Available on CMS information server

CMS CR -2020/149

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

25 September 2020 (v6, 17 December 2020)

Recent CMS results on exotic hadron states

Ivan Lilienberg for the CMS Collaboration

Abstract

Recent CMS results on exotic states, including X(3872), and searches for new states decaying into $\Upsilon(1S)\mu^+\mu^-$ are presented. The analyses are based on data collected by the CMS experiment in pp collisions at $\sqrt{s} = 13$ TeV.

Presented at *ICPPA-2020 5th International Conference on Particle Physics and Astrophysics*

Recent CMS results on exotic hadron states

I Lilienberg on behalf of the CMS Collaboration
Moscow Institute of Physics and Technology (MIPT), Moscow, Russia
E-mail: lilienberg.iv@mipt.ru

Abstract. Recent CMS results on exotic states, including $X(3872)$, and searches for new states decaying into $\Upsilon(1S)\mu^+\mu^-$ are presented. The analyses are based on data collected by the CMS experiment in pp collisions at $\sqrt{s} = 13$ TeV.

Published in J. Phys.: Conf. Ser. ***1690*** *012150 (2020), doi: 10.1088/1742-6596/1690/1/012150*

1. Introduction

In this proceeding we present the new results of the CMS experiment [1] at the CERN LHC concerning the study of exotic hadrons. In particular, we report the first observation of the $B_s^0 \to X(3872)\phi$ process and the measurement of its branching fraction relative to the $B^+ \to X(3872)K^+$ decay [2]. Measurement of the $\Upsilon(1S)$ pair production cross section, determination of the double-parton scattering fraction in $\Upsilon(1S)\Upsilon(1S)$ production and search for heavy resonances in $\Upsilon(1S)\mu^+\mu^-$ final state are also performed [3]. These results provide important information about quarkonium production mechanism in pp collisions, which is essential for quantum chromodynamics models.

2. First observation of the $B_s^0 \to X(3872)\phi$ decay

Despite 17 years of experimental and theoretical research, the nature of $X(3872)$ remains unclear. The information about its production mechanism is important for understanding its structure. The CMS collaboration previously reported the study of $X(3872)$ production in pp collisions [4]. The fraction of nonprompt production depending on $X(3872)$ transverse momentum was measured. $X(3872)$ has never been found in B_s^0 decays before. Observation of its new production mode provides important information for understanding its nature.

2.1. Data sample and event selection

This result is obtained on CMS data taken in 2016-2018 years corresponding to 140 fb^{-1}. B_s^0 is reconstructed via its decay to $X(3872)\phi$, where $X(3872) \to J/\psi\pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$ processes are used to reconstruct the intermediate states. A normalization decay $B_s^0 \to \psi(2S)\phi$ with $\psi(2S) \to J/\psi\pi^+\pi^-$ is used to cancel the majority of systematic uncertainties in the ratio of the branching fractions.

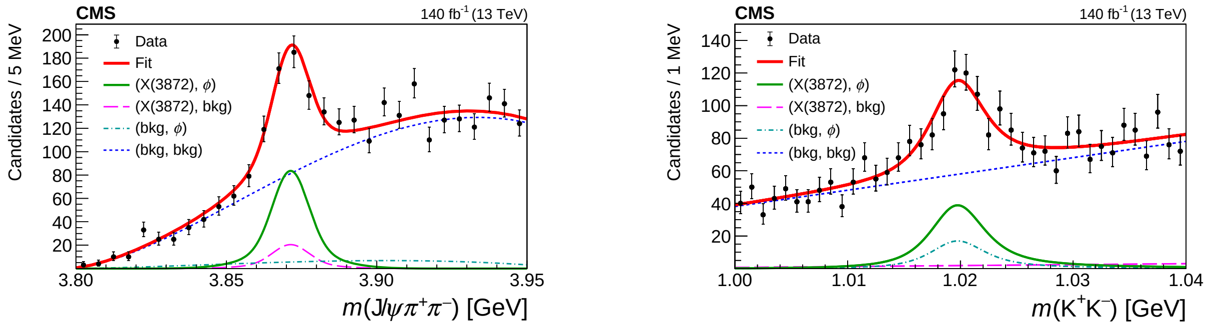
A pair of soft muons matching trigger requirements and having invariant mass consistent with J/ψ meson standard mass value [5] is selected. These muons together with four high-purity tracks are fitted to a common vertex with a constraint on $\mu^+\mu^-$ invariant mass. Pion or kaon mass assignment is done according to the following restrictions on invariant masses:

- $3.60\ \text{GeV} < M_{J/\psi\pi^+\pi^-} < 3.95\ \text{GeV}$;
- $1.00\ \text{GeV} < M_{K^+K^-} < 1.04\ \text{GeV}$;
- $5.32\ \text{GeV} < M_{J/\psi\pi^+\pi^-K^+K^-} < 5.42\ \text{GeV}$.

If a candidate passes these requirements in more than one combination, it is rejected. Other selection criteria, including the B_s^0 transverse momentum, B_s^0 the vertex fit probability, minimum and maximum track transverse momenta, the B_s^0 decay length significance, cosine of angle between the B_s^0 momentum and a vector from the primary vertex to the B_s^0 vertex, $\pi^+\pi^-$ invariant mass, are optimized using the Punzi figure of merit [6].

2.2. Signal yield determination

Two-dimensional (2D) maximum-likelihood fit of $J/\psi\pi^+\pi^-$ versus K^+K^- invariant mass distribution is performed to measure the number of signal events. The corresponding one-dimensional distributions and fit projections are presented in Fig. 1. The number of signal events is estimated to be $N_{X(3872)} = 299 \pm 39$. The same procedure for normalization channel gives signal yield $N_{\psi(2S)} = 15359 \pm 171$.



a) b)

Figure 1. Invariant mass distributions of $J/\psi\pi^+\pi^-$ (a) and K^+K^- (b) together with the projections of the 2D fit. The fitting functions are described in details in [2].

Then $J/\psi\pi^+\pi^-K^+K^-$ invariant mass distribution is obtained by sPlot technique [7] from 2D distribution of $J/\psi\pi^+\pi^-$ versus K^+K^- invariant mass. The result is plotted on Fig. 2. The statistical significance of the B_s^0 signal exceeds 10 standard deviations.

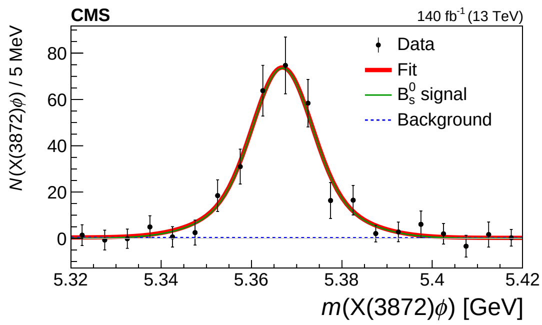


Figure 2. Invariant mass distribution of the $X(3872)\phi$ state with sibtracted background and its fit components. The fit functions are described in details in [2].

2.3. Branching ratio measurement
The obtained numbers of signal events are used to calculate the ratio

$$R = \frac{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{X(3872)}\phi) \times \mathcal{B}(\mathrm{X(3872)} \to \mathrm{J}/\psi\pi^+\pi^-)}{\mathcal{B}(\mathrm{B_s^0} \to \psi(2\mathrm{S})\phi) \times \mathcal{B}(\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-)} = \frac{N_{\mathrm{X(3872)}}}{N_{\psi(2\mathrm{S})}} \times \frac{\varepsilon_{\psi(2\mathrm{S})}}{\varepsilon_{\mathrm{X(3872)}}}, \tag{1}$$

where ε is the reconstruction efficiency of the corresponding process estimated on simulated signals. Accounting for systematic uncertainties from fit model selection, limited simulation sample and combinatorial $\mathrm{B_s^0}$ one obtains $R = (2.21 \pm 0.29 \pm 0.17)\%$. Accounting for known $\mathcal{B}(\mathrm{B_s^0} \to \psi(2\mathrm{S})\phi) \times \mathcal{B}(\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-))$ and $\mathcal{B}(\mathrm{B^+} \to \mathrm{X(3872)K^+}) \times \mathcal{B}(\mathrm{X(3872)} \to \mathrm{J}/\psi\pi^+\pi^-)$ we get

$$\frac{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{X(3872)}\phi)}{\mathcal{B}(\mathrm{B^+} \to \mathrm{X(3872)K^+})} = 0.482 \pm 0.063\ (\mathrm{stat})\ \pm 0.037\ (\mathrm{syst})\ \pm 0.070\ (\mathcal{B}), \tag{2}$$

where the third uncertaingy originates from branching fractions products uncertainties. This value is lower than the corresponding ratio for the decays to $\psi(2\mathrm{S})$. This discrepancy can be explained in terms of tetraquark $\mathrm{X(3872)}$ model [8].

3. Study of $\Upsilon(1\mathrm{S})\mu^+\mu^-$ state

In this part the study of $\Upsilon(1\mathrm{S})\mu^+\mu^-$ production mechanisms in pp collisions is described. We report the measurement of $\Upsilon(1\mathrm{S})$ pair production cross section and determination of double-parton scattering fraction within $\Upsilon(1\mathrm{S})$ rapidity range $|y| < 2.0$. A search for exotic states decaying to $\Upsilon(1\mathrm{S})\mu^+\mu^-$ is also performed. This research extends mass and angular area studied by the the LHCb Collaboration [9] in the search for $\mathrm{bb\overline{b}\overline{b}}$ tetraquarks.

3.1. Data sample and event reconstruction
This analysis is performed using the data collected by the CMS experiment in 2016 corresponding to 35.9 fb^{-1} integrated luminosity. The selection criteria are determined using the simulated samples of heavy resonances decaying to $\Upsilon(1\mathrm{S})\mu^+\mu^-$ with masses 14–26 GeV.

We require four muons to be separated from each other, fitted to a common vertex with a maximum χ^2 probability. At least three of them must be associated with trigger-level objects. Two oppositely charged muons are required to have invariant mass consistent with $\Upsilon(1\mathrm{S})$ world-average mass. The alternatively paired $\mu^+\mu^-$ combinations must not have invariant mass close to known J/ψ mass.

3.2. $\Upsilon(1S)$ pair production cross section measurement
The fiducial production cross section is measured using the formula

$$\sigma = \frac{N^{\mathrm{corr}}}{\mathcal{L}\mathcal{B}^2(\Upsilon(1\mathrm{S})\mu^+\mu^-)}, \tag{3}$$

where N^{corr} is the signal yield corrected by reconstruction efficiencies and detector acceptance, $\mathcal{L}$ refers to integrated luminosity. Each event is assigned a weight according to the probability of passing kinematic selection, vertex fit and trigger requirements. These weights are estimated using the simulated data.

After the selection we obtain distributions on two pairs of $\mu^+\mu^-$ invariant masses. 2D fit is performed on the observed distribution. The resulting projections of the 2D fit are presented in Fig. 3.

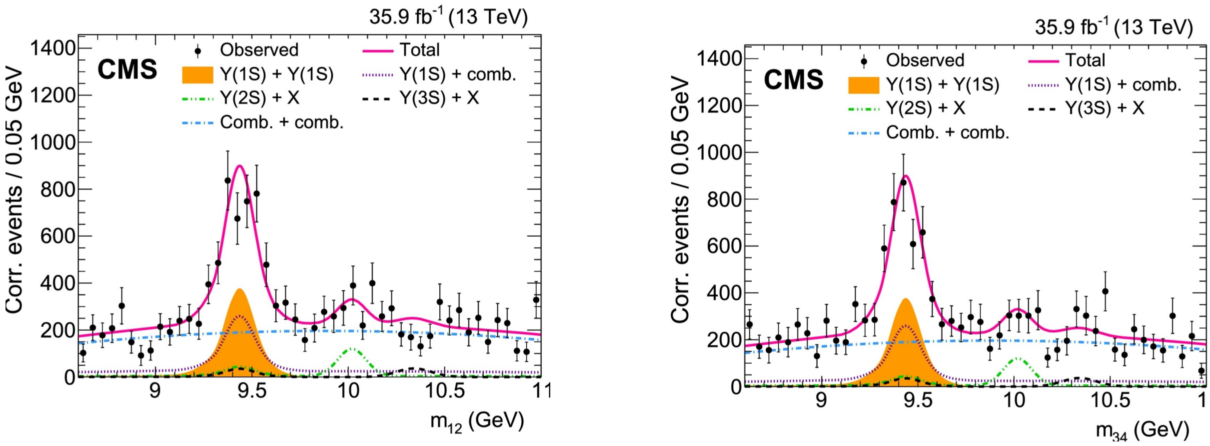


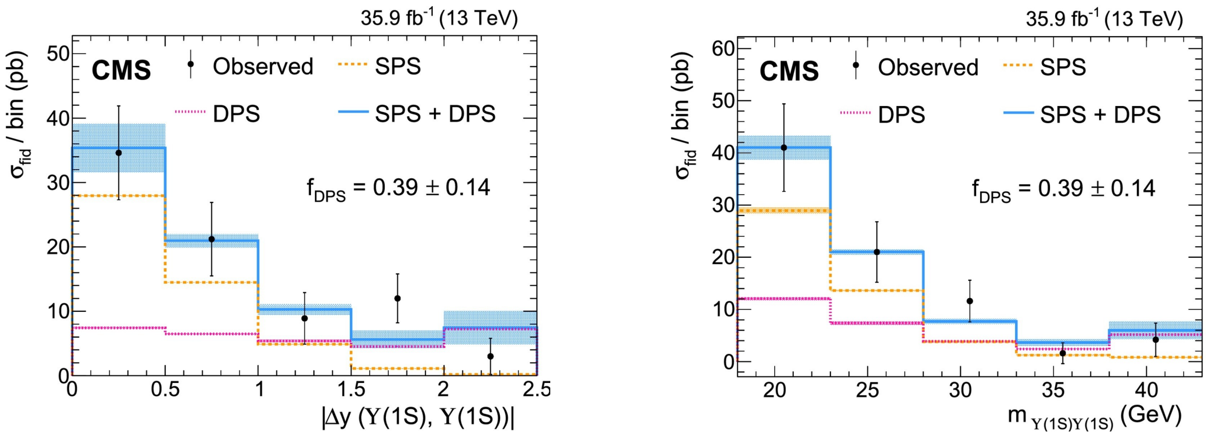
Figure 3. Invariant mass distributions of two $\mu^+\mu^-$ pairs together with the results of the 2D fit. The details of fitting procedure can be found in [3].

This fit gives 111 ± 16 signal events of $\Upsilon(1\mathrm{S})$ pair production. Including the systematic uncertainties related to luminosity uncertainty, muon reconstruction, fit model, N^{corr} calculation method and $\Upsilon(1\mathrm{S}) \rightarrow \mu^+\mu^-$ branching fraction uncertainty,the cross section is measured to be

$$\sigma = 79 \pm 11 \text{ (stat) } \pm 6 \text{ (syst) } \pm 3 \ (\mathcal{B}) \text{ pb}. \tag{4}$$

In this analysis we assume $\Upsilon(1\mathrm{S})$ are produced unpolarized. Possible polarization effects may shift the obtained σ from -60% to +25%.

$\Upsilon(1\mathrm{S})$ pairs produced in single-parton scattering and double-parton scattering have different distributions of $\Upsilon(1\mathrm{S})\Upsilon(1\mathrm{S})$ invariant mass and rapidity difference $|\Delta y(\Upsilon(1\mathrm{S})_1, \Upsilon(1\mathrm{S})_2)|$. The distributions obtained in data are compared with the simulation for single-parton scattering and double-parton scattering on Fig. 4. The double-parton scattering fraction $f = (39 \pm 14)\%$ is determined using this comparison.

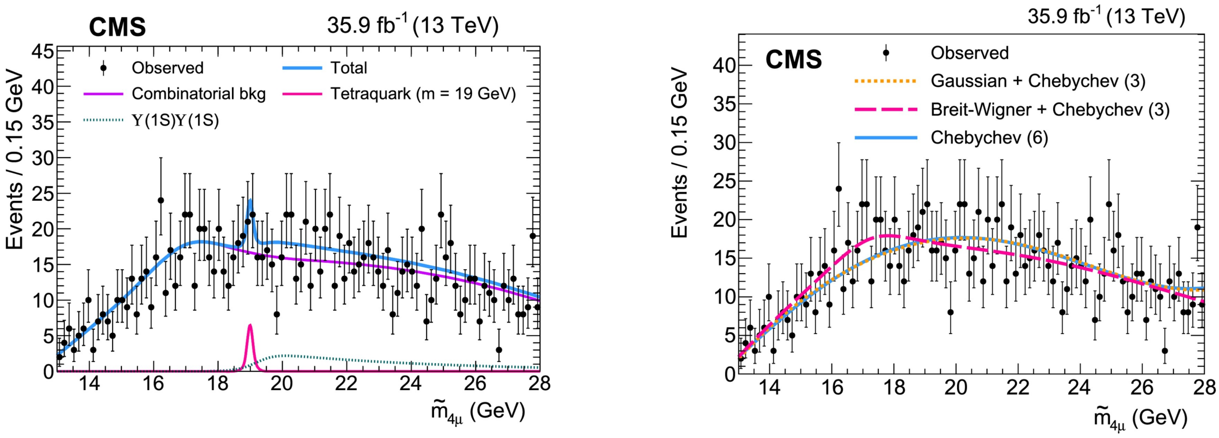


a) b)

Figure 4. Fiducial cross section shown in bins of rapidity difference (a) and $\Upsilon(1\mathrm{S})\Upsilon(1\mathrm{S})$ invariant mass (b) compared to predicted distributions from the different production mechanisms. Details are described in [3].

3.3. Search for exotic states

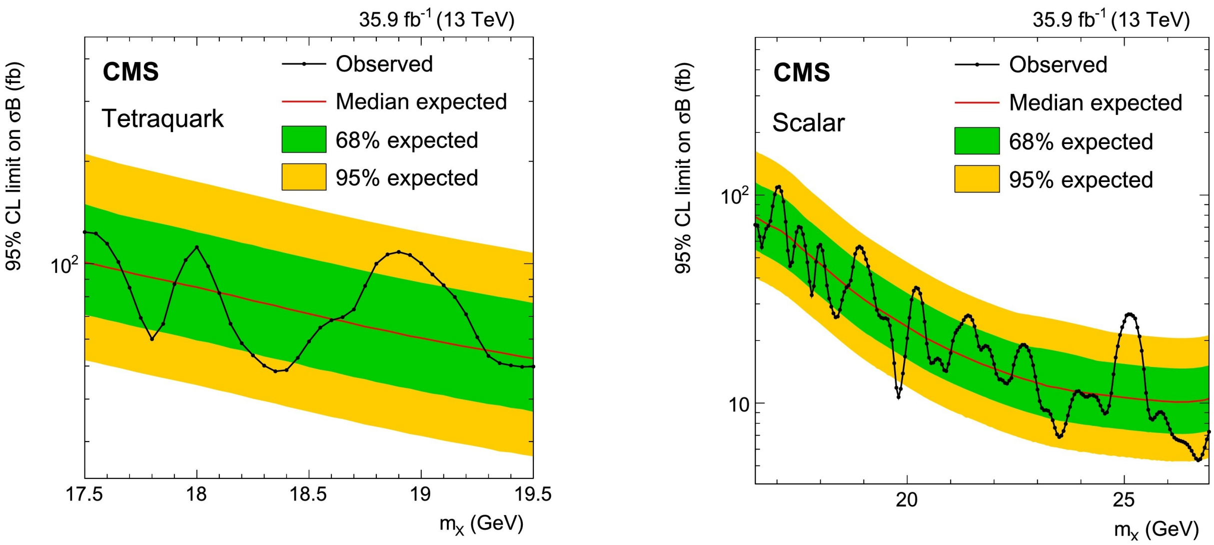
We perform a search for exotic hadrons in 4μ final state. To improve the signal resolution, the four muon invariant mass is corrected by $\Upsilon(1S)$ known mass: $\tilde{m}_{4\mu} = m_{4\mu} - m_{\mu^+\mu^-} + m_{\Upsilon(1S)}$. The resulting distribution is presented in Fig. 5.



a) b)

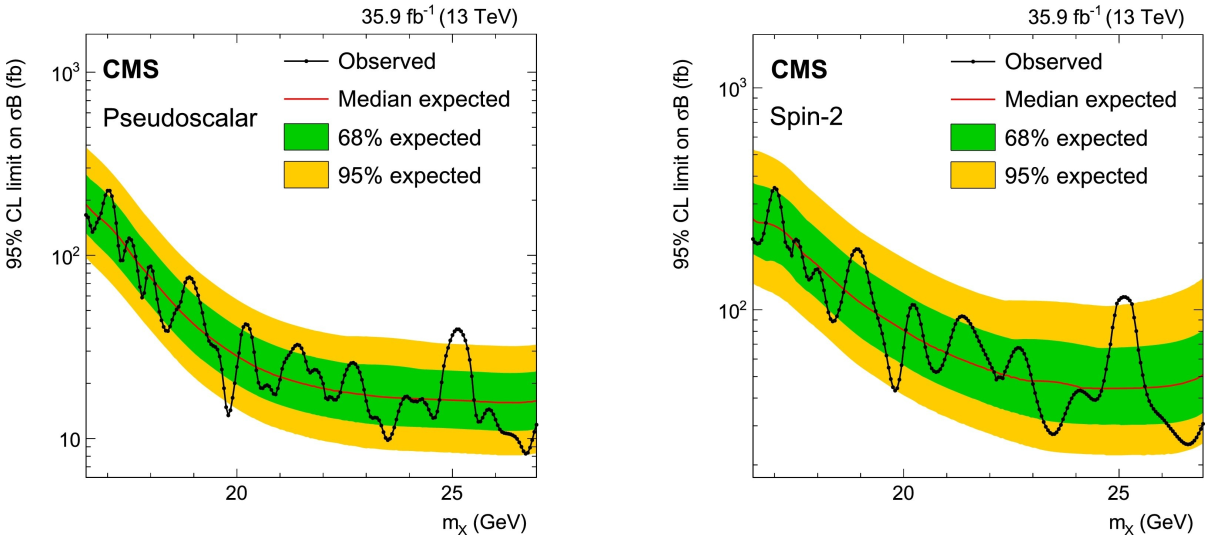
Figure 5. Invariant mass distribution $\tilde{m}_{4\mu}$ on real data in the signal (a) and the control region of vertex fit probability 10^{-10}–10^{-3} (b). An example of a narrow resonance with the statistical significance of one standard deviation is shown. The details are discussed in [3].

No significant discrepancy from pure background hypothesis is seen. The greatest deviation at 25.1 GeV has a local statistical significance of 2.4 standard deviations for the scalar hypothesis. Upper limits are set on the product of the cross section and branching fraction for different models of possible resonances. The corresponding distributions are presented in Fig. 6 and 7.



a) b)

Figure 6. Expected production cross section for tetraquark (a)) and scalar (b)) resonance models compared to one obtained on data. Details can be found in [3].



a) b)

Figure 7. Expected production cross section for pseudoscalar (a)) and spin-2 (b)) resonance models compared to one obtained on data. Details can be found in [3].

4. Results and conclusion

This proceeding summarizes recent CMS results on exotic hadrons studies. The $B_s^0 \to X(3872)\phi$ decay is observed for the first time and the ratio

$$\frac{\mathcal{B}(B_s^0 \to X(3872)\phi)}{\mathcal{B}(B^+ \to X(3872)K^+)} = 0.482 \pm 0.063 \pm 0.037 \pm 0.070 \quad (5)$$

is measured. The obtained value differs from the predictions for pure charmonium state. The $\Upsilon(1S)$ pair production cross section is $\sigma = 79 \pm 11$ (stat) ± 6 (syst) ± 3 ($\mathcal{B}$) pb and the double-parton scattering fraction $f = (39 \pm 14)\%$ is measured. No significant signal is found in the search for exotic states in $\Upsilon(1S)\mu^+\mu^-$ combination.

Acknowledgements

We acknowledge the ICPPA-2020 organizing committee for the opportunity to participate in the conference and to present our recent results at a time when the possibility of communication was strongly limited.

References

[1] Chatrchyan S *et al.* (CMS collaboration) 2008 *JINST* **3** S08004
[2] Sirunyan A M *et al.* (CMS collaboration) 2020 Accepted by PRL (*Preprint* `2005.04764`)
[3] Sirunyan A M *et al.* (CMS collaboration) 2020 *Phys. Lett. B* **808** 135578 (*Preprint* `2002.06393`)
[4] Chatrchyan S *et al.* (CMS collaboration) 2013 *JHEP* **2013** 154 (*Preprint* `1302.3968`)
[5] Zyla P M *et al.* (Particle Data Group) 2020 *PTEP* **2020** 083C01
[6] Punzi G 2003 (*Preprint* `physics/0308063`)
[7] Pivk M and Diberder F R L 2005 *Nucl. Instr. Meth. A* **555** 356369 (*Preprint* `physics/0402083`)
[8] Maiani L, Polosa A D and Riquer V 2020 *Phys. Rev. D* **102** (*Preprint* `2005.08764`)
[9] Aaij R *et al.* 2018 *JHEP* **2018** (*Preprint* `1806.09707`)