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Exotic hadron production in pp and pPb collisions at LHCb

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Abstract. In the last decade, hadron spectroscopy has unveiled a wealth of states that do not have the properties expected of particles composed of two or three valence quarks. Foremost among these is the X(3872), which is thought to contain a $c\bar{c}$ pair plus two light quarks. In heavy ion collisions, these multiquark states are especially sensitive to a range of phenomena that can suppress or enhance their production. With a full range of precision vertexing, tracking, and particle ID capabilities covering forward rapidity, the LHCb experiment is especially well suited to measurements of both prompt and non-prompt exotic hadrons. This talk will present recent LHCb measurements of exotic hadrons, including the first measurement of the nuclear modification factor of the exotic hadron X(3872) in pPb collisions.

1 Introduction

Exotic hadrons with more than three valence quarks have been expected since the first formulation of the quark model more than 60 years ago [1, 2]. However, it is only within the last 10 years that these states have started to be studied and characterized in detail at the Large Hadron Collider (LHC) and b factories. The LHCb detector [3] at the LHC has a unique set of capabilities that make it particularly well suited to study production mechanisms and properties of exotic hadrons, as well as their interactions in the nuclear medium. These proceedings discuss several new measurements from LHCb, including the first measurement of exclusive production of exotic hadrons [4], the first measurement of exotic hadron fragmentation in jets [5], and the first measurement of the nuclear modification factor of an exotic hadron in proton+nucleus collisions [6].

2 Exclusive production of exotic states

Exotic hadrons are often discovered as products of b hadron decays. For example, an amplitude analysis of the $B^+ \to J/\psi\phi K^+$ decay showed exotic resonances in the $J/\psi\phi$ mass spectrum [7–9]. Recently there has been growing interest in exploring new production mechanisms of exotic hadrons via photon-induced processes on nuclei [10–13]. These processes can be accessed in diffractive pp interactions, ultraperipheral collisions of heavy nuclei, and in electron-nucleus interactions.

LHCb has performed the first measurement of exotic X states produced in diffractive pp interactions [4], using 5 fb^{-1} of pp collisions recorded at center of mass energy $\sqrt{s}$ = 13 TeV. In this measurement, beam crossings that produce exactly four tracks in the LHCb

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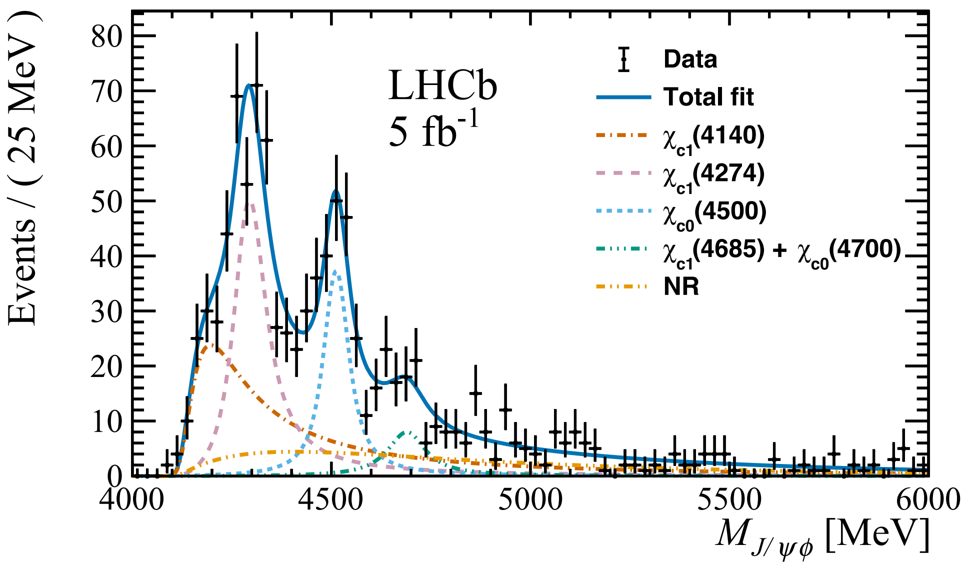

Figure 1. Invariant mass distribution of exclusive $J/\psi\phi$ produced in pp collisions with exactly four reconstructed tracks [4].

spectrometer are selected. Two of the tracks are required to meet muon identification criteria and form an invariant mass consistent with the J/ψ meson mass. The other two tracks are required to be identified as kaons and have an invariant mass consistent with the decay $\phi \to K^+K^-$. The resulting invariant mass spectrum of the combined $J/\psi\phi$ candidates is shown in Fig. 1, showing multiple peaks corresponding to $J/\psi\phi$ resonances. No such structures are observed in events with more than four tracks, indicating that exclusive resonance production is occurring. A fit to the $J/\psi\phi$ mass spectrum returns masses and widths that are consistent with exotic X hadrons previously observed in b hadron decays [7–9]. The observation of this new production mechanism for exotic hadron opens a new window for studies of their properties.

3 Exotic hadrons in jets

A different way to study the behavior of exotic hadrons is to measure their properties within a jet. Such measurements can provide information on the way heavy quarks fragment, and comparisons with charmonia states allow differences between the formation of exotic versus conventional to be probed. Fragmentation functions are measured in terms of the fraction of the jet's transverse momentum p_T(jet) carried by the hadron h of interest, giving the fraction $p_T(h)/p_T$(jet). At LHCb, the conventional charmonia states J/ψ and ψ(2S) and the exotic hadron χ_{c1}(3872) have been studied within jets in pp collsions at $\sqrt{s}$ = 13 TeV [5, 14]. Jets are reconstructed by the anti-k_T algorithm with a radius of 0.5.

The fragmentation functions for prompt J/ψ, prompt ψ(2S) and prompt χ_{c1}(3872) are shown in Fig. 2, along with calculations from the event generator PYTHIA. The J/ψ fragmentation in the left panel is significantly more isolated than expected from PYTHIA calculations, although interpretation of this data is complicated by the the large fraction of J/ψ produced through feeddown from higher charmonia states. The center panel shows the ψ(2S)

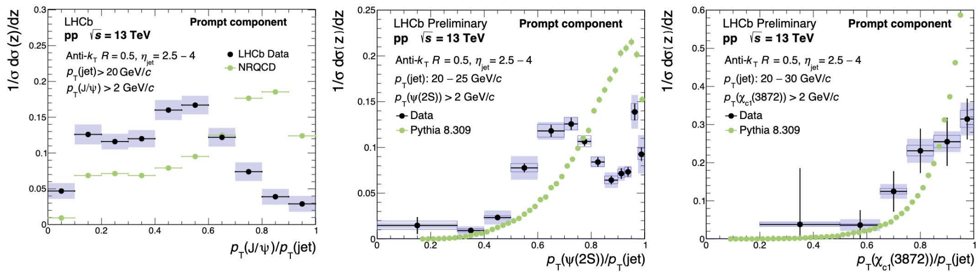

Figure 2. Fragmentation functions for (left) prompt J/ψ, (center) prompt $\psi(2S)$, and (right) prompt $\chi_{c1}(3872)$, compared to PYTHIA calculations [5].

data, which has very little feeddown. These data displays a two-peak structure that may correspond to different production mechanisms (i.e. color singlet versus color octet), and is very different from the J/ψ data. The left panel of Fig. 2 shows the fragmentation function for the exotic hadron $\chi_{c1}(3872)$, which shows different behavior from the conventional charmonia states J/ψ and $\psi(2S)$, and is dominantly produced at high values of $p_T(h)/p_T(\text{jet})$.

4 Nuclear modification of χ_{c1}(3872) in pPb collisions

Exotic hadrons produced in collisions involving heavy nuclei are subject to a range of nuclear effects that are not accessible in pp or e^+e^- collisions. These can include energy loss when crossing the nucleus, modification of hadronization mechanisms in parton-dense environments, and the effects of the deconfined quark-gluon plasma. The way these phenomena affect hadrons comprised of more than three valence quarks offers a new way to probe these effects, and the exotic hadrons themselves.

The ratio of production cross sections of the exotic $\chi_{c1}(3872)$ to the charmonium state $\psi(2S)$ is shown in the left panel of Fig. 3, for pp collisions at forward rapidity, pPb collisions at forward (p-going) and backward (Pb-going) rapidities, and PbPb collisions at midrapidity [6, 15, 16]. The ratio increases from ~0.08 in pp to ~1 in PbPb, suggesting that exotic states may experience different dynamics in the nuclear medium than conventional charmonia, although significant uncertainties preclude drawing firm conclusions. In this ratio, initial state effects (such as shadowing in the nuclear gluon distribution) should largely cancel, leaving final state effects dominant. However, there remains an ambiguity: with this ratio alone it cannot be determined if $\chi_{c1}(3872)$ is enhanced, or if $\psi(2S)$ suppression alone can explain the variation across system sizes.

This ambiguity is lifted by measuring the nuclear modification factor in pPb collisions R_{pPb} for $\chi_{c1}(3872)$ and $\psi(2S)$ separately, as shown in the right panel of Fig. 3. These data suggest that $\chi_{c1}(3872)$ production may be enhanced in pPb collisions as compared to pp, although conclusions are tempered by significant uncertainties. This may be due to the same mechanisms that increase baryon production in high-multiplicity collision environments [17, 18].

5 Outlook

The LHCb collaboration continues to pursue a vigorous study of exotic hadrons with an incomparably wide range of observables across different collision systems. Upgrades to the

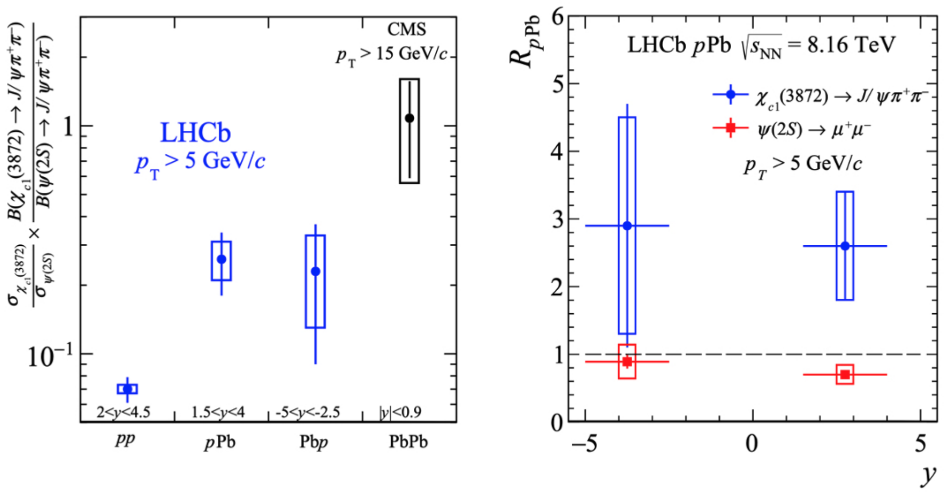

Figure 3. Left: the ratio of $\chi_{c1}(3872)$ to $\psi(2S)$ cross sections measured in the $J/\psi\pi^+\pi^-$ decay channel in *pp* [15], *p*Pb [6], and PbPb [16] collisions. Right: the $\chi_{c1}(3872)$ and $\psi(2S)$ nuclear modification factors R_{pPb} [6].

LHCb spectrometer have already dramatically increased the luminosity sampled in *pp* collisions, allowed for new reach into central heavy ion collisions, and enabled a unique, high statistics fixed target program [19]. Further upgrades are planned in the future [20, 21]. These upgrades will have a direct impact on LHCb's ability to study exotic hadrons, and will enable new understanding of the totality of bound states allowed by Quantum Chromodynamics and their properties.

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