Heavy quark meson spectroscopy 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

these states are called X/Y/Z

Outline

CDF has been involved the first X states—X(3872) and continues to contribute to it: determine quantum number, precisely measures X(3872) mass.

CDF new contribution to X/Y/Z:  Y(4140) \rightarrow J/ψΦ
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 $p$
- **Silicon**: track $p$
- **dEdx**
- **vertex**
CDF hadron PID

K-π separation

summarizing dEdx and ToF into a log-likelihood ratio

Typical B decay daughter momentum ~GeV, Main background: prompt pions
**X(3872)--2003**

**Mass**

- $\eta_c(1S)$
- $J/\psi(1S)$
- $h_c(1P)$
- $X(3872)$

**Decay**

$X(3872) \rightarrow J/\psi \pi^+ \pi^-$

- $M = 3871.8 \pm 0.7 \pm 0.4$ MeV
- $\Gamma < 3.5$ MeV @ 90% CL

**Table: N^2S+1_L_J J^{PC}**

<table>
<thead>
<tr>
<th>N, 2S+1, L, J</th>
<th>J^{PC}</th>
<th>$u\bar{u}$, $u\bar{u}$, $d\bar{d}$</th>
<th>$u\bar{u}$, $d\bar{d}$, s\bar{s}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1S_0$</td>
<td>0--</td>
<td>$\pi$</td>
<td>$\eta$, $\eta'$, $\eta_c(1S)$</td>
</tr>
<tr>
<td>$^1S_1$</td>
<td>1--</td>
<td>$\rho$</td>
<td>$\omega$, $\phi$ $J/\psi(1S)$</td>
</tr>
<tr>
<td>$^1P_1$</td>
<td>1++</td>
<td>$b_1(1235)$, $h_1(1170)$, $h_1(1380)$</td>
<td>$h_c(1P)$</td>
</tr>
<tr>
<td>$^1P_0$</td>
<td>0++</td>
<td>$a_0(1450)^<em>$, $f_0(1370)^</em>$, $f_0(1710)^*$</td>
<td>$X_0(1P)$</td>
</tr>
<tr>
<td>$^1P_1$</td>
<td>1++</td>
<td>$a_1(1260)$, $f_1(1285)$, $f_1(1420)$</td>
<td>$X_1(1P)$</td>
</tr>
<tr>
<td>$^1P_2$</td>
<td>2++</td>
<td>$a_2(1320)$, $f_2(1270)$, $f_2'(1525)$</td>
<td>$X_2(1P)$</td>
</tr>
<tr>
<td>$^1D_2$</td>
<td>2++</td>
<td>$\pi_2(1670)$, $\eta_2(1645)$, $\eta_2(1870)$</td>
<td>$X_0(1P)$</td>
</tr>
<tr>
<td>$^1D_1$</td>
<td>1--</td>
<td>$\rho(1700)$, $\omega(1650)$, $\psi(3770)$</td>
<td>$X_1(1P)$</td>
</tr>
<tr>
<td>$^3D_2$</td>
<td>2--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^3D_3$</td>
<td>3--</td>
<td>$\rho_3(1690)$, $\omega_3(1670)$, $\phi_3(1850)$</td>
<td>$X_2(1P)$</td>
</tr>
<tr>
<td>$^3P_4$</td>
<td>4++</td>
<td>$a_4(2040)$, $f_4(2080)$, $f_4(2220)$</td>
<td>$X_0(1P)$</td>
</tr>
<tr>
<td>$^1S_0$</td>
<td>0--</td>
<td>$\pi(1300)$, $\eta(1295)$, $\eta(1440)$, $\eta_c(2S)$</td>
<td>$X_1(1P)$</td>
</tr>
<tr>
<td>$^3S_1$</td>
<td>1--</td>
<td>$\rho(1450)$, $\omega(1420)$, $\phi(1680)$, $\psi(2S)$</td>
<td>$X_2(1P)$</td>
</tr>
<tr>
<td>$^3P_2$</td>
<td>2++</td>
<td>$a_2(1700)$, $f_2(1950)$, $f_2(2010)$</td>
<td>$X_0(1P)$</td>
</tr>
<tr>
<td>$^3S_0$</td>
<td>0--</td>
<td>$\pi(1800)$, $\eta(1760)$</td>
<td>$X_1(1P)$</td>
</tr>
</tbody>
</table>

**Diagrams:**

- **Graph:** Events/5 MeV/c²
- **Graph:** $M(\pi^+\pi^- J/\psi)$ (MeV/c²)
- **Graph:** $|\cos(\theta_{vJ})| < 0.5$
- **Graph:** $|\cos(\theta_{vJ})| > 0.5$

**CDF Run II**

- $L = 780$ pb⁻¹

X(3872)

- data points
- acc. corrected prediction for $J^{PC} = 1^{++}$ or $2^{++}$

- $0^+_p$
- $1^-_p$
- $1^{++}_p$
- $2^{++}_p$
New X(3872) Mass Measurement at CDF

~6000 signals

The largest sample to date

Use neural network to select

I. Test the hypothesis of: X(3872) composed of two states?

II. Make (most) precise mass measurement Relevant to DD* molecule hypothesis
New X(3872) Mass Measurement at CDF

Assuming different fraction for possible two states.

Breit-Wigners convoluted with resolution (assuming same width-1.34 MeV/c²)

Consistent with one state in data, set limit for two state mass difference:

\[ \Delta m < 3.2 \text{ (3.6) MeV/c}^2 \text{ at 90\% (95\%) C.L.} \]

Conclusion:
Consistent with one state hypothesis.

\[ m(X(3872)) = 3871.61 \pm 0.16 \text{ (stat) } \pm 0.19 \text{ (syst) MeV/c}^2 \]
(assuming one state hypothesis)
New X(3872) Mass Measurement at CDF

Consistent with one state hypothesis

The most precise measurement to date, still within the D*D threshold uncertainty
Motivation to search for new state

Above $D\bar{D} && D\bar{D}^*$ threshold, tiny Branching Fraction expected
New mass and width from BaBar:
$M \approx 3914^{+3.8}_{-3.4}\pm 2.0$, $\Gamma \approx 34^{+12}_{-8}\pm 5$ MeV
at the $J/\psi\omega$ threshold

Many more, for instance, $Z(4430)^+$, but no heavier quark such as $s$ involved.

Well above $D\bar{D} && D\bar{D}^*$ threshold, tiny Branching Fraction expected
$J^{PC}=1^{--}$, plus $Y(4350)$, $Y(4660)$ too many $1^{--}$? 
Why search $J/\Psi\Phi$?

- 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 easy
$B \rightarrow J/\Psi\Phi K$ 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

Diagram:

- Primary vertex
- Secondary vertex
- Particle Identification
- Vertex separation
- $J/\psi$
- $\phi$
- $\mu^+$
- $\mu^-$
- $K^+$
- $K^-$
- $L_{xy}$
I) Reconstruct $B^+ \rightarrow J/\psi\phi K^+$
The key to reconstruct B signal

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

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

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

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

CDF II Preliminary, 2.7 fb$^{-1}$

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?

Kaon PID reduce background by a factor of $\sim 100$
clear $B^+ \rightarrow J/\psi \phi K^+$ signal
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 $f_0 \rightarrow K^+K^-$ 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

$\Delta M = m(\mu^+\mu K^+K^-) - m(\mu^+\mu)$
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: $B_s \rightarrow \psi(2S)\phi$, $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$

$$(B_s \rightarrow \psi(2S)\phi, \psi(2S) \rightarrow J/\psi\pi^+\pi^-) \rightarrow B^+ \rightarrow J/\psi\phi K^+ \text{ due to kaon mis-identification}$$

- $B_s$ 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

Default cuts

\[ \Delta M = m(\mu^+\mu K^+K^-) - m(\mu^+\mu) \]

- 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

\[ \Delta M = m(\mu^+\mu^+K^+K^-) - m(\mu^+\mu^-) \]

\[ \sqrt{-2\log(L_{\text{max}}/L_0)} = 5.3, \text{ need Toy MC to determine significance for low statistics} \]
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 $-2\log(L_{\text{max}}/L_0)$ ($-2\Delta \ln$) $\geq -2\Delta \ln$ value in data

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?

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

Opportunities

- **Determine $J^{PC}$ ($c=+$)? 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 more structures?
- $B^+ \rightarrow \phi K^+$, $B_s \rightarrow J/\psi \phi$, ...
- $\Upsilon(nS) \phi$, ...

![Luminosity projection curves for Run II](image)
Summary

I. CDF observes a new structure in $J/\psi\phi$ spectrum through $B$ decays, at least 3.8\(\sigma\)

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

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

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

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

II. CDF continues to contribute to $X(3872)$:

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

Most precise to date!

Stay tuned!
Backup 1

$J/\psi \to ee$ is difficult but not impossible

Trigger is gone 😞

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

$m_{\mu\mu\pi\pi}$

$\sim 400 \text{ fb}^{-1}$

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

$X(4160) \rightarrow D^*D^*$
ΔM = \mu^+ \mu^- K^+ K^- - m(\mu^+ \mu^-)
CDF II Preliminary, 2.7 fb$^{-1}$

Candidates/10 MeV/$c$

$m_{J/\psi \phi}$ (GeV/$c^2$)
Tevatron

Luminosity projection curves for Run II

- Today
- FY10 start
- Results up to here
- FY09 start

Integrated luminosity (fb⁻¹)

Time since FY04
The challenge

- Start with typical requirements for B hadron at CDF:
  - $p(\chi^2)$ for $B^+$ vertex fit > 1%
  - $p_T(\text{track}) > 0.4$ GeV,
  - $\geq 4$ r-$\varphi$ silicon hits
  - $p_T(B^+) > 4$ GeV
  - Mass window:
    - $J/\psi$ (±50 MeV) and $\phi$ (± 7 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 $B^+ \rightarrow J/\psi \phi K^+$ 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 $\sim 200$
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**