
# Latest Results on B-hadron Spectroscopy from CDF

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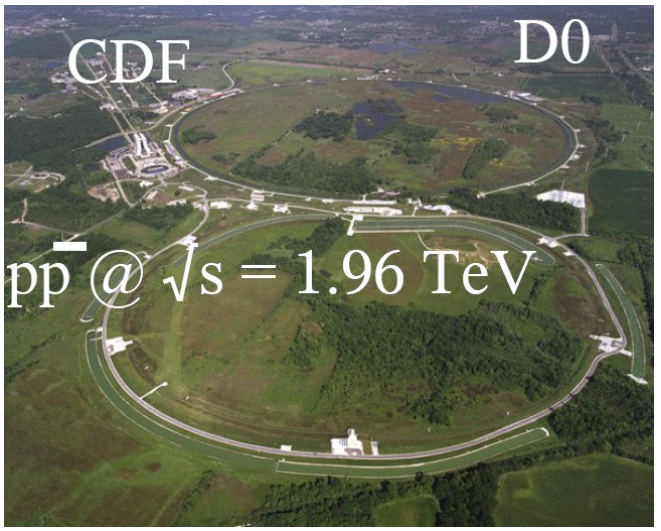
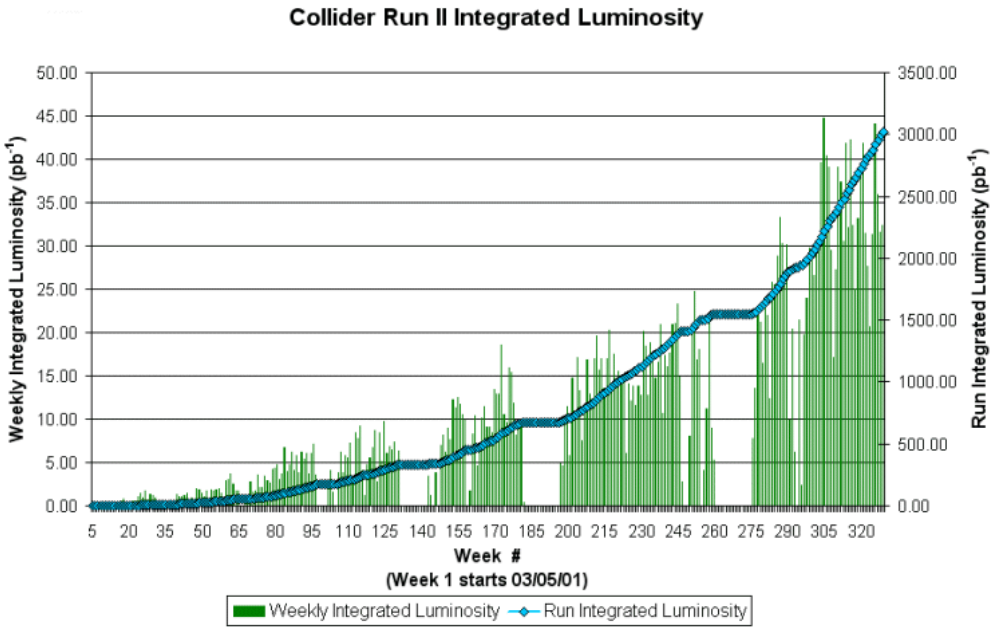
# Overview

- The experimental setup: Tevatron and CDF
- b-meson spectroscopy at CDF
  - Observation of the $B_c^+$
  - Search for the $\eta_b$
  - Orbitally excited B** mesons ($B_d^{**}$ and $B_s^{**}$)
- Baryon spectroscopy at CDF
  - Talk by J. Heuser on Saturday
- Summary

# The Tevatron

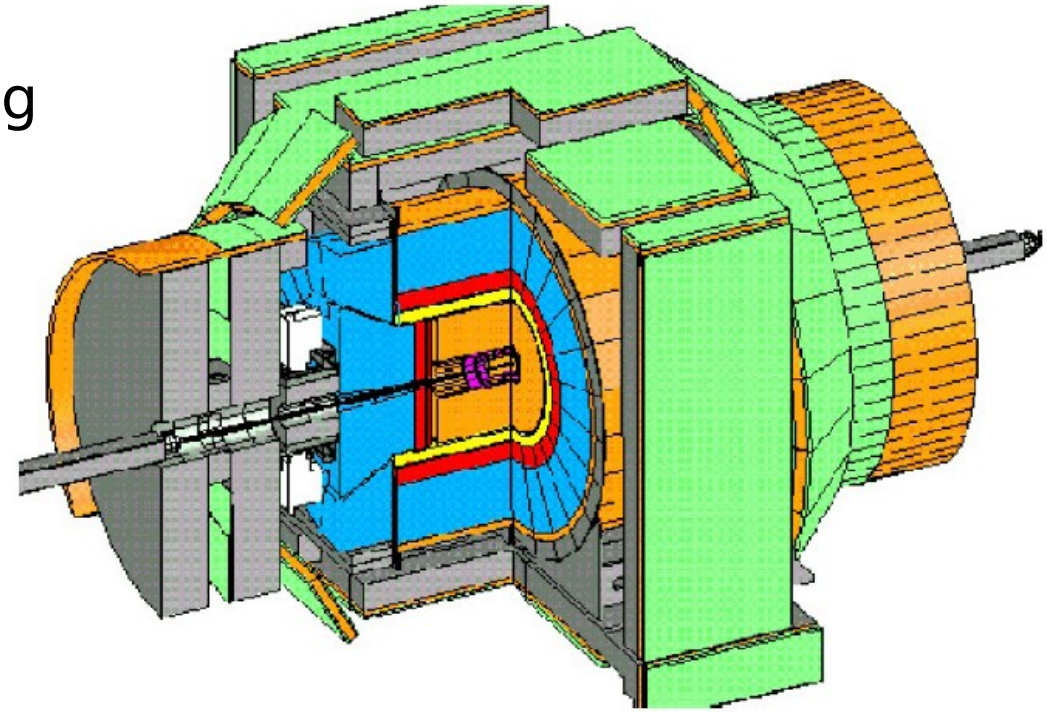
- Proton anti-proton collider
  - $\sqrt{s} = 1.96$ TeV
  - Currently 2.5 $fb^{-1}$ on tape
- Large bb cross section
  - ~ 50 µb
  - ~ $10^{11}$ pairs produced
- Production of all b-hadron species



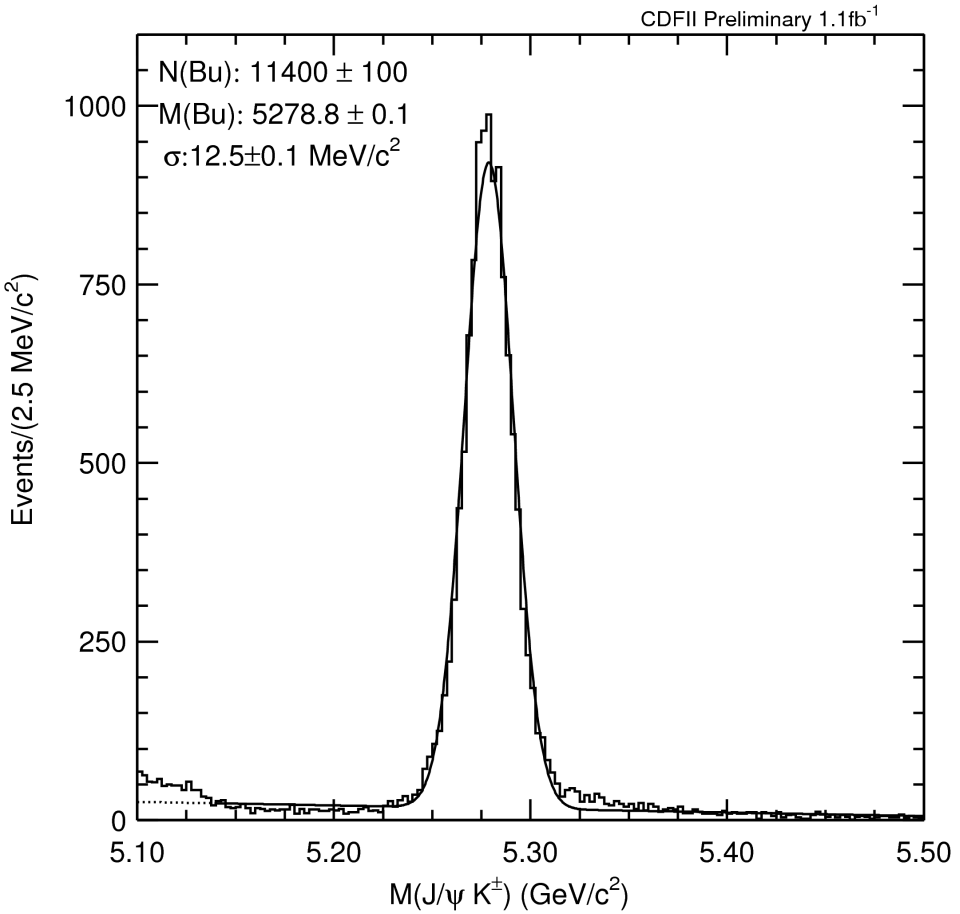
# The CDF Detector

- Multi purpose detector
  - Precise tracking and vertexing
  - Solenoid and calorimeters
  - Good muon coverage
- Trigger system to select events
- For b-physics most important
  - Di-muon trigger
    - $J/\psi \rightarrow \mu\mu$
  - Silicon Vertex Trigger (SVT)
    - 2 charged tracks with
      - Transverse momentum $\geq$ 1.5 GeV
      - Forming a secondary vertex



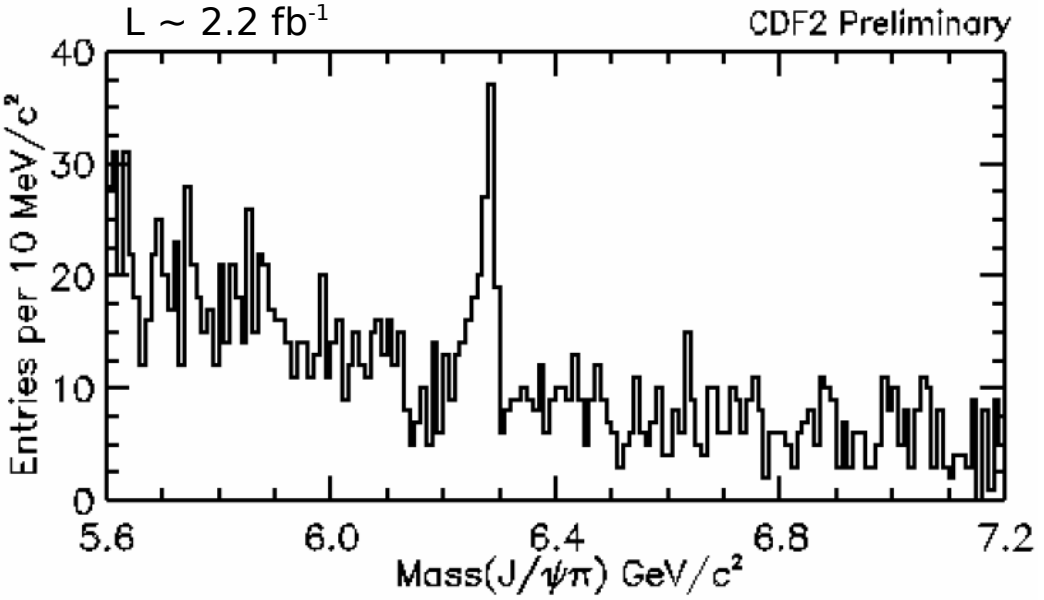
# Observation of the $B_c^+$

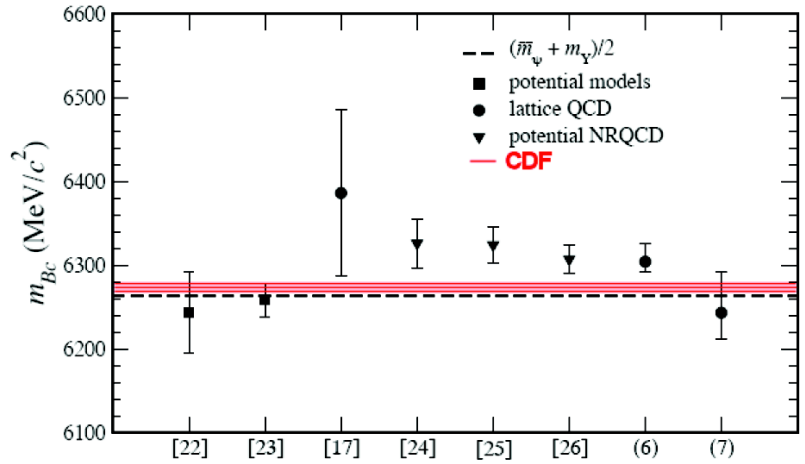
- $B_c$ is not produced at B factories
- Low production rate f(b → $B_c$) ~ 0.05%
- Weak decay modes
  - J/ψ $\ell\nu$ X  Missing neutrino
  - J/ψ $\pi^+$  Fully reconstructed
- Analysis
  - Optimize selection cuts on reference decay $B_u$ → J/ψ $K^+$
  - Apply blindly on J/ψ $\pi^+$
  - Significant signal in 1.1 $fb^{-1}$



# Spectrum of the $B_c^+$

- Peak in ($J/\psi\,\pi$) mass spectrum
  - Significance > 8σ
  - Fit: Linear plus Gaussian
    - 87.1 signal events
  - $m(B_c) = 6274.1 \pm 3.2 \pm 2.6$ MeV/$c^2$

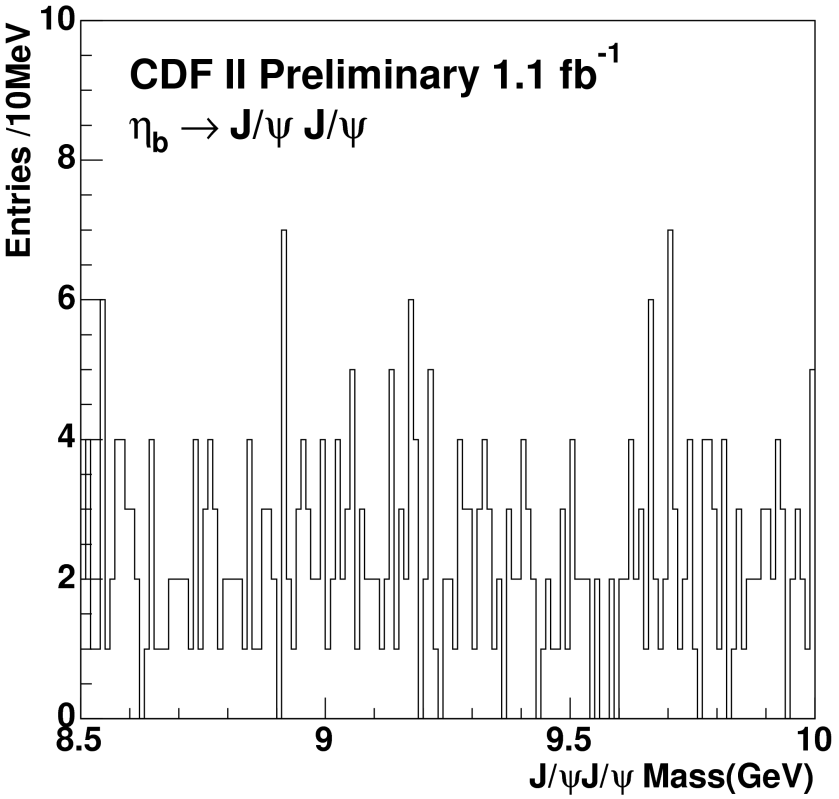



- Lattice calculations for predicting the $B_c$ mass
- Old world average
  - $m(B_c) = 6400 \pm 400$ MeV/$c^2$

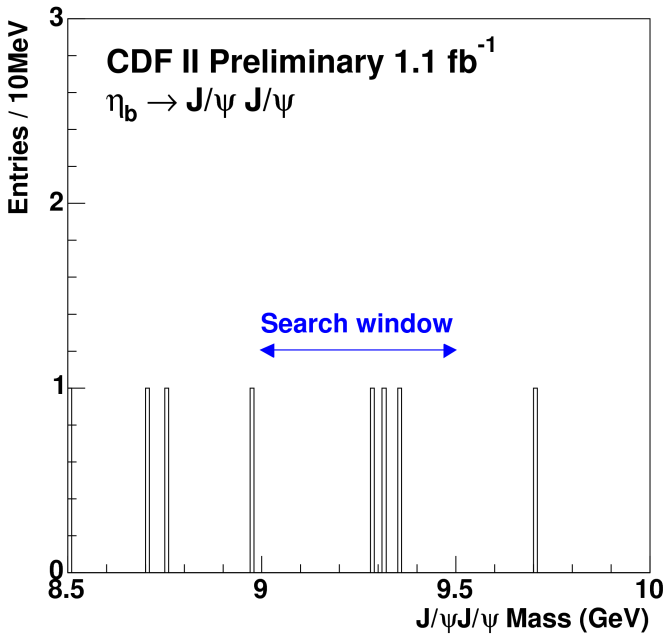
# Search for the $\eta_b$

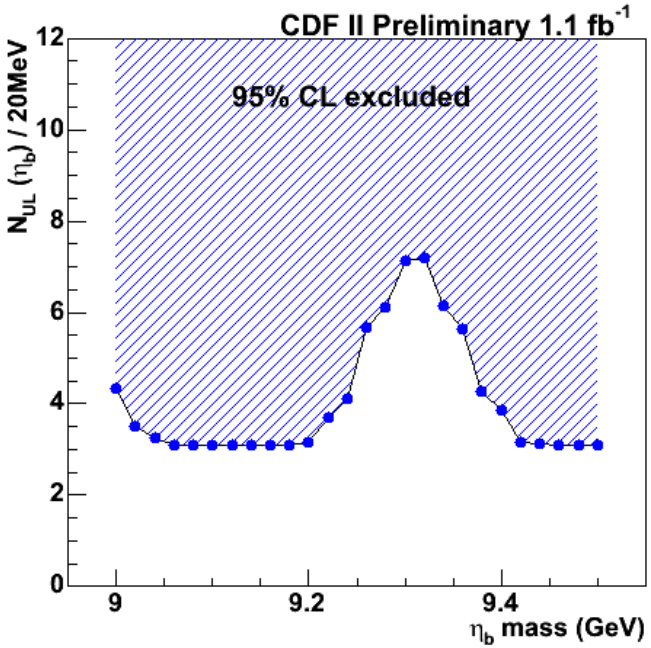
- Pseudo-scalar meson
  - Has not been observed yet
  - Last undiscovered ground state meson
- Predictions of the properties
  - m($\Upsilon$(1s))-m($\eta_b$) = 30..160 MeV/c$^2$
  - $\Gamma(\eta_b) < \Gamma(\eta_c) = 25.5 \pm 3.4$ MeV/c$^2$
  - BR($\eta_b \rightarrow J/\psi\, J/\psi$) = $7 \cdot 10^{-4\pm1}$
  - 0.2 .. 20 events in 1.1 fb$^{-1}$
- Search for $\eta_b \rightarrow J/\psi\, J/\psi$
  - No significant resonance



# Limit for the $\eta_b$

- Search window
  - Tighter cuts
  - 3 events
- Upper limit
  - Bayesian method
- Give upper limit
  - Relative production limit



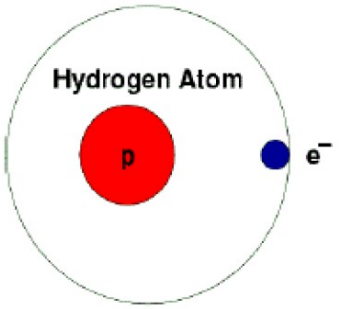

$$\sigma(pp \to \eta_b X) \cdot BR(\eta_b \to J/\psi\, J/\psi) \,/\, \sigma(pp \to Hb \to J/\psi\, X) < 5 \times 10^{-3}$$

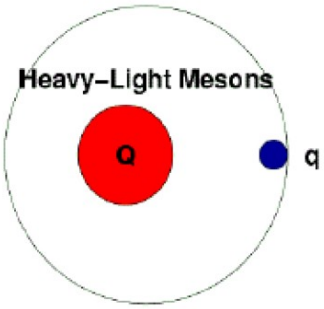
  - combined with $\sigma(pp \to b \to J/\psi\, J/\psi)$

$$\sigma(pp \to \eta_b X) \cdot BR(\eta_b \to J/\psi\, J/\psi) \cdot [BR(J/\psi \to \mu\mu)]^2 < 2.6\ \text{pb (C.L. 95\%)}$$

# Orbitally excited b-mesons

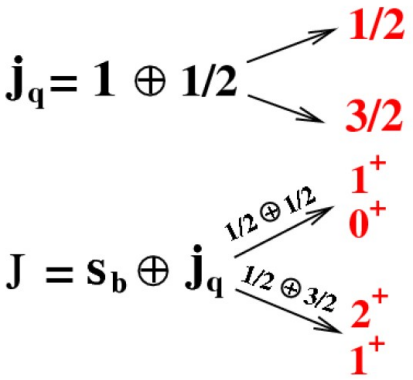
- Heavy Quark Effective Theory (HQET)
  - Qq-mesons with $m_Q \rightarrow \infty$
  - Analogy to hydrogen atom
- Spins of the quarks are decoupled
  - Total spin of the light quark
  - Total spin of the meson
- Four $B_{(s)}^{**}$ states
  - $j_q = 1/2$ states are broad
    - Do not expect to see them
  - $j_q = 3/2$ states are narrow



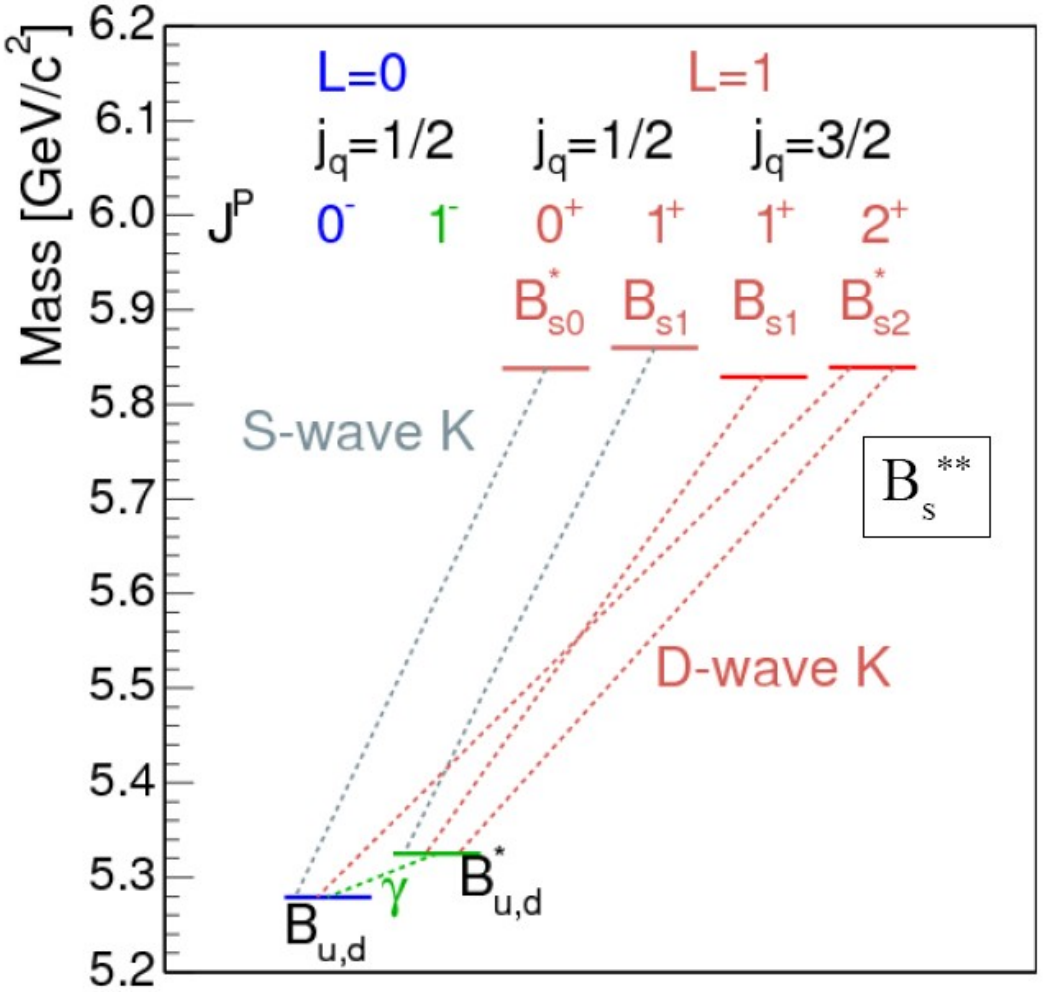




$$\vec{j}_q = \vec{s}_q + \vec{L}$$

$$\vec{J} = \vec{j}_q + \vec{S}_Q$$



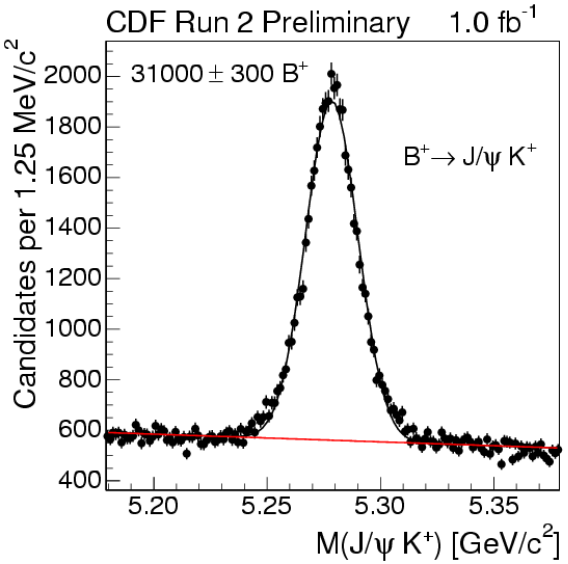
# Transition diagram

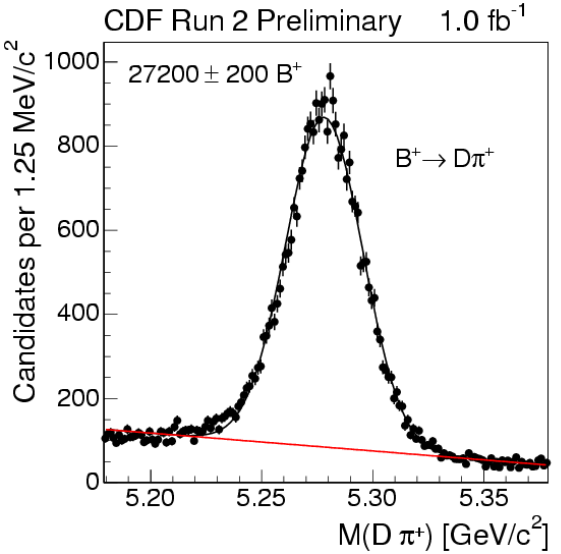



- Emission of a K, $\pi$
- $B_d^{**}$ decays into $B^{(*)}$ $\pi$
- $B_s^{**}$ decays into $B^{(*)}$ K
  - $B_s^{(*)}$ $\pi$ forbidden by isospin
- Narrow states (D-wave)
  - Expected 3 peaks
    - $B_{(s)1}$ → B* $\pi$ (K)
    - $B_{(s)2}$ → B* $\pi$ (K)
    - $B_{(s)2}$ → B $\pi$ (K)

# Outline of the $B_{(s)}^{**}$ analysis

- Decay $B^{**} \rightarrow B^{(*)+} \pi^-$ (K)
  - $B^{*+} \rightarrow B^+ \gamma$ ($\gamma$ undetected)
  - $B^+ \rightarrow J/\psi\, K$
  - $B^+ \rightarrow D^0 \pi^+$
  - $B^+ \rightarrow D^0 3\pi^{\pm}$ (for B** only)
- Selection of the B**
  - Neural networks for $B^+$ and B**
  - Cut on network ouput
  - Cut on number of candidates



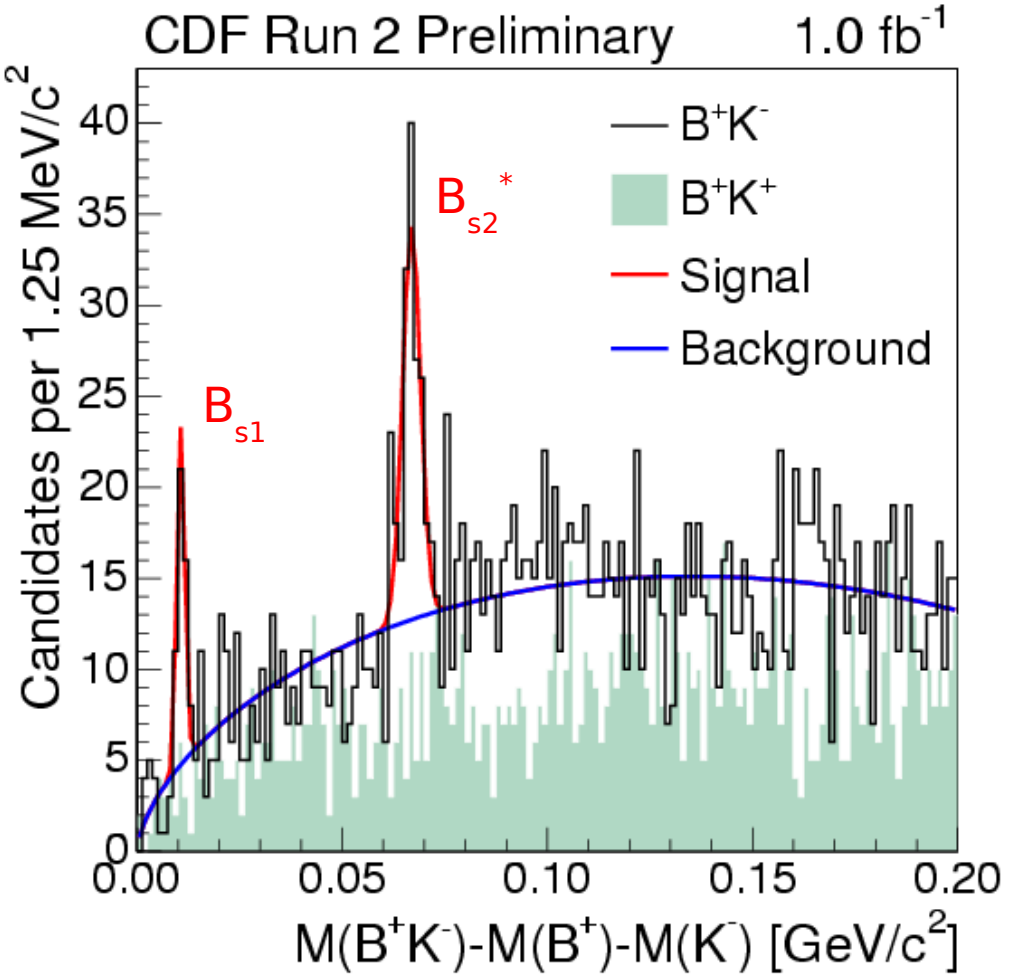



# Observation of the $B_s^{**}$

- Q value distribution
  - Q = m(B**) - m(B) – m(K)
- Fit description
  - Signal: Gaussian
  - Background:

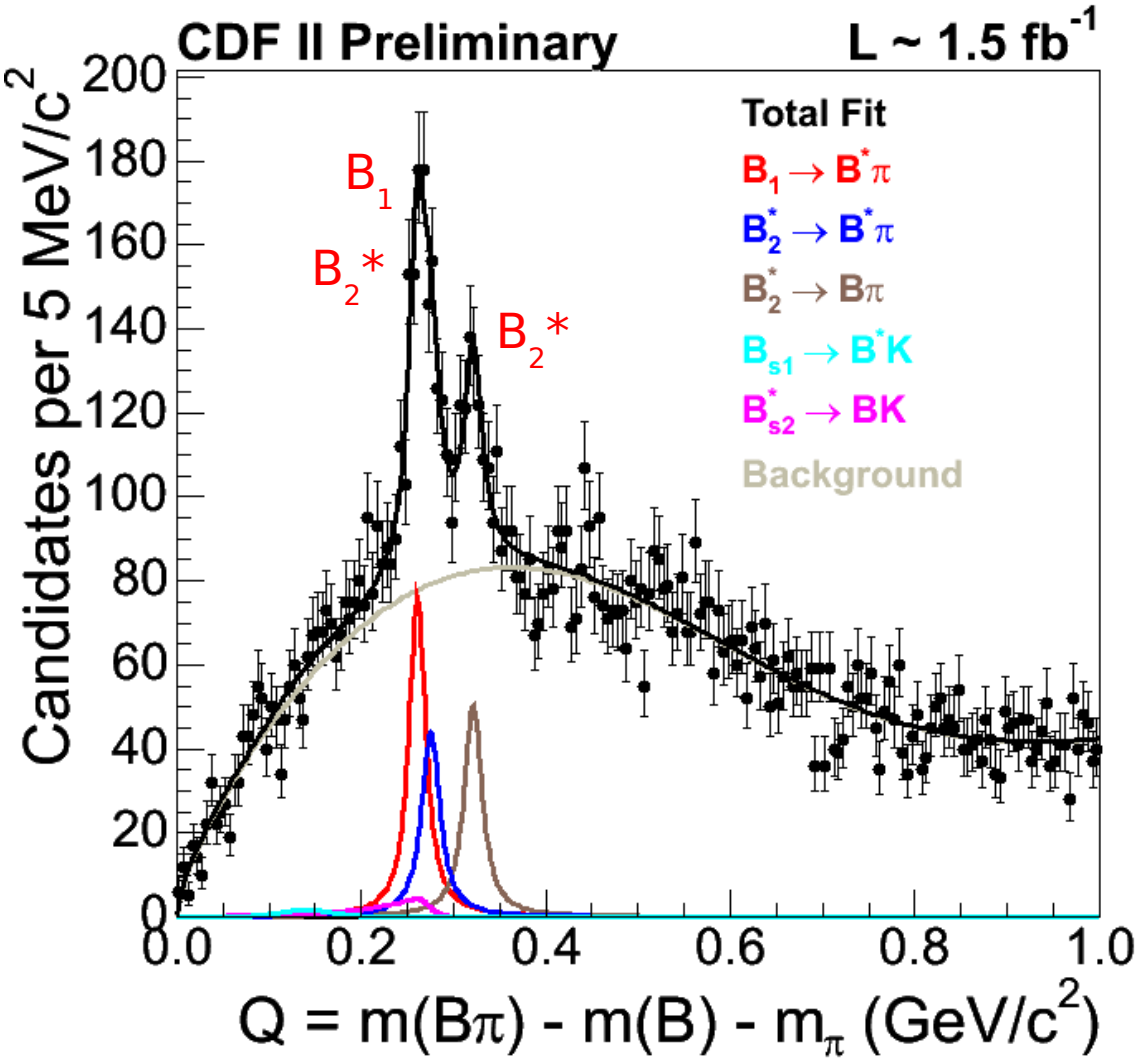
$$Q \cdot (Q - \beta)^{\gamma} \cdot \exp(-\gamma \cdot Q)$$

- Results
  - Significance > 5σ
  - $m(B_{s2}^*) = 5839.64 \pm 0.30 \pm 0.14 \pm 0.5$ MeV/$c^2$
  - $m(B_{s1}) = 5829.41 \pm 0.21 \pm 0.14 \pm 0.6$ MeV/$c^2$



# Observation of the B**

- Q value distribution
  - Clean signal
- Update to to more data
  - 1.7 $fb^{-1}$: $B^+ \rightarrow J/\psi\, K$
  - 1.35 $fb^{-1}$: $B^+ \rightarrow D^0\, (3)\pi^{\pm}$
  - $B^+ \rightarrow D^0\, 3\pi^{\pm}$ also increases statistics



# Summary

- Competitive studies of b-states at CDF
  - First direct observation of the $B_c$
  - Best limit of $\eta_b$ production
  - First observation of both narrow $B_s^{**}$ states
  - Mass measurement of B** states
- For more information and details
  - See: www-cdf.fnal.gov/physics/new/bottom/bottom.html
- B-baryon spectroscopy at CDF (talk by J. Heuser)
- More data expected to come
  - Already on tape and will improve precision

# Backup

# $B_{s1}$ Significance

- Toy MC ensemble according to background only fit
- Fit with and without signal Gaussian
- Calculate difference in log likelihood
- p-Value: Integral over all Toy MCs with at least a given difference over all Toy MCs