Isospin breaking effects in the dynamical generation of the $X(3872)$

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Talk

- Facts about the $X(3872)$
- The $X(3872)$ as a Dynamically generated state
- Couplings of the X to its building blocks
- The decay of the X to J/ψ and pions
- The negative C-parity state
- Overview

Facts About the $X(3872)$

- First observation of the $X(3872)$ by Belle (PRL91,262001) with subsequent confirmation by CDFII, BaBar and D0 collaborations.
- The $X(3872)$ has been discovered and confirmed in the decay channel $J/\psi\pi^+\pi^-$.
  - The $\pi^+\pi^-$ mass spectrum shape and the non-observation of $\pi^0\pi^0$ suggest that this pion pair comes from a ρ^0.
- The non-observation of charged partners indicates an isospin zero state.
- Other decay channels observed: $J/\psi\gamma$ and $J/\psi\pi^+\pi^-\pi^0$.
  - The decay $J/\psi\gamma$ implies positive C-parity for the X.
  - $\frac{\mathcal{B}(X\to J/\psi\pi^+\pi^-\pi^0)}{\mathcal{B}(X\to J/\psi\pi^+\pi^-)} = 1.0\pm0.4\pm0.3$ as measured by Belle which implies large isospin violation if the dipion comes from a ρ and the three pion from a ω.
- A careful analysis of all the data concludes that the J^{PC} of the X should be either 1^{++} or 2^{-+} (PRL98,132002).
- The X mass is very close to the $D\bar{D}^*$ threshold, strongly suggesting a s-wave $D\bar{D}^*$ molecular structure for this state with $J^{PC}=1^{++}$.

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The $X(3872)$ as a D.G. state I

- To build our phenomenological model we start from $SU(4)$ fields for the mesons described by a 15-plet of $SU(4)$ plus a singlet:

$$\Phi = \begin{pmatrix} \frac{\eta}{\sqrt{3}} + \frac{\pi^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{6}} & \pi^+ & K^+ & \overline{D}^0 \\ \pi^- & \frac{\eta}{\sqrt{3}} - \frac{\pi^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{6}} & K^0 & D^- \\ K^- & \overline{K}^0 & \sqrt{\frac{2}{3}}\eta' - \frac{\eta}{\sqrt{3}} & {D_s}^- \\ D^0 & D^+ & {D_s}^+ & \eta_c \end{pmatrix}$$

and a similar field for the vector mesons, $\mathcal{V}_\mu$.

The $X(3872)$ as a D.G. state II

- We define hadronic currents:

$$
\begin{aligned}
J_\mu &= (\partial_\mu \Phi)\Phi - \Phi \partial_\mu \Phi \\
\mathcal{J}_\mu &= (\partial_\mu \mathcal{V}_\nu)\mathcal{V}^\nu - \mathcal{V}_\nu \partial_\mu \mathcal{V}^\nu .
\end{aligned}
$$

- Next, we couple them in order to create a Lagrangian:

$$
\mathcal{L}_{PPVV} = -\frac{1}{4f^2} Tr\left(J_\mu \mathcal{J}^\mu\right).
$$

- This Lagrangian is $SU(4)$ symmetric, but this is a badly broken symmetry in Nature. To break this symmetry we suppress terms in this Lagrangian containing processes that are driven by the exchange of heavy vector mesons in the underlying dynamics of the interaction and we also use two different values of f, one for light and another for heavy mesons.

The $X(3872)$ as a D.G. state III

- For a given process $(P(p)V(k))_i \to (P'(p')V'(k'))_j$ we have the amplitude:

$$\mathcal{M}_{ij}(s,t,u) \quad = \quad -\frac{\xi_{ij}}{4 f_i f_j}(s-u)\epsilon.\epsilon'$$

- These amplitudes are projected in s-wave and plugged in the scattering equation for all the coupled channels:

$$T \quad = \quad V + VGT.$$

- The matrix G contains the loop functions for the channels. This loop function is regularized and has a free parameter, α which we tune within a natural range.
- Poles in the second Riemann sheet of the T-matrix are interpreted as resonances.
  - Real part of the pole $\longrightarrow M_{res}$ (resonance mass)
  - Imaginary part of the pole $\longrightarrow \Gamma_{res}$ (resonance width)
  - Residues of the pole $\longrightarrow g_i$ (couplings to all channels)

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Couplings of the X I

- From the residues of the T-matrix calculated for the pole at s_R we can evaluate the couplings of the X to the different channels, since close to the pole we can write:

$$T_{ij} = \frac{g_i g_j}{s - s_R}$$

- For simplicity consider a two channel potential:

$$V = \begin{pmatrix} v & v \\ v & v \end{pmatrix}$$

- Solving the scattering equation we get:

$$T = \frac{V}{1 - vG_{11} - vG_{22}}$$

Couplings of the X II

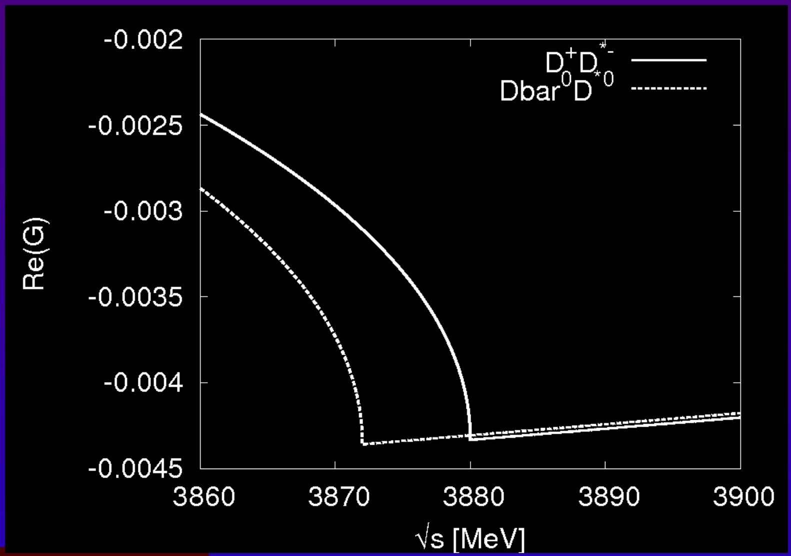
- Now we can calculate the residues:

$$\lim_{s \to s_R} (s - s_R) T_{ij} = \lim_{s \to s_R} (s - s_R) \frac{V_{ij}}{1 - vG_{11} - vG_{22}}$$

- Applying the l'Hôpital rule to this expression and we get:

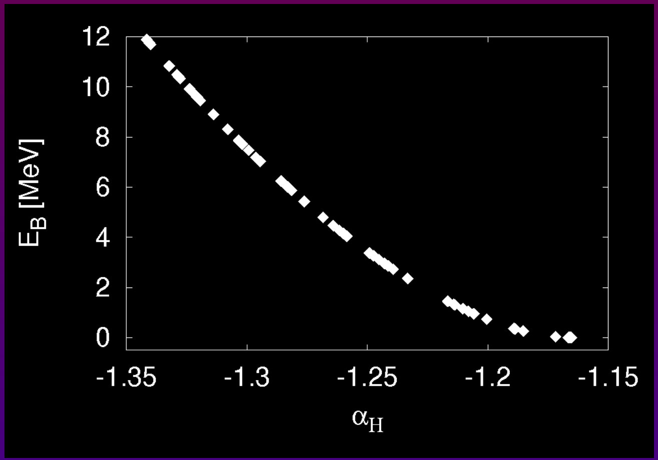
$$\lim_{s \to s_R} (s - s_R) T_{ij} = \frac{V_{ij}}{-v(\frac{dG_{11}}{ds} + \frac{dG_{22}}{ds})}$$

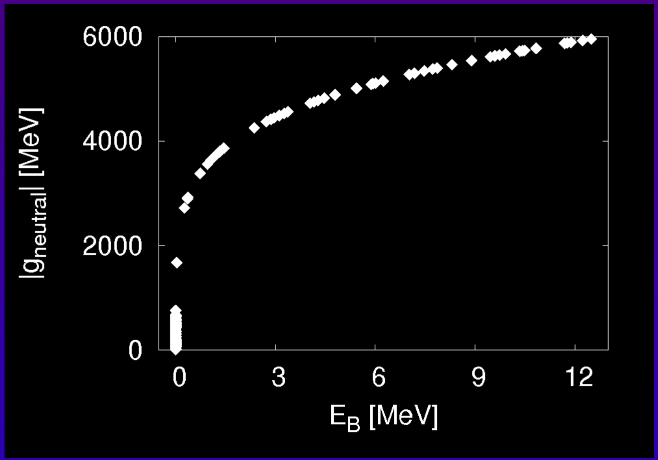
- Look at plots of $Re(G_{ii})$:

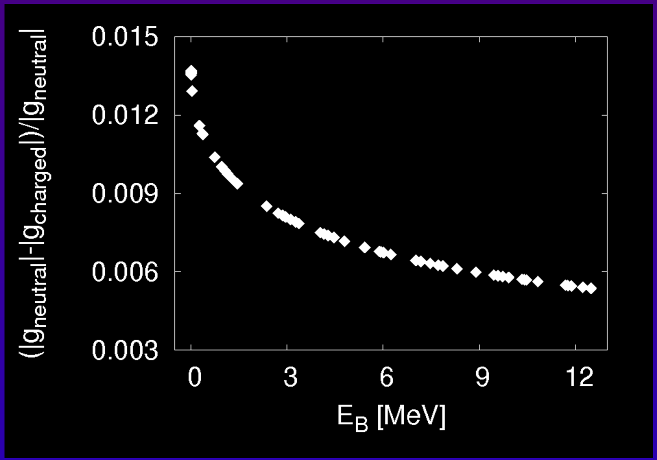


Couplings of the X III

- At threshold $\frac{dG_{11}}{ds} \to \infty$, so $g_i \to 0$.. This is a general result (PRD77,034001).







Couplings of the X IV

- Note the expresion:

$$g_i g_j = \frac{V_{ij}}{-v(\frac{dG_{11}}{ds} + \frac{dG_{22}}{ds})}$$

- For only one channel it becomes:

$$g^2 \left(\frac{dG_{11}}{ds} \right) = 1$$

- And this expresion is the one used to calculate the coupling g from the compositness condition of Weinberg.

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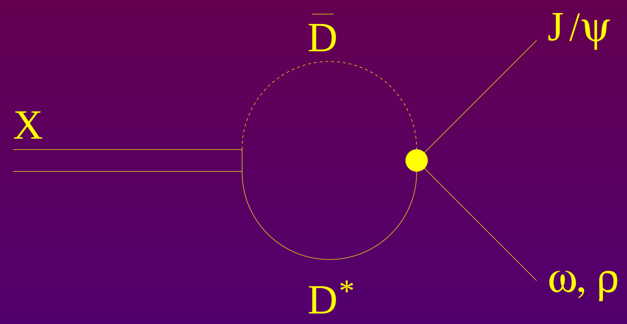
The decay of the X to J/ψ and pions I

- Consider the following diagram for the decay of the X:



- If the vertices for ω and ρ from D^+D^{*-} & $c.c.$ and $D^0\bar{D}^{*0}$ & $c.c.$ production have the same strenght, the ratio of the amplitudes for ρ and ω production will be given by:

$$R_{\rho/\omega} \quad = \left(\frac{G_{11}-G_{22}}{G_{11}+G_{22}}\right)^2 \quad = 0.032$$

The decay of the X to J/ψ and pions II

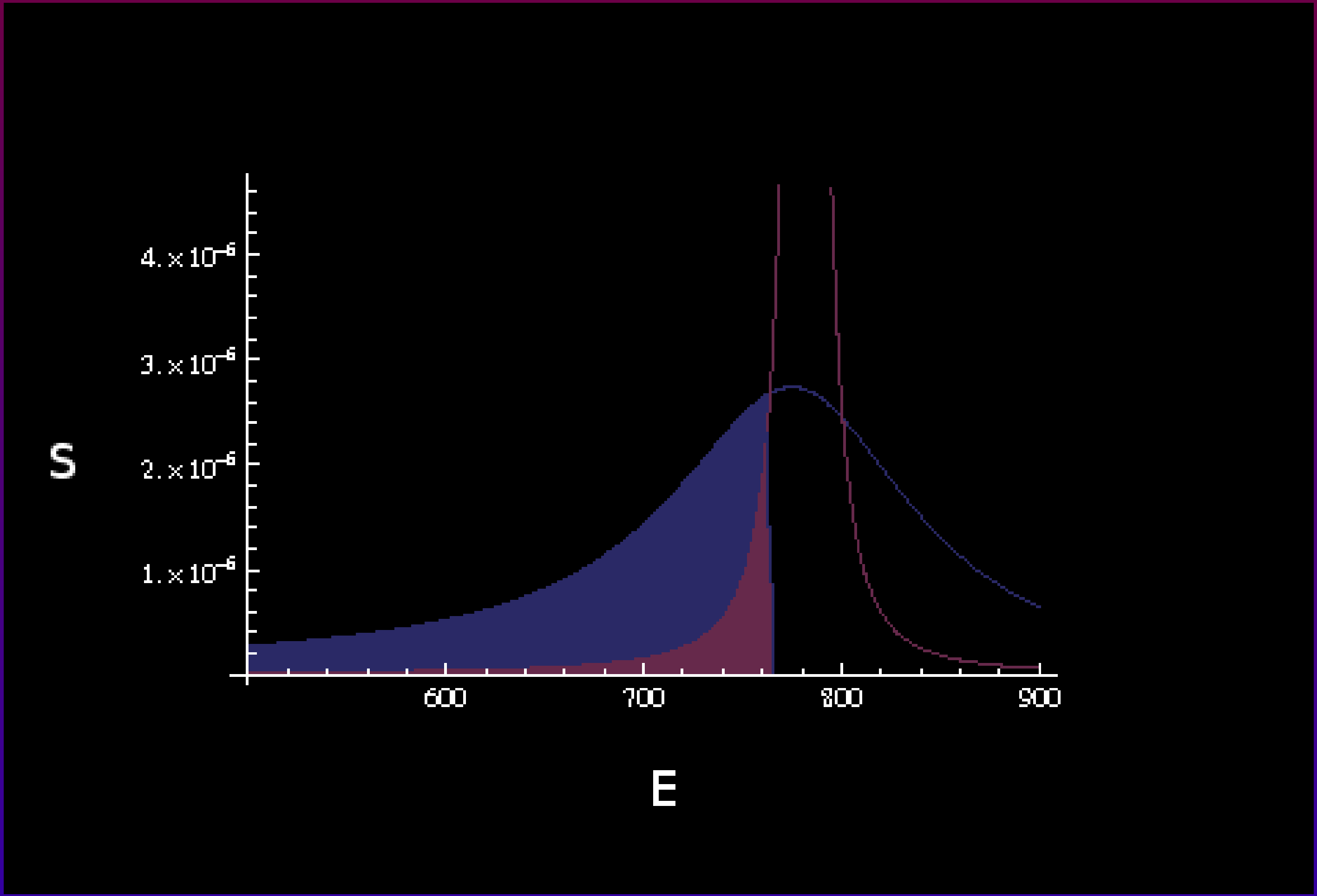
- But $M_X \sim M(J/\psi\rho)$ and M_X < $M(J/\psi\omega)$.
  - M_X=3872 MeV
  - $M(J/\psi\rho)$=3872 MeV (m_ρ=775 MeV)
  - $M(J/\psi\omega)$=3879 MeV (m_ω=782 MeV)
- To observe these two processes one has to see the pion resulting from the decays of ρ and ω, so one has to take into account the width of these mesons and the phase-space avaible for each decay:

$$\frac{\mathcal{B}(X \to J/\psi\pi\pi)}{\mathcal{B}(X \to J/\psi\pi\pi\pi)} = \left(\frac{G_{11} - G_{22}}{G_{11} + G_{22}}\right)^2 \frac{\int_0^\infty q\mathcal{S}\left(s, m_\rho, \Gamma_\rho\right)\theta\left(m_X - m_{J/\psi} - \sqrt{s}\right)\, ds}{\int_0^\infty q\mathcal{S}\left(s, m_\omega, \Gamma_\omega\right)\theta\left(m_X - m_{J/\psi} - \sqrt{s}\right)\, ds} \frac{\mathcal{B}_\rho}{\mathcal{B}_\omega}$$

- The $\mathcal{S}$ is the spectral funcion of the vector mesons:

$$\mathcal{S}\left(s, m, \Gamma\right) = -\frac{1}{\pi} Im\left(\frac{1}{s - m^2 + i\Gamma m}\right)$$

The decay of the X to J/ψ and pions III



The decay of the X to J/ψ and pions IV

- The value of $R_{\rho/\omega}$ is maximum at threshold where $G_{11} - G_{22}$ is maximal. At this point:

  $R_{\rho/\omega} = 0.032 \qquad R_{\omega/\rho} = 31$

- If we calculate the full branching fraction ratio:

$$\frac{\mathcal{B}(X \to J/\psi\pi^+\pi^-\pi^0)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = 1.4$$

- Which is compatible with the experimental value:

$$\frac{\mathcal{B}(X \to J/\psi\pi^+\pi^-\pi^0)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$$

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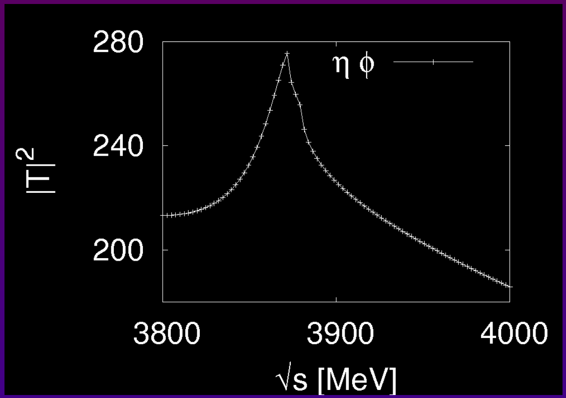
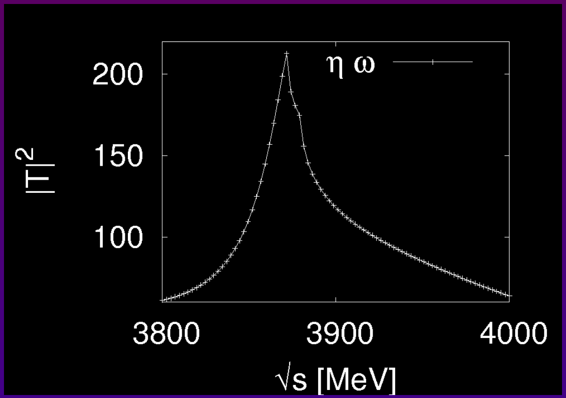
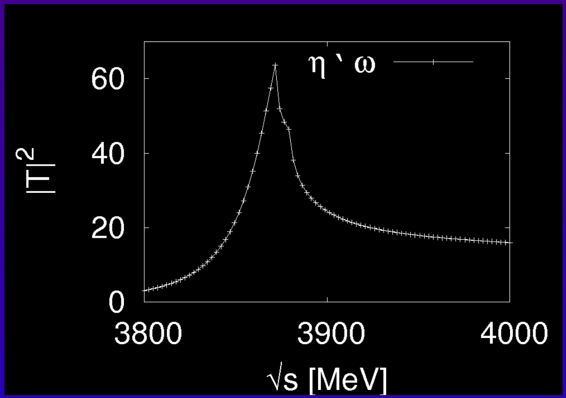
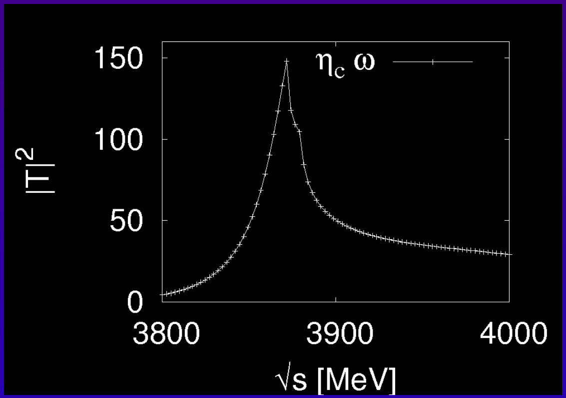
The negative C-parity State

- Together with the postive C-partity state there is also a pole with negative C-parity, almost degenerate in mass, but with a bigger width ($\sim$ 50 MeV).
- It could be seen in decays to light mesons:









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Overview

- Observations lead to the conclusion that the $X(3872)$ state probably has J^{PC} quantum numbers equal to 1^{++}.
- The interaction of $D\bar{D}^*$ mesons is attractive and the $X(3872)$ is naturally generated in our framework.
- Although the couplings of the X to its constituents do not largely violate isospin, the much bigger phase-space avaible for a decay into $J/\psi\rho$ than $J/\psi\omega$ naturally explain the branching ratio $\frac{\mathcal{B}(X\to J/\psi\pi^+\pi^-\pi^0)}{\mathcal{B}(X\to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$.
- The interaction in our model also leads to the generation of a negative C-parity state that could be observed in its decays to light mesons: $\eta\phi$, $\eta\omega$ and $\eta\prime\omega$.

This talk is based on arXiv:0905.0402 [hep-ph].

Thank You

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