Evidence for a bottom baryon resonance $\Lambda_b^{*0}$ in CDF data

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Outline of the talk

- The Tevatron and the CDF II Detector
- Motivation and Bottom Baryon Resonance states $\Lambda_{b}^{*0}$
- Data Sample and Trigger
- Analysis and Fit Model
- Systematic Uncertainties
- Results and Conclusions
Introduction

The Tevatron Accelerator at Fermilab near Chicago
The Tevatron collided $p$ with $\bar{p}$ at 1.96TeV center of mass energy from 2001-2011

- Instantaneous Luminosity upto $4 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$
- $\int L \, dt \simeq 12.0 \text{fb}^{-1}$ delivered
- $\int L \, dt \simeq 10.0 \text{fb}^{-1}$ on tape, accessible for CDF II
Silicon Vertex Detector, Drift Chamber and Muon Detectors.

- B=1.4T and the transverse momentum resolution of the tracking system is $\sigma(p_T)/p_T^2 \approx 0.07\%/(\text{GeV}/c)$
Motivation

- Baryons with a heavy quark $Q$ and a light diquark $q_1 q_2$ (Helium atoms of QCD) are useful for probing QCD in its confinement domain.
- Observing a new HQ baryons, measuring properties provides constraints to QCD models
  - Quark potential models: non-relativistic, relativistic
  - HQET framework at LO and NLO in $1/m_Q, 1/N_c$ combined expansions
- Goal of the analysis: search for the resonant states in $\Lambda_b^0 \pi^- \pi^+$ modes.

$Qq_1q_2$ System: Orbital Angular Momenta.

- $m_Q \gg \Lambda_{QCD} \gg m_{qq}$
- $m_Q \simeq 4.8 \text{ GeV}, Q \equiv b$
- HQET: $S_Q$ decouples from $(q_1 q_2)$ degrees of freedoms.
Pion Transitions into $\Lambda_b^0$ Singlet.

- HQET: pion transitions are governed by the light diquark.
- Resonant, $S$-wave, $\Sigma$-like states:
  \[ \Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \pi^\pm \]
  - single-pion $\pi^\pm$ in $P$-wave with
    \[ qq(1^+) \rightarrow qq(0^+) + \pi_0^\pm \otimes 1^- \]
- Orbital excitations, $P$-wave, $\Lambda$-like states:
  \[ \Lambda_b^{(*)0} \rightarrow \Lambda_b^0 \pi^+ \pi^- \text{ given sufficient phase space.} \]
  - single-pion $\pi^0$ forbidden due to:
    - isospin conservation,
    - parity conservation (strong decays)
  - di-pion $\pi^+ \pi^-$ are soft and emitted in $P$-wave with
    \[ qq(1^-) \rightarrow qq(0^+) + (\pi^+ \pi^-)_{1^-} \]
Experimental Status

CDF first observation, then measurements: $\Sigma_b^{(*)\pm}$ resonances

LHCb observation: $\Lambda_b^*0(5912)$ and $\Lambda_b^*0(5920)$, interpreted as $J^P = \frac{1}{2}^-$ and $J^P = \frac{3}{2}^-$ resonant states.

CMS observation: bottom-strange $\Xi_b^*0$, interpreted as $J^P = \frac{3}{2}^+$ resonant state.

CDF, D0 observations: ground bottom-strange $\Xi_b^-$

CDF, D0 observations: ground bottom doubly-strange $\Omega_b^-$

CDF observation: ground neutral bottom-strange baryon $\Xi_b^0$
Decay Chain of $\Lambda_b^{*0}$

$\bar{p} \rightarrow \Lambda_b^{*0}$

$\Lambda_b^{*0} \rightarrow \Lambda_b^0 \rightarrow \Lambda_c^+ \rightarrow K^- \pi^+$

$\pi^-_{\text{soft}} \quad \pi^+_{\text{soft}} \quad |d_0| \quad \pi^-_b$
**Two Displaced Track Trigger**

*b*-Triggers at @1.96 TeV

- Enormous inelastic total cross-section of $\sigma_{\text{tot}}^{\text{inel}} \sim 60 \text{ mb}$
- $\sigma_b \approx 20 \mu\text{b} \ (|\eta| < 1.0)$, @1.96 TeV

Trigger on Hadronic Modes: CDF Two Track Trigger

- Exploit long $c_T$ (b-hadrons)
- $p_T \geq 2 \text{ GeV/c}$ for each of the two tracks
- Trigger on $\geq 2$ tracks with large $|d_0|$
**Total CDF Luminosity of**

\[ \int \mathcal{L} \, dt \approx 9.6 \text{ fb}^{-1} \]

**Reconstruct inclusive base \( \Lambda_b^0 \) signal in**

\( M(\Lambda_c^+ \pi_b^-) \), a pion \( \pi_b^- \) produced in the weak decay

\( \Lambda_b^0 \rightarrow \Lambda_c^+ \pi_b^- \).

**Combine \( \Lambda_b^0 \) signal candidates with two soft pions to reconstruct**

\( \Lambda_b^{*0} \rightarrow \Lambda_b^0 \pi_s^- \pi_s^+ \)

**candidates.**

**require \( p_T(\Lambda_b^0) \) to be large to get soft \( \pi_s^\pm \) within the detector kinematical acceptance**

- \( p_T(\Lambda_b^0) > 9.0 \text{ GeV/c} \)
- \( ct(\Lambda_b^0)/\sigma_{ct} > 6.0 \)
- \( N(\Lambda_b^0) \approx 15400 \)
- \( p_T(\pi_b^-) > 1.0 \text{ GeV/c} \)
- \( p_T(\pi_s^\pm) > 0.2 \text{ GeV/c} \), loose trk. req-s.
- \( |d_0/\sigma_d_0|(\pi_s^\pm) < 3.0 \), w.r.t. primary VX.
Signal Model and Scale

We reconstruct $\Lambda_b^{*0}$ candidates in a mass difference spectrum: $Q$ value

$$Q = M(\Lambda_b^{0}\pi_s^+\pi_s^-) - m(\Lambda_b^{0}) - 2 \cdot m(\pi^{\pm})$$

The mass resolution of the $\Lambda_b^{0}$ signal and most of the systematic uncertainties cancel in the $Q$ value spectrum.

- The signal: double Gaussian to model the detector resolution; shape fixed from MC; position $Q$ and $N_{cands}$ floating.
- The background: second order polynomial; floating.
- The full model for the $Q$ value spectra: a single narrow structure on top of a smooth background.
- Use high statistics CDF $D^{*+} \rightarrow D^0\pi_s^+$ sample to analyze the soft pions momentum scale for $\Lambda_b^{*0} \rightarrow \pi_s^-\pi_s^+$ candidates.
  - **Adjust scale:** $Q(\Lambda_b^{*0}) = Q(\Lambda_b^{*0}) - 0.28$, MeV/$c^2$,
  - set 100% syst. uncertainty: $-0.28 \pm 0.28$(syst) MeV/$c^2$
**Q- Spectrum and Results: \( \Lambda^*_b \)**

The projection of the unbinned LH fit onto the binned distribution of the **raw Q** spectrum of \( \Lambda^*_b \) candidates.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q ), MeV/( c^2 )</td>
<td>( 20.96 \pm 0.35 )</td>
</tr>
<tr>
<td>( N ), evts</td>
<td>( 17.3^{+5.3}_{-4.6} )</td>
</tr>
</tbody>
</table>

The scale adjusted **Q-value** is

\[ Q, \text{ MeV/} c^2 = 20.68 \pm 0.35 \]
Significance of the Signal

**Significance Estimated with toy MC expts.**

- Generate Null Hypothesis $\mathcal{H}_0$, fit with $\mathcal{H}_1$
- Parameter of interest, $N_{cands}$
- Signal position Q left floating within $[6.0, 45.0]$ MeV/$c^2$ search window
- Signal shape fixed
- Background shape floating
- p-value = $2.3 \times 10^{-4}$ or $3.5\sigma$
Systematic Uncertainties

- Momentum Scale:
  - B field knowledge,
  - Uncertainty due to detector material on the $dE/dx$ correction.
- Detector resolution model and its parameters.
- Choice of the background model.
- Systematics propagated from the previous CDF measurement of the $\Lambda^0_b$ mass.
<table>
<thead>
<tr>
<th>Source</th>
<th>Value, MeV/$c^2$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum scale</td>
<td>±0.28</td>
<td>propagated from high statistics calibration $D^{*+}$ sample; 100% of the found adjustment value.</td>
</tr>
<tr>
<td>Signal model</td>
<td>±0.11</td>
<td>MC underestimates the resolution; choice of the model’s parameters</td>
</tr>
<tr>
<td>MC resolution stat.</td>
<td>±0.012</td>
<td>finite MC sample size induces the stat. uncertainty of the shape parameters.</td>
</tr>
<tr>
<td>Background model</td>
<td>±0.03</td>
<td>consider 3-rd, 4-th power polynomials</td>
</tr>
<tr>
<td>Total:</td>
<td>±0.30</td>
<td>added in quadrature</td>
</tr>
</tbody>
</table>
Results

Results on $\Lambda^*_b$ with $\int \mathcal{L} dt \approx 9.6 \text{ fb}^{-1}$.

<table>
<thead>
<tr>
<th>Value</th>
<th>MeV/$c^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>$20.68 \pm 0.35\text{(stat)} \pm 0.30\text{(syst)}$</td>
</tr>
<tr>
<td>$\Delta M$</td>
<td>$299.82 \pm 0.35\text{(stat)} \pm 0.30\text{(syst)}$</td>
</tr>
<tr>
<td>$M(\Lambda^*_b)$</td>
<td>$5919.22 \pm 0.35 \text{(stat)} \pm 0.30 \text{(syst)} \pm 0.70 \text{(PDG)}$</td>
</tr>
<tr>
<td>$M(\Lambda^*_b)$</td>
<td>$5919.22 \pm 0.84$</td>
</tr>
</tbody>
</table>

To determine the absolute masses for $\Lambda^*_b$,

$m(\Lambda^*_b) = 5619.4 \pm 0.7, \text{ MeV}/c^2 \text{ (PDG 2012)}.$
Comparison with LHCb

- Result is consistent with the higher state $\Lambda_b^0(5920)$ found with $\int L \, dt = 1.0 \, \text{fb}^{-1}$ at $\sqrt{s} = 7 \, \text{TeV}$ (year 2011) by LHCb.

- LHCb reports also a state at $\approx 5912 \, \text{MeV}/c^2$ (same data).

- Assume

  - similar $\sigma \cdot B(\Lambda_b^0(5912)) / \sigma \cdot B(\Lambda_b^0(5920))$
  - similar $\epsilon(\Lambda_b^0(5912))/\epsilon(\Lambda_b^0(5920))$, i.e. $\approx 1$

- Then the lack of a visible $\Lambda_b^0(5912)$ signal in the CDF II is statistically consistent within $2\sigma$ with the $\Lambda_b^0(5912)$ reported by LHCb.
Conclusions

- We conduct a search for the $\Lambda_b^{*0} \rightarrow \Lambda_b^0 \pi^- \pi^+$ resonance state in its $Q$ value spectrum.
- A narrow structure is identified at $5919.22 \pm 0.84$ MeV/$c^2$ mass.
- The significance of the signal is $3.5\sigma$.
- The signal is attributed to the orbital excitation of the bottom baryon $\Lambda_b^0$.
- The result supports similar findings by LHCb.
Afterglow Light Pattern 400,000 yrs.

Dark Ages

Development of Galaxies, Planets, etc.

Dark Energy Accelerated Expansion

Inflation

Quantum Fluctuations

1st Stars about 400 million yrs.

Big Bang Expansion

13.7 billion years
Masses and Q-values of $\Lambda_b^*0$ Resonance States

- \[ Q \equiv M(\Lambda_b^*0 \rightarrow \Lambda_b^0 \pi^+ \pi^-) - M(\Lambda_b^0) - 2m(\pi^\pm) \]
i.e. the amount of energy released by the decay reaction

- Various theoretical models predict that the mass of the first excited state $\Lambda_b^*0, (1/2)^-$ lies very close to the hadronic three-body mode threshold with $Q \equiv [20...47]$ MeV/$c^2$

- The higher excited state, $\Lambda_b^*0(3/2)^-$ has $Q \equiv [2...17]$ MeV/$c^2$ higher than the lower state.