
The X Files
The Truth Is Out There

The $X(3872)$ Files

Eric Braaten
Ohio State University

support
DOE, Division of High Energy Physics

The *X(3872)* Files

- What is the X(3872)?
- Universal properties
- Misconceptions
- Partial Width into $p\,\bar{p}$
- X(3872) as source of correlated charm pairs

X(3872)

discovered by Belle Collaboration in August 2003

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

confirmed by CDF Collaboration in November 2003

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

other observed decay modes: Belle, Babar

$J/\psi\, \pi^+ \pi^- \pi^0 \qquad J/\psi\, \gamma \qquad D^0\, \bar{D}^0\, \pi^0$

$\psi(2S)\, \gamma$ (?) $\qquad D^0\, \bar{D}^0\, \gamma$

Mass of X(3872)

mass measured in $J/\psi\ \pi^+\pi^-$ channel

CDF, Belle, Babar, D0

$$M_X = 3871.52 \pm 0.20 \text{ MeV}$$

mass relative to $D^{*0}\,\bar{D}^0$ threshold

$$\boxed{-E_X = -0.42 \pm 0.39 \text{ MeV}}$$

Quantum numbers of X(3872)

a) decay into $J/\psi\ \gamma$

$\Rightarrow$ $C=+$ Belle, Babar

b) momentum distributions for $J/\psi\ \pi^+\pi^-$

$\Rightarrow$ $J^P = 1^+$ or 2^- Belle, CDF

c) decay into $D^0\bar{D}^0\pi^0$

$\Rightarrow$ $J^P = 2^-$ disfavored Belle, Babar

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

Quantum numbers of X(3872)

new Babar analysis of decay into $J/\psi\ \pi^+\pi^-\pi^0$

$\Rightarrow$ $J^P = 2^{-}$ favored over 1^+

$$\boxed{J^{PC} = 2^{-+}?}$$

Quantum numbers of X(3872)

new Babar analysis of decay into $J/\psi\ \pi^+\pi^-\pi^0$

$\Rightarrow\ J^P = 2^{-}$ favored over 1^+

$$\boxed{J^{PC} = 2^{-+}?}$$

What is the X(3872)?

Two crucial experimental inputs:

1. Quantum numbers: $J^{PC} = 1^{++}$

2. Mass is below $D^{*0}\,\bar{D}^0$ threshold by
   $E_X = 0.42 \pm 0.39$ MeV

<u>Inevitable conclusion</u>

X(3872) is loosely-bound charm meson molecule

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

with large separation between charm mesons

What is the X(3872)? (cont.)

Two crucial experimental inputs:

1. Quantum numbers: $J^{PC} = 1^{++}$
   $\Rightarrow$ *X(3872)* has <u>S-wave</u> coupling to $D^{*0}\bar{D}^0$

2. Mass is below $D^{*0}\bar{D}^0$ threshold by
   $E_X = 0.42 \pm 0.39$ MeV
   $\Rightarrow$ *X(3872)* has <u>resonant</u> coupling to $D^{*0}\bar{D}^0$

Quantum mechanics implies that
S-wave near-threshold resonances
have universal properties
determined by the large scattering length *a*

What is the X(3872)? (cont.)

Universal properties

of an S-wave near-threshold resonance with *a>0*

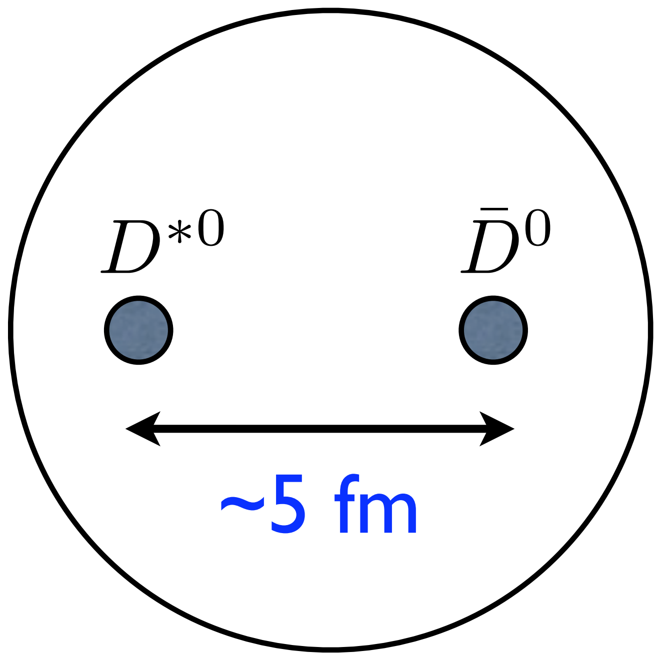
a) binding energy: $E_X = \hbar^2/(2\mu a^2)$

b) rms separation: $r_X = a/\sqrt{2}$

Apply to *X(3872)*:

E_X = *0.42 ± 0.39* MeV

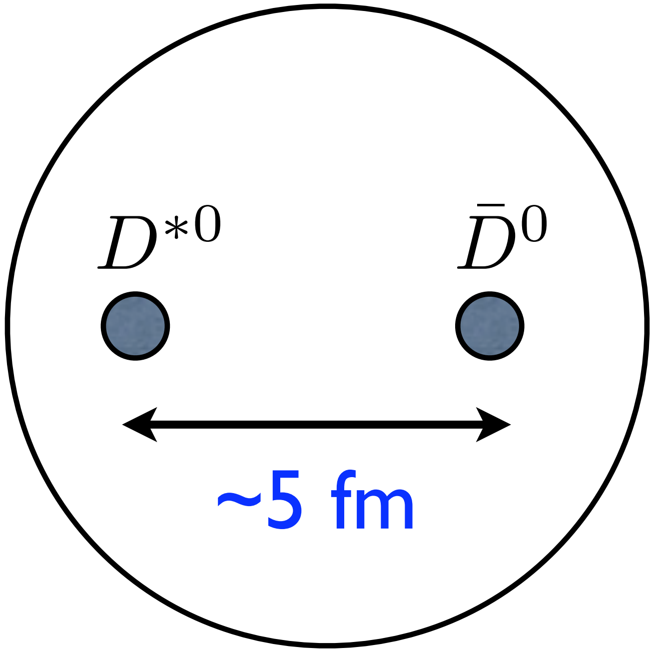
$\Rightarrow \boxed{r_X = 4.9^{+13.4}_{-1.4} \text{ fm}}$



What is the X(3872)?

Universal properties of X(3872)
do not depend on binding mechanism!

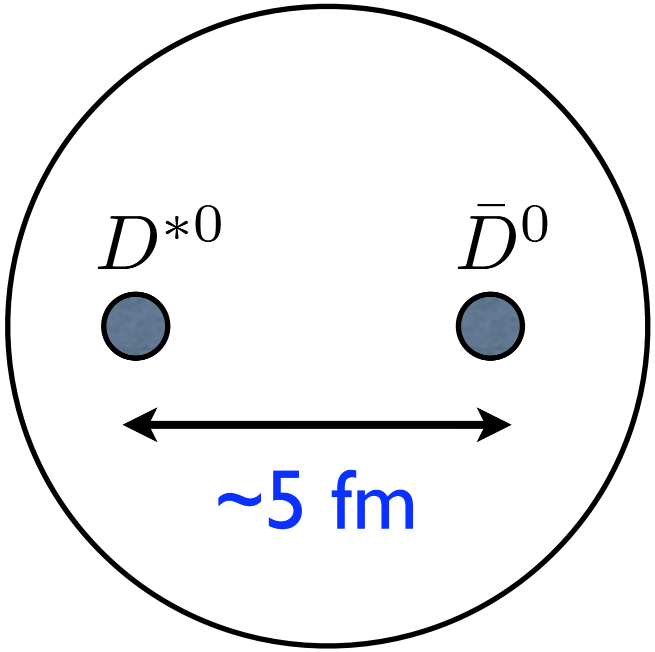
- potential between $D^{*0}\,\bar{D}^0$
  just deep enough for bound state?
- P-wave charmonium state $\chi_{c1}(2P)$
  near $D^{*0}\,\bar{D}^0$ threshold?
- tetraquark state
  near $D^{*0}\,\bar{D}^0$ threshold?



Resonant interactions with $D^{*0}\,\bar{D}^0$
will transform it into a charm meson molecule

What is the X(3872)? (cont.)

X(3872) is a charm meson molecule
with large separation between charm mesons



Why is this conclusion not universally accepted?

- lack of familiarity with S-wave threshold resonances
- failure to distinguish between universal predictions and predictions of specific models
- confusion from $D^{*0}\bar{D}^0$ decay modes

Universal Properties of X(3872)

Universal properties

of S-wave near-threshold resonance

can be derived from

universal scattering amplitude

$$f(E) = \frac{1}{-\gamma + \sqrt{-2\mu(E + i\epsilon)}}$$

E = energy relative to threshold

γ = inverse scattering length

Inclusive line shape (summed over decay channels)

$$\mathrm{Im}\, f(E)$$

Universal properties (cont.)

Scattering amplitude for $D^{*0}\,\bar{D}^0$

Take into account

- D^{*0} width: $\Gamma_{*0} \approx 70\ \mathrm{keV}$
- inelastic scattering channels ($J/\psi\ \pi^+\pi^-$, etc.)

⟹ complex scattering length

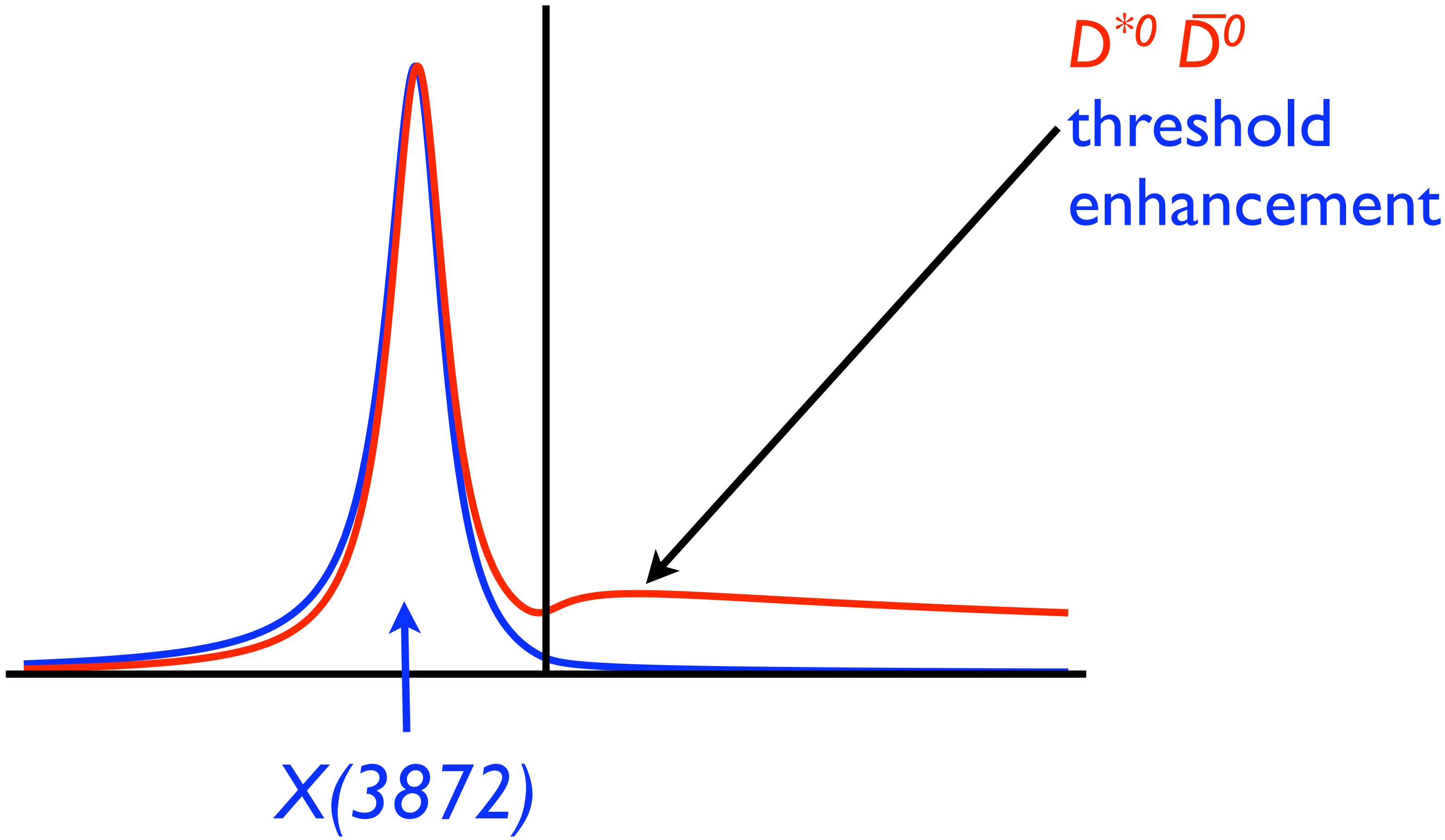
$$f(E) = \frac{1}{-(\gamma_{\mathrm{re}} + i\gamma_{\mathrm{im}}) + \sqrt{-2\mu(E + i\Gamma_{*0}/2)}}$$

Universal line shape (summed over decay channels)

$$\mathrm{Im}\, f(E)$$

Universal properties (cont.)

Line shapes in $J/\psi\ \pi^+\pi^-$ versus $D^0\bar{D}^0\pi^0$



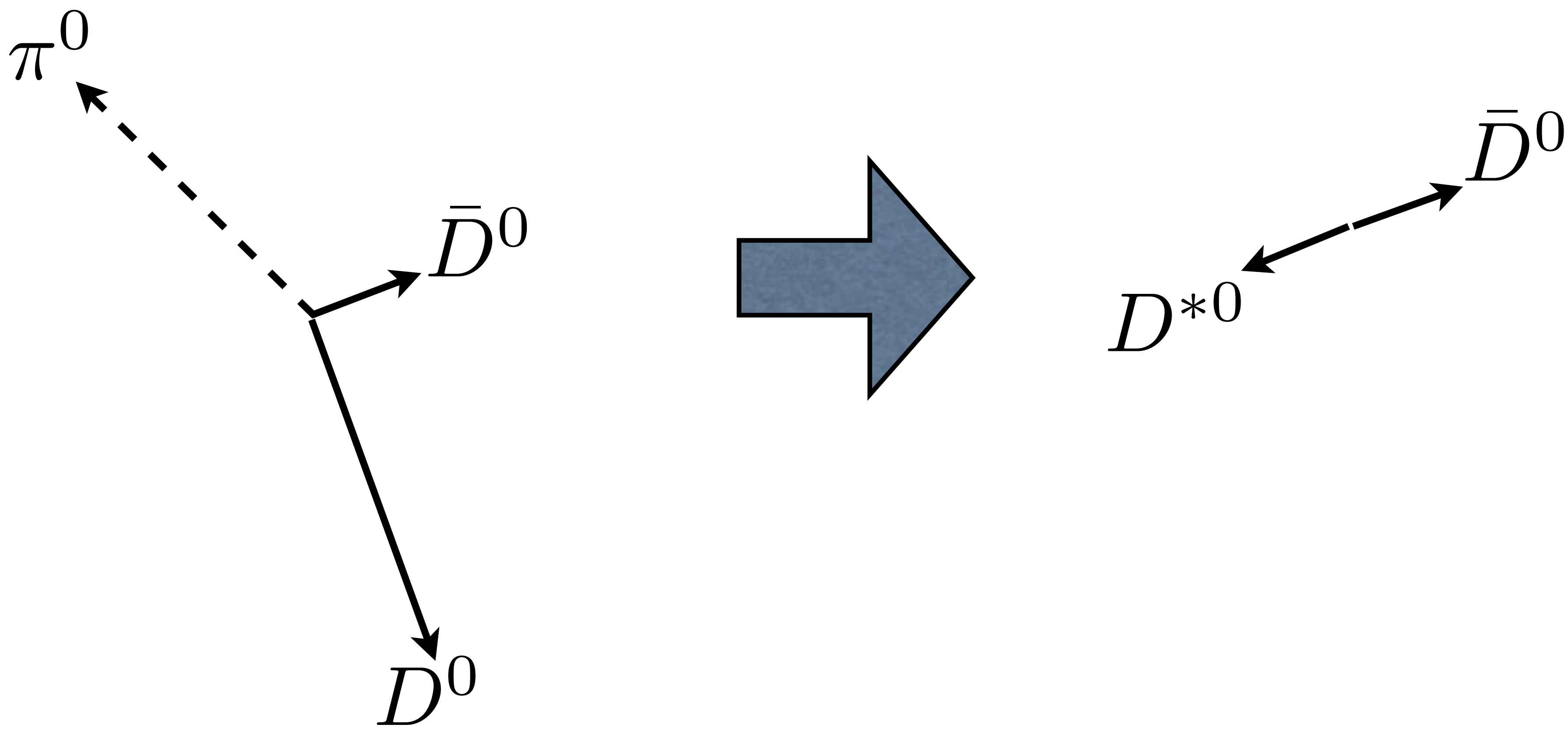
position and width of peak in $D^0\bar{D}^0\pi^0$
are not mass and width of $X(3872)$!

Line shapes (cont.)

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

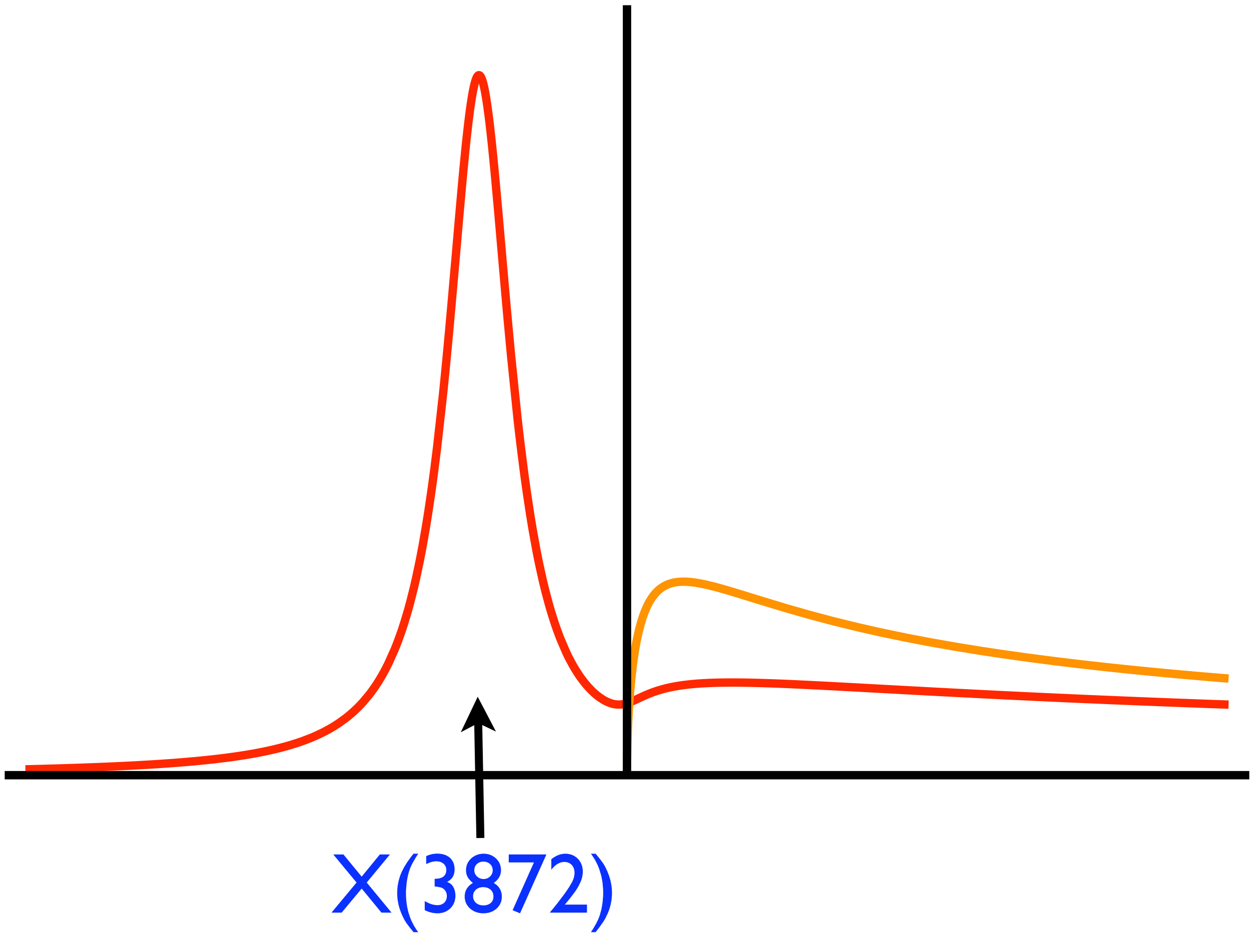
If $D^0\pi^0$ has invariant mass close enough to D^{*0} mass
(within 6 MeV for Belle,
within 10 MeV for Babar)

impose constraint that it comes from decay of D^{*0}



Line shapes (cont.)

$D^0\bar{D}^0\pi^0$ versus $D^{*0}\bar{D}^0$



position and width of peak in $D^{*0}\bar{D}^0$ are not mass and width of X(3872)!

Misconceptions about X(3872)

- PDG averages for Mass and Width
- *X(3872)* might be a virtual state
- branching ratio
  for radiative decays into $\psi(2S)$ and J/ψ
  is inconsistent with molecule
- production rate at the Tevatron
  is orders of magnitude too large
  for a molecule

Misconceptions about X(3872) (cont.)

PDG averages 2008, 2009

Mass: 3872.3 +/- 0.8 MeV

from combining measurements

in $J/\psi\ \pi^+\pi^-$, $D^0\bar{D}^0\pi^0$, $D^{*0}\bar{D}^0$ channels

Belle, CDF, Babar, D0

Width: $3.4\ ^{+2.1}_{-1.7}$ MeV

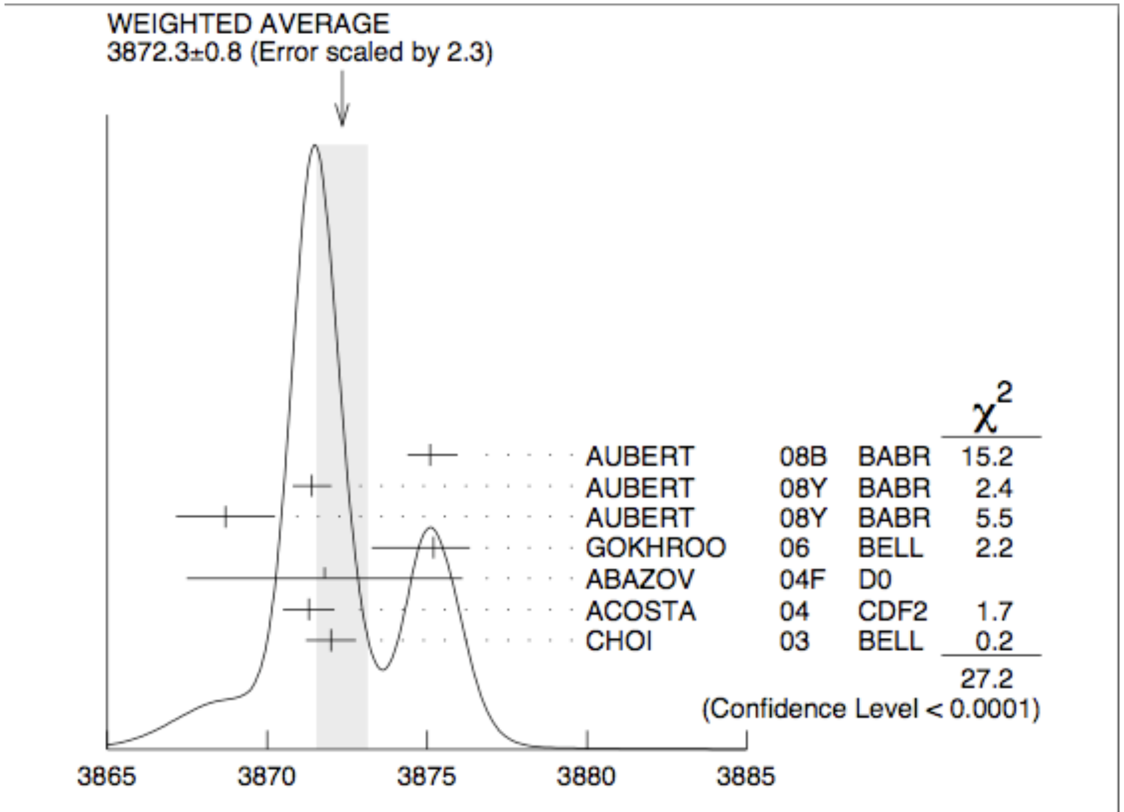
from one measurement in $D^{*0}\bar{D}^0$ channel

Babar

BUT measurements in $D^0\bar{D}^0\pi^0$, $D^{*0}\bar{D}^0$ channels
are <u>NOT</u> measurements of mass and width of *X(3872)*!

Misconceptions about X(3872) (cont.)

measurements of mass of X(3872)



4 lowest measurements: $J/\psi\,\pi^+\pi^-$

2 highest measurements: $D^0\bar{D}^0\pi^0,\;\; D^{*0}\bar{D}^0$

incompatible sets of measurements

PDG: combine them anyway

and inflate error by 2.3

Misconceptions about X(3872) (cont.)

best unbiased measurements
of mass and width of *X(3872)*
are from $J/\psi\ \pi^+\pi^-$ channel

Mass: 3871.52 +/- 0.20 MeV
from measurements in $J/\psi\ \pi^+\pi^-$ channel
Belle, CDF, Babar, D0

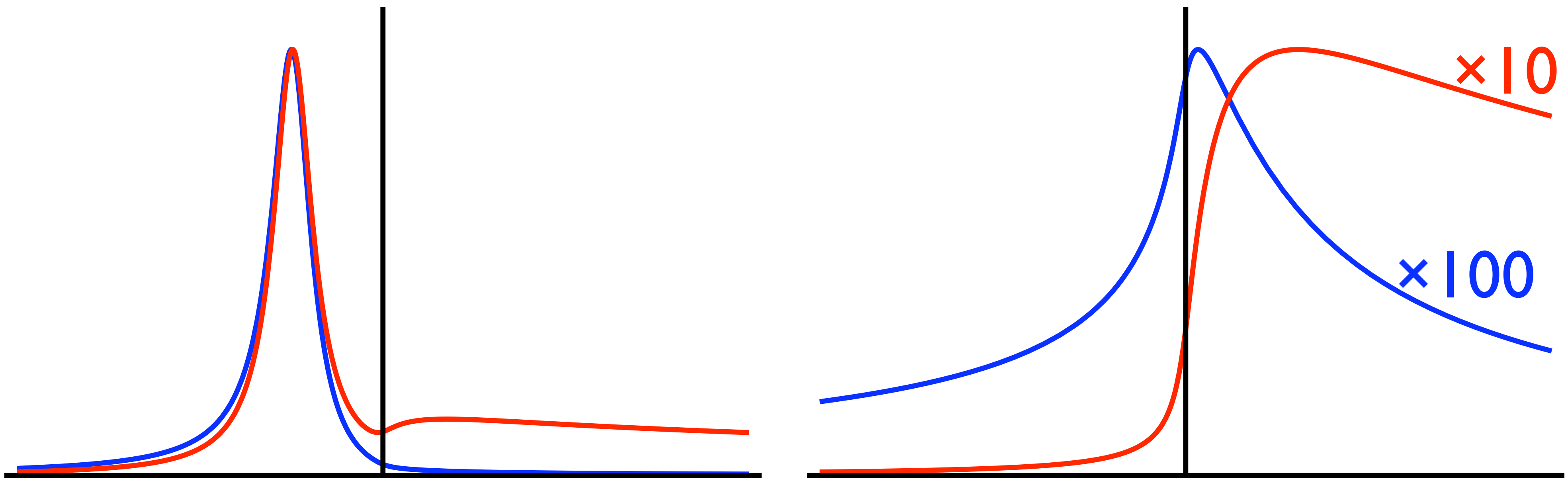
Width: < 2.2 MeV at 90% C.L.
from measurement in $J/\psi\ \pi^+\pi^-$ channel
Belle, Babar

What will PDG listing for *X(3872)* be in 2010?

Misconceptions about X(3872) (cont.)

- *X(3872)* might be a virtual state

$J/\psi\ \pi^+\pi^-$ versus $D^0\bar{D}^0\pi^0$



"bound state" "virtual state"

all analyses that prefer a virtual state
have ignored decays into $D^0\bar{D}^0\pi^0$
from resonant peak below threshold

Misconceptions about X(3872) (cont.)

- Branching ratio

  for radiative decays into $\psi(2S)$ and J/ψ
  is inconsistent with molecule

$$\frac{\mathrm{Br}[X \to \psi(2S)\,\gamma]}{\mathrm{Br}[X \to J/\psi\,\gamma]} = 3.4 \pm 1.4$$ Babar 2009

"generally inconsistent
with a purely $D^{*0}\bar{D}^0$ molecular interpretation"

NO! inconsistent with model by Swanson
in which X(3872) is bound state of

$$D^*\bar{D},\ D\bar{D}^*,\ J/\psi\,\rho,\ J/\psi\,\omega$$

Misconceptions about X(3872) (cont.)

- Production rate at the Tevatron is orders of magnitude too large for a molecule

proposed upper bound: Bignamini et al.

$$\sigma[X] < \sigma_{\text{naive}}[D^{*0}\bar{D}^0, k < \sqrt{2\mu E_X}]$$

integrate charm meson cross section up to binding momentum

estimate of cross section: Artoisenet, Braaten

$$\sigma[X] \approx \sigma_{\text{naive}}[D^{*0}\bar{D}^0, k < m_\pi] \frac{6\pi\sqrt{2\mu E_X}}{m_\pi}$$

takes into account rescattering of charm mesons
orders of magnitude larger than proposed upper bound

Partial width for $X(3872) \to p\,\bar{p}$

partial width for $\psi(3686)$

$$\Gamma[\psi' \to p\,\bar{p}] = 87 \pm 5 \text{ eV}$$

partial width for $\chi_{c1}(3511)$

$$\Gamma[\chi_{c1} \to p\,\bar{p}] = 59 \pm 6 \text{ eV}$$

estimate of partial width for $X(3872)$

$$\Gamma[X \to p\,\bar{p}] \approx 30 \text{ eV} \times (E_X/0.42 \text{ MeV})^{1/2}$$

Braaten, Phys. Rev. D 77, 03419 (2008)

from estimated cross section for $p\,\bar{p} \to D^{*0}\bar{D}^0$

obtained by scaling cross section for $p\,\bar{p} \to K^{*+} K^{-}$

Partial Width (cont.)

Comparison of $p\,\bar{p}$ partial widths

for X(3872), $\chi_{c1}(3511)$

- creation of light quark pairs

  with large relative momentum $2m_p/3$

  X(3872) requires creation of $u\bar{u}$, $d\bar{d}$

  $\chi_{c1}(3511)$ requires creation of $u\bar{u}$, $u\bar{u}$, $d\bar{d}$

  $\Rightarrow$ suppression by $\alpha_s^2(2m_p/3)\ (\Lambda_{QCD}/m_p)^2$

- wavefunction near the origin

  X(3872) is suppressed by $(2\mu E_X)^{1/2}/m_\pi$

  $\chi_{c1}(3511)$ is suppressed by $m_c^5\ |R'(0)|^2 \sim v^5$

Partial Width (cont.)

Comparison of total widths

for X(3872), $\chi_{c1}(3511)$

- $\chi_{c1}(3511)$

  $\Gamma[\chi_{c1}]$ = 890 ± 5 keV

- X(3872)

  $\Gamma[X] > \Gamma[D^{*0}] = 65$ keV at 90% C.L.

  $\Gamma[X] < 2200$ keV at 90% C.L.

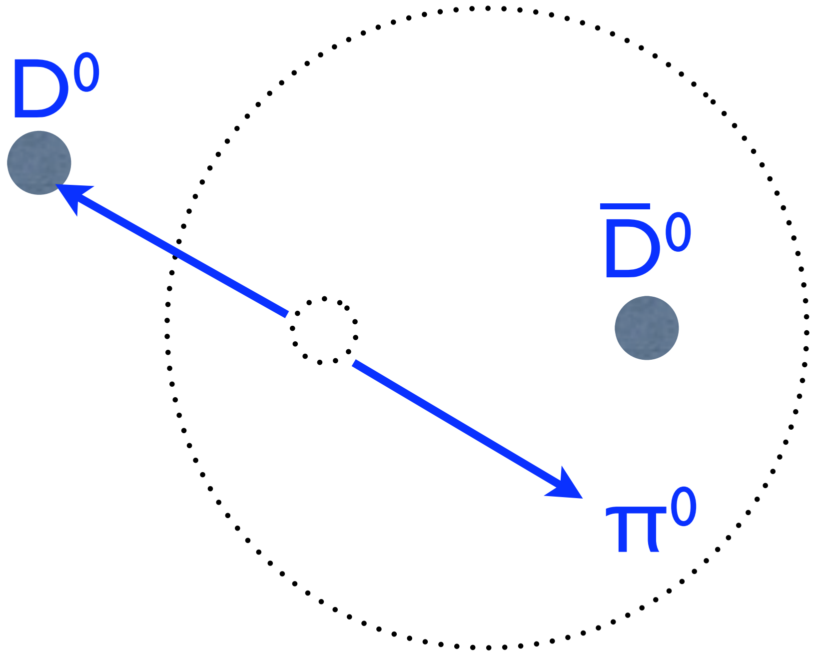
  from $J/\psi\ \pi^+\pi^-$ channel (Belle, Babar)

X(3872) is probably narrower than $\chi_{c1}(3511)$

could be much narrower

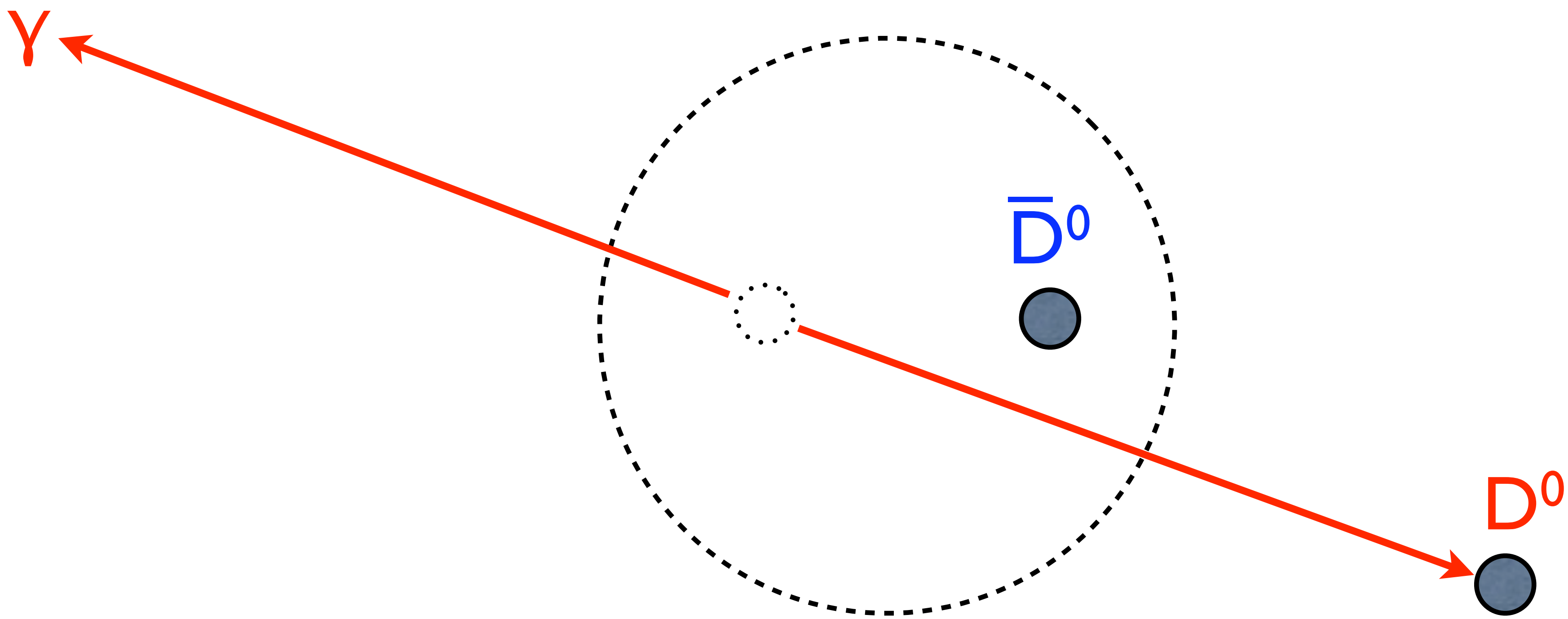
X(3872) as Source of Correlated Charm Pairs

Decay of X(3872) into $D^0\bar{D}^0\pi^0$ produces
$D^0\ \bar{D}^0$ pair with charge conjugation +
(and relative momentum ~50 MeV)



Correlated Charm Pairs (cont.)

Decay of X(3872) into $D^0\bar{D}^0\gamma$ produces
$D^0\,\bar{D}^0$ pair with charge conjugation --
(and relative momentum ~150 MeV)



Can charm pair correlations be exploited
to study charm mixing ?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