Recent results in excited charm and beauty hadron spectroscopy

Anton Poluektov

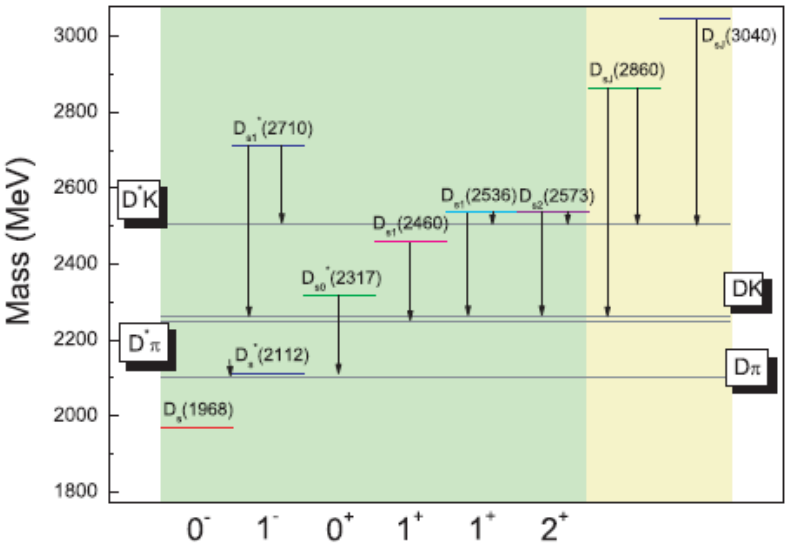
The University of Warwick, UK
Budker Institute of Nuclear Physics, Novosibirsk, Russia

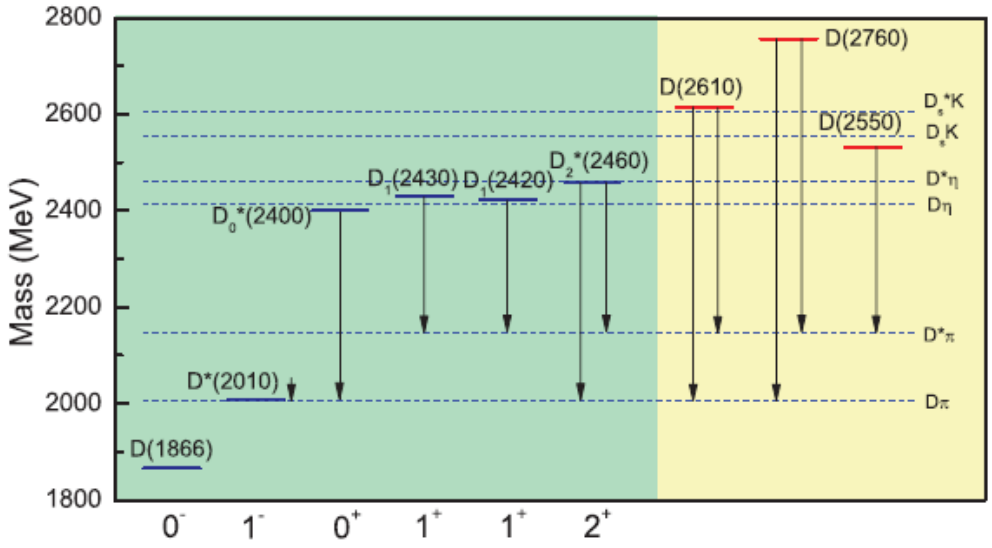
11 June 2012

- Charm mesons: D_{sJ} measurements at LHCb[New!].
- Beauty mesons: Measurement of B^{**} parameters at LHCb
- Latest beauty baryon results: Ω_b^-, $\Sigma_b^{(*)}$, $\Xi_b^{(*)0}$, Λ_b^{*0} from Tevatron and LHC.

System of the heavy and the light quarks: $Q\bar{q}$. $\vec{S} = \vec{s}_Q + \vec{s}_{\bar{q}}$, $\vec{J} = \vec{L} + \vec{S}$.

- $L = 0$. Doublet with $J^P = (0^-, 1^-)$: (D, D^*).
- Orbital excitations with $L = 1$. Two doublets:
  - $\vec{j}_q = \vec{L} + \vec{s}_{\bar{q}} = 1/2$. $J^P = (0^+, 1^+)$: (D_0^*, D_1').
  - $\vec{j}_q = \vec{L} + \vec{s}_{\bar{q}} = 3/2$. $J^P = (1^+, 2^+)$: (D_1, D_2^*).

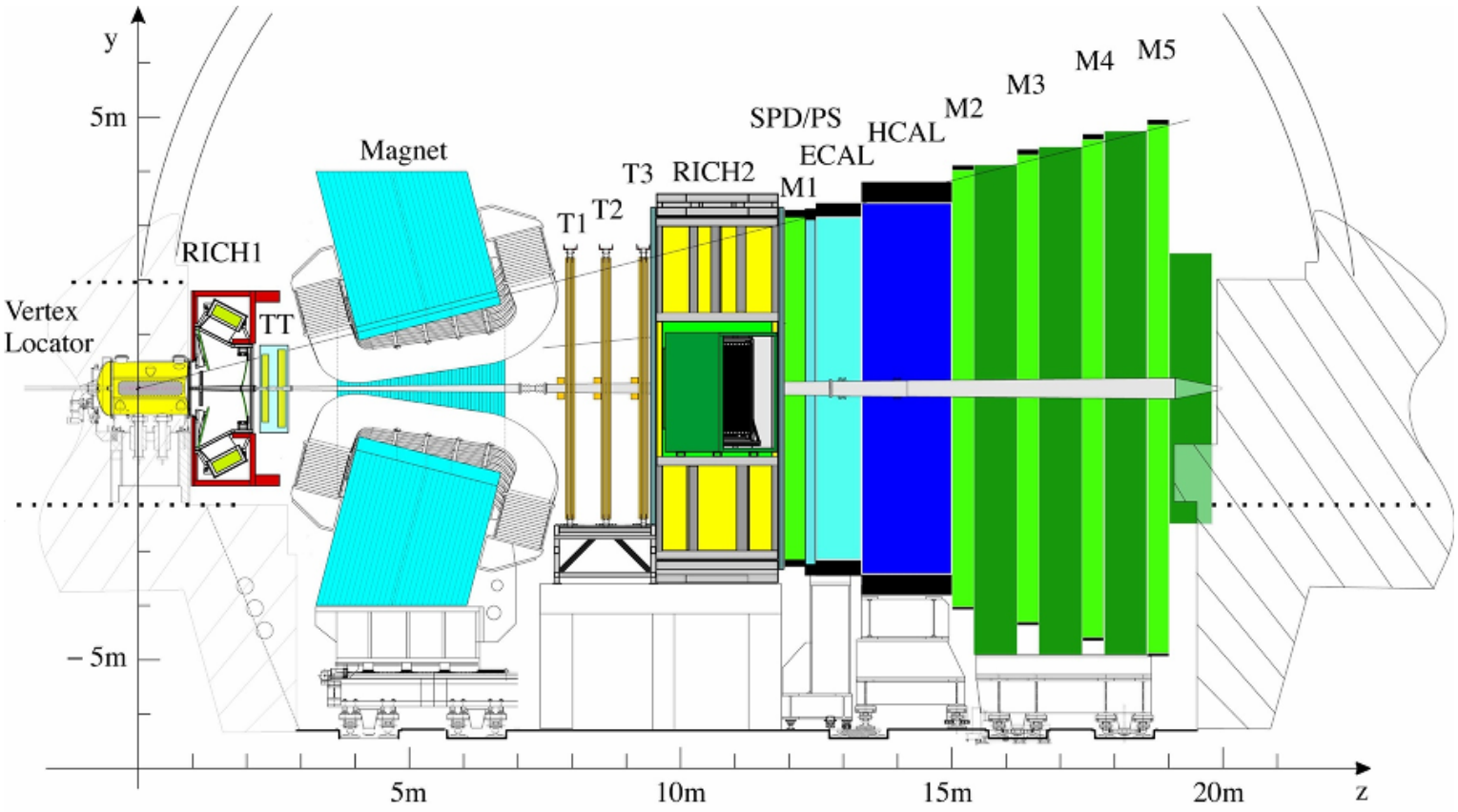




[Image: Xiang Liu, Charm 2010]

- Charm-strange system is the most interesting case, after the unexpected discovery of $D_{s0}^*(2317)^+ \to D_s^+\pi^0$ by BaBar (2003), followed by $D_{s1}(2460)^+$ (BaBar, Belle, 2004) with masses lower than HQET expectations.
- Second wave of observations: $D_{s1}^*(2710)^+$ and $D_{sJ}^*(2860)^+$ (Belle, BaBar, 2006–2007).
- These states are now confirmed by LHCb.

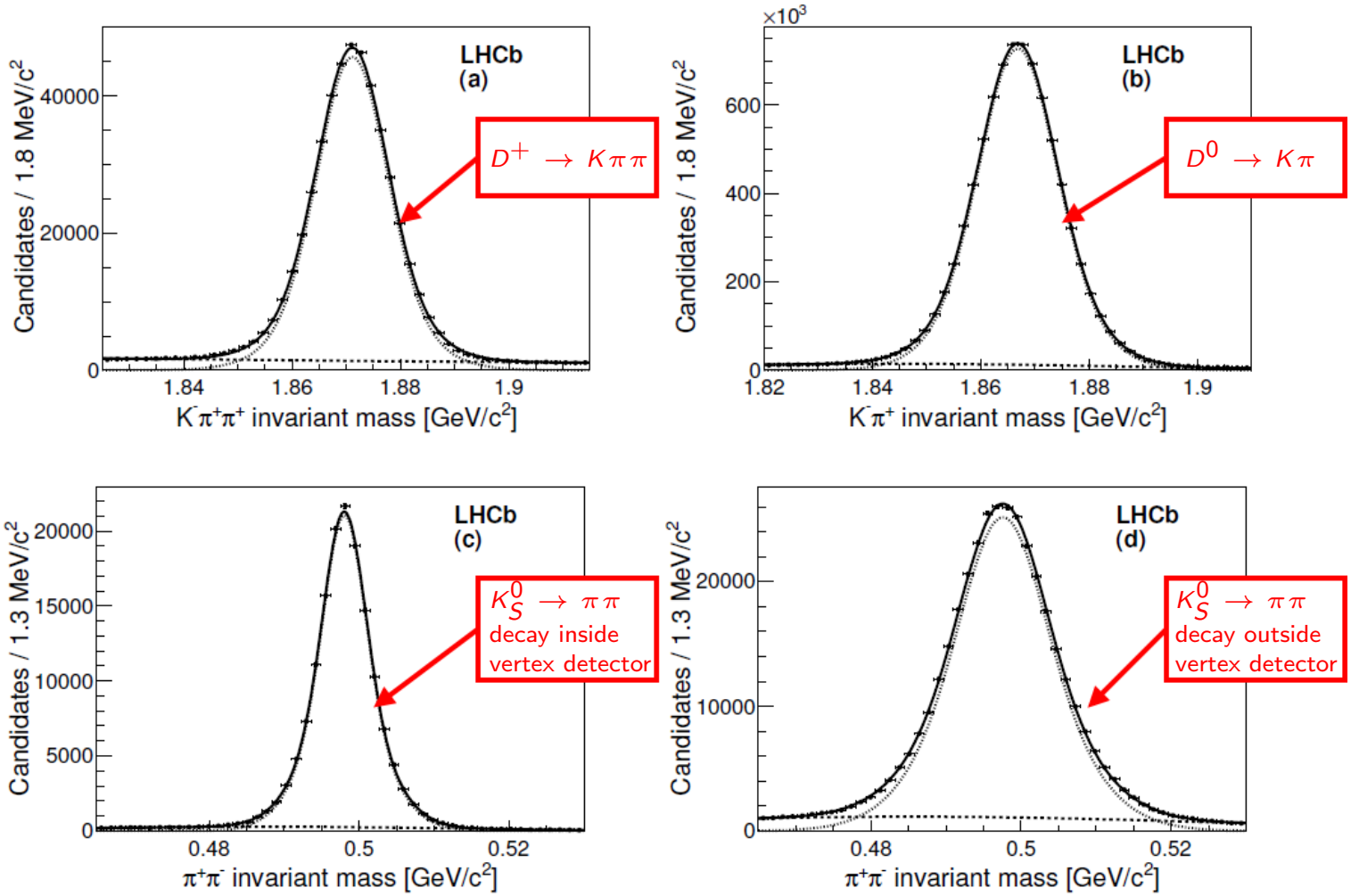
LHCb experiment



- Forward spectrometer at the LHC, optimized for b acceptance.
- Efficient trigger incl. fully hadronic charm and beauty modes.
- 1 fb^{-1} dataset in 2011 ($\sqrt{s} = 7$ TeV). $L = (3 - 3.5) \times 10^{32}$ cm^{-2}s^{-1}.
- Expect 1.5 fb^{-1} in 2012 ($\sqrt{s} = 8$ TeV). $L = 4 \times 10^{32}$ cm^{-2}s^{-1}. Increased bandwidth for prompt-charm modes.

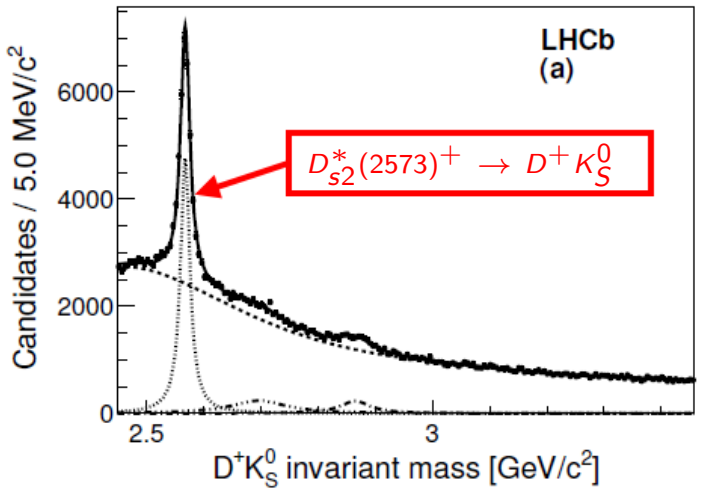
[LHCb preliminary, LHCb-PAPER-2012-016]

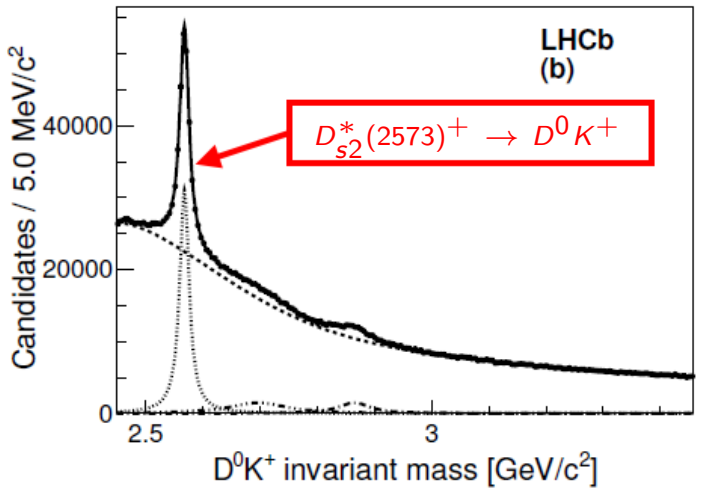
- 1 fb^{-1} data sample of pp collisions with $\sqrt{s} = 7$ TeV (2011).
- Reconstruct $D^+K^0_S$, and D^0K^+ with prompt D and K (pointing to primary vertex of pp interaction).

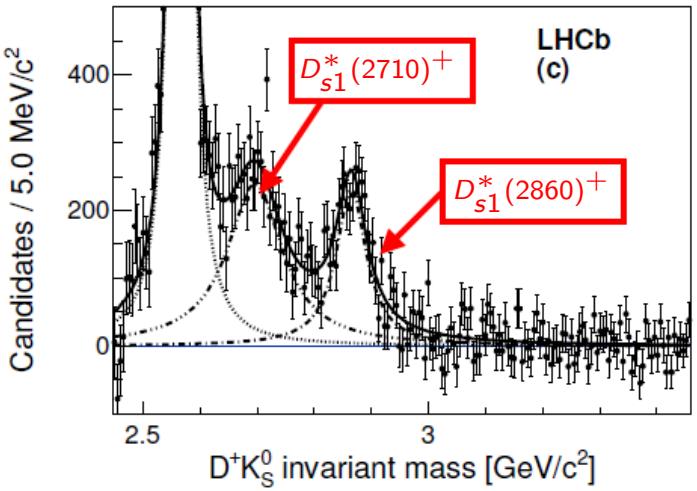


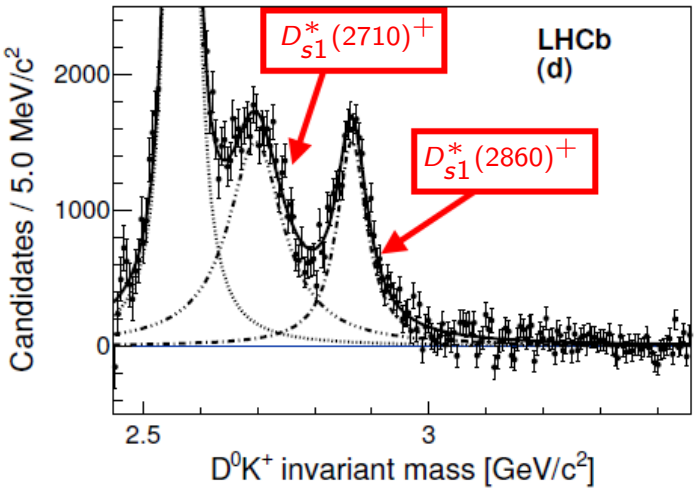
[LHCb preliminary, LHCb-PAPER-2012-016]

- Create $D^+K^0_S$ and D^0K^+ combinations.









[LHCb preliminary, LHCb-PAPER-2012-016]

- Combined fit to both $D^+K^0_S$ and D^0K^+ spectra.

Decay mode	$D^*_{s1}(2710)^+$	$D^*_{sJ}(2860)^+$
$D^+K^0_S$	7897 ± 637	4456 ± 332
D^0K^+	49871 ± 2659	29172 ± 1306

Systematic uncertainties:

Source	$D^*_{s1}(2710)^+$		$D^*_{sJ}(2860)^+$	
	ΔM	$\Delta\Gamma$	ΔM	$\Delta\Gamma$
Signal model	2.2	3.0	5.5	3.4
Background model	2.1	10.2	3.8	4.2
High mass state	0.0	0.3	0.0	0.2
Selection criteria	2.1	3.5	1.0	2.7
Mass resolution	2.1	3.6	2.8	2.4
Feed-down reflections	1.2	2.9	0.1	1.4
Bin size	0.2	0.9	0.0	0.2
Total	4.5	12.1	6.3	6.6

$$M(D^*_{s1}(2710)^+) = (2709.4 \pm 1.9_{\rm stat} \pm 4.5_{\rm syst})\,{\rm MeV}/c^2$$
$$\Gamma(D^*_{s1}(2710)^+) = (121.7 \pm 7.3_{\rm stat} \pm 12.1_{\rm syst})\,{\rm MeV}$$
$$M(D^*_{sJ}(2860)^+) = (2866.7 \pm 1.0_{\rm stat} \pm 6.3_{\rm syst})\,{\rm MeV}/c^2$$
$$\Gamma(D^*_{sJ}(2860)^+) = (64.5 \pm 3.2_{\rm stat} \pm 6.6_{\rm syst})\,{\rm MeV}$$

- Good consistency with older Belle and BaBar results.
- No evidence for states above 3 GeV/c^2.
- Nature of $D^*_{sJ}(2860)$ still remains unknown. Radial excitation, $L = 2$ states (or their mixture), multiquark states. More studies are needed to constrain quantum numbers.

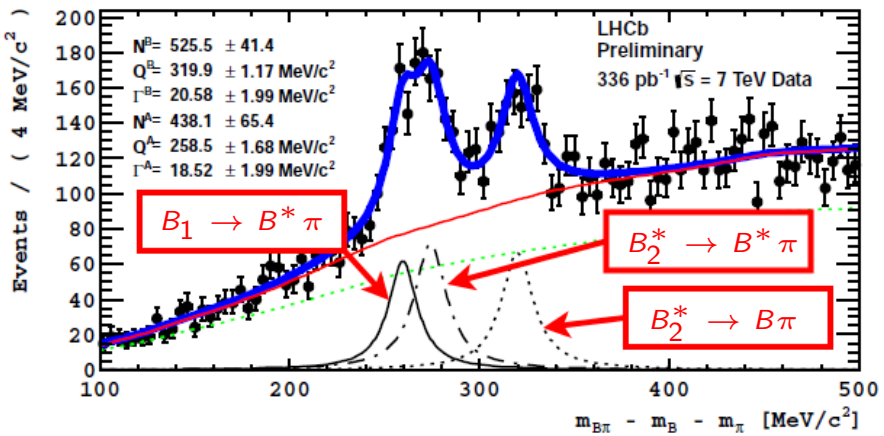
[LHCb preliminary, LHCb-CONF-2011-053]

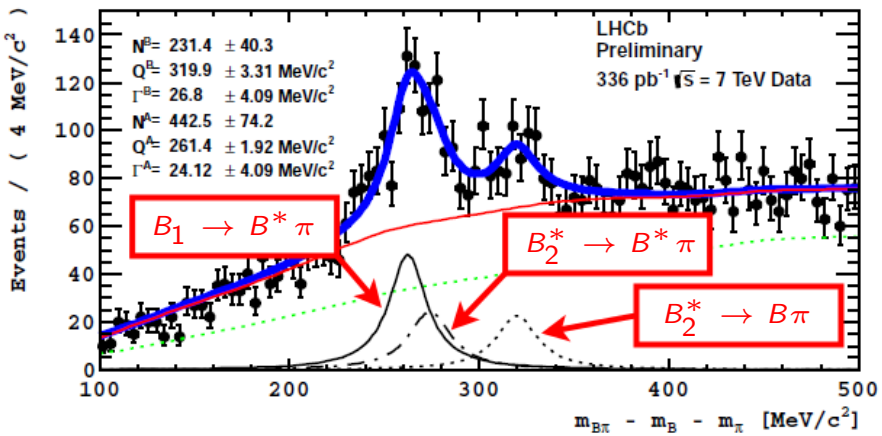
Excited B mesons have been studied at LEP and Tevatron so far.

- $L = 0$ excited state B^*. $M(B^*) - M(B) = 45.78 \pm 0.35\,\mathrm{MeV}/c^2$. $B^* \to B\gamma$.
- $j_q = 1/2$ states (B_0^*, B_1') are expected to be wide (100-200 MeV), decay to $B^{(*)}\pi$.
- $j_q = 3/2$ states (B_1, B_2^*) are narrower (10-20 MeV). Neutral states have been observed by D0 and CDF.

336 pb^{-1} data sample of pp collisions with $\sqrt{s} = 7$ TeV (2011).
B mesons are reconstructed in $J/\psi K^{(*)}$, $D\pi$, $D\pi\pi\pi$ modes.
Study the $M(B\pi) - M(B) - M(\pi)$ spectrum.

$B^{0,\pm}$ is combined with $\pi^{\mp}$. Soft γ from the B^* decay is not reconstructed. Thus, two peaks for $B_2^* \to B\pi$ and $B^*\pi$. B_1 decays only to $B^*\pi$.



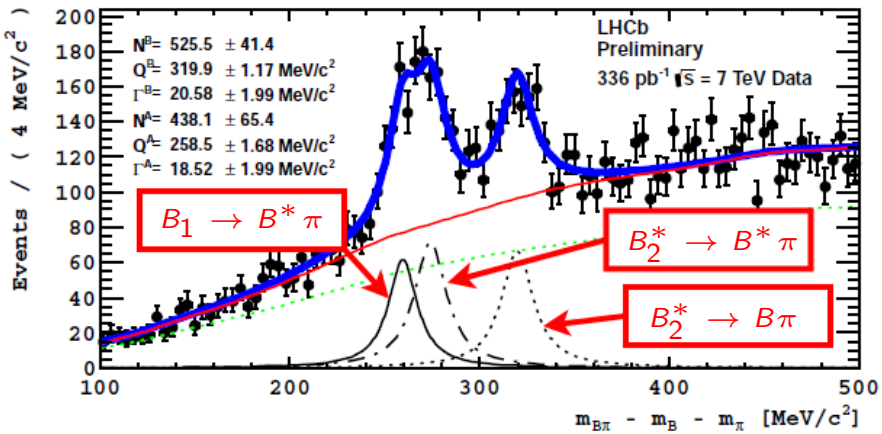


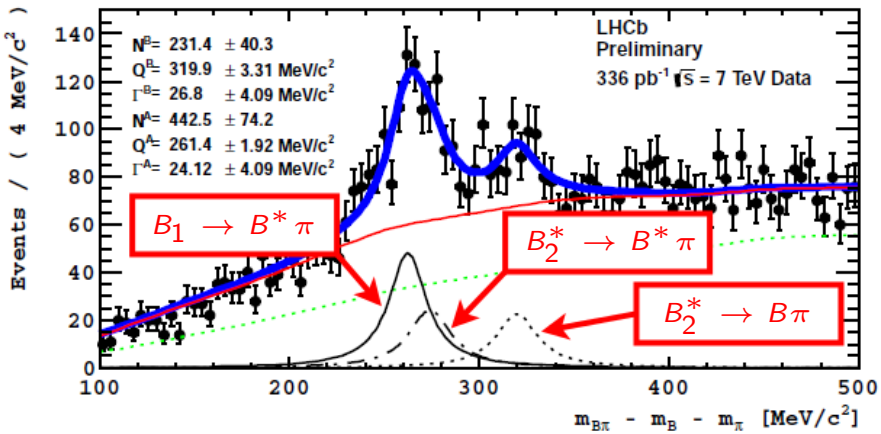
[LHCb preliminary, LHCb-CONF-2011-053]

- Mass resolution $\ll$ natural width $\Rightarrow$ Breit-Wigner for signals
- Fix $B_2^* \to B\pi$ and $B^*\pi$ yield (0.93 ± 0.18), ratio of B_1 and B_2^* width (0.9 ± 0.2)

$$M(B_1^0) = (5724.1 \pm 1.7_{\text{stat}} \pm 2.0_{\text{syst}} \pm 0.5_{\text{B mass}})\,\text{MeV}/c^2$$
$$M(B_1^+) = (5726.3 \pm 1.9_{\text{stat}} \pm 3.0_{\text{syst}} \pm 0.5_{\text{B mass}})\,\text{MeV}/c^2$$
$$M(B_2^{*0}) = (5738.6 \pm 1.2_{\text{stat}} \pm 1.2_{\text{syst}} \pm 0.3_{\text{B mass}})\,\text{MeV}/c^2$$
$$M(B_2^{*+}) = (5739.0 \pm 3.3_{\text{stat}} \pm 1.6_{\text{syst}} \pm 0.3_{\text{B mass}})\,\text{MeV}/c^2$$

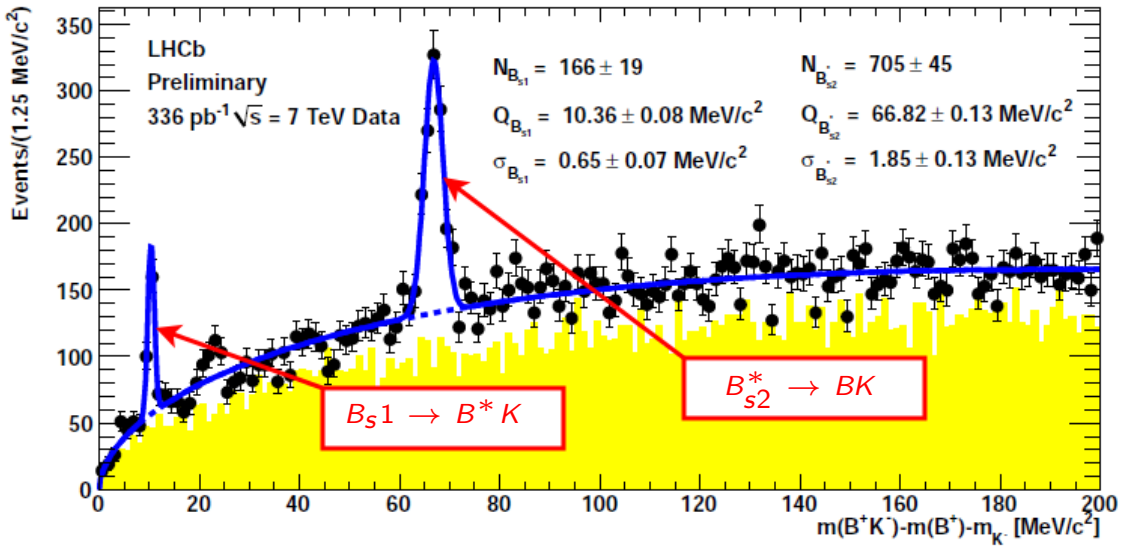
First observation of charged B_1^+ and B_2^{*+} states. First particles discovered at LHC.
Good agreement with earlier measurements of B_1^0 and B_2^{*0} parameters by CDF and D0.





[LHCb preliminary, LHCb-CONF-2011-053]

- B_{s1}, B^*_{s2} states with $j_q = 3/2$. Narrow width due to proximity of kinematic threshold.
- $B_{s1} \to B^* K$ (BK forbidden by parity conservation), $B^*_{s2} \to BK$.
- Natural width $\ll$ mass resolution (~ 1 MeV)



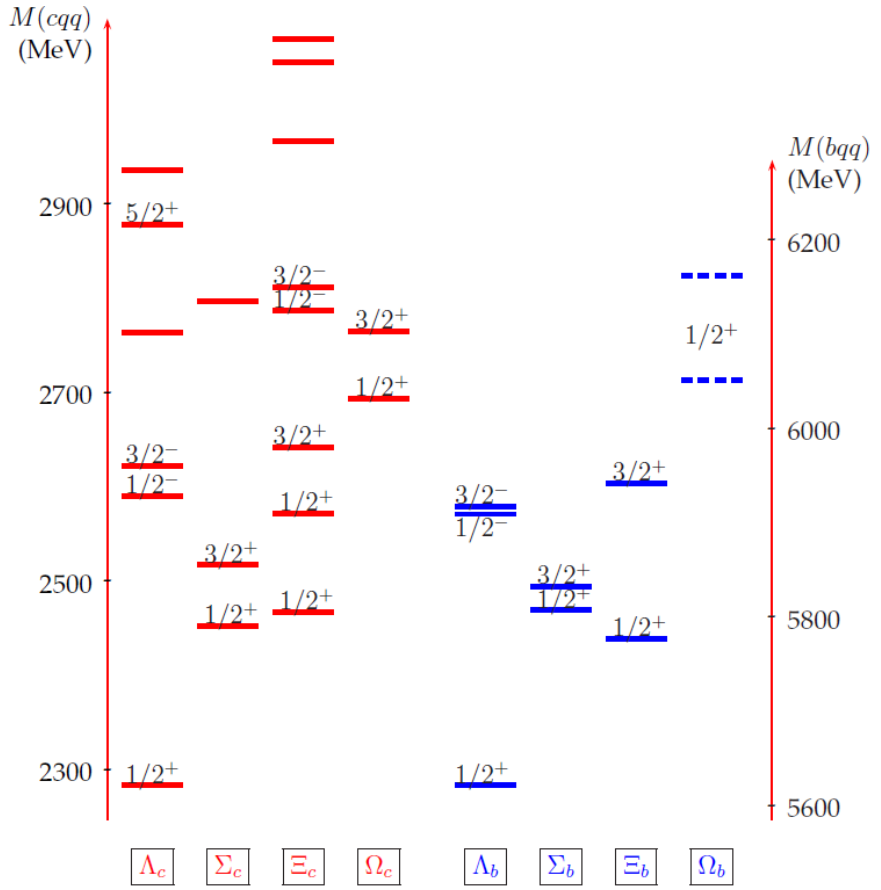
$$M(B^0_{s1}) = (5828.99 \pm 0.08_{\text{stat}} \pm 0.13_{\text{syst}} \pm 0.45_{\text{B mass}})\,\text{MeV}/c^2$$
$$M(B^{*0}_{s2}) = (5839.67 \pm 0.13_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.29_{\text{B mass}})\,\text{MeV}/c^2$$

Heavy baryon spectroscopy

- System of a heavy quark and a light diquark
- States with $L = 0$

		I	j^p	J^P
Λ_c	$c[ud]$	0	0^+	$1/2^+$
Σ_c	cqq	1	1^+	$1/2^+$
Σ_c^*	cqq	1	1^+	$3/2^+$
Ξ_c	csq	1/2	0^+	$1/2^+$
Ξ_c'	csq	1/2	1^+	$1/2^+$
Ξ_c^*	csq	1/2	1^+	$3/2^+$
Ω_c	css	0	1^+	$1/2^+$
Ω_c^*	css	0	1^+	$3/2^+$

- Lowest excited states: $L = 1$ between heavy quark and diquark.
- Higher excitations: $L = 2$, radial excitations, etc.



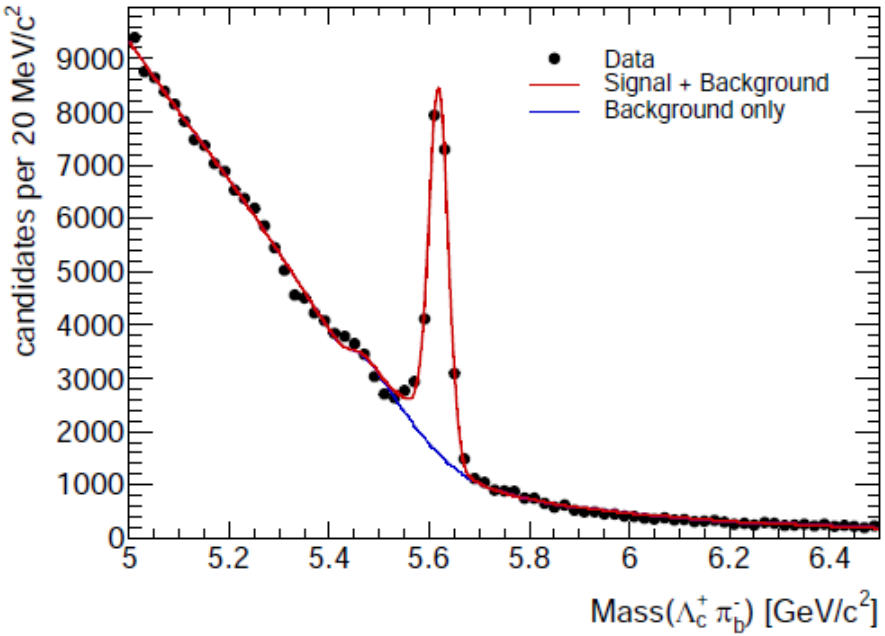
[Image: J.-M. Richard, arXiv:1205.4326]

Large number of charmed baryonic states has been found by BaBar and Belle. Beauty baryons are less well studied. Until recently, only some of the ground states have been seen experimentally.

Ground-state beauty baryons: Λ_b^0 signals

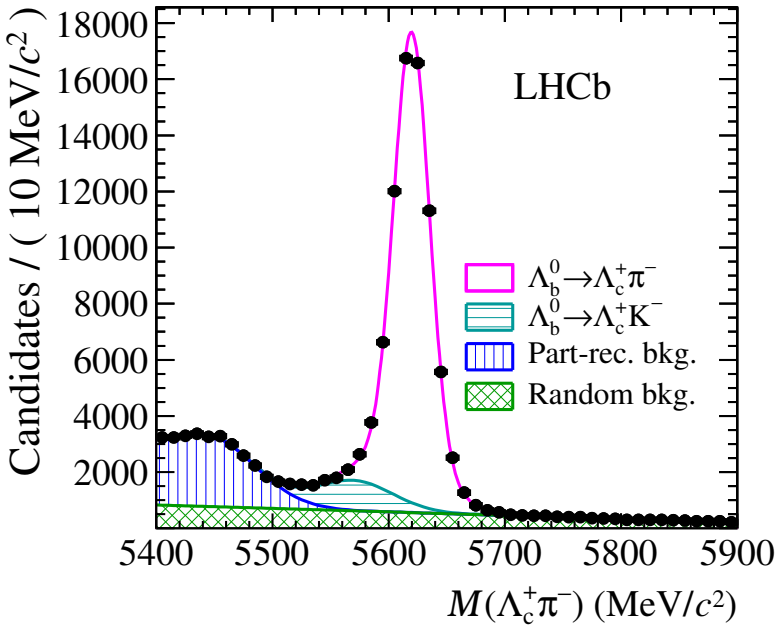
[CDF, arXiv:1112.2808]

- 6 fb^{-1} $p\bar{p}$ data sample
- 19300 signal events
- Purity $S/B \simeq 1.9$



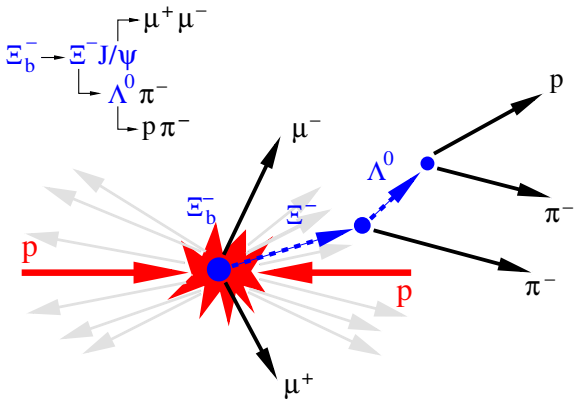
[LHCb, arXiv:1205.3452]

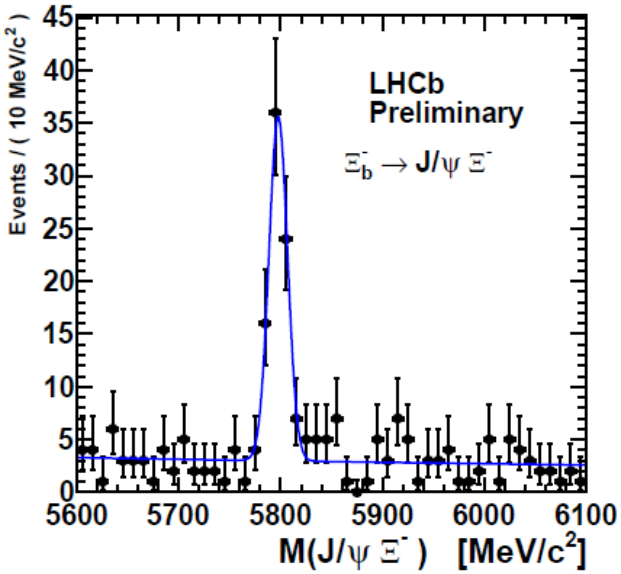
- 1 fb^{-1} pp data sample, $\sqrt{s} = 7$ TeV.
- 70540 ± 330 signal events
- Purity $S/B \simeq 11$

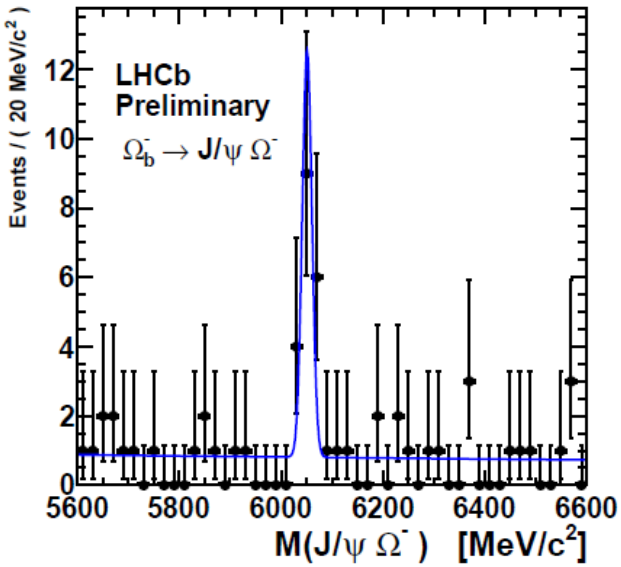


Large and clean signals of ground state b baryons is essential for spectroscopy studies.

- 576 pb^{-1} pp data sample, $\sqrt{s} = 7$ TeV. [LHCb-CONF-2011-060]
- $\Xi_b^- \to J/\psi \Xi^-$, $\Xi^- \to \Lambda^0 \pi^-$, $\Lambda^0 \to p\pi^-$: 72.2 ± 9.4 events
- $\Omega_b^- \to J/\psi \Omega^-$, $\Omega^- \to \Lambda^0 K^-$, $\Lambda^0 \to p\pi^-$: $13.9^{+4.5}_{-3.8}$ events, $> 5\sigma$ significance.







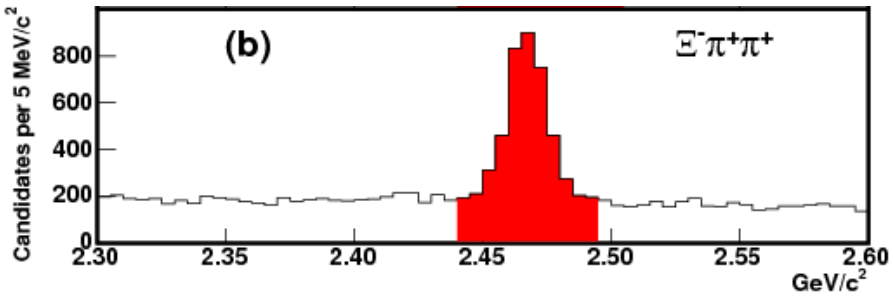
$$M(\Xi_b^-) = 5796.5 \pm 1.2_{\text{stat}} \pm 1.2_{\text{syst}}\ \text{MeV}/c^2$$
$$M(\Omega_b^-) = 6050.3 \pm 4.5_{\text{stat}} \pm 2.2_{\text{syst}}\ \text{MeV}/c^2$$

CDF-D0 inconsistency resolved in favor of CDF.

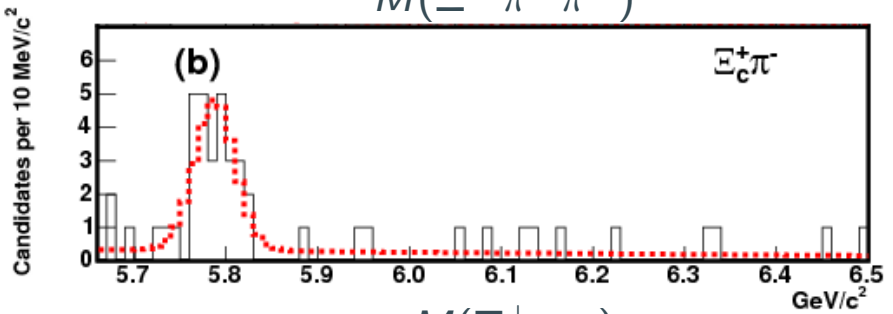
	$M(\Xi_b^-)$, MeV/c^2	$M(\Omega_b^-)$, MeV/c^2
D0	5774 ± 19	6165 ± 16
CDF	5790.9 ± 2.7	6054.4 ± 6.9
PDF	5790.5 ± 2.7	6071 ± 40
LHCb	5796.5 ± 1.7	6050.3 ± 5.0

[CDF, PRL 107(2011)102001]

- 4.2 fb^{-1} $p\bar{p}$ data sample.
- Decay chain: $\Xi_b^0 \to \Xi_c^+ \pi^-$, $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$, $\Xi^- \to \Lambda^0 \pi^-$



$M(\Xi^-\pi^+\pi^+)$

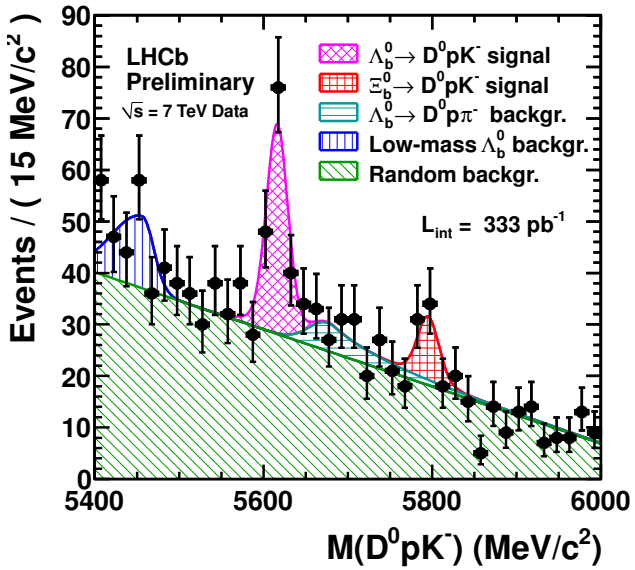


$M(\Xi_c^+\pi^-)$

$M(\Xi_b^0) = 5787.8 \pm 5.0 \pm 1.3$ MeV/c^2
$25.3^{+5.6}_{-5.4}$ signal events, 6.8σ

[LHCb-CONF-2011-036]

- 330 pb^{-1} pp data sample, $\sqrt{s} = 7$ TeV.

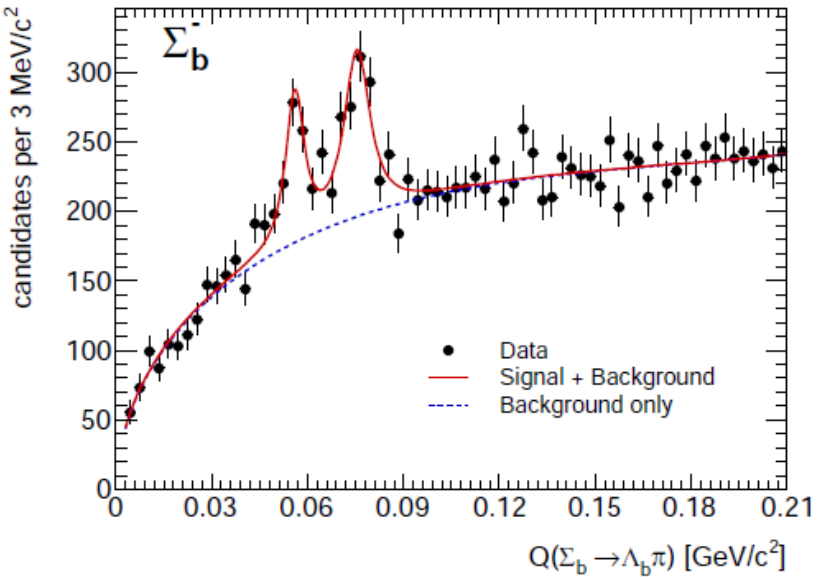


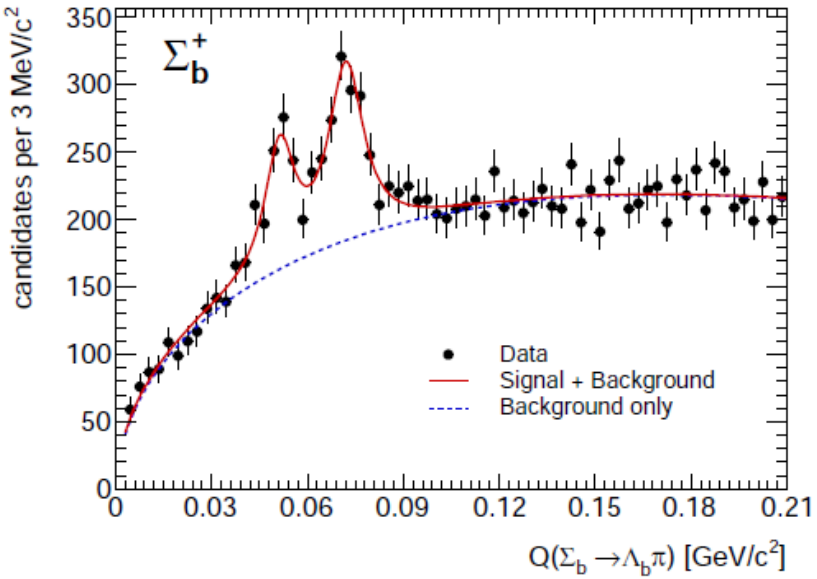
Hint of Ξ_b^0 appeared in D^0pK^- spectrum (the main goal is to study CP violation in $\Lambda_b^0 \to D^0pK^-$).

$N(\Lambda_b^0 \to D^0pK^-) = 92 \pm 15$ events, 6.5σ.
$N(\Xi_b^0 \to D^0pK^-) = 27 \pm 10$ events, 2.6σ.
$M(\Xi_b^0) = 5802.0 \pm 5.5 \pm 1.7$ MeV/c^2.

CDF: Study of $\Sigma_b^{(*)}$ baryons

- 6 fb^{-1} $p\bar{p}$ data sample [CDF, arXiv:1112.2808]
- Λ_b^0 (reconstructed in $\Lambda_c^+\pi^-$) is combined with $\pi^\pm$.



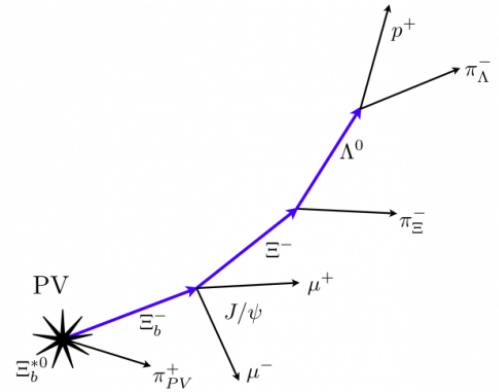


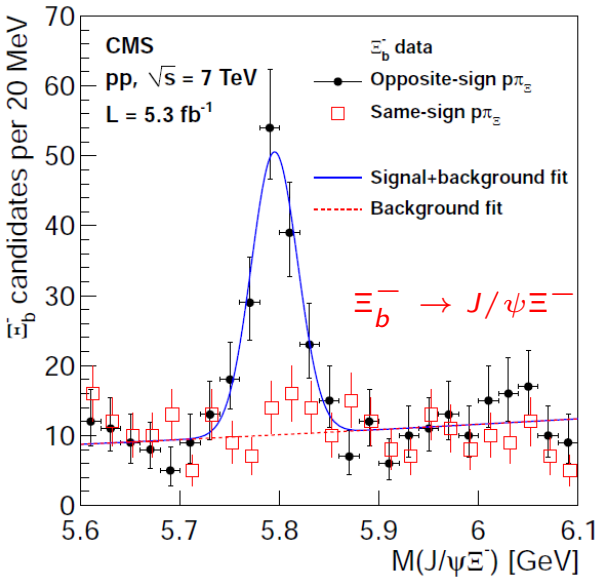
State	Q, MeV/c^2	Mass M, MeV/c^2	Width Γ, MeV
Σ_b^-	$56.2^{+0.6\,+0.1}_{-0.5\,-0.4}$	$5815.5^{+0.6}_{-0.5} \pm 1.7$	$4.9^{+3.1}_{-2.1} \pm 1.1$
Σ_b^{*-}	$75.8 \pm 0.6^{+0.1}_{-0.6}$	$5835.1 \pm 0.6^{+1.7}_{-1.8}$	$7.5^{+2.2\,+0.9}_{-1.8\,-1.4}$
Σ_b^+	$52.1^{+0.9\,+0.1}_{-0.8\,-0.4}$	$5811.3^{+0.9}_{-0.8} \pm 1.7$	$9.7^{+3.8\,+1.2}_{-2.8\,-1.1}$
Σ_b^{*+}	$72.8 \pm 0.7^{+0.1}_{-0.6}$	$5832.1 \pm 0.7^{+1.7}_{-1.8}$	$11.5^{+2.7\,+1.0}_{-2.2\,-1.5}$

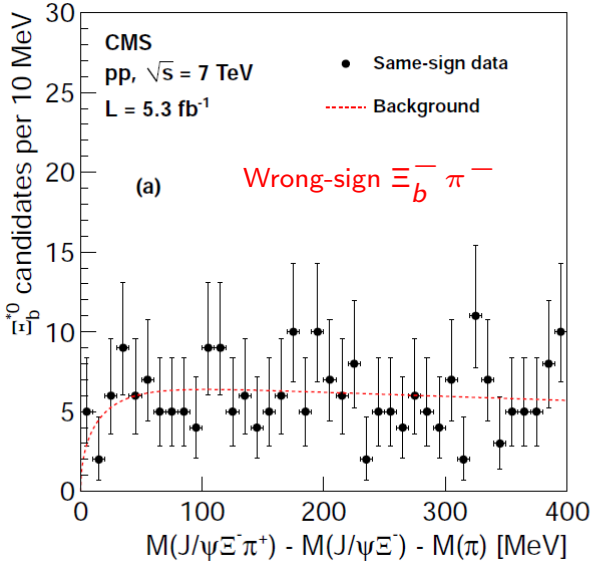
- Neutral states $\Sigma_b^{(*)0}$ remain unobserved: $\Lambda_b^0\pi^0$ final state with soft π^0 is challenging.

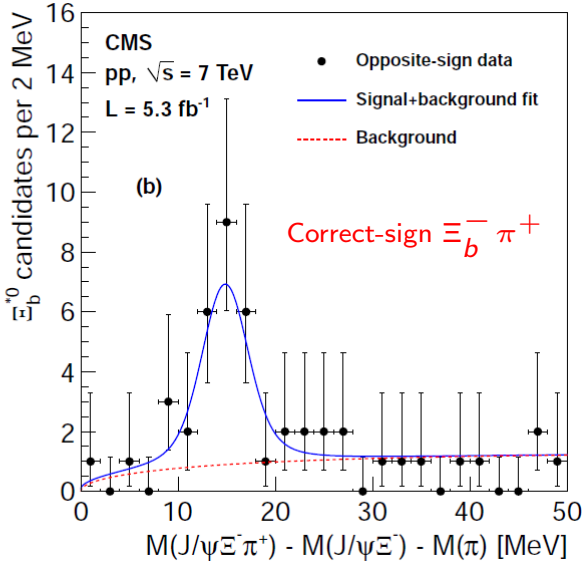
[CMS, arXiv:1204.5955]

- 5.3 fb^{-1} pp dataset with $\sqrt{s} = 7$ TeV.
- Decay chain: $\Xi_b^{*0} \to \Xi_b^- \pi^+$, $\Xi_b^- \to J/\psi \Xi^-$, $\Xi^- \to \Lambda^0 \pi^-$, $\Lambda^0 \to p\pi^-$.
- Ξ_b^-: 108 ± 14 signal events, $M = 5795 \pm 3$ MeV/c^2, $\sigma_M = 24 \pm 3$ MeV/c^2.
- 21 events peak in $\Xi_b^- \pi^+$, significance 5.7σ (for $Q < 50$ MeV window)





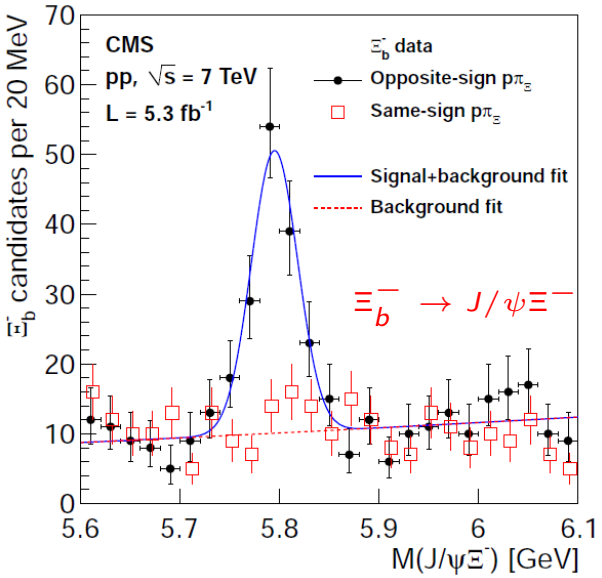


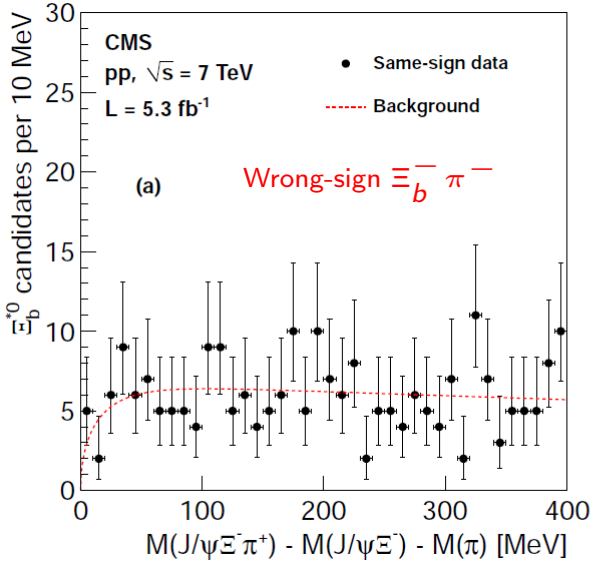


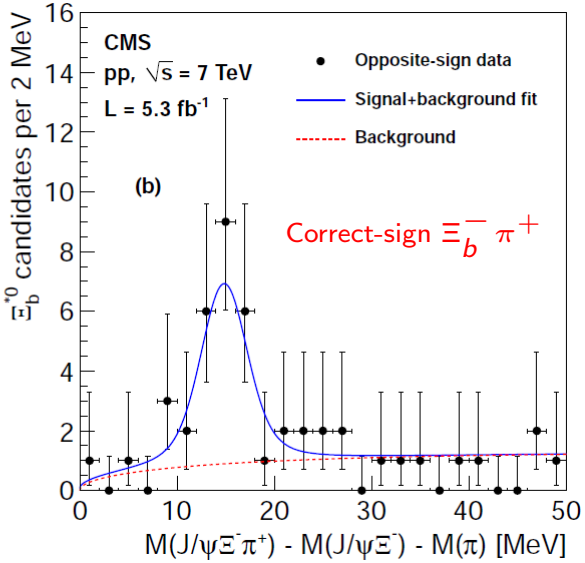
[CMS, arXiv:1204.5955]

$$Q = 14.84 \pm 0.74(\text{stat}) \pm 0.28(\text{syst}) \ \text{MeV}/c^2$$
$$M(\Xi_b^{*0}) = 5945.0 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}) \pm 2.7(\text{PDG}) \ \text{MeV}/c^2$$

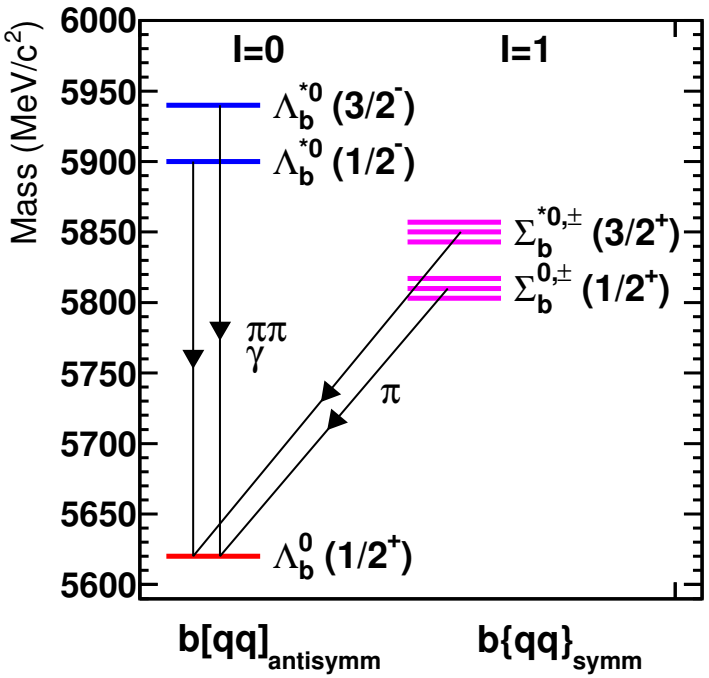
- Interpreted as Ξ_b^{*0}, $J^P = 3/2^+$ state
  ($\Xi_b' \to \Xi_b\pi$ is expected to be below threshold, while Ξ_b^{**} with $L = 1$ and $J^P = 1/2^-$ and $3/2^-$ are forbidden in $\Xi_b\pi$ by parity conservation)







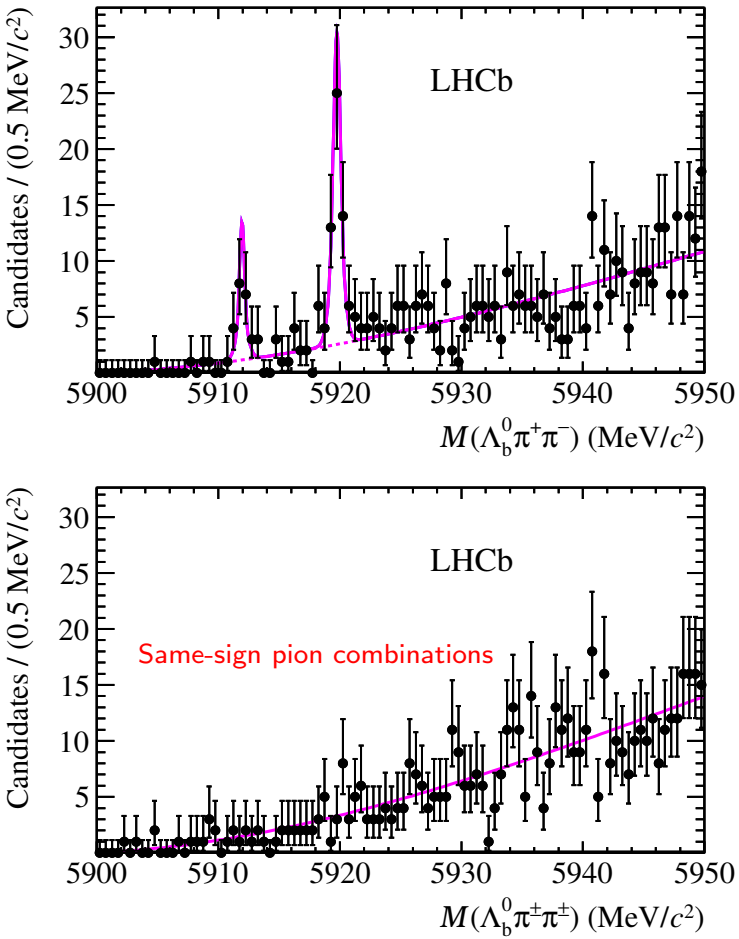
- Excited Λ_b^0 states: two states with $J^P = 1/2^-$ and $3/2^-$
- Orbital excitations with $L = 1$.
- Should decay to $\Lambda_b^0\pi^+\pi^-$ or $\Lambda_b^0\gamma$ depending on mass.
- No experimental evidence was available until now.



Predictions for Λ_b^{*0} masses:

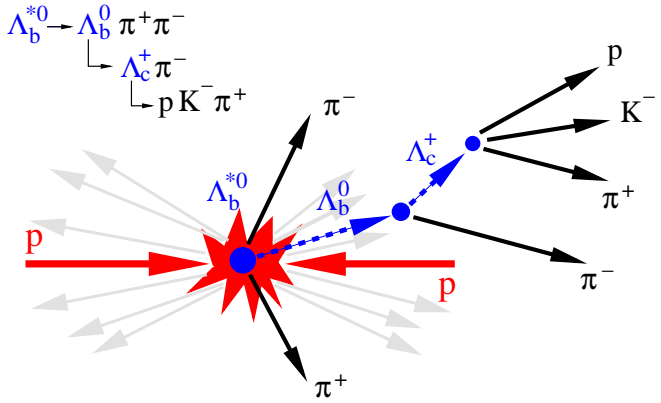
Reference	$M[\Lambda_b^{*0}(1/2^-)]$	$M[\Lambda_b^{*0}(3/2^-)]$
Capstick, Isgur [PRD 34 2809 (1986)]	5912	5920
Baccouche, et al. [hep-ph/0105148]	5920 (spin-averaged)	
Garcilazo, et al. [hep-ph/0703257]	5890	5890
Ebert, et al. [arXiv:0705.2957]	5930	5947
Karliner, et al. [arXiv:0804.1575]	5929 ± 2	5940 ± 2
Roberts, Pervin [arXiv:0711.2492]	5939	5941

Most predictions are above $\Lambda_b^0\pi\pi$ (5900 MeV/c^2) but below $\Sigma_b\pi$ (around 5950 MeV/c^2).



[LHCb, arXiv:1205.3452]

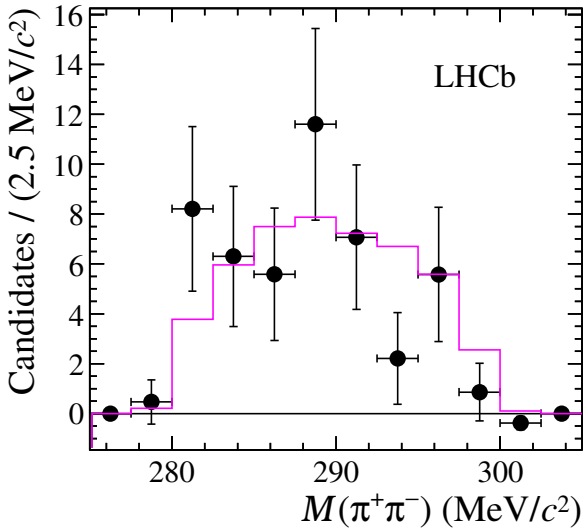
- 1 fb^{-1} pp data sample, $\sqrt{s} = 7$ TeV.
- $\Lambda_b^0 \to \Lambda_c^+\pi^+$, $\Lambda_c^+ \to pK^-\pi^+$ combined with a pair of pions from the primary vertex.



- Kinematic fit with vertex and mass constraints on Λ_b^0 and Λ_c^+.
- Two peaks are evident with masses around 5912 MeV/c^2 (16.4 ± 4.7 events, 4.9σ), 5920 MeV/c^2 (49.5 ± 7.9 events, 10.1σ).
- Remarkably good mass resolution due to kinematic fit and proximity of threshold: $\sigma_M \simeq 0.2 - 0.3$ MeV/c^2.

LHCb: Observation of excited Λ_b^0 baryons

[LHCb, arXiv:1205.3452]



Invariant mass of $\pi^+\pi^-$ from $\Lambda_b^{*0}(5920) \to \Lambda_b^0\pi^+\pi^-$. Consistent with phase-space decay.

$$M_{\Lambda_b^{*0}(5912)} = 5911.95 \pm 0.12 \pm 0.03_{\rm syst} \pm 0.66_{\Lambda_b^0 \text{ mass}}\ {\rm MeV}/c^2$$
$$M_{\Lambda_b^{*0}(5920)} = 5919.76 \pm 0.07 \pm 0.02_{\rm syst} \pm 0.66_{\Lambda_b^0 \text{ mass}}\ {\rm MeV}/c^2$$
$$\Delta M_{\Lambda_b^{*0}(5912)} = 292.58 \pm 0.12_{\rm stat} \pm 0.05_{\rm syst}\ {\rm MeV}/c^2$$
$$\Delta M_{\Lambda_b^{*0}(5920)} = 300.39 \pm 0.07_{\rm stat} \pm 0.04_{\rm syst}\ {\rm MeV}/c^2$$

Limits on natural width (95% CL):

$$\Gamma_{\Lambda_b^{*0}(5912)} < 0.82\ {\rm MeV}$$
$$\Gamma_{\Lambda_b^{*0}(5920)} < 0.71\ {\rm MeV}$$

- First observation of orbitally-excited b baryons ($L > 0$)
- Masses are only slightly above $\Lambda_b^0\pi^+\pi^-$ threshold ($Q = 12, 20$ MeV). Well below $\Sigma_b^0\pi$ threshold.

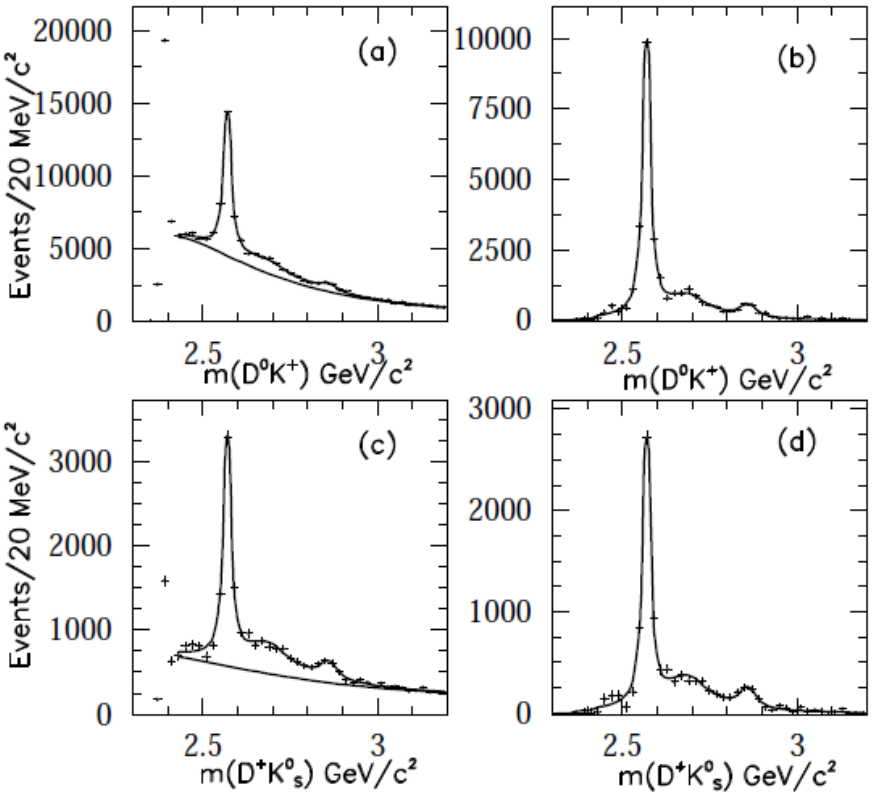
Conclusion

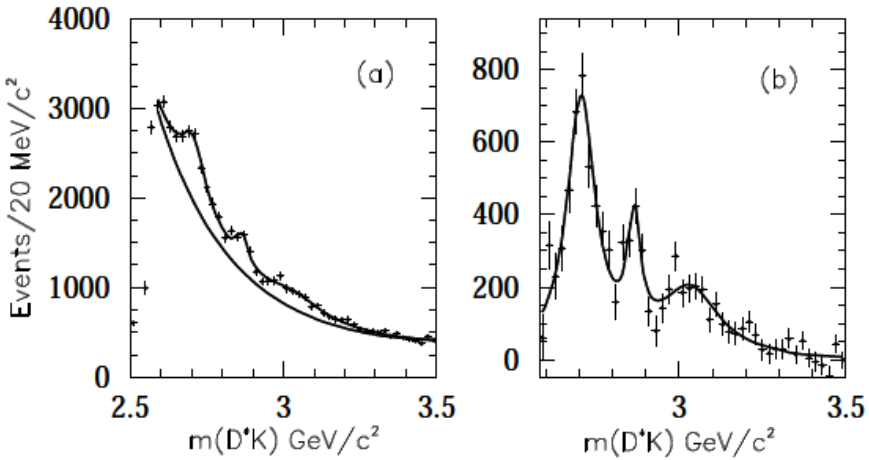
- Recent progress on open charm and beauty spectroscopy is coming mostly from experiments at hadron machines: CDF, LHCb and CMS.
- LHCb has entered the game in the field of charm meson spectroscopy: first presentation of measurements of D_{sJ} states in DK spectrum. Belle and BaBar observations of $D^*_{s1}(2710)^+$ and $D^*_{sJ}(2860)^+$ confirmed, parameters are consistent.
- Orbitally-excited B mesons by LHCb: confirmed $B^{**0}_{(s)}$ states, first measurement of $B^{**\pm}$ states.
- A lot of progress recently on beauty baryons:
  - Observation of Ξ_b^0 by CDF, the last weakly-decaying beauty baryon.
  - Observation of excited Ξ_b^0 by CMS.
  - Observation of excited Λ_b^0 by LHCb: the first orbital excitation in beauty baryons.

  Expect more new results soon.

BaBar: Study of DK and D^*K spectra

[BaBar, PRD 80, 092003 (2009)]

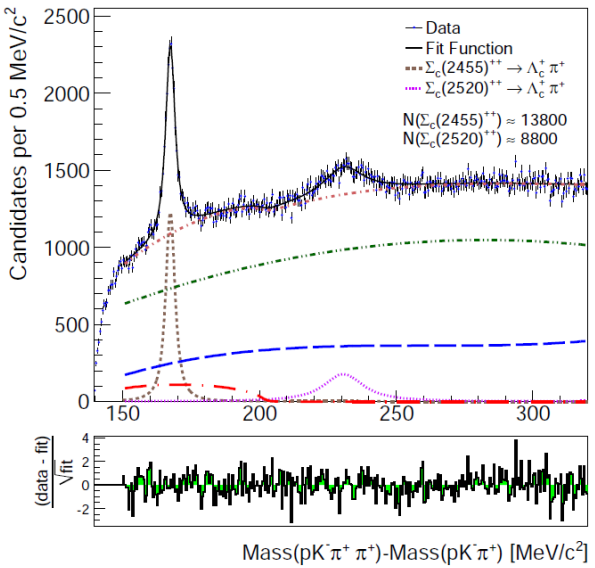


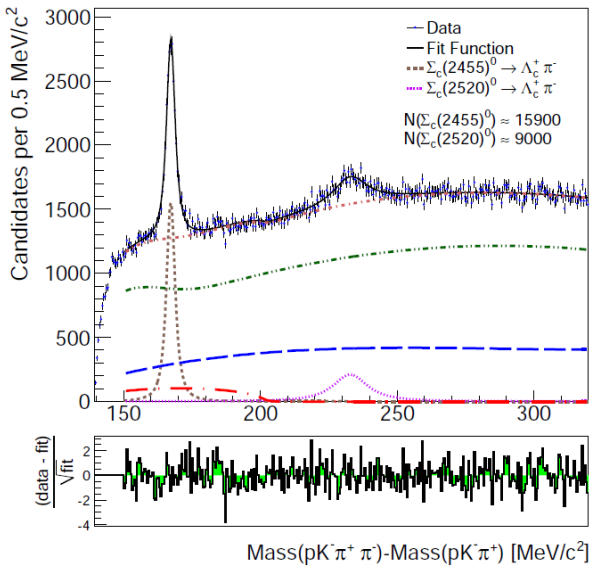


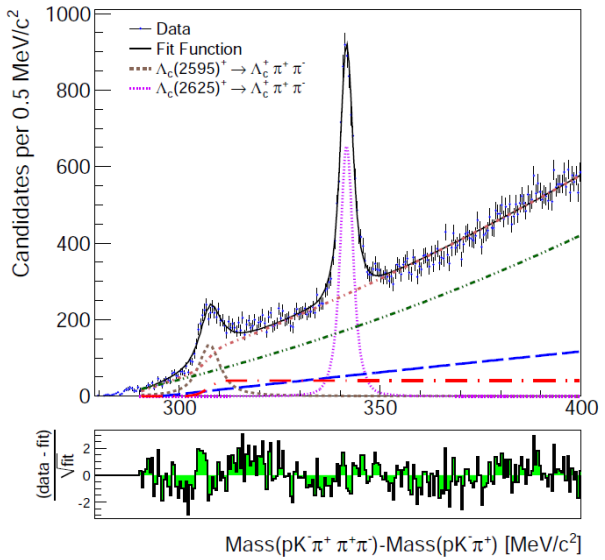
		$D_{s1}^*(2710)^+$	$D_{sJ}^*(2860)^+$	$D_{sJ}(3040)^+$
DK	Mass, MeV/c^2	2710.0 ± 3.3	2860.0 ± 2.3	
	Width, MeV	178 ± 19	53 ± 6	
D^*K	Mass, MeV/c^2	2712 ± 3	2865.2 ± 3.5	3042 ± 9
	Width, MeV	103 ± 8	44 ± 8	214 ± 34

CDF: Study of Λ_c and Σ_c baryons

[CDF, PRD 84 (2011) 012003]







Hadron	M [MeV/c^2]	Γ [MeV/c^2]
$\Sigma_c(2455)^{++}$	$2453.90 \pm 0.13 \pm 0.14$	2.34 ± 0.47
$\Sigma_c(2455)^0$	$2453.74 \pm 0.12 \pm 0.14$	1.65 ± 0.50
$\Sigma_c(2520)^{++}$	$2517.19 \pm 0.46 \pm 0.14$	15.03 ± 2.52
$\Sigma_c(2520)^0$	$2519.34 \pm 0.58 \pm 0.14$	12.51 ± 2.28
$\Lambda_c(2595)^+$	$2592.25 \pm 0.24 \pm 0.14$	$h_2^2 = 0.36 \pm 0.08$
$\Lambda_c(2625)^+$	$2628.11 \pm 0.13 \pm 0.14$	< 0.97 at 90% C.L.