Quarkonium Spectroscopy and Decay results from CDF

Thomas Kuhr
KIT

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Outline

- Tevatron and CDF
  - $B_c$
    - Mass
    - Lifetime

- $X(3872)$
  - Mass splitting and mass
Tevatron

\( \sqrt{s} = 1.96 \text{ TeV} \)

- \( B_c \) mass, \( X(3872) \) mass
- \( B_c \) lifetime
- Delivered to tape
- 4.3 fb\(^{-1} \) on tape

CDF
Heavy hadron production at the Tevatron

➔ Huge $b\bar{b}$ and $c\bar{c}$ cross section

➔ Production of all heavy hadron species in fragmentation

but

✗ inelastic cross section

$\sim 10^3$ times larger than $\sigma(b\bar{b})$

➔ Trigger: muon pairs, displaced tracks

✗ Background tracks from fragmentation

➔ High combinatorial background

CDF

Belle
CDF Detector

Muon Chambers
→ Muon ID

Central Drift Chamber
→ Momentum, mass
→ PID

Silicon vertex tracker
→ Lifetime

Time of flight
→ PID

Calorimeters
→ Electron ID

$J/\psi \rightarrow \mu^+ \mu^-$ Trigger
**B_c Mass**

- Only meson with two different heavy quarks
  - Test of QCD models and calculations
  - Mass measurement in $J/\psi \pi$ decay channel
  - Full reconstruction
- Update to 2.4 fb$^{-1}$
- Significance $> 8\sigma$
  - $M(B_c) = 6275.6 \pm 2.9$ (stat) $\pm 2.5$ (syst) MeV/c$^2$
Full reconstruction in $J/\psi \pi$ mode

- Cuts optimized on $B^+ \rightarrow J/\psi K^+$ data and $B_c$ MC
- 1.3 fb$^{-1}$
- Significance $> 5\sigma$

$M(B_c) = 6300 \pm 14$ (stat) $\pm 5$ (syst) MeV/c$^2$
B_c Mass Results

- CDF and D0 results agree within $1.6\sigma$

- Lattice QCD
  [PRL 94, 72001 (2005)]
  and NRQCD
  [PRD 65, 034001 (2002)]:
  - $\sim 2\sigma$ higher than CDF result
  - Less precise than exp.

- Progress on theory side welcome
**$B_c$ Lifetime**

- $B_c$ decay width has contributions from:
  - Decay of $b$ quark
  - Decay of $c$ quark
  - Weak annihilation

  \[ \Gamma_{B_c} \approx \Gamma_b + \Gamma_c + \Gamma_W \]

- Spectator model expectation:
  \[ \tau(B_c) < \tau(B^{0/+}) = 1.5 \text{ ps} \]
  \[ \tau(B_c) \lesssim \tau(D^{0/+}) = 0.4 / 1.0 \text{ ps} \]

  \[ \Rightarrow \text{Predictions: } \tau(B_c) = 0.4 - 0.6 \text{ ps} \]

[hep-ph/0308214 and references therein]
B_c Lifetime Measurement

Use inclusive decay $B_c \rightarrow J/\psi \, \ell \, X$, with $\ell = e \text{ or } \mu$

- ✔ trigger on $J/\psi \rightarrow \mu \mu$
  - ➔ no lifetime bias
- ✔ high statistics
- ✗ partial reconstruction
  - ➔ have to model missing momentum in decay time reconstruction
  - ➔ no narrow mass peak
- ➢ Understanding of backgrounds crucial
Decay Time Reconstruction

- $\mu\mu\ell$ vertex fit $\rightarrow$ decay length $L$

\[
ct = \frac{L}{\beta\gamma} = \frac{L \cdot m(B_c)}{p(B_c)}
\]

\[
ct^* = \frac{L \cdot m(B_c)}{p(J/\psi\ell)} = ct \cdot \frac{p(B_c)}{p(J/\psi\ell)} = ct/K
\]

$\Rightarrow f_{meas}(ct^*) = \exp(-Kct^*/c\tau) \otimes f(K) \otimes \text{res}$

- K-factor distribution from MC
  - Branching ratios (mainly $J/\psi\ell\nu$, $O(1\%)$ $J/\psi\tau\nu$ and $\psi(2S)\ell\nu$)
  - $B_c$ momentum spectrum
Data Sample

- 1 fb\(^{-1}\)
- 5.5 million J/\(\psi\)

→ **Muon selection:**
  muon det., dE/dx
  → 572 J/\(\psi\)\(\mu\) candidates

→ **Electron selection:**
  \(E_{\text{em}}\), \(E_{\text{had}}\), dE/dx

→ Veto conversion electrons by identifying partner track
  → 1935 J/\(\psi\)\(e\) candidates

CDF Run II Preliminary: \(\sim 1\) fb\(^{-1}\)

\(J/\psi\) Signal = 5564.9(2.5) \times 10^3

S/B = 4.4 in \(3.10 \pm 0.50\) GeV/c\(^2\)
Backgrounds

- Fake J/ψ
  - Estimated from J/ψ mass sidebands
- Prompt J/ψ from charm production plus lepton
  - Prompt component in lifetime fit
- J/ψ plus hadron faking a lepton
  - μ: decay-in-flight or punch-through
  - e: hadron with electron like signature
- b¯b events with J/ψ from one and lepton from other b quark
- J/ψ plus conversion electron
  - Estimated from conversion suppression efficiency
Fake Lepton Background

- Proton, kaon, pion fake probability measured from $\Lambda \rightarrow p\pi$ and $D^0 \rightarrow K\pi$ data
- Particle fractions determined from fit to $dE/dx$, ToF
- Number of fake events and their $ct^*$ distribution determined from $J/\psi$+track sample weighted with fake rate
\textbf{bb Background}

- Estimated from MC with production process fractions reweighted to match measured $\Delta \phi(J/\psi, \ell)$ distribution
- Normalized to $B^+ \rightarrow J/\psi K^+$

![Diagram showing the production process fractions reweighted to match measured $\Delta \phi(J/\psi, \ell)$ distribution and normalized to $B^+ \rightarrow J/\psi K^+$]
Lifetime Fit

- Background yields and $c t^*$ distributions
- Signal lifetime model
  - Likelihood fit
  - Systematic uncertainties:
    - Resolution function: $3.8 \mu m$
    - $b \bar{b}$ MC composition: $2.4 \mu m$
    - Silicon detector alignment: $2.0 \mu m$
    - Conversion estimate: $1.5 \mu m$
    - $B_c$ momentum spectrum: $1.3 \mu m$
  - Total: $5.5 \mu m$

<table>
<thead>
<tr>
<th></th>
<th>$J/\psi_\mu$ (fit)</th>
<th>$J/\psi_e$ (fit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fake $J/\psi$</td>
<td>141.5 ± 8.4</td>
<td>315.2 ± 10.0</td>
</tr>
<tr>
<td>Prompt $J/\psi$</td>
<td>96.1 ± 4.6</td>
<td>312.0 ± 4.1</td>
</tr>
<tr>
<td>Fake lepton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b \bar{b}$</td>
<td>77.5 ± 7.9</td>
<td>222.5 ± 11.2</td>
</tr>
<tr>
<td>Conversions</td>
<td></td>
<td>416.8 ± 41.5</td>
</tr>
</tbody>
</table>
**B_c Lifetime Result**

CDF Run II Preliminary: \( \sim 1 \text{ fb}^{-1} \)

- Data - J/ψ µ
  - Total Fit
  - Signal
  - Total Background
  - Fit prob. = 0.51

- Data - J/ψ e
  - Total Fit
  - Signal
  - Total Background
  - Fit prob. = 0.70

\[
\begin{align*}
\c	mu(B_c) & = 179.1^{+32.6}_{-27.2} \text{ (stat) } \mu\text{m} \\
\c	e(B_c) & = 121.7^{+18.0}_{-16.3} \text{ (stat) } \mu\text{m}
\end{align*}
\]

- Combined fit: \( \c\tau(B_c) = 142.5^{+15.8}_{-14.8} \text{ (stat) } \pm 5.5 \text{ (syst) } \mu\text{m} \)

http://www-cdf.fnal.gov/physics/new/bottom/080327.blessed-BC_LT_SemiLeptonic
B_c Lifetime Summary

- CDF and D0 measurements agree well
- Lifetime of $\tau(B_c) = 0.475^{+0.053}_{-0.049}$ (stat) ± 0.018 (syst) ps within predicted range of 0.4-0.6 ps

→ Lifetime measurement in $J/\psi\pi$ mode in progress
We know:

- Decays to $J/\psi \pi^+\pi^-$ (and $D^0\bar{D}^0\pi^0$)
- Mass $\approx 3872$ MeV/c$^2$
- Narrow resonance
- $J^{PC} = 1^{++}$ or $2^{-+}$
- Observed in B decays and prompt production in $p\bar{p}$

We don't know:

- What is it?
- Charmonium
  - Does not fit
- $D^0\bar{D}^0*$ molecule
  - $m(X) \leq m(D^0) + m(D^{0*})$
  - Mass measurement
- 4-quark state
  - Two neutral states
  - Prediction
    
    \[ \Delta m = 8 \pm 3 \text{ MeV/c}^2 \]
    
    Check for two peaks
J/ψπ⁺π⁻ Data Sample

- 2.4 fb⁻¹
- Triggered by J/ψ → μμ
- Vertex fit with two further tracks

CDF II Preliminary

2.4 fb⁻¹

X(3872)

CDF II Preliminary

ψ(2S)

Candidates per 2.5 MeV/c²

J/ψππ Mass (GeV/c²)

Candidates per 1.25 MeV/c²

J/ψππ Mass (GeV/c²)
Selection

- Selection with neural network
  - Variables: $Q$, $p_T(\pi)$, $\chi^2$, muon ID, ...
  - Background from sidebands, signal from MC
  - Check for bias with wrong-charge candidates

- Cut on number of candidates per event

- Selection optimized on significance $N_{\text{MC}} / \sqrt{N_{\text{data}}}$
Mass Shape Fit

Maximum likelihood fit

- **Background**: 2\textsuperscript{nd} order polynomial
- **Signal**:
  - Non-relativistic Breit-Wigner
    - \( \Gamma = 1.34 \pm 0.64 \text{ MeV} \)
      - (average of Belle/BaBar results in \( J/\psi \pi \pi \) decay mode [PRL 91,262001; PRD 77,111101])
  - Resolution function
    - Sum of two Gaussians
    - Determined from MC
      - \( f_{\text{meas}}(m) = \text{BW}(\Gamma) \otimes \text{res}(\sigma_1, \sigma_2) \)
One-Peak Hypothesis Test

- Expect broader peak in case of two states
  - Scale width and resolution by fit parameter $t$
    $$\Gamma \rightarrow t \cdot \Gamma \quad \sigma \rightarrow t \cdot \sigma$$

- Test statistics $t$:
  - Is fitted value of $t$ consistent with hypothesis of one peak?

- Generate pseudo experiments

- Take into account resolution correction by $\sim 5\%$
  - determined from $\psi(2S)$

- Answer: yes
Two-Peak Hypothesis Test

- Is fitted value of \( t \) consistent with hypothesis of two peaks with mass difference \( \Delta m \) and light state fraction \( f_1 \)?

- Generate pseudo experiments with two states (same shape)
Limit on Mass Splitting

For equal mixture of both states ($f_1 = 0.5$):

- $\Delta m < 3.2 \text{ MeV/c}^2$ at 90% C.L.
- $\Delta m < 3.6 \text{ MeV/c}^2$ at 95% C.L.

Disfavors 4-quark model

Belle: $\delta m = m(X|B^+)-m(X|B^0) = (0.18 \pm 0.89 \pm 0.26) \text{ MeV/c}^2$

Mass Measurement

- Mass shape consistent with one peak → measure mass
- Unbinned likelihood fit

Systematic uncertainties:
- Fit model → negligible
- Momentum scale:
  - Check absolute scale on $\psi(2S)$:
    $$m_{\text{fit}}(\psi(2S)) = 3686.03 \pm 0.02 \text{ MeV/c}^2$$
    $$m_{\text{PDG}}(\psi(2S)) = 3686.09 \pm 0.04 \text{ MeV/c}^2$$
    → 60 keV
  - Dependence of $\psi(2S)$ mass on kinematic var. → 100 keV
  - Total (scaled by Q value) → 190 keV
X(3872) Mass Result

\[ m(X) = 3871.61 \pm 0.16 \text{ (stat)} \pm 0.19 \text{ (syst)} \text{ MeV/c}^2 \]

- Most precise measurement
- Consistent with previous results
- Improves precision of world average by factor \(~1.5\)

New average 0.35 MeV/c^2 (0.9\(\sigma\)) below DD* mass

Summary

$B_c$ mass precisely measured

- Can theory catch up?

$B_c$ lifetime measured in inclusive $J/\psi \ell X$ decays

- Precision of measurement and predictions at similar level
- Measurement in exclusive $J/\psi \pi$ mode in progress

Limit on $X(3872)$ mass splitting determined

- 4-quark model disfavored

$X(3872)$ mass precisely measured

- Need more precise $DD^*$ mass for conclusion on molecule model
- What else?
Backup
X(3872) Mass Splitting Limit

- Assume mass of one of the states is measured by B-factories in $B^+$ decays
- Assume we measure average mass of mixture of two states
  - Limit on mass difference