First Observation of Bottom Baryon Σ_b States at CDF

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On behalf of

CDF Collaboration

P-25 Seminar

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1 – Outline

- Introduction: Heavy Baryons with HQET.
- Experimental Status.
- Principle of an Analysis.
- b-Physics at Tevatron with CDF II detector.
- CDF II Triggers and Datasets involved.
  - $\surd$ Λ_b^0 base signal.
  - $\surd$ Reconstruction of Σ_b Candidates - Blind.
  - $\surd$ Opened Box.
  - $\surd$ Fits.
  - $\surd$ Systematics.
  - $\surd$ Significance.
- Summary.

2 – Multiplets of Heavy Baryons

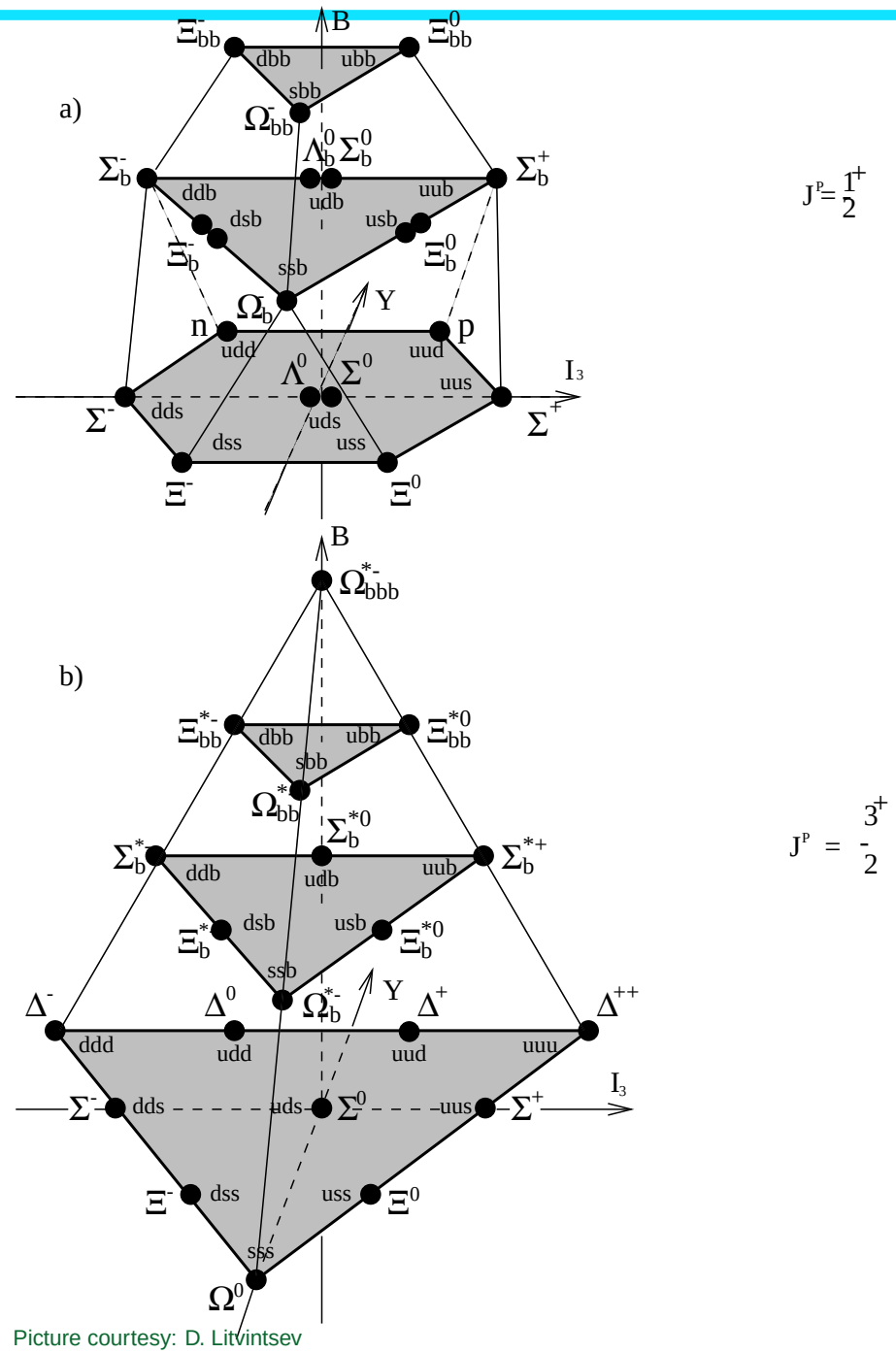
State	Quarks	J^P	(I, I_3)
Ground Bottom Baryon States			
Λ_b^0	$b[ud]$	$(1/2)^+$	$(0,0)$
Σ_b^+	buu	$(1/2)^+$	$(1,+1)$
Σ_b^0	$b\{ud\}$	$(1/2)^+$	$(1,0)$
Σ_b^-	bdd	$(1/2)^+$	$(1,-1)$
Σ_b^{*+}	buu	$(3/2)^+$	$(1,+1)$
Σ_b^{*0}	$b\{ud\}$	$(3/2)^+$	$(1,0)$
Σ_b^{*-}	bdd	$(3/2)^+$	$(1,-1)$
Orbital P- wave Bottom Baryon States			
Λ_b^{*0}	$b[ud]$	$(1/2)^-$	$(0,0)$
Λ_b^{*0}	$b[ud]$	$(3/2)^-$	$(0,0)$

$\Rightarrow$ **Bottom baryon Λ- and Σ- states.**

- **Heavy Baryon quark content:**
  $Q\, q_1\, q_2$
- **The $[q_1 q_2]$ denotes a pair** *antisymmetric* **in flavor and spin.**
- **The $\{q_1 q_2\}$ denotes a pair** *symmetric* **in flavor and spin.**

⇒ Baryons: Bottom Sector

- **Baryon:** $\mathbf{q_{f_1}, q_{f_2}, q_{f_3}}$
- **Ordinary SU$_f$(3) with** $\mathbf{f_i \in u, d, s}$
- **Bottom SU$_f$(5) with** $\mathbf{f_i \in u, d, s, c, b}$
- $\mathbf{Y \equiv \mathcal{B} + S - \frac{B}{3}}$**, hypercharge.**
- $\mathbf{B = -1}$**, for** b**- quark.**
  - **SU$_f$(3) "ground-state" (no orbital excitations!)**
  - **SU$_f$(5) adds to "ground-states" additional floors along** $B-$**axis**
  - **do not consider here double "b-c" baryons like** $\mathbf{(q\,c\,b)}$
- Up today established bottom ones:
  - **ONLY** $\mathbf{\Lambda_b^0 \equiv b\,[u\,d]}$



Picture courtesy: D. Litvintsev

3 – Motivation for an Experimental Search on Σ_b

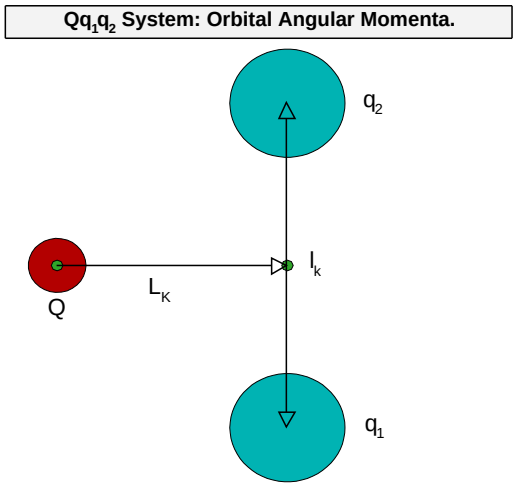
- **Well established charm baryon sector.**
- **Wealth of experimental data on bottom B-mesons from e^+e^- and hadron beams.**
- Yet **only one bottom baryon, the Λ_b^0,** has been directly observed:
  - $\Lambda_b^0 \to J/\psi\, \Lambda^0$
  - $\Lambda_b^0 \to \Lambda_c^+ \pi^-$
  - $\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu$
- World's largest data sample of bottom baryons at CDF...
  - $\sim 3000,\ \Lambda_b^0 \to \Lambda_c^+ \pi^-$
- **None of Σ_b states have been established so far.**
- Excellent track resolution of CDF tracker ...
- precise vertex reconstruction by Si-Detector SVX II ...
- provide fine mass resolution and ...
  - make possible to observe $\Sigma_b^{(*)\pm} \to \Lambda_b^0 \pi^\pm$

4 – Spectroscopy with QCD

⇒ H.Q.E.T. Phenomenology:

- QCD simplifies substantially in a presence of a heavy $\mathbf{Q}$
- $\mathbf{m_Q \gg \Lambda_{QCD} \gg m_{qq}}$, $\mathbf{m_Q \simeq 4.8\,GeV}$, $\mathbf{Q \equiv b}$
- $\mathbf{m_Q} \longrightarrow \infty$: heavy quark spin **decouples** from light quark degrees of freedoms.
- Heavy baryons' properties are governed by the dynamics of the $\mathbf{qq}$ in a gluon field created by the $\mathbf{Q}$ acting as a static source of QCD field: Λ_b^0 baryon as a "helium atom" of QCD.
- **Ground states,** $L_{qq} = 0$
  - Total $\mathbf{qq}$ spin $\mathbf{s_{qq}}$: $\mathbf{\frac{1}{2}^+ \otimes \frac{1}{2}^+ \longrightarrow 0^+ \oplus 1^+}$
  - $\mathbf{0^+ \otimes \frac{1}{2}^+ \longrightarrow \frac{1}{2}^+}$, $\mathbf{\Lambda_Q}$- like ground (i.e. $\mathbf{L_{qq} = 0}$) states
  - $\mathbf{1^+ \otimes \frac{1}{2}^+ \longrightarrow \frac{1}{2}^+ \oplus \frac{3}{2}^+}$, $\mathbf{\Sigma_Q}$- like ground states.

⇒ Heavy Q - Light $(\mathbf{q_1\, q_2})$



$$\Rightarrow \mathbf{j_{qq} = s_{qq} + L_{qq}}$$
$$\Rightarrow \mathbf{J_{Qqq} = s_Q + j_{qq}}$$

⇒ **Low Lying Bottom Baryons**

⇒ **Theoretical Expectations:**

$\mathbf{\Sigma_b}$ **property**	MeV/c^2
$\mathbf{m(\Sigma_b) - m(\Lambda_b^0)}$	$\mathbf{180 - 210}$
$\mathbf{m(\Sigma_b^*) - m(\Sigma_b)}$	$\mathbf{10 - 40}$
$\mathbf{m(\Sigma_b^-) - m(\Sigma_b^+)}$	$\mathbf{5 - 7}$
$\mathbf{m(\Lambda_b^0)}$, **fixed**	$\mathbf{5619.7}$
from CDF II	$\pm 1.2 \pm 1.2$
$\mathbf{\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)}$	$\sim 8, \sim 15$
see next slide...	

⇒ HQET

⇒ Potential models

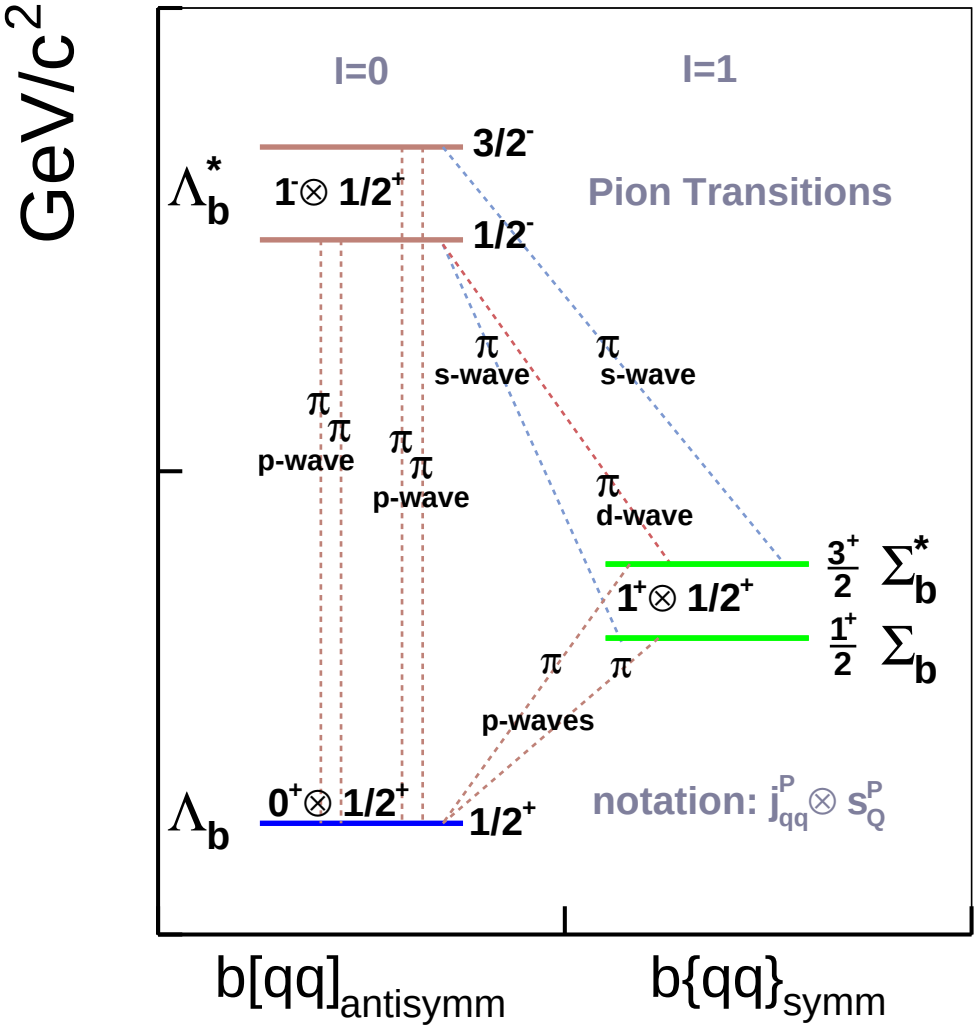
⇒ $1/N_c$ expansions

⇒ Lattice QCD calc.

- In a physics reality $\mathbf{m_Q}$ is finite.
- Degeneration of a $\{\mathbf{\Sigma_b}, \mathbf{\Sigma_b^*}\}$ doublet is resolved by a hyperfine mass splitting.
- Isospin mass splitting within isotriplets $\mathbf{\Sigma_b}$ and $\mathbf{\Sigma_b^*}$:
  - The size of the splitting is different (J. L. Rosner, hep-ph/0611207):
    $(\mathbf{\Sigma_b^{*+}} - \mathbf{\Sigma_b^{*-}}) - (\mathbf{\Sigma_b^+} - \mathbf{\Sigma_b^-})$
    $= \mathbf{0.40 \pm 0.07}\,\mathrm{MeV}/\mathbf{c^2}$.
  - Contribution to the systematic uncertainty.

⇒ Pion Transitions into Λ_b^0 Singlet.

- H.Q.E.T.: pion transitions are governed by the light diquark.
- Ground states (or S-wave)
  $\Sigma_b^{(*)\pm} \to \Lambda_b^0 \pi^\pm$
  - single- $\pi^\pm$ in P-wave with
    $qq(1^+) \to qq(0^+) + \pi^\pm_{0^- \otimes 1^-}$
- Orbital states (or P-wave)
  $\Lambda_b^{*0} \to \Lambda_b^0 \pi^+ \pi^-$ **given sufficient phase space.**
  - single- $\pi^\pm$ are forbidden:
    - $\mathbf{I}$- spin conservation.
    - parity conservation (strong decays!) (for $\Lambda_b^{*0}(\frac{3}{2}^-)$ state)
  - 2- $\pi^\pm$ in P-wave with
    $qq(1^-) \to qq(0^+) + (\pi^+\pi^-)_{1^-}$



5 – Natural Width of $\Sigma_b^{(*)\pm}$ Baryons

- $\mathbf{M}(\Sigma_b^{(*)})$(theor. pred.) $\simeq$ $\mathbf{M}(\Lambda_b^0) + (\mathbf{180} - \mathbf{210})\,\mathrm{MeV}/\mathbf{c^2}$
- Dominated by single P-wave π_{Σ_Q}-transitions.

$$\Gamma_{\Sigma_Q \to \Lambda_Q \pi} \sim |\vec{p}_\pi|^{2L+1}\,, L = 1$$

$$\Gamma_{\Sigma_Q \to \Lambda_Q \pi} = \frac{1}{6\pi} \frac{M_{\Lambda_Q}}{M_{\Sigma_Q}} |f_p|^2 |\vec{p}_\pi|^3$$

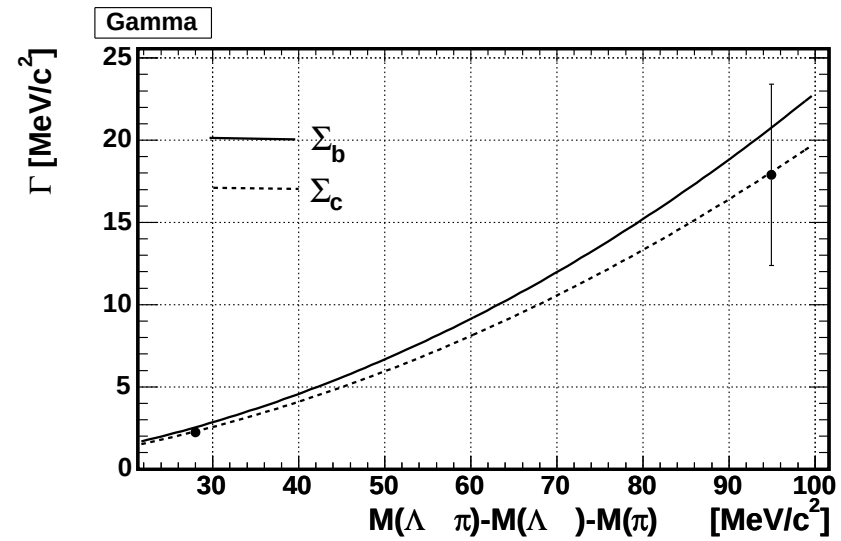
$$f_p \equiv g_A/f_\pi;\ f_\pi = 92\,\mathrm{MeV}; g_A = 0.75;$$

- depends from the phase space of $\pi^{\pm}_{\Sigma_b}$
- **Excellent agreement with $\Gamma_{PDG}(\Sigma_c^{(*)})$.**
- **Fit to $\Gamma_{PDG}(\Sigma_c^{(*)})$: $g_A = 0.75 \pm 0.05$**
- **± 0.05 contributes to our (syst) uncertainties.**

$\Rightarrow$ Natural width Γ of Σ_c and Σ_b baryons

$\Rightarrow$ as a function of the decay Q-value

$\Rightarrow$ $\mathbf{Q} = \mathbf{M}(\Sigma_b) - \mathbf{M}(\Lambda_b^0) - \mathbf{M}(\pi)$



Using fitted g_A and $M_{CDF\,II}(\Lambda_b^0)$:

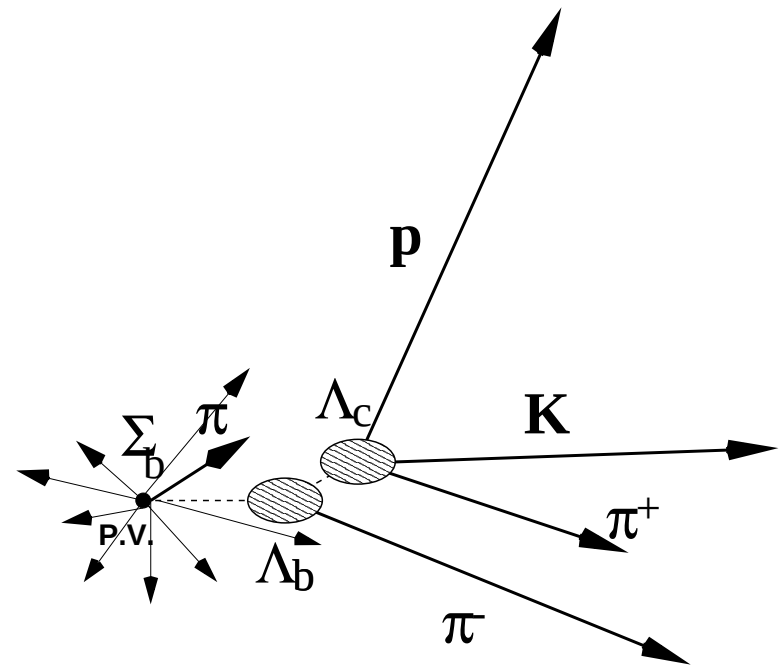
$\Gamma(\Sigma_b) \approx 8\,\mathrm{MeV}/\mathbf{c^2}$ and

$\Gamma(\Sigma_b^*) \approx 15\,\mathrm{MeV}/\mathbf{c^2}$

6 – Principle of the Analysis

- **Reconstruct Λ_b^0 candidates:**
  - $\mathbf{\Lambda_b^0 \to \Lambda_c^+ \pi^-}$
  - with $\mathbf{\Lambda_c^+ \to pK^- \pi^+}$
- Candidates: $\mathbf{\Sigma_b \to \Lambda_b^0 \pi^\pm_{\Sigma_b}}$
- $\pi^\pm_{\Sigma_b}$**, soft track from Prim. Vtx....**
- **...coming along with tracks from hadronization and underlying event**
- **To remove the mass resolution of each Λ_b^0 candidate search for narrow signatures in spectum:**
- $\mathbf{Q = M(\Lambda_b^0 \pi^\pm_{\Sigma_b}) - M(\Lambda_b^0) - M_{PDG}(\pi^\pm)}$
- **Blind signal region, develop cuts...**
- **using the L/R.S.B. representing Σ_b background.**

$\Rightarrow$ **Topology of Σ_b event.**

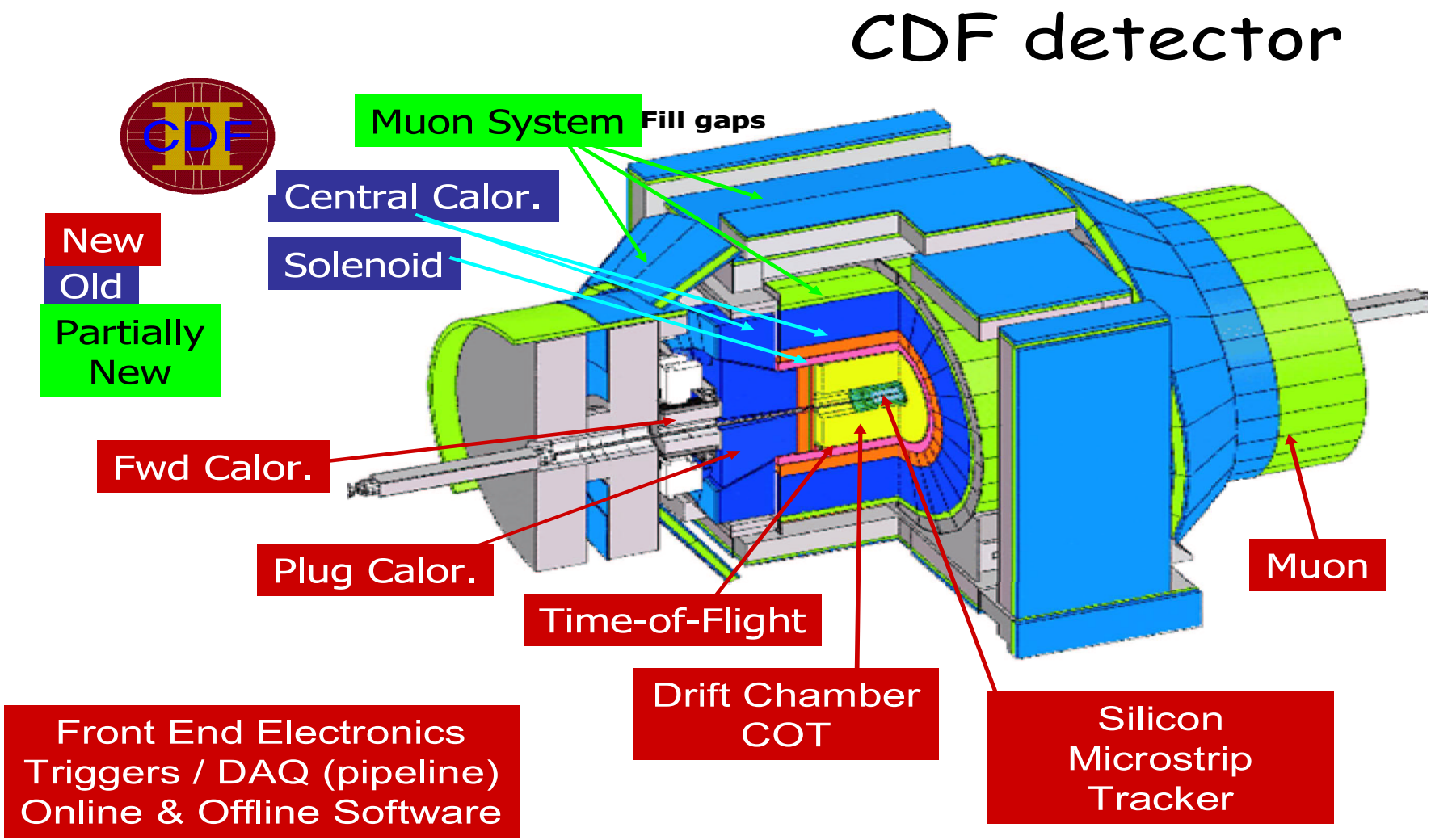


$\Rightarrow$ $\mathbf{B^0 \to D^+ \pi^-}$ **can fake** $\mathbf{\Lambda_c^+ \to pK^- \pi^+}$

$\Rightarrow$ **L.S.B.:** $\mathbf{0 \lesssim Q \lesssim 30\,\mathrm{MeV/c^2}}$

$\Rightarrow$ **R.S.B.:** $\mathbf{100 \lesssim Q \lesssim 500\,\mathrm{MeV/c^2}}$.

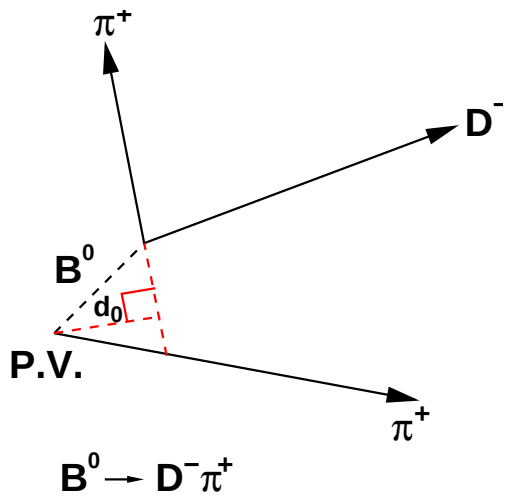
7 – CDF II Detector at Tevatron

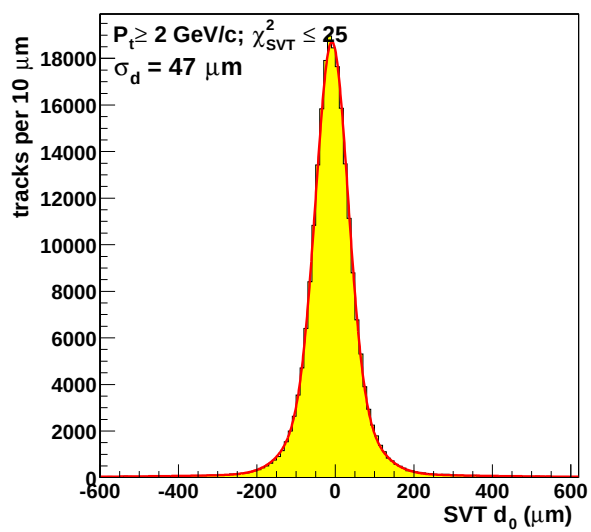


⇒ **Critical for our results: COT (central tracker) and SVX II (Si) vertex detector**

8 – b- Physics Triggers in CDF II

- Enormous inelastic total cross- section of $\sigma_{\mathbf{tot}}^{\mathbf{inel}} \sim \mathbf{60}\,\mathrm{mb}$ at Tevatron.
- $\sigma_{\mathbf{b}} \approx \mathbf{20}\,\mu\mathrm{b}\,(|\eta| < \mathbf{1.0}), @\mathbf{1.96\,TeV}$
- Selective three-level trigger.
- Trigger on Hadron Modes.
- Two displaced Tracks Trigger:
  - Exploits "long" $c\tau$(b-hadrons),
  - Triggers on ≥ 2 tracks with large $d_0 > 120\,\mu\mathrm{m}$,
  - ...and with high $p_T > 2.0\,\mathrm{GeV}/c$.
  - Realized by Silicon Vertex Trigger (SVT) hardware as a part of CDF Level 2
- Present $\Sigma_{\mathbf{b}}$ analysis, base mode: $\Lambda_{\mathbf{b}}^{\mathbf{0}} \rightarrow \Lambda_{\mathbf{c}}^{+}\pi_{\mathbf{b}}^{-}\,, \Lambda_{\mathbf{c}}^{+} \rightarrow \mathbf{pK}^{-}\pi^{+}$, $(\mathbf{p}, \pi_{\mathbf{b}}^{-})$ are most likely in trigger.





9 – Λ_b^0 Candidates and Signal

⇒ **Reconstruction of Candidates:**

$\Lambda_b^0 \to \Lambda_c^+ \pi_b^-$, $\Lambda_c^+ \to pK^-\pi^+$

- **The total Luminosity:** $\mathcal{L} \simeq 1.1\,\text{fb}^{-1}$
- $''\Lambda_c^+''[(pK^-\pi^+) \in (2286.0 \pm 16.0)\,\text{MeV}/c^2,$ $(pK^-\pi^+)_{\text{3DVxFit}},\ M = M_{PDG}^{\Lambda_c^+}]$
- $''\Lambda_b^0''[(''\Lambda_c^+'')\,\pi_b^-]_{\text{3DVxFit}},$ $\text{Prob}(\chi^2_{3D}) > 0.1\%$
- **proper decay times:**

  $c\tau(\Lambda_b^0) > 250\,\mu\text{m}$

  $-70 < c\tau(\Lambda_c^+ \leftarrow \Lambda_b^0) < 200\,\mu\text{m}$

  $c\tau \equiv L_{xy} \cdot m_{\Lambda_Q}/p_T,$

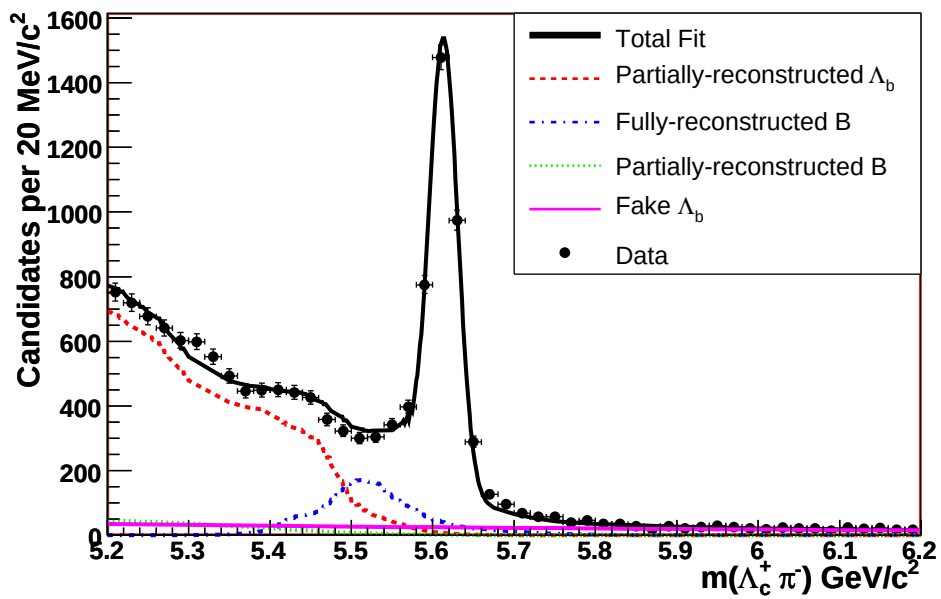
  $L_{xy} = \vec{D_{xy}} \cdot \vec{p_T}/p_T$
- **impact parameter w.r.t. Primary Vx:**

  $d_0(\Lambda_b^0) < 80\,\mu\text{m}$

  $d_0 = |\vec{D_{xy}} \times \vec{p_T}/p_T|$

⇒ **The Λ_b^0 invariant Mass Plot**

CDF II Preliminary, L=1.1 fb^{-1}



⇒ **Binned Max. Neg.Log.Likelihood fit**

⇒ **Signal region:** $\mathbf{M(\Lambda_b^0) \in [5.565, 5.670]}\,\text{GeV}$

⇒ **Combin. bgr.:** $\mathbf{M(\Lambda_b^0) \in [5.8, 7.0]}\,\text{GeV}$

⇒ **Left S.B.: partially reconstr. Λ_b^0, 4-prong B**

⇒ **The fitted Λ_b^0 yield:** $\mathbf{3125 \pm 62}(\text{stat})$ entries.

$\Rightarrow \Lambda_b^0$ Signal Window:

- **The *other* Λ_b^0- components are normalized to $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ signal:**
  - $\Lambda_b^0 \to \Lambda_c^{*+} \pi^-$, $\Lambda_c^+ K^-$, $\Lambda_c^+ \mu^- \bar{\nu}_\mu$ etc.
- **The B- components are normalized to the $B^0 \to D^+ \pi^-$, $D^+ \to K^- \pi^+ \pi^+$ signal on *this* Λ_b^0 sample with p hypothesis replaced with the π^+ one.**
- **pure combinatorial background extrapolated from the upper side-band into the signal area.**

- **All Λ_b^0- components: 90.1%**
- **The B- components: 6.3%**
- **The random combinatorial backgr. component: 3.6%**
- **Use these weights to normalize the Σ_b backgrounds components in the Q-value spectra.**
- **The uncertainty of weights contributes to (syst)**

10 – Σ_b Candidates: Blind Analysis

⇒ **Reconstruction of Candidates**

⇒ Σ_b^-, Σ_b^{*-} + chrg. conj.

⇒ Σ_b^+, Σ_b^{*+} + chrg. conj.

⇒ $\Sigma_b \to \Lambda_b^0 \pi^\pm_{\Sigma_b}$ + chrg. conj.

- **Based on a collection of reconstructed Λ_b^0 cands:**
- signal 3σ window of $''\Lambda_b^0''[(''\Lambda_c^+'')\,\pi_b^-] \in (5.565, 5.670)\,\mathrm{GeV}/c^2$
- **Couple $''\Lambda_b^0''$ with direct soft π_{Σ_b} with very loose quality reqs.**
- $[(''\Lambda_b^0'')_{\mathrm{VxFit}}\,\pi_{\Sigma_b}]_{\mathrm{VxFit}}$, NO $M(\Lambda_b^0)$ constraint, $\mathrm{Prob}(\chi^2_{3D}) > 0.1\%$

- $Q = M(\Lambda_b^0 \pi^\pm_{\Sigma_b}) - M(\Lambda_b^0) - M_{\mathrm{PDG}}(\pi^\pm)$
- **Blind signal region:** $Q \in (30, 100)\,\mathrm{MeV}/c^2$
- **Right S.B.:** $Q \in (100, 500)\,\mathrm{MeV}/c^2$
- **Left S.B.:** $Q \in (0, 30)\,\mathrm{MeV}/c^2$

- **The cuts to be applied and optimized while signal is blinded:**
  - $p_T(\mathbf{\Sigma_b}) > \mathrm{cut};$
  - **Significance of an impact parameter:** $|d_0/\sigma_{d_0}|\,(\pi_{\mathbf{\Sigma_b}})$
  - **Polar angle of the soft pion in a "$\mathbf{\Sigma_b}$"-rest frame:** $\cos\theta^*\,(\pi_{\mathbf{\Sigma_b}}) = \vec{\mathbf{p}}_{\mathbf{\Sigma_b}} \cdot \vec{\mathbf{p}}^*_\pi / (|\vec{\mathbf{p}}_{\mathbf{\Sigma_b}}| \cdot |\vec{\mathbf{p}}^*_\pi|)$
- **Optimize cuts maximizing** $\epsilon(\mathbf{S})/\sqrt{(\mathbf{B})}$
- **Signal is taken from PYTHIA**
- **Background is taken from side bands of** $Q(\Sigma_b)$

$\Rightarrow$ **Optimized cuts**

Variable	Cut value
$p_T(\Sigma_b)$	$> 9.5\,\mathrm{GeV}/c$
$\lvert d_0/\sigma_{d_0}\rvert(\pi_{\Sigma_b})$	< 3.0
$\cos\theta^*(\pi_{\Sigma_b})$	> -0.35

$\Rightarrow$ **Only** $\cos\theta^*(\pi_{\Sigma_b})$ **has substantial**

$\Rightarrow$ **rejection power.**

$\Rightarrow$ **The composition of the background in $Q(\Sigma_b)$- value Spectra.**

$\Rightarrow$ **before unblinding...**

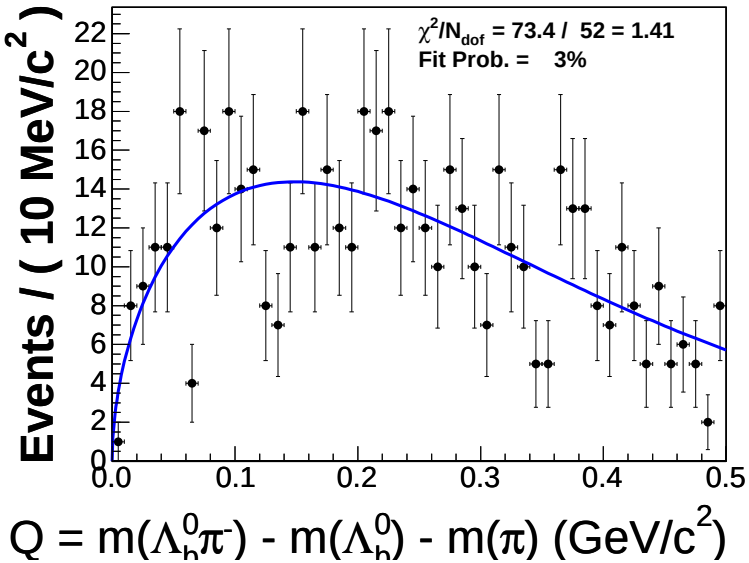
- **Λ_b^0 hadronization: $W = 90.1\%$**
  - **Use PYTHIA to analyze Q- Spectra of $\Lambda_b^0 + \text{soft rndm. track.}$ Dominating source.**
- **B- meson hadronization: $W = 6.3\%$ faked $\Lambda_b^0 + \text{soft random track.}$**
  - **use exper. data sample of reconstructed $\overline{B^0} \to D^+\pi_b^-$, $D^+ \to K^-(''\pi^+ \to p'')\pi^+$**
- **comb. backgr. underneath the Λ_b^0 peak: $W = 3.6\%$; use Right S.B. of $M(\Lambda_c^+\pi^- \in [5.8, 7.0]$ of comb. bgr.**
- **5-track contributions: $B \to D^*/D_J + X$, $D^*/D_J \to D\pi_{soft}$ or $B_J \to B\pi_{soft}$ decays with possible π_{soft}. Use PYTHIA to estimate. Both contributions are negligible and will be ignored.**
- **Fit all three sources with the same functional form:**

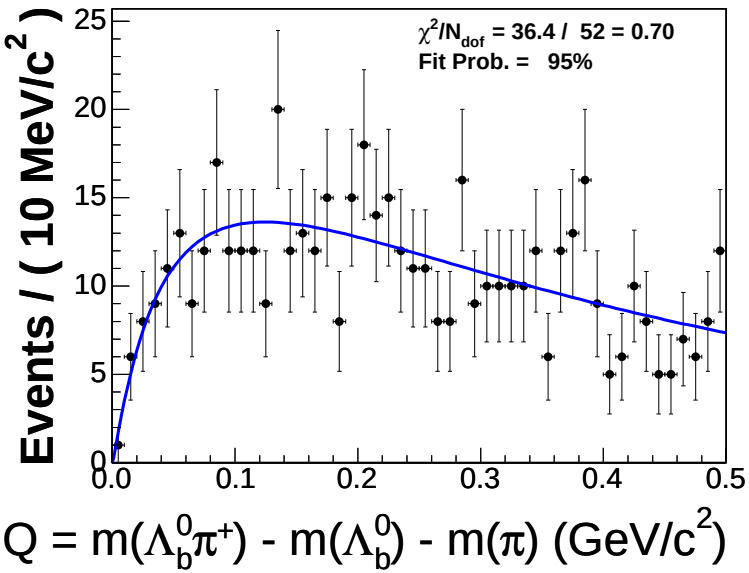
$$f(Q; \alpha, Q_{max}, \gamma) = \left(\frac{Q}{Q_{max}}\right)^{\alpha} e^{-\frac{\alpha}{\gamma}\left(\left(\frac{Q}{Q_{max}}\right)^{\gamma} - 1\right)}$$

Use alternative forms for (syst).

⇒ The combinatorial background:

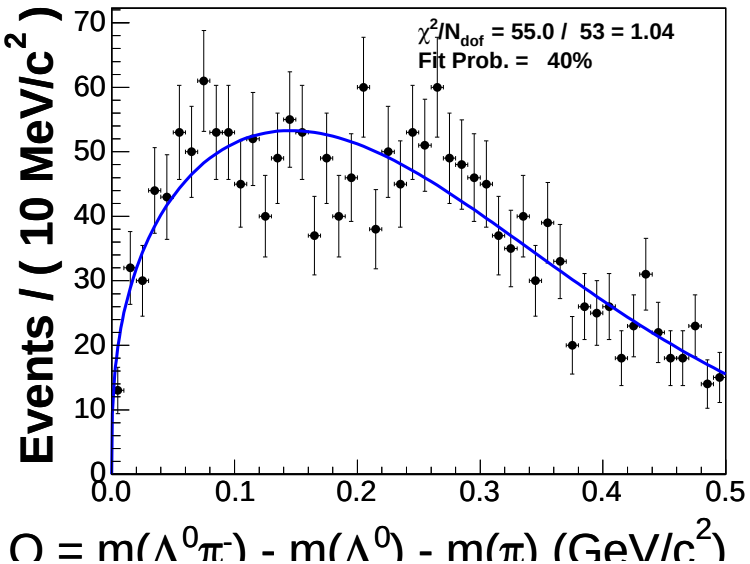
CDF II Preliminary. L=1.1 fb^{-1}

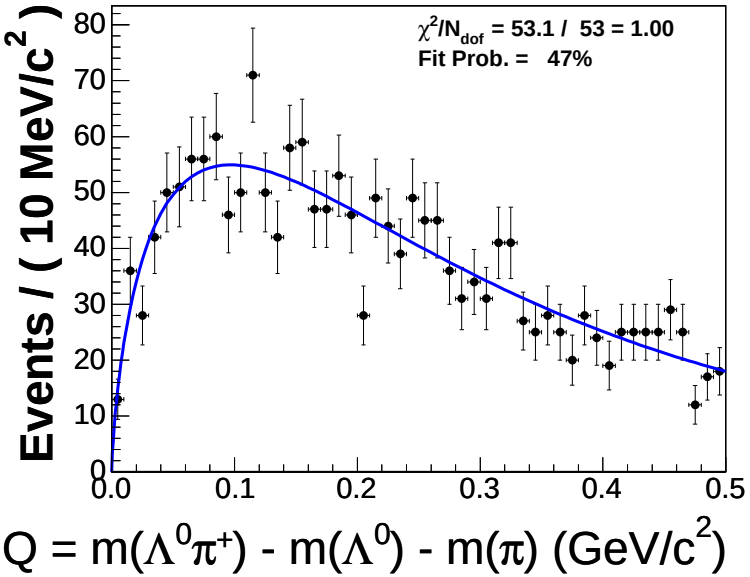




⇒ The B^0 Physical background:

CDF II Preliminary. L=1.1 fb^{-1}

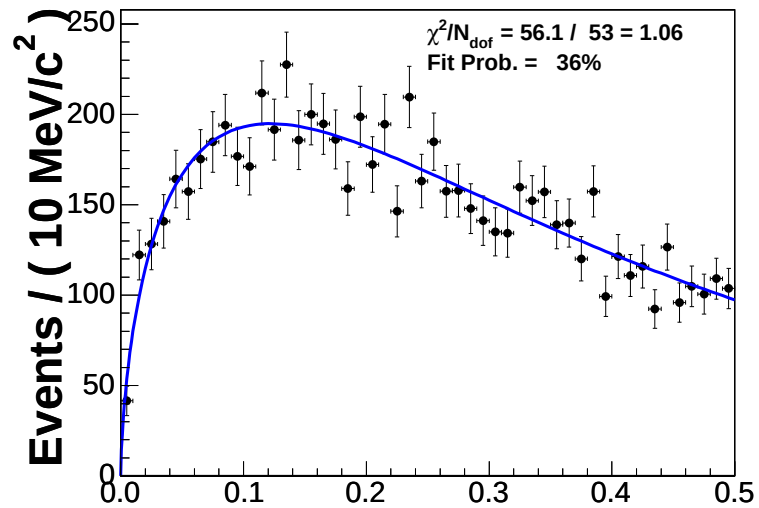




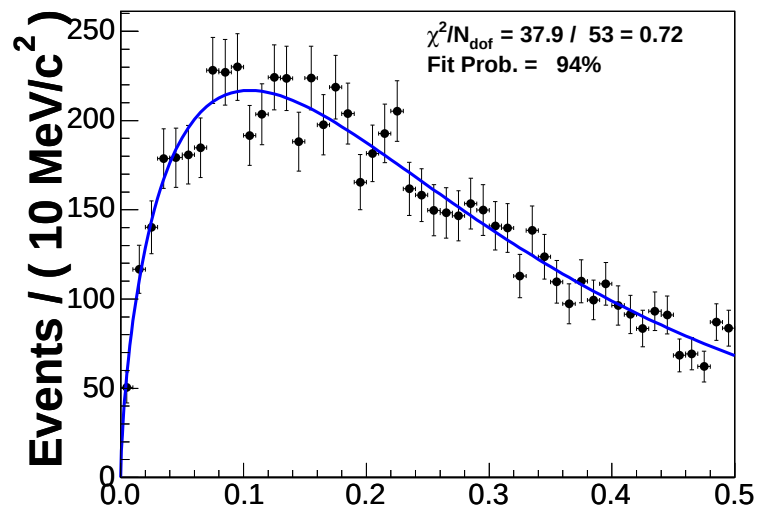
$\Rightarrow \Lambda_b^0$ **Hadronization Background:**

- $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ **PYTHIA sample.**
- **MC events reweighted: for $p_T(\Lambda_b^0)$ spectrum to agree with data.**
- **MC events reweighted: for $p_T(\pi_{soft})$ spectrum to agree with data.**
- **The MC Q- value spectrum is fitted with the same function.**
- **SMOOTH shape in the signal area.**

CDF II Preliminary, L=1.1 fb^{-1}



Q = m($\Lambda^0\pi^-$) - m(Λ^0) - m(π) (GeV/c^2)



Q = m($\Lambda^0\pi^+$) - m(Λ^0) - m(π) (GeV/c^2)

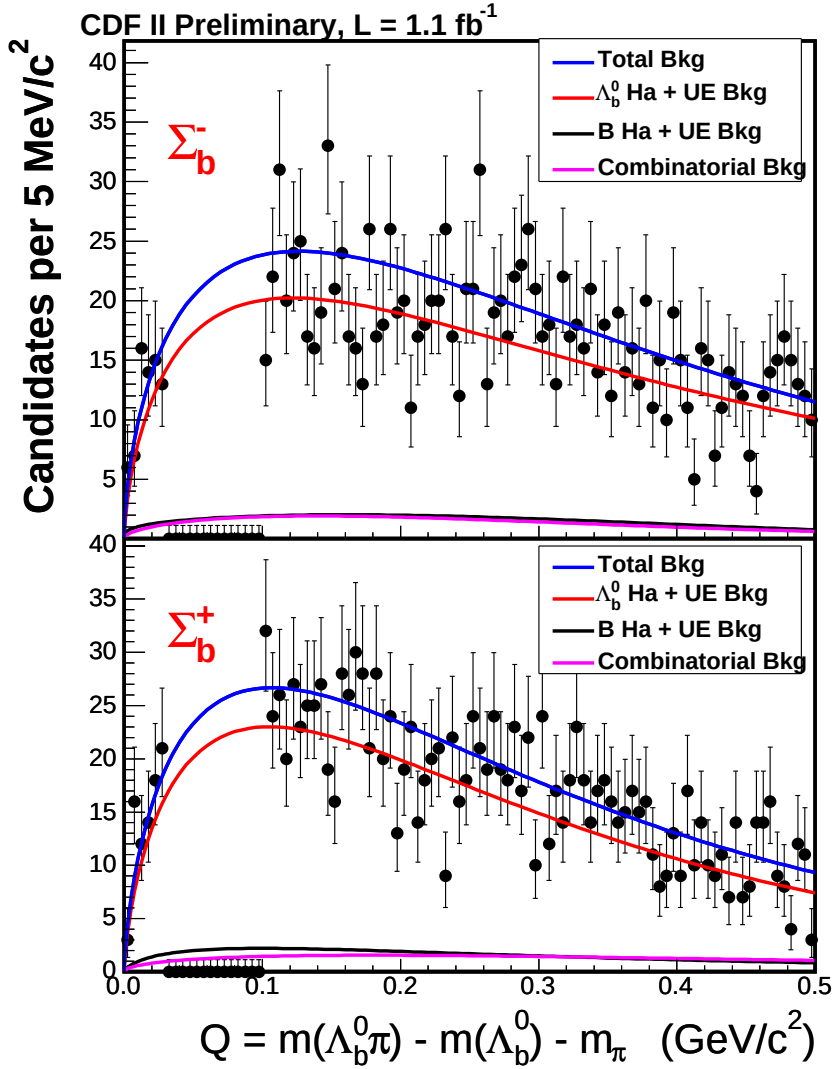
⇒ **The sources of background:**

⇒ **before unblinding...**

- Λ_b^0 **hadronization component is normalized to total(all modes) experimental yield :**
  $\mathbf{N^{exp.}(\Lambda_b^0) = 3180 \pm 180(stat)}$

- **SMOOTH BGR. SHAPE in signal area!**

- **These contributions are fixed in Σ_b signal fits.**



11 – Σ_b Candidates: Unblinded

⇒ **Upon unblinding the signal**

⇒ **in $Q \in (30, 100)\,\mathrm{MeV}/c^2$**

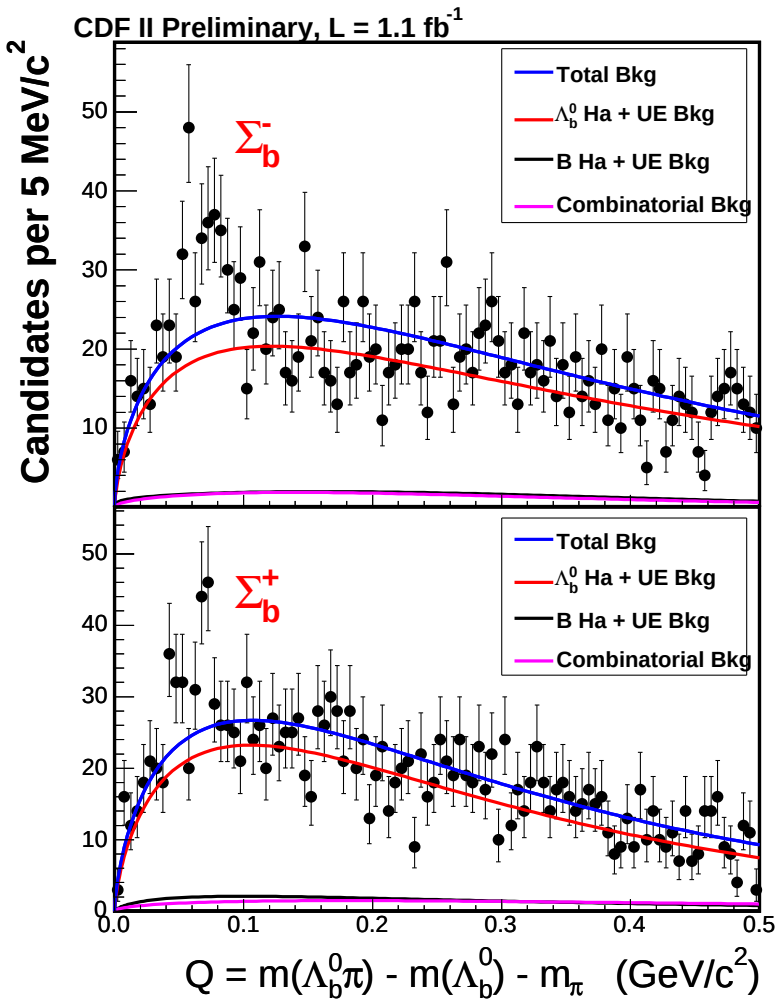
⇒ **count number of evts:**

Statistics	$\Lambda_b^0\pi^-$	$\Lambda_b^0\pi^+$
$S+B$	416	406
B	268	298
S	148	108
$S/\sqrt{S+B}$	7.3	5.4

⇒ **The fit of the background**

⇒ **predicts B at signal area.**

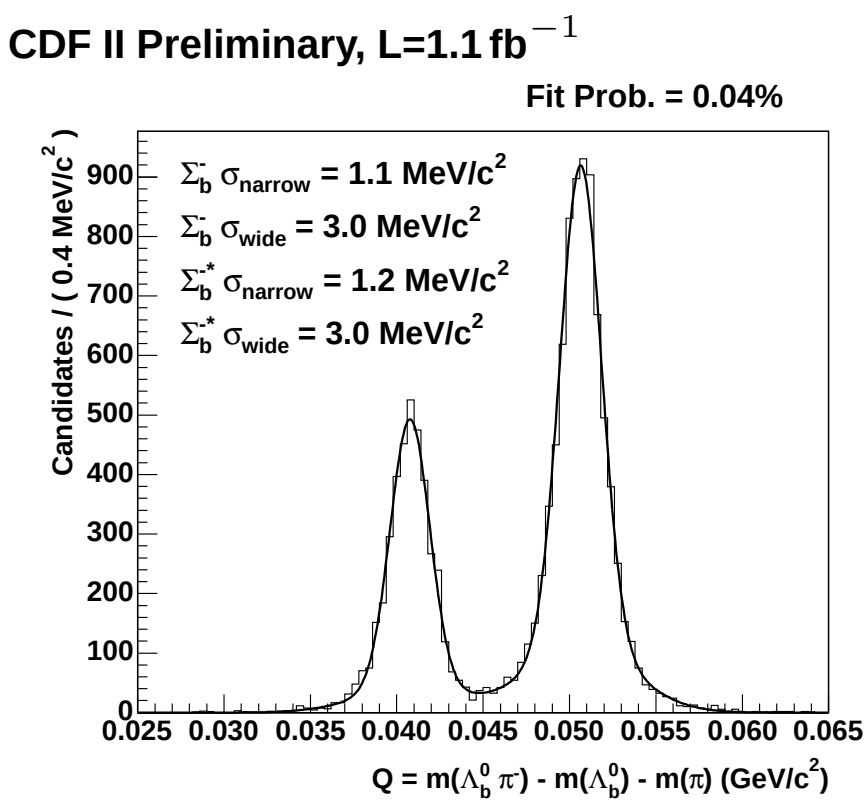
⇒ **There is an excess in both spectra...**



12 – Characterization of Σ_b Spectra

⇒ The Signal $Q(\Sigma_b^{(*)\pm})$: Detector Resolution

- MC PYTHIA for $\Sigma_b^{(*)\pm} \to \Lambda_b^0 \pi^\pm_{\Sigma_b}$, $\Lambda_b^0 \to \Lambda_c^+ \pi_b^-$, $\Lambda_c^+ \to pK^-\pi^+$.
- Natural width set to: $\Gamma(\Sigma_b^{(*)\pm}) = 0$.
- Two Gaussians: a dominant narrow core, a small broad component for the tails.
- Compare MC width with exp. data for reconstructed reference states $\Sigma_c^{0,++}$, D^{*+}.
  - disagreement of $15 - 20\%$ is taken as (syst).

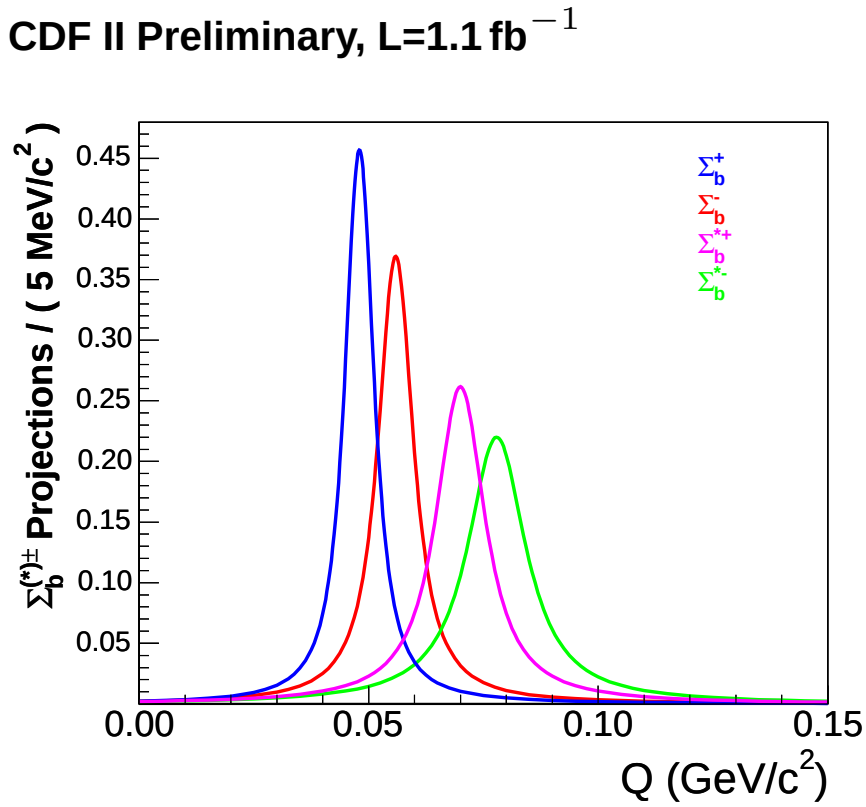


⇒ **The Signal $Q(\Sigma_b^{(*)\pm})$ Description:**

- Signal terms:

$$G_{1,2} \otimes BW(Q; Q_{\Sigma_b}, \sigma^{1,2}_{\Sigma_b}, \Gamma_{\Sigma_b}) + G_{1,2} \otimes BW(Q; Q_{\Sigma_b^*}, \sigma^{1,2}_{\Sigma_b^*}, \Gamma_{\Sigma_b^*})$$

- The widths $\Gamma(\Sigma_b^{(*)\pm})$ are calculated at $Q_{\Sigma_b^{(*)\pm}}$ using HQET formula from Section 5 (or Körner J G, Krämer M and Pirjol D 1994 *Prog. Part. Nucl. Phys.* **33** 787)
- The widths dominate over resolution.
- The larger $M(\Sigma_b^{(*)})$ the wider gets a Breit-Wigner.



⇒ **The Fits.**

- **Signals: 2 peaks Σ_b^-, Σ_b^{*-} and 2 peaks Σ_b^+, Σ_b^{*+}.**
  - 2 Breit-Wigners convoluted with 2 Gaussians
  - From HQET formula: $\Gamma(Q^{\text{being fit}}_{\Sigma_b^{(*)\pm}})$
- **The shape and normalization of a background is frozen.**
- **Constraint:**
  - $(\Sigma_b^{*+} - \Sigma_b^+) - (\Sigma_b^{*-} - \Sigma_b^-) \sim 0.40\,\text{MeV}$, **below our sensitivity.**
  - $Q(\Sigma_b^{*+}) - Q(\Sigma_b^+) = Q(\Sigma_b^{*-}) - Q(\Sigma_b^-)$, for both charged cands.
- **Seven parameters floating:**
  - $Q(\Sigma_b^-)$, $Q(\Sigma_b^+)$
  - $\Delta_{\Sigma_b^*} = Q(\Sigma_b^*) - Q(\Sigma_b)$
  - Number of entries in every of 4 peaks: $N(\Sigma_b^{(*)\pm})$
- **Perform a simultaneous unbinned negative likelihood fit using full statistics of both spectra.**

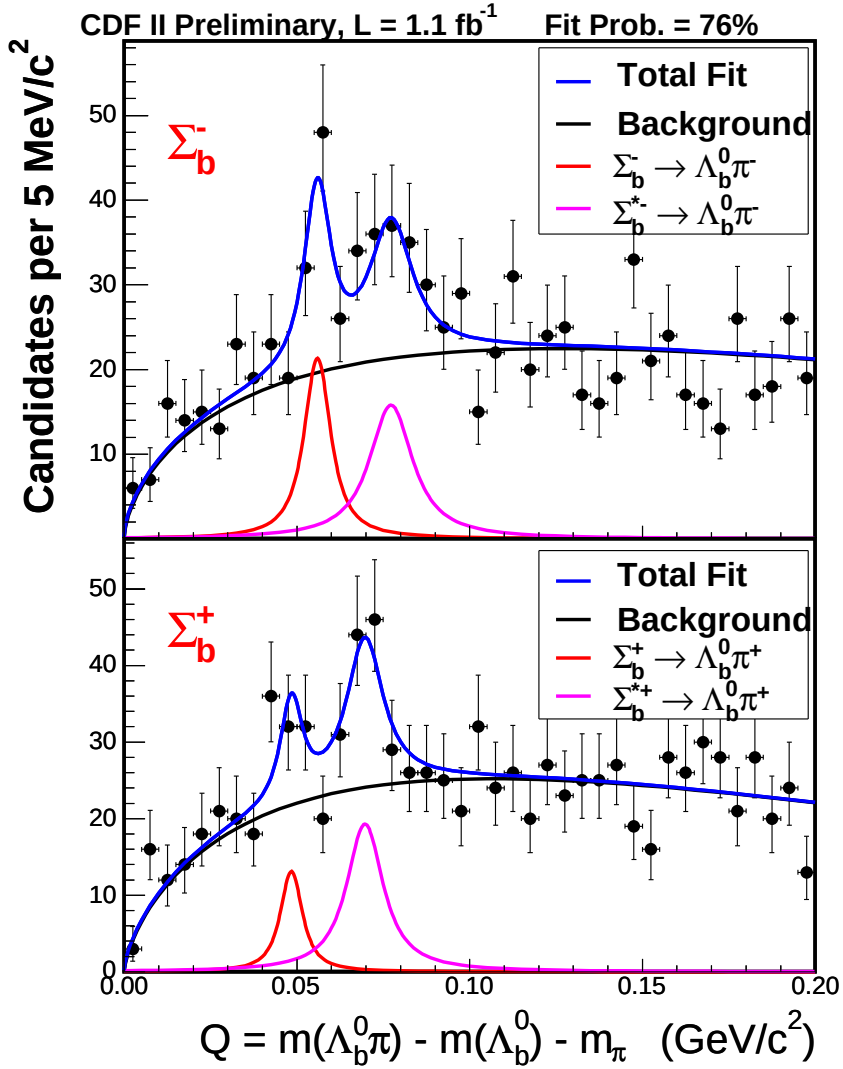
$\Rightarrow -\ln(\mathbf{Lh})$ **Fit Results:**

Parameter	Value$\pm\delta(\mathrm{stat})$
$Q(\Sigma_b^+)\,\mathrm{MeV}/c^2$	$48.2^{+1.9}_{-2.2}$
$Q(\Sigma_b^-)\,\mathrm{MeV}/c^2$	$55.9^{+1.0}_{-0.9}$
$\Delta_{\Sigma_b^*} = [Q(\Sigma_b^*) - Q(\Sigma_b)]\,\mathrm{MeV}/c^2$	$21.5^{+2.0}_{-1.9}$
Σ_b^+ events	33^{+13}_{-12}
Σ_b^- events	62^{+15}_{-14}
Σ_b^{*+} events	82^{+17}_{-17}
Σ_b^{*-} events	79^{+18}_{-18}

$\Rightarrow$ **Errors come from MINOS.**

$\Rightarrow$ Σ_b^+ **yield is weak** $\Rightarrow$

$\Rightarrow$ $Q(\Sigma_b^+)$ **has large correlation with** $\Delta_{\Sigma_b^*}$



13 – Σ_b: Systematics

⇒ Contributions to Systematics

- **Tracking, due to the calibration**
  - Check out $\mathbf{M(D^{*+}) - M(D^0)}$
  - $\mathbf{\Delta\, M}(\mathrm{data}) - \mathbf{\Delta\, M}(\mathrm{MC})$, $\sim \mathbf{0.06}\,\mathrm{MeV/c^2}$
- **Assumptions of the Fit.**
  - The predicted width fitted to Σ_c PDG, $\mathbf{g_A = 0.75 \pm 0.05}$
  - The constraint that $\mathbf{\Delta_{\Sigma_b^{*+}} = \Delta_{\Sigma_b^{*-}}}$. The equality is skewed by $\sim \mathbf{0.5}\,\mathrm{MeV/c^2}$.
  - **Uncertainty of resolution** $\sigma^{1,2}_{\Sigma_b^{(*)}}$ **(from CDF MC sim.)**
  - **Uncertainty of the weights of the** Λ_b^0 **background components.**

⇒ Assumptions of the Fit cont-d ...

- **Normalization of the** Λ_b^0 **hadronization background.**
- **Use another functional form of the background PDF.**
- **Extreme reweighting of** $p_T(\mathrm{track})$ **in PYTHIA.**
- **Mass measurements:** (syst) **uncertainties are much smaller than** (stat) **ones.**
- **Signal yields:** (syst) **errors are comparable with the** (stat) **ones.**
- **The largest contribution to a yield** (syst) **comes from the track reweighting in PYTHIA.**

⇒ **Signal Yields with Systematics Included:**

⇒ **Number of events for each state:**

$$\mathbf{N}(\Sigma_b^+) = 33^{+13}_{-12}\ \text{(stat.)}^{+5}_{-3}\ \text{(syst.)}$$

$$\mathbf{N}(\Sigma_b^-) = 62^{+15}_{-14}\ \text{(stat.)}^{+9}_{-4}\ \text{(syst.)}$$

$$\mathbf{N}(\Sigma_b^{*+}) = 82^{+17}_{-17}\ \text{(stat.)}^{+10}_{-6}\ \text{(syst.)}$$

$$\mathbf{N}(\Sigma_b^{*-}) = 79^{+18}_{-18}\ \text{(stat.)}^{+16}_{-5}\ \text{(syst.)}$$

14 – Σ_b: Significance of the Signals

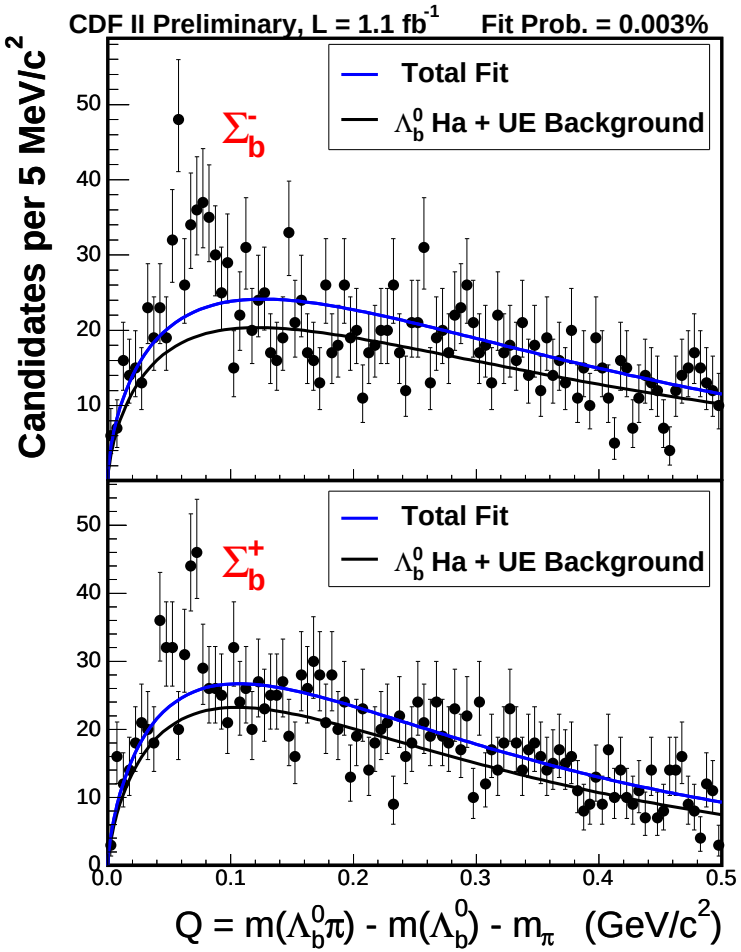
- **In total a very significant signal:**
  - **Naive estimation with $S/\sqrt{S+B}$ gives $\sim 9\sigma$**
  - **p-value estimates: statistical Monte-Carlo pseudo-experiments.**
    - **Hard to reach 9σ level.**
- **Prove the strength of 4-peak $\Sigma_b^{(*)\pm}$ hypothesis using Likelihood Ratio LR :**

$$LR \equiv \frac{L_{4\text{ peak fit}}}{L_{\text{no peak fit}}}$$

  - **$L_{\text{no peak fit}}$ corresponds the the least favorable to 4 Σ_b peak hypothesis (using (syst) variations of bgr. and signal PDFs).**

Σ_b: Significance of the Signals

Hypothesis	$\Delta(-\ln L)$	$\sqrt{2 \cdot \Delta(-\ln L)}$
Null	**42.9**	**9.3**
2 peaks	14.1	5.3
No Σ_b^- Pk.	9.8	4.4
No Σ_b^+ Pk.	1.8	1.9
No Σ_b^{*-} Pk.	9.1	4.3
No Σ_b^{*+} Pk.	10.7	4.6



$\Rightarrow$ **Fit with Null Hypothesis.**

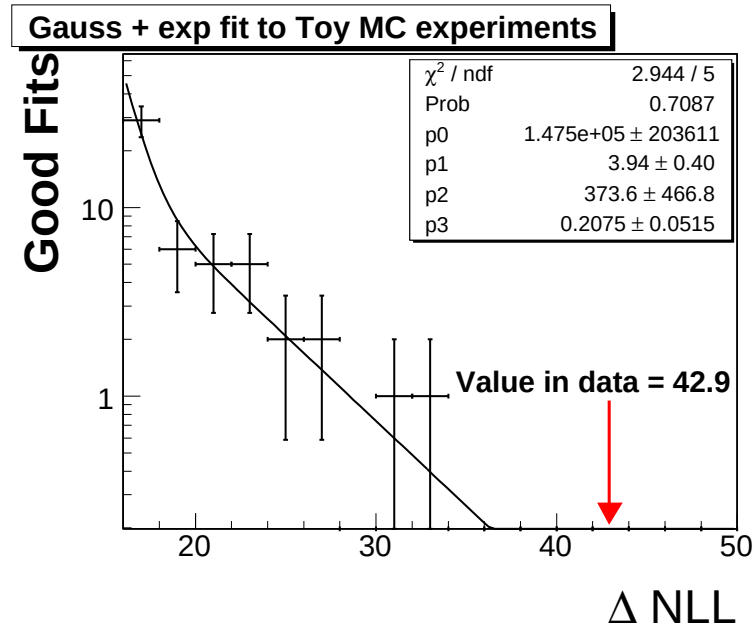
⇒ Running Statistical Experiments: Toy MC

Hypothesis	$\Delta(-\ln L)$	p-value
Null	**42.9**	$\mathbf{6.4 \cdot 10^{-8}}$

⇒ **that it is here for a 4-peak $\Sigma_b^{(*)\pm}$**

⇒ **the NULL hypothesis is excluded**

⇒ **at least at the 5σ level.**



⇒ **The $\Delta(-\ln L)$ distribution**

⇒ **for the NULL signal Toy MC samples.**

⇒ **The largest value in Toy MC**

⇒ **is below 34**

⇒ **Extrapolate tail with Gaus+Exp**

⇒ **This gives us $6.4 \cdot 10^{-8}$**

15 – Summary

- The lowest lying charged $\Lambda_b^0\pi^\pm$ resonant states are observed in $\mathcal{L} \simeq 1.1\,\text{fb}^{-1}$ of CDF II data
  - ~ 256 events in total.
- The widths and masses are consistent with the lowest lying charged $\Sigma_b^{(*)\pm}$ baryons.
- The Q values of Σ_b^- and Σ_b^+, and the $\Sigma_b^* - \Sigma_b$ mass difference, are measured to be:
  - $M(\Sigma_b^-) - M(\Lambda_b^0) - M(\pi) = 55.9^{+1.0}_{-0.9}(\text{stat})^{+0.1}_{-0.1}(\text{syst})\,\text{MeV}/c^2$
  - $M(\Sigma_b^+) - M(\Lambda_b^0) - M(\pi) = 48.2^{+1.9}_{-2.2}(\text{stat})^{+0.1}_{-0.2}(\text{syst})\,\text{MeV}/c^2$
  - $M(\Sigma_b^{*-}) - M(\Sigma_b^-) = M(\Sigma_b^{*+}) - M(\Sigma_b^+) =$
    $= 21.5^{+2.0}_{-1.9}(\text{stat})^{+0.4}_{-0.3}(\text{syst})\,\text{MeV}/c^2$
- This result represents the first observation of the $\Sigma_b^{(*)}$ baryons.

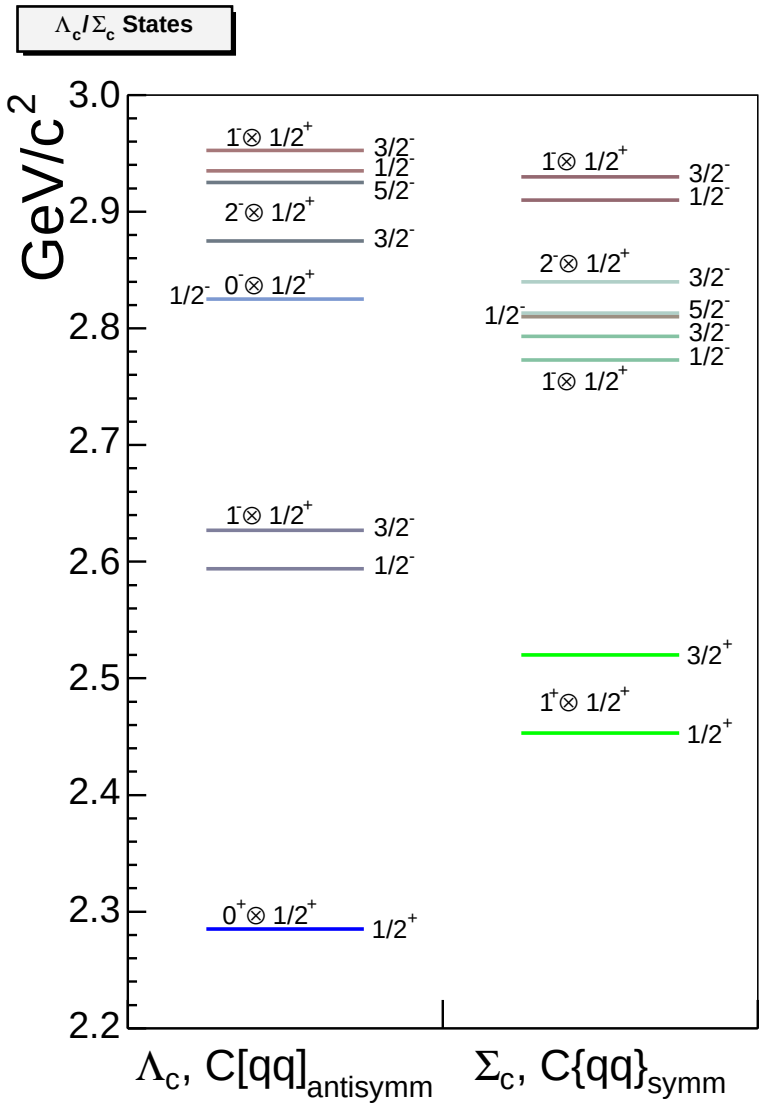
THE END OF THE TALK.

16 – Backup Slides...

$\Rightarrow \mathbf{j_{qq} = s_{qq} + L_{qq}}$

$\Rightarrow \mathbf{J_{Qqq} = s_Q + j_{qq}}$

- **Ground states,** $L_{qq} = 0$
  - Total qq momentum j_{qq}: $\frac{1}{2}^+ \otimes \frac{1}{2}^+ \rightarrow \mathbf{0}^+ \oplus \mathbf{1}^+$
  - $\mathbf{0}^+ \otimes \frac{1}{2}^+ \rightarrow \frac{1}{2}^+$, $\mathbf{\Lambda_Q}$- like states
  - $\mathbf{1}^+ \otimes \frac{1}{2}^+ \rightarrow \frac{1}{2}^+ \oplus \frac{3}{2}^+$, $\mathbf{\Sigma_Q}$- like states.
  - $m_Q \rightarrow \infty : (\mathbf{\Sigma_Q}, \mathbf{\Sigma_Q^*})$ degenerates, but...
    - m_Q is finite: splitting due to $s_Q \cdot s_{qq}$ interaction.
    - $I = 1$: $(\mathbf{\Sigma_Q^{(*)-}}, \mathbf{\Sigma_Q^{(*)+}})$ isospin splitting.
- $L_{qq} = 1$, orbital qq excitations add more **higher lying states due to** $s \cdot L$



$\Rightarrow$ The picture is based on L. A. Copley *et al.*,Phys. Rev. D **20**,768(1979)

⇒ Reconstruction of Candidates

$\mathbf{\Lambda_b^0 \to \Lambda_c^+ \pi_b^-}$, $\mathbf{\Lambda_c^+ \to pK^- \pi^+}$

- $\mathcal{L} = \mathbf{1070 \pm 60}\,\text{pb}^{-1}$ with Two displaced Track Trigger
- The trigger conditions are confirmed for any 2 out of 4 tracks $(\mathbf{pK^-}\pi^+, \pi_\mathbf{b}^-)$
- 3-d Vertex Fit for $''\Lambda_c^+{}''(pK^-\pi^+)$ constrained to $M_{PDG}(\Lambda_c^+)$
- 3-d Vertex Fit for $''\Lambda_b^0{}''(\Lambda_c^+\pi_b^-)$
- L_{xy} and d_0 are decay path and I.P. of Λ_b^0 vertex.
- $c\tau = L_{xy} \cdot (M/p_T)_{\Lambda_b^0}$
- **Optimize cuts to get max. of** $S/\sqrt{(S+B)}$

$p_T(\pi_b^-)$	$> 2\,\text{GeV}/c$
$p_T(p)$	$> 2\,\text{GeV}/c$
$p_T(p)$	$> p_T(\pi^+)$
$p_T(K^-)$	$> 0.5\,\text{GeV}/c$
$p_T(\pi^+)$	$> 0.5\,\text{GeV}/c$
$c\tau(\Lambda_b^0)$	$> 250\,\mu\text{m}$
$c\tau(\Lambda_b^0)/\sigma_{c\tau}$	> 10
$\lvert d_0(\Lambda_b^0)\rvert$	$< 80\,\mu\text{m}$
$c\tau(\Lambda_c^+ \leftarrow \Lambda_b^0)$	$> -70\,\mu\text{m}$
$c\tau(\Lambda_c^+ \leftarrow \Lambda_b^0)$	$< 200\,\mu\text{m}$
$\lvert\Delta_{\Lambda_c^+} M(pK^-\pi^+)\rvert$	$< 16\,\text{MeV}/c^2$
$p_T(\Lambda_b^0)$	$> 6.0\,\text{GeV}/c$
$p_T(\Lambda_c^+)$	$> 4.5\,\text{GeV}/c$
$\text{Prob}(\chi^2_{3D}; \Lambda_b^0)$	$> 0.1\%$

⇒ The systematics is summarized in a table below:

Parameter	Track.	Λ_b^0 Comp.	Λ_b^0 Nrm.	Λ_b^0 Shp.	Rewght.	Reso.	Σ_b Width	Total
$Q(\Sigma_b^+)$	0.06	0.03	0.013	0.013	0.0	0.0	0.01	**0.07**
MeV/c^2	-0.06	0.0	-0.013	0.0	-0.11	-0.014	-0.02	**-0.13**
$Q(\Sigma_b^-)$	0.06	0.0	0.009	0.0	0.04	0.0	0.009	**0.07**
MeV/c^2	-0.06	-0.03	-0.002	-0.011	-0.0004	-0.011	-0.005	**-0.07**
$Q(\Sigma_b^*)$	0.06	0.05	0.14	0.04	0.32	0.02	0.07	**0.37**
- $Q(\Sigma_b)$	-0.06	0.0	-0.13	0.0	0.0	0.0	-0.07	**-0.16**
Σ_b^+ evts	0.0	3.3	2.1	1.2	**2.3**	0.3	1.8	5.0
	0.0	0.0	-2.1	0.0	**-1.8**	0.0	-2.0	-3.4
Σ_b^- evts	0.0	0.7	2.2	0.3	**7.4**	0.3	3.4	8.5
	0.0	0.0	-2.2	0.0	**0.0**	0.0	-3.4	-4.0
Σ_b^{*+} evts	0.0	7.3	4.8	2.8	**4.6**	0.2	0.8	10.3
	0.0	0.0	-4.8	0.0	**-2.9**	0.0	-0.8	-5.7
Σ_b^{*-} evts	0.0	0.4	4.8	0.3	**14.7**	0.1	1.7	15.6
	0.0	0.0	-4.7	0.0	**0.0**	0.0	-1.7	-5.0

⇒

Track p_T reweighting is largest for yields...

⇒ While total systematics for mass measurements is small.