

Intrinsic heavy flavor production of tetraquarks

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Abstract. A number of new four-quark states containing from one to four heavy quarks have been observed recently. Many of these new states have been discovered at the LHC. The production of these states containing charm quarks via intrinsic charm in the proton is investigated. The tetraquark masses obtained in this approach agree well with the measured masses. These calculations provide insight into the nature of the tetraquark candidates, whether as a bound pair of mesons or as a looser configuration of four uncorrelated partons. The final-state configuration can influence their interactions in nuclear matter. The kinematic distributions of these states as a function of y and p_T were also studied. Previous studies of J/ψ and \bar{D} mesons produced from such states manifest themselves at forward rapidity and relatively high p_T . The extension to bottom tetraquark candidates is also considered.

Tetraquarks are exotic mesons, consisting of four valence quarks, two quarks and two antiquarks. The $X(3872)$, the first tetraquark state, was measured by the Belle Collaboration [1] in e^+e^- collisions. Several other tetraquark candidate states followed but, since the advent of the LHC, the number of candidate states measured has greatly increased, see Ref. [2]. Many still await confirmation.

The structure of these states is still unconfirmed. Several configurations have been postulated, including a small, tightly bound (less than ~ 1 fm) state of four quarks; an atom-like structure where two quarks, presumably light quarks, orbit around the other two at a distance of 2-3 fm; or a molecular-type state of two mesons separated by a relatively large distance, > 3 fm. The behavior of states with such different sizes would be quite different in heavy-ion collisions, as has been observed by LHCb [3] and CMS [4]. Indeed, a significant enhancement of $X(3872)$ production has been seen in $p + \text{Pb}$ and $\text{Pb}+\text{Pb}$ collisions. On the other hand while a strong suppression of the ratio $X(3872)/\psi(2S)$ was observed in $p + p$ collisions as a function of the track multiplicity. The measurements have been made relative to $\psi(2S)$ production and the $X(3872)$ has been shown separately to be enhanced, albeit with large uncertainties, while the $\psi(2S)$ is suppressed [3]. Here tetraquark candidate production is calculated within the intrinsic charm (IC) model [5].

While IC in the proton was introduced in the early 1980s [5], there has been renewed interest in the last several years. The basic IC model assumes a $c\bar{c}$ pair in the proton, a single $|uudc\bar{c}\rangle$ configuration, can produced hadrons containing charm quarks, unlike pQCD production where a parton, typically a gluon, from each colliding particle makes a $c\bar{c}$ pair at midrapidity. In the IC picture, the large mass of the charm quarks requires them to carry a

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larger fraction of the proton momentum than the light quarks to keep the proton together. The IC state can be broken up by a soft interaction and come on shell, forming charm hadrons through coalescence. The rapidity boost means that these charm hadrons are produced away from midrapidity. The larger the energy, the more forward the production, such that production by this method may not be observable at the highest LHC collider energies [7]. However, contributions from intrinsic charm may contribute to J/ψ and \bar{D} production at backward rapidity in the SMOG configuration of LHCb [8].

At minimum a 7-particle IC state, $|uudc\bar{c}q\bar{q}\rangle$, is required to calculate tetraquark production since *e.g.* the $X(3872)$ is comprised of a $c\bar{c}$ pair and $q\bar{q}$ pair. The configuration of the quarks in the state has a strong effect on the masses and widths calculated in the IC model.

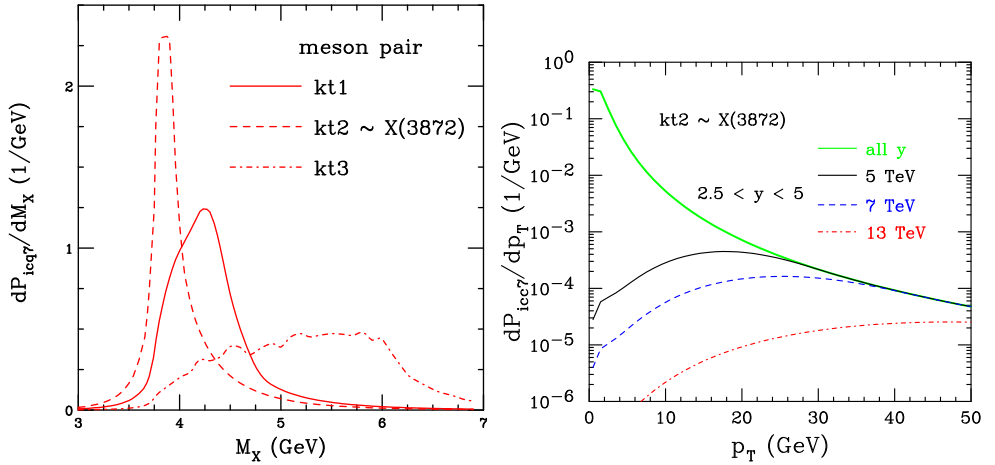


Figure 1. (Left) The $X(3872)$ probability distribution, calculated assuming that the X is a bound meson pair as a function of mass of the state. (Right) The probability distribution as a function of p_T for $X(3872)$ production at $\sqrt{s} = 5$ (solid black), 7 (dashed blue), and 13 TeV (dot-dashed red), all calculated using parameter set kt2. (From Ref. [9].)

The frame-independent probability distribution of a n -particle Fock state in the proton containing at least one $c\bar{c}$ pair is [5, 6]

$$dP_{icn} = P_{icn}^0 N_n \int dx_1 \cdots dx_n \int dk_{x1} \cdots dk_{xn} \int dk_{y1} \cdots dk_{yn} \times \frac{\delta(1 - \sum_{i=1}^n x_i) \delta(\sum_{i=1}^n k_{xi}) \delta(\sum_{i=1}^n k_{yi})}{(m_p^2 - \sum_{i=1}^n (m_{T_i}^2/x_i))^2}, \quad (1)$$

where states with $n = 7$ and 9 are required to produce tetraquarks containing one or more charm quarks. Here N_n normalizes the probability to unity and P_{icn}^0 scales the unit-normalized probability to the assumed intrinsic charm content of the proton. The delta functions conserve longitudinal (z) and transverse (x and y) momentum. The denominator of Eq. (1) is minimized when the heaviest quarks carry the largest fraction of the longitudinal momentum, $\langle x_c \rangle > \langle x_q \rangle, \langle x_s \rangle$. The masses and kinematic distributions are calculated by assuming simple kinematic coalescence.

As illustrated in Fig. 1 for three different transverse momentum ranges of k_{xi}, k_{yi} , with kt2 the narrowest, kt1 as an intermediate value, and kt3 largest. The smallest k_T range leads

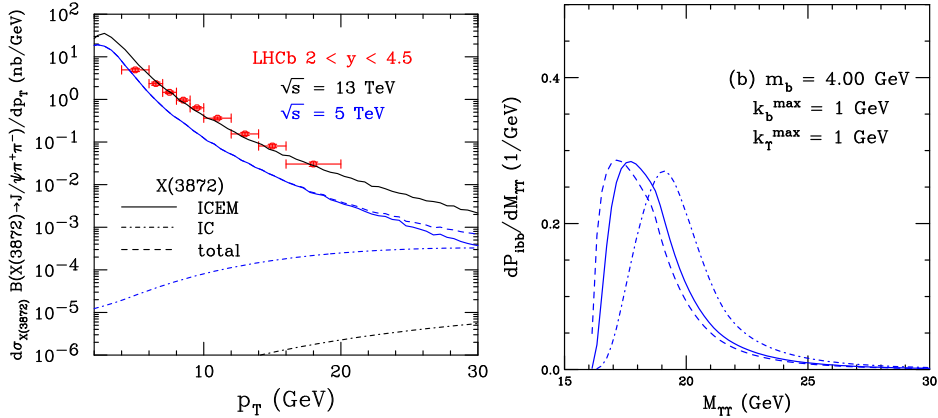


Figure 2. (Left) The cross section of $X(3872)$ production as a function of p_T . The distributions calculated in the ICEM are shown by the solid lines, the dot-dashed lines give the contributions from IC and the dashed lines are the sum of the two contributions. The black curves are for 13 TeV while the blue show the results at 5 TeV. The data from LHCb [12] (red points) at $\sqrt{s} = 13$ TeV and $2 < y < 4.5$ are also shown. (From Ref. [9].) (Right) The probability for double Υ production from a seven-particle Fock state as a function of the pair mass for three different k_T integration ranges are shown: $k_q^{\max} = 0.2$ GeV, $k_b^{\max} = 1.0$ GeV and $k_T^{\max} = 1.0$ GeV (solid); $k_q^{\max} = 0.1$ GeV, $k_b^{\max} = 0.5$ GeV and $k_T^{\max} = 1.0$ GeV (dashed); and $k_q^{\max} = 0.4$ GeV, $k_b^{\max} = 2.0$ GeV and $k_T^{\max} = 2.0$ GeV (dot-dashed). All distributions use $m_b = 4$ GeV and are normalized to unity. (From Ref. [11].)

to the smallest mass and the narrowest width. The set kt2 set gives good agreement with the measured $X(3872)$ mass. If the $X(3872)$ consists of a $D(c\bar{u})$ and $\bar{D}(\bar{c}u)$ pair, it could be interpreted as a molecular state albeit with a short distance between the two mesons, given the width. Other states, such as the $T_{cs0}(2900)^0$, with only one charm quark, cannot be described a pair of heavy mesons but only as a collection of uncorrelated partons with a wider width. Thus, in the IC model, the meson pair molecule-like state, is more tightly bound than a configuration of four independent partons and thus harder to break up than such a state. See Ref. [9] for details of the calculations and for the description of more tetraquark candidates.

The p_T distributions for the $X(3872)$ are shown on the right-hand side of Fig. 1. These distributions exhibit a markedly different behavior from production in typical perturbative QCD. The p_T distribution is independent of energy as long as the condition $x_F \leq 1$ is satisfied and no kinematic cuts are applied, see the green curve. If the rapidity is restricted to the range $2.5 < y < 5$, thanks to the large boost in y , there is effectively no low p_T contribution. As p_T increases, higher x_F is achievable and a finite, energy-dependent contribution appears. At 13 TeV, only about 0.1% of the IC distribution is captured, see the red curve. The p_T contribution from IC is seen to increase with decreasing energy.

As an example of the potential contribution of intrinsic charm to tetraquark production, Fig. 2 shows the $X(3872)$ p_T distribution at $\sqrt{s} = 13$ TeV in the rapidity range $2 < y < 4.5$. The data from LHCb [12] are shown by the red points. The solid curve shows an improved color evaporation model (ICEM) [13] prediction with the mass range adjusted to encompass the $X(3872)$ mass. Since the $X(3872)$ mass is only ~ 200 MeV larger than that of the $\psi(2S)$, the p_T distributions are effectively identical. The ICEM coefficient is adjusted to these data. The agreement of the calculation with the shape of the distribution is excellent. Applying this same coefficient, along with the upper bound of $P_{icc,7}^0$ [9], gives the dot-dashed

IC curve appearing in the bottom right corner. IC is negligible in the $X(3872)$ p_T distribution, unsurprising because $\langle y \rangle = 7.42$ for the $X(3872)$ at 13 TeV. The average p_T is thus very high, $\langle p_T \rangle \sim 48$ GeV. However, because the lower energy results in a larger IC contribution in the same rapidity range, at 5 TeV the IC contribution is similar to that from the ICEM at $p_T \sim 30$ GeV, as shown in the blue curves.

The first application of the IC model to tetraquark production was in response to a proposed $b\bar{b}b\bar{b}$ forward tetraquark measurement at RHIC [10]. Because the proposed pair mass was below $2m_\Upsilon$ and thus too low to be consistent with an IC-type mechanism, as shown for an Υ pair distribution on the right-hand side of Fig. 2. The calculated $b\bar{b}b\bar{b}$ mass in a Υ pair configuration was, however, in good agreement with the predicted mass from other tetraquark models, see Ref. [11] for details.

This work is being followed up by expanding the bottom tetraquarks in Ref. [11] to bottom tetraquarks with one, two and three b and \bar{b} quarks. Predictions for the masses and kinematic distributions for these states will appear in upcoming work [14].

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