Quarkonium Spectroscopy Results at CDF

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Challenges from charmonium-like states

Quark model works pretty well so far

however, it is challenged by newly discovered charmonium-like states

theses states are called $X/Y/Z$

Outline

CDF experimental aspects

CDF contributions to $X/Y/Z$ before $Y(4140)$

CDF new contribution to $X/Y/Z$: $Y(4140) \rightarrow J/\Psi\Phi$
Strong Points for CDF

Heavy hadrons at Tevatron are:

• copiously produced

• boosted
  --vertex separation
  --boost low $p_T$ daughters

CDF has:

• excellent mass resolution
• excellent vertex resolution
• reasonable hadron PID
CDF detector

- **Muon**: $\mu$ ID
- **ToF**: TOF
- **COT**: track $p$
  - dEdx
- **Silicon**: track $p$
  - vertex
CDF hadron PID

**K-π separation**

**CDF Time-of-flight—TOF mass**

**Summarizing dEdx and ToF into a log-likelihood ratio**

Typical B decay daughter momentum ~GeV,
Main background: prompt pions
CDF recent contributions to Quarkonium Physics

First confirmation of $X(3872)$, first $J^{PC}$ determination

Most precise mass measurement of $X(3872)$:  
$PRL, 103, 152001 (2009)$

$m(X(3872)) = 3871.61 \pm 0.16 \text{ (stat)} \pm 0.19 \text{ (syst)} \text{ MeV/c}^2$

What is new from CDF?
More unexplained states ($cc$+light quark pair) after $X(3872)$ have been observed, no ($cc$+heavy quark pair) reported before CDF's $Y(4140) \rightarrow J/\psi \phi$

$PRL 102, 242002 (2009)$
Why search for $J/\Psi\Phi$?

- Possibilities of four-quark states, hybrid etc have been proposed

$J/\psi\phi$
- extends to heavy quark
- reaches for four-quark states
- reaches for hybrid
- reaches for other possibilities such as nuclear-bound states etc.

Search through exclusive $B$ decays is experimentally more promising
$B \rightarrow J/\Psi\Phi K$ decays have been observed
No structure has been reported so far
Analysis strategy

• I) Reconstruct $B^+$ as:

\[ B^+ \rightarrow J/\psi \phi K^+ \]
\[ J/\psi \rightarrow \mu^+ \mu^- \]
\[ \phi \rightarrow K^+ K^- \]

• II) Search for structure in $J/\psi \phi$ mass spectrum inside $B^+$ mass window
I) Reconstruct $B^+ \rightarrow J/\psi \phi K^+$
The key to reconstruct $B$ signal

Before $L_{xy}>500$ um, kaon PID$>0.2$

![Graph showing candidates distribution before cuts](image1)

After $L_{xy}>500$ um, kaon PID$>0.2$

![Graph showing candidates distribution after cuts](image2)

Hard to see $B$ signal without $L_{xy}$ and kaon PID

Reduce background by a factor of 20 000 by using $L_{xy}$ and kaon PID cuts while keeping about 20% of signal as estimated by control channels.
Applying $L_{xy}$ and kaon PID

Kaon PID reduce background by a factor of $\sim 100$

clear $B^+ \rightarrow J/\psi \phi K^+$ signal

Gaussian function
mean fixed to PDG
rms fixed to resolution (5.9 MeV)

define $\pm 3\sigma$ as $B^+$ signal region
(17.7 MeV obtained from MC)

Purity $\sim 80\%$ in $B^+$ region

Is $\phi$ pure?
Verify $B^+ \rightarrow J/\psi \phi K^+$

- Investigate components of $B^+$ peak
  -- relax $K^+K^-$ mass window to:
  $[1.0,1.04]$ MeV
  -- do $B^+$ sideband subtraction for $K^+K^-$
  -- fit to sideband subtracted $K^+K^-$ mass

- A P-wave relativistic BW only fit to data with $\chi^2$ probability $28\%$, no evidence for $f_0 \rightarrow K^+K^-$ or $K^+K^-$ phase space components with our $\phi$ mass window

Conclusion

pure $B^+ \rightarrow J/\psi \phi K^+$ for $B^+$ peak
negligible $B^+ \rightarrow J/\psi f_0 K^+, J/\psi K^+K^- K^+$ components
II) Search for structures in $J/\psi \phi$ spectrum from $B$
Investigate $J/\psi \phi$ mass spectrum in MC

- MC simulated phase space, full detector simulation

- MC events smoothly distributed in Dalitz plot

- No artifacts in the $J/\psi \phi$ mass spectrum
Investigate $J/\psi \phi$ mass spectrum in MC

- We simulate generic B hadron decays with a $J/\psi$ in the final state and we identified a contamination channel: $B_s \rightarrow \psi(2S)\phi, \psi(2S) \rightarrow J/\psi \pi^+\pi^-$

$PRL.~96,~231801~(2006)$

$B_s$ contamination at $\Delta M > 1.56$ GeV, cut it off for simplification

$20$ times Luminosity of data
Search for structures in \( J/\psi \phi \) mass--Data

Three-body Phase Space Background shape is different from data
An near threshold enhancement is observed
Robustness test

- Extensive cross checks by varying $L_{xy}$, kaon PID, $B^+$ mass window, vertex probability, # of silicon hits, ...

Robust against variations

More signal but with more background
Search for structures in $J/\psi \phi$ mass--Data

- We model the Signal (S) and Background (B) as:
  
  $S$: S-wave relativistic Breit-Wigner  
  $B$: Three-body decay Phase Space

  $\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$  
  $\sqrt{-2\log(L_{max}/L_0)} = 5.3$, need Toy MC to determine significance for low statistics
Significance study

• We determine significance from simulation (Toy MC):

--Generate $\Delta m$ spectrum using Phase Space
--Find most significant fluctuation for each trial anywhere with floating width
--Count it if $-2\log \left( L_{\text{max}} / L_0 \right) (-2\Delta \ln) \geq -2\Delta \ln$ value in data

$\chi^2$ PDF

$$f(z; n) = \frac{z^{n/2-1} e^{-z/2}}{2^{n/2} \Gamma(n/2)} ; \quad z \geq 0$$

P-value: $9.3 \times 10^{-6}$, corresponding to $4.3\sigma$

P-value from $\chi^2$ PDF: $6.5 \times 10^{-6}$, $4.3\sigma$

Most conservative: Phase Space and flat for non-B background, $3.8\sigma$
What is it?

Charmonium Spectrum

- Well **above** charm pair threshold
- Expect **tiny** BF to $J/\psi\phi$
- Does **not** fit into charmonium
- Close $J/\psi\phi$ threshold like $Y(3940)$

Many potential explanations

**Increased B yield by 50-60% by adding more data (up to 5.1 fb$^{-1}$) and adding events from an additional trigger, cuts unchanged**

**large chance for $Y(4140)$ significance to pass 5$\sigma$**
Opportunities

- Determine $J^{PC}$ ($C=\pm$)? Need statistics
  -- increase efficiency, reduce background
  -- add more data, $\Rightarrow 5\sigma$
  -- investigate efficiencies against angles?
  ...

- More channels for this structure?
  -- open charm pair?

**Note:** Search for potential additional structures?

$B^+ \rightarrow \phi\phi K^+$, $B_s \rightarrow J/\psi\phi\phi$,...

$\Upsilon(nS)\phi$, ...
Summary

CDF has been active in Quarkonium studies
--The first confirmation of X(3872)
--The determination of JPC, most precise mass measurement

CDF observes a new structure in $J/\psi \phi$ spectrum

$\text{Mass} = 4143.0 \pm 2.9 \text{ (stat)} \pm 1.2 \text{ (syst)} \text{ MeV}/c^2$

$\text{Width} = 11.7^{+8.3}_{-5.0} \text{ (stat)} \pm 3.7 \text{ (syst)} \text{ MeV}$

$J^{PC} = ? ? ^+ \quad \text{tentatively name it as Y(4140)}$

$B^+ \rightarrow Y(4140)K^+, Y(4140) \rightarrow J/\psi \phi$ \text{ BF estimation: } \sim (9 \pm 3.4 \text{ (stat)} \pm 2.9 \text{ (BF)}) \times 10^{-6}$

About $10 fb^{-1}$ to be recorded by CDF by the end of 2011

Stay tuned!
$J/\psi \rightarrow ee$ is difficult but not impossible

Trigger is gone 😞

$220 \text{ fb}^{-1}$

$m_{\mu\mu\pi\pi}$
Not close from the PDF comparison although they both have $C=+$

$X(4160) \rightarrow D^*D^*$
$\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$
Backup 4

CDF II

2.7 fb⁻¹

Candidates/10 MeV/c

m_{J/ψφ} (GeV/c²)

4.1 4.2 4.3 4.4 4.5 4.6
Tevatron

Luminosity projection curves for Run II

Integrated luminosity (fb⁻¹)

9.3 fb⁻¹
7.8 fb⁻¹

FY09 start
FY10 start

Results up to here

today

time since FY04
The challenge

• Start with typical requirements for $B$ hadron at CDF:

  -- $p(\chi^2)$ for $B^+$ vertex fit $> 1\%$
  -- $p_T(\text{track}) > 0.4 \text{ GeV},$
  -- $\geq 4$ $r \cdot \varphi$ silicon hits
  -- $p_T(B^+) > 4 \text{ GeV}$
  -- mass window:
    $J/\psi (\pm 50 \text{ MeV})$ and $\phi (\pm 7 \text{ MeV})$
  -- constrain $\mu^+\mu^-$ to $J/\psi$ PDG mass value

• NOT applied yet: $L_{xy}$ and kaon PID

Typical hadron collider environment
Applying $L_{xy}$

- Maximize $S/\sqrt{(S+B)}$ for $B^+ \to J/\psi \phi K^+$ signal, has nothing to do with $J/\psi \phi$

- Maximized cuts: $L_{xy} > 500 \, \mu m$, kaon LLR > 0.2

$L_{xy}$ Reduce background by a factor of \(~200\)
Control channels

• We also reconstruct two control channels with similar cuts:

\[ \sim 3 \,000 \, B_s \rightarrow J/\psi \phi, \sim 50 \,000 \, B^+ \rightarrow J/\psi K^+ \]

before \( L_{xy} \) and kaon LLR cuts

• Clean control signals after \( L_{xy} \) and kaon LLR cuts

cross check and efficiency evaluation

\[ B_s \rightarrow J/\psi \phi \]
\[ \sim 800 \text{ events} \]

\[ B^+ \rightarrow J/\psi K^+ \]
\[ \sim 21k \text{ events} \]