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New $B_s^0\pi^\pm$ and $D_s^\pm\pi^\pm$ states in high energy multi-production process

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The production rate of the X(5568) measured by D0 collaboration is quite large and difficult to be understood by various general hadronization mechanism. We propose the inclusive production formulation for the cross section, and predict the distributions and production rates of X(5568) at LHC energies, which are crucial information for the relevant measurements. We also suspect $D_s^\pm\pi^\pm$ state can be copiously produced and observed.

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Recent years one witnesses the observation of exotic multi-quark hadrons [1–5]. The flavour number presented in the exotic hadron exceeding three is very crucial in clearly identifying the valence quark number. For a hadron with non zero quantum numbers as bottom or charm besides the isospin (I_3) and strangeness, one has no other choice than to introduce more than three quarks carrying them. Exotic multi-quark hadron with only ‘light’ (u, d, s) quarks might have produced in various processes, but it is not easy to confirm the valence quark number. *Light* Pentaquark is special, but yet of no confirmed evidence of its production.

Another significant fact should also be paid great attention on is that the confirmed multi-quark states were all produced from heavier hadron decays. However, this situation may be changed: The D0 collaboration just found a new $B_s^0\pi^\pm$ state, X(5568) [6], with *four flavours* in this hadron, —if it is really a particle. This will be quite remarkable, as the first solid evidence of multi-quark state *directly produced in the multi-production process of high energy collision*, rather than from hadron decays. The bottom flavour here is very decisive. Because of the bottom flavour and the mass, it is hardly possible produced from decay of a heavier hadron (For the charm sector, however, one has to distinguish prompt ones from those from bottom decay).

This observation of the X(5568) [6] surely turns on the significant new page in the study of the multi-quark states. Now one can study their *production mechanism* which is tightly related with the inner structure of the relevant hadrons [7, 8], *in multi-production processes* at high energy colliders like Tevatron and LHC. It is noticeable that in the high energy multi-production processes, the space-time evolution of the quark system and the produced hadron system are quite different from that of the decay processes. Besides the different partonic processes and kinematic phase space distributions, the final state interaction (if existing) is also different. So comparing the production of the ‘exotic hadron’ in the decay and multi-production processes can eliminate the misleading information possibly rendered by, e.g., phase space effects and final state interactions, etc.

As a matter of fact, the measurement [6] has provided

the important information of the production. The ratio ρ of the yield of X(5568) to the yield of the B_s^0 meson in two kinematic ranges, $10 < p_T(B_s^0) < 15$ GeV/c and $15 < p_T(B_s^0) < 30$ GeV/c, is measured. The results for ρ are $(9.1 \pm 2.6 \pm 1.6)\%$ and $(8.2 \pm 2.7 \pm 1.6)\%$, respectively, with an average of $(8.6 \pm 1.9 \pm 1.4)\%$. Here we assume $B_s^0\pi^\pm$ is the dominant decay mode of this new state. This large production rate itself first of all excludes the possibility of decay from heavier particles like B_c , which are difficult to produce. In this paper we investigate the production mechanism of this new $B_s^0\pi^\pm$ state, taking it as a particle, say, X(5568). We emphasize that its production rate is quite large, and difficult to be understood by various general hadronization models. So we propose the inclusive resonance production formulation to calculate its cross sections for various collision processes as well as energies, which provides useful information for the relevant detections, e.g., those at LHC. We demonstrate that the transverse and longitudinal momentum distributions, together with the special property of the decay channel are important for the set of the triggers and data selection requirements. When just the bottom quark is replaced by the charm quark in X(5568), assuming the structure hence the production mechanism for the corresponding four-quark charm hadron do not change, the production of the ‘new $D_s^\pm\pi^\pm$ state’ is studied.

As mentioned above, the production mechanism is tightly related with the inner structure of the relevant hadron [7, 8]. Our analysis starts from assuming X(5568) as four quark state and directly produced together with other general mesons and baryons, employing various hadronization mechanism [9].

1) **String fragmentation model** [10]. The bottom quark can only be produced by hard scattering between partons. In the hadronization process it links with another antiquark \bar{q} by a string. Then this string fragments into several hadrons, among which are the bottom hadrons, e.g., B_s^0 . It is well known that the relative probabilities of the creation of light flavours u, d, s from vacuum are $1 : 1 : \lambda$, with $\lambda \sim 0.3$ [9, 11]. These values can be extracted by looking into the production ratios, e.g., $B_s/B_0 \sim 0.3$ in various high energy multi-production processes. For the investigation here, we also

need the production of diquark. Since we only want to estimate the production rate, not concentrating on correlations, we adopt the diquark mechanism rather than the popcorn mechanism for simplicity. And this will be consistent with the X(5568) structure when considered as diquark antidiquark pair. From the production ratios such as $\Lambda_b/B_s \sim 1/2$, we take it as $\lambda/2$. However, if the diquark has a strange flavour, e.g., us , a further factor λ is introduced. Here is the relative probabilities:

$$\begin{aligned} u : d : s : ud : uu : dd : us : ds : ss \\ = 1 : 1 : \lambda : \frac{\lambda}{2} : \frac{\lambda}{2} : \frac{\lambda}{2} : \frac{\lambda^2}{2} : \frac{\lambda^2}{2} : \frac{\lambda^3}{2}. \end{aligned} \quad (1)$$

In string model, quarks and diquarks are created from vacuum in pair, so here ‘ u ’ means ‘ $u\bar{u}$ ’, ‘ ud ’ means ‘ $ud\bar{u}\bar{d}$ ’, etc. These relative ratios are consistent with the production rates of Ξ , Σ , non-strange baryons, as well as their relative production ratios to the relevant mesons in a jet [11].

On the other hand, the production of X(5568) needs a special string: The bu or bd diquark as one of the end of the string connecting another quark as the other end [13–15]. Needless to say, this kind of colour connection is suppressed. We set an ansatz that this special kind of string $bq - q$, relative to the usual $b - \bar{q}$ one, receives a suppression factor $\lambda/2$. This is reasonable since when the strings are ‘short’ enough and they just correspond to a single particle, the suppression factor just gives the correct relative production rate. Hence we estimate the production ratio $X(5568)/B_s^0$ in the string model as:

$$P_X = \frac{2 \times \lambda/2}{D_1} \times \frac{\lambda^2/2}{D_2}. \quad (2)$$

Here $D_1 = 1 + 1 + \lambda + \lambda/2 + \lambda/2 + \lambda^2/2$, and $D_2 = 1 + 1 + \lambda + \lambda/2 + \lambda/2 + \lambda/2 + \lambda^2/2 + \lambda^2/2 + \lambda^3/2$.

$$P_{Bs} = \frac{1 + 1 + \lambda}{D_1} \times \frac{\lambda}{D_2}; \quad (3)$$

$$\rho_{string} = \frac{P_X}{P_{Bs}} \sim 2\%. \quad (4)$$

This is much smaller than the average 8.6%. Even, we emphasize that the decreasing nature with respect to the increasing of the transverse momentum indicated by the experiment (we will clarify that it must be) of the above relative ratio ρ renders that the total production ratio is larger than 8.6%. Furthermore, we ignore the fragmentation into several kinds of hadrons with similar flavour but different spins, which will even decrease the ratio. To get a higher production rate, one needs to tune the relative ratios in Eq. (2), i.e., to increase the relative ratio of the diquarks containing strange quark(s). However, similar problems as in other models [17] to give correct production rates of the strange baryons will be raised.

2) **cluster model and final state interaction** [12]. In cluster model, we have to introduce a free

parameter to describe the probability the cluster with mass large enough to decay into X(5568). The value of the parameter can be obtained by fitting the data. So it is not very meaningful to say it is large or small. By the help of the recent work [16], we find that if this peak is not a real particle but some kind of final state interaction effect, the observed ‘rate’ is also very small. The reason is that this kind of peak is quite sensitive to the cluster (referred as A in [16]) mass. But the probability for the mass of the cluster around the proper value is very small. So explaining the large ‘production rate’ needs fine tuning by the final state interaction models.

3) **Combination model**. The key thing is how the light flavour produced and combined with the bottom quark, to become X(5568). The probability of creation of each flavour is as the above, only we do not need to introduce the diquark. So it is the b quark combined with $\bar{s}u\bar{d}$ or $\bar{s}d\bar{u}$ for X(5568). If we assume that the total probability of any three light (anti)quarks combined with b as 1, then

$$P_X = \frac{\lambda}{D} \frac{1}{D} \frac{1}{D} \times 2. \quad (5)$$

Here $D = 2(1 + 1 + \lambda)$. If we assume that b combines with any other antiquark with probability 1, then

$$P_{Bs} = \frac{\lambda}{(D/2)}, \quad (6)$$

$$\rho_{combination}^{max} = \frac{P_X}{P_{Bs}} \sim 5\%. \quad (7)$$

Here we write the superscript ‘ max ’ to address the fact: We did not take into account that the above two cases, b combining with an antiquark or b combining with three quark cluster $q\bar{q}'\bar{q}''$ excludes each other, and there should be other cases, e.g., b combining with qq to form a baryon. All these possibilities add up to 1. This reflects the unitarity of the combination process [7, 17], i.e., one quark can combine with many other quarks or clusters, according to some law, but the total probability must be 1, since the quark is confined and has to go into a hadron. For the calculation of ρ here, we can introduce a relative probability $\zeta = (b \text{ combines with any } q\bar{q}'\bar{q}'')/(b \text{ combines with any } \bar{q})$. In general ζ is smaller than 1, according to the fact that four quark state is not copiously found in hadronization. Hence $\rho_{combination} = \rho_{combination}^{max} \times \zeta$, smaller than 5%.

The above analysis is dependent on the SU(3) flavour symmetry breaking parameter λ , with different sensitivities for string model and combination model, respectively. In concrete, the result of the combination model is less sensitive to λ , and our up limit varies from about 3% to 6% for λ from 1 to 0. The result of the string model is much more sensitive, varies from 0 to about 16% for λ from 0 to 1. Especially, if we want to get 8.6% in the string model, we need to take λ to be 0.65. However, λ is a very steady value, and corresponds to the physics of

producing a strange quark pair from the vacuum by tunneling effect in the hadronization process, independent from colliding particles (except heavy nuclei) and energies. It is taken as 0.3 in Pythia [20], and confirmed by experiments up to LHC energies [21].

Though the above results can be considered consistent with data at the order of magnitude level, the tension is obvious. Since no other plausible parameters to tune, one has difficulty to raise to a larger production ratio (if confirmed by experiment) in these models. On the other hand, the combination model has provided a clue to improve the description on the large production ratio. If there is a special large ζ_X which is only applicable to this special X(5568) production, it can provide an enhancement factor. In the combination model, if it can take the value around 2, then we can get the experimental result. In the mean time, for the measurement [6], $B_s K$ and $B_d \pi$ are searched as cross check and no signal of new state found [19]. It seems another evidence implying that the X(5568) is a very special structure. Its production may be quite unique, different from the other particles produced, though QCD is flavour blind. So this plays another support for us to deal it independently, ignoring the constraints from the unitarity as well as the general hadronization mechanism applied to the general hadrons. For other cases, the ζ is quite small, as the ansatz for the string model, a value of order of magnitude 10 per cent, so even the other combination can lead to a 4-quark state but no observable signal [7].

The above idea of special ζ_X can be more systematically realized in analogy of the inclusive resonance production framework, as that for the quarkonium. The key point is to describe its production in two steps, whatever taking it as a bound state of hadrons or 2-quark clusters, or even, two pieces of strings. And since this special production mechanism, the probability is not added with others to exhaust the unitarity constrain [7, 17, 18] mentioned above, besides not applied to other light flavours.

As [7], we start from the amplitude

$$A(P) = \langle H(A, B), X | \hat{T} | p\bar{p} \rangle = \frac{1}{\sqrt{\mu}} \int \frac{d^3 k}{(2\pi)^3} \Phi(\vec{k}) \mathbf{M}(\vec{k}). \quad (8)$$

μ is the reduced mass. A and B are two clusters to be combined as the X(5568). Here we take the $p\bar{p}$ collision process as the example.

The relative momentum q of these two clusters can be considered as small in the rest frame of X(5568), we get

$$A(P) = \frac{1}{\sqrt{\mu}} \Psi(0) \hat{O}(q=0), q = P_A - P_B. \quad (9)$$

Here Ψ is the wave function. \hat{O} is the amplitude of production of two free ingredient particles (with vanishing relative momentum and proper angular momentum state). We only consider the simplest S-wave case. For the cross section, we need the absolute value square, with the proper initial flux factor $1/F$ and phase space integral.

From this formula, the X(5568) is produced in two steps: First, the production of the ingredient hadron/cluster pair; second, the combination of this pair to X(5568) with probability described by $|\Psi(0)|^2$. For the first step, it is the

$$\frac{1}{F} \sum_{j \neq A, B} \prod \frac{d^3 p_j}{(2\pi)^3 2E_j} |\hat{O}|^2(p_j, P_A + P_B = P_H, q=0) \times (2\pi)^4 \delta^{(4)}(P_{initial} - \sum_{j \neq A, B} p_j - P_H) \quad (10)$$

to be calculated. Here the average is taken on various spin states. It is not possible to be calculated directly with some effective quantum field theory/model when the initial state is (anti) protons and A and B are hadrons or diquarks. However,

$$\frac{1}{N} \frac{dN}{d^3 P_H d^3 q} \quad (11)$$

$$\propto \frac{1}{F} \sum_{j \neq A, B} \prod \frac{d^3 p_j}{(2\pi)^3 2E_j} |\hat{O}|^2(p_j, P_A + P_B = P_H, q)$$

$$\times (2\pi)^4 \delta^{(4)}(P_{initial} - \sum_{j \neq A, B} p_j - P_A - P_B)$$

can be calculated by an event generator such as Pythia [20] or equivalently SDQCM [9] for the case that hadrons/diquarks A and B on shell. It is the advantage that in the framework we employ, only the on shell case is considered, so that the numerical calculation with event generator is plausible. The quantity of Eq. (11) describes the two hadrons/diquarks A and B correlation in the phase space. For the hadron case, by proper integral on components of P_H and/or q , the resulting correlations can directly be compared with data and serve for tuning the parameters.

Employing the event generator, one gets

$$\frac{1}{N} \frac{dN}{d^3 P_H d^3 q}, \forall q, \quad (12)$$

then extrapolates to the special case $q=0$. Numerically, one can take an average around $q=0$ for the above quantity [7].

For $B_s \pi$, we take the simple average of two cases, hadron bound state (B, K) and diquark pair as mentioned above, then fit the X(5568) spectrum measured by D0 Collaboration to get the effective wave function at origin (Fig. 1(a)). The X(5568) transverse spectrum is softer than that of B_s , as demonstrated here and indicated from the experiment. This is from the fact that we require the two clusters near to each other in phase space for combination. Realized in the above formulation, is the relative momentum vanishing. This is in contrary to the fragmentation spectrum, the more massive, the harder.

The cross sections of X(5568) in other collision processes and energies are easy to be obtained, since the

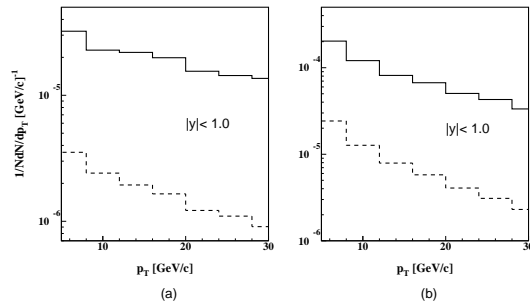


FIG. 1: Transverse momentum distributions at Tevatron. (a) The dashed line is that for X(5568), with the best fitting of the wave function to get the correct ρ measured by D0 collaboration. The solid line is for B_s as reference. (b) For the charm sector, dashed - $X_c(D_s^\pm \pi^\pm)$; solid - D_s .

effective wave function at origin is process- and energy-independent. Here we show the pseudo-rapidity η distributions for proton-proton collisions at $\sqrt{s} = 8$ TeV as an example (Fig. 2(a)). For others we refer to [7]. The production rate begins to fall beyond $\eta = 3$, as general B hadrons. The ‘rapidity plateau’ is much more narrow than those of light charged hadrons (mainly pions).

These results are useful for various detectors. Based on our calculation, one can go further to estimate the kinematic distributions of the signal particles which are from the decay of X(5568) and directly detected. As an example, Fig. 2 (b) shows the $k_T - k$ (transverse momentum and total momentum) distribution for the signal pions from the decay process $X \rightarrow B_s + \pi$ in the LHCb detector ranges ($2 < \eta < 5$). The mass difference between X(5568) and $B_s + \pi$ is small, and the pion mass is small. These facts lead to that the produced pions are not energetic, e.g., only around 10% of the signal pions with $k_T > 0.5$ GeV/c (the requirement of the relevant measurement by LHCb Collaboration [22]).

The formulation is also applicable for the cross section of $X_c(D_s^\pm \pi^\pm)$ state production. Both charm and bottom are heavy, and can be calculated by perturbative QCD in the exactly same way once taking into account the different value of the mass. If X_c exists, it is not difficult to be detected. D_s^\pm can be detected from $D_s^\pm \rightarrow \phi\pi$ channel, by proper 3 charged particle tracks from the vertex displaced from the primary one. Then this reconstructed D_s^\pm can be combined with a proper charged particle track considered as π from the *primary vertex* to give the invariant mass distribution to look for the resonance. If K_s^0 is well measured, D_s^\pm can also be reconstructed from the 2K channel and then combined with the π from the primary vertex. This kind of pions can eliminate the possibility that the X_c produced from the decay of bottom. Of course just by keeping or not this restriction, one can preliminarily investigate X_c from multi-production or from weak decay. Here we would like to emphasize that, since the mass of X_c are around half

of X(5568), it has a larger boost factor γ about two times of that of X(5568) for the same momentum. This means whether Tevatron or LHC, in both central and large rapidity regions, the signal pions are more energetic to be detectable.

The transverse distribution of X_c at Tevatron energy, comparing with that of D_s , can be seen from Fig. 1 (b). Here we assume that replacing b by c quark will not change the value of the wave function at origin, since the reduced mass is insensitive to the heavy ingredient. The production ratio $\rho_c = X_c/D_s$ for the transverse momentum region $10 < p_T(D_s) < 15$ GeV/c and $15 < p_T(D_s) < 30$ GeV/c, is 10.2% and 7.9%, respectively, almost similar as those of the bottom sector. It is copious enough and the search from experiments is reasonable.

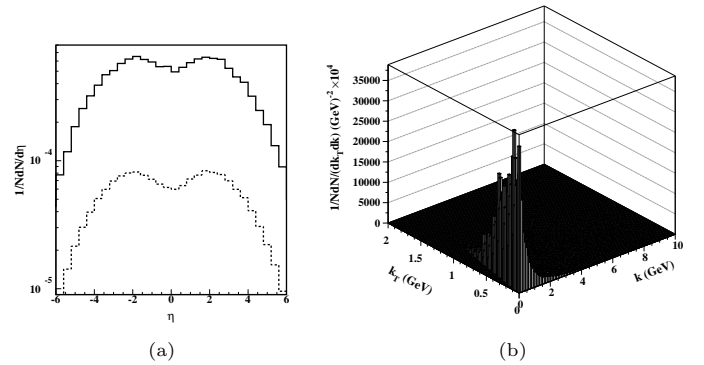


FIG. 2: (a) Pseudo-rapidity distributions. The dashed line is for X(5568), the solid is for B_s . (b) $k_T - k$ (transverse momentum and total momentum) distribution of the signal pions. A Breit-Wigner form of the X(5568) mass distribution is convoluted ($\Gamma_X = 21.9$ MeV/c²) [6].

We look forward for the new charm four quark partner. This will shed light to the understanding of this special new state, as well as deepen our understanding on the hadronization mechanism, besides its structure [23]. These productions of X(5568) or possible X_c can also be realized in high energy heavy ion collisions, with a larger rate since there strangeness and/or diquark is enhanced. The large number of quarks in unit phase space volume in heavy ion collisions also indicates that one can get a larger value of \hat{O} . These lead to larger production ratio $X(5568)/B_s^0$ (X_c/D_s), hence larger B_s^0/B^0 from X(5568) decay (also D_s/D). This can be measured as the ‘anomalous strangeness enhancement’ in the B (D) meson sector. Furthermore, it is also interesting to combine X(5568) with other tracks to look for heavier hadron, e.g., B_c , as complementary study. If one finds an X_c , to study those from multi-production and from heavier hadron decay are also very helpful, as mentioned above.

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