Is the $X(3872)$ molecular hypothesis compatible with CDF data?

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Outline

- ⋆ the nature of $X(3872)$ is still enigmatic
- ⋆ molecular and diquark-antidiquark interpretations not completely satisfactory
- ⋆ assuming the molecular hypothesis, we try to simulate prompt $X(3872)$ production at CDF and compare an upper theoretical and lower experimental bound
- ⋆ a possible alternative mechanism is discussed qualitatively
- ⋆ Summary and outlook

Prompt production: lower experimental bound

CDF measured the fraction of *prompt* $X(3872)_{\to J/\psi\pi^+\pi^-}$: 83.9 $\pm$ 5.2%

CDF Coll. PRL **98** 132002 (2007)

Assuming the same detection efficiency for $\psi(2S)$ and $X(3872)$ and using the well measured $\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$

$$\frac{\sigma(p\bar{p} \to X(3872) + \mathrm{All})_{\mathrm{prompt}} \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-))}{\sigma(p\bar{p} \to \psi(2S) + \mathrm{All})} = 4.7 \pm 0.8\%$$

Lower experimental bound

$$\begin{aligned} \sigma(p\bar{p} \to X(3872) + \mathrm{All})^{\mathrm{min}}_{\mathrm{prompt}} \quad &> \quad \sigma(p\bar{p} \to X + \mathrm{All}) \times \mathcal{B}(X \to J/\psi\pi^+\pi^-) \\ &= \quad 3.1 \pm 0.7 \ \mathrm{nb} \end{aligned}$$

for $p_\perp(X) > 5\ \mathrm{GeV}, |y(X)| < 0.6$

Upper theoretical bound

Hypothesis: $X(3872)$ is an S-wave bound state of two D mesons

E.S. Swanson, E. Braaten et al.

$$
\begin{aligned}
\sigma(p\bar{p} \to X(3872)) &\sim \left| \int d^3\mathbf{k} \langle X | D\bar{D}^*(\mathbf{k}) \rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle \right|^2 \\
&\simeq \left| \int_{\mathcal{R}} d^3\mathbf{k} \langle X | D\bar{D}^*(\mathbf{k}) \rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle \right|^2 \\
&\leq \int_{\mathcal{R}} d^3\mathbf{k} |\psi(\mathbf{k})|^2 \int_{\mathcal{R}} d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2 \\
&\leq \int_{\mathcal{R}} d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2 \sim \sigma(p\bar{p} \to X(3872))^{\text{max}}_{\text{prompt}}
\end{aligned}
$$

- $\mathbf{k}$ is the rest-frame relative 3-momentum between the D and D^*
- $|\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2$ can be computed with MC simulations
- $\mathcal{R}$ has to be given with a reasonable conservative Ansatz for the bound state wave function (we use a simple gaussian form)

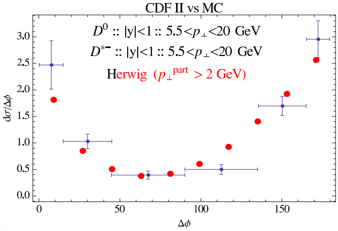
$|\langle D\bar{D}^*(\mathbf{k})|p\bar{p}\rangle|^2$

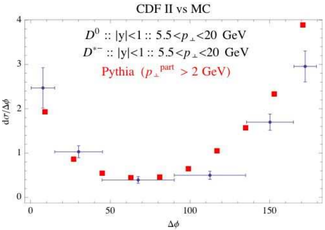
- we expect the bulk of the contribution from events with a gluon recoiling against an almost collinear $c\bar{c}$ pair
- the standard Parton Shwower MC Event Generators (like Herwig and Pythia) describe well the events with gluons radiated at small p_{T}, which are enhanced by collinear logarithms
- contributions from large p_{T} gluons are expected to be suppressed. We checked this numerically with ALPGEN finding a totally negligible contribution

We used both Herwig and Pythia for the simulations, since they include two completely different hadronization schemes, to have an estimate of the uncertainty introduced by the hadronization model

Herwig and Pythia tuning on CDF data for $D^0 D^{*-}$ pairs

We generated two samples of $2 \rightarrow 2$ QCD processes with parton showering and hadronization (with loose partonic cuts)





The $\Delta\phi$ shape is well reproduced once an overall k-factor is applied to the MC predictions, $\simeq 1.8$ for Herwig and $\simeq 0.7$ for Pythia

Estimate of $\mathcal{R}$

We need an estimate of the momentum and its spread in the gaussian. Assuming a Yukawa potential between the D mesons

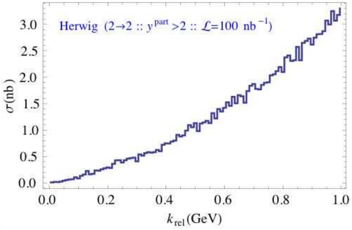
$$\frac{\hbar^2}{\mu r_0^2} - \frac{g^2}{4\pi}\frac{e^{-\frac{m_\pi c}{\hbar} r_0}}{r_0} = \mathcal{E}_0 \sim M_X - M_D - M_{D^*}$$

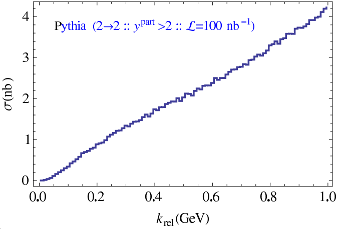
Solving for r_0 we find $r_0 = 8.6 \pm 1.1$ fm

- minimal uncertainty relation gives $\Delta k \simeq 12$ MeV
- $k \simeq \sqrt{\lambda(m_X^2, m_D^2, m_D^{*2})}/2m_X \simeq 27$ MeV

We consider the region within a sphere of radius $\mathcal{R} = 35$ MeV

$D^0\bar{D}^{0*} k_{rel}$ distributions





- To integrate 3.1 ± 0.7 nb we need k_{rel} up to 205 ± 20 MeV for Herwig and 130 ± 15 MeV
- in the region of relative momentum R Herwig and Pythia integrate 0.071 nb and 0.11 nb respectively, too low by more than one order of magnitude!

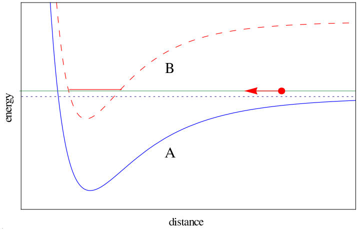
Further strange feature of the X molecule

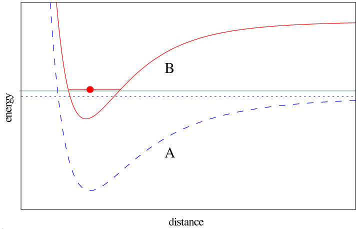
- small width < 3 MeV (below the experimental resolution), compatible with the decay $D^{0*} \to D^0\pi$
- the interaction should have a range $\sim 1/m_\pi$
- the relative orbital angular momentum is at most $l \leq k/m_\pi \Rightarrow$ only S-wave resonant scattering is allowed. But attractive potentials do not generate long-lived resonances in S-wave. Bound metastable states can be formed by means of centrifugal angular barrier

An alternative molecule: Fano-Feshbach resonance

This mechanism is well known in atomic physics (in particular in cold atom gases)
Idea: the reduced mass particle moves in a molecular term A with a small energy. It can happen that this energy matches the discrete level of some other potential term B coupled with A (e.g. spin triplet and spin singlet states for two electrons in the Alkalii atomic systems) $\Rightarrow$ the transition $A \to B \to A$ induces a metastable molecule
The $A - B$ transition could be the colour singlet - octet

e.g. B. Gavela et al., Phys. Lett. **B82** 431 (1979)





Summary and outlook

- The picture of $X(3872)$ as a $D^0 \bar{D}^{0*}$ bound state through pion exchange presents some difficulties
- Moreover its small with is incompatible with an attractive potential in S-wave
- A possible alternative mechanism could be the formation of a Fano-Feshbach resonance. Preliminary results tell us that the small width can be nicely accomodated.
- Important to test this mechanism with other data, e.g. at the future experiments PANDA and/or (in the b sector) LHCb