Latest D0 results on exotic hadrons produced in $p\bar{p}$ collisions

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Prompt and nonprompt productions of exotic multiquark states are studied using the ~10.4 fb^{-1} data sample collected by the D0 experiment in Tevatron $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV. The recent D0 results on the prompt and nonprompt production of the $X(3872)$ and $Z_c^+(3900)$ states and the P_c pentaquarks at the 4450 MeV region are reported. Signals corresponding to these states are found in the nonprompt production, whereas only the $X(3872)$ state is seen in the prompt production. The ratio of prompt to nonprompt $X(3872)$ production is about three times larger in the D0 measurement than that obtained by the ATLAS experiment at 8 TeV. Theoretically, the production, formation, coalescence, and disassociation processes are expected to be quite different for conventional mesons with a spatial size of (0.4–0.8) fm, compact multiquark states such as tetraquarks with a size of a few fm, and spatially extended molecular states with a size of (4–10) fm. They can be differently affected in prompt hadron-hadron collisions where there are many additional particles emitted from the interaction point. Consequently, the prompt to nonprompt production ratio of spatially extended exotic states can be suppressed at LHC comparing with the Tevatron conditions, because of large difference in the hadron-hadron collisions particle multiplicity. The prompt production studies provide an opportunity to better understand the nature of exotic states.

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1. Introduction

Since the discovery of the state $X(3872)$ (also named $\chi_{c1}(3872)$) in 2003 by the Belle collaboration [1], many new exotic states have been observed. Whereas the conventional states consist of a quark-antiquark pair or three quarks, exotic states include a quark-antiquark pair in addition to the conventional configurations. Theoretically, the exotic states can be described as compact tetraquark (or pentaquark) states or spatially extended molecular configurations. The spatial dimensions of these states are very different and usually estimated to be about (0.4–0.8) fm for conventional states, (1–4) fm for compact tetraquarks, and (4–10) fm for molecular states. This can have a significant impact on production processes of these states.

Many experimental measurements of new exotic states performed during the last decade stimulated a wide theoretical discussion about possible interpretations of these states. Most of these efforts have been focused on the measurements and theoretical interpretations of the decays of exotic states, whereas less attention has been paid to the production mechanism studies. At hadron colliders exotic states can be produced nonpromptly in the secondary vertices of b hadron decays or promptly in hadron collisions with many particles coming from the primary vertex (Fig. 1).
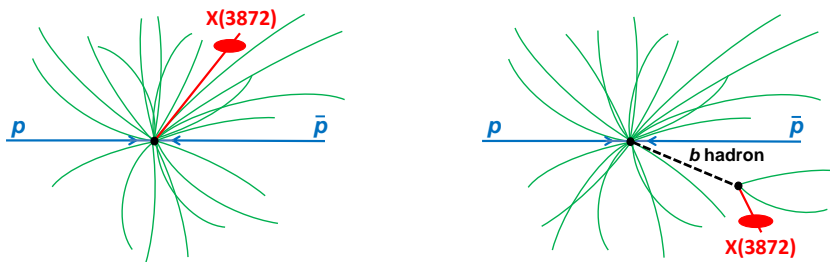

Figure 1: The prompt (left) and nonprompt (right) production of the $X(3872)$ state.

A theoretical discussion of potential production mechanisms was motivated by the experimental observation of the copious prompt production of the $X(3872)$ in hadron colliders. Prompt production of a loosely bound molecular state like $X(3872)$ in violent strong interactions is difficult to explain. These studies indicated the possibility for getting more insight about configurations of exotic states using information about their production in different processes, in particular in the prompt hadron-hadron collisions. The large difference in the spatial sizes of conventional, compact multiquark and molecular states implies suppressed production rates for spatially extended configurations in the primary vertices at hadron-hadron collisions. The dependence of the prompt $X(3872)$ production rate on the number of particles produced in the primary vertex at hadron colliders was observed by the LHCb experiment [2] and was theoretically discussed in [3], in which the disassociation of spatially extended and weakly bound $X(3872)$ state by comoving particles was calculated. However the production dynamics of a spatially large object in the primary vertex of hadron-hadron collisions requires additional theoretical investigations.

Up to now, at LHC the only exotic states observed in prompt hadron-hadron collisions are the $X(3872)$ and the $X(6900)$ state observed recently by the LHCb experiment in the invariant mass of two J/ψ mesons. The $X(3872)$ state is often assumed to be a mixture of conventional $\chi_{c1}(2P)$ and molecular configurations, therefore the copious prompt production could possibly come through its

conventional $\chi_{c1}(2P)$ component. The $X(6900)$ state decaying in two J/ψ mesons consists of four heavy quarks and should have a small spatial size, so its production would not be suppressed. At Tevatron, additionally to the observation of the prompt $X(3872)$ production, an evidence of $4.7\,\sigma$ was found for the prompt $X(4140)$ signal [4] and the promptly produced $X(5568)$ state was observed in the $B_s^0 \pi^{\pm}$ system [5]. The $X(5568)$ signal was not confirmed by LHC experiments. However the direct comparison of the prompt production ratios of the spatially extended four-quark $X(5568)$ state to the conventional B_s^0 meson at LHC and Tevatron conditions is not appropriate. This ratio can be strongly suppressed at LHC compared to the Tevatron measurement, where about half as many particles on average are produced in the primary hadron collision vertex as at LHC.

2. Prompt and nonprompt production of $X(3872)$ and $\psi(2S)$ states

The pseudo-proper time distributions for the $X(3872)$ and $\psi(2S)$ states were studied by the D0 collaboration with a ~10.4 fb^{-1} data sample [6]. The pseudo-proper time t_{pp} is calculated using the formula $t_{pp} = \vec{L}_{xy} \cdot \vec{p}_T \, m/(p_T^2 \, c)$, where $\vec{p}_T$ and m are the transverse momentum and mass of the charmonium state $\psi(2S)$ or $X(3872)$ and c is the speed of light. To obtain the t_{pp} distributions, the numbers of events are extracted from fits for the $X(3872)$ ($\psi(2S)$) mass in 12 (24) exponentially increasing t_{pp} bins. The t_{pp} distributions are fitted using the χ^2 method with a model that includes prompt and nonprompt components. The prompt production is assumed to have a strictly zero lifetime, whereas the nonprompt component is assumed to be distributed exponentially starting from zero. Both shapes are smeared by the detector vertex resolution.

The large D0 sample allows the study of the t_{pp} distributions in several p_T intervals and the nonprompt contribution fraction f_{NP} can be extracted in each. Figure 2 (left) shows the D0 f_{NP} as a function of p_T for the $\psi(2S)$, compared with the measurements by ATLAS [7] at 8 TeV, CMS [8] at 7 TeV, and CDF [9] at 1.96 TeV. Figure 2 (right) shows similar distributions for the $X(3872)$ obtained in the D0 analysis, together with the ATLAS [7] and CMS [10] measurements.
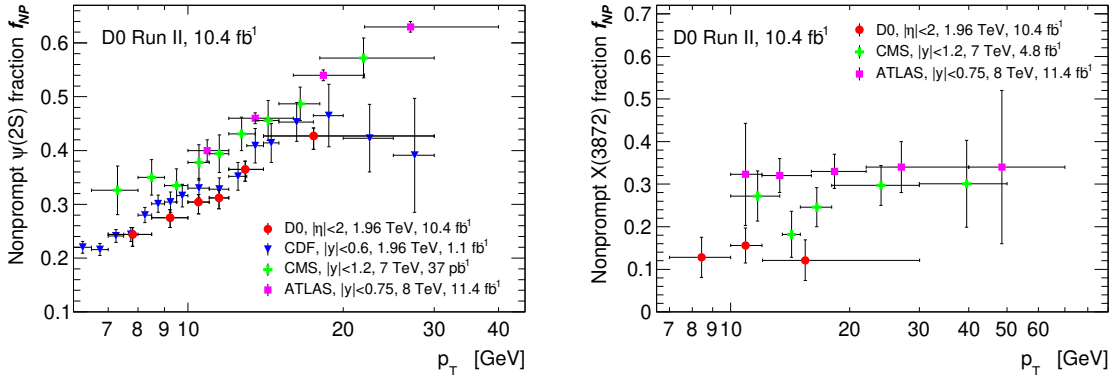

Figure 2: The nonprompt component f_{NP} for the $\psi(2S)$ (left) and $X(3872)$ (right) states as a function of p_T, in comparison with the ATLAS, CMS and CDF measurements.

The nonprompt fractions f_{NP} for $\psi(2S)$ increase as a function of p_T, whereas those for $X(3872)$ are consistent with being independent of p_T, similar to the measurements of other experiments. The ratio of prompt to nonprompt $\psi(2S)$ production, $R_{p/np} = (1 - f_{NP})/f_{NP}$, is only about 25 % larger

at the Tevatron than at the LHC, but for the $X(3872)$ production at the Tevatron exceeds that at the LHC by about 3. This indicates that the prompt production of the exotic state $X(3872)$ is strongly suppressed at the LHC relative to that from b hadron decays. This suppression is possibly due to the larger number of particles produced in the primary collision at the LHC than at the Tevatron, thus increasing the probability for disassociating the nearly unbound and spatially extended $X(3872)$.

Recent theoretical works predict a sizable contribution to the production of the $X(3872)$ from the formation of the $X(3872)$ in association with a comoving pion, both directly in the hadronic beam collisions [11] and in b hadron decays [12]. The $X(3872)$ state can be produced by the creation of $D^*\bar{D}^*$ at short distances, followed by a rescattering of the charm-meson pair into a $X(3872)\pi$ pair by exchanging a D meson, where the $X\pi$ kinetic energy in the $X\pi$ center of mass frame is expected to be $T < 11.8$ MeV.

The $X(3872)$ signal obtained by D0 using the prompt sample [6] within the $T(X\pi) < 11.8$ MeV region is shown in Fig.3 (a). The fit yields 18 ± 16 events. In the absence of the soft-pion process, 6 events are expected in this region, to be compared with an estimated 245–730 events from the soft-pion process. Therefore no evidence for the soft-pion effect is seen in the prompt sample. For the nonprompt $X(3872)$ sample, a signal of 27 ± 12 events is observed in the low $T(X\pi)$ region (Fig.3 (b)), whereas only 2 events are expected from the energy distribution extrapolation. The expected number of soft-pion events is between 30 and 90. The observed number of events differs from that without the soft-pion process only by 2σ, preventing a definite conclusion.
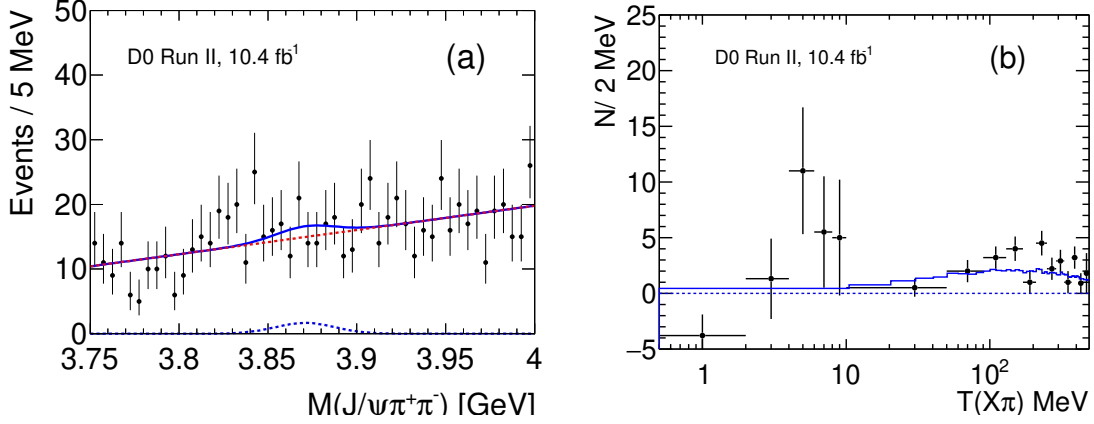

Figure 3: (a) The $X(3872)$ signal at the $T(X\pi) < 11.8$ MeV region for prompt events and (b) the $X(3872)$ signal yield as a function of $T(X\pi)$ for nonprompt events.

3. Prompt and nonprompt production of $Z_c^{\pm}(3900)$

The prompt and nonprompt production of the exotic charged state $Z_c^{\pm}(3900)$ was studied by the D0 collaboration [13] through the sequential process $\psi(4260) \rightarrow Z_c^{\pm}(3900)\pi^{\mp}$, $Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}$. The nonprompt events are selected semi-inclusively, requiring that all final tracks form a secondary vertex displaced from the primary $p\bar{p}$ collision vertex. The events are selected in the $M(J/\psi\pi^+\pi^-)$ range 4.1–4.7 GeV that includes the exotic $\psi(4260)$ state. The fits of the $M(J/\psi\pi^{\pm})$ distributions are performed in the vicinity of the $Z_c^{\pm}(3900)$ for the six 1 GeV wide intervals of

$M(J/\psi\pi^+\pi^-)$. The fit results are shown in Fig. 4 for the prompt (a) and nonprompt (b) samples. No signal is observed for the prompt data sample in any $M(J/\psi\pi^+\pi^-)$ interval. For the nonprompt sample a clear enhancement is seen for the events in the range $4.2 < M(J/\psi\pi^+\pi^-) < 4.3$ GeV. For events in this range the $M(J/\psi\pi^\pm)$ distribution fit is performed and the $Z_c^\pm(3900)$ signal is observed with parameters: $M = 3902.6^{+5.2}_{-5.0}$ GeV, $\Gamma = 32^{+28}_{-21}$ GeV, and the statistical significance $S = 5.4\,\sigma$.
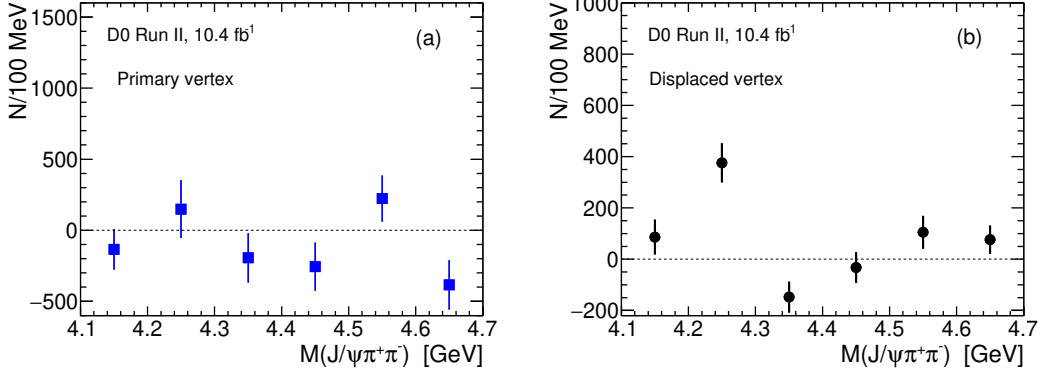

Figure 4: The $Z_c^\pm(3900)$ signal yield obtained from fits for six 1 GeV wide intervals in the $4.1 < M(J/\psi\pi^+\pi^-) < 4.7$ GeV range for (a) prompt and (b) nonprompt data samples.

4. Evidence for inclusive nonprompt production of P_c states

The mass spectrum for the $J/\psi p$ combination was studied with the full D0 data sample [14]. The preliminary results are obtained for the inclusive production of the $J/\psi p$ final state, where muons from the J/ψ and a proton originate from a common secondary vertex, displaced in the transverse plane from the $p\bar{p}$ interaction vertex by at least $5\,\sigma$. The invariant $M(J/\psi p)$ mass distribution is shown in Fig. 5.
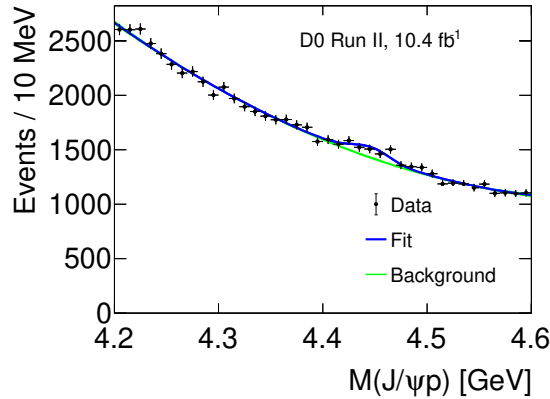

Figure 5: The invariant $M(J/\psi p)$ mass distribution with a superimposed fit, described in the text.

In the fit the signal is modeled by a sum of two Breit-Wigner resonances, corresponding to the $P_c(4400)$ and $P_c(4457)$ pentaquarks, with parameters equal to those obtained by the LHCb experiment [15]. The background is described by a second-order Chebyshev polynomial. Evidence for the signal is found with a significance of $3.2\,\sigma$.

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