
The X Files
The Truth Is Out There

Analysis of $J/\psi\ \pi^+\pi^-$ and $D^{*0}\bar{D}^0$ Decays of the $X(3872)$

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Analysis of $J/\psi\ \pi^+\pi^-$ and $D^{*0}\bar{D}^0$ Decays of the X(3872)

- What is the X(3872)?
- Universal properties
- Confusion from $D^{*0}\bar{D}^0$ decay modes
- Line shapes
- Analysis of recent data from Belle, Babar

X(3872)

discovered by Belle Collaboration in August 2003

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

final-state J/ψ  contains $c\bar{c}$

- mass not consistent with charmonium spectrum predicted by potential models
- decays violate isospin symmetry:

$$X \longrightarrow J/\psi\,\pi^+\pi^- \qquad \text{isospin } 1$$
$$X \longrightarrow J/\psi\,\pi^+\pi^-\pi^0 \qquad \text{isospin } 0$$

Belle

What is the X(3872)?

Two crucial experimental inputs:

1. Quantum numbers: $J^{PC}=1^{++}$
   - a. $X \longrightarrow J/\psi\,\gamma$ ⟹ C=+ Belle, Babar
   - b. $X \longrightarrow J/\psi\,\pi^+\pi^-$ angular distribution ⟹ 1^{++} or 2^{-+} Belle, CDF
   - c. 2^{-+} is disfavored by
     - $X \longrightarrow \psi(2S)\,\gamma$ Babar
     - $X \longrightarrow D^{*0}\bar{D}^0$ Belle, Babar

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

$$M_X - (M_{D^{*0}} + M_{D^0}) = -0.25 \pm 0.40 \text{ MeV}$$

measured in $J/\psi\,\pi^+\pi^-$ channel Belle, Babar, CDF

What is the X(3872)?

Two crucial experimental inputs:

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

   ⟹ S-wave coupling to $D^{*0}\bar{D}^0$

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

$$M_X - (M_{D^{*0}} + M_{D^0}) = -0.25 \pm 0.40 \text{ MeV}$$

   ⟹ resonant coupling!

Conclusion:

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

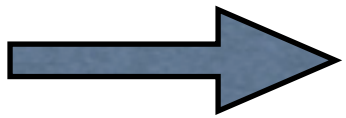
$$X = \frac{1}{\sqrt{2}} \left(D^{*0} \bar{D}^0 + D^0 \bar{D}^{*0} \right)$$

with large separation between charm mesons

What is the X(3872)?

Nonrelativistic Quantum Mechanics

- short-range interactions
- S-wave resonance close enough to threshold



large scattering length a (>> range)
universal features depend only on a,
insensitive to shorter distances

X(3872) close to $D^{*0}D^0$ threshold

universal features depend only on
large scattering length for $D^{*0}D^0$

What is the X(3872)?

Universal features

scattering

- cross section: $4\pi a^2$

bound state (a>0)

- small binding energy: $\hbar^2/(2\mu a^2)$
- large rms separation: $a/\sqrt{2}$

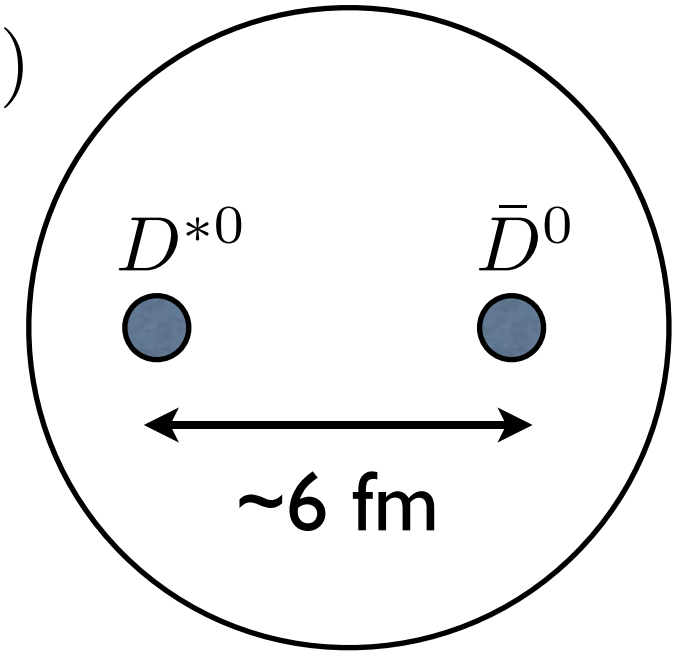
X(3872)

- binding energy: 0.25 ± 0.40 MeV
- rms separation: $6.3^{+\infty}_{-2.4}$ fm

What is the X(3872)?

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

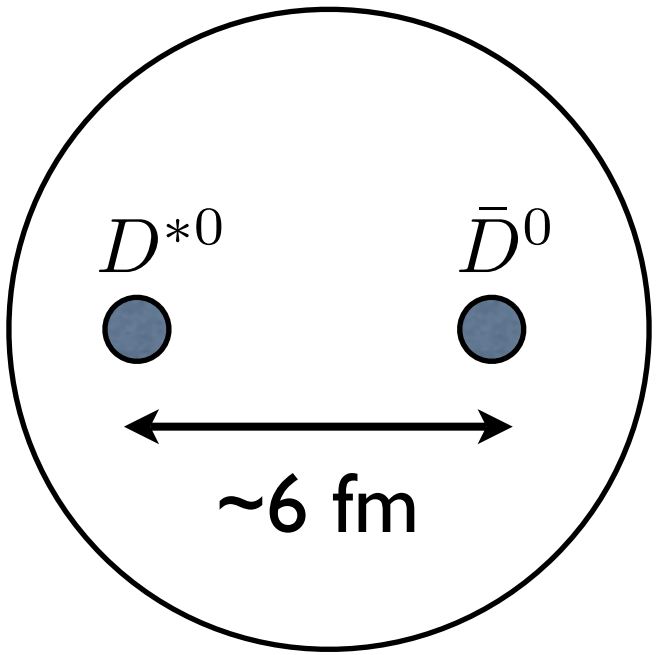
- potential between $D^{*0}\bar{D}^0$
  just deep enough for bound state?
- P-wave charmonium state $\chi_{c1}(2P)$
  near $D^{*0}\bar{D}^0$ threshold?
- tetraquark state $(cq\bar{c}\bar{q})$
  near $D^{*0}\bar{D}^0$ threshold?



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

What is the X(3872)?

X(3872) is a weakly-bound 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
  and nonuniversal predictions
- confusion from $D^{*0}\bar{D}^0$ decay modes

What is the X(3872)?

Example of failure to distinguish between
universal and nonuniversal predictions

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

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

Mass of the X(3872)

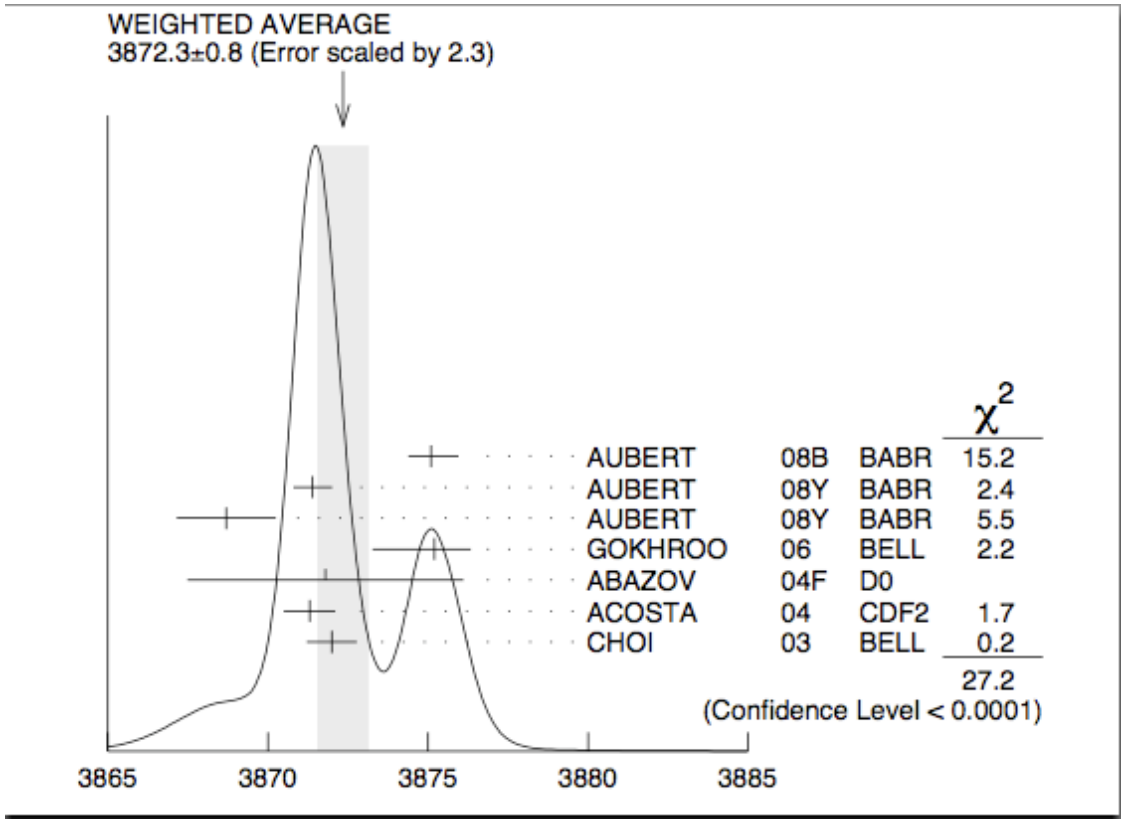
PDG average 2008, 2009:
3872.3 +/- 0.8 MeV

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

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

most recent measurements in $J/\psi\,\pi^+\pi^-$ channel
Babar, Belle, CDF
3871.55 +/- 0.20 MeV

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

Width of the X(3872)

PDG average 2008, 2009:
$3.4\ ^{+2.1}_{-1.7}$ MeV

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

BUT measurement in $D^{*0}\bar{D}^0$ channel
is NOT a measurement of width of X(3872)!

measurements in $J/\psi\,\pi^+\pi^-$ channel

< 2.3 MeV at 90% C.L.	Belle (2003)
< 3.3 MeV	Babar (2008)

Line Shapes of the X(3872)

Braaten and Lu, Phys. Rev. D 76, 094028 (2007)
Phys. Rev. D 77, 014029 (2008)

Scattering amplitude
for S-wave threshold resonance

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

E = energy relative to threshold

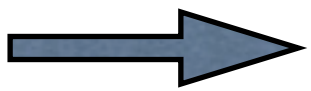
γ = inverse scattering length

Line shapes

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

Take into account

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



complex scattering length

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

binding energy: $E_X = (\gamma_{\rm re}^2 + \gamma_{\rm im}^2)/(2\mu)$

width: $\Gamma_X = \Gamma_{*0} + 2\gamma_{\rm re}\gamma_{\rm im}/\mu$

Line shapes

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

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

spectral function

$$\mathrm{Im} f(E) = |f(E)|^2\,\gamma_{\rm im} + |f(E)|^2 \left(\mu\sqrt{E^2 + \Gamma_{*0}^2/4} + \mu E\right)^{1/2}$$

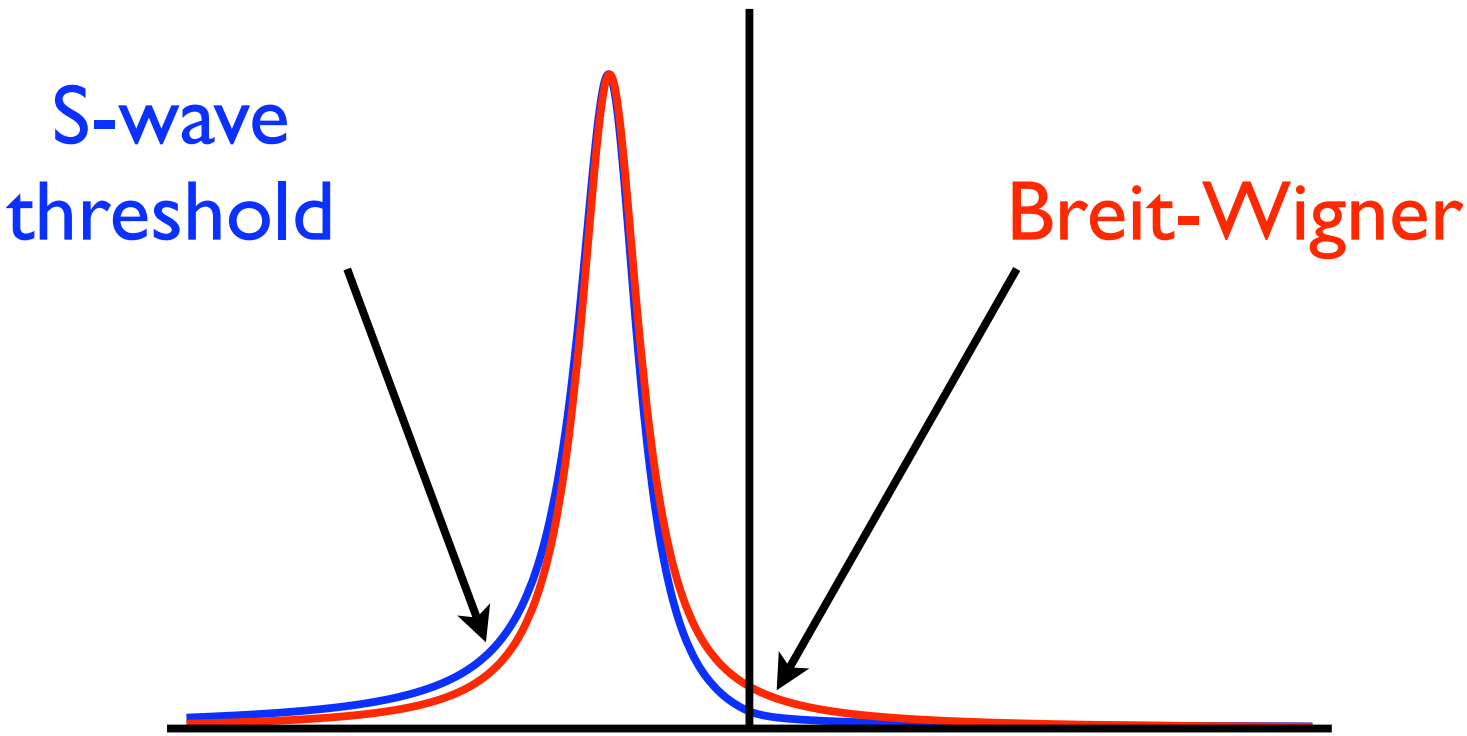
line shape in other channels: $J/\psi\,\pi^+\pi^-$, etc.

line shape in $D^0\bar{D}^0\pi^0$, $D^0\bar{D}^0\gamma$

Line shapes

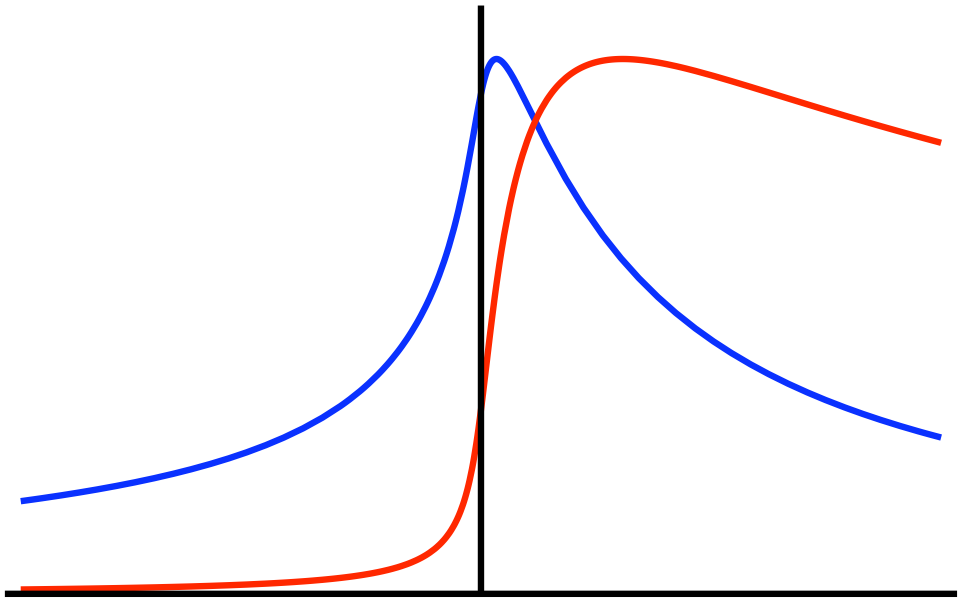
Breit-Wigner resonance: $$\frac{1}{\left|E + E_X + i\Gamma_X/2)\right|^2}$$

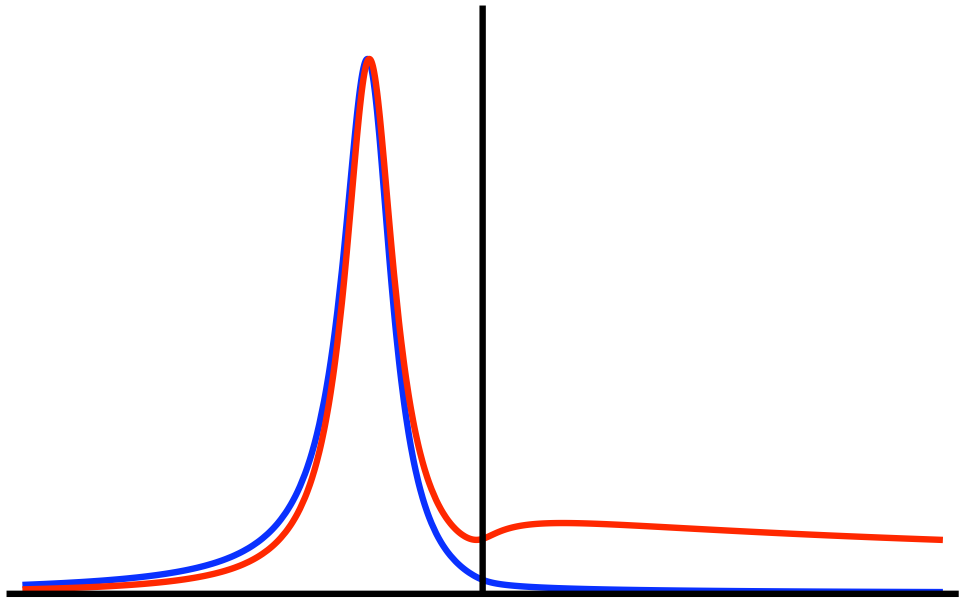
S-wave threshold resonance: $$\frac{1}{\left|-(\gamma_{\rm re} + i\gamma_{\rm im}) + \sqrt{-2\mu(E + i\Gamma_{*0}/2)}\right|^2}$$



Line shapes

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





"virtual state"

$\gamma_{re} < 0$

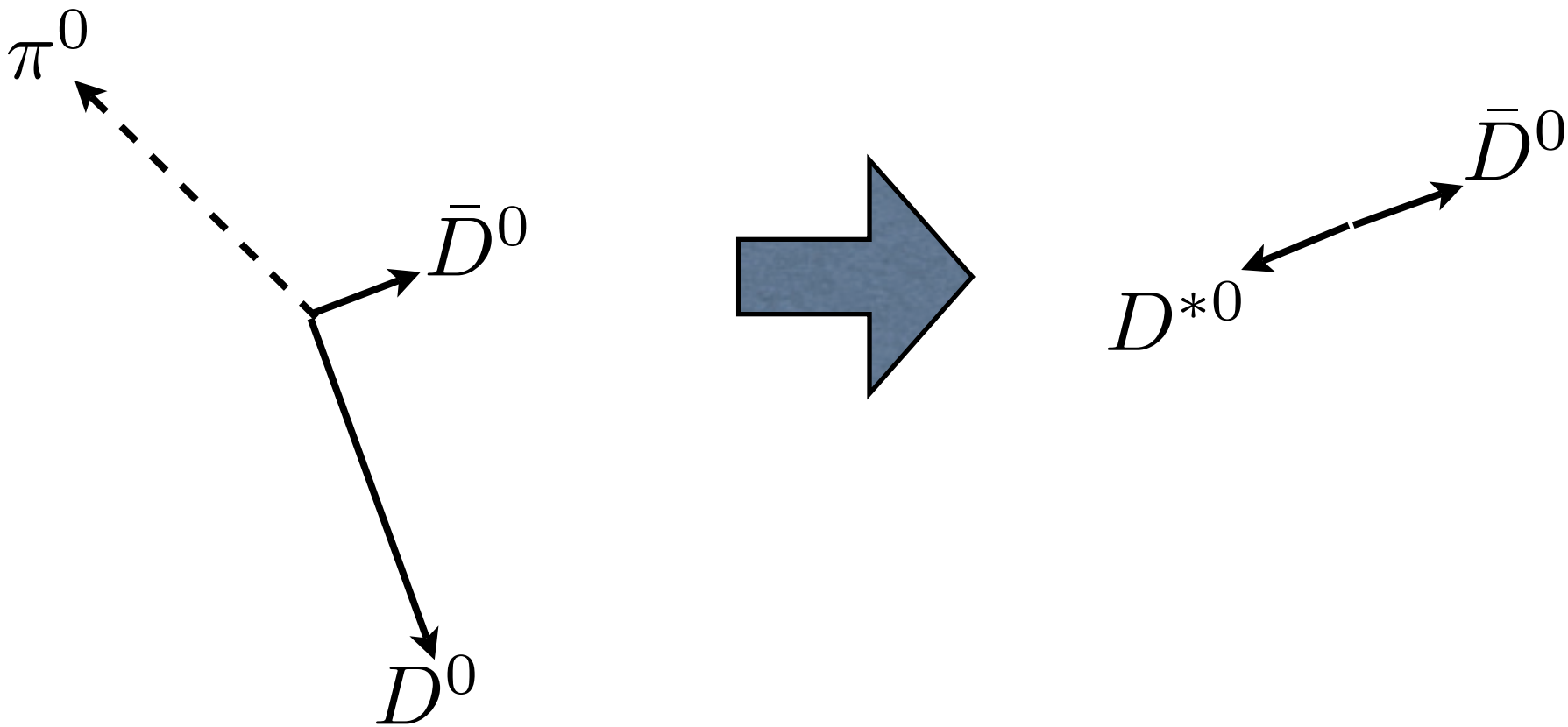
"bound state"

$\gamma_{re} > 0$

Line shapes

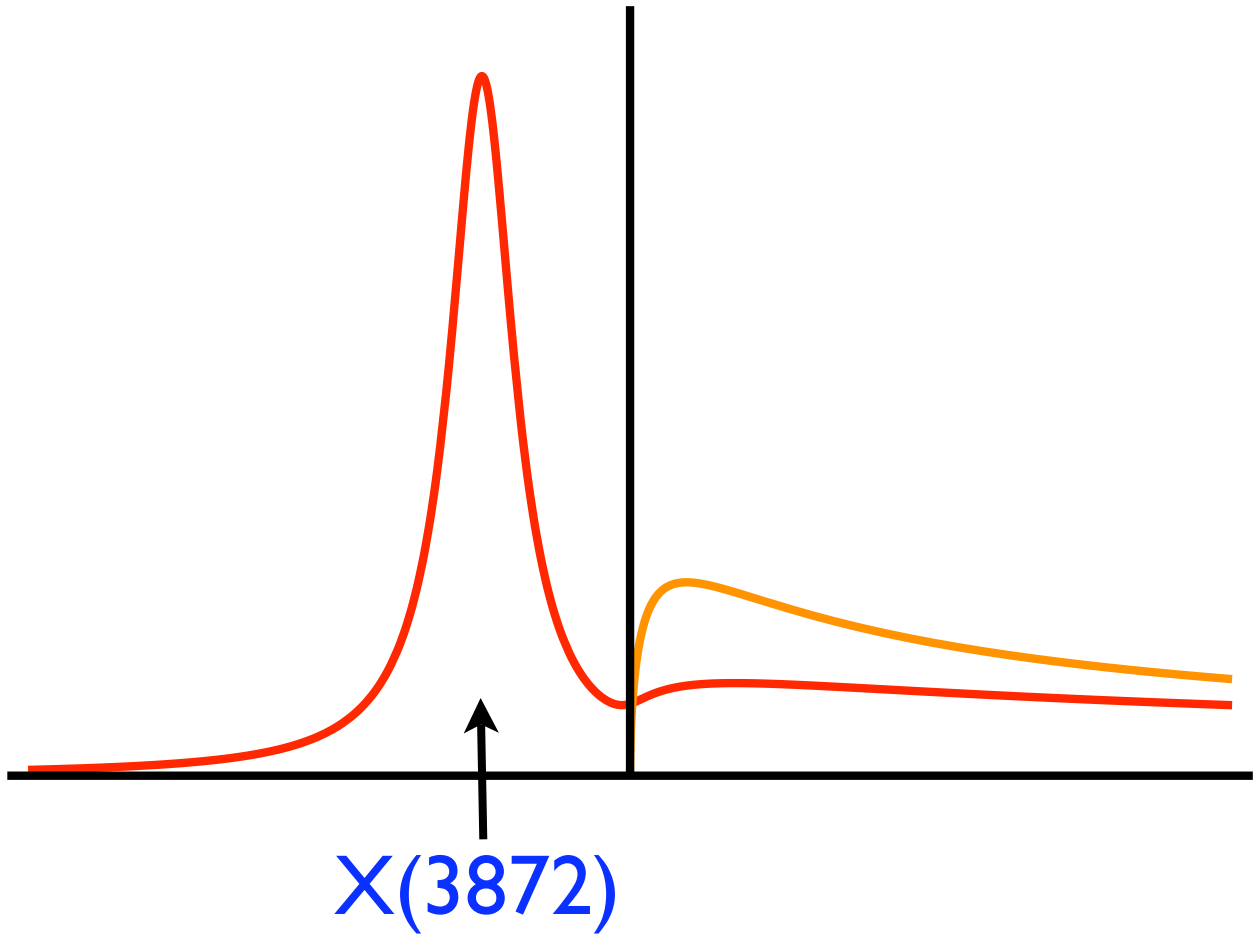
X(3872) resonance in $D^{*0}\ \bar{D}^0$

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

$D^0\bar{D}^0\pi^0$ 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)!

Analysis of recent data from Babar and Belle
on X(3872) resonance in J/ψ $\pi^+\pi^-$ and $D^0\bar{D}^0\pi^0$

Braaten and Stapleton, arXiv:0907.3167

- signal: S-wave threshold resonance
  with parameters $\gamma_{\rm re}$, $\gamma_{\rm im}$

- background: $J/\psi\,\pi^+\pi^-$ constant
  $D^{*0}\bar{D}^0$ $\sim\sqrt{E}$

- experimental resolution: model by Gaussian smearing

$J/\psi\,\pi^+\pi^-$ $\sigma \sim$ constant
$D^{*0}\bar{D}^0$ $\sigma(E) \sim \sqrt{E}$

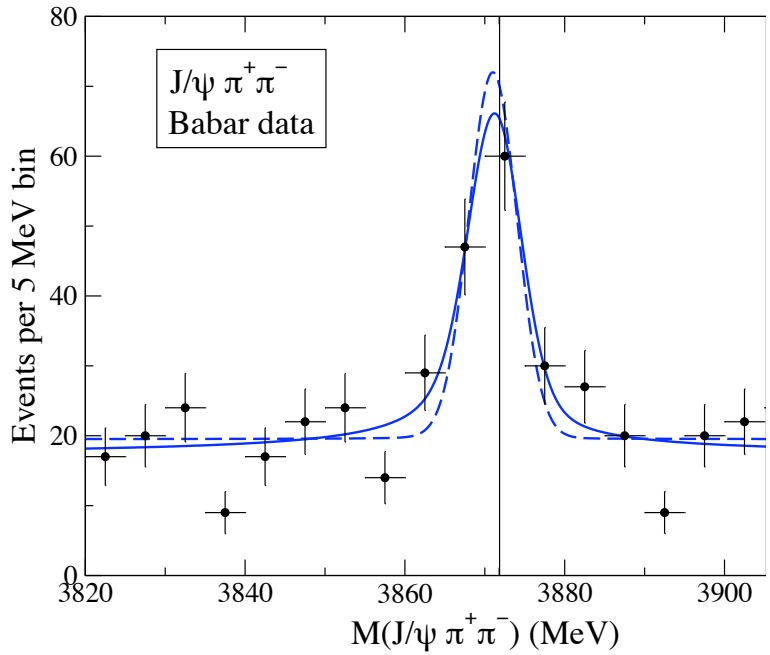
- maximize Log(likelihood)

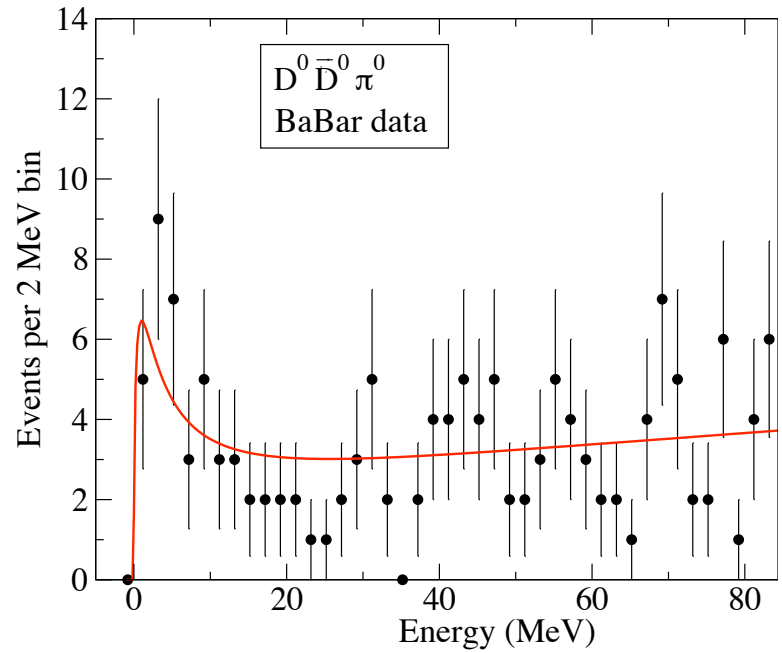
Analysis of recent data

$J/\psi\ \pi^+\pi^-$

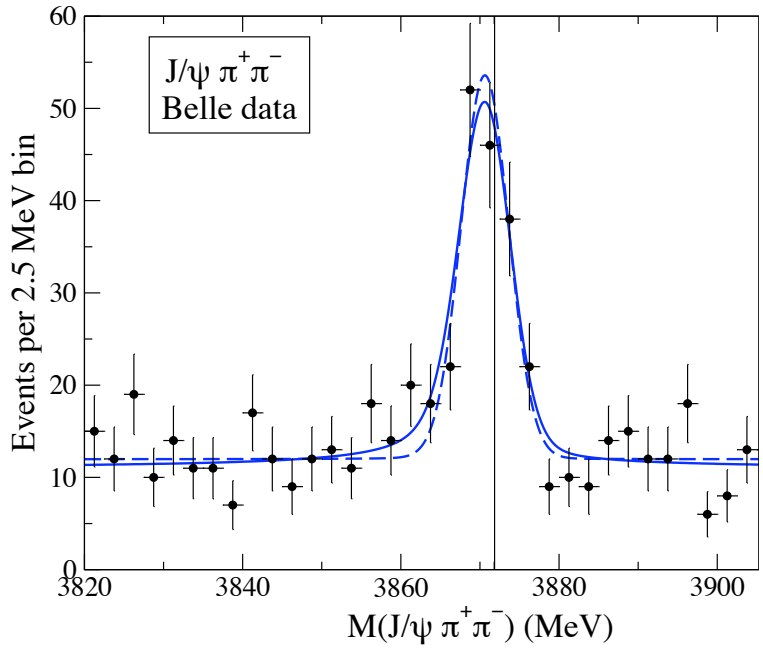
$D^{*0}\bar{D}^0$

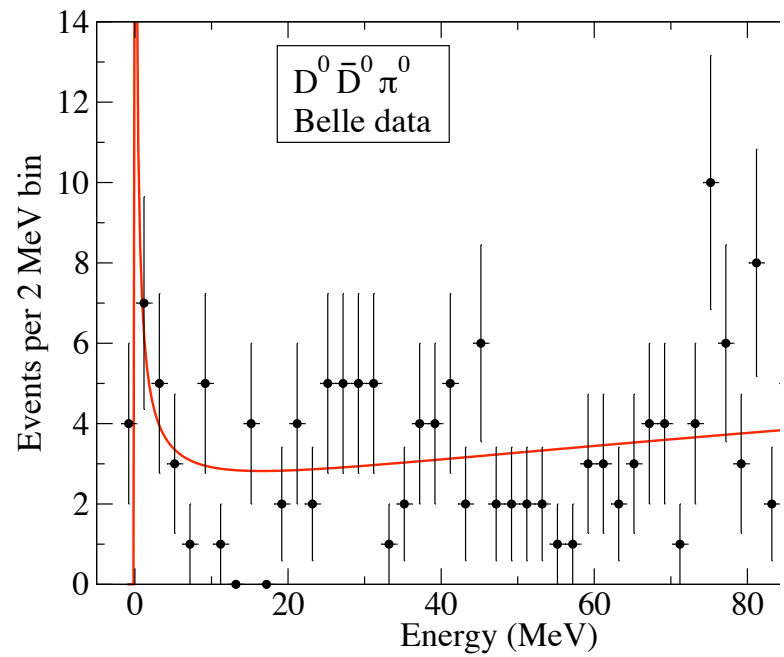
Babar data





Belle data



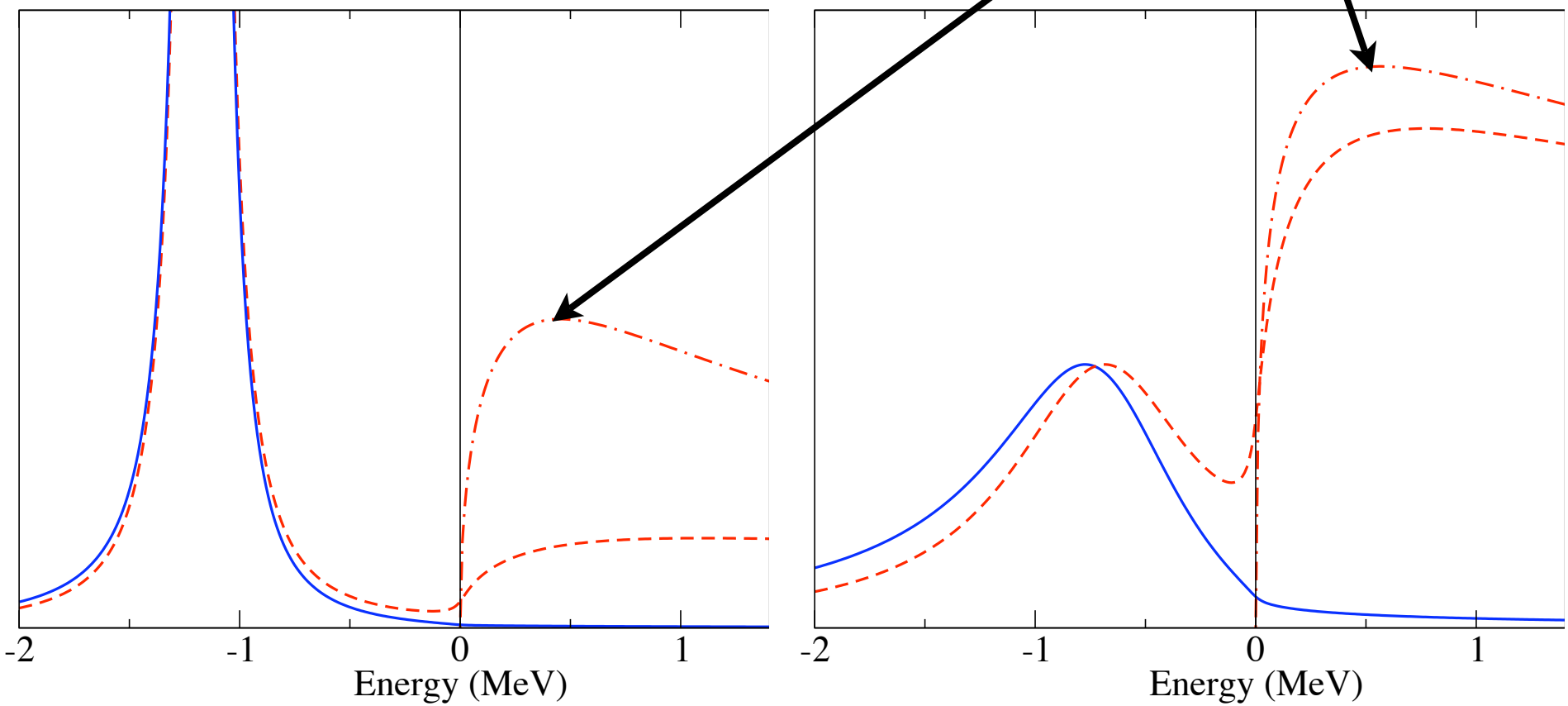


Line shapes from fits to Belle data in $J/\psi\,\pi^+\pi^-$

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

γ_{re} = 47.5 MeV
γ_{im} = 0

γ_{re} = 38.4 MeV
γ_{im} = 12.0 MeV



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

Summary

- PDG averages for mass and width of X(3872) are wrong!
- position and width of peak in $D^0\bar{D}^0\pi^0$ or $D^{*0}\bar{D}^0$ should NOT be interpreted as mass and width of X(3872)
- among existing measurements, only $J/\psi\,\pi^+\pi^-$ should be included in PDG averages
- instead of analyzing $D^0\bar{D}^0\pi^0$ channel as $D^{*0}\bar{D}^0$, it would be preferable to analyze it as $D^0\bar{D}^0\pi^0$ (like 2006 Belle analysis)


The Truth is Our There