Production of the X (3872) in B meson Decay by the Coalescence of Charm Mesons

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Outline

1. What is the X(3872)?

2. Low-Energy Universality

3. Decay amplitude for $B^+ \to X K^+$

4. Invariant mass distribution at threshold

5. Estimate for $\mathcal{B}[B^+ \to X K^+]$

6. Summary

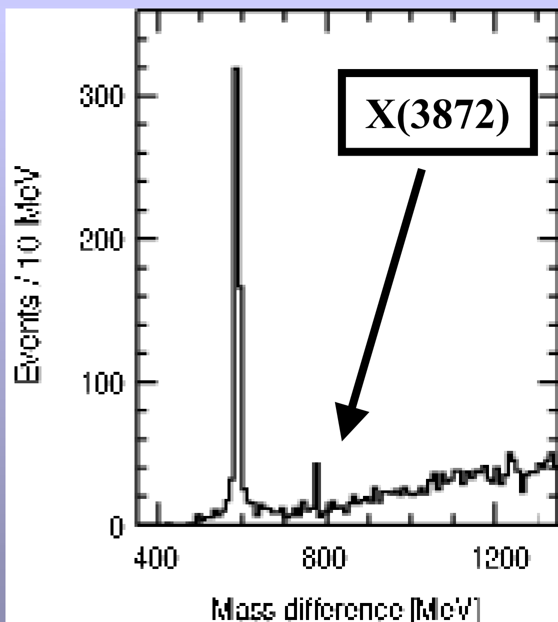
What is the X(3872)?

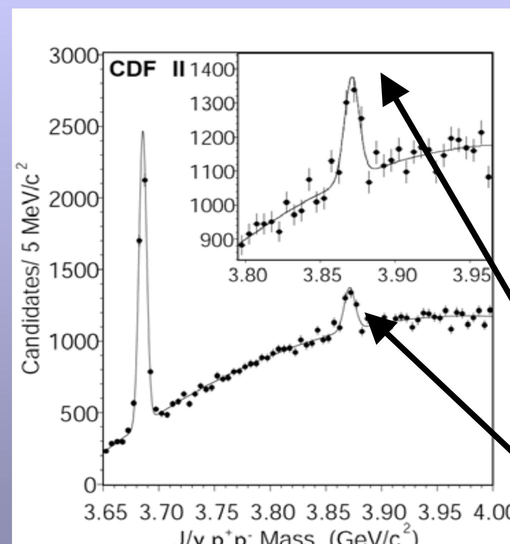
Discovery by Belle $B^+ \to X(3872)K^+$ $X \to J/\psi\pi^+\pi^-$

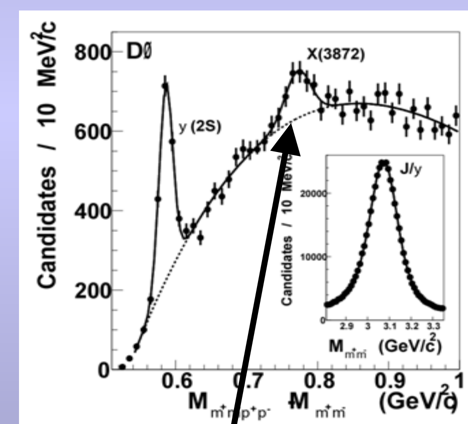
$$3872.0 \pm 0.6 \pm 0.5 \text{ MeV} \qquad \Gamma < 2.3 \text{ MeV}$$

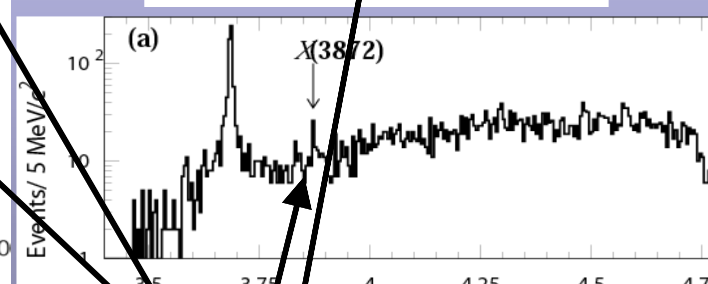
Confirmed by CDF II, D0 and BABAR

$$M(J/\psi\pi^+\pi^-) = 3871.4 \pm 0.7 \pm 0.4 \text{ MeV}$$









X(3872)

Proposed Interpretations

1. Charmonium

D-wave: $J^{PC} = 2^{-\pm}$

P-wave: $J^{PC} = 1^{+\pm}$

(Eichten, Lane, Quigg)
(Barns, Godfrey)

Hybrid $(c\bar{c}g)$: mass 4100 ± 200 MeV (ground-state)

(Juge, Kuti, Morningstar)

2. Loosely-bound $\overline{D}D^*$ Molecule

$$m_D + m_{D^*} = 3871.2 \pm 0.7 \text{ MeV}$$

$$m_X = 3871.9 \pm 0.6 \text{ MeV (Average)}$$

Bound by one pion exchange

$J^{PC} = 1^{++}$ (S-wave)

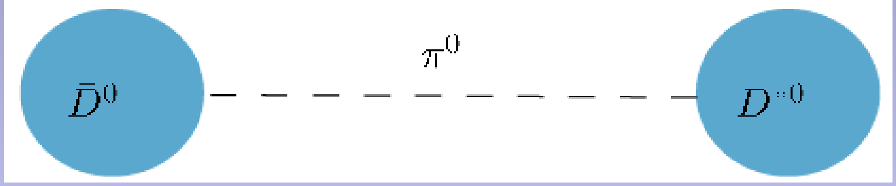
$J^{PC} = 0^{-+}$ (P-wave)

(Tornqvist)

If molecule, it is important to know the production rate

Low-Energy Universality

If X is S-wave $\overline{D}^0 D^{*0} / D^0 \overline{D}^{*0}$ Molecule:



Natural scale for the binding energy $\simeq m_\pi^2 / 2\mu = 10 \text{ MeV}$

1. Extremely small binding energy (< 0.4 MeV)

$$E_b = m_D + m_{D^*} - m_X \simeq \frac{1}{2\,\mu\, a^2}$$

>7 fm

2. Some properties depend only on a (s-wave scattering length),

   insensitive to shorter scales of QCD ⟶ low-energy universality

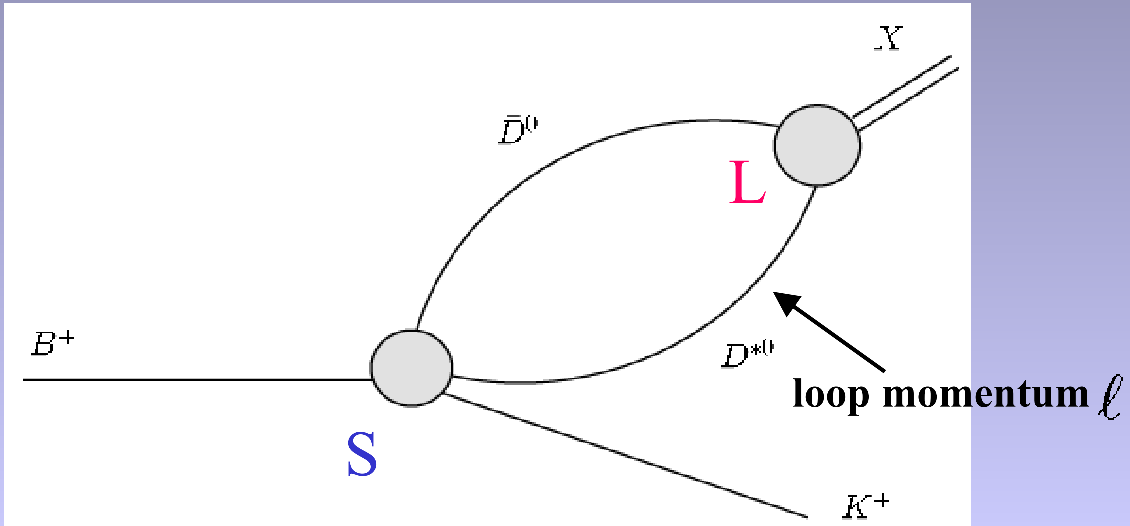
3. Universal wave function

$$|\boldsymbol{k}| \ll m_\pi \qquad \Psi(\boldsymbol{k}) = \left(\frac{8\pi}{a}\right)^{1/2} \frac{1}{\boldsymbol{k}^2 + 1/a^2}$$

Production of X from the B^+ Decay

Discovery mode:

$$B^+ \longrightarrow X K^+$$



Short-distance Process: $B^+ \longrightarrow \overline{D}^0 D^{*0} K^+$

Long-distance Process: $\overline{D}^0 D^{*0} \longrightarrow X$

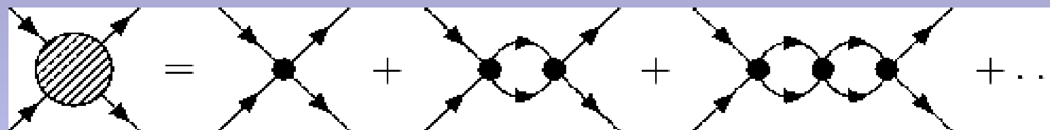
Amplitude $\mathcal{A}_1[B^+ \to X K^+]$ is

$$-i \int \frac{d^4\ell}{(2\pi)^4} \mathcal{A}[B^+ \to D^0 \bar{D}^{*0} K^+] \, \mathcal{A}[D^0 \bar{D}^{*0} \to X] \times \frac{1}{(q+\ell)^2 - m_D^2 + i\epsilon} \frac{1}{(q'-\ell)^2 - m_{D*}^2 + i\epsilon}$$

Coalescence Process $\mathcal{A}[\bar{D}^0 D^{*0} \longrightarrow X]$

Large S-wave Scattering Length a $\longrightarrow$ Resonant Scattering

$k_{\rm cm} \ll m_\pi$



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

Universal elastic scattering amplitude:

$$\mathcal{A}[\bar{D}^0 D^{*0} \to \bar{D}^0 D^{*0}] \simeq \frac{8\pi m_D m_{D^*}}{\mu\,(-1/a - i k_{\rm cm})}$$

Universal coalescence amplitude:

$$\mathcal{A}[\bar{D}^0 D^{*0} \to X] = \left(\frac{16\pi Z m_X m_D m_{D^*}}{\mu^2 a}\right)^{1/2} \epsilon_X^* \cdot \epsilon_{D^*}$$

What about the loop integral over ℓ ?

$$\int \frac{d^4\ell}{(2\pi)^4} \frac{1}{(q+\ell)^2 - m_D^2 + i\epsilon} \frac{1}{(q'-\ell)^2 - m_{D^*}^2 + i\epsilon}$$

$$\simeq \int^{\Lambda} \frac{d^3\boldsymbol{\ell}}{(2\pi)^3} \frac{i\mu a^{1/2}}{4\sqrt{2}\pi^{1/2} m_D m_{D^*}} \Psi(\boldsymbol{\ell})$$

$$= \frac{i\mu\Lambda}{4\pi^2 m_D m_{D^*}}$$

Momentum-space wave function

→ Linearly depend on the ultraviolet cutoff Λ

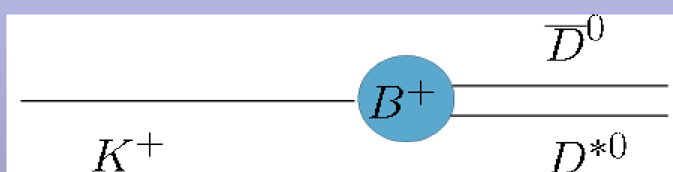
$(\Lambda \simeq m_\pi)$: chosen for an order-of-magnitude estimate

What about the short-distance process?

$$\mathcal{A}[B^+ \longrightarrow \overline{D}^0 D^{*0} K^+] \quad (\text{ or } \quad \mathcal{A}[B^+ \longrightarrow D^0 \overline{D}^{*0} K^+] \quad)$$

In order to produce X(3872) by coalescence, D mesons should have small relative momentum and are almost collinear

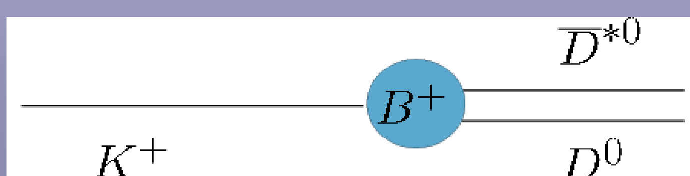
At the corner of phase space where $\overline{D}^0$ and D^{*0} are collinear:



$$= c_1 \, P \cdot \epsilon^*$$

constant → c_1

momentum of B^+ → P



$$= c_2 \, P \cdot \epsilon^*$$

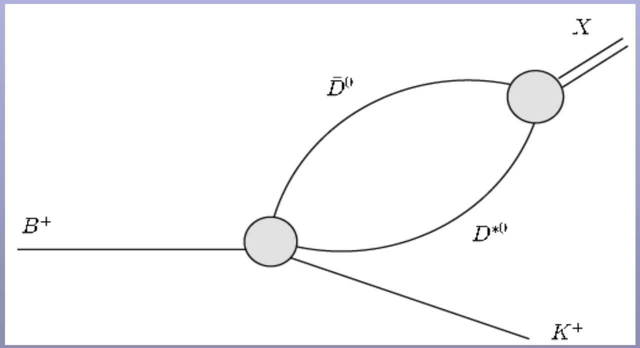
Putting all together…

$$\Gamma[B^+ \to X K^+] = \frac{\lambda^{3/2}(m_B, m_X, m_K)}{64\pi^4 m_B^3 m_X^2 \mu\, a} |c_1 \pm c_2|^2 \Lambda^2$$

$+$: C = even

$-$: C = odd

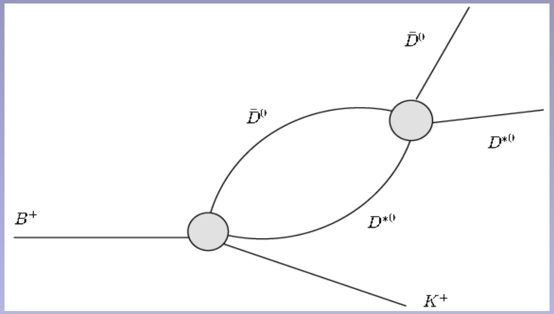
$$\frac{1}{\sqrt{2}}\left(|D^0 \overline{D}^{*0}\rangle \pm |\overline{D}^0 D^{*0}\rangle\right)$$

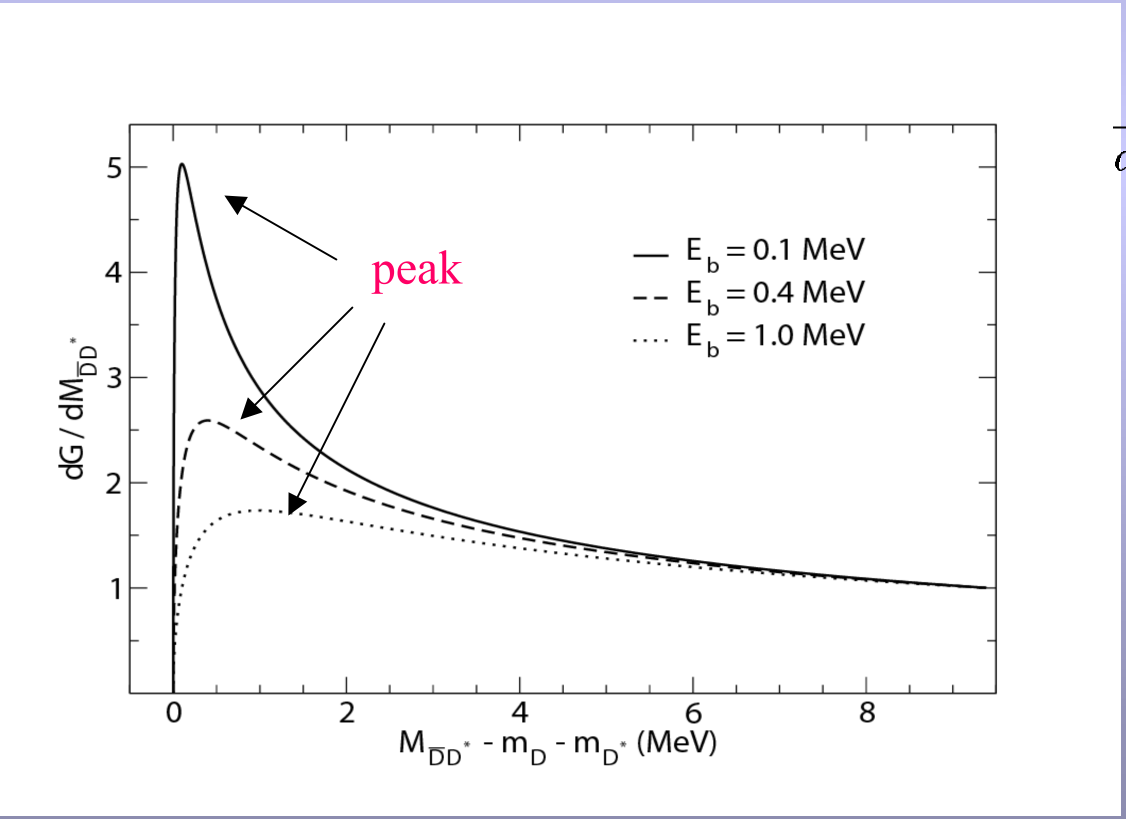


$$\pm \begin{pmatrix} D^0 & \longleftrightarrow & \overline{D}^0 \\ \overline{D}^{*0} & & D^{*0} \end{pmatrix}$$

$\bar{D}^0 D^{*0}$ invariant mass distribution at the threshold

$B^+ \to \bar{D}^0 D^{*0} K^+$ near the threshold





$$\frac{d\Gamma}{dM_{\bar{D}D^*}}[B^+ \to \bar{D}^0 D^{*0} K^+]$$

$$= \Gamma[B^+ \to X K^+] \frac{\mu a^3 k_{\rm cm}}{\pi(1 + a^2 k_{\rm cm}^2)}$$

Observation of a peak would confirm the X(3872) as a loosely-bound molecule

An Estimate for c_1 and c_2 from Babar data

$$\mathcal{A}[B^+ \longrightarrow \overline{D}^0 D^{*0} K^+] \quad = c_1\, P \cdot \epsilon^*$$

Babar has measured the branching fractions of $B \to \bar{D}^{(*)} D^{(*)} K$

1. <u>Use factorization assumption</u> and Isospin relations (Bauer et.al.)

For example,

$$\mathcal{A}[B^+ \to \bar{D}^0 D^{*0} K^+] \to \lambda_1 \langle \bar{D}^0 | \bar{c}\gamma^\mu (1-\gamma_5) b | B^+ \rangle \langle D^{*0} K^+ | \bar{s}\gamma^\mu (1-\gamma_5) c | 0 \rangle$$

$$+\lambda_2 \langle K^+ | \bar{s}\gamma^\mu (1-\gamma_5) b | B^+ \rangle \langle \bar{D}^0 D^{*0} | \bar{c}\gamma^\mu (1-\gamma_5) c | 0 \rangle$$

$$\mathcal{A}[B^+ \to \bar{D}^0 D^+ K^0] \to \lambda_1 \langle \bar{D}^0 | \bar{c}\gamma^\mu (1-\gamma_5) b | B^+ \rangle \langle D^+ K^+ | \bar{s}\gamma^\mu (1-\gamma_5) c | 0 \rangle$$

2. Need <u>4 form factors</u> from <u>Heavy-quark spin symmetry</u>

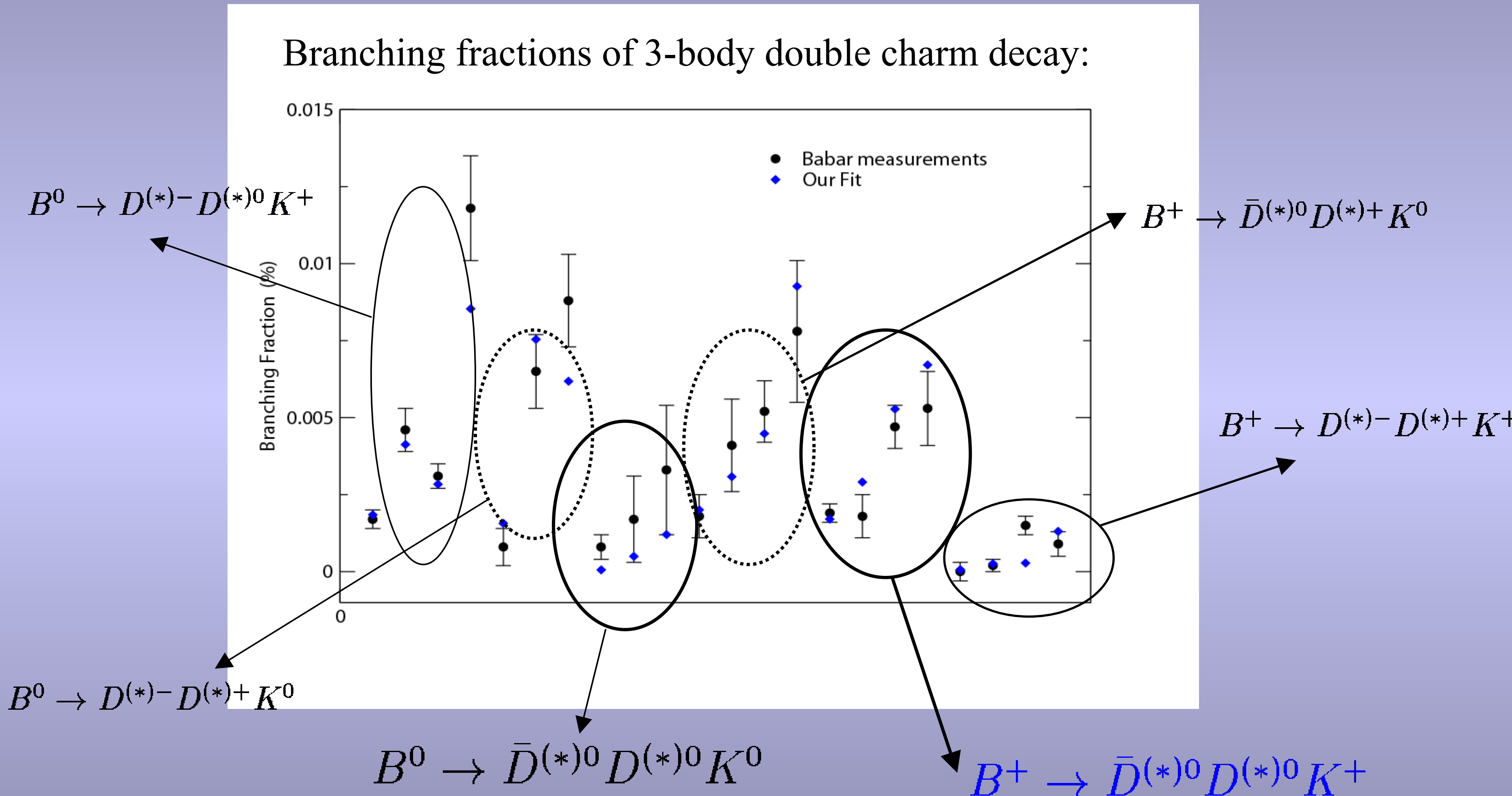
For example,

$$\mathcal{A}[B^+ \to \bar{D}^0 D^{*0} K^+] = -iG_1 \epsilon^* \cdot (V+v)$$

$$-i(G_2/m_B)\epsilon^*_\nu \left[v_* \cdot k (V+v)^\nu - v_* \cdot (V+v) k^\nu \right.$$

$$\left. -i\epsilon^{\nu\mu\alpha\beta} (V+v)_\mu v_{*\alpha} k_\beta \right]$$

3. Fit $G_{i=1,2,3,4}$ for the best description of the data, assuming they are constants (7 parameters to fit)



One can estimate c_1 and c_2 from this analysis:

$$c_1 = c_2 = -i[m_B G_1 - (m_B + m_D + m_{D^*}) G_2]/m_B^2$$

If $\mathcal{C} = +$ (constructive interference),

$$\mathcal{B}[B^+ \to XK^+] \approx 3.9 \times 10^{-5} \frac{\Lambda^2}{m_\pi^2} \left(\frac{E_b}{0.4\,\mathrm{MeV}} \right)^{1/2}$$

If we take $\Lambda \simeq m_\pi$ and $E_b = 0.4$ MeV and if C = +, $(J^{PC} = 1^{++})$

$$\mathcal{B}[B^+ \to XK^+] \simeq 3.9 \times 10^{-5}$$ (our estimate)

(Belle collaboration)

$$\mathcal{B}[B^+ \to XK^+] \times \mathcal{B}[X \to J/\psi\, \pi^+\pi^-] = (1.3 \pm 0.3) \times 10^{-5}$$

Our estimate is compatible, if $J^{PC} = 1^{++}$

and $X \to J/\psi\pi^+\pi^-$ is one of the major decay modes of X(3872)

Summary

Applied the low-energy universality analysis, assuming the X(3872) is S-wave $\overline{D}^0 D^{*0} / D^0 \overline{D}^{*0}$ molecule.

Invariant mass distribution $d\Gamma/dM_{DD^*}[X \to \overline{D}^0 D^{*0}]$ should have a peak at the threshold

Applied the heavy-quark spin symmetry to estimate unknown constants c_1 and c_2 from Babar measurements

An order of magnitude estimate is compatible if X has $J^{PC} = 1^{++}$ and $X \to J/\psi\pi^+\pi^-$ is one of the major decay modes