Recent results on B-physics and multiquark states from LHCb

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2016-04/Adeva

A review is made of recent results on flavour physics and multiquark states by the LHCb experiment. These cover a wide range of topics discussed at the School, which are briefly summarized here, with reference to the relevant publications. The topics range from a complete review of the $B^0_{(s)} - \bar{B}^0_{(s)}$ meson oscillations, with and without CP violation, with a specific discussion of CPT non conservation, to axion and inflaton searches at a hadron collider. Results on rare decays and weak anomalies are also summarized, and a follow-up is made of the charmonium-pentaquark discovery and of recent findings on tetraquark-like states.

1 B-meson mixing, CP- and CPT-violation

Only four long-lived neutral mesons exist in Nature: K^0, D^0, B^0, and B^0_s. Their particle-antiparticle oscillations are important assets to constrain models beyond the Standard Model of Particle Physics (SM), because they probe high masses through quantum fluctuations in the vacuum polarization diagrams. Under CPT conservation, the mixing matrix contains 5 real observables: $m_{H,L}$, $\Gamma_{H,L}$, and the CP-violating phase ϕ, where $\Delta m \equiv m_H - m_L$ and $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$ are the mass and lifetime differences between the two mass eigenstates. As discussed at the School (see this communication on Indico), the oscillation can be observed either in self-tagging modes (only accessible from B^0 or $\bar{B}^0$) or in CP-eigenstates, where interference between mixing and decay amplitudes is possible.

Using semimuonic decays and flavour tagging at production and decay times, the LHCb experiment has performed a measurement of the mass difference between the B^0 mass eigenstates [1]: $\Delta m_d = (0.5050 \pm 0.0021 \pm 0.0010)\, ps^{-1}$. A much faster oscillation is observed with the B^0_s meson [2], seen by LHCb from hadron decays such as $B^0_s \to D^-_s \pi^+$, with $D_s \to \phi(K^+K^-)\pi^-$. These measurements are the most precise to date, and both agree with the SM prediction.

Concerning CP-violation in the mixing, earlier non-zero observations at the Tevatron [3] have been reassessed recently, including LHCb results from non CP-symmetric pp collisions at the LHC. LHCb has succeeded in separating the contributions from the B^0_s [4] and B^0 [5] mesons in the semimuonic asymmetries, with the results $a^s_{SL} = (0.39 \pm 0.25 \pm 0.20)\%$ and $a^d_{SL} = (-0.02 \pm 0.19 \pm 0.30)\%$, showing consistency with the SM prediction of null asymmetry.

An important test of the Kobayashi-Maskawa theory is measuring the very small CP-violating phase that arises from the unitarity triangle having a very short side:

$$V_{us}^* V_{ub}(\approx 0) + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0$$

which is given by the phase difference between the last two terms, called β_s. This can only be achieved at hadron colliders, mainly by using the golden channel $B_s^0 \to J/\psi\phi$. The result reported by LHCb from the above channel is further improved when adding together the information from the $B_s^0 \to J/\psi\pi^+\pi^-$ final states [6], yielding the final measurement: $\phi_s^{c\bar{c}s} = -2\beta_s = -10 \pm 39$ mrad [7]. The time analysis of the CP-asymmetry, performed with an average resolution of $46fs$ at LHCb, provides as a by-product the lifetime difference between the mass eigenstates $\Delta\Gamma_s$. With leading precision from LHCb, overall agreement is found among the different collider experiments (ATLAS, CMS, D0, CDF and LHCb). World averaged values are found: $\phi_s^{c\bar{c}s} = -33 \pm 33$ mrad and $\Delta\Gamma_s = 88 \pm 20$ ns^{-1}, in very good agreement with the SM predictions of: $\phi_s^{c\bar{c}s} = -37.6 \pm 0.8$ mrad and $\Delta\Gamma_s = 88 \pm 20$ ns^{-1}. Further improvement will require assessment of higher order corrections, related to penguin loop diagrams [8, 9].

In addition, recent major contributions have been performed to the standard unitarity triangle of the CKM matrix: $V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0$, defined by the phases β and γ, by providing direct measurements of γ from the BaBar, BELLE, and LHCb experiments [10, 11, 12]. The combined measurement of γ by LHCb from tree-level diagrams [12], that handles together the interference parameters from all decays of the generic form $B \to DK$, has provided the most accurate result: $\gamma = (70.9^{+7.1}_{-8.5})^\circ$. It is worth mentioning that γ is the only CP-violating phase that can be determined from tree-level diagrams alone, and can therefore be used as a reference candle for the SM contribution, when compared to additional measurements to come that may be sensitive to loop diagrams. Concerning the β phase, LHCb has recently contributed to the already existing very precise measurements by BaBar and BELLE [13], with the new result [14]: $S = \sin^2(2\beta) = 0.731 \pm 0.035 \pm 0.020$, and with a constraint to the cosine term of the time dependent asymmetry: $C = -0.038 \pm 0.032 \pm 0.005$.

The level of precision attained in $B-\bar{B}$ oscillations opens the possibility to explore CPT violation, which would imply Lorentz non invariance [15]. The so-called Standard Model Extension (SME) postulates interactions that would destabilize the vacuum and spontaneously generate a non-zero vacuum expectation value (VEV) of Lorentz tensors [16]. Should the masses ($\delta m \neq 0$) or lifetimes ($\delta\Gamma \neq 0$) of B and $\bar{B}$ mesons not be equal, a phase angle shift in the $B - \bar{B}$ asymmetry oscillation would be observed through the complex number [17]:

$$z = \frac{\delta m - i\delta\Gamma/2}{\Delta m - i\Delta\Gamma/2}$$

Given the fact that the denominator is quite small as compared with the B-meson masses (either B^0 or B_s^0), the figure of merit may become, in relative terms, comparable to the ratio $m_W/M_P \approx 10^{-17}$ of Planck mass effects at the electroweak scale. Since the numerator of z depends on the 4-velocity $\beta^\mu = \gamma(1, \vec{\beta})$ of the meson as $\beta^\mu \Delta a_\mu$ [16], the sensitivity is enhanced by an additional factor of 20 at LHCb, once the LHC beam location is specified on the Earth's rotating frame. The time analysis revealed no significant periodicities, and Δa_μ was determined, for B^0 and B_s^0, with precisions of order 10^{-15} and 10^{-14} GeV, respectively [17]. The following constraints were obtained: Re$z = -0.022 \pm 0.033 \pm 0.005$ and Im$z = -0.022 \pm 0.011 \pm 0.002$.

2 Rare b-decays and weak anomalies

Final states with dileptons are a particularly sensitive probe to search for contributions of Wilson operators in precision tests of flavor-changing neutral currents (FCNC) in $b \to s$ and $b \to d$ transitions, beyond those of the Standard Model at loop level. Well known examples are the very rare decays $B^0_{(s)} \to \mu^+\mu^-$ and exclusive $b \to s\mu^+\mu^-$ processes.

A joint effort has been performed by the LHCb and CMS experiments at the LHC [18] to assess the elusive $B^0_{(s)} \to \mu^+\mu^-$ decays, under scrutiny for many years at several accelerator facilities. Taking into account the distinct geometrical acceptance and resolution properties of both experiments, the combination of the data has resulted in the final discovery of the $B_s \to \mu^+\mu^-$ mode with branching fraction $\mathcal{B}(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.8}) \times 10^{-9}$ and in a 3σ effect for $B^0 \to \mu^+\mu^-$, with $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$. The fit for the ratios of the branching fractions relative to their SM predictions yields $\mathcal{S}^{B_s}_{SM} = 0.76^{+20}_{-18}$ and $\mathcal{S}^{B^0}_{SM} = 3.7^{+1.6}_{-1.4}$. The measurements are compatible with the respective SM predictions at the 1.2σ and 2.2σ level, when computed from the one-dimensional hypothesis tests. Finally, the fit for the ratio of branching fractions yields $\mathcal{R} = 0.14^{+0.08}_{-0.06}$, which is compatible with the SM at the 2.3σ level.

Rare $b \to s\mu^+\mu^-$ FCNC's are only allowed in the SM by calculable electroweak penguin and box diagrams, open to contributions of new heavy particles (extra Z' bosons, or new Higgs particles, among them). The angular observables of the decay $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$ are characterized by 6 amplitudes: $\mathcal{A}^{L,R}_{0,\|,\perp}$, related to the three helicity states of the K^{*0} and the two chiralities (L,R) of the dimuon system. The full set of 9 (CP-averaged) observables was analized by LHCb in 2013 as function of $q^2(\mu^+\mu^-)$, showing statistical agreement with the SM predictions in all of them, except in the particular observable:

$$P'_5 = \sqrt{2}\mathrm{Re}(\mathcal{A}^L_0\mathcal{A}^{L*}_\perp - \mathcal{A}^R_0\mathcal{A}^{R*}_\perp)/\sqrt{F_L(1-F_L)} \quad \text{with} \quad F_L = |\mathcal{A}^L_0|^2 + |\mathcal{A}^R_0|^2$$

which showed a local discrepancy of 3.7σ [19]. Possible interpretations of this discrepancy and consistency of all $b \to s\mu^+\mu^-$ transitions were widely discussed in the literature, and LHCb has updated the above result with the full $3fb^{-1}$ data sample from the LHC Run-1, and performed a global fit to all observables, in order to better assess the difference with respect to the SM predictions. A discrepancy in the P'_5 observable within the interval $2 < q^2 < 6\,\mathrm{GeV}^2$ was confirmed with the new data [20]. Such discrepancy has also been observed in a recent measurement by the Belle experiment [21]. Various theoretical analyses [22, 23] showed that the difference can consistently be accounted for by modifying the real part of the coefficients C_9 and C_{10} associated with the (V,A) Wilson operators in $b \to s\mu^+\mu^-$ transitions:

$$\mathcal{O}_9 \equiv (\bar{s}\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\mu) \qquad \mathcal{O}_{10} \equiv (\bar{s}\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\gamma^5\mu)$$

Because C_{10} is already being constrained by the $B_s \to \mu^+\mu^-$ branching fraction, LHCb has performed a global χ^2-fit to all angular observables and determined the best-fit value to be displaced from the SM prediction of 4.27 by $\Delta\mathrm{Re}C_9 = -1.04 \pm 0.25$ (3.4σ significance) [20]. This shift could be caused by an unexpectedly high hadronic effect that changes the SM predictions, or by contributions to the decay from non-SM vector particles.

An additional topic that has attracted a great deal of interest from various experiments, including LHCb, is lepton universality. It is well known that gauge interactions in the SM are flavor-universal at tree level, and all flavor-dependent interactions originate from the Yukawa couplings to the Higgs boson. It is actually the smallness of neutrino masses that makes lepton interactions go universal for e, μ, τ, and the only uncertainty in ratios of semileptonic decays must come from the different lepton masses. Two such ratios are particularly sensitive to physics beyond the SM, and have drawn specific recent attention from experiments. They are defined as follows:

$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} [d\Gamma(B^+ \to K^+\mu^+\mu^-/dq^2)]dq^2}{\int_{q^2_{min}}^{q^2_{max}} [d\Gamma(B^+ \to K^+e^+e^-/dq^2)]dq^2} \qquad R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\nu_\tau)}{\Gamma(B \to D^{(*)}\mu\nu_\mu)}$$

The first ratio is essentially free of all hadronic uncertainties, notably form factors, and was measured by LHCb in the interval $1 < q^2 < 6\ GeV^2$ [24], which excludes the J/ψ region and the region above $\psi(2s)$, affected by broad charmonium resonances. To cope with the very different bremsstrahlung properties of electrons and muons, LHCb takes strong advantage from the copious J/ψ production in the control channel $B^+ \to J/\psi(l^+l^-)K^+$, to cancel potential sources of systematics (assuming e, μ universality in $J/\psi \to l^+l^-$). The value $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$ is obtained, which is only 2.6σ from the SM prediction of unity within $\mathcal{O}(10^{-3})$ uncertainty, but suggestive of a possible deviation. No new measurements have been issued since then, for this important observable.

In an influential publication made by the BaBar experiment in 2013 [25], both ratios R_D and R_{D^*} were reported to have anomalously high values, exceeding the SM expectation by more than 3σ. Universality breakup by the τ lepton is particularly sensitive to new physics contributions, mainly from two Higgs doublet models (2HDM). In these models, scalar contributions $S_{L,R}$ from Wilson operators $(\bar{c}P_{L,R}b)(\bar{\tau}P_L\nu_\tau)$ with $P_{L,R} \equiv (1 \mp \gamma_5)/2$, make the helicity amplitudes H_s of $B \to D^{(*)}\tau\nu_\tau$ receive distinct extra contributions from D and D^* mesons (from their different spin), such that [25]:

$$H_s^{2HDM} \approx H_s^{SM}\left(1 + (S_R \pm S_L)\frac{q^2}{m_\tau(m_b \mp m_c)}\right)$$

In fact, the BaBar measurements appear to exclude 2HDM's where $S_L = 0$ (the so-called type II model, present in minimal Supersymmetry), in the full range of the $\tan\beta - m_{H^\pm}$ plane, but are compatible with more general 2HDM's having $|S_R + S_L| < 1.4$.

Reconstruction of τ leptons is challenging in *pp* collisions, including muonic decays, because of the presence of three final state neutrinos, and the lack of the energy constraint that is provided by the beam energy in e^+e^- machines. Yet LHCb has performed, for the first time at a hadron collider, the reconstruction of a $b \to \tau$ decay signal, leading to a measurement of R_{D^*} [26]. The three-body decay $D^{*+} \to D^0(K^-\pi^-)\pi^+$ was chosen, that produces identical reconstruction topologies in the τ and μ final states, when subject to the ratio:

$$R_{D^*} = \frac{\Gamma(\bar{B}^0 \to D^{*+}\tau^-(\mu^-\bar{\nu}_\mu\nu_\tau)\bar{\nu}_\tau)}{\Gamma(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$

where the B^0 rest-frame variables m^2_{miss}, E^*_μ, $q^2 = (p_B - p_D)^2$ are measured from the estimation of $\vec{p}_B$ achieved with charged particles. Control samples of the different backgrounds allow precise corrections to the signal yield.

The LHCb result: $\mathcal{R}(D^*) = 0.336 \pm 0.027 \pm 0.030$ [26] confirms the excess to the SM value of 0.252 ± 0.003 found by BaBar. The fit also extracts form factor parameters that appear to agree with world averages. Two further independent measurements of $\mathcal{R}(D^*)$ have been issued by the Belle experiment [27, 28], that indicate consistency with LHCb results. The world average of measurements in the $(\mathcal{R}(D^*), \mathcal{R}(D))$ plane [29] currently shows a 3.9σ deviation with respect to the SM expectation. This exciting situation is clearly calling for new measurements, both at hadron colliders and e^+e^- machines. Given the feasibility of τ reconstruction at LHCb, a wealth of new measurements are forseen using other B-hadrons, such as B_s ,B_c, and Λ_b, that will soon help understand the picture.

Other very rare decays, sensitive to new particles beyond the SM, have been recently examined by LHCb, in particular the three-body decay $B^\pm \to \pi^\pm \mu^+ \mu^-$. The ratio of its branching fraction to the more precisely measured kaon decay has been determined, in the regions $1.0 < q^2 < 6.0\,\text{GeV}^2$ and $15.0 < q^2 < 22.0\,\text{GeV}^2$ separately [30]. We quote the latter result:

$$\frac{\mathcal{B}(B^\pm \to \pi^\pm \mu^+ \mu^-)}{\mathcal{B}(B^\pm \to K^\pm \mu^+ \mu^-)} = 0.037 \pm 0.008 \pm 0.001$$

which implies a total branching fraction: $\mathcal{B}(B^\pm \to \pi^\pm \mu^+ \mu^-) = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$, with CP asymmetry: $\mathcal{A}_{CP}(B^\pm \to \pi^\pm \mu^+ \mu^-) = -0.11 \pm 0.12 \pm 0.01$ [30]. These are the most precise measurements of these observables to date. In addition, the differential branching fraction with respect to the dimuon invariant mass squared was measured for the first time [30], and found to be consistent with SM theoretical predictions [31, 32, 33]. The ratio of branching fractions above has been used for a precision determination of $|V_{td}/V_{ts}|$ where the form factor uncertainties are greatly reduced [34]. In fact, independent extractions of $|V_{td}/V_{ts}|$ from different sources, such as rare B decays, B^0 and B^0_s oscillation frequencies, and CKM unitarity, constitute a sensitive test of the SM and its possible extensions, including the Minimal Flavor Violation hypothesis (MFV) [35].

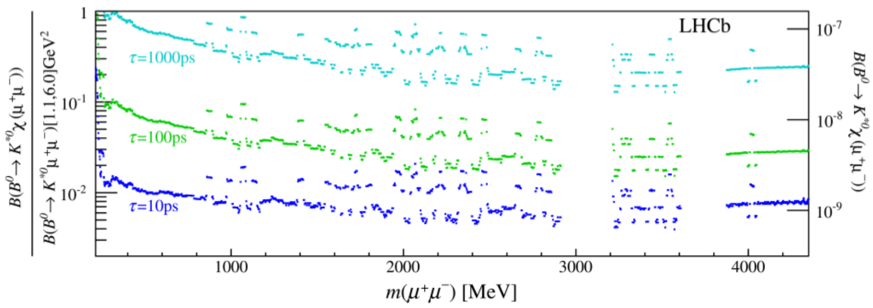
3 Hidden-sector searches

Dark matter (DM) may arise from quasi-stable particles in the Supersymmetry breaking sector at 1-10 TeV scale, that interact feably with all known particles. On the other hand, spontaneous breaking of the Peccei-Quinn symmetry, which is a U(1) rotation of the right-handed u,d-type quarks, leads to a light pseudo Nambu-Goldstone boson, the axion (χ). Its observation would provide fundamental understanding of why CP-violation is not seen in strong interactions [36]. The axion has been postulated to explain the e^+ excess observed in cosmic ray experiments [37, 38], because TeV-scale DM would decay into axions and get therefore long lived. This axion-like particle should then be light (GeV scale), in order to couple mainly to e and μ.

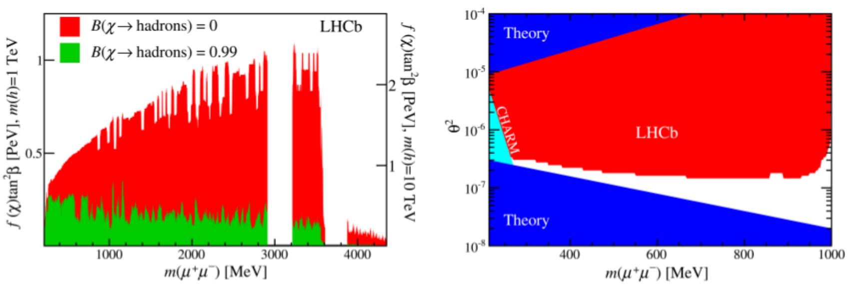
A possibility to detect the axion at high energy accelerators has been put forward [39], through its mixing with a CP-odd Higgs boson A^0 (either in Supersymmetry or in 2HDM's) with vacuum expectation values (VEV): $< H_{1,2} >= v_{1,2}$. The top quark can host this portal through flavor-changing neutral current (FCNC) loop decays such $b \to s\chi$, with amplitude [39]:

$$\mathcal{M}(b \to s\chi) = -\sin\theta \mathcal{M}(b \to sA^0) \qquad \tan\theta = n\frac{v_{EW}}{f_\chi \tan\beta} \quad \tan\beta \equiv \frac{v_1}{v_2}$$

where f_χ is the axion decay constant and $v_{EW} = \sqrt{v_1^2 + v_2^2}$, where $n = 2$ (DFSZ axion, [40, 41]) or $n = 1$ (NMSSM [42]). For large values of the axion decay constant, this particle does not decay at its production vertex, so its detection must involve wide range vertexing, combined with high $\mu^+\mu^-$ mass resolution, in order to search for narrow states in $b \to s\mu\mu$. To this end, $B^0 \to K^{*0}\mu^-\mu^-$ was chosen by LHCb.



(a) Upper limits at 95% CL for the indicated ratios in the left and right axes. Excluding the region near $2m_\mu$, the relative limits for $\tau < 10$ ps are between 0.005-0.05 and all relative limits for $\tau < 1000$ ps are less than 1.



(b) Exclusion regions at 95% C.L: (left) constraints on the axion model of Ref. [39]; (right) constraints on the mixing angle squared θ^2 of the inflaton model of Ref. [43]. The regions excluded by the theory [43] and by the CHARM experiment [46] are also shown.

Similar methodological principles, using the above decay, govern the search for a χ field responsible for an inflationary period at the early Universe, that may have generated the baryon asymmetry observed today. The portal is provided in this case by its mixing with the SM Higgs boson, and the associated inflaton particle is expected to have a mass in the range $270 \lesssim m(\chi) \lesssim 1800\,\text{MeV}$ [43]. Above the dimuon threshold, its lifetime is a strong function of the mass, and it rapidly falls down from being long-lived $(10^{-6}s)$ to the $10\,ps$ region.

The LHCb experiment has determined the product of branching fractions [44]:

$$\mathcal{B}(B^0 \to K^{*0}\chi(\mu^+\mu^-)) \equiv \mathcal{B}(B^0 \to K^{*0}\chi) \times \mathcal{B}(\chi \to \mu^+\mu^-)$$

which is measured relative to $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$, within a normalization region that is taken from prompt decays and restricted by $1.1 < m^2(\mu^+\mu^-) < 6.0\,GeV^2$. Many uncertainties cancel when doing this normalization, including some concerning hidden-sector theory.

The $m(\mu^+\mu^-)$ distribution was scanned for an excess of χ signal candidates over the expected background. The dimuon mass resolution is less than 8 MeV for the entire range, and it is as small as 2 MeV below 220 MeV. The $\chi \to \mu^+\mu^-$ decay vertex is permitted, but not required, to be displaced from the $B^0 \to K^{*0}\chi$ decay vertex. Two regions of reconstructed dimuon lifetime,

$\tau(\mu^+\mu^-)$ are defined for each mass $m(\chi)$: a prompt region $|\tau(\mu^+\mu^-)| < 3\sigma$, and a displaced region with larger distances. The lifetime resolution σ is about 0.2 ps for $m(\mu^+\mu^-) \gtrsim 250\,\text{MeV}$ and 1ps near $2m_\mu$. Narrow resonances are vetoed to avoid contamination from unassociated dimuon and K^{*0} resonances.

Upper limits on $\mathcal{B}(B^0 \to K^{*0}\chi(\mu^+\mu^-))/\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$ are set at 95% confidence level for several values of $\tau(\chi)$, as shown in Fig. 1a. As $\tau(\chi) \gtrsim 10$ ps, the limits become less stringent, since the probability of a χ boson decaying within the vertex detector (about 1m long) decreases. Fig. 1a shows exclusion regions for the DFSZ [40, 41] axion model of Ref. [39], set in the limit of large Higgs-doublet VEV's, $\tan\beta \gtrsim 3$, for charged-Higgs masses $m_H = 1\,\text{TeV}$ and $m_H = 10\,\text{TeV}$. Fig. 1b shows the results for two extreme cases: $\mathcal{B}(\chi \to \text{hadrons}) = 0$ and 0.99. While $\mathcal{B}(\chi \to \mu^+\mu^-)$ is 100 times larger when $\mathcal{B}(\chi \to \text{hadrons}) = 0$, $\tau(\chi)$ is also larger, which results in the model probing the region where the upper limits are weaker. The constraints are loose for $m(\chi) > 2m_\tau$, since the axion preferentially decays to $\tau^+\tau^-$ if kinematically allowed. Fig. 1b also shows exclusion regions for the inflaton model of Ref. [43], which only considers $m_\chi < 1$ GeV. The branching fraction into hadrons is taken directly from Ref. [45]. Constraints are placed on the mixing angle between the Higgs and the inflaton fields, θ, which exclude most of the previously allowed region.

In summary, no evidence for a narrow signal is observed, and upper limits are placed on $\mathcal{B}(B^0 \to K^{*0}\chi(\mu^+\mu^-))/\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$. This is the first dedicated search over a large mass range for a hidden-sector boson in a decay mediated by a $b \to s$ transition at leading order, and the most sensitive search to date over the entire accessible mass range. Stringent constraints are placed on theories that predict the existence of additional scalar or axial-vector fields.

4 Pentaquark states

Five-quark states of matter, beyond the simple quark model picture, have been an inspiring case of QCD models for five decades, ever since they were first conjectured by Gell-Man and Zweig in 1964 [47]. However no convincing findings were established at the onset of the LHC operation [51]. After processing a total integrated luminosity of 3 fb^{-1} of 8 TeV pp collisions at the LHC, the LHCb experiment collected a sample of over 26000 events of the three-body decay $\Lambda_b \to J/\psi(\mu^+\mu^-)K^-p$. As a consequence of the triggering on displaced vertices, of the large acceptance for low p_T dimuons, and of the 2-3 MeV mass resolution in the two-particle combinations of this final state, the background under this signal is nearly zero.

Analysis of the Dalitz plot showed that, in addition to a large number of known resonant Λ^* structures in the K^-p mass, an unexpected feature in the $J/\psi p$ mass was present. In order to investigate whether the above structure can be attributed to a reflection from the Λ^* resonances or not, a full amplitude fit was performed by LHCb to the $\Lambda_b^0 \to J/\psi K^-p$ decay [48], that included interference between two decay chains: the standard $\Lambda_b \to J/\psi\Lambda^*$, $\Lambda^* \to K^-p$, and the exotic $\Lambda_b \to P_c^+K^-$, $P_c^+ \to J/\psi p$, where P_c^+ represents a pentaquark state with given spin-parity asignment J^P. All possible known Λ^* states were tried (up to 13 different J^P combinations, with spins ranging from 1/2 to 9/2).

A significant Λ^* production recoiling against the J/ψ is observed, and the data cannot be satisfactorily described without including two Breit-Wigner shaped resonances in the $J/\psi p$ invariant mass distribution. Adding one pentaquark state improves the fit by $\Delta(-2\ln\mathcal{L}) = 14.7^2$, and the addition of a second P_c^+ state causes a further decrease of the likelihood of $\Delta(-2\ln\mathcal{L}) = 11.6^2$. The model with both P_c^+ states together has a 18.7σ significance. These structures cannot be accounted for by reflections from $J/\psi\Lambda^*$ resonances or other known sources. Interpreted as resonant states they must have minimal quark content $c\bar{c}uud$, and can therefore be called charmonium pentaquark states. The lighter state $P_c(4380)^+$ has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the heavier state $P_c(4450)^+$ has a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The best-fit asignments are $J^P = (3/2^-, 5/2^+)$, but the combinations $(5/2^-, 3/2^+)$ and $(3/2^+, 5/2^-)$ cannot be excluded. All other J^P combinations are excluded with high significance.

It is found that the interference between two opposite parity P_c^+ states is needed to explain the observed asymmetric distribution of the P_c^+ helicity angle (angle of the J/ψ in the P_c^+ rest frame), which appears to be correlated with the mass of the K^-p system. As a consequene, the opposite sign of the parity of the two states is highly significant. In addition, the analysis of the phase of the Breit-Wigner amplitudes as function of $m(J\psi p)$ shows unambiguous counterclockwise rotation, as expected for a true resonance, in the case of $P_c^+(4450)$, and it is well compatible with such behaviour in the case of $P_c^+(4380)$.

The above analysis was later confirmed by a model independent approach to the same data, with minimal assumptions about K^-p contributions [49]. It has been demostrated with more than 9σ significance that the $\Lambda_b \to J/\psi K^-p$ decays cannot be described with K^-p sources alone, and that $J/\psi p$ contributions play a dominant role in this incompatibility [49].

The above pentaquark states have been re-assessed by LHCb in the Cabibbo suppressed channel $\Lambda_b \to J/\psi\pi^-p$, with measured 8.2% relative branching fraction, in a more recent publication [50]. A full amplitude model was carried out, following the lines of the previous $\Lambda_b \to J/\psi K^-p$ amplitude model, and a significantly better description of the data was achieved by either including the two P_c^+ observed in $\Lambda_b \to J/\psi K^-p$, or the $Z_c(4200)$ state reported by Belle and LHCb. The total significance was 3.1σ when both types of exotics were included. Within the statistical and systematic errors, the $\Lambda_b \to J/\psi\pi^-p$ data are consistent with the $P_c(4380)^+$ and $P_c(4450)^+$ production rates expected from the previous observation in $\Lambda_b \to J/\psi K^-p$. Assuming $Z_c(4200)$ is negligible, a 3.3σ significance is found for both P_c^+ states together.

5 Exotic $J/\psi\phi$ states

LHCb has performed the first full amplitude analysis of a sample of 4289 ± 151 $B^+ \to J/\psi\phi K^+$ decays, with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$, obtained with the $3fb^{-1}$ integrated luminosity of the LHC Run-1 [52]. A good description of the data in the 6D phase space, composed of invariant masses and decay angles, is obtained. The data cannot be described by a model that contains only excited kaon states decaying into ϕK^+, and four structures are observed [52], each with significance over 5σ. The J^{PC} quantum numbers of these structures and their significance within the fit model are indicated in Table 1.

The K^{*+} amplitude model extracted from the data is consistent with expectations from the quark model and from the previous experimental results in such resonances. The model includes signicant contributions from a number of expected kaon excitations, including the first observation of the $K^*(1680)^+ \to \phi K^+$ transition. The J^{PC} quantum numbers of the X(4140) structure have been determined to be 1^{++}. This has a large impact on its possible interpretations, in particular ruling out 0^{++} or 2^{++} $D_s^{*+}D_s^{*-}$ molecular models. The X(4140) width is substantially larger than previously determined. As discussed in [53], the data indicate that this structure is possibly an effect due to the below-threshold $D_s^{\pm}D_s^{*\mp}$ cusp. The near coincidence

	Mass (MeV)	Width	J^{PC}	nσ
X(4140)	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^{++}	8.4 / 5.7
X(4274)	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	1^{++}	6.0 / 5.8
X(4500)	$4506.0 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^{++}	6.1 / 4.0
X(4700)	$4704.0 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^{++}	5.6 / 4.1

Table 1: Summary of resonance parameters and quantum numbers of the $J/\psi\phi$ structures, with their significance $n\sigma$ (resonance/J^{PC}).

of the $D_s^{\pm}D_s^{*\mp}$ and $J/\psi\phi$ mass thresholds provides suitable conditions for the rearrangement of $(c\bar{s})(\bar{c}s)$ to $(c\bar{c})(\bar{s}s)$.

The existence of the X(4274) structure has been established with a significance of $6.0\,\sigma$, and its quantum numbers determined to be 1^{++}. Due to interference effects, the data peak above the pole mass, underlining the importance of proper amplitude analysis. Molecular bound states or cusps cannot account for the observed J^{PC} assignment. A hybrid charmonium state would have $J^{PC} = 1^{-+}$. A discussion of its feasibility in various tetraquark models and lattice QCD calculations can be found in Refs. [52, 53]

The high $J/\psi\phi$ mass region was investigated for the first time with good sensitivity and shows very significant structures, which can be described as two 0^{++} resonances: X(4500) and X(4700). Its possible concordance with predicted virtual $D_s^{*+}D_s^{*-}$ states is also discussed in [52]. None of the observed $J/\psi\phi$ states is consistent with the state seen in the two-photon collisions by the Belle collaboration [54].

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