Observation of Structures in the $J/\psi\phi$ from $B^+ \rightarrow J/\psi\phi K^+$ Decay at CMS

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BNL Particle Physics Seminar, Feb 7, 2013
• LHC yields large amounts of data at the world's highest energy
• Besides confirmation of the SM (i.e. Higgs), enormous opportunities to search for new phenomena in high-pt & low-pt regimes

This talk focuses on a new phenomena in low-pt QCD (2011, 7 TeV)
Outline

• Introduction & motivation
• $Y(4140) \rightarrow J/\Psi \phi$? CDF vs LHCb
• CMS detector and trigger
• CMS searches of structures in $J/\Psi \phi$
• Observation of two structures in $J/\Psi \phi$ @CMS
• Comparison & implications
• Summary
**Quark Model**

- **The birth of quark model (M. Gell-Mann & G. Zweig):** M. Gell-Mann, Phys. Lett. 8, 214 (1964)

- **All (known) hadrons are bound states of quarks**
  - **Baryons:** $(qqq)$
  
  - **Mesons:** $(q\bar{q})$
  
  - **quarkonia:** $(ss), (cc), (bb)$ (hidden)

- **J/ψ establishes the quark model, Y(1S) further confirms it**

- **Gell-Mann also suggested exotic states $(qq\bar{q}\bar{q}), (qq\bar{q}\bar{q})$ at the birth of quark model, but evidence has never been solidly established**

*Interest in exotics revitalized by the discovered charmonium-like states despite almost a decade, still mysterious!*
From strange to bottom discovery

$\Omega^-$ discovery

J/\psi (\bar{c}c) discovery

Y (\bar{b}b) discovery

BNL

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BNL

SLAC

FNAL

1964

1968

1974

1974

1977

Heavy flavor quarkonium spectroscopy helped turn quarks into a reality!

What we can learn more from quarkonium(-like) spectroscopy?
Charmonium (c\bar{c}) Potential Model (Cornell Model)

- simple QCD-inspired phenomenological potential:

\[ V(r) = -\frac{\kappa}{r} + \frac{r}{a^2} , \quad \kappa = 0.61, \quad m_c = 1.84 \text{ GeV}, \quad a = 2.38 \text{ GeV}^{-1} \]

- non-relativistic (charm quark is “heavy” compared to binding energy)

- quark confinement (increases linearly with separation)

- extendable to include spin-dependent terms, relativistic corrections, etc.

- Lattice QCD provides calculation of the masses and widths

Eichten et. al., PRD 17, 3090 (1978)
Godfrey & Isgur, PRD 32, 189 (1985)
Barnes et. al., PRD 72, 054026 (2005)
# Charmonium States

<table>
<thead>
<tr>
<th>Notation:</th>
<th>Quantum numbers</th>
<th>Name</th>
<th>Mass (MeV/c²)</th>
<th>width(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2S⁺¹[L]J</td>
<td>N  L  JPC</td>
<td>N²S⁺¹L_J</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L=S,P,D</td>
<td>0  0  0⁺</td>
<td>1¹S₀</td>
<td>2980.4±1.2</td>
<td>26.7±3</td>
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<tr>
<td></td>
<td>0  1  1⁻</td>
<td>1³S₁</td>
<td>3096.916±0.011</td>
<td>93.2±0.02×10⁻³</td>
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<tr>
<td></td>
<td>1  0  0⁺⁺</td>
<td>1³P₀</td>
<td>3414.75±0.31</td>
<td>10.2±0.7</td>
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<tr>
<td></td>
<td>1  1  1++</td>
<td>1³P₁</td>
<td>3510.66±0.07</td>
<td>0.89±0.05</td>
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<tr>
<td></td>
<td>1  1  2++</td>
<td>1³P₂</td>
<td>3556.20±0.09</td>
<td>2.03±0.12</td>
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<td></td>
<td>1  1  1⁺⁻</td>
<td>1³P₁</td>
<td>3525.93±0.27</td>
<td>&lt;1</td>
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<tr>
<td></td>
<td>1  2  1⁻</td>
<td>1³D₁</td>
<td>ψ(3770)</td>
<td>27.3±1.0</td>
</tr>
<tr>
<td></td>
<td>2  0  0⁺</td>
<td>2¹S₀</td>
<td>3637±4</td>
<td>14±7</td>
</tr>
<tr>
<td></td>
<td>2  0  1⁻</td>
<td>2³S₁</td>
<td>ψ(2S)</td>
<td>3686.09±0.04</td>
</tr>
<tr>
<td></td>
<td>2  1  2⁺⁺</td>
<td>2³P₂</td>
<td>χc₂(2P)</td>
<td>3929±5</td>
</tr>
<tr>
<td></td>
<td>3  0  1⁻</td>
<td>3³S₁</td>
<td>ψ(4040)</td>
<td>4039±1</td>
</tr>
<tr>
<td></td>
<td>2  2  1⁻</td>
<td>2³D₁</td>
<td>ψ(4160)</td>
<td>4153±3</td>
</tr>
<tr>
<td></td>
<td>4  0  1⁻</td>
<td>4³S₁</td>
<td>ψ(4415)</td>
<td>4421±4</td>
</tr>
</tbody>
</table>

**Notation:**

\[ 2S⁺¹[L]J \]

\[ L=S,P,D \ (0,1,2) \]

(No cand. with \[ L>=3 \])

\[ J = L+S \]

\[ S(q\bar{q}) = 0 \ or \ 1 \]

**Parity:** \[ P = (-1)^{L+1} \]

**Charge conjugation eigenvalues:**

\[ C=(-1)^{L+S} \]

**N:** Radial Quantum Numbers

*These states work well with charmonium model, until the appearance of \( X(3872) \)*
Hints before the discovery of $X(3872) \rightarrow J/\psi \pi^+ \pi^-$

CDF internal, 1994

BaBar internal, 2003

CDF saw a hint in 1994, unpublished
BaBar saw a hint in 2003, unpublished

Both CDF and Babar spotted hints of $X(3872)$ before its discovery!
**X(3872)--2003**

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

\[ M = 3871.8 \pm 0.7 \pm 0.4 \text{ MeV} \]
\[ \Gamma < 3.5 \text{ MeV} \text{ @ 90% CL} \]

**First particle challenging charmonium model, revitalized exotic meson study**

<table>
<thead>
<tr>
<th>( N^{2S+1}L_J )</th>
<th>( J^{PC} )</th>
<th>( u \bar{u}, d \bar{d}, s \bar{s} )</th>
<th>( u \bar{d}, u \bar{d}, d \bar{d} )</th>
<th>( I = 1 )</th>
<th>( I = 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1( ^3 )S_0</td>
<td>0^-</td>
<td>( \pi )</td>
<td>( \eta, \eta' )</td>
<td>( \eta_c(1S) )</td>
<td></td>
</tr>
<tr>
<td>1( ^3 )S_1</td>
<td>1^-</td>
<td>( \rho )</td>
<td>( \omega, \phi )</td>
<td>( J/\psi(1S) )</td>
<td></td>
</tr>
<tr>
<td>1( ^3 )P_1</td>
<td>1^-</td>
<td>( b_1(1235) )</td>
<td>( h_1(1170), h_2(1380) )</td>
<td>( h_c(1P) )</td>
<td></td>
</tr>
<tr>
<td>1( ^3 )P_0</td>
<td>0^++</td>
<td>( a_0(1450)^* )</td>
<td>( f_0(1370)^<em>, f_0(1710)^</em> )</td>
<td>( \chi_c(0P) )</td>
<td></td>
</tr>
<tr>
<td>1( ^3 )P_1</td>
<td>1^+</td>
<td>( a_1(1260) )</td>
<td>( f_1(1285), f_1(1420) )</td>
<td>( \chi_c(1P) )</td>
<td></td>
</tr>
<tr>
<td>1( ^3 )P_2</td>
<td>2^+</td>
<td>( a_2(1320) )</td>
<td>( f_2(1270), f_2'(1525) )</td>
<td>( \chi_c(2P) )</td>
<td></td>
</tr>
<tr>
<td>1( ^1 )D_2</td>
<td>2^-</td>
<td>( \pi_2(1670) )</td>
<td>( \eta_2(1445), \eta_2(1870) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1( ^3 )D_1</td>
<td>1^-</td>
<td>( \rho(1700) )</td>
<td>( \omega(1650) )</td>
<td>( \psi(3770) )</td>
<td></td>
</tr>
<tr>
<td>1( ^3 )D_2</td>
<td>2^-</td>
<td>( \omega_3(1670) )</td>
<td>( \phi_3(1850) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1( ^3 )D_3</td>
<td>3^-</td>
<td>( \rho_3(1690) )</td>
<td>( \omega_3(1670), \phi_3(1850) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1( ^3 )F_4</td>
<td>4^+</td>
<td>( a_4(2040) )</td>
<td>( f_4(2050), f_4'(2220) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2( ^1 )S_0</td>
<td>0^-</td>
<td>( \pi(1300) )</td>
<td>( \eta(1295), \eta(1440) )</td>
<td>( \eta_c(2S) )</td>
<td></td>
</tr>
<tr>
<td>2( ^3 )S_1</td>
<td>1^-</td>
<td>( \rho(1450) )</td>
<td>( \omega(1420), \phi(1680) )</td>
<td>( \psi(2S) )</td>
<td></td>
</tr>
<tr>
<td>2( ^3 )P_2</td>
<td>2^+</td>
<td>( a_2(1700) )</td>
<td>( f_2(1950), f_2(2010) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3( ^1 )S_0</td>
<td>0^-</td>
<td>( \pi(1800) )</td>
<td>( \eta(1760) )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*(Problematic) features*

- Mass ~70 MeV > \( 1^3D_2 \) charmonium, \( J^{PC} = 1^{++} \) or \( 2^+ \)
- \( M(\pi^+\pi^-) \) peaks as a \( \rho, C=+, isospin=1 \) (charmonium--0)
- Decays to \( J/\psi\gamma \) & \( \Psi'\gamma \), suppressed for \( 2^+ \)

**Mass close to DD*, molecule is speculated**

- No charged partners observed, tetra-quark?
- Similar rate as charmoniums at hadron colliders.
- Mixture of a \( DD^* \) molecule and the \( 2^3P_1 \) charmonium?

\[ \text{PRL 91, 262001} \]
$Y(3940) \to J/\psi \omega$, $Y(4260) \to J/\psi \pi^+ \pi^-$ -- 2005

Above $D\bar{D}$ & $D\bar{D}^*$ threshold,
Tiny branching fraction expected
New mass and width from BaBar:
$M \approx 3919.1^{+3.8}_{-3.4} \pm 2.0$, $\Gamma \approx 31^{+10}_{-8} \pm 5$ MeV
arXiv:1012.0074 [hep-ex]
at the $J/\psi \omega$ threshold?

Well above $D\bar{D}$ & $D\bar{D}^*$ threshold,
Tiny branching fraction expected
$J^{PC}=1^{-}$, plus $Y(4350)$, $Y(4660)$
too many $1^{-}$ ?
Z(4430)$^+\rightarrow\psi(2S)\pi^+$ -- 2008

The first charged charmonium-like state, a smoking gun if confirmed

Babar disagrees with Belle

Many more new states...
They do not fit into charmonium expectation
Has been extended to bottomonium system

Beyond (q̅q) mesons: exotic mesons?
**Exotic Models-I**

**Molecular**
Loosely *bound state* of a pair of *mesons*. The dominant binding mechanism should be *pion exchange*. Being weakly bound the mesons tend to decay as if they were free.

![Molecular Diagram](image)

**Tetraquark**
Bound state of *four quarks*, i.e. $qq\bar{q}\bar{q}$ in which the quarks group into color triplet scalar or vector clusters.

Strong decays proceed via rearrangement processes.

![Tetraquark Diagram](image)

**Diquark-diantiquark**

**Distinctive features of multi-quark picture with respect to charmonium:**
- prediction of many new states
- possible existence of states with non-zero charge, strangeness or both
Exotic Models-II

Charmonium hybrids
States with excited gluonic degrees of freedom; exotic $J^{PC}=0^{+-}, 1^{+-}, 2^{+-}...$ not allowed for charmonium. Smoking gun for exotic states.

Lattice QCD for $1^{-+}$: $m \sim 4.3 \pm 0.05$ GeV (C. Thomas)

Threshold, cusp, or coupled-channel effect giving a cross section enhancement which may not correspond to resonance production at all.

Hadro-charmonium
Light hadrons bounded by van der Waal’s force to a charmonium core in the case where the light hadron is a highly excited resonance.

We know something is going on even though we do not know exactly what!

New kind(s) of spectroscopy with complex binding forces?

How about $J/\psi \phi$ system? (threshold @4.116 GeV, $VV, C=+$) ($cc$) with a mass above 4.116 GeV, expect tiny branching fraction to $J/\Psi \phi$. 

13
Charmonium hybrid $\rightarrow J/\psi \phi$?

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>Open charm</th>
<th>Hidden charm</th>
</tr>
</thead>
</table>
| $0^{+-}$ | Quantum numbers forbid | $J/\psi \{ f_{0,1,2} \}, \{ \pi \pi \} \, S$  
  $h_c \eta, \, \eta_c h_1$  
  $\chi_{c0} \omega$  
  $\chi_{c1,2} \{ \omega, h_1, \gamma \}$ |
| $0^{--}$ | $D^* D$ | $h_c (\pi \pi)_S$  
  $J/\psi \{ f_{1,2} \}, \eta^{(')} \}$  
  $\chi_{c0} h_1; \, \eta_c \{ \omega, \phi \}$  
  $\chi_{c1,2} \{ \omega, h_1, \gamma \}$ |
| $1^{-+}$ | $D^* D, \, D^* D^*$ | $\chi_{c0,1,2} (\pi \pi)_S$  
  $\eta_c \{ f_{1,2}, \eta^{(')} \}$  
  $\chi_{c1,2} \eta$  
  $\{ h_c , J/\psi \} \{ \omega, h_1, \phi, \gamma \}$ |
| $2^{++}$ | $D^* D, \, D^* D^*$ | $\{ h_c , J/\psi \} \{ f_{0,1,2} \}, (\pi \pi)_S \}$  
  $\{ h_c , J/\psi \} \eta^{(')} \}$  
  $\{ \eta_c , \chi_{c0,1,2} \} \{ \omega, h_1, \phi, \gamma \}$ |

Considered to be the ground exotic state, mass prediction from 3.9 to 5.3 GeV

Most recent Lattice QCD calculation: 4.3 ± 0.05 GeV
Multi-quark states $\rightarrow J/\psi \phi$?

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>M (MeV)</th>
<th>Decay Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^{++}$</td>
<td>3834</td>
<td>-</td>
</tr>
<tr>
<td>0$^{++}$</td>
<td>3927</td>
<td>$J/\psi \omega$</td>
</tr>
<tr>
<td>0$^{-+}$</td>
<td>4277(+15)</td>
<td>$J/\psi \phi, J/\psi \omega, D_{s}^{+}D_{s}^{-}$</td>
</tr>
<tr>
<td>0$^{-+}$</td>
<td>4312(+30)</td>
<td>$J/\psi \phi, J/\psi \omega, D_{s}^{+}D_{s}^{-}$</td>
</tr>
<tr>
<td>0$^{--}$</td>
<td>4297(-5)</td>
<td>$\psi \eta(\eta'), D_{s}^{+}D_{s}^{-}$</td>
</tr>
<tr>
<td>1$^{++}$</td>
<td>3890</td>
<td>$J/\psi \omega$</td>
</tr>
<tr>
<td>1$^{+-}$</td>
<td>3870</td>
<td>$J/\psi \eta$</td>
</tr>
<tr>
<td>1$^{+-}$</td>
<td>3905</td>
<td>$J/\psi \eta$</td>
</tr>
<tr>
<td>1$^{-+}$</td>
<td>4321(+15)</td>
<td>$J/\psi \omega, J/\psi \phi$</td>
</tr>
<tr>
<td>1$^{-+}$</td>
<td>4356 (+30)</td>
<td>$J/\psi \omega, J/\psi \phi$</td>
</tr>
<tr>
<td>1$^{--}$</td>
<td>4330</td>
<td>$\psi \eta(\eta'), D_{s}^{(<em>)+}D_{s}^{(</em>)-}; J/\psi f_{0}(980)$</td>
</tr>
<tr>
<td>1$^{--}$</td>
<td>4341(-5)</td>
<td>$\psi \eta(\eta'), D_{s}^{(<em>)+}D_{s}^{(</em>)-}; J/\psi f_{0}(980)$</td>
</tr>
<tr>
<td>1$^{--}$</td>
<td>4390(+40)</td>
<td>$\psi \eta(\eta'), D_{s}^{(<em>)+}D_{s}^{(</em>)-}; J/\psi f_{0}(980)$</td>
</tr>
<tr>
<td>1$^{--}$</td>
<td>4289(-41)</td>
<td>$\psi \eta(\eta'), D_{s}^{(<em>)+}D_{s}^{(</em>)-}; J/\psi f_{0}(980)$</td>
</tr>
</tbody>
</table>

J/\psi \phi is well motivated!

How to search?

Inclusive? Challenge!

Through B decays!
Search structures $\rightarrow J/\psi \phi$ through $B$ decays

- Experimentally attractive to search through clean $B \rightarrow J/\psi \phi K$ channel
  - taking advantage of $B$ lifetime and narrow $B$ mass window
  - $B \rightarrow J/\psi \phi K$ is OZI suppressed, so low rate from phase space decays
  - constrained phase space favor forming of two-body structures.

**Vacuum Polarization**

**Gluon Coupling**
The status before Original CDF Report

- The status through $B \rightarrow J/\psi \phi K$

  \[ M^2(J/\psi \phi K) \text{ (GeV}^2/c^4) \]

  \[ M^2(\phi K) \text{ (GeV}^2/c^4) \]

  \[ J/\psi \rightarrow \mu \mu \text{ and } ee, \ 10 \ B^+ \text{ and } B^0 \]

  \[ J/\psi \rightarrow \mu \mu \text{ and } ee \]

- Statistically limited, no structures reported

CLEO 1999, PRL 84, 1393

BaBar 2003, PRL 91, 071801

23 $B^+$

13 $B^0$
First Report by CDF w/ 2.7 fb^{-1} (2009)

\[ B \rightarrow J/\psi \phi K \]

\[ \phi \rightarrow K^+ K^- \]

Purity \(~80\%\) in \(B^+\) region

Nice \(\phi\) shape

Near threshold peak, called \(Y(4140)\)

Significance: \(~4\sigma\)

Yield = \(14 \pm 5\)

\[ M = 4143.0 \pm 2.9 \text{ (stat)} \pm 1.2 \text{ (syst)} \text{ MeV} \]

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

Not likely to be charmonium:

High mass w/ narrow width

\[ \Delta M = m(\mu^+ \mu^- K^+ K^-) - m(\mu^+ \mu^-) \]
Reflection in Three-body Decays

Three resonances:

\[ A \rightarrow M_{12} \]
\[ B \rightarrow M_{23} \]
\[ C \rightarrow M_{13} \]

Example: \( \rho^+, N^{++}, N^{*+} \) in \( \pi^+ + p \rightarrow \pi^+ + \pi^0 + p \)

Depending on \( J^{PC} \), \( B \) & \( C \) can be structure-less or structures in \( M_{12} \). In this example, \( B \) shows flat distribution in \( M_{12} \) and \( C \) shows up two structures in \( M_{12} \).

There are no established resonances in \( m(\phi K^+) \) (possible hint for \( K_1 \) & \( K_2 \)) and \( m(J/\Psi K^+) \), CDF was limited by statistics and state:

"We find no evidence for any other structure in the \( \phi K^+ \) and \( J/\psi K^+ \) spectrum; the only structure [i.e. \( K_2(1770) \)] that has been claimed in the \( \phi K^+ \) spectrum by previous experiments is too broad to alter our analysis"  Re-visit later.
Update from CDF w/ 6.0 fb$^{-1}$ (2010)

**Yield**

$Y_{1} = 19 \pm 6; >5\sigma$

$Y_{2} = 22 \pm 8; 3.1\sigma$

$M_{1} = 4143.4^{+2.9}_{-3.0}\text{ (stat)} \pm 0.6\text{ (syst)} \text{ MeV}$

$M_{2} = 4277.4^{+8.4}_{-6.7}\text{ (stat)} \pm 1.9\text{ (syst)} \text{ MeV}$

$\Gamma_{1} = 15.3^{+10.4}_{-6.1}\text{ (stat)} \pm 2.5\text{ (syst)} \text{ MeV}$

$\Gamma_{2} = 32.3.7^{+21.9}_{-15.3}\text{ (stat)} \pm 7.6\text{ (syst)} \text{ MeV}$

$\chi^{2}/\text{dof} \text{ between old and new } \Delta m \text{ is } 7.2/3, \text{ p-value}=6.5\% \text{ w/ four regions}$

$$\frac{B(B^{+}\rightarrow Y(4140)K^{+}, Y(4140)\rightarrow J/\psi K^{+})}{B(B^{+}\rightarrow J/\psi K^{+})} = 0.149 \pm 0.039\text{ (stat) } \pm 0.034\text{ (syst)}$$

**arXiv:1101.6058 [hep-ex]**

115±12
**Belle: Confirm or Refute? (2009, 2010)**

**Summary**
- B factories suffer from low pt track efficiency
- Belle cannot confirm or deny the existence of Y(4140)
- Tevatron edge over B factories: Low $p_T$ kaons are boosted from B momentum
  
  no verdict from Babar

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Kenkichi Miyabayashi  
(Nara Women’s Univ.)  
2010 May QWG7

QWG 2010
LHC\(_b\): Contests CDF Report (2011)

\[ \text{LHC\(_b\) confirms neither structure(s) 2.4}\sigma \text{ disagreement with CDF measurement @90\% CL:} \]

\[ \frac{B(B^+ \rightarrow X(4140)K^+)}{B(B^+ \rightarrow J/\psi K^+)} \times \frac{B(X(4140) \rightarrow J/\psi \phi)}{B(X(4274) \rightarrow J/\psi \phi)} < 0.07. \]

\[ \frac{B(B^+ \rightarrow X(4274)K^+)}{B(B^+ \rightarrow J/\psi K^+)} \times \frac{B(X(4274) \rightarrow J/\psi \phi)}{B(X(4274) \rightarrow J/\psi \phi)} < 0.08. \]

LHC\(_b\) Versus CDF: Two Punches In The Face!

By Tommaso Dorigo | July 27th 2011 05:48 AM | 10 comments | Print | E-mail | Track

The first is the tentative observation of a new hadron, called \(Y(4140)\), a bump observed in the invariant mass of pairs of \(J/\psi\) result. Note that, as reported in the figure, if the CDF signal were as estimated by CDF, LHC\(_b\) would have been able to fit 39\(\pm\)9\(\pm\)6 events. The \(Y(4140)\) is on very shaky ground at the moment, and the new PDG will likely change its status in the particle zoo... This is punch number 1.
LHCb is specifically designed to select Bottom/charm/exotic-quarkonium particles and the products of their decays

Excellent lepton and hadron Identification

Excellent mass resolution

~2.5 MeV for X(3872) decays

BUT LHCb did not confirm the existence of Y(4140). A serious challenge!

A result from a 3rd experiment is important!

For instance, CMS?
The CMS Detector

Key:
- **Muon**
- **Electron**
- **Charged Hadron** (e.g. Pion)
- **Neutral Hadron** (e.g. Neutron)
- **Photon**

Relevant sub-detectors for exotic meson
CMS Detector Performance

Excellent muon/silicon detectors for quarkonium:

- **Muon system**
  - High-purity muon identification
  - Good dimuon mass resolution ($\Delta m/m \sim 0.6\%$ for $J/\Psi$)

- **Silicon Tracking detector**
  - Excellent track momentum resolution ($\Delta p_T/p_T \sim 1\%$)
  - Excellent vertex reconstruction and impact parameter resolution

**LHC luminosity and CMS trigger:**

- Collect data at increasing instantaneous luminosity
  - About 5$fb^{-1}$ from 2011 data at $\sqrt{s}=7$ TeV (used for this analysis)

- Triggers are essential ingredients
  - Special trigger for different analysis
  
For this analysis:

  displaced dimuon vertex & minimum (di)muon transverse momentum
**J/Ψφ analysis strategy (CMS 2012)**

- 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 showing primary and secondary vertices, $B^+$ decays, and particle identification](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11026

CMS: BPH-11-026
Event Selections (CMS 2012)

-- $|\eta|$ for all tracks $\leq 2.4$

-- $probability(\chi^2)$ for $J/\psi$ vertex fit $> 10\%$, $probability(\chi^2)$ for $B^+$ vertex fit $> 1\%$

-- $p_T(\text{kaon track}) > 1$ GeV

-- $J/\psi$ vertex flight length significance $\geq 3$

&

Dataset A: $p_T(J/\psi) > 7$ GeV  [first part of the run w/ low lumi, pileup]

Dataset B: $p_T(J/\psi) > 7$ GeV  & both muon $p_T > 4$ GeV  

[second part of the run w/ high lumi, pileup]

-- mass window:

$J/\psi$ ($\pm 150$ MeV) and $\phi$ in [1.008, 1.035] GeV (Breit-Wigner shape)

constraint $\mu^+\mu^-$ to $J/\psi$ PDG mass value

Requirements are not optimized to be unbiased, confirm trigger requirements
The $B$ Signal (CMS 2012)

$B^+ \rightarrow J/\psi \phi K^+$ decay

Signal PDF: Gaussian

Background PDF: 2$^{\text{nd}}$-order Chebyshev polynomial

Mass: consistent with PDG value

Width: consistent with simulation

two $(K^+K^-)$ combinations, only keep $m(K^+K^-)_{\text{min}}$ as $\phi$ candidate, <2\% from another combination based on MC

Largest $B^+ \rightarrow J/\psi \phi K^+$ sample collected in the world to date

$\sim$20 times CDF statistics (115±12); $\sim$7.2X LHCb statistics (346±20)
J/Ψ and φ Signal (CMS 2012)

\[ m(\mu^+\mu^-) \] before forming the B signal

The \( B^+ \) sideband subtracted \( m(K^+K^-) \) where \( m(J/\Psi\phi K^+) \) is within ±3\( \sigma \) of \( m(B^+) \)

- A clear and clean J/Ψ signal
- Nice φ lineshape, consistent with PDG parameters
- \( B(J/\Psi\phi K^+) \) dominates after φ mass restriction

Mass: 1019.4±0.1MeV
Width: 4.7±0.4MeV
The $\phi$ Signal (CMS 2012)

CMS Preliminary, $\sqrt{s} = 7$ TeV, $L = 5.2$ fb$^{-1}$

- w/o hadron PID, we still see a clear $\phi$ signal inside $B$ mass peak
Various Components (CMS 2012)

Two big components:

\[ B^+ \rightarrow J/\Psi \phi K^+ \]

Random combinatory background (need to be subtracted, next slide)

Possible components for \( B^+ \rightarrow J/\Psi \phi K^+ \) final state (ignoring interference):

1. Phase space events: 3-body decay: \( B^+ \rightarrow J/\Psi \phi K^+ \)
2. Possible structures in \( m(J/\Psi \phi) \):
   \( B^+ \rightarrow X \phi, X \rightarrow J/\Psi K^+ \rightarrow J/\Psi \phi K^+ \)
3. Possible structures in \( m(J/\Psi K^+) \):
   \( B^+ \rightarrow X \phi, X \rightarrow J/\Psi K^+ \rightarrow J/\Psi \phi K^+ \)
4. Possible structures in \( m(\phi K^+) \):
   \( B^+ \rightarrow X J/\Psi, X \rightarrow \phi K^+ \rightarrow J/\Psi \phi K^+ \)

We need to sort out each component
**J/ψφ Invariant Mass Spectrum** *(CMS 2012)*

- The mass difference $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ is used

- **Extracting the $\Delta m$ spectrum**
  - Divide the dataset into the 20 MeV $\Delta m$ bins
  - Extract the number of $B$ events for each $\Delta m$ by fitting the $J/\psi\phi K$ spectrum
  - Plot the $B$ yield as a function of $\Delta m$

![Graphs showing candidates per 20 MeV and relative efficiency]

- We cut-off $\Delta m > 1.568$ GeV
- Region to avoid background
- From $B_s \rightarrow \psi'\phi$, $\psi' \rightarrow J/\psi\pi\pi$
- Correct the spectrum by efficiency before fitting
- Relative efficiency over $\Delta m$: approx. flat
Background Shape Studies (CMS 2012)

The phase space Dalitz projection on $m^2(J/\psi\phi)$ generated events (red) Vs reconstructed events (black)

Sideband subtracted KKK mass Phase Space MC (red) Vs data (black)

CMS detector does not produce peaks
Also imply relative flat efficiency

Possible $K_2(1770)$, $K_2(1820)$?
Does it effect $\Delta m$?
Event mixing to study the $\Delta m$ shape

- $J/\Psi$, $\phi$, $K^+$ from different event

- $\phi$, $K^+$ from the same event, $J/\Psi$ from different event. This is to get the impact on $\Delta m$ from possible $\phi K^+$ resonances

Require the $J/\Psi \phi K^+$ mass around $B$ mass

Event-mixing $\Delta m$ shapes are slightly distorted compared to three-body phase space

However, the possible effect is on high $\Delta m$ region and the three-body phase space shape is more conservative at low $\Delta m$ region where the two structures are observed.
Preliminary $\phi K^+$ Resonances Studies (CMS 2012)

- Generated simple Dalitz plot for $(\phi K^+)$ resonances. No similar structures seen in $m(J/\Psi \phi)$ from reflections.

- No evidence of structures or deviation from phase space background shape found in $m(\phi K^+)$ mass distribution after removing the two structures in $m(J/\Psi \phi)$ in the data.

- No evidence for $m(J/\Psi K^+)$ so far.

- Possible interference? Could affect lineshape parameters, no big signal.

- A full amplitude analysis is desirable, limited by statistics and high non-B combinatoric background.

Fig. 7. Corrected $K^-\Phi$ mass spectrum for $t' < 0.8$ GeV$^2$. NPB 221, 1(1985)
Null- and Signal-hypothesis Fits

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>Signal Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Peak</td>
<td>1051.5 ± 2.0</td>
</tr>
<tr>
<td>Second Peak</td>
<td>1220.0 ± 3.0</td>
</tr>
</tbody>
</table>

Background: 3-body phase space

Signal: S-wave relativistic Breit-Wigner functions convolved with a Gaussian resolution function

Significance: >5σ for 1st peak
evidence for 2nd peak

background + 1 signal

background + 2 signal
Robust Checks

- Many checks to investigate the robustness of the two structures
  - Variations on selection cuts, different background and signal shapes, different $\Delta m$ binning...
  - Different Background-subtraction technique: $sPlot$

$sPlot$ is a technique of background-subtraction by weighting each event based on observed signal to background ratio.
Robust Checks

- All main requirements are varied step by step to investigate possible bias
- Each sideband-subtracted $\Delta m$ distribution is compared to the default one
- No indication of bias was found
  one example with tighter cuts and purer $B$ sample is shown below:
  keep $\sim 40\%$ $B$ signal, reduce background by a factor of 12!

- $B$ purity $\sim 60\%$ within $\pm 1.5\sigma$ of $m(B^+)$
- Similar $\Delta m$ spectrum
**Result**

- The efficiency-corrected $\Delta m = m(\mu^+ \mu K^+ K^-) - m(\mu^+ \mu)$

![Graph showing distribution of mass differences](image)

- Observed a $J/\psi \phi$ structure at 4148 MeV with a significance greater than 5σ confirms the existence of $Y(4140)$ for the first time from another experiment

  CDF $Y(4140)$: $m=4143.4^{+2.9}_{-3.0}$ (stat) ± 0.6 (syst)

- Evidence for a second structure at ~4317 MeV in the same mass spectrum
CDF, Belle, and LHCb are shown with their respective data distributions. The CDF data shows a flat relative efficiency. The Belle data also shows a relative efficiency curve, while the LHCb data includes a simulation plot. CMS data is also presented, indicating relative efficiency corrected distributions. The CDF/BELLE/LHCb distributions are raw without efficiency correction.
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 $Y(3940)$
- What is it? Molecule/hybrid/threshold CUSP?

Charmonium Spectrum

2$^{\text{nd}}$ peak $Y(4140)$
Possible Interpretation of the Structures?

- Possible $J^{PC}$: S-wave: $0^{++}, 1^{++}, 2^{++}$
  P-wave: $0^{-+}, 1^{-+}, 2^{-+}, 3^{-+}$
- Lattice QCD for $1^{+}$ (ccg): $4.3 \pm 0.05$ GeV
- $M = 4316.7 \pm 3.0$ (stat) $\pm 7.3$ (syst) MeV (CMS 2$^\text{nd}$ structure)
- Can the 2$^\text{nd}$ structure be $1^{-+}$ hybrid? Expect to see it in J/$\Psi\omega$ if so

- What is the 1$^\text{st}$ structure? The same kind or it can be a different kind compared to the 2$^\text{nd}$ one?
  Similar to Y(3940), both close to VV threshold? Same kind?

A topic to be investigated more
Mini Summary of near VV threshold behavior

$I(V,V)=0$, observed near VV threshold enhancement, through (double) OZI suppressed process

$I(V)=1$, no clear enhancement
Skip complicated $\omega \omega, \rho \rho$

Observed near $V(I=0)V (I=0)$ threshold enhancement. Strong decay. Above $(qq'+q'q)$ threshold. What are they?
Search Possible Charged Exotics in $J/\Psi K^+$ Spectrum

arXiv: 0708.3496 [hep-ph], Jonathan Rosner
Mechanism to produce $Z^+(4430)$:
$B \rightarrow K Z^+(4430), Z^+(4430) \rightarrow \Psi(2S)\pi^+$

Same mechanism, we can search for:
$B^+ \rightarrow \phi Z^+(xxxx), Z^+(xxxx) \rightarrow J/\Psi K^+$
Summary

- CMS observed two structures in the J/ψφ spectrum at 4148 MeV and 4317 MeV using 5.2 fb⁻¹ of data at 7 TeV collision energy

\[ m_1 = 4148.2 \pm 2.0 \text{ (stat.)} \pm 4.6 \text{ (syst.) MeV (}>5\text{sigma}) \]
\[ m_2 = 4316.7 \pm 3.0 \text{ (stat.)} \pm 7.3 \text{ (syst.) MeV (}>3\text{sigma}) \]

- Confirm the existence of the Y(4140), consistent with CDF result
  
  &
  
  find evidence for a second structure

- Preliminary investigation find no evidence of reflection from \( K_{1,2} \)

- More to be expected with the large data sample (4X) from 2012
  
  There are lots of mysteries in this system, it is trying to tell us something, may be something new! Stay tuned!
Backup
**Exotic $J^{PC}$**

- For $q\bar{q}$ meson system, let $L$ to be the orbital angular momentum. The meson spin $J$ is given by $|L-S|<J<|L+S|$, where $S=0$ (antiparallel quark spin) or $1$ (parallel quark spin).

- The parity $P$ and charge parity $C$ of the meson system can be expressed as:
  \[
  P=(-1)^{L+1},
  C=(-1)^{L+S}
  \]

- In the configuration of $P=(-1)^{J}$, $S=1$, $CP=+1$, $\Rightarrow$ **Exotic $J^{PC}$** (not allowed for $q\bar{q}$ meson):
  \[
  0^-, 0^{++}, 1^{++}, 2^{++}, ...
  \]
  But exotic mesons can have these $JPC$ due to additional degree of freedom.

- Identify *exotic $J^{PC}$* is helpful to identify *exotic mesons*
Jet Reconstruction

- **Anti-kt (AK) clustering algorithm with cone size of 0.5 (AK5) and 0.7 (AK7)**
  - Infrared and collinear safe

- **Jet types:**
  - **Calorimeter Jets:**
    Reconstructed from energy deposits in the ECAL and HCAL, grouped in projective calo towers
  - **Particle Flow (PF) Jets (Details in next slide):**
    Use all detector elements to reconstruct particles and cluster to jets.
  - **Fat Jets:**
    Clusters of AK5 PF Jets within radius of 1.1, optimize dijet resonance resolution by recombining FSR into the two leading jets

- **Jet energy corrections: using MC truth information and real data (i.e. γ+Jet) for residual correction**
  - Uncertainty on jet energy scale ~2%
  - Uncertainty on Jet energy resolution ~10%

- **MET: negative of vector sum of transverse momenta of all particle**
Particle Flow Jet

Particles

Clusters and tracks

Detector

PFlow
Particle Flow Jet

**HCAL**: \(120\% \sqrt{E} + 6.9\%\)

**ECAL**: \(\sim 1\% \sqrt{E}\)

**Tracker** \(\sigma(p_T)/p_T\): 1-2\% for 10 GeV track

\(<10\%\) for 100 GeV track

- 60\% of pileup mitigation using charged hadrons attached to secondary tracks
- Remaining mitigation using jet area
Motivation for NP

• Why Search for “new” physics after the discovery of a “Higgs”-like particle?

• We have a hierarchy problem if this is the SM Higgs and it is so light. Possible solutions from “new” physics:
  – SUSY: R-parity conserved and violated scenarios
  – Warped Extra Dimension

• We expect new physics if this is not the SM Higgs:
  – Need to find out a “Higgs”-like mechanism
  – Strong Dynamics?

• Jets are copiously produced, with several orders of magnitude higher cross section than other processes.Jets are either part of searching signal or background. This talk focus on the searches with jet(s) in the final state
Dijet Resonances Search

- Parton resonances decaying into dijets from various models
- Search for 3 generic types of narrow dijet resonances
  - $qq,qg,gg$ resonances
  - Using fat jet in this search
  - Fat jets show better resolution due to more recovery of FSR

Experimentally jet resolution dominates signal width

<table>
<thead>
<tr>
<th>Models</th>
<th>X</th>
<th>Color</th>
<th>$J^P$</th>
<th>$\Gamma/(2M)$</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excited quark</td>
<td>$q^*$</td>
<td>Triplet</td>
<td>$\frac{1}{2}^+$</td>
<td>0.02</td>
<td>$qq$</td>
</tr>
<tr>
<td>$E_6$ Diquark</td>
<td>$D$</td>
<td>Triplet</td>
<td>$0^+$</td>
<td>0.004</td>
<td>$qq$</td>
</tr>
<tr>
<td>Axigluon</td>
<td>$A$</td>
<td>Octet</td>
<td>$1^+$</td>
<td>0.05</td>
<td>$qq$</td>
</tr>
<tr>
<td>Coloron</td>
<td>$C$</td>
<td>Octet</td>
<td>$1^-$</td>
<td>0.05</td>
<td>$q\bar{q}$</td>
</tr>
<tr>
<td>RS Graviton</td>
<td>$G$</td>
<td>Singlet</td>
<td>$2^+$</td>
<td>0.01</td>
<td>$qq, gg$</td>
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<tr>
<td>Heavy W</td>
<td>$W'$</td>
<td>Singlet</td>
<td>$1^-$</td>
<td>0.01</td>
<td>$q\bar{q}$</td>
</tr>
<tr>
<td>Heavy Z</td>
<td>$Z'$</td>
<td>Singlet</td>
<td>$1^-$</td>
<td>0.01</td>
<td>$q\bar{q}$</td>
</tr>
<tr>
<td>String</td>
<td>$S$</td>
<td>Mixed</td>
<td>Mixed</td>
<td>0.003-0.037</td>
<td>$qq, q\bar{q}, gg$</td>
</tr>
</tbody>
</table>
Dijet Resonances with 8 TeV

- Fat PF Jet, $|\eta|<2.5$ & $|\Delta\eta|<1.3$
- Data are in good agreement with QCD
- Fit to a parameterization
- No evidence of new physics

8TeV EXO-12-016

\[
\frac{d\sigma}{dm} = \frac{p_0 \cdot (1 - m/\sqrt{s})^{p_1}}{(m/\sqrt{s})^{p_2} + p_3 \ln(m/\sqrt{s})}
\]
Paired Dijet Resonance Search (4-jets)

- Benchmark model: pair produced colorons

- Require well separated central jets: all jet $|\eta|<2.5, \text{deltaR}(j,j)>0.7$

- $\geq 4$ jets with $p_T>150$ GeV, optimized for a generic coloron search

- 3 pairs, examine average dijet mass of pairs—$(m_{\text{avg}})$, select the best matched pair—$\Delta m/m_{\text{avg}}<15\%$

- Diagonal cut to have a smooth falling background:
  $\Delta=(p_{T_i} + p_{T_j} - m_{ij}) > 25$ GeV

7TeV EXO-11-016
Paired Dijet Resonance Search (4-jets)

- $\Delta > 25$ GeV cut removes the second broad structure and the dijet mass smoothly falling

A typical paired dijet event
Paired Dijet Resonance Search (4-jets)

- Well described by QCD MC and parameterization (same as in the dijet search)
- No evidence for new physics
- Exclude pair production of colorons with mass in $[320, 560]$ GeV @95% CL
Lowered jet $p_T$ threshold to 110 GeV to be more sensitive to low mass stop production

- Well described by QCD MC and parameterization (same as in the dijet search)
- No evidence for new physics
- Exclude pair production of colorons @95%: with mass in [250, 740] GeV assuming coloron decays to only to $qq\bar{q}$, or mass in [250, 580] GeV assuming competition from $S_8$
- Start to be sensitive to stop
Summary for (paired)-Dijet Searches

• *CMS new physics searches using jets have been presented based on 2011 and 2012 data.*

• No evidence for new physics yet.

• *Data significantly constrain many models of new physics.*

• *Much more data in 2012 is quickly supersede 2011 results*
  – ~20 fb$^{-1}$ on tape

• *Ample space for discoveries.*

*Stay tuned!*