Inclusive Production of the X(4140) State in pp[over ¯] Collisions at D0

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We present a study of the inclusive production of the $X(4140)$ with the decay to the $J/\psi\phi$ final state in hadronic collisions. Based on 10.4 fb^{-1} of $p\overline{p}$ collision data collected by the D0 experiment at the Fermilab Tevatron collider, we report the first evidence for the prompt production of $X(4140)$ and find the fraction of $X(4140)$ events originating from b hadrons to be $f_b = 0.39 \pm 0.07\,(\text{stat}) \pm 0.10\,(\text{syst})$. The ratio of the non-prompt $X(4140)$ production rate to the B_s^0 yield in the same channel is $R = 0.19 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst})$. The values of the mass $M = 4152.5 \pm 1.7(\text{stat})^{+6.2}_{-5.4}\,(\text{syst})$ MeV and width $\Gamma = 16.3 \pm 5.6\,(\text{stat}) \pm 11.4\,(\text{syst})$ MeV are consistent with previous measurements.

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The $X(4140)$ state [1] was first seen in 2009 as a narrow structure in the $J/\psi\phi$ system near threshold. The CDF Collaboration reported the first evidence [2] for this state (then designated $Y(4140)$) in the decay $B^+ \to X(4140)K^+ \to J/\psi\phi K^+$ (charge conjugation is implied throughout this paper) and measured the invariant mass $M = 4143.0 \pm 2.9(\text{stat}) \pm 1.2\,(\text{syst})$ MeV and width $\Gamma = 11.7^{+8.3}_{-5.0}\,(\text{stat}) \pm 3.7\,(\text{syst})$ MeV. The LHCb Collaboration found no evidence for the $X(4140)$ state [3] in a 2.4 standard deviation disagreement with the CDF measurement. However, the presence of $X(4140)$ in B^+ decay was later confirmed by the CMS [4] and D0 [5] Collaborations. The BaBar Collaboration searched for resonant production in the $J/\psi\phi$ mass spectrum in $B^{+,0}$ decays and obtained a significance below 2σ, but noted that the hypothesis that the events are distributed uniformly on the Dalitz plot gives a poorer description of the data [6]. The quantum numbers of the $X(4140)$ state have not been measured. Since both the J/ψ and ϕ mesons have $I^G J^{PC} = 0^-1^{--}$, the state has positive G and C parities.

A meson decaying into a charmed quark pair might be an excited charmonium state. However, the standard nonrelativistic quark model of a single $c\overline{c}$ pair does not predict a narrow hadronic state at this mass. Also, at masses above the open-charm threshold of 3740 MeV such states are expected to decay predominantly to pairs of charmed mesons and to have a much larger width than is experimentally observed. It has been suggested that $X(4140)$ could be a molecular structure made of two charmed mesons, e.g. $(D_s, \overline{D}_s)$. Other possible states are hybrids composed of two quarks and a valence gluon ($q\overline{q}g$), four-quark combinations ($c\overline{c}s\overline{s}$), or states with higher Fock components [7]. For details see the reviews in Ref. [8] and [9] and references therein. The Belle Collaboration found no evidence for $X(4140)$ in the process $\gamma\gamma \to J/\psi\phi$ [10], making its interpretation as a hadronic molecule with spin-parity $J^P = 0^+$ or 2^+ unlikely.

In addition to $X(4140)$, the CDF Collaboration reported [2] seeing a second enhancement in the same channel, located near 4280 MeV. A similar structure is seen by the CMS Collaboration [4] at a slightly higher mass of $4316.7 \pm 3.0\,(\text{stat}) \pm 7.3\,(\text{syst})$ MeV. Belle also reports [10] a new structure at $M = 4350.6^{+4.6}_{-5.1}\,(\text{stat}) \pm 0.7\,(\text{syst})$ MeV.

In this Article we present results of a search for the $X(4140)$ resonance in the $J/\psi\phi$ system produced inclusively in $p\overline{p}$ collisions, either promptly, by pure QCD, or through weak decays of b hadrons. The measured production rates are normalized to the rate of the process $B_s^0 \to J/\psi\phi$ measured with the same dataset. The

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data sample corresponds to an integrated luminosity of 10.4 fb^{-1} collected with the D0 detector in $p\overline{p}$ collisions at 1.96 TeV at the Fermilab Tevatron collider.

The D0 detector consists of a central tracking system, calorimeters, and muon detectors [11]. The central tracking system comprises a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located inside a 1.9 T superconducting solenoidal magnet. The tracking system is designed to optimize tracking and vertexing for pseudorapidities $|\eta| < 3$, where $\eta = -\ln[\tan(\theta/2)]$, and θ is the polar angle with respect to the proton beam direction. The SMT can reconstruct the $p\overline{p}$ interaction vertex (primary vertex) for interactions with at least three tracks with a precision of 0.004 cm in the plane transverse to the beam direction. The muon detector, positioned outside the calorimeter, consists of a central muon system covering the pseudorapidity region $|\eta| < 1$ and a forward muon system covering the pseudorapidity region $1 < |\eta| < 2$. Both central and forward systems consist of a layer of drift tubes and scintillators inside 1.8 T iron toroidal magnets with two similar layers outside the toroids [12].

Events used in this analysis are collected with both single-muon and dimuon triggers. Muon triggers require a coincidence of signals in trigger elements inside and outside the toroidal magnets. Dimuon triggers in the central rapidity region require at least one muon to penetrate the toroid. In the forward region, both muons are required to penetrate the toroid.

We study a wide range of the $J/\psi\phi$ invariant mass, from threshold to 5.7 GeV, covering both the $X(4140)$ and the decay $B_s^0 \to J/\psi\phi$. Candidate events are required to include a pair of oppositely charged muons in the invariant mass range $2.9 < M(\mu^+\mu^-) < 3.3$ GeV, consistent with J/ψ decay, accompanied by two additional particles of opposite charge, assumed to be kaons, with $p_T > 0.4$ GeV and $1.011 < M(K^+K^-) < 1.030$ GeV. In the event selection, both muons are required to be detected in the muon chambers inside the toroidal magnet, and at least one of the muons is required to be also detected outside the iron toroid [12]. Each muon candidate is required to match a track found in the central tracking system, and each of the four final-state tracks is required to have at least one SMT hit and at least one CFT hit. The J/ψ signal purity and the ϕ signal purity in the selected sample are approximately 75% and 20%, respectively.

The dimuon invariant mass is constrained to the world-average J/ψ mass [1], and the four-track system is constrained to a common vertex. To reconstruct the primary vertex, tracks are selected that do not originate from the $J/\psi\phi$ candidate, and a constraint is applied to the average beam position in the transverse plane. We require $J/\psi\phi$ candidates to have $5 < p_T < 20$ GeV and rapidity $|y| < 2$.

We define the signed decay length of the $J/\psi\phi$ system, L_{xy}, to be the vector pointing from the primary vertex to the decay vertex, projected onto the direction of the transverse momentum. The distribution of L_{xy} for the selected events is shown in Fig. 1.

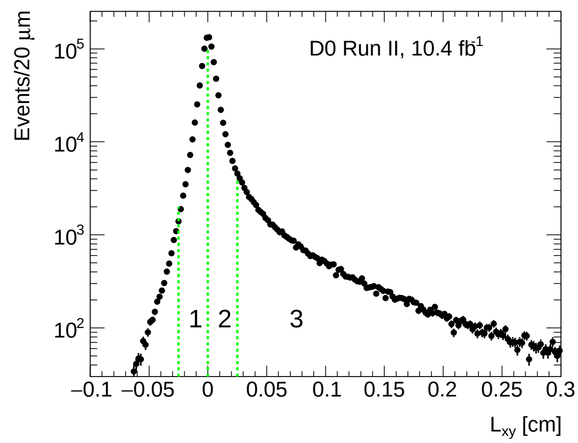

FIG. 1: Transverse decay length distribution of $J/\psi\phi$ candidates. The vertical lines define the three regions discussed in the text.

We focus on two ranges of the $J/\psi\phi$ invariant mass, $M(J/\psi\phi) < 4.36$ GeV and $4.8 < M(J/\psi\phi) < 5.7$ GeV. The low-mass range includes the $X(4140)$ state. The high-mass range includes the reference decay process, $B_s^0 \to J/\psi\phi$. Background arises primarily from non-resonant pairs in the ϕ mass window. At low L_{xy}, background comes from J/ψ mesons directly produced in $p\overline{p}$ collisions combined with random particles from the underlying event. At higher values of L_{xy}, background consists of J/ψ mesons paired with random products of b hadron decays.

We divide the data in each mass range into three independent subsamples according to the value of L_{xy}: (1) $-0.025 \leq L_{xy} < 0$ cm, (2) $0 \leq L_{xy} \leq 0.025$ cm, and (3) $L_{xy} > 0.025$ cm. Region 1 includes half of the prompt events and almost no B-decay events (the fit result shown in Table I is 37 ± 26 events). Region 2 includes the remaining half of all prompt events and a fraction of non-prompt events. The rest of the non-prompt events populate region (3). Given the average resolution of 0.006 cm in L_{xy}, we assume that the fraction of prompt events in Region 3 is negligible. We perform binned maximum likelihood fits to the distributions of the $J/\psi\phi$ invariant mass for events in the six subsamples defined above. In the fits in the B_s^0 mass region, the signal is described by a Gaussian function and background is described by a second-order Chebychev polynomial. We also allow for the presence of the decay $B^0 \to J/\psi\phi$, where we set the mass to the world-average B^0 mass, and we find no evidence of a signal. The fit for Region 3 yields 3166 ± 81 B_s^0 events.

In fitting the low mass range, we assume a signal described by an $\mathcal{S}$-wave relativistic Breit-Wigner function convolved with a Gaussian resolution of $\sigma(M) = 4$ MeV. The background is parametrized by the function $f(m) \propto m \cdot (m^2/m_{\text{thr}}^2 - 1)^{c_1} \cdot e^{-m \cdot c_2}$ where m_{thr} is the kinematic threshold, and c_1 and c_2 are free parameters. For events in the L_{xy} Region 3, we allow the signal mass and width parameters to vary. The fit yields 616 ± 170 signal events, a mass of 4152.5 ± 1.7 MeV, and a width of 16.3 ± 5.6 MeV. The statistical significance of the signal, based on the increase of the likelihood with respect to the fit with no signal, $-2\Delta \ln \mathcal{L} = 42.5$ for 3 degrees of freedom, is 5.9 standard deviations. For the fits in L_{xy} Regions 1 and 2 we set the mass and width to the Region 3 values.

The mass distributions with superimposed fits for both mass regions and for all three L_{xy} are shown in Fig. 2. The $X(4140)$ and B_s^0 yields are presented in Table I. We also show the expected number of $X(4140)$ events originating from b-hadron decays in the two low L_{xy} regions assuming that the L_{xy} distribution of the "non-prompt" $X(4140)$ is similar to that of B_s^0. For the Regions 1 and 2, we find an excess of signal events, indicating prompt production of $X(4140)$. For events in Region 2, the increase in the likelihood between the fit with a free signal yield and the fit with the expected non-prompt contribution only, $-2\Delta \ln \mathcal{L} = 23.6$, corresponds to a statistical significance of 4.9σ for the net prompt signal. The statistical significance of the total signal in this L_{xy} region is 6.2σ. For Region 1, the corresponding values of statistical significance are 3.9σ and 4.2σ. If the mass and width parameters are allowed to vary, the fit for Region 2 gives the total yield $N = 932 \pm 216$, $M = 4146.8 \pm 2.4$ MeV, and $\Gamma = 15.8 \pm 3.8$ MeV. The data in Region 1 do not yield a stable fit. Fixing the $X(4140)$ mass to 4152.5 MeV in this region, as obtained in Region 3, we fit a total yield of $N = 601 \pm 205$ and Γ of 19.8 ± 5.9 MeV. A common fit to all three regions yields $N = 2312 \pm 343$, $M = 4149.6 \pm 1.2$ MeV, and $\Gamma = 17.7 \pm 2.5$ MeV.

There are several uncertainties that may affect measurements of the $X(4140)$ yield, mass, and width, the ratio R of the yields of non-prompt $X(4140)$ and B_s^0, and the fraction f_b of all $X(4140)$ events that originate from weak decays of b hadrons.

The mass resolution of 4.0 MeV, obtained in simulations, is in agreement with an approximately linear rise with the released kinetic energy for decays with a similar topology: $\psi(2S) \to J/\psi\pi^+\pi^-$, $X(3872) \to J/\psi\pi^+\pi^-$, and the decay $B_s^0 \to J/\psi\phi$. We assign an uncertainty of ± 0.1 MeV to the resolution at the $X(4140)$ mass.

We assign an asymmetric uncertainty of 3 MeV to the $J/\psi\phi$ mass scale in the vicinity of $X(4140)$, based on the range of the mass deficit between 1 MeV and 5 MeV compared to world-average values, found in several channels with this topology. We assign the uncertainty in the signal model, taken from the range of results obtained with relativistic and nonrelativistic Breit-Wigner shapes and a relativistic P-wave Breit-Wigner shape. Simulations show the event reconstruction and selection efficiency to be independent of the $M(J/\psi\phi)$ invariant mass, with a possible variation of $\pm 10\%$ [5]. The possible variation of the efficiency within the $X(4140)$ mass range affects the mass, width, and yield of the signal. We have assessed the effects of the fitting procedure and background size and shape by lowering the upper edge to 4.28 GeV and raising it to 4.4 GeV, and by using 8-MeV instead of 10-MeV bins. For each of the measured quantities we assign a symmetric uncertainty equal to one half of the difference between the extreme results.

Some of the single-muon triggers include a trigger term requiring a presence of tracks with non-zero impact parameter. Events recorded solely by such triggers constitute approximately 5% of all events. Assuming that such triggers are 100% efficient for events originating from weak decays of b hadrons and reject all prompt events, we apply a 5% correction to the prompt yield. We assign a systematic uncertainty of $\pm 5\%$ on the fraction f_b due to this correction. Finally, our assumption of the equality of the relative rates in regions (1) – (3) for the non-prompt $X(4140)$ and B_s^0 is based on expectation of the equality of the average lifetime of b-hadron parents of the $X(4140)$ and that of the B_s^0 in the $J/\psi\phi$ channel. The world-average of the B_s^0 lifetime is 6% lower than the lifetime averaged over all b hadron species [1]. We assign an asymmetric uncertainty in the ratio R and the fraction f_b based on this difference. The systematic uncertainties are summarized in Table II.

We test the stability of the results to the event selection by changing the ϕ mass window to $1.012 < M(K^+K^-) < 1.029$ GeV. As additional cross-checks, we perform fits to subsamples corresponding to the transverse momentum ranges $5 < p_T < 10$ GeV and $10 < p_T < 20$ GeV; to early and late data-taking periods; and to events in the central ($|y| < 1$) and forward rapidity regions. In each case, the background shape in the two subsamples is well described by the same functional form although it requires different values of the parameters. In all cases the sums of the resulting signal yields agree with the total yield within a few events.

Our measured values of the mass and width of the $X(4140)$ state are compared with earlier measurements in Table III. The ratio of the $X(4140)$ to B_s^0 yield for events with $L_{xy} > 0.025$ cm is $R = 0.19 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst})$. After correcting for the efficiency of this L_{xy} cut and for the trigger bias, we find the fraction of $X(4140)$ events originating from b hadrons to be $f_b = 0.39 \pm 0.07\,(\text{stat}) \pm 0.10\,(\text{syst})$. The yield for the $X(4140)$ state at $L_{xy} > 0.025$ cm can also be compared with the yield of 52 ± 19 events of $X(4140)$ from the decay process $B^+ \to J/\psi\phi K^+$ obtained by D0 [5] for the same data set. After correcting for a factor of 2.5 ± 0.5 for the efficiency of the full reconstruction of the B^+ decay and lower kaon p_T threshold, we expect the yield from the B^+ decay to be $\approx 130 \pm 60$ events in this analysis. Our observed yield of 616 ± 170 events exceeds this estimate suggesting that decays of b hadrons other than the decay $B^+ \to J/\psi\phi K^+$ contribute to the non-prompt production of $X(4140)$.

The $J/\psi\phi$ invariant mass distributions presented in Fig. 2 show no evidence for states in the mass region $4250 < M(J/\psi\phi) < 4375$ MeV. Fits allowing for the states reported by CDF, CMS, and Belle, at $L_{xy} >$

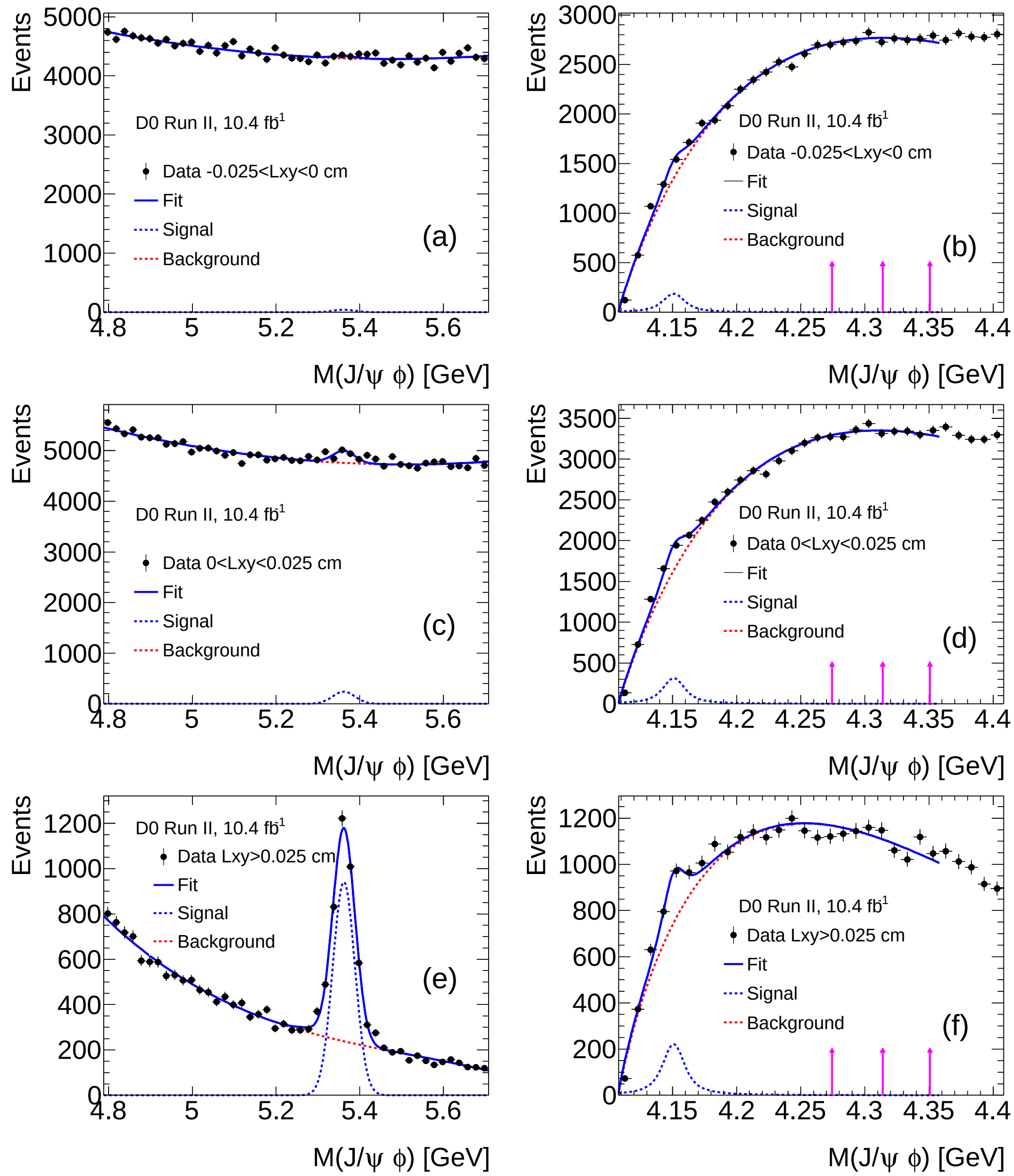

FIG. 2: (color online) Invariant mass distribution of $J/\psi\phi$ candidates in the mass window around (left) B_s^0 and (right) $X(4140)$, for events with (a,b) $-0.025 < L_{xy} < 0$ cm, (c,d) $0 < L_{xy} < 0.025$ cm and (e,f) $L_{xy} > 0.025$ cm. The arrows indicate the structures seen by CDF [2], CMS [4], and Belle [10]. The signal and background models are described in the text.

TABLE I: Summary of event yields in three L_{xy} regions and their sum for B_s^0 and $X(4140)$. For Regions 1 and 2 the mass of $X(4140)$ is assumed to be 4152.5 MeV and the width is taken to be 16.3 MeV. Also shown are the deduced yields for the non-prompt and prompt production of $X(4140)$. The uncertainties are statistical.

Parent	$-0.025 < L_{xy} < 0$ cm	$0 < L_{xy} < 0.025$ cm	$L_{xy} > 0.025$ cm	Sum
B_s^0	191 ± 143	804 ± 169	3166 ± 81	4161 ± 236
$X(4140)$	511 ± 120	837 ± 135	616 ± 170	1964 ± 248
$X(4140)$ non-prompt	37 ± 26	156 ± 54	616 ± 170	809 ± 175
$X(4140)$ prompt	474 ± 123	681 ± 149	$\equiv 0$	1155 ± 193

TABLE II: Summary of systematic uncertainties.

Source	Mass (MeV)	Width (MeV)	Rate non-prompt (%)	Rate prompt (%)
Mass resolution	± 0.1	± 0.2	± 1	± 1
Mass bias	$^{+3}_{-0}$	–	–	–
Efficiency	± 4	± 5	± 4	± 4
Signal model	± 1	± 2.7	± 13	± 15
Fitting range	± 3	± 7.0	± 20	± 6
Bin size	± 1.6	± 7.0	± 25	± 10
Trigger bias	–	–	–	± 5
Mean lifetime	–	–	-1.5	$+1.5$
Total	$^{+6.2}_{-5.4}$	± 11.4	± 35	± 19

-0.025 cm, yield 351 ± 268, -283 ± 468, and -382 ± 247 events, respectively. Using the CL_s method [13], we obtain the 95% upper limits of 808, 750, and 296 events for the three states. In this upper limit calculation we did not account for systematic uncertainties as they were checked to have a negligible impact. The corresponding 95% upper limits on the rate ratios relative to the total yield of the $X(4140)$ state are 0.48, 0.42, and 0.18, where the statistical and systematic uncertainties on the measured yield of $X(4140)$ are taken into account.

In summary, we have carried out the first search for inclusive production of the state $X(4140)$ in hadronic collisions. We find strong evidence for its direct, prompt production, and observe its production in weak decays of b hadrons with a rate exceeding the expected rate for the known decay $B^+ \to J/\psi\phi K^+$. The significance of the prompt production, including systematic uncertainties, is 4.7σ. This is the first evidence for the prompt production of $X(4140)$. The significance of the non-prompt production, including systematic uncertainties, is 5.6σ. The non-prompt production rate of $X(4140)$ relative to B_s^0 observed in the same final state is $R = 0.19 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst})$. Assuming a relativistic Breit-Wigner line shape, we measure the mass and width of the $X(4140)$ state to be $M = 4152.5 \pm 1.7(\text{stat})^{+6.2}_{-5.4}\,(\text{syst})$ MeV and width $\Gamma = 16.3 \pm 5.6\,(\text{stat}) \pm 11.4\,(\text{syst})$ MeV, consistent with previous measurements [2, 4, 5].

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[1] K. A. Olive *et al.*, "Review of Particle Physics", Chin. Phys. C **38**, 090001 (2014).

[2] T. Aaltonen *et al.* (CDF Collaboration), "Evidence for a Narrow Near-Threshold Structure in the $J/\psi\phi$ Mass Spectrum in $B^+ \to J/\psi\phi K^+$ Decays", Phys. Rev. Lett. **102**, 242002 (2009).

[3] R. Aaij *et al.* (LHCb Collaboration), "Search for the $X(4140)$ state in B^+ to $J/\psi\phi K^+$ decays", Phys. Rev. D **85**, 091103 (2012).

[4] S. Chatrchyan *et al.* (CMS Collaboration), "Observation of a peaking structure in the $J/\psi\phi$ spectrum of $B^+ \to J/\psi\phi K^+$ decays", Phys. Lett. B **734**, 261 (2014).

[5] V. M. Abazov *et al.* (D0 Collaboration), "Search for the $X(4140)$ state in $B^+ \to J/\psi\phi K^+$ decays with the D0 detector", Phys. Rev. D **89**, 012004 (2014).

[6] J. P Lees *et al.* (BaBar Collaboration), "Study of $B^{+,0} \to J/\psi K^+ K^- K^{+,0}$ and search for $B^0 \to J/\psi\phi$ at BABAR", Phys. Rev. D **91**, 012003 (2015).

[7] Ya. I. Azimov, "Unexpected Mesons X, Y, Z... (tetraquarks? hadron molecules?...)", arXiv:1502.01279, to be published in Nucl. Phys. B Proceedings Supplement.

[8] N. Drenska, R. Faccini, F. Piccinini, A. Polosa, F. Renga and C. Sabelli, "New Hadronic Spectroscopy," Riv.

TABLE III: Summary of $X(4140)$ measurements.

Experiment	Process	Mass (MeV)	Width (MeV)
CDF [2]	$B^+ \to J/\psi\phi K^+$	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$
CMS [4]	$B^+ \to J/\psi\phi K^+$	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$
D0 [5]	$B^+ \to J/\psi\phi K^+$	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+3.0}_{-8.0}$
D0 (this work)	$\overline{p}p \to J/\psi\phi + \text{anything}$	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$

Nuovo Cim. **033**, 633 (2010).

[9] K. Yi, “Experimental Review of Structures in the $J/\psi\phi$ Mass Spectrum”, Int. J. Mod. Phys. A **28**, 1330030 (2013).

[10] C. Shen *et al.* (Belle Collaboration), “Evidence for a new resonance and search for the $Y(4140)$ in $\gamma\gamma \to \phi J/\psi$”, Phys. Rev. Lett. **104**, 112004 (2010).

[11] V. M. Abazov *et al.* (D0 Collaboration), “The Upgraded D0 detector”, Nucl. Instrum. Methods Phys. Res. A **565**, 463 (2006).

[12] V. M. Abazov *et al.* (D0 Collaboration), “Muon reconstruction and identification with the Run II D0 detector”, Nucl. Instrum. Methods Phys. Res. A **737**, 281 (2014).

[13] T. Junk, “Confidence level computation for combining searches with small statistics”, Nucl. Instum. Methods Phys. Res., A **434**, 435 (1999); A. L. Read, “Presentation of search results: the ‘CL_s technique”, J. Phys. G **28**, 2693(2002). We explicitly use eq. 38.73 of K. A. Olive *et al.*, Ref. [1].