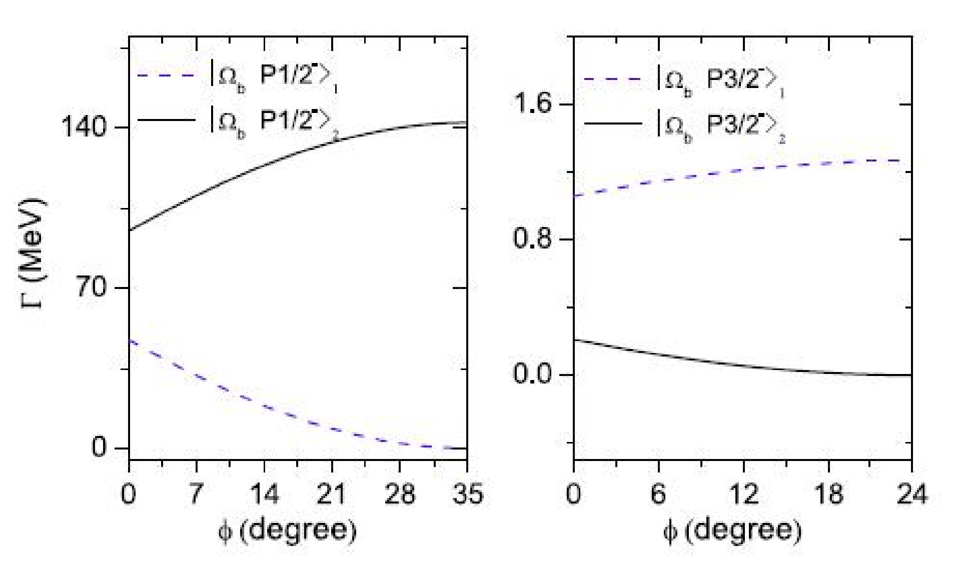
YX Yao, KL Wang, XH, PRD98,076015(2018)

Decay properties of the P-wave Ω_b states

TABLE X. Partial widths for the strong and radiative decays of the Ω_b baryons.

State	Mass (MeV) [24]	$\Gamma[\Xi_b K]$ (MeV)	$\Gamma[\Omega_b \gamma]$ (keV)	$\Gamma[\Omega_b^* \gamma]$ (keV)	Γ_{total} (MeV)
$\lvert\Omega_b\,{}^4S\tfrac{3}{2}^+\rangle$	6088	...	0.09	...	...
$\lvert\Omega_b\,{}^2P_{\lambda}\tfrac{1}{2}^-\rangle$	6339	49.38	154	1.49	49.53
$\lvert\Omega_b\,{}^2P_{\lambda}\tfrac{3}{2}^-\rangle$	6340	1.82	83.4	1.51	1.90
$\lvert\Omega_b\,{}^4P_{\lambda}\tfrac{1}{2}^-\rangle$	6330	94.98	0.64	99.23	95.08
$\lvert\Omega_b\,{}^4P_{\lambda}\tfrac{3}{2}^-\rangle$	6331	0.22	1.81	70.68	0.29
$\lvert\Omega_b\,{}^4P_{\lambda}\tfrac{5}{2}^-\rangle$	6334	1.60	1.21	63.26	1.66

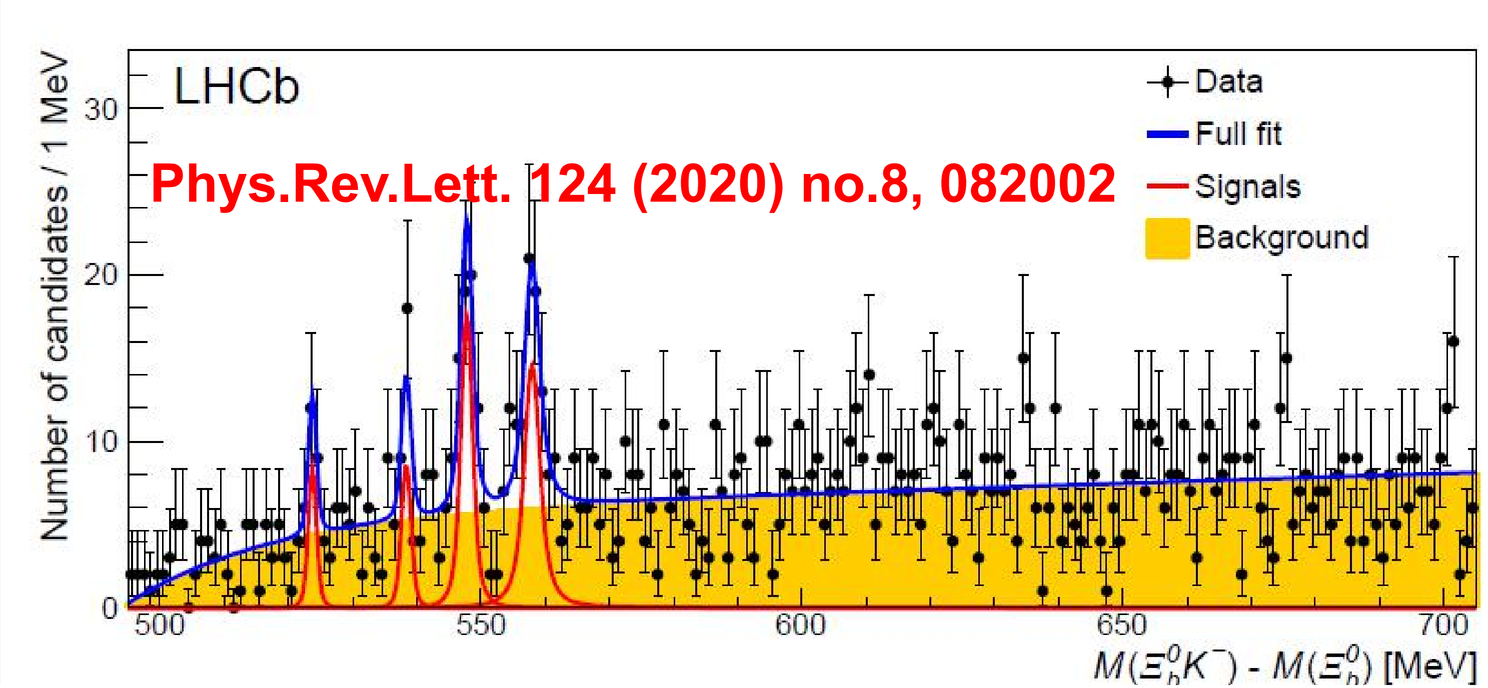
KL Wang, YX Yao, XH, QZ, PRD96,116016 (2017)



- **Four narrow P-wave states!**
- **One broad P-wave state.**
- **Mainly decay into Ξ_bK.**
- **Radiative decays are important.**

KL Wang, QF Lv, XH, PRD99,014011 (2019)

LHCb observed four excited Ω_b states!



	$\delta M_{\rm peak}$ [MeV]	Mass [MeV]	Width [MeV]
$\Omega_b(6316)^-$	$523.74 \pm 0.31 \pm 0.07$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.50$	$< 2.8\ (4.2)$
$\Omega_b(6330)^-$	$538.40 \pm 0.28 \pm 0.07$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	$< 3.1\ (4.7)$
$\Omega_b(6340)^-$	$547.81 \pm 0.26 \pm 0.05$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	$< 1.5\ (1.8)$
$\Omega_b(6350)^-$	$557.98 \pm 0.35 \pm 0.05$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.50$	$< 2.8\ (3.2)$ $1.4^{+1.0}_{-0.8} \pm 0.1$

Our explaination

Table 4 Partial decay widths (MeV) of the $1P$ states within the j-j coupling scheme in the Ω_b family. The value inside of the braces denotes the reference mass (MeV) of the corresponding state

State	$\|J^P, j\rangle$	$\Gamma[\Xi_b K]$ (MeV)
$\Omega_b(6316)$	$\|J^P = \frac{1}{2}^-, 1\rangle$	$\cdots$
$\Omega_b(6316)$	$\|J^P = \frac{1}{2}^-, 0\rangle$	126
$\Omega_b(6340)$	$\|J^P = \frac{3}{2}^-, 2\rangle$	2.2
$\Omega_b(6330)$	$\|J^P = \frac{3}{2}^-, 1\rangle$	$\cdots$
$\Omega_b(6350)$	$\|J^P = \frac{5}{2}^-, 2\rangle$	3.4

Decays and masses are consistent with the predictions.

Good candidates of the P wave Ω_b states!

Where is the broad P wave state?

Looking for D-wave Ω_b states @ 6.5 GeV

		$\lvert\Omega_b\,{}^2D_{\lambda\lambda}\frac{3}{2}^+\rangle(6530)$		$\lvert\Omega_b\,{}^2D_{\lambda\lambda}\frac{5}{2}^+\rangle(6520)$		$\lvert\Omega_b\,{}^4D_{\lambda\lambda}\frac{1}{2}^+\rangle(6540)$		$\lvert\Omega_b\,{}^4D_{\lambda\lambda}\frac{3}{2}^+\rangle(6549)$		$\lvert\Omega_b\,{}^4D_{\lambda\lambda}\frac{5}{2}^+\rangle(6529)$		$\lvert\Omega_b\,{}^4D_{\lambda\lambda}\frac{7}{2}^+\rangle(6517)$	
Decay mode	M_f	Γ_i	$\mathcal{B}_i$ (%)	Γ_i	$\mathcal{B}_i$ (%)	Γ_i	$\mathcal{B}_i$ (%)	Γ	$\mathcal{B}_i$ (%)	Γ_i	$\mathcal{B}_i$ (%)	Γ_i	$\mathcal{B}_i$ (%)
$\Xi_b K$	5795	$11.2^{+5.5}_{-5.1}$	55.5	$6.18^{-1.36}_{+1.71}$	75.83	$22.1^{+11.7}_{-10.5}$	76.98	$10.9^{+6.1}_{-5.4}$	53.48	$2.07^{-0.49}_{+0.48}$	28.09	$7.83^{-1.69}_{+2.13}$	90.84
$\Xi_b' K$	5935	$8.43^{+1.17}_{-1.38}$	41.8	$0.30^{-0.09}_{+0.13}$	3.68	$4.69^{+0.73}_{-0.86}$	16.34	$2.55^{+0.44}_{-0.51}$	12.51	0.03	0.41	0.09	1.04
$\Xi_b'^* K$	5955	$0.51^{-0.09}_{-0.10}$	2.52	$1.65^{+0.15}_{-0.16}$	20.25	$1.86^{+0.23}_{-0.27}$	6.48	$6.87^{+1.85}_{-1.01}$	33.71	$5.24^{+0.37}_{-0.43}$	71.10	$0.68^{+0.06}_{-0.07}$	7.89
$\lvert\Omega_b 1^2P_\lambda \frac{1}{2}^-\rangle\gamma$	6301	$33.2^{-5.1}_{+6.5}$	0.16	$4.03^{-0.66}_{+0.86}$	0.05	$0.55^{-0.08}_{+0.10}$	< 0.01	$1.20^{-0.16}_{+0.19}$	< 0.01	$0.32^{-0.05}_{+0.05}$	< 0.01	$\simeq 0.0$	< 0.01
$\lvert\Omega_b 1^2P_\lambda \frac{3}{2}^-\rangle\gamma$	6304	$17.9^{-2.9}_{+3.7}$	0.09	$16.8^{-2.8}_{+3.6}$	0.21	$0.26^{-0.04}_{+0.05}$	< 0.01	$0.10^{-0.02}_{+0.02}$	< 0.01	$0.73^{-0.10}_{+0.12}$	< 0.01	$0.56^{-0.07}_{+0.09}$	< 0.01
$\lvert\Omega_b 1^4P_\lambda \frac{1}{2}^-\rangle\gamma$	6312	$0.47^{-0.06}_{+0.07}$	< 0.01	0.024	< 0.01	$40.4^{-6.1}_{+7.5}$	0.14	$18.8^{-2.9}_{+3.5}$	0.09	$2.72^{-0.43}_{+0.57}$	0.04	$0.50^{-0.11}_{+0.15}$	< 0.01
$\lvert\Omega_b 1^4P_\lambda \frac{3}{2}^-\rangle\gamma$	6311	$0.74^{-0.10}_{+0.13}$	< 0.01	$0.27^{-0.04}_{+0.04}$	< 0.01	$17.9^{-2.8}_{+3.5}$	0.06	$31.0^{-4.7}_{+5.9}$	0.15	$15.4^{-2.5}_{+3.2}$	0.21	$2.70^{-0.44}_{+0.58}$	0.03
$\lvert\Omega_b 1^4P_\lambda \frac{5}{2}^-\rangle\gamma$	6311	$0.21^{-0.03}_{+0.04}$	< 0.01	$0.91^{-0.13}_{+0.17}$	< 0.01	$2.83^{-0.56}_{+0.81}$	0.01	$8.98^{-1.50}_{+1.98}$	0.04	$14.6^{-3.3}_{+2.0}$	0.20	$12.1^{-2.0}_{+2.6}$	0.14
Sum		$20.19^{+6.57}_{-6.57}$		$8.15^{-1.30}_{+1.68}$		$28.71^{+12.65}_{-11.61}$		$20.38^{+8.38}_{-6.91}$		$7.37^{-0.11}_{+0.04}$		$8.62^{-1.63}_{+2.06}$	

Decay widths are relatively narrow (about 10-20 MeV).

Decay modes $\Xi_b K$, $\Xi'_b K$, $\Xi'_b{}^* K$ are worth observing!

Sevaral states may overlap with each other.

YX Yao, KL Wang, XH, PRD98,076015(2018)

Σ_c and Σ_b states

State	Σ_c RQM [21]	Σ_c NQM [27]	Σ_c NQM [33]	Σ_c PDG [24]	Σ_b RQM [21]	Σ_b NQM [27]	Σ_b PDG [24]
$1^2S_{\frac{1}{2}}^{\frac{1}{2}+}$	2443	2460	2456	2455	5808	5823	5811
$1^4S_{\frac{3}{2}}^{\frac{3}{2}+}$	2519	2523	2515	2520	5834	5845	5832
$1^2P_{\lambda}\frac{1}{2}^-$	2713	2802	2702	?	6101	6127	?
$1^2P_{\lambda}\frac{3}{2}^-$	2798	2807	2785	?	6096	6132	?
$1^4P_{\lambda}\frac{1}{2}^-$	2799	2826	2765	?	6095	6135	?
$1^4P_{\lambda}\frac{3}{2}^-$	2773	2837	2798	?	6087	6141	?
$1^4P_{\lambda}\frac{5}{2}^-$	2789	2839	2790	?	6084	6144	?
$1^2D_{\lambda\lambda}\frac{3}{2}^+$	3043	3065	2952	?	6326	6356	?
$1^2D_{\lambda\lambda}\frac{5}{2}^+$	3038	3099	2942	?	6284	6397	?
$1^4D_{\lambda\lambda}\frac{1}{2}^+$	3041	3103	2949	?	6311	6395	?
$1^4D_{\lambda\lambda}\frac{3}{2}^+$	3040	3094	2964	?	6285	6393	?
$1^4D_{\lambda\lambda}\frac{5}{2}^+$	3023	3114	2962	?	6270	6402	?
$1^4D_{\lambda\lambda}\frac{7}{2}^+$	3013	...	2943	?	6260	...	?

Only the ground states are established!

Decay properties of the P-wave $\Sigma_{c/b}$ states

TABLE V. Partial widths (MeV) and branching fractions for the strong decays of the 1P-wave states in the Σ_c and Σ_b families.

$\|^{2S+1}L_\lambda J^P\rangle$	Σ_c states	Channel	Γ_i (MeV)	$\mathcal{B}_i$	Σ_b states	Channel	Γ_{th} (MeV)	$\mathcal{B}_i$
$\|^2P_{\lambda}\frac{1}{2}^-\rangle$	$\Sigma_c(2713)$	$\Lambda_c\pi$	6.49	28.65%	$\Sigma_b(6101)$	$\Lambda_b\pi$	1.74	7.68%
		$\Sigma_c\pi$	16.08	70.99%		$\Sigma_b\pi$	19.26	85.00%
		$\Sigma_c^*\pi$	0.08	0.35%		$\Sigma_b^*\pi$	1.66	7.33%
		total	22.65			total	22.66	
$\|^2P_{\lambda}\frac{3}{2}^-\rangle$	$\Sigma_c(2798)$	$\Lambda_c\pi$	22.53	61.73%	$\Sigma_b(6096)$	$\Lambda_b\pi$	29.31	74.60%
		$\Sigma_c\pi$	8.84	24.22%		$\Sigma_b\pi$	4.81	12.24%
		$\Sigma_c^*\pi$	5.13	14.05%		$\Sigma_b^*\pi$	5.17	13.16%
		total	36.5			total	39.29	
$\|^4P_{\lambda}\frac{1}{2}^-\rangle$	$\Sigma_c(2799)$	$\Lambda_c\pi$	6.66	37.78%	$\Sigma_b(6095)$	$\Lambda_b\pi$	4.00	28.15%
		$\Sigma_c\pi$	10.30	58.42%		$\Sigma_b\pi$	9.50	66.85%
		$\Sigma_c^*\pi$	0.67	3.80%		$\Sigma_b^*\pi$	0.71	5.0%
		total	17.63			total	14.21	
$\|^4P_{\lambda}\frac{3}{2}^-\rangle$	$\Sigma_c(2773)$	$\Lambda_c\pi$	3.62	14.66%	$\Sigma_b(6087)$	$\Lambda_b\pi$	5.38	20.46%
		$\Sigma_c\pi$	0.29	1.17%		$\Sigma_b\pi$	0.20	0.76%
		$\Sigma_c^*\pi$	20.78	84.16%		$\Sigma_b^*\pi$	20.71	78.78%
		total	24.69			total	26.29	
$\|^4P_{\lambda}\frac{5}{2}^-\rangle$	$\Sigma_c(2789)$	$\Lambda_c\pi$	25.03	75.35%	$\Sigma_b(6084)$	$\Lambda_b\pi$	31.38	81.85%
		$\Sigma_c\pi$	2.29	6.89%		$\Sigma_b\pi$	1.09	2.84%
		$\Sigma_c^*\pi$	5.90	17.76%		$\Sigma_b^*\pi$	5.77	15.05%
		total	33.22			total	38.34	

Relatively narrow states!

KL Wang, YX Yao, XH, QZ, PRD96,116016(2017)

jj coupling scheme

State	$\|J,j\rangle$	Channel	Γ_i (MeV)	$\mathcal{B}_i$	$\|^{2S+1}L_J\rangle$	Channel	Γ_i (MeV) [16]	$\mathcal{B}_i$ [16]
$\Sigma_b(6101)$	$\|J=\frac{1}{2}^-,1\rangle$	$\Lambda_b\pi$	$\cdots$	$\cdots$	$\|^2P_{1/2}\rangle$	$\Lambda_b\pi$	1.74	7.68%
		$\Sigma_b\pi$	28.89	92.04%		$\Sigma_b\pi$	19.26	85.00%
		$\Sigma_b^*\pi$	2.50	7.96%		$\Sigma_b^*\pi$	1.66	7.33%
		total	31.39			total	22.66	
$\Sigma_b(6095)$	$\|J=\frac{1}{2}^-,0\rangle$	$\Lambda_b\pi$	6.00	100.0%	$\|^4P_{1/2}\rangle$	$\Lambda_b\pi$	4.00	28.15%
		$\Sigma_b\pi$	$\cdots$	$\cdots$		$\Sigma_b\pi$	9.50	66.85%
		$\Sigma_b^*\pi$	$\cdots$	$\cdots$		$\Sigma_b^*\pi$	0.71	5.0%
		Total	6.00			Total	14.21	
$\Sigma_b(6096)$	$\|J=\frac{3}{2}^-,2\rangle$	$\Lambda_b\pi$	35.18	90.07%	$\|^2P_{3/2}\rangle$	$\Lambda_b\pi$	29.31	74.60%
		$\Sigma_b\pi$	3.25	8.32%		$\Sigma_b\pi$	4.81	12.24%
		$\Sigma_b^*\pi$	0.63	1.61%		$\Sigma_b^*\pi$	5.17	13.16%
		Total	39.06			Total	39.29	
$\Sigma_b(6087)$	$\|J=\frac{3}{2}^-,1\rangle$	$\Lambda_b\pi$	$\cdots$	$\cdots$	$\|^4P_{3/2}\rangle$	$\Lambda_b\pi$	5.38	20.46%
		$\Sigma_b\pi$	1.47	5.28%		$\Sigma_b\pi$	0.20	0.76%
		$\Sigma_b^*\pi$	26.39	94.72%		$\Sigma_b^*\pi$	20.71	78.78%
		Total	27.86			Total	26.29	
$\Sigma_b(6084)$	$\|J=\frac{5}{2}^-,2\rangle$	$\Lambda_b\pi$	31.38	81.85%	$\|^4P_{5/2}\rangle$	$\Lambda_b\pi$	31.38	81.85%
		$\Sigma_b\pi$	1.09	2.84%		$\Sigma_b\pi$	1.09	2.84%
		$\Sigma_b^*\pi$	5.77	15.05%		$\Sigma_b^*\pi$	5.77	15.05%
		Total	38.34			Total	38.34	

Configuration mixing within the states in LS scheme!

KL Wang, Qi-Fang Lv, XH, PRD99,014011 (2019)

Evidence of the P-wave Σ_c states from Exp.

$\Sigma_c(2800)$ $I(J^P) = 1(?^?)$ Status: ∗∗∗

Seen in the $\Lambda_c^+\pi^+$, $\Lambda_c^+\pi^0$, and $\Lambda_c^+\pi^-$ mass spectra.

$\Sigma_c(2800)^{++}$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
75^{+18+12}_{-13-11}	2810^{+1090}_{-775}	MIZUK	05	BELL	$e^+e^- \approx \Upsilon(4S)$

$\Sigma_c(2800)^{+}$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
62^{+37+52}_{-23-38}	1540^{+1750}_{-1050}	MIZUK	05	BELL	$e^+e^- \approx \Upsilon(4S)$

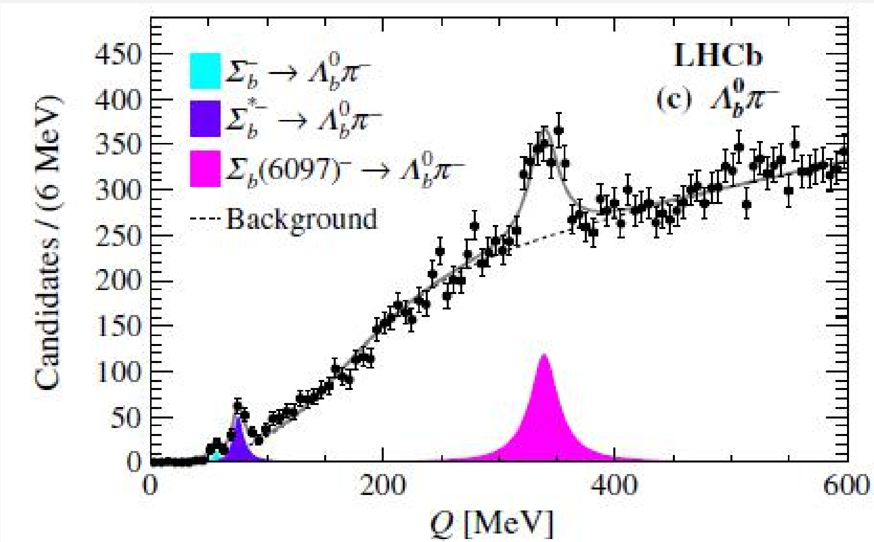
$\Sigma_c(2800)^{0}$ WIDTH

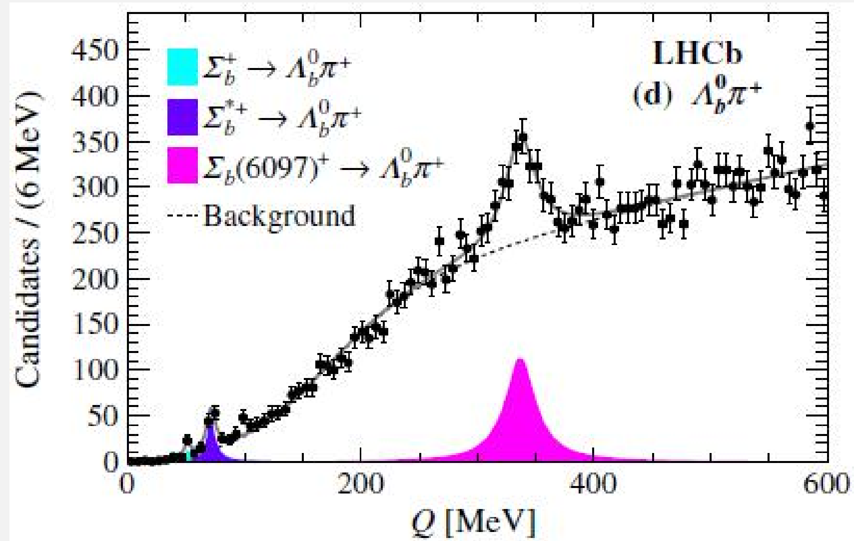
VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
72^{+22}_{-15} OUR AVERAGE					
$86^{+33}_{-22}+12$		AUBERT	08BN	BABR	$B^- \to \overline{p}\Lambda_c^+\pi^-$

◆ A good candidate of P wave state with $J^P=3/2^-$ or $5/2^-$!

◆ Looking for more P wave states in the $\Sigma_c^{(*)}\pi$ final states.

LHCb observed P wave candidate $\Sigma_b(6097)$





$$m[\Sigma_b(6097)^-] = 6098.0 \pm 1.7 \pm 0.5 \text{ MeV},$$

$$\Gamma[\Sigma_b(6097)^-] = 28.9 \pm 4.2 \pm 0.9 \text{ MeV},$$

$$m[\Sigma_b(6097)^+] = 6095.8 \pm 1.7 \pm 0.4 \text{ MeV},$$

$$\Gamma[\Sigma_b(6097)^+] = 31.0 \pm 5.5 \pm 0.7 \text{ MeV}.$$

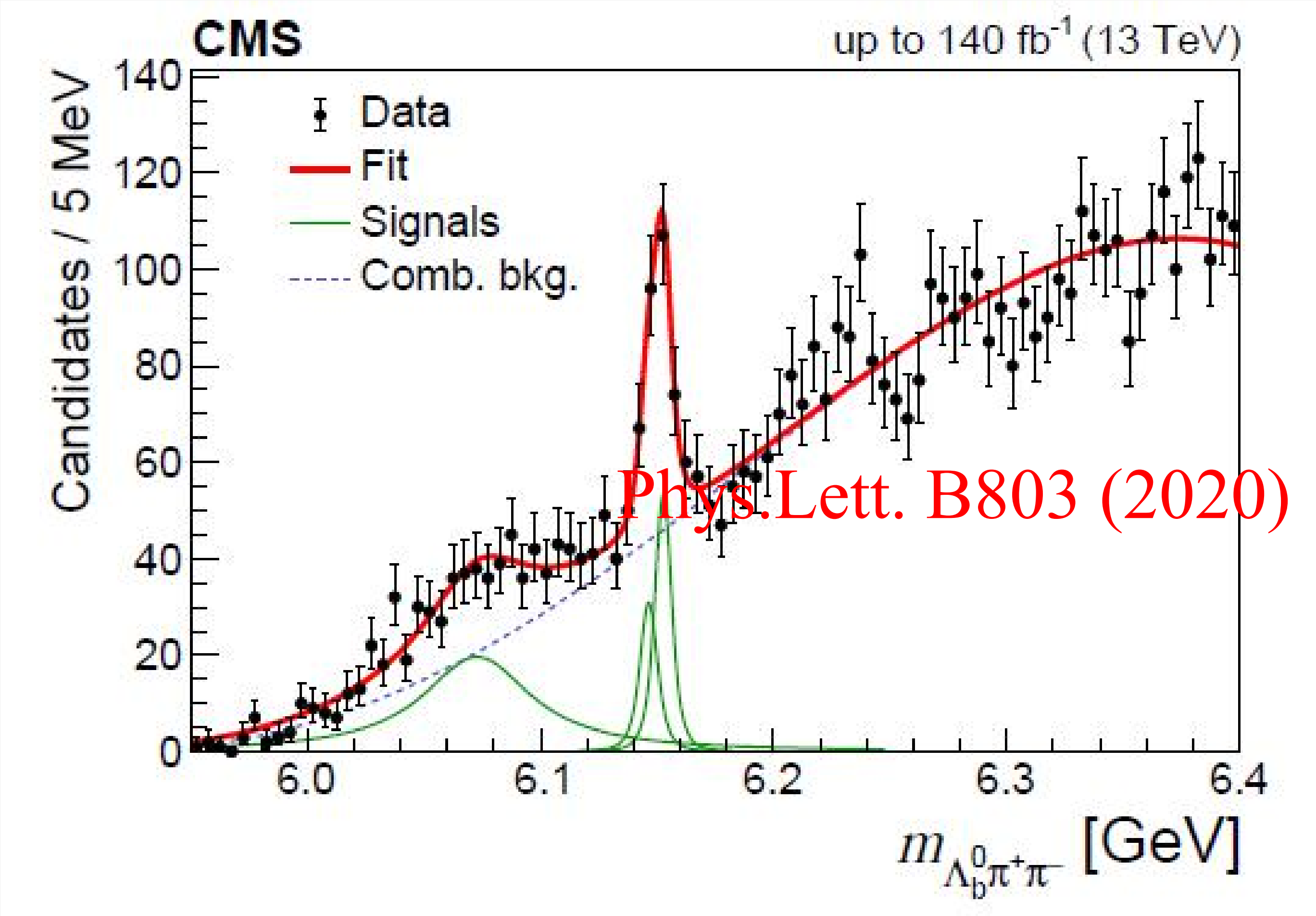
Mass, width, and decay mode are consistent with a P wave candidate with $J^P=3/2^-$ or $5/2^-$.

Looking for the missing narrow 1P $J^P=1/2^-$ state in the $\Lambda_b\pi$.

KL Wang, Qi-Fang Lv, XH, PRD99,014011 (2019)

CMS found broad structure @ 6070 MeV in the $\Lambda_b\pi^+\pi^-$

Confirmed by LHCb [JHEP 2006 (2020) 136]



Phys.Lett. B803 (2020) 135345

M=6072 MeV, Γ=72 MeV

Our explaination with P wave Σ_b state

TABLE III. The decay properties of the λ-mode $1P$-wave Σ_b states. The units of mass and width are in MeV.

State	Mass	$\Gamma[\Sigma_b\pi]$	$\Gamma[\Lambda_b\pi]$	$\Gamma[\Sigma_b^*\pi]$	$\Gamma[\Lambda_b(5912)\pi]$	$\Gamma[\Lambda_b(5920)\pi]$	Γ[total]
$\lvert J^P=\frac{1}{2}^-,1\rangle$	6072	26.2	$\cdots$	1.11	0.42	0.44	28.2
$\lvert J^P=\frac{1}{2}^-,0\rangle$	6072	$\cdots$	9.18	$\cdots$	0.12	0.13	9.43
$\lvert J^P=\frac{3}{2}^-,2\rangle$	6097	3.26	35.2	1.97	0.50	0.75	41.7
$\lvert J^P=\frac{3}{2}^-,1\rangle$	6087	1.46	$\cdots$	26.4	$\cdots$	$\cdots$	27.8
$\lvert J^P=\frac{5}{2}^-,2\rangle$	6107	1.84	38.9	7.00	0.71	1.12	49.5

- As the $\Lambda_b(2S)$, our predicted width is too narrow.
- Decay mode can be understand with cascade decay: Σ_b (6072)--- $\Sigma_b^{(*)}\pi$---$\Lambda_b\pi^+\pi^-$
- Two overlapping states with $J^P=1/2^-$ and $3/2^-$, which can explain the broad width.
- More observations for the $\Sigma_b^{(*)}\pi$ channels.

Li-Ye Xiao, XH, PRD102,014009 (2020)

Decay properties of the D-wave Σ_c states

		$\lvert\Sigma_c\,{}^2D_{\lambda\lambda}\frac{3}{2}^+\rangle(3043)$	$\lvert\Sigma_c\,{}^2D_{\lambda\lambda}\frac{5}{2}^+\rangle(3038)$	$\lvert\Sigma_c\,{}^4D_{\lambda\lambda}\frac{1}{2}^+\rangle(3041)$	$\lvert\Sigma_c\,{}^4D_{\lambda\lambda}\frac{3}{2}^+\rangle(3040)$	$\lvert\Sigma_c\,{}^4D_{\lambda\lambda}\frac{5}{2}^+\rangle(3023)$	$\lvert\Sigma_c\,{}^4D_{\lambda\lambda}\frac{7}{2}^+\rangle(3013)$
Decay mode	M_f	Γ_i (MeV)	Γ_i (MeV)	Γ_i (MeV)	Γ_i (MeV)	Γ_i (MeV)	Γ_i (MeV)
$\Lambda_c\pi$	2286	$1.29^{+2.54}_{-1.22}$	$11.9^{-1.65}_{+1.51}$	$2.62^{+5.09}_{-2.46}$	$1.15^{+2.32}_{-1.09}$	$3.1^{-0.46}_{+0.42}$	$13.1^{-2.06}_{+1.83}$
$\Sigma_c\pi$	2455	$7.06^{+4.66}_{-3.95}$	$8.78^{-1.86}_{+2.25}$	$3.53^{+2.31}_{-1.96}$	$1.77^{+1.14}_{-0.98}$	$0.54^{-0.11}_{+0.14}$	$2.18^{-0.48}_{+0.60}$
$\Sigma_c^*\pi$	2520	$2.44^{-0.33}_{+0.48}$	$2.91^{+0.72}_{-0.61}$	$1.71^{+0.79}_{-0.76}$	$7.47^{+2.04}_{-1.77}$	$11.6^{+0.80}_{-0.34}$	$1.45^{+0.13}_{-0.02}$
$\Xi_c K$	2470	$1.17^{+0.12}_{-0.14}$	0.03	$2.27^{+0.22}_{-0.27}$	$1.12^{+0.10}_{-0.13}$	< 0.01	0.01
$\lvert\Lambda_c\,{}^2P_{\lambda}\frac{1}{2}^-\rangle\pi$	2592	$4.93^{+0.25}_{-0.19}$	$10.3^{-0.83}_{+0.68}$	$52.6^{-3.2}_{+2.7}$	$3.06^{+2.44}_{-1.70}$	$11.2^{-0.8}_{+0.9}$	$11.1^{+3.5}_{-3.0}$
$\lvert\Lambda_c\,{}^2P_{\lambda}\frac{3}{2}^-\rangle\pi$	2628	$52.8^{+6.76}_{-5.77}$	$10.9^{+2.1}_{-2.4}$	$64.0^{+22.2}_{-18.8}$	$43.1^{+4.4}_{-3.7}$	$1.92^{+0.02}_{<+0.01}$	$24.2^{+0.05}_{-0.04}$
$\lvert\Sigma_c\,{}^2P_{\lambda}\frac{1}{2}^-\rangle\pi$	2713	$4.09^{+0.35}_{-0.29}$	$5.85^{-0.75}_{+0.86}$	$7.56^{-0.77}_{+0.89}$	$2.10^{+0.99}_{-0.82}$	$1.13^{-0.16}_{+0.18}$	$2.83^{+0.76}_{-0.68}$
$\lvert\Sigma_c\,{}^2P_{\lambda}\frac{3}{2}^-\rangle\pi$	2798	$25.6^{+4.82}_{-4.29}$	$0.76^{-0.05}_{+0.18}$	$15.8^{+4.0}_{-3.6}$	$3.58^{+0.39}_{-0.34}$	0.01	$0.95^{+0.06}_{-0.04}$
$\lvert\Sigma_c\,{}^4P_{\lambda}\frac{1}{2}^-\rangle\pi$	2799	0.09	$1.30^{+0.38}_{-0.33}$	$0.46^{-0.07}_{+0.10}$	$22.4^{+3.4}_{-3.0}$	$12.1^{+2.1}_{-1.9}$	< 0.01
$\lvert\Sigma_c\,{}^4P_{\lambda}\frac{3}{2}^-\rangle\pi$	2773	$3.42^{+0.22}_{-0.16}$	$1.26^{+0.11}_{-0.09}$	$4.18^{+0.05}_{+0.02}$	$18.9^{+2.4}_{-2.0}$	$4.54^{+2.16}_{-1.80}$	$1.03^{-0.03}_{+0.04}$
$\lvert\Sigma_c\,{}^4P_{\lambda}\frac{5}{2}^-\rangle\pi$	2789	$2.20^{+0.06}_{<+0.01}$	$4.51^{+0.57}_{-0.45}$	$6.1^{+1.96}_{-1.72}$	$16.8^{+4.8}_{-4.3}$	$23.0^{+3.3}_{-2.9}$	$1.26^{-0.05}_{+0.09}$
Sum		$105^{+19.5}_{-15.5}$	$58.5^{-1.3}_{+1.6}$	$160.8^{+32.6}_{-25.9}$	$121.5^{+24.4}_{-19.8}$	$69.1^{+6.9}_{-5.3}$	$58.1^{+1.9}_{-1.2}$

Broader than the P wave states.

The $J^P=5/2^+$ and $7/2^+$ states are worth observing!

YX Yao, KL Wang, XH, PRD98,076015(2018)

Decay properties of the D-wave Σ_b states

		$\vert\Sigma_b{}^2D_{\lambda\lambda}\frac{3}{2}^+\rangle(6326)$	$\vert\Sigma_b{}^2D_{\lambda\lambda}\frac{5}{2}^+\rangle(6284)$	$\vert\Sigma_b{}^4D_{\lambda\lambda}\frac{1}{2}^+\rangle(6311)$	$\vert\Sigma_b{}^4D_{\lambda\lambda}\frac{3}{2}^+\rangle(6285)$	$\vert\Sigma_b{}^4D_{\lambda\lambda}\frac{5}{2}^+\rangle(6270)$	$\vert\Sigma_b{}^4D_{\lambda\lambda}\frac{7}{2}^+\rangle(6260)$
Decay mode	M_f	Γ_i (MeV)	Γ_i (MeV)	Γ_i (MeV)	Γ_i (MeV)	Γ_i (MeV)	Γ_i (MeV)
$\Lambda_b\pi$	5620	$0.56^{+2.76}_{-0.46}$	$17.3^{-1.1}_{+1.6}$	$1.56^{+5.81}_{-1.51}$	$1.21^{+3.07}_{-1.20}$	$4.43^{-0.58}_{+0.45}$	$18.5^{-2.6}_{+2.1}$
$\Sigma_b\pi$	5811	$8.28^{+5.54}_{-4.66}$	$6.32^{-1.44}_{+1.82}$	$4.16^{+2.51}_{-2.20}$	$2.03^{+1.03}_{-0.96}$	$0.37^{-0.09}_{+0.11}$	$1.43^{-0.33}_{+0.46}$
$\Sigma_b^*\pi$	5832	$4.21^{-0.58}_{+0.80}$	$3.26^{+0.81}_{-0.70}$	$2.05^{+1.08}_{-1.00}$	$8.36^{+2.26}_{-2.01}$	$12.6^{+0.9}_{-0.5}$	$1.54^{+0.15}_{-0.05}$
$\Xi_b K$	5794	$0.89^{+0.06}_{-0.06}$	...	$0.88^{+0.03}_{-0.04}$	...	...	...
$\vert\Lambda_b{}^2P_{\lambda}\frac{1}{2}^-\rangle\pi$	5912	$5.70^{+0.22}_{-0.13}$	$6.96^{-0.61}_{+0.54}$	$51.6^{-2.9}_{+2.2}$	$3.05^{+2.13}_{-1.55}$	$7.68^{-0.65}_{+0.66}$	$8.89^{+2.77}_{-2.34}$
$\vert\Lambda_b{}^2P_{\lambda}\frac{3}{2}^-\rangle\pi$	5920	$70.0^{+8.3}_{-7.5}$	$10.4^{-2.0}_{+2.3}$	$66.0^{+24.1}_{-20.1}$	$40.5^{+4.1}_{-3.4}$	$1.90^{-0.001}_{+0.02}$	$21.1^{+0.06}_{-0.1}$
$\vert\Sigma_b{}^2P_{\lambda}\frac{1}{2}^-\rangle\pi$	6101	$1.18^{+0.15}_{-0.13}$	$0.13^{-0.02}_{+0.03}$	$0.71^{-0.07}_{+0.09}$	$0.81^{+0.22}_{-0.20}$	0.01	$0.43^{+0.09}_{-0.08}$
$\vert\Sigma_b{}^2P_{\lambda}\frac{3}{2}^-\rangle\pi$	6096	$25.6^{+4.8}_{-4.2}$	$0.28^{+0.09}_{-0.05}$	$13.1^{+3.2}_{-2.9}$	$1.49^{+0.20}_{-0.18}$	< 0.01	$0.24^{+0.03}_{-0.03}$
$\vert\Sigma_b{}^4P_{\lambda}\frac{1}{2}^-\rangle\pi$	6095	$0.10^{-0.04}_{+0.07}$	$0.79^{+0.21}_{-0.18}$	$0.33^{-0.06}_{+0.07}$	$10.5^{+1.81}_{-1.55}$	$5.30^{+1.0}_{-0.90}$	< 0.01
$\vert\Sigma_b{}^4P_{\lambda}\frac{3}{2}^-\rangle\pi$	6087	$2.53^{+0.16}_{-0.12}$	$0.41^{+0.05}_{-0.05}$	$2.24^{+0.04}_{-0.01}$	$6.44^{+1.01}_{-0.88}$	$3.52^{+1.09}_{-0.97}$	$0.15^{+0.01}_{<-0.01}$
$\vert\Sigma_b{}^4P_{\lambda}\frac{5}{2}^-\rangle\pi$	6084	$2.39^{+0.02}_{+0.03}$	$2.09^{+0.32}_{-0.27}$	$5.46^{+1.72}_{-1.52}$	$10.7^{+2.8}_{-2.5}$	$10.8^{+1.8}_{-1.6}$	$0.34^{+0.02}_{-0.01}$
Sum		$121.4^{+21.4}_{-16.4}$	$47.9^{-3.7}_{+5.0}$	$148.0^{+35.5}_{-26.9}$	$85.1^{+18.6}_{-14.4}$	$48.5^{+3.5}_{-2.7}$	$52.6^{+0.2}_{-0.05}$

Broader than the P wave states.
The $J^P=5/2^+$ and $7/2^+$ states are worth observing!

YX Yao, KL Wang, XH, PRD98,076015(2018)

Ξ'_c and Ξ'_b states

State	Ξ'_c RQM [21]	Ξ'_c NQM [22]	Ξ'_c NQM [33]	Ξ'_c PDG [24]	Ξ'_b RQM [21]	Ξ'_b NQM [22]	Ξ'_b PDG [24]
$1^2S\frac{1}{2}^+$	2579	2592	2579	2575	5936	5958	5935
$1^4S\frac{3}{2}^+$	2649	2650	2649	2645	5963	5982	5955
$1^2P_{\lambda}\frac{1}{2}^-$	2936	2859	2839	?	6233	6192	?
$1^2P_{\lambda}\frac{3}{2}^-$	2935	2871	2921	?	6234	6194	?
$1^4P_{\lambda}\frac{1}{2}^-$	2854	⋯	2900	?	6227	⋯	?
$1^4P_{\lambda}\frac{3}{2}^-$	2912	⋯	2932	?	6224	⋯	?
$1^4P_{\lambda}\frac{5}{2}^-$	2929	2905	2927	?	6226	6204	?
$1^2D_{\lambda\lambda}\frac{3}{2}^+$	3167	⋯	3089	?	6459	⋯	?
$1^2D_{\lambda\lambda}\frac{5}{2}^+$	3166	⋯	3091	?	6432	6402	?
$1^4D_{\lambda\lambda}\frac{1}{2}^+$	3163	⋯	3075	?	6447	⋯	?
$1^4D_{\lambda\lambda}\frac{3}{2}^+$	3160	⋯	3081	?	6431	⋯	?
$1^4D_{\lambda\lambda}\frac{5}{2}^+$	3153	3080	3077	?	6420	⋯	?
$1^4D_{\lambda\lambda}\frac{7}{2}^+$	3147	3094	3078	?	6414	6405	?

Only the ground states are established!

Decay properties of the P-wave $\Xi'_{c/b}$ states

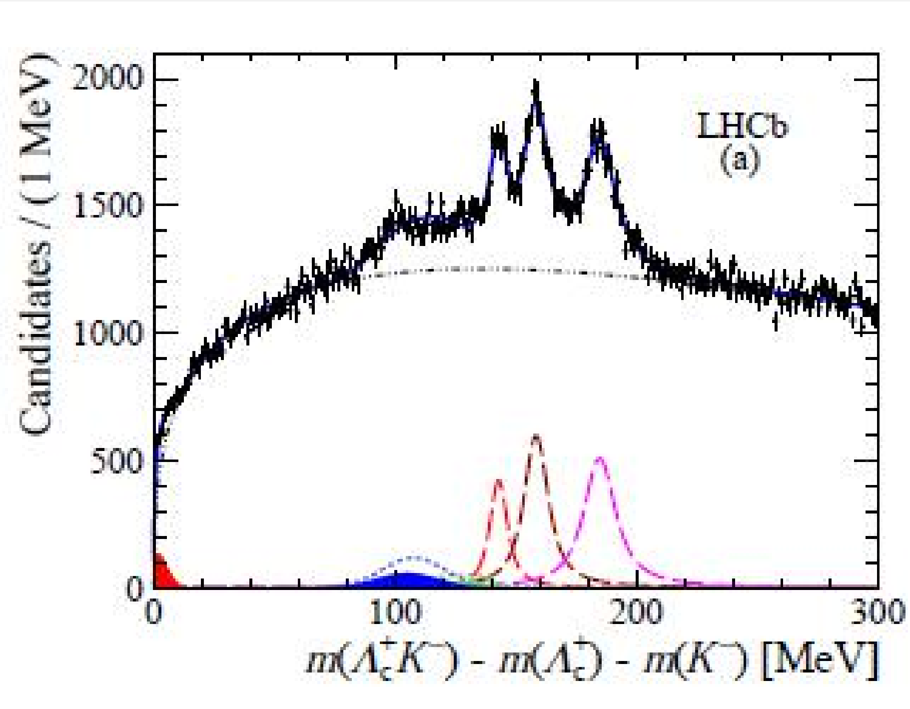
$\|^{2S+1}L_\lambda J^P\rangle$	State	Channel	Γ_i (MeV)	$\mathcal{B}_i$	State	Channel	Γ_i (MeV)	$\mathcal{B}_i$
$\|^2P_{\lambda}\frac{1}{2}^-\rangle$	$\Xi'_c(2936)$	$\Lambda_c K$	7.11	32.81%	$\Xi'_b(6233)$	$\Lambda_b K$	12.11	44.77%
		$\Xi_c\pi$	3.90	18.00%		$\Xi_b\pi$	4.77	17.63%
		$\Xi'_c(2580)\pi$	10.08	46.52%		$\Xi'_b\pi$	9.23	34.12%
		$\Xi'_c(2645)\pi$	0.58	2.68%		$\Xi'_b(5945)\pi$	0.94	3.48%
		total	21.67			total	27.05	
$\|^2P_{\lambda}\frac{3}{2}^-\rangle$	$\Xi'_c(2935)$	$\Lambda_c K$	3.73	17.86%	$\Xi'_b(6234)$	$\Lambda_b K$	4.14	17.14%
		$\Xi_c\pi$	10.85	51.94%		$\Xi_b\pi$	14.91	61.74%
		$\Xi'_c(2580)\pi$	3.89	18.62%		$\Xi'_b\pi$	2.37	9.81%
		$\Xi'_c(2645)\pi$	2.42	11.58%		$\Xi'_b(5945)\pi$	2.73	11.30%
		total	20.89			total	24.15	
$\|^4P_{\lambda}\frac{1}{2}^-\rangle$	$\Xi'_c(2854)$	$\Lambda_c K$	18.56	50.09%	$\Xi'_b(6227)$	$\Lambda_b K$	17.28	53.60%
		$\Xi_c\pi$	15.02	40.54%		$\Xi_b\pi$	10.01	31.05%
		$\Xi'_c(2580)\pi$	3.44	9.28%		$\Xi'_b\pi$	4.54	14.08%
		$\Xi'_c(2645)\pi$	0.03	0.07		$\Xi'_b(5945)\pi$	0.41	1.27%
		total	37.05			total	32.24	
$\|^4P_{\lambda}\frac{3}{2}^-\rangle$	$\Xi'_c(2912)$	$\Lambda_c K$	0.50	4.06%	$\Xi'_b(6224)$	$\Lambda_b K$	0.98	6.19%
		$\Xi_c\pi$	1.70	13.79%		$\Xi_b\pi$	2.67	16.87%
		$\Xi'_c(2580)\pi$	0.13	1.05%		$\Xi'_b\pi$	0.10	0.63%
		$\Xi'_c(2645)\pi$	10.00	81.10%		$\Xi'_b(5945)\pi$	12.08	76.31%
		total	12.33			total	15.83	
$\|^4P_{\lambda}\frac{5}{2}^-\rangle$	$\Xi'_c(2929)$	$\Lambda_c K$	4.06	20.10%	$\Xi'_b(6226)$	$\Lambda_b K$	4.20	17.22%
		$\Xi_c\pi$	12.24	60.59%		$\Xi_b\pi$	16.37	67.12%
		$\Xi'_c(2580)\pi$	1.06	5.25%		$\Xi'_b\pi$	0.60	2.46%
		$\Xi'_c(2645)\pi$	2.84	14.06%		$\Xi'_b(5945)\pi$	3.22	13.20%
		total	20.2			total	24.39	

Relatively narrow states!

KL Wang, YX Yao, XH, QZ, PRD96,116016(2017)

LHCb observed three P-wave candidates $\Xi_c(2923)$, $\Xi_c(2939)$, $\Xi_c(2965)$!

Phys.Rev.Lett. 124 (2020), 222001



$$m[\Xi_c(2923)^0] = 2923.04 \pm 0.59\ \text{MeV},$$
$$\Gamma[\Xi_c(2923)^0] = 7.1 \pm 2.6\ \text{MeV},$$
$$m[\Xi_c(2939)^0] = 2938.55 \pm 0.52\ \text{MeV},$$
$$\Gamma[\Xi_c(2939)^0] = 10.2 \pm 1.9\ \text{MeV},$$
$$m[\Xi_c(2965)^0] = 2964.88 \pm 0.54\ \text{MeV},$$
$$\Gamma[\Xi_c(2965)^0] = 14.1 \pm 2.2\ \text{MeV}.$$

Mass, and decay mode are consistent with P wave candidates.

Our explaination with P wave Ξ'_c states

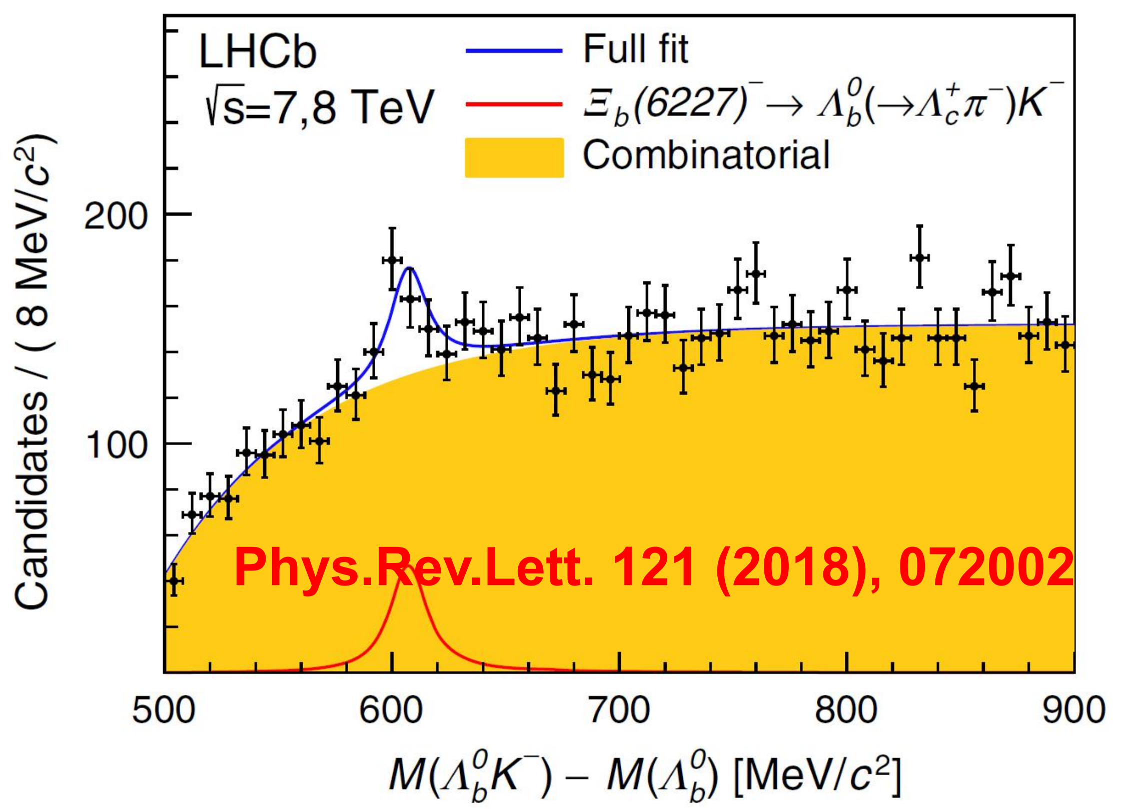
State	Mass	$\Gamma[\Xi_c \pi]$	$\Gamma[\Xi'_c \pi]$	$\Gamma[\Xi^*_c \pi]$	$\Gamma[\Lambda_c K]$	Γ^{th}_{total}	Γ^{exp}_{total}	Possible assignment
$\lvert 1P_{\lambda}\frac{1}{2}^-\rangle_1$	2880	0.86	12.9	0.18	1.17	15.1	$\cdots$	$\cdots$
$\lvert 1P_{\lambda}\frac{1}{2}^-\rangle_2$	2880	21.7	0.51	0.01	29.6	51.8	$\cdots$	$\cdots$
$\lvert 1^4P_{\lambda}\frac{3}{2}^-\rangle$	2923	1.74	0.15	10.7	0.48	13.1	$7.1 \pm 0.8 \pm 1.8$	$\Xi_c(2923)^0$
$\lvert 1^2P_{\lambda}\frac{3}{2}^-\rangle$	2939	10.2	3.80	2.46	3.74	20.2	$10.2 \pm 0.8 \pm 1.1$	$\Xi_c(2939)^0$
$\lvert 1^4P_{\lambda}\frac{5}{2}^-\rangle$	2965	15.5	1.64	3.57	5.43	26.1	$14.1 \pm 0.9 \pm 1.3$	$\Xi_c(2965)^0$

- $\Xi_c(2923)$, $\Xi_c(2939)$ may correspond to two $J^P=3/2^-$ states.
- $\Xi_c(2965)$ may be the $J^P=5/2^-$ state.
- To confirm the nature, the other dominant decay modes should be further observed.

Kai-Lei Wang, Li-Ye Xiao, XH, PRD102,034029 (2020)

LHCb observed P-wave candidate $\Xi_b(6227)$

$$\Gamma[\Xi_b(6227)^-] = 18.1 \pm 5.4 \pm 1.8\ \text{MeV},$$



Mass, width, and decay mode are consistent with a P wave candidate with J^P=3/2$^-$ or 5/2$^-$.

KL Wang, Qi-Fang Lv, XH, PRD99,014011 (2019)

Decay properties of the D-wave Ξ'_c states

Decay mode	M_f	$\lvert\Xi_c'\,^2D_{\lambda\lambda\frac{3}{2}^+}\rangle(3167)$ Γ_i (MeV)	$\lvert\Xi_c'\,^2D_{\lambda\lambda\frac{5}{2}^+}\rangle(3166)$ Γ_i (MeV)	$\lvert\Xi_c'\,^4D_{\lambda\lambda\frac{1}{2}^+}\rangle(3163)$ Γ_i (MeV)	$\lvert\Xi_c'\,^4D_{\lambda\lambda\frac{3}{2}^+}\rangle(3160)$ Γ_i (MeV)	$\lvert\Xi_c'\,^4D_{\lambda\lambda\frac{5}{2}^+}\rangle(3153)$ Γ_i (MeV)	$\lvert\Xi_c'\,^4D_{\lambda\lambda\frac{7}{2}^+}\rangle(3147)$ Γ_i (MeV)
$\Xi_c\pi$	2470	$2.43^{+2.13}_{-1.59}$	$5.13^{-0.96}_{+1.05}$	$4.92^{+4.18}_{-3.19}$	$2.48^{+2.06}_{-1.60}$	$1.32^{-0.25}_{+0.29}$	$5.68^{-1.10}_{+1.24}$
$\Xi_c'\pi$	2578	$3.51^{+1.79}_{-1.66}$	$2.77^{-0.62}_{+0.77}$	$1.75^{+0.88}_{-0.81}$	$0.87^{+0.44}_{-0.40}$	$0.17^{-0.03}_{+0.05}$	$0.73^{-0.17}_{+0.21}$
$\Xi_c'^*\pi$	2645	$0.74^{-0.09}_{+0.13}$	$1.18^{+0.27}_{-0.26}$	$0.76^{+0.27}_{-0.28}$	$2.94^{+0.72}_{-0.69}$	$4.28^{+0.34}_{-0.24}$	$0.56^{+0.06}_{-0.04}$
$\Lambda_c K$	2286	$1.23^{+1.13}_{-0.83}$	$1.25^{-0.43}_{+0.53}$	$2.51^{+2.24}_{-1.67}$	$1.27^{+1.12}_{-0.84}$	$0.72^{-0.13}_{+0.15}$	$3.09^{-0.58}_{+0.63}$
$\Sigma_c K$	2455	$6.37^{+1.97}_{-2.07}$	$1.72^{-0.43}_{+0.58}$	$3.16^{+0.96}_{-1.0}$	$1.57^{+0.46}_{-0.49}$	$0.11^{-0.03}_{+0.04}$	$0.40^{-0.10}_{+0.14}$
$\Sigma_c^* K$	2520	$0.47^{-0.01}_{+0.04}$	$1.57^{+0.25}_{-0.28}$	$1.22^{+0.23}_{-0.26}$	$3.97^{+0.62}_{-0.70}$	$4.18^{+0.37}_{-0.40}$	$0.59^{+0.08}_{-0.08}$
$\lvert\Lambda_c\,^2P_{\lambda\frac{1}{2}^-}\rangle K$	2592	$0.84^{+0.11}_{-0.10}$	$0.55^{+0.08}_{-0.06}$	$3.66^{-0.30}_{+0.38}$	$3.55^{+1.22}_{-1.06}$	$0.65^{-0.05}_{+0.07}$	$10.1^{+2.5}_{-2.3}$
$\lvert\Lambda_c\,^2P_{\lambda\frac{3}{2}^-}\rangle K$	2628	$10.9^{+2.4}_{-2.1}$	$0.24^{+0.10}_{-0.05}$	$39.1^{+9.5}_{-8.6}$	$7.25^{+1.53}_{-1.36}$	$0.15^{+0.02}_{-0.02}$	$1.15^{+0.15}_{-0.13}$
$\lvert\Xi_c\,^2P_{\lambda\frac{1}{2}^-}\rangle\pi$	2792	$1.85^{+0.15}_{-0.13}$	$1.83^{+0.15}_{-0.13}$	$14.5^{-1.28}_{+2.11}$	$9.28^{+1.53}_{-1.43}$	$3.37^{-0.31}_{+0.36}$	$14.4^{+4.0}_{-3.5}$
$\lvert\Xi_c\,^2P_{\lambda\frac{3}{2}^-}\rangle\pi$	2815	$47.3^{+7.7}_{-7.3}$	$3.54^{-0.82}_{+1.13}$	$40.2^{+11.9}_{-10.5}$	$11.8^{+1.7}_{-1.4}$	$0.67^{+0.03}_{-0.02}$	$8.81^{+0.04}_{-0.04}$
$\lvert\Xi_c'\,^2P_{\lambda\frac{1}{2}^-}\rangle\pi$	2936	$0.39^{+0.05}_{-0.05}$	$0.21^{-0.03}_{+0.04}$	$0.26^{-0.03}_{<+0.01}$	$0.51^{+0.15}_{-0.14}$	0.03	$0.92^{+0.21}_{-0.19}$
$\lvert\Xi_c'\,^2P_{\lambda\frac{3}{2}^-}\rangle\pi$	2935	$8.53^{+1.70}_{-1.50}$	$0.22^{-0.03}_{+0.04}$	$5.50^{+1.33}_{-1.21}$	$1.0^{+0.13}_{-0.11}$	< 0.01	$0.33^{+0.02}_{-0.02}$
$\lvert\Xi_c'\,^4P_{\lambda\frac{1}{2}^-}\rangle\pi$	2854	$0.23^{-0.07}_{+0.10}$	$1.00^{+0.32}_{-0.30}$	$0.75^{-0.11}_{+0.14}$	$20.5^{+2.9}_{-2.6}$	$13.0^{+2.1}_{-2.0}$	< 0.01
$\lvert\Xi_c'\,^4P_{\lambda\frac{3}{2}^-}\rangle\pi$	2912	$1.01^{+0.10}_{-0.07}$	$0.41^{+0.04}_{-0.04}$	$1.10^{+0.03}_{-0.02}$	$5.62^{+0.82}_{-0.72}$	$2.85^{+1.08}_{-0.94}$	$0.34^{<-0.01}_{<+0.01}$
$\lvert\Xi_c'\,^4P_{\lambda\frac{5}{2}^-}\rangle\pi$	2929	$0.59^{+0.04}_{-0.02}$	$1.46^{+0.22}_{-0.18}$	$2.23^{+0.64}_{-0.57}$	$5.75^{+1.51}_{-1.35}$	$7.55^{+1.17}_{-1.05}$	$0.37^{<-0.01}_{+0.01}$
Sum		$86.4^{+19.1}_{-17.2}$	$23.1^{-1.9}_{+2.8}$	$121.6^{+30.4}_{-25.5}$	$78.4^{+16.9}_{-14.9}$	$39.1^{+4.3}_{-3.7}$	$47.5^{+5.1}_{-4.1}$

Broader than the P wave states.

The $J^P=5/2^+$ and $7/2^+$ states are worth observing!

YX Yao, KL Wang, XH, PRD98,076015(2018)

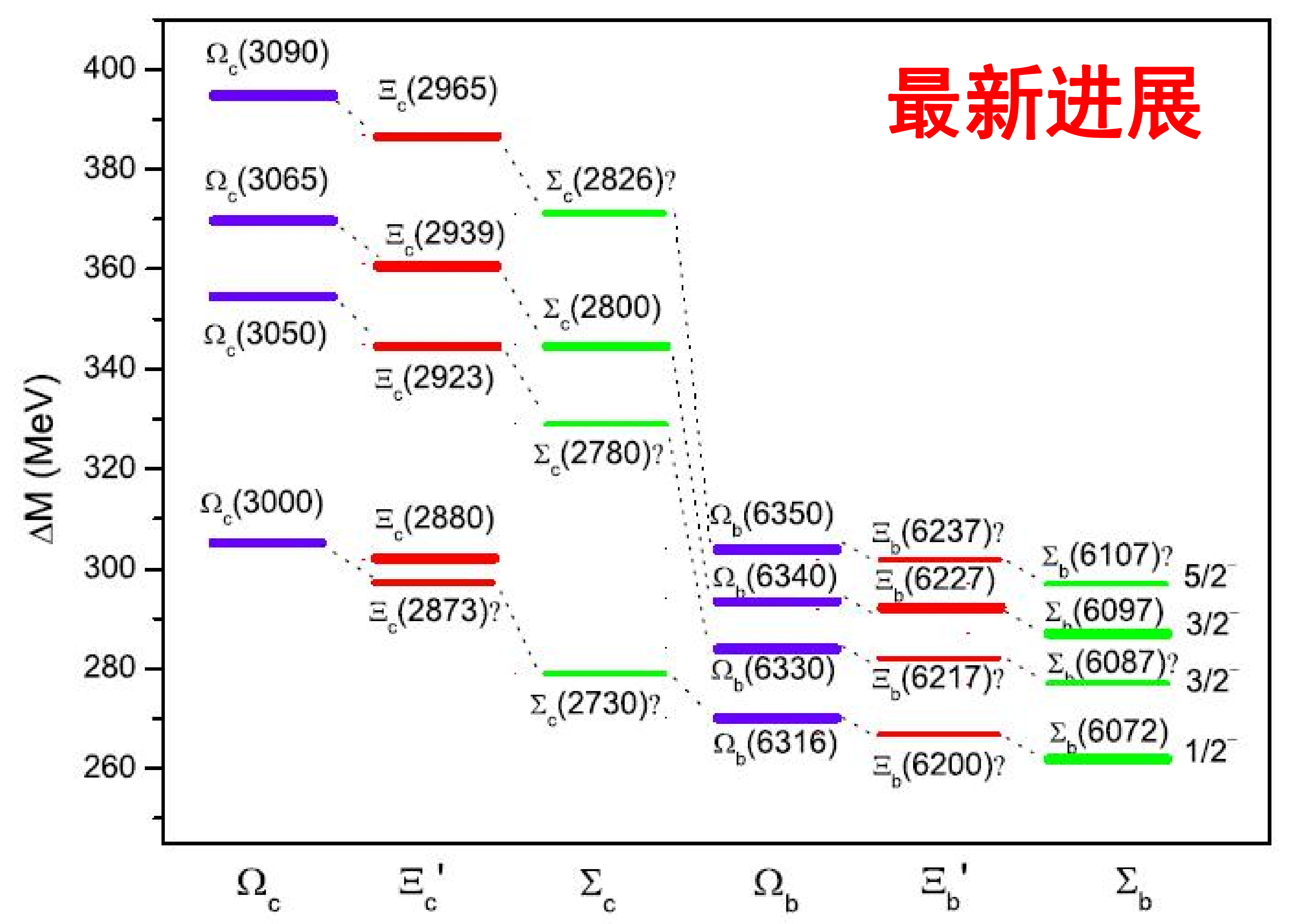
Decay properties of the D-wave Ξ'_b states

		$\lvert\Xi_b'^2D_{\lambda\lambda\frac{3}{2}^+}\rangle(6459)$	$\lvert\Xi_b'^2D_{\lambda\lambda\frac{5}{2}^+}\rangle(6432)$	$\lvert\Xi_b'^4D_{\lambda\lambda\frac{1}{2}^+}\rangle(6447)$	$\lvert\Xi_b'^4D_{\lambda\lambda\frac{3}{2}^+}\rangle(6431)$	$\lvert\Xi_b'^4D_{\lambda\lambda\frac{5}{2}^+}\rangle(6420)$	$\lvert\Xi_b'^4D_{\lambda\lambda\frac{7}{2}^+}\rangle(6414)$
Decay mode	M_f	Γ_i (MeV)	Γ_i (MeV)	Γ_i (MeV)	Γ_i (MeV)	Γ_i (MeV)	Γ_i (MeV)
$\Xi_b\pi$	5795	$2.02^{+3.07}_{-1.72}$	$9.41^{-1.51}_{+1.44}$	$4.41^{+6.04}_{-3.64}$	$2.43^{+2.93}_{-1.89}$	$2.42^{-0.40}_{+0.40}$	$10.3^{-1.73}_{+1.81}$
$\Xi_b'\pi$	5935	$4.18^{+2.37}_{-2.13}$	$2.82^{-0.64}_{+0.81}$	$2.06^{+1.10}_{-0.99}$	$1.01^{+0.48}_{-0.46}$	$0.17^{-0.04}_{+0.05}$	$0.71^{-0.17}_{+0.22}$
$\Xi'^*_b\pi$	5955	$1.60^{-0.21}_{+0.29}$	$1.59^{+0.39}_{-0.35}$	$1.00^{+0.47}_{-0.45}$	$4.03^{+1.09}_{-0.99}$	$6.16^{+0.46}_{-0.29}$	$0.79^{+0.08}_{-0.03}$
$\Lambda_b K$	5620	$1.04^{+1.67}_{-0.90}$	$2.45^{-0.89}_{+0.83}$	$2.39^{+3.36}_{-1.98}$	$1.40^{+1.47}_{-1.19}$	$1.29^{-0.21}_{+0.20}$	$5.45^{-0.90}_{+0.90}$
$\Sigma_b K$	5811	$7.80^{+2.16}_{-2.31}$	$0.86^{-0.22}_{+0.33}$	$4.03^{+0.98}_{-1.07}$	$1.83^{+0.37}_{-0.42}$	0.04	$0.16^{-0.04}_{+0.06}$
$\Sigma_b^* K$	5835	$0.85^{-0.04}_{+0.08}$	$1.95^{+0.28}_{-0.32}$	$1.77^{+0.34}_{-0.39}$	$5.11^{+0.74}_{-0.85}$	$4.77^{+0.41}_{-0.45}$	$0.68^{+0.08}_{-0.09}$
$\lvert\Lambda_b{}^2P_{\lambda\frac{1}{2}^-}\rangle K$	5912	$0.77^{+0.11}_{-0.10}$	0.06	$1.54^{-0.10}_{+0.14}$	$3.18^{+0.81}_{-0.74}$	0.04	$3.65^{+0.79}_{-0.71}$
$\lvert\Lambda_b{}^2P_{\lambda\frac{3}{2}^-}\rangle K$	5920	$14.6^{+3.07}_{-2.8}$	$0.17^{+0.10}_{-0.07}$	$30.2^{+7.48}_{-6.65}$	$5.87^{+1.25}_{-1.13}$	0.06	...
$\lvert\Xi_b{}^2P_{\lambda\frac{1}{2}^-}\rangle\pi$	6120	$1.90^{+0.14}_{-0.11}$	$1.35^{+0.12}_{-0.09}$	$13.2^{-1.19}_{+1.28}$	$7.36^{+1.22}_{-1.13}$	$2.15^{-0.20}_{+0.25}$	$11.0^{+3.0}_{-2.6}$
$\lvert\Xi_b{}^2P_{\lambda\frac{3}{2}^-}\rangle\pi$	6130	$54.4^{+8.22}_{-6.92}$	$2.80^{-0.66}_{+0.93}$	$39.3^{+12.0}_{-10.5}$	$10.5^{+1.47}_{-1.29}$	$0.56^{+0.03}_{<-0.01}$	$6.79^{+0.07}_{<-0.01}$
$\lvert\Xi_b'{}^2P_{\lambda\frac{1}{2}^-}\rangle\pi$	6233	$0.47^{+0.06}_{-0.05}$	$0.10^{-0.01}_{+0.02}$	$0.28^{-0.03}_{+0.04}$	$0.43^{+0.11}_{-0.11}$	0.01	$0.65^{+0.14}_{-0.14}$
$\lvert\Xi_b'{}^2P_{\lambda\frac{3}{2}^-}\rangle\pi$	6234	$9.60^{+1.87}_{-1.66}$	$0.14^{+0.04}_{-0.02}$	$5.33^{+1.31}_{-1.18}$	$0.72^{+0.10}_{-0.09}$	0.001	$0.18^{+0.01}_{-0.012}$
$\lvert\Xi_b'{}^4P_{\lambda\frac{1}{2}^-}\rangle\pi$	6227	0.03	$0.43^{+0.11}_{-0.10}$	$0.13^{-0.02}_{+0.02}$	$5.80^{+0.94}_{-0.87}$	$3.35^{+0.61}_{-0.56}$	< 0.01
$\lvert\Xi_b'{}^4P_{\lambda\frac{3}{2}^-}\rangle\pi$	6224	$0.89^{+0.08}_{-0.05}$	$0.21^{+0.03}_{-0.03}$	$0.81^{+0.03}_{-0.01}$	$3.16^{+0.49}_{-0.43}$	$1.80^{+0.59}_{-0.52}$	$0.12^{<+0.01}_{<-0.01}$
$\lvert\Xi_b'{}^4P_{\lambda\frac{5}{2}^-}\rangle\pi$	6226	$0.72^{+0.03}_{<-0.01}$	$0.96^{+0.14}_{-0.13}$	$2.21^{+0.65}_{-0.58}$	$4.80^{+1.23}_{-1.12}$	$5.26^{+0.89}_{-0.76}$	$0.20^{+0.01}_{<-0.01}$
Sum		$100.8^{+22.6}_{-18.4}$	$25.3^{-2.7}_{+3.3}$	$108.7^{+32.4}_{-26.0}$	$57.6^{+14.7}_{-12.7}$	$28.1^{+2.1}_{-1.7}$	$40.7^{+1.3}_{-4.6}$

The $J^P=5/2^+$ and $7/2^+$ states are worth observing!

YX Yao, KL Wang, XH, PRD98,076015(2018)

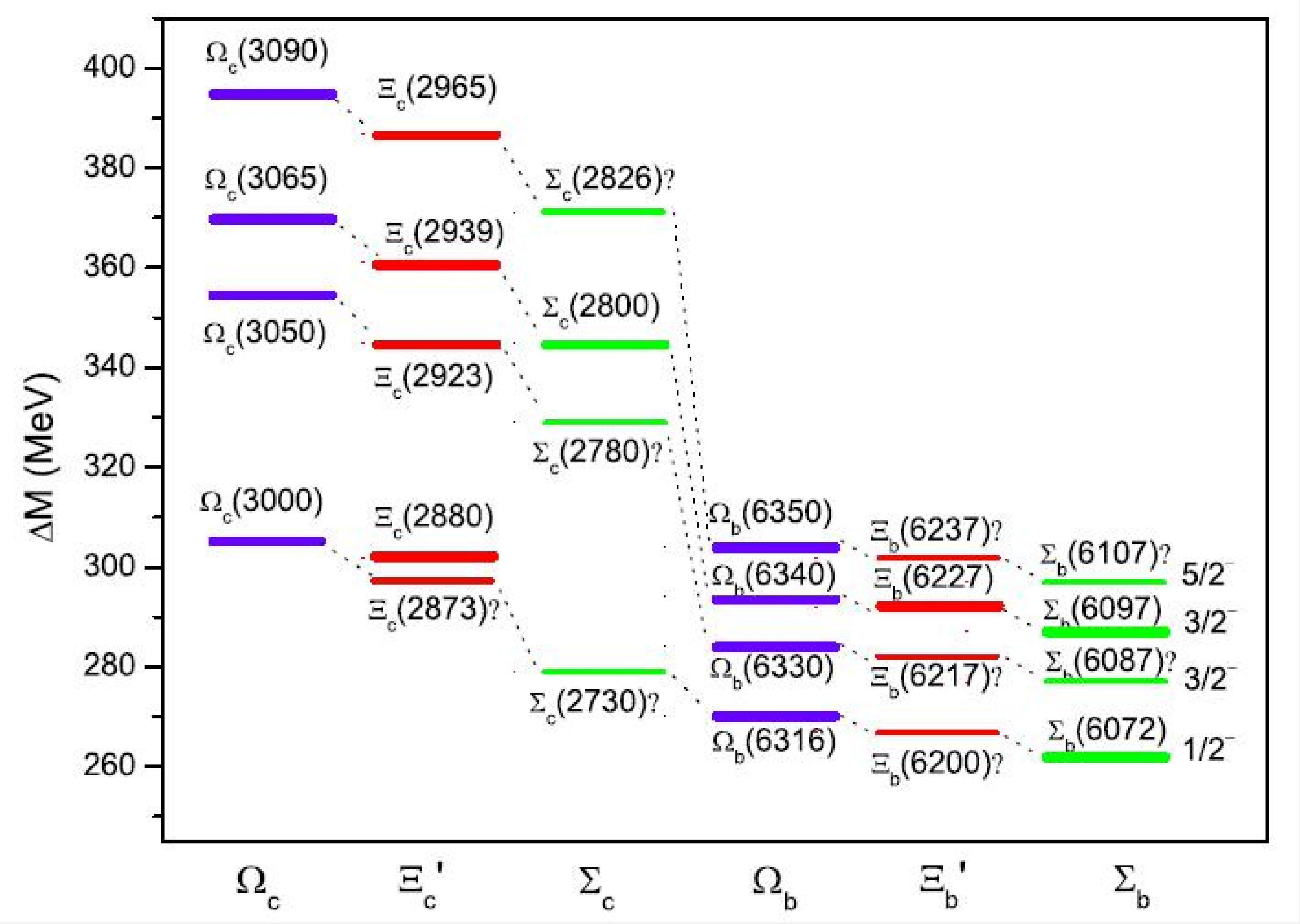
Summary



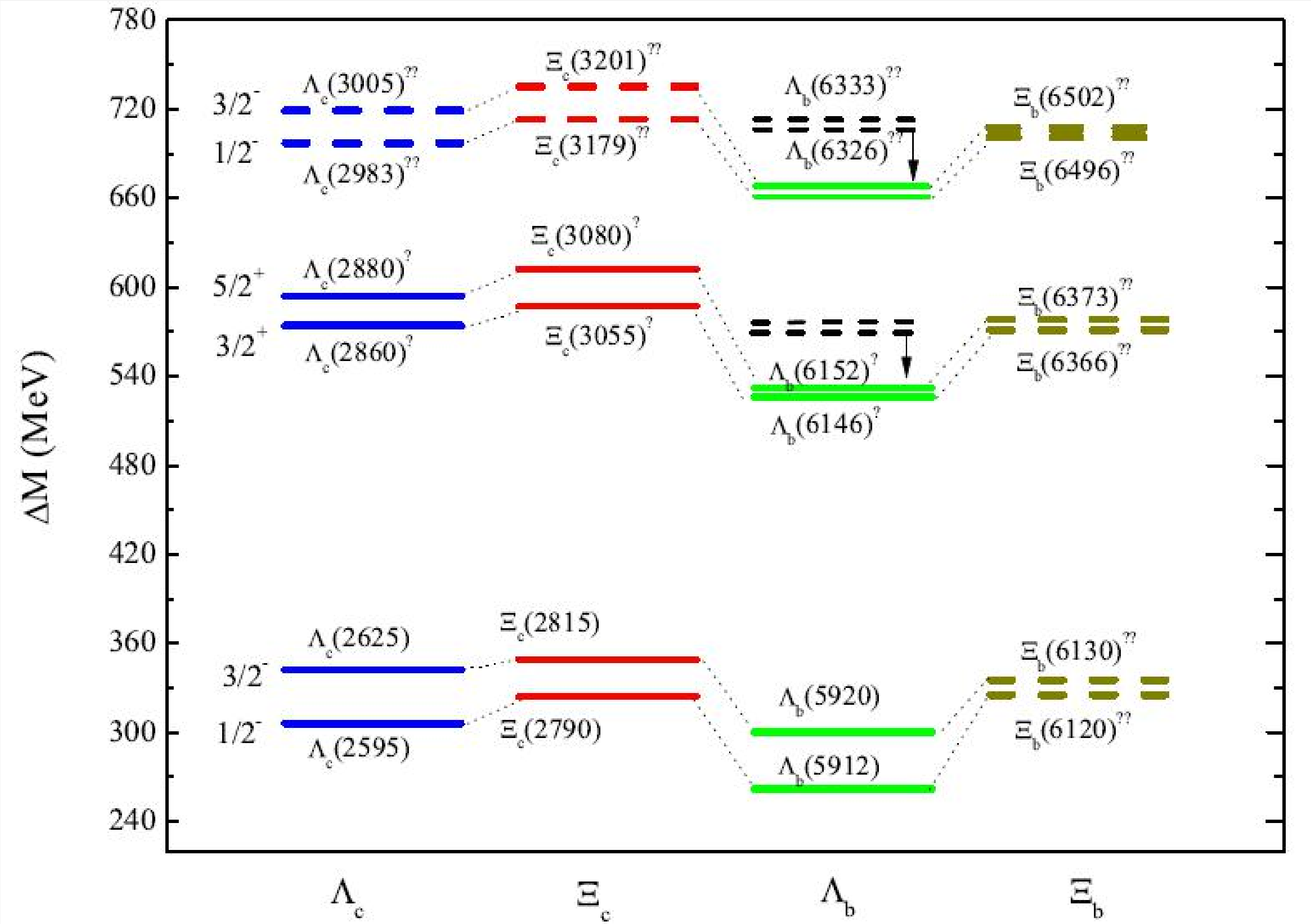
最新进展
ΔM (MeV)
400
380
360
340
320
300
280
260
Ωc(3090)
Ωc(3065)
Ωc(3050)
Ωc(3000)
Ξc(2965)
Ξc(2939)
Ξc(2923)
Ξc(2880)
Ξc(2873)?
Σc(2826)?
Σc(2800)
Σc(2780)?
Σc(2730)?
Ωb(6350)
Ωb(6340)
Ωb(6330)
Ωb(6316)
Ξb(6237)?
Ξb(6227)
Ξb(6217)?
Ξb(6200)?
Σb(6107)?
Σb(6097)
Σb(6087)?
Σb(6072)
5/2⁻
3/2⁻
3/2⁻
1/2⁻
Ωc
Ξc'
Σc
Ωb
Ξb'
Σb

Summary

6_F states



3_F states



Predicted masses are taken from Ebert et al., arXiv:1105.0583.

LHCb,Belle II为我们研究重味重子谱带来机遇！

许多夸克模型预言的态值得实验寻找。

谢谢！