A Mechanism for Hadron Molecule Production in proton-(anti)proton Collisions

International School of Subnuclear Physics 2013
51st Course: REFLECTIONS ON THE NEXT STEP FOR LHC

Angelo Esposito
Università degli Studi “La Sapienza” – Dipartimento di Fisica

Talk based on:
Outline

• What is the $X(3872)$?
• The molecular model: solved and unsolved problems
• Introducing a new formation mechanism
• Monte Carlo simulations
• Results
• Conclusions
What is the X(3872)?

- First observation made by BELLE in 2003 in B-decays \( B^+ \rightarrow K^+ X \)
- Also found by CDF and DØ in prompt proton-antiproton collisions
- Recently observed at LHCb

**BELLE**
[Belle coll. - PRL91 262001]

**CDF**
[CDF coll. - PRL93 072001]
Very exotic properties!

The two main interpretations are:

- **Tetraquark model**: diquark-antidiquark bound state  
  
  - [Maiani et al. – PRD71 014028]

- **Molecular model**: bound state of open charm mesons  
  
  - [see for example: Braaten, Kusunoki – PRD69 074005]
The Molecular Model

\[ M_X \simeq M_{D^0} + M_{D^{*0}} \] suggests that it could be a \( D^0 \bar{D}^{*0} / \bar{D}^0 D^{*0} \) loosely bound state.

It should have extremely small binding energy:

\[ \mathcal{B} \simeq -0.14 \pm 0.22 \text{ MeV} \]

- **Advantages:**
  1. The value of the mass is explained
  2. The observed isospin breaking is explained

- **Disadvantages:**
  1. Quantum theory predicts very high cross sections for scattering via a virtual \( X \) \( \Rightarrow \) *How to reconcile it with small width?*
  2. *How can a very weakly bound state be produced by prompt high energy collisions?*
Prompt production: an unsolved question

- Only charmed mesons with relative momentum $k_0 < 50 \text{ MeV}$ can form the loosely bound $X(3872)$
- Prompt production cross section @ Tevatron is orders of magnitude too large! $\sigma_{\text{exp}} \simeq 30 \text{ nb}$
  
  [Bignamini et al. - PRL103 162001]

- Some models which manage to match theoretical and experimental cross sections have been proposed
  
  [Artoisenet, Braaten - PRD81 114018]

- No definitive answer to the question about the prompt production has been found

The problem is still unsolved
Introducing a new mechanism

- High energy collisions produce many pions
- Elastic scattering of the $D^0$ (or the $\bar{D}^*0$) with such pions may decrease $k_0$

It could increase the production cross section!

- Such an interaction could also take place more than once
- The mechanism also implies: $D$ mesons actually “pushed” inside the potential well $\rightarrow$ $X(3872)$ is a real, negative energy bound state (stable)

It also explains small width ($\simeq \Gamma_{D^*}$)
Monte Carlo simulations

• We reproduced our mechanism using HERWIG and PYTHIA

• We implement two different simulations:
  1. $p\bar{p} \rightarrow c\bar{c}$ (c-cbar run) \(\rightarrow\) only a qualitative hint
  2. $p\bar{p} \rightarrow q\bar{q}, gg, gq, \ldots$ (full-QCD run)

• The parameters of our simulation are:

\[
\begin{array}{ccc}
\text{COM energy} & \text{parton cuts} & \text{final mesons cuts} \\
\sqrt{s} = 1.96 \text{ TeV} & p_{\perp}^{\text{part}} > 2 \text{ GeV} & 5.5 \text{ GeV} < p_{\perp} < 20 \text{ GeV} \\
 & |y^{\text{part}}| < 6 & |y| < 1
\end{array}
\]

Same as Tevatron
The first $\pi$-D interaction

Very evident slow-down effect!!

The mechanism is working but the very first bins are still too poorly populated

We must iterate the $\pi$-D scattering

We develop an iteration algorithm similar to a Markov chain

Angelo Esposito
University “La Sapienza”
Erice, 27 June 2013
How many subsequent interactions?

• We need an estimation of the number of scatterings → need for a model
• We can imagine the final state as composed by flying-out hadrons “living” on an expanding spherical surface
• Simulations suggest that pions are produced in a small angular region around the D mesons

We can estimate the density of pions and extract the average number of interactions

The scattering can take place (on average) up to 3 times
For the $X(3872)$ to be formed $k_0$ cannot exceed 100 MeV
Final results of the full-QCD run

<table>
<thead>
<tr>
<th>$k_0^{\text{max}}$</th>
<th>HERWIG</th>
<th>PYTHIA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 MeV</td>
<td>100 MeV</td>
</tr>
<tr>
<td>No. of events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 scatt.</td>
<td>52</td>
<td>253</td>
</tr>
<tr>
<td>1 scatt.</td>
<td>44</td>
<td>299</td>
</tr>
<tr>
<td>3 scatt.</td>
<td>843</td>
<td>2069</td>
</tr>
<tr>
<td>4 scatt.</td>
<td>1166</td>
<td>2802</td>
</tr>
<tr>
<td>5 scatt.</td>
<td>1689</td>
<td>4167</td>
</tr>
<tr>
<td>$\sigma$ [nb]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 scatt.</td>
<td>0.10</td>
<td>0.50</td>
</tr>
<tr>
<td>1 scatt.</td>
<td>0.09</td>
<td>0.59</td>
</tr>
<tr>
<td>3 scatt.</td>
<td>1.67</td>
<td>4.10</td>
</tr>
<tr>
<td>4 scatt.</td>
<td>2.31</td>
<td>5.55</td>
</tr>
<tr>
<td>5 scatt.</td>
<td>3.34</td>
<td>8.25</td>
</tr>
</tbody>
</table>

Striking increase of the cross section after each scattering!

- Down by a factor of 7 for HERWIG and 5 for PYTHIA with respect to the experim. value (30 nb)

Obtained cross sections within one order of magnitude from experimental one (further increases with 4/5 scatterings)!
Conclusions

• We can explain the narrow width of the X(3872)
• *The proposed mechanism is definitively effective* in reducing the relative momenta of the would-be-molecules
• Although the final cross sections are below the experimental one, we must consider:
  1. Results from HERWIG and PYTHIA cannot be considered as the exact values of the production cross section (many assumptions)
  2. The cross sections increase after further interactions: one should take into account the presence of other kinds of light particles

*There is still space for investigation but the proposed mechanism has strong probabilities to be the right one to explain the prompt production of X(3872)!*
Thanks for Your Attention!
Isospin violation in the molecular model

• From *one-pion exchange* $1^{++}$ bound state attractive in $I=0$ configuration. [Tornqvist - Z.Phys. C61 525–537]

• Pure $I=0$ state is:

$$\left| \frac{D^0 \bar{D}^*0}{\sqrt{2}} + |D^+ D^{*-}\rangle \right|$$

• But $M(D^+ D^{*-}) - M(X) \simeq 8 \text{ MeV}$

• Greater weight for the $D^0 \bar{D}^*0$ component

Isospin breaking
Shallow Bound States and the X(3872)

• Predicted cross section for $D^0 \bar{D}^{*0} \rightarrow X \rightarrow D^0 \bar{D}^{*0}$ (virtual $X$):

\[ \sigma_{\text{scatt}} = \frac{4\pi}{2\mu B} \]

• Very high because $\mathcal{B}$ is very small. One finds 18 barn!

• We can extrapolate such a cross section from experimental data.

\[ \langle D^0 (p) \bar{D}^{*0} (q, \epsilon) | X (k, \eta) \rangle = g_{XDD^*}(\epsilon \cdot \eta) \]

Extrapolated from data on $\mathcal{B}\mathcal{R}(X \rightarrow D^0 \bar{D}^{*0})$
Shallow Bound States and the $X(3872)$

- The extrapolated cross section is:

![Graph showing the cross section vs. $\Gamma_{TOT}$ [MeV]]

- Much smaller than the predicted one

$X(3872)$ can be hardly regarded as a virtual state. Must be real
Relative momentum of the would-be-molecules

- We can model the $D^0 \bar{D}^{*0}$ interaction with a square well (like deuterium) tuned to have discrete level at -0.14 MeV.
- Solving the Schrödinger equation one gets:

\[
|\psi(r)|^2 \text{ [MeV]} = \frac{1}{r_0 \sqrt{\pi}} e^{-r^2/r_0^2}
\]

We expect the $X(3872)$ to be a very extended molecule (9 fm)

Strating from the wave function one finds:

\[
\langle k_0 \rangle_\psi \text{ [MeV]} \quad \sigma(k_0)_\psi \text{ [MeV]}
\]

\[
\sim 50 \quad \sim 52
\]

Molecules formed for $k_0$ up to 100 MeV
The c-cbar simulation

- We compare the $D^0 D^{*-}$ pairs produced as a function of relative azimuthal angle with the results from CDF:

- In the first bin, $k_0 < 50$ MeV, of the c-cbar simulation only 3 would-be-molecules for PYTHIA and 10 for HERWIG

The c-cbar run underestimate the low angles (low-$k_0$) region!

c-cbar run only usable as a qualitative hint
The first $\pi$-D interaction in the c-cbar run

Slow-down effect more striking than in the full-QCD!

The mechanism is governed by the high-$k_0$ region. Such area is much more populated than in the full-QCD. Why?

- In the c-cbar run most charmed mesons come from the hadronization of $c\bar{c}$ produced by the hard scattering $\rightarrow$ highly energetic
- In the full-QCD only a small fraction of $c\bar{c}$ is promptly produced. Others come from parton showering $\rightarrow$ soft enhanced

Angelo Esposito
University “La Sapienza”
Erice, 27 June 2013
Results from the c-cbar run

Number of open charm pairs after each interaction:

<table>
<thead>
<tr>
<th>$k_0 &lt; 50$ MeV</th>
<th>$0\pi$</th>
<th>$1\pi$</th>
<th>$2\pi$</th>
<th>$3\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HERWIG</strong></td>
<td>10</td>
<td>19</td>
<td>456</td>
<td><strong>802</strong></td>
</tr>
<tr>
<td><strong>PYTHIA</strong></td>
<td>3</td>
<td>21</td>
<td>307</td>
<td><strong>814</strong></td>
</tr>
</tbody>
</table>

Each scattering increases the number of pairs in the very first bin

Strong qualitative indication of the effectiveness of the mechanism!

Angelo Esposito
University “La Sapienza”

Erice, 27 June 2013

Page 22