Review of the $X(3872)$

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collaborators
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support:
DOE, Division of High Energy Physics
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New $c\bar{c}$ Mesons

$X(3872)$  
Belle, August 2003
decays into $J/\psi \pi^{+}\pi^{-}$, $J/\psi \pi^{+}\pi^{-}\pi^{0}$, $J/\psi \gamma$, $D^{0}\bar{D}^{0}\pi^{0}$

$Y(3940)$  
Belle, August 2004
decays into $J/\psi \omega$

$Y(4260)$  
BaBar, June 2005
decays into $e^{+}e^{-}$, $J/\psi \pi^{+}\pi^{-}$, $J/\psi \pi^{0}\pi^{0}$, $J/\psi K^{+}K^{-}$

$X(3940)$  
Belle, July 2005
decays into $D^{*}\bar{D}$

$Z(3930)$  
Belle, July 2005
decays into $\gamma\gamma$, $D\bar{D}$
Discovery of $X(3872)$ in $B$ decay

Belle collaboration, August 2003

$B^\pm \rightarrow X + K^\pm, \quad X \rightarrow J/\psi \pi^+\pi^-$

confirmed by Babar

$0.40 \quad 0.80 \quad 1.20$

$M(\pi^+\pi^-l^+l^-) - M(l^+l^-)$ (GeV)

Events/0.010 GeV

hep-ex/0309032

hep-ex/0406022
Observation of $X(3872)$ in $p\bar{p}$ collisions

CDF collaboration, September 2003  

$p\bar{p} \rightarrow X + \text{anything}$, $X \rightarrow J/\psi \pi^+\pi^-$

confirmed by D0 

CDF II

$\text{Candidates/5 MeV/c}^2$

$J/\psi\pi^+\pi^-$ Mass (GeV/c$^2$)
What is the $X(3872)$?

**Belle:** $D$-wave charmonium? $D^*\bar{D}$ molecule?

- **charmonium**
  Close and Paige (9-03); Pakvasa and Suzuki (9-03); Barnes and Godfrey (11-03); Eichten, Lane, and Quigg (1-04); Olsen (7-04); Meng, Gao, and Chao (6-05)
motivated by $J/\psi$ among decay products

- **$D^*\bar{D}$ molecule**
  Tornqvist (8-03, 2-04); Close and Paige (9-03); Pakvasa and Suzuki (9-03); Voloshin (9-03, 8-04, 9-05, 5-06); Wong (11-03); Braaten and Kusunoki (11-03, 2-04, 12-04, 6-05, 7-05, 9-06); Swanson (11-03, 6-04); Braaten, Kusunoki, and Nussinov (4-04); Kalashnikova (6-05); AlFiky, Gabbiani, and Petrov (6-05); ElHady (3-06)
motivated by proximity to $D^*\bar{D}$ threshold

- **threshold cusp** from interactions with $D^*\bar{D}$
  Bugg (10-04)
motivated by proximity to $D^*\bar{D}$ threshold
What is the $X(3872)$? (cont.)

- tetraquark: $(cq)_3^* (\bar{c}q)_3$
  Vijande, Fernandez, and Valcarce (7-04); Maiani, Piccinini, Polosa, and Riquer (12-04); Ishida, Ishida, and Maeda (9-05, 10-06); Ebert, Faustov, and Galkin (12-05); Karliner and Lipkin (1-06); Chiu and Hsieh (3-06)

- tetraquark: $(c\bar{c})_8 (q\bar{q})_8$
  Hogassen, Richard, and Sorba (11-05)

- charmonium hybrid: $c\bar{c}g$
  Close and Paige (9-03); Li (10-04)

- glueball: $gg$
  Seth (11-04)

See also Ko (5-04); Rosner (8-04)
Mass and Width of the $X(3872)$

Mass

\[ M_X = 3871.9 \pm 0.5 \text{ MeV} \]

Belle, CDF, Babar, D0

Width

\[ \Gamma_X < 2.3 \text{ MeV} \quad (90\% \text{ C.L.}) \]

Belle, hep-ex/0309032

Mass is extremely close to the $D^*\bar{D}^0$ threshold

\[ M_X - (M_{D^*0} + M_{D^0}) = +0.6 \pm 1.1 \text{ MeV} \]

\[ \Rightarrow (M_{D^*0} + M_{D^0}) - M_X < 0.7 \text{ MeV} \quad (90\% \text{ C.L.}) \]

most of uncertainty comes from $2M_{D^0} = 3729 \pm 1 \text{ MeV}$
Quantum Numbers of the $X(3872)$

$X \to J/\psi \gamma$  
$\Rightarrow C = +$  

Belle, hep-ex/0505037

$X \to J/\psi \pi^+\pi^-$  
angular correlations $\Rightarrow$ not $J^{PC} = 0^{++}, 0^{-+}$  
$\pi\pi$ mass distribution $\Rightarrow$ not $1^{-+}, 2^{-+}$  
$1^{++}$ “strongly favored”, but $2^{++}$ “not ruled out”

$X \to D^0 \bar{D}^0 \pi^0$  
8 MeV above threshold $\Rightarrow 2^{++}$ ruled out

$J^{PC} = 1^{++}$  

Belle, preliminary
What is the $X(3872)$?

Assumption: $M_X < M_{D^*0} + M_{D^0}$

Experimental inputs

- Mass is extremely close to the $D^*0 \bar{D}^0$ threshold
  \[(M_{D^*0} + M_{D^0}) - M_X < 0.7 \text{ MeV} \quad \text{(90\% C.L.)}\]

- $J^{PC} = 1^{++}$
  \[\Rightarrow \text{S-wave coupling to } D^*0 \bar{D}^0, \; D^0 \bar{D}^*0\]

Conclusion

$X(3872)$ is a weakly-bound charm meson molecule

\[X = \frac{1}{\sqrt{2}} (D^*0 \bar{D}^0 + D^0 \bar{D}^*)\]

with universal properties that are insensitive to details of QCD.
Charm meson molecules

Bander, Shaw, Thomas, and Meshkov (1976); Voloshin and Okun (1976); de Rujula, Georgi, and Glashow (1977); Nussinov and Sidhu (1978)

Meson potential model with pion-exchange


possibility of weakly-bound charm meson molecules

in several $J^{PC}$ channels with $I = 0$

$D\bar{D}$: none

$D^*\bar{D}/D\bar{D}^*$: S-wave 1++; P-wave 0−+

$D^*\bar{D}^*$: S-wave 0++, 1++, 2++; P-wave 0−+

$D^*\bar{D}$ molecule with $J^{PC} = 1^{++}$, $I = 0$

$$X = \frac{1}{2} \left( D^{*0} \bar{D}^0 + D^0 \bar{D}^{*0} + D^{*+}D^- + D^+D^{*-} \right)$$
Charm meson molecules (cont.)

Splitting between $D^+D^-$ and $D^*0\bar{D}0$ thresholds: 8.1 MeV
$D^*0\bar{D}0$ threshold and $X(3872)$: < 0.7 MeV

$\leftrightarrow$ resonant enhancement of $D^*0\bar{D}0$ component
(large breaking of isospin symmetry)
Tornqvist(8-03, 2-04); Swanson (11-03)

$D^*0\bar{D}0$ molecule with $J^{PC} = 1^{++}$

$$X = \frac{1}{\sqrt{2}} (D^*0\bar{D}0 + D^0\bar{D}^*0)$$
Universal Aspects of $X(3872)$

Basic Quantum Mechanics
2-body system with short-range interactions
and S-wave bound state sufficiently close to threshold
has universal properties
that depend only on the large scattering length $a$

“Universality of Few-Body Systems with Large Scattering Length”
Braaten and Hammer, arXiv:cond-mat/0410417 (Physics Reports)

Existence of $X(3872)$
$\implies D^*0 \bar{D}^0, \ D^0 \bar{D}^*0$ have large scattering length in $C = \uparrow$ channel
$\implies$ universal properties that depend only on
binding energy $E_X$ and width $\Gamma_X$ of $X$
Universal aspects of $X$ (cont.)

Universal results

• cross section at low energy $E$

$$\sigma(E) = \frac{4\pi a^2}{1 + 2M_{\text{red}}a^2E}$$

• shallow bound states

$a < 0$: none

$a > 0$: one, S-wave
- energy: $E = -\hbar^2/(2M_{\text{red}}a^2)$
- wavefunction: $\psi(r) = \exp(-r/a)/r$

$$\implies \langle r \rangle = a/2$$
- constituents almost always outside range of potential!
Universal aspects of $X$ (cont.)

Systems with large scattering length

- $^4$He atoms: $a \approx +100$ Å
  $\implies$ dimer with binding energy $8 \times 10^{-9}$ Ry

- spin-polarized $^3$H atoms: $a \approx -82$ Å

- alkali atoms near Feshbach resonance
  \[ a(B) = a_\infty + \frac{\Delta}{B - B_0} \]
  can be tuned experimentally: $a(B) \to \pm \infty$ as $B \to B_0$

- nucleons: $a_s \approx -23.8$ fm, $a_t \approx +5.4$ fm
  $\implies$ deuteron with binding energy 2.2 MeV

- charm mesons $D^{*0}D^0$ and $D^0\bar{D}^{*0}$ !!
Universal aspects of $X$ (cont.)

$D^* \bar{D}^0 / D^0 \bar{D}^* \ / \ X(3872)$

Natural scales from pion exchange

- length: $1/m_\pi = 1.4$ fm
- momentum: $m_\pi = 140$ MeV
- energy: $m_\pi^2/(2M_{\text{red}}) = 10$ MeV

$\Rightarrow$ large scattering length: $a \gg 1.4$ fm

$\Rightarrow$ small binding energy: $E_X \ll 10$ MeV

Binding energy of $X(3872)$

$E_X < 0.7$ MeV \hspace{1cm} (90\% \ C.L.)

Belle, Babar, CDF, D0
Universal aspects of $X$ (cont.)

Since $X$ decays,
there must be inelastic scattering channels for $D^*0\bar{D}^0$, $D^0\bar{D}^*$

$\implies$ Scattering length $a$ is complex

$$\frac{1}{a} = \gamma_{re} + i\gamma_{im}$$

Real and imaginary parts of $1/a$ determine

binding energy: $E_X = \gamma_{re}^2/(2M_{red})$
decay width: $\Gamma_X = 2\gamma_{re}\gamma_{im}/M_{red}$

Constraints on $E_X$ and $\Gamma_X$

$$0 < E_X < 0.7 \text{ MeV}$$
$$0.07 \text{ MeV} < \Gamma_X < 2.3 \text{ MeV}$$
Universal aspects of \(X\) (cont.)

Universal results

- elastic \(D^0 \bar{D}^0\) cross section at low energy \(E\)

\[
\sigma(E) = \frac{\pi}{\gamma_{re}^2 + (\gamma_{im} + \sqrt{2M_{red}E})^2}
\]

huge cross section at threshold: \(\sigma(E = 0) > 0.6\) barns !!

- shallow S-wave bound state: \(X(3872)\)

wavefunction:

\[
\psi(r) = \exp(-\gamma_{re}r)/r
\]

\[\Rightarrow \langle r \rangle = 1/(2\gamma_{re})\]

huge mean separation: \(\langle r \rangle_X > 3\) fm !!
Why is the $X(3872)$?

$X(3872)$ is a weakly-bound charm meson molecule

$$X = \frac{1}{\sqrt{2}} \left( D^{*0} \bar{D}^0 + D^0 \bar{D}^{*0} \right)$$

with universal properties that depend on large scattering length but are insensitive to other details of QCD.

Insensitive to mechanism for binding

- $\chi_{c1}(2P)$ near $D^{*0} \bar{D}^0$ threshold?
- $1^{++}$ tetraquark near $D^{*0} \bar{D}^0$ threshold?
- Depth of pion-exchange potential between charm mesons?
- Coupling of charmonium to charm meson pairs?

Kalashnikova (6-05)
Why is the $X(3872)$? (cont.)

Mechanisms for binding of $X$

- $\chi_{c1}(2P)$ near $D^* D^0$ threshold?
  ruled out if $Z(3930)$ is identified as $\chi_{c2}(2P)$
  $X(3930)$ is identified as $\chi_{c0}(2P)$ or $\chi_{c1}(2P)$

- $1^{++}$ tetraquark near $D^* D^0$ threshold?
  test by searching for charged partners of $X$

  \[
  \text{Br}[B^0 \rightarrow K^+ + X^-] \text{Br}[X^- \rightarrow J/\psi \pi^- \pi^0] < 5.4 \times 10^{-6} \quad (90\% \text{ C.L.})
  \]

  Babar hep-ex/0412051

- depth of pion-exchange potential between charm mesons?
  test by searching for other heavy meson molecules
  predicted by meson potential models
Why is the $X(3872)$? (cont.)

**Binding energies of heavy meson molecules** predicted by **meson potential models** with pion exchange ultraviolet cutoff tuned by deuteron binding energy  

Tornqvist (10-93)  
Swanson (1-06)

molecules in $I = 0$ channels only

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>Tornqvist (10-93)</th>
<th>Swanson (1-06)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^<em>\bar{D}/D\bar{D}^</em>$</td>
<td></td>
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<tr>
<td>0$^-$+</td>
<td>$\approx$ 0</td>
<td>$-$</td>
</tr>
<tr>
<td>1+-+</td>
<td>$\approx$ 0</td>
<td>0</td>
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<tr>
<td>$D^<em>\bar{D}^</em>$</td>
<td></td>
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<tr>
<td>0++</td>
<td>$\approx$ 0</td>
<td>1.0</td>
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<td>0$^-$+</td>
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<td>$-$</td>
</tr>
<tr>
<td>1+-+</td>
<td>$\approx$ 0</td>
<td>$-$</td>
</tr>
<tr>
<td>2++</td>
<td>$\approx$ 0</td>
<td>$-$</td>
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<tr>
<td>$B^<em>\bar{B}/B\bar{B}^</em>$</td>
<td>58</td>
<td>61</td>
</tr>
<tr>
<td>1++</td>
<td>41</td>
<td>43</td>
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<tr>
<td>$B^<em>\bar{B}^</em>$</td>
<td>67</td>
<td>71</td>
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<tr>
<td>0$^-$+</td>
<td>59</td>
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<tr>
<td>1+-+</td>
<td>41</td>
<td>44</td>
</tr>
<tr>
<td>2++</td>
<td>47</td>
<td>50</td>
</tr>
</tbody>
</table>
Decays of the $X(3872)$

**Long-distance decays**

\[ X \rightarrow D^0 \bar{D}^0 \pi^0 \]
\[ \rightarrow D^0 \bar{D}^0 \gamma \]

dominated by $D^{*0} \bar{D}^0$, $D^0 \bar{D}^{*0}$ components of $X$
proceed through decays of constituent $D^{*0}$ or $\bar{D}^{*0}$
universal, determined by $E_X$, $\Gamma_X$ only

**Short-distance decays**

\[ X \rightarrow \text{charmonium} + \text{light hadrons} \]
\[ \rightarrow D^+ D^- \gamma \]
\[ \rightarrow \text{light hadrons} \]

dominated by short-distance (“core”) components of $X$
factorization formula with universal long-distance factor
Long-distance Decays of $X(3872)$

$X(3872) \rightarrow D^0\bar{D}^0\pi^0,\ D^0\bar{D}^0\gamma$

Voloshin (9-03); El-Hady (3-06)

donated by $D^*\bar{D}^0,\ D^0\bar{D}^*$ components
proceeds through decay of constituent: $D^*\rightarrow D^0\pi^0,\ D^0\gamma$
$\bar{D}^*\rightarrow \bar{D}^0\pi^0,\ \bar{D}^0\gamma$

• absolute predictions of partial widths
  \[
  \Gamma[X \rightarrow D^0\bar{D}^0\pi^0] = \Gamma[D^*\rightarrow D^0\pi^0] \\
  \Gamma[X \rightarrow D^0\bar{D}^0\gamma] = \Gamma[D^*\rightarrow D^0\gamma]
  \]

• lower bound on total width
  \[
  \Gamma[X] > \Gamma[D^*] \approx 70 \pm 15 \text{ keV}
  \]

• momentum distributions for $D^0\bar{D}^0\pi^0,\ D^0\bar{D}^0\gamma$
determined by $E_X, \Gamma_X$ only
Long-distance Decays of $X$ (cont.)

Use $\Gamma[X \rightarrow D^0 \bar{D}^0 \pi^0]$ to normalize other rates

$$\Gamma[X \rightarrow D^0 \bar{D}^0 \pi^0] \approx \Gamma[D^{*0} \rightarrow D^0 \pi^0] \approx 42 \pm 10 \text{ keV}$$

Belle, preliminary ??

(as reported by 3rd parties)

$$\frac{\text{Br}[X \rightarrow J/\psi \pi^+\pi^-]}{\text{Br}[X \rightarrow D^0 \bar{D}^0 \pi^0]} \approx 0.059 \pm 0.025 ??$$

$$\Gamma[X \rightarrow J/\psi \pi^+\pi^-] \approx 2.5 \text{ keV}$$

Belle

hep-ex/0309032

$$\text{Br}[B^+ \rightarrow K^+ + X] \text{Br}[X \rightarrow J/\psi \pi^+\pi^-] = (1.3 \pm 0.3) \times 10^{-5}$$

Assume $D^0 \bar{D}^0 \pi^0$, $D^0 \bar{D}^0 \gamma$ are dominant decay modes of $X$:

$$\text{Br}[B^+ \rightarrow K^+ + X] \approx 4 \times 10^{-4}$$
Short-distance Decays of $X(3872)$

dominated by short-distance components of $X$

\[ X \rightarrow \text{charmonium} + \text{light hadrons} \]
\[ \rightarrow D^+D^-\gamma \]
\[ \rightarrow \text{light hadrons} \]

Factorization formula

Braaten and Kusunoki (7-05); Braaten and Lu (6-06)

\[
\Gamma[X \rightarrow H] = \Gamma_{\text{short}}[H] \times \left( E_X + \frac{\Gamma_X^2}{16E_X} \right)^{1/2}
\]

• long-distance factor cancels in ratio of decay rates
  \( \Rightarrow \) ratios are insensitive to $E_X$, $\Gamma_X$

• constraints on long-distance factor from bounds on $E_X$, $\Gamma_X$

\[
0.3 < \left( \frac{E_X + \Gamma_X^2/16E_X}{1 \text{ MeV}} \right)^{1/2} < 1
\]
Short-distance decays of $X$ (cont.)

Decays of $X$ into $J/\psi$ and pions

$$\frac{\text{Br}[X \to J/\psi \pi^+\pi^-\pi^0]}{\text{Br}[X \to J/\psi \pi^+\pi^-]} = 1.0 \pm 0.4 \pm 0.3$$

Belle, hep-ph/0505038

$X \rightarrow J/\psi \pi^+\pi^-\pi^0$ dominated by $X \rightarrow J/\psi + \omega^* (I = 0)$

$X \rightarrow J/\psi \pi^+\pi^-$ dominated by $X \rightarrow J/\psi + \rho^* (I = 1)$

Assume decays proceed through coupling of $X$ to $J/\psi + V$

followed by decay of $V$ into pions

Swanson (6-04); Braaten and Kusunoki (7-05)

$$\Gamma[X \to J/\psi \pi^+\pi^-] = |G_{X\psi\rho}|^2 (223 \text{ keV})$$

$$\Gamma[X \to J/\psi \pi^+\pi^-\pi^0] = |G_{X\psi\omega}|^2 (19.4 \text{ keV})$$

$$\implies \frac{|G_{X\psi\rho}|^2}{|G_{X\psi\omega}|^2} = 0.09 \pm 0.05$$

$X(3872)$ couples to both $I = 0$ and $I = 1$,

but it couples more strongly to $I = 0$
Short-distance decays of $X$ (cont.)

Meson potential model

one-pion-exchange, quark exchange

5 coupled channels: $D^* \bar{D}^0 + D^0 \bar{D}^*$, S-wave and P-wave

$D^+ D^-$, S-wave

$J/\psi \rho$, S-wave

$J/\psi \omega$, S-wave

- correctly predicted $\text{Br}[X \to J/\psi \pi^+ \pi^- \pi^0] \sim \text{Br}[X \to J/\psi \pi^+ \pi^-]$
- $E_X$ is sensitive to ultraviolet cutoff
- $\Gamma_X$ is ignored
- predicts $\Gamma[X \to J/\psi \pi^+ \pi^- \pi^0] = 820 \text{ keV}$ if $E_X = 1 \text{ MeV}$

Use factorization formula to extend to arbitrary $E_X, \Gamma_X$

\[
\Gamma[X \to J/\psi \pi^+ \pi^- \pi^0] = (820 \text{ keV}) \times \left(\frac{E_X + \Gamma_X^2 / 16E_X}{1 \text{ MeV}}\right)^{1/2}
\]
Decays of $X$ (cont.)

Other Decay Measurements

• measurement of $J/\psi \gamma$  
  \[
  \frac{\text{Br}[X \to J/\psi \gamma]}{\text{Br}[X \to J/\psi \pi^+\pi^-]} = 0.14 \pm 0.05
  \]
  compatible with coupling of $X$ to $J/\psi + V$ plus vector meson dominance

• upper limit on $J/\psi \pi^0\pi^0$  
  \[
  \frac{\text{Br}[X \to J/\psi \pi^0\pi^0]}{\text{Br}[X \to J/\psi \pi^+\pi^-]} < 0.8 \quad (90\% \text{ C.L.})
  \]

• upper limits that are moot if $J^{PC} = 1^{++}$
  
  $D^0 \bar{D}^0, \ D^+D^-$  
  $J/\psi \eta$  
  $X_{c1} \gamma, \ X_{c2} \gamma$

Belle, hep-ex/0505037

Belle, hep-ex/0408116

Belle, hep-ex/0307061

Babar, hep-ex/0402025

Belle, hep-ex/0408116
Decays of $X$ (cont.)

**Other Decay Predictions**

**Charmonium decays**

- $J/\psi \, \pi^0\gamma$ \quad Swanson (11-03); Braaten and Kusunoki (7-05)
- $\psi(2S) \, \gamma, \psi(3770) \, \gamma, \psi(3838) \, \gamma$ \quad Swanson (6-04)
- $\chi_{cJ} \, \pi^0$ \quad Voloshin (4-08)

**charm meson decays**

- $D^+D^- \, \gamma$ \quad Swanson (11-03); Voloshin (9-05)

**light hadron decays**

- $K^+K^{*-}, \, K^0\bar{K}^{*0}, \, \pi^+\rho^-$ \quad Swanson (11-03)
- $2(\pi^+\pi^-), \, K^+K^-\pi^+\pi^-, \, 2(K^+K^-)$ ??
- $p\bar{p} \, \pi^+\pi^-$ ??
Production of $X(3872)$

Production in $B$ meson decay

- $B^\pm \rightarrow X + K^\pm$  
  Belle, BaBar
- $B^0 \rightarrow X + K^0$  
  BaBar
- $B^\pm \rightarrow X + \text{anything}$  
  BaBar

Production in $p\bar{p}$ collisions

- $p\bar{p} \rightarrow X + \text{anything}$  
  CDF, D0
- $b \rightarrow X + \text{anything}$  
  CDF
Production of $X$ in decays of $B^0$, $B^+$

\[ R \equiv \frac{\Gamma[B^0 \rightarrow K^0 + X]}{\Gamma[B^+ \rightarrow K^+ + X]} = \frac{\Gamma^{0\text{short}}}{\Gamma^{+\text{short}}} \]

\[ \frac{d\Gamma[B^0 \rightarrow K^0 + D^{*0} \bar{D}^0]}{d\Gamma[B^+ \rightarrow K^+ + D^{*0} \bar{D}^0]} \rightarrow \frac{\Gamma^{0\text{short}}}{\Gamma^{+\text{short}}} \quad \text{as } E_{D^{*0}\bar{D}^0} \rightarrow 0 \]

**Estimate of $\Gamma^{0\text{short}}/\Gamma^{+\text{short}}$**

Analysis of Babar data on 16 branching fractions for $B \rightarrow K + D^{(*)} \bar{D}^{(*)}$ [hep-ex/0305003]

example:

\[ \frac{\text{Br}[B^0 \rightarrow K^0 + D^{*0} \bar{D}^0, D^{0} \bar{D}^{*0}]}{\text{Br}[B^+ \rightarrow K^+ + D^{*0} \bar{D}^0, D^{0} \bar{D}^{*0}]} = 0.26 \pm 0.24 \]

Use heavy-quark symmetry and isospin symmetry.

Assume factorization and constant form factors.

Prediction: $R \lesssim 0.1$ [Braaten and Kusunoki (12-04)]

Measurement by Babar [hep-ex/0507090]

\[ R = 0.50 \pm 0.30 \pm 0.10 \]
Inclusive Production of $X$ in $B^+$ decay

$K^+$ momentum distribution in $B^+ \rightarrow K^+ + X_{cc}$

Babar, hep-ex/0510070

![Graph showing kaon momentum distribution](image)

$\text{Br}[B^+ \rightarrow K^+ + X(3872)] < 3.2 \times 10^{-4}$  \ (90\% C.L.)

$\implies \text{Br}[X \rightarrow J/\psi \pi^+\pi^-] > 4.2\%$
Production of $X$ in $p\bar{p}$ collisions

Inclusive production of $X$

$$p\bar{p} \rightarrow X + \text{anything}$$

- from decay of $b$ hadrons
- from QCD mechanisms (prompt)

Results from D0

production characteristics of $X \rightarrow J/\psi \pi^+\pi^-$

similar to $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$

transverse momentum

rapidity

$\pi^+\pi^-$ decay angle

proper decay length

isolation
Production of $X$ in $p\bar{p}$ collisions (cont.)

Results from CDFII

- fraction of $X$ from $b$ hadron decay

  \[ f_X = 16.1 \pm 4.9 \pm 2.0 \% \]
  \[ f_{\psi(2S)} = 28.3 \pm 1.0 \pm 0.7 \% \]

- prompt cross section for $X$

  \[ \frac{\sigma[\text{prompt } X]}{\sigma[\text{prompt } \psi(2S)]} = \frac{0.045 \pm 0.008}{\text{Br}[X \rightarrow J/\psi \pi^+\pi^-]} \times \frac{\epsilon_{\psi(2S)}}{\epsilon_X} \]

- inclusive production from $b$ hadron decay

  \[ \text{Br}[b \rightarrow X + \text{ anything}] = \frac{0.011 \pm 0.006}{\text{Br}[X \rightarrow J/\psi \pi^+\pi^-]} \times \frac{\epsilon_{\psi(2S)}}{\epsilon_X} \]

- $\pi^+\pi^-$ mass distribution

  compatible with $X \rightarrow J/\psi \rho^*$
Production of $X(3872)$

If there are no charm particles in the initial state, production of $X$ involves

- creation of $c\bar{c}$ (scales $m_c$ and larger)
- formation of $D^{*0}\bar{D}^0$, $D^0\bar{D}^{*0}$ (scales $\Lambda_{QCD}$ and $m_\pi$)
- binding into $X$ (scale $E_X$)

$$E_X \ll m_\pi, \Lambda_{QCD} \ll m_c, \ldots$$

Heavy quark spin selection rule

Voloshin, hep-ph/0408321

production dominated by creation of spin-triplet $c\bar{c}$

NRQCD Factorization Formula

Braaten (8-04, v. 2)

inclusive production of $X$ may be dominated by $\langle O_8(3S_1) \rangle$

$\Longrightarrow$ polarization at large $p_T$ ??
Production of $X$ (cont.)

**Factorization**

Braaten and Kusunoki (6-05), Braaten and Lu (6-06)

Separate **short** distances $\lesssim 1/m_\pi, 1/\Lambda_{QCD}, 1/m_c$
from **long** distances $\gtrsim |a|$

**Factorization formulas** for amplitudes

$$\mathcal{A} = \mathcal{A}_{\text{short}} \times \mathcal{A}_{\text{long}}$$

$\mathcal{A}_{\text{short}}$ has smooth limit as $a \to \infty$
$\mathcal{A}_{\text{long}}$ is determined by $a$ only

Amplitudes for $X(3872)$

$D^{*0}\bar{D}^0$ near threshold
$D^0\bar{D}^{*0}$ near threshold

Same **short-distance** factor $\mathcal{A}_{\text{short}}$
Long-distance factors $\mathcal{A}_{\text{long}}$ determined by $E_X$ and $\Gamma_X$
Ratios of production rates

determined by same short-distance factors for $X$ and $D^*\bar{D}^0$

\[
\frac{\sigma[pp \rightarrow X + \text{any}]}{\Gamma[B \rightarrow X + K]} = \frac{\sigma_{\text{short}}}{\Gamma_{\text{short}}}
\]

\[
\frac{d\sigma[pp \rightarrow D^*\bar{D}^0 + \text{any}]}{d\Gamma[B \rightarrow D^*\bar{D}^0 + K]} \rightarrow \frac{\sigma_{\text{short}}}{\Gamma_{\text{short}}} \quad \text{as } E_{D^*\bar{D}} \rightarrow 0
\]

measurements of $\sigma[D^*\bar{D}^0]$ can be used to predict $\sigma[X]$

Can $\sigma[D^*\bar{D}^0]$ be measured for processes other than $B$ decay??

Babar measurements

\[
\begin{align*}
\text{Br}[B^+ \rightarrow K^+ + D^*\bar{D}^0] &= 0.47 \pm 0.07 \pm 0.07 \% \\
\text{Br}[B^+ \rightarrow K^+ + D^0\bar{D}^*] &= 0.18 \pm 0.07 \pm 0.04 \% \\
\text{Br}[B^0 \rightarrow K^0 + D^*\bar{D}^0, D^0\bar{D}^*] &= 0.17 \pm 0.14 \pm 0.07 \%
\end{align*}
\]
\[ B \to K + X(3872), \quad K + D^*0 \bar{D}^0 \]

Braaten, Kusunoki, and Nussinov (4-04), Braaten and Kusunoki (12-04)

Factorization formulas

\[
\begin{align*}
\Gamma[B \to X + K] &= \Gamma_{\text{short}} \times \frac{\pi}{M_{\text{red}}} \left[ \frac{\gamma_{\text{re}}^2 + \gamma_{\text{im}}^2}{\gamma_{\text{re}} + (\gamma_{\text{im}} + \sqrt{2M_{\text{red}}E})^2} \right]^{1/2} \\
\frac{d\Gamma}{dM}[B \to D^*0 \bar{D}^0 + K] &= \Gamma_{\text{short}} \times \frac{\sqrt{2M_{\text{red}}E}}{\gamma_{\text{re}} + (\gamma_{\text{im}} + \sqrt{2M_{\text{red}}E})^2} \\
M &= (M_{D^0} + M_{D^*0}) + E,
\end{align*}
\]
$B \rightarrow K + X, \ K + D^* \bar{D}$ (cont.)

Decay $B^+ \rightarrow K^+ + D^{*0} \bar{D}^0$

$$\frac{d\Gamma}{dM}[B \rightarrow K + D^{*0} \bar{D}^0] = \Gamma_{\text{short}} \times \frac{\sqrt{2M_{\text{red}} E}}{\gamma_{\text{re}} + (\gamma_{\text{im}} + \sqrt{2M_{\text{red}} E})^2}$$

$D^{*0} \bar{D}^0$ invariant mass distribution peaks at $E = E_X + \frac{\Gamma_X^2}{16E_X}$
Line Shape of $X$

invariant mass distribution of decay products of $X$

short-distance decay channel: $X \rightarrow H$

$$H = J/\psi \pi^+\pi^-, J/\psi \pi^+\pi^-\pi^0, \ J/\psi \gamma, \ D^+D^- \gamma \ldots$$

Factorization formula

$$\frac{d\Gamma}{dM}[B \rightarrow K + H] = \Gamma_{\text{short}} \times \left| \frac{1}{\gamma_{re} + i\gamma_{im} - \sqrt{-2M_{\text{red}}}E} \right|^2$$

$$M = (M_{D^*0} + M_{D^0}) + E$$
Line Shape of $X$ (cont.)

invariant mass of $H$: $M = (M_{D^*0} + M_{D^0}) + E$

$$\frac{d\Gamma}{dM}[B \to K + H] = \Gamma_{\text{short}} \times \left| \frac{1}{\gamma_{\text{re}} + i\gamma_{\text{im}} - \sqrt{-2M_{\text{red}}E}} \right|^2$$

$\gamma_{\text{re}} > 0$
resonance near $E = -E_X$

$\gamma_{\text{re}} < 0$
cusp near $E = 0$ (Bugg)
The Truth is Out There