New Results on Bottom Baryons $\Sigma_b^{(*)\pm}$ with the CDF II Detector

Igor V. Gorelov
(On behalf of the CDF Collaboration)

Department of Physics & Astronomy,
University of New Mexico, USA

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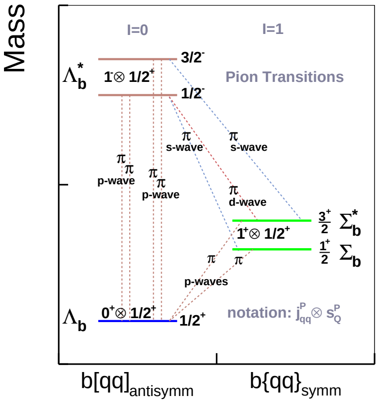
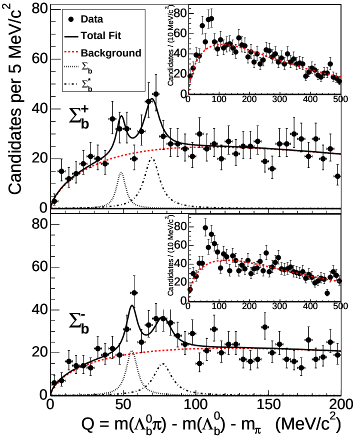
Motivation

- Measurements of masses/widths of heavy baryons provide input to critical tests for different non-perturbative QCD approaches to a spectroscopy of bottom hadron states
  - HQET framework
  - Potential models
  - $1/N_c$ expansion methods
  - and finally several large scale projects on Lattice QCD calculations
- The measurement of widths provides the insight into a dynamical aspect of bottom baryon resonances governed by strong forces. The comparison of our width measurements with few available theoretical calculations of widths for bottom baryon resonances will certainly stimulate further theoretical study.
- **Goal of the analysis: confirm the observation of discovered $\Sigma_b^{(*)\pm}$ states with a data driven method and measure their resonance properties.**

Published Discovery (Sep 2006) on Heavy Baryons Σ_b and Σ_b^* with CDF II





$Q = M(\Lambda_b^0 \pi_{soft}) - M(\Lambda_b^0) - m(\pi^\pm)$

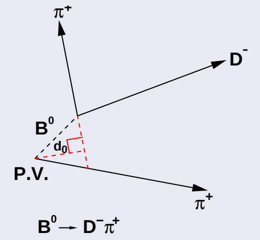
...was based on $\int \mathcal{L}\, dt = 1.1\, fb^{-1}$

- PRL **99**, 202001 (2007)
- *SPIRES topcite 50+ paper*

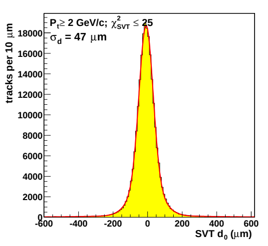
b- Triggers at @1.96 TeV

- Enormous inelastic total cross-section of $\sigma_{\mathbf{tot}}^{\mathbf{inel}} \sim \mathbf{60}\,\mathrm{mb}$ at Tevatron.
- $\sigma_{\mathbf{b}} \approx \mathbf{20}\,\mu\mathrm{b}\,(|\eta| < \mathbf{1.0})$, **@1.96 TeV** to compare with
  - $e^+e^- \to \Upsilon(4S) \approx 1\ \mathrm{nb}$ (only B^0, B^+)
  - $e^+e^- \to Z^0 \approx 7\ \mathrm{nb}$
- Selective three-level triggers
- **Trigger on Hadron Modes: CDF Two Track Trigger .**
  - Exploit “long” $c\tau$(b-hadrons)
  - Trigger on $\geq$ 2 tracks with large $|d_0|$.

Displaced Track: π^+

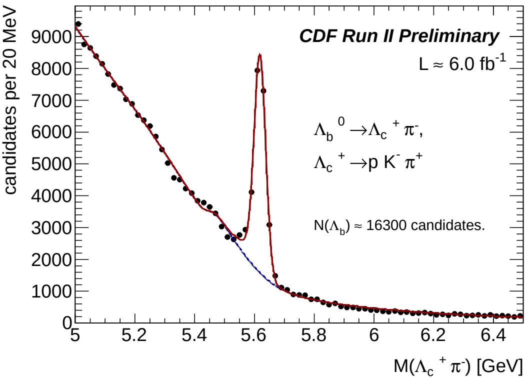


$|d_0|$ Resolution $\oplus$ beam-line = 47 μm



Analysis Criteria

- Luminosity of $\int \mathcal{L}\, dt \approx 6.0\,\mathrm{fb}^{-1}$
- Data collected by CDF **Two Track Trigger**
- Reconstruct inclusive base Λ_b^0 signal as $M(\Lambda_b^0 \to \Lambda_c^+ \pi_b^-)$ with $\Lambda_c^+ \to pK^-\pi^+$, applying vertex fits both to Λ_c^+ and Λ_b^0.
- Combine Λ_b^0 signal candidates with soft pions to reconstruct $\Sigma_b^{(*)\pm} \to \Lambda_b^0 \pi_{soft}^{\pm}$ candidates.



- $c\tau(\Lambda_b^0)/\sigma_{c\tau} > 12.0$
- $p_T(\pi_b^-) > 1.5\,\mathrm{GeV}/c$ $N(\Lambda_b^0) \approx 16300$
- $p_T(\pi_{soft}^{\pm}) > 0.2\,\mathrm{GeV}/c$, very loose.
- $|d_0/\sigma_{d_0}|(\pi_{soft}^{\pm}) < 3.0$, w.r.t. primary VX.

Signal Model

We reconstruct $\Sigma_b^{(*)\pm}$ candidates in a mass difference spectrum: Q-value

$$Q = M(\Sigma_b^{(*)} \to \Lambda_b^0 \pi_{soft}^{\pm}) - M(\Lambda_b^0) - m(\pi^{\pm})_{PDG} \quad (1)$$

Improved resolution as Λ_b^0 contribution and many systematic uncertainties get canceled leaving only $\pi_{soft}^{\pm}$ contribution.

- The signal is described by non-relativistic Breit-Wigner function
  - convoluted with a double Gaussian to model the detector resolution: σ_1, σ_2 and fraction f_1 are fixed from MC.
  - the width of the Breit-Wigner is modified by P-wave factor: width is variable.

B.-W. width modified by P-wave factor: $\pi_{soft}^{\pm}$ emitted in a P-wave.

$$\Gamma(Q; Q_0, \Gamma_0) = \Gamma_0 \cdot \left(\frac{p_{\pi}^{*}}{p_{\pi}^{*0}}\right)^3 \quad (2)$$

Background Model and Complete Fitter

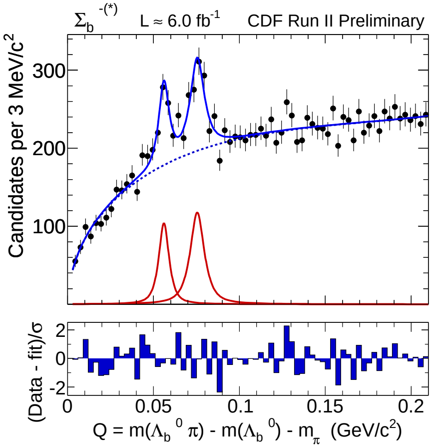
Phase space motivated background.

$$\mathcal{BGR}(Q; thr, C, b_1, b_2) = \sqrt{(Q+m_\pi)^2 - thr^2} \cdot \left(C + b_1 \cdot Q + b_2 \cdot (2 \cdot Q^2 - 1)\right) \quad (3)$$

- parameter fixed to $thr = 0.140$

- Each charge state spectrum, $\Sigma_b^{(*)-}$ and $\Sigma_b^{(*)+}$, fit independently to measure its properties.
- The independent fits are an essential improvement w.r.t. to discovery analysis published in 2007
- Unbinned fitter with extended LH: $2 \times 3 + 3 = 9$ floating parameters in total.

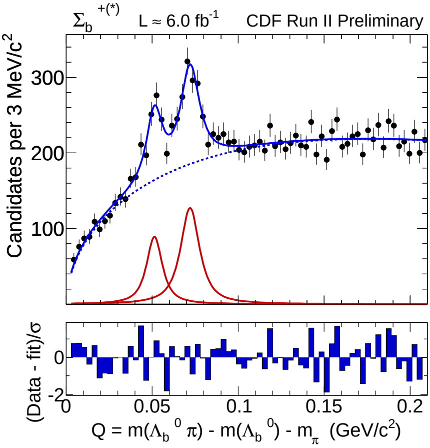
Q- Spectrum and Results: $\Sigma_b^{(*)-}$



The projection of the unbinned LH fit onto the binned Q- distribution of $\Sigma_b^{(*)-}$ candidates.

Σ_b^- and Σ_b^{*-}	
Parameters	**Value**, MeV/c^2
Q_0, pole Σ_b^-	$56.2^{+0.6}_{-0.5}$
Q_0^*, pole Σ_b^{*-}	75.7 ± 0.6
Γ_0, width Σ_b^-	$4.3^{+3.1}_{-2.1}$
Γ_0^*, width Σ_b^{*-}	$6.4^{+2.2}_{-1.8}$
Parameters	**Value**, evts
N_s, yield Σ_b^-	333^{+93}_{-73}
N_s^*, yield Σ_b^{*-}	522^{+85}_{-76}

Q- Spectrum and Results: $\Sigma_b^{(*)+}$



The projection of the unbinned LH fit onto the binned Q- distribution of $\Sigma_b^{(*)+}$ candidates.

Σ_b^+ and Σ_b^{*+}	
Parameters	**Value**, MeV/c^2
Q_0, pole Σ_b^+	$52.0^{+0.9}_{-0.8}$
Q_0^*, pole Σ_b^{*+}	72.7 ± 0.7
Γ_0, width Σ_b^+	$9.2^{+3.8}_{-2.9}$
Γ_0^*, width Σ_b^{*+}	$10.4^{+2.7}_{-2.2}$
Parameters	**Value**, evts
N_s, yield Σ_b^+	468^{+110}_{-95}
N_s^*, yield Σ_b^{*+}	782^{+114}_{-103}

Significance of the Signals: $\Sigma_b^{(*)-}$ and $\Sigma_b^{(*)+}$

Null Hypothesis	$-2 \cdot \Delta(\log \mathcal{L})$	Δndf	Prob(χ^2)	N_σ	Comment
			Σ_b^-, Σ_b^{*-} Signals		
Any single peak	$-2 \cdot (-32.0)$	3	$\approx 8.2 \cdot 10^{-14}$	7.5	w.r.t. doub. peak
No signal	$-2 \cdot (-55.0)$	3	$\approx 1.1 \cdot 10^{-23}$	10.0	w.r.t. single peak
No signal	$-2 \cdot (-87.0)$	6	$\approx 6.4 \cdot 10^{-35}$	12.3	w.r.t. doub. peak
			Σ_b^+, Σ_b^{*+} Signals		
Any single peak	$-2 \cdot (-30.0)$	3	$\approx 5.9 \cdot 10^{-13}$	7.2	w.r.t. doub. peak
No signal	$-2 \cdot (-79.0)$	3	$\approx 4.9 \cdot 10^{-34}$	12.2	w.r.t. singl. peak
No signal	$-2 \cdot (-109.0)$	6	$\approx 2.8 \cdot 10^{-44}$	14.0	w.r.t. doub. peak

Tests of the baseline fit hypothesis against several null hypotheses.
Robust significance above Gaussian 7.0σ.

Systematics Uncertainties

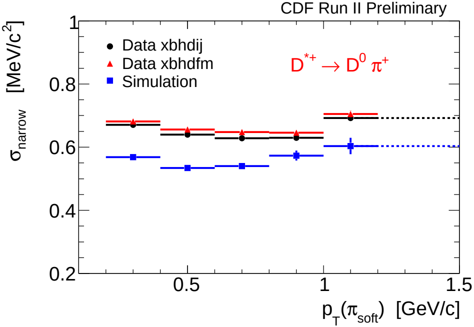
- Mass Scale: B field knowledge, uncertainties of dE/dx corrections to the momentum scale.
- Detector resolution model and its parameters.
- Choice of a Background Model.
- Fit procedure.
- Systematics propagated from the external source:

$$M(\Lambda_b^0) = 5619.7 \pm 1.2(\mathrm{stat}) \pm 1.2(\mathrm{syst}),\ \mathrm{MeV}/c^2$$

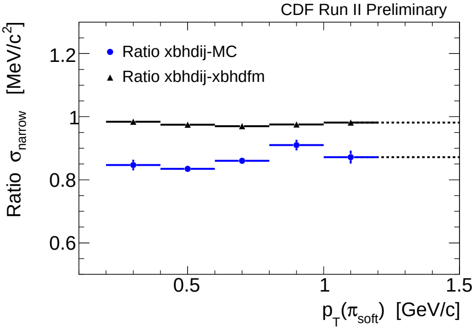
taken from CDF published results.

Resolution studies with D^{*+} as a reference

Detector resolution is a critical parameter for our measurements especially for the fits of natural widths.. D^{*+} is a good candle, has a similar $p_T(\pi_{soft})$ spectrum but very narrow intrinsic width.



Fitted Gaussian σ of D^{*+}: various data taking periods w.r.t. MC prediction.



Conservative 25% is included into systematics uncertainties

Systematics Uncertainties

Signal Pars.	Mass Scale	Fit Procedure	Res.	Back.	Total	%
Σ_b^+ Q	-0.35		0.07 -0.12	0.05 -0.05	0.09 -0.37	0.2 1
Σ_b^+ Γ	0.20 -0.20	-0.38	0.94 -0.89	0.40 -0.40	1.04 -1.07	11 12
Σ_b^+ events			16 -11	9 -9	18 -15	4 3
Σ_b^- Q	-0.38		0.05 -0.07	0.04 -0.04	0.07 -0.39	0.1 1
Σ_b^- Γ	0.20 -0.20	-0.27	0.85 -0.87	0.50 -0.50	1.01 -1.06	23 25
Σ_b^- events			9 -8	34 -34	35 -35	11 10
Σ_b^{*+} Q	-0.52		0.06 -0.13	0.10 -0.10	0.12 -0.55	0.2 1
Σ_b^{*+} Γ	0.20 -0.20	-0.29	0.64 -1.01	0.50 -0.50	0.83 -1.18	8 11
Σ_b^{*+} events			7 -13	24 -24	25 -27	3 4
Σ_b^{*-} Q	-0.56		0.06 -0.08	0.06 -0.06	0.08 -0.57	0.1 1
Σ_b^{*-} Γ	0.20 -0.20	-0.23	0.65 -0.96	0.30 -0.30	0.74 -1.05	12 16
Σ_b^{*-} events			7 -8	28 -28	29 -29	6 6

Summary on Q and Γ Results

Mass Difference and Natural Widths Measurements with $\int \mathcal{L}\, dt \approx 6\,\text{fb}^{-1}$.

State	Q_0, MeV/c^2	Γ_0, MeV/c^2
Σ_b^+	$52.0^{+0.9}_{-0.8}(\text{stat})^{+0.09}_{-0.4}(\text{syst})$	$9.2^{+3.8}_{-2.9}(\text{stat})^{+1.0}_{-1.1}(\text{syst})$
Σ_b^{*+}	$72.7 \pm 0.7(\text{stat})^{+0.12}_{-0.6}(\text{syst})$	$10.4^{+2.7}_{-2.2}(\text{stat})^{+0.8}_{-1.2}(\text{syst})$
Σ_b^-	$56.2^{+0.6}_{-0.5}(\text{stat})^{+0.07}_{-0.4}(\text{syst})$	$4.3^{+3.1}_{-2.1}(\text{stat})^{+1.0}_{-1.1}(\text{syst})$
Σ_b^{*-}	$75.7 \pm 0.6(\text{stat})^{+0.08}_{-0.6}(\text{syst})$	$6.4^{+2.2}_{-1.8}(\text{stat})^{+0.7}_{-1.1}(\text{syst})$

Isospin Mass Splitting in Σ_b and Σ_b^* $I = 1$ Isotriplets.

State	ΔM^{+-}, MeV/c^2
$\Sigma_b^+ - \Sigma_b^-$	$-4.2^{+1.1}_{-0.9}(\text{stat})^{+0.07}_{-0.09}(\text{syst})$
$\Sigma_b^{*+} - \Sigma_b^{*-}$	$-3.0 \pm 0.9\,(\text{stat})^{+0.12}_{-0.13}(\text{syst})$

Summary on Absolute Masses

Results on Absolute Masses with $\int \mathcal{L}\, dt \approx 6\,\text{fb}^{-1}$.

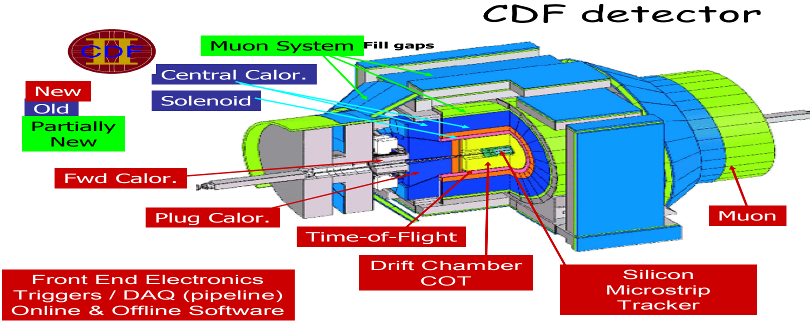
State	M, MeV/c^2
Σ_b^+	$5811.2^{+0.9}_{-0.8}\,(\text{stat}) \pm 1.7\,(\text{syst})$
Σ_b^{*+}	$5832.0 \pm 0.7\,(\text{stat}) \pm 1.8\,(\text{syst})$
Σ_b^-	$5815.5^{+0.6}_{-0.5}\,(\text{stat}) \pm 1.7\,(\text{syst})$
Σ_b^{*-}	$5835.0 \pm 0.6\,(\text{stat}) \pm 1.8\,(\text{syst})$

To determine the absolute masses for $\Sigma_b^{(*)\pm}$,
$m(\Lambda_b^0) = 5619.7 \pm 1.2\,(\text{stat}) \pm 1.2\,(\text{syst}),\ \text{MeV}/c^2$ (CDF II).

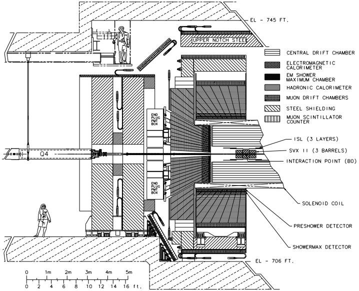
Conclusions

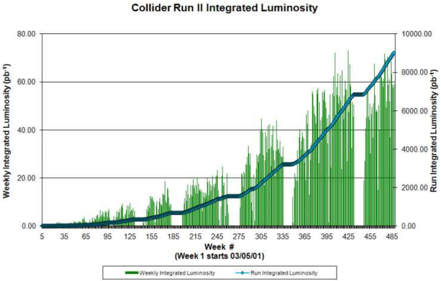
- The first observation of $\Sigma_b^{(*)\pm}$ bottom baryons made by CDF Collaboration (Sep 2006) is **confirmed: all signals are significant with** $\gtrsim 7\sigma$ in Gaussian terms.
- The **direct mass difference measurements** have been found with the statistical precision by a factor of $\gtrsim 2.3$ better w.r.t. to the published (CDF) numbers and according to the amount of the available statistics with $\int \mathcal{L}\, dt \approx 6\,\mathrm{fb}^{-1}$.
    - The measurements are in agreement with the published CDF results
- **The isospin mass splitting** within isotriplets Σ_b and Σ_b^* is measured for the **first time.**
- **The natural widths** of both $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ are measured for the **first time.**
    - The measurements are in a good agreement with the theoretical predictions made by Korner *et al.*, *arXiv:hep-ph/9406359*, by Guo *et al.*, *arXiv:0710.1474 [hep-ex]*.

Backup Slides



- Critical: COT (central tracker), Si vertex detector (SVX II)
- Muon system.





- **CDF II** detector at Tevatron
- Critical for *this* analysis: Si vertexing with SVX II
- Critical for *this* analysis: central tracker, COT

- p and $\overline{p}$ beams
- $36 \times 396\,\mathrm{ns}$ bunches with $E_{beam} = 980\,\mathrm{GeV}$
- collisions in **CDF II** and in **DØ**
- $\int \mathcal{L}\,dt \gtrsim 9.0\,\mathrm{fb}^{-1}$ delivered.
- $\int \mathcal{L}\,dt \gtrsim 7.5\,\mathrm{fb}^{-1}$ on tape, accessible for **CDF II**.

Fitter: unbinned, $-\log(\text{likelihood})$, extended.

The full model for $Q-$value spectra of every isospin partner state $\Sigma_b^{(*)+}$, $\Sigma_b^{(*)-}$ describes two peaks sitting on top of a smooth background with a threshold behavior:

$$
\begin{aligned}
-\log(\mathcal{L}) \quad = \quad & -\sum_{k=1}^{N_{obs}} \log(N_{s1} \cdot \mathcal{S}_1 + N_{s2} \cdot \mathcal{S}_2 + N_b \cdot \mathcal{BGR}) \\
& +(N_{s1} + N_{s2} + N_b) \\
& -N_{obs} \cdot \log(N_{s1} + N_{s2} + N_b)
\end{aligned}
$$

- NLL constructed individually per Σ_b^+ and Σ_b^{*+}
- The fits over unbinned ensemble of experimental $Q-$value, $Q_k \binom{N_{obs}}{k=1}$ are performed for every charge state separately.
- 9 floating parameters: 2×3 (signals) $+3$ (background)
- CPU timing: 10 minutes (2.8KHz core)/spectrum, with MINOS error calculation activated.

Significance of the Signals: $\Sigma_b^{(*)-}$

Null Hypothesis	$-2 \cdot \Delta(\log \mathcal{L})$	Δndf	Prob(χ^2)	N_σ	Comment
Any single peak	$-2 \cdot (-32.0)$	3	$\approx 8.2 \cdot 10^{-14}$	7.5	w.r.t. doub. peak
No Σ_b^-, **with** Σ_b^{*-}	$-2 \cdot (-35.0)$	4	$\approx 2.3 \cdot 10^{-14}$	7.6	w.r.t. doub. peak $\Gamma_{02} = 12\,\mathrm{M}$
No Σ_b^{*-}, **with** Σ_b^-	$-2 \cdot (-57.0)$	4	$\approx 1.0 \cdot 10^{-23}$	10.0	w.r.t. doub. peak $\Gamma_{01} = 7\,\mathrm{Me}$
No any signal	$-2 \cdot (-55.0)$	3	$\approx 1.1 \cdot 10^{-23}$	10.0	w.r.t. single peak
No any signal	$-2 \cdot (-87.0)$	6	$\approx 6.4 \cdot 10^{-35}$	12.3	w.r.t. doub. peak

Tests of the baseline fit results against several null hypotheses.
Robust significance above Gaussian 7.0σ.

Significance of the Signals: $\Sigma_b^{(*)+}$

Null Hypothesis	$-2 \cdot \Delta(\log \mathcal{L})$	$\Delta\mathrm{ndf}$	$\mathrm{Prob}(\chi^2)$	N_σ	Comment
Any single peak	$-2 \cdot (-30.0)$	3	$\approx 5.9 \cdot 10^{-13}$	7.2	w.r.t. doub. peak
No Σ_b^+, **with** Σ_b^{*+}	$-2 \cdot (-33.0)$	4	$\approx 1.6 \cdot 10^{-13}$	7.4	w.r.t. doub. peak
No Σ_b^{*+}, **with** Σ_b^+	$-2 \cdot (-84.0)$	4	$\approx 2.8 \cdot 10^{-35}$	12.4	$\Gamma_{02} = 12\,\mathrm{M}$ w.r.t. doub. peak
No any signal	$-2 \cdot (-79.0)$	3	$\approx 4.9 \cdot 10^{-34}$	12.2	$\Gamma_{01} = 7\,\mathrm{Me}$ w.r.t. singl. peak
No any signal	$-2 \cdot (-109.0)$	6	$\approx 2.8 \cdot 10^{-44}$	14.0	w.r.t. doub. peak

Tests of the baseline fit results against several null hypotheses.
Robust siginificance above Gaussian 7.0σ.

First Observation of $\Sigma_b^{(*)\pm}$ by CDF Collaboration (Sep 2006)

Results on Mass Measurements and Yields

State	Yield	Q or $\Delta_{\Sigma_b^*}$ (MeV/c^2)	Mass (MeV/c^2)
Σ_b^+	32^{+13+5}_{-12-3}	$Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3}$	$5807.8^{+2.0}_{-2.2} \pm 1.7$
Σ_b^-	59^{+15+9}_{-14-4}	$Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2$	$5815.2 \pm 1.0 \pm 1.7$
Σ_b^{*+}	77^{+17+10}_{-16-6}	$\Delta_{\Sigma_b^*} = 21.2^{+2.0+0.4}_{-1.9-0.3}$	$5829.0^{+1.6+1.7}_{-1.8-1.8}$
Σ_b^{*-}	69^{+18+16}_{-17-5}		$5836.4 \pm 2.0^{+1.8}_{-1.7}$
Λ_b^0	3180 ± 60		

The combined 4-peak, $\Sigma_b^{(*)\pm}$, signal significance w.r.t. to null (no any peak, background only) hypothesis exceeds 5.2 Gaussian σ.