



Associated production of prompt J/ψ and Υ mesons in pp collisions at $\sqrt{s} = 13 \text{ TeV}$

LHCb collaboration[†]

Abstract

The associated production of prompt J/ψ and Υ mesons in pp collisions at a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ is studied using LHCb data, corresponding to an integrated luminosity of 4 fb^{-1} . The measurement is performed for J/ψ (Υ) mesons with a transverse momentum $p_T < 10$ (30) GeV/c in the rapidity range $2.0 < y < 4.5$. In this kinematic range, the cross-section of the associated production of prompt J/ψ and $\Upsilon(1S)$ mesons is measured to be $133 \pm 22 \pm 7 \pm 3 \text{ pb}$, with a significance of 7.9σ , and that of prompt J/ψ and $\Upsilon(2S)$ mesons to be $76 \pm 21 \pm 4 \pm 7 \text{ pb}$, with a significance of 4.9σ . The first uncertainty is statistical, the second systematic, and the third due to uncertainties on the used branching fractions. This is the first observation of the associated production of J/ψ and $\Upsilon(1S)$ in proton-proton collisions. Differential cross-sections are measured as functions of variables that are sensitive to kinematic correlations between the J/ψ and $\Upsilon(1S)$ mesons. The effective cross-sections of the associated production of prompt J/ψ and Υ mesons are obtained and found to be compatible with measurements using other particle productions.

Published in JHEP 08 (2023) 093

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[†]Authors are listed at the end of this paper.

1 Introduction

Hadroproduction of heavy quarkonia has been extensively studied to probe quantum chromodynamics (QCD) [1]. Various theoretical treatments have been proposed that model the production of quark-antiquark pairs $Q\bar{Q}$ and their subsequent hadronisation into quarkonia. Promising approaches include the colour-singlet model (CSM) [2–4] and the non-relativistic QCD (NRQCD) framework [5]. The CSM considers only the colour-singlet intermediate $Q\bar{Q}$ state with the same J^{PC} quantum numbers as the final-state quarkonium, while the NRQCD framework considers both colour-singlet and colour-octet $Q\bar{Q}$ states. The NRQCD framework assumes process-independent long-distance matrix elements (LDMEs) to describe the transition probabilities from the intermediate $Q\bar{Q}$ states to the final-state quarkonium. Quarkonium hadroproduction cross-sections as a function of the transverse momentum (p_T) are successfully described by NRQCD calculations [6–11]. However, there are still challenges in providing a coherent description of all heavy quarkonium hadroproduction data, *e.g.* there is no unified description of the cross-sections and polarisation of the vector quarkonium states; and the inconsistency between the LDMEs of the η_c and J/ψ states—which are related to the heavy-quark spin symmetry—remains to be understood [12–19].

In hadron collisions, a pair of heavy quarkonia can be produced through either single-parton scattering (SPS), or double-parton scattering (DPS), depending on the number of parton-parton scatterings in the process. A representative Feynman diagram of each process is presented in Fig. 1. In the SPS process, two quarkonia are produced in the same parton-parton interaction, leading to kinematic correlations between them. In contrast, two parton-parton interactions occur simultaneously and independently in the DPS process, producing two quarkonia with weak kinematic correlations. While the SPS process provides new insights into the heavy quarkonium production mechanism according to the left Feynman diagram in Fig. 1 [20–23], the DPS process probes the parton distribution function inside the colliding hadrons and provides valuable information on the hadronic wave functions describing correlations among partons [1]. Taking the J/ψ and Υ associated production (referred to as J/ψ – Υ production throughout) as an example¹, the DPS cross-section $\sigma_{\text{DPS}}(J/\psi\text{--}\Upsilon)$ can be estimated from the J/ψ and Υ cross-sections,

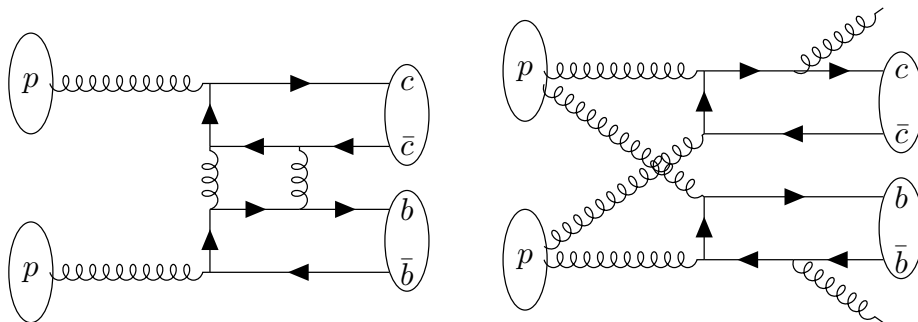


Figure 1: Representative Feynman diagrams of the (left) SPS and the (right) DPS process with colour-singlet LDMEs.

¹Throughout the paper, Υ represents $\Upsilon(1S)$, $\Upsilon(2S)$, or $\Upsilon(3S)$.

$\sigma(J/\psi)$ and $\sigma(\Upsilon)$, as

$$\sigma_{\text{DPS}}(J/\psi\text{-}\Upsilon) = \frac{\sigma(J/\psi) \times \sigma(\Upsilon)}{\sigma_{\text{eff}}}, \quad (1)$$

where σ_{eff} is the effective cross-section parameter encoding the transverse overlapping region between partons in the protons [24–26]. The effective cross-section is expected to be universal based on the assumptions that the two sets of colliding partons are uncorrelated and the longitudinal and transverse components of the parton distribution function factorise. Measurements in different processes for the effective cross-section are mostly within the range of 5 to 35 mb [27, 28]. Further study is needed to test its universality [29].

A range of associated production processes of heavy quarkonia has been studied experimentally [20, 28, 30–42]. Heavy-quarkonium-pair production was first observed by the NA3 collaboration in the study of J/ψ -pair production in π^- -induced interactions [43]. Subsequently, J/ψ -pair production was measured by the LHCb experiment [44] and the CMS experiment [45] at $\sqrt{s} = 7$ TeV, by the D0 collaboration at $\sqrt{s} = 1.96$ TeV in $p\bar{p}$ collisions [33], by the ATLAS experiment at $\sqrt{s} = 8$ TeV [34], and by the LHCb experiment at $\sqrt{s} = 13$ TeV [46]. In the di- J/ψ invariant-mass spectrum, a structure of fully charmed tetraquark states was observed by LHCb [47], and recently confirmed by CMS [48] and ATLAS [49]. Production of Υ pairs was observed by the CMS experiment in pp collisions at $\sqrt{s} = 8$ TeV [50]. For $J/\psi\text{-}\Upsilon$ production, experimental evidence was found by the D0 collaboration [51], but to date, no significant signals have been reported.

In this paper, $J/\psi\text{-}\Upsilon$ production in pp collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV is studied for J/ψ (Υ) mesons with a transverse momentum $p_{\text{T}} < 10$ (30) GeV/ c in the rapidity range $2.0 < y < 4.5$ using data collected by LHCb in the years 2016, 2017, and 2018. The data correspond to an integrated luminosity of $\mathcal{L} = 4.18 \pm 0.08 \text{ fb}^{-1}$. The J/ψ and Υ mesons are reconstructed in the dimuon final state. The polarisation of the J/ψ and Υ mesons is assumed to be zero. The polarisation of $J/\psi\text{-}\Upsilon$ pairs is not yet measured, but all the LHC measurements so far indicate a small polarisation for quarkonia [52–57].

2 Detector and dataset

The LHCb detector [58, 59] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of the momentum, p , of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/ c . The minimum distance of a track to a primary pp collision vertex (PV), the impact parameter, is measured with a resolution of $(15 + 29/p_{\text{T}}) \mu\text{m}$, where p_{T} is in GeV/ c . Particle identification (PID) for charged hadrons uses information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The online event selection is performed by a trigger [60], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. For this analysis, data were collected with varying trigger conditions particularly for the hardware stage, which requires two muons with $p_T(\mu_1) \times p_T(\mu_2) > (1.3)^2, (1.5)^2$ or $(1.8)^2 \text{ GeV}^2/c^2$. In the software trigger stage, at least two muons with $p_T > 300 \text{ MeV}/c$, $p > 6 \text{ GeV}/c$, and dimuon invariant mass $m(\mu^+\mu^-) > 2.7 \text{ GeV}/c^2$ are required. Candidate J/ψ and Υ mesons are built from two oppositely charged tracks that are identified as muons and form a good vertex. These muons from the J/ψ (Υ) decays are required to be in the kinematic region $2 < \eta < 5$, $p_T > 650$ (3000) MeV/c , and $p > 6 \text{ GeV}/c$. The decay vertices of the J/ψ and Υ mesons have to be consistent with the same PV. The invariant mass of the J/ψ candidates is required to be within $[3.0, 3.2] \text{ GeV}/c^2$ and that of the Υ candidates within $[9, 11] \text{ GeV}/c^2$.

Two independent simulated samples of J/ψ and Υ decays are used to model effects of the detector acceptance and the imposed selection requirements for J/ψ and Υ decays respectively. Primary pp collisions are generated using Pythia 8 [61] with a specific LHCb configuration [62]. Decays of unstable particles are simulated using EvtGen [63], in which the final-state radiation is generated with PHOTOS [64]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [65] as described in Ref. [66]. All simulated events are reconstructed and selected in the same way as the data.

3 Cross-section determination

The J/ψ - Υ production cross-section is measured according to

$$\sigma(J/\psi\text{-}\Upsilon) = \frac{N_{\text{cor}}}{\mathcal{L} \times \mathcal{B}_{J/\psi \rightarrow \mu^+\mu^-} \times \mathcal{B}_{\Upsilon \rightarrow \mu^+\mu^-}}, \quad (2)$$

where N_{cor} is the efficiency-corrected signal yield of the J/ψ - Υ associated production, $\mathcal{B}_{J/\psi \rightarrow \mu^+\mu^-}$ and $\mathcal{B}_{\Upsilon \rightarrow \mu^+\mu^-}$ are the branching fractions of the $J/\psi \rightarrow \mu^+\mu^-$ and $\Upsilon \rightarrow \mu^+\mu^-$ decays [67], respectively, and $\mathcal{L} = 4.18 \pm 0.08 \text{ fb}^{-1}$ is the integrated luminosity determined with the van-der-Meer-scan method [68, 69].

The total detection efficiency ϵ_{tot} for the offline selected J/ψ - Υ candidates is factorised as

$$\epsilon_{\text{tot}} = \epsilon_{\text{acc}} \times \epsilon_{\text{rec\&sel}} \times \epsilon_{\text{PID}} \times \epsilon_{\text{trig}}, \quad (3)$$

where ϵ_{acc} is the geometrical acceptance, $\epsilon_{\text{rec\&sel}}$ is the reconstruction and selection (not including PID requirements) efficiency of all the candidates within the geometrical acceptance, ϵ_{PID} is the PID selection efficiency of candidates reconstructed and passing other selection requirements, and ϵ_{trig} is the trigger selection efficiency of candidates passing all selection requirements. The first three terms on the right-hand side of Eq. 3 are computed by multiplying the individual efficiencies for J/ψ and Υ candidates, *i.e.*,

$$\epsilon_i = \epsilon_i^{J/\psi} \times \epsilon_i^{\Upsilon}, \quad (4)$$

where i denotes acc, rec&sel, or PID. For the trigger selection, it is required that either the J/ψ or Υ candidate meets the trigger requirements specified in Sec. 2; therefore the trigger efficiency ϵ_{trig} can be factorised as

$$\epsilon_{\text{trig}} = 1 - (1 - \epsilon_{\text{trig}}^{J/\psi})(1 - \epsilon_{\text{trig}}^{\Upsilon}). \quad (5)$$

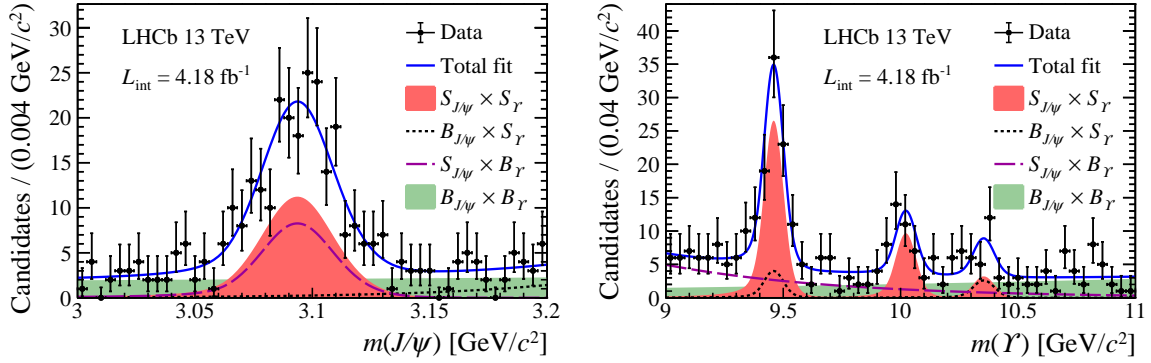


Figure 2: Two-dimensional invariant mass distribution of the J/ψ - Υ candidates projected on (left) the J/ψ invariant mass $m(J/\psi)$ and (right) the Υ invariant mass $m(\Upsilon)$. The black points with error bars represent the data. The blue solid line represents the result of the fit to the data sample. The red shaded area represents the signal component. The black (dotted) and violet (dashed) lines represent the background where one dimuon candidate is a true meson decay and the other is combinatorial background. The green shaded area indicates the background where both the J/ψ and Υ candidates are combinatorial background.

Each efficiency component is determined separately for J/ψ and Υ mesons as a function of their p_T and rapidity y . The acceptances, the reconstruction and selection efficiencies, and the trigger efficiencies are estimated using simulation, while the PID efficiencies are obtained using a data-driven method [70].

To extract the signal yield, an unbinned extended maximum-likelihood fit is performed to the two-dimensional J/ψ - Υ invariant-mass distribution. Defining the signal distribution to be S and combinatorial-background distribution B , the components in the model used to fit the data fall into three categories, each corresponding to the following cases:

- the signal J/ψ - Υ candidates ($S_{J/\psi} \times S_{\Upsilon}$, in which S_{Υ} is $S_{\Upsilon(1S)} + S_{\Upsilon(2S)} + S_{\Upsilon(3S)}$),
- a true J/ψ (Υ) candidate associated with a combinatorial Υ (J/ψ) background candidate ($S_{J/\psi} \times B_{\Upsilon}$ and $B_{J/\psi} \times S_{\Upsilon}$),
- and a purely combinatorial background ($B_{J/\psi} \times B_{\Upsilon}$).

The two-dimensional probability density function for each component factorises into the product of two one-dimensional distributions for the J/ψ and Υ candidates. The signal invariant-mass distribution of the J/ψ meson and that of each Υ meson are described by a combination of a double-sided Crystal Ball (DSCB) function [71] and a Gaussian function with a shared mean. The DSCB power-law tail parameters, the ratio of the width of the Gaussian function to that of the Gaussian core in the DSCB function, and the relative fraction of the DSCB to the Gaussian function are fixed to values estimated from simulation. The ratios between the means of the Υ Gaussian functions are fixed to the ratios of the known Υ masses. As the mass resolution of signals is linearly dependent on invariant mass, the width ratios of the Gaussian functions are also fixed to the known mass ratios [67]. The mean value and the width of the Gaussian function for the $\Upsilon(1S)$ are free parameters in the fit.

Table 1: Raw yields from the fit, the efficiency-corrected yields (N_{cor}) and the signal significances.

Signal	Raw yields	N_{cor}	Significances
$J/\psi\text{-}\Upsilon(1S)$	76 ± 12	840 ± 140	7.9σ
$J/\psi\text{-}\Upsilon(2S)$	30 ± 7	370 ± 100	4.9σ
$J/\psi\text{-}\Upsilon(3S)$	10 ± 6	-	1.7σ

Each combinatorial background is modelled by an exponential function. The invariant-mass distributions of the J/ψ and Υ candidates, together with the fit projections, are shown in Fig. 2. Associated $J/\psi\text{-}\Upsilon(1S)$ production is observed with a significance of 7.9σ , and evidence for $J/\psi\text{-}\Upsilon(2S)$ production with a significance of 4.9σ is seen. The total significance for the associated production of J/ψ with a combination of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states is determined to be 8.5σ . The significance is estimated by comparing the likelihood of the fit with and without the considered component in the fit, with relevant systematic uncertainties taken into consideration. The raw yields of signals from the fit and their significances are summarised in Table 1.

Based on the fit result, a signal weight w_i is calculated with the *sPlot* method [72] for each $J/\psi\text{-}\Upsilon$ candidate, using the J/ψ and Υ invariant masses as discriminating variables. These weights are used to determine the efficiency corrected yield $N^{\text{cor}} = \sum_j w_j / \epsilon_{\text{tot},j}$, where j runs over all the $J/\psi\text{-}\Upsilon$ candidates in data. The total efficiency for the j^{th} candidate, $\epsilon_{\text{tot},j}$, is defined in Eq. 3 and determined as a function of the p_T and y of the J/ψ and Υ candidate. The corrected yield, N_{cor} , is shown in Table 1.

The signal extracted from the fit also contains J/ψ mesons produced from b -hadron decays (denoted $J/\psi\text{-from-}b$). The fraction of $J/\psi\text{-from-}b$ decays is determined to be 2.1% using the prompt J/ψ and $J/\psi\text{-from-}b$ production cross-sections measured by LHCb in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ [73]. The difference between the average reconstruction and selection efficiencies of the two components is evaluated from simulation; the selection criteria constraining J/ψ and Υ decay vertices to the PV favour the prompt J/ψ candidates and suppress the $J/\psi\text{-from-}b$ candidates. With current measurements of σ_{eff} , the $J/\psi\text{-}\Upsilon$ associated production is predicted to be dominated by the DPS process. It is therefore assumed that in events with J/ψ and Υ candidates the relative cross-section of the $J/\psi\text{-from-}b$ production with respect to the prompt J/ψ production is the same as the relative cross-section of $J/\psi\text{-from-}b$ in inclusive J/ψ events. An uncertainty is assigned for systematic effects due to this assumption. The $J/\psi\text{-from-}b$ component is subtracted when calculating the total cross-section of the associated $J/\psi\text{-}\Upsilon$ production.

4 Systematic uncertainties

Systematic uncertainties from various sources are studied and summarised in Table 2. The total relative systematic uncertainty is 5.5% for $J/\psi\text{-}\Upsilon(1S)$ and 10.3% for $J/\psi\text{-}\Upsilon(2S)$ production, corresponding to the quadratic sum of all the contributions discussed below.

The uncertainty introduced by the imperfect modelling of the signal shape is estimated by fitting the data with an alternative signal model. The alternative shape is the shape of the simulated signal distribution, convolved with a Gaussian function to account for the different invariant-mass resolution observed between data and simulation. The 2.0% relative change of the signal yield is assigned as the systematic uncertainty for both

Table 2: Relative systematic uncertainties on the measurement of the $J/\psi\text{-}\Upsilon(1S)$ and $J/\psi\text{-}\Upsilon(2S)$ cross-sections.

Source	$\sigma(J/\psi\text{-}\Upsilon(1S))$ (%)	$\sigma(J/\psi\text{-}\Upsilon(2S))$ (%)
Signal shape	2.0	2.0
Limited simulation size	0.7	1.6
Tracking efficiency	3.3	3.3
PID efficiency	0.5	0.5
J/ψ -from- b fraction	1.1	1.1
Trigger efficiency	1.0	1.0
Radiative tail	2.0	2.0
Vertex fit	0.6	0.6
Luminosity	1.9	1.9
$\mathcal{B}_{J/\psi\rightarrow\mu^+\mu^-}$	0.6	0.6
$\mathcal{B}_{\Upsilon(1S)\rightarrow\mu^+\mu^-}$	2.0	–
$\mathcal{B}_{\Upsilon(2S)\rightarrow\mu^+\mu^-}$	–	8.8
Total	5.5	10.3

$J/\psi\text{-}\Upsilon(1S)$ and $J/\psi\text{-}\Upsilon(2S)$ signals.

Due to the limited sizes of the simulation samples, the efficiencies obtained from simulation are subject to fluctuations. The statistical uncertainties of the efficiencies are propagated to the efficiency-corrected signal yield with a pseudoexperiment Monte Carlo method. The variations of the efficiency-corrected signal yields in pseudoexperiments are taken as the systematic uncertainty and are 0.7% for $J/\psi\text{-}\Upsilon(1S)$ production and 1.6% for $J/\psi\text{-}\Upsilon(2S)$ production.

The track reconstruction efficiency as a function of muon p and η is estimated with $J/\psi \rightarrow \mu^+\mu^-$ decays in a calibration data sample using a tag-and-probe technique [74]. The difference between data and simulation is used to calibrate the reconstruction efficiency estimated using simulated signal decays. The uncertainties on these calibrations are propagated to the efficiency-corrected yield using a pseudoexperiment Monte Carlo method. The uncertainty is 0.9% for both the $J/\psi\text{-}\Upsilon(1S)$ and $J/\psi\text{-}\Upsilon(2S)$ signals. An additional uncertainty of 0.8% per track is assigned to account for the difference in detector occupancy between data and simulation [74]. A total relative uncertainty of 3.3% is attributed to the tracking efficiency calibration.

The muon PID efficiency is calculated with $J/\psi \rightarrow \mu^+\mu^-$ decays using a data-driven tag-and-probe method [70]. The efficiency is estimated in bins of p_T and η of the probe track, for which the binning scheme introduces an uncertainty. Alternative binning schemes are used to estimate variations of the PID efficiency. The relative change with respect to the default value, 0.5%, is quoted as the systematic uncertainty.

The trigger efficiency estimated from simulation is compared with that from data with a data-driven method [46, 75]. A relative difference of 1.0% is quoted as the systematic uncertainty.

The uncertainties introduced by the mismodelling of the radiative decay tails and the requirement on the vertex fit quality is estimated to be 2% and 0.6%, respectively, following Ref. [73, 76] by comparing data and simulation.

The fraction of J/ψ -from- b is calculated from the p_T - and y -dependent J/ψ -from- b fraction in single J/ψ production and the relative detection efficiency between J/ψ -from- b and prompt production, convolved with the J/ψ kinematic distributions in simulation. The uncertainty of J/ψ kinematic distributions used to estimate the fraction and the possible difference of J/ψ -from- b fraction between inclusive J/ψ production and associated J/ψ - Υ production are sources of systematic uncertainties. The first uncertainty is evaluated using the maximum and minimum values of the inclusive J/ψ -from- b fraction in the studied kinematic range of this analysis. The second source is estimated conservatively by varying the effective cross-section σ_{eff} of the Υ - B hadron associated production by 50%. In total, this systematic uncertainty is estimated to be 1.1%. The effect of events where J/ψ and Υ mesons originate from different PVs is estimated to be negligible.

The relative uncertainty on the luminosity is estimated to be 1.9%. The relative uncertainties on the branching fractions $\mathcal{B}_{J/\psi \rightarrow \mu^+ \mu^-}$, $\mathcal{B}_{\Upsilon(1S) \rightarrow \mu^+ \mu^-}$ and $\mathcal{B}_{\Upsilon(2S) \rightarrow \mu^+ \mu^-}$ are 0.6%, 2.0% and 8.8%, respectively [67]. They are propagated to the cross-section uncertainties.

5 Results and comparison to theory

The J/ψ - Υ production is measured in the fiducial region, $2 < y < 5$ and $p_T < 10 \text{ GeV}/c$ for the J/ψ meson, $2 < y < 5$ and $p_T < 30 \text{ GeV}/c$ for the Υ meson. The associated prompt-production cross-section of J/ψ - $\Upsilon(1S)$ is measured to be

$$\sigma(J/\psi\text{-}\Upsilon(1S)) = 133 \pm 22 \pm 7 \pm 3 \text{ pb},$$

and the associated prompt-production cross-section of J/ψ - $\Upsilon(2S)$ is measured to be

$$\sigma(J/\psi\text{-}\Upsilon(2S)) = 76 \pm 21 \pm 4 \pm 7 \text{ pb},$$

where the first uncertainties are statistical, the second systematic, and the third due to the uncertainties on the quarkonium decay branching fractions.

The ratio of the cross-sections of J/ψ - $\Upsilon(2S)$ and J/ψ - $\Upsilon(1S)$ multiplied by the respective branching ratio is calculated to be

$$\frac{\mathcal{B}_{\Upsilon(2S) \rightarrow \mu^+ \mu^-} \times \sigma(J/\psi\text{-}\Upsilon(2S))}{\mathcal{B}_{\Upsilon(1S) \rightarrow \mu^+ \mu^-} \times \sigma(J/\psi\text{-}\Upsilon(1S))} = 0.442 \pm 0.143 \pm 0.004,$$

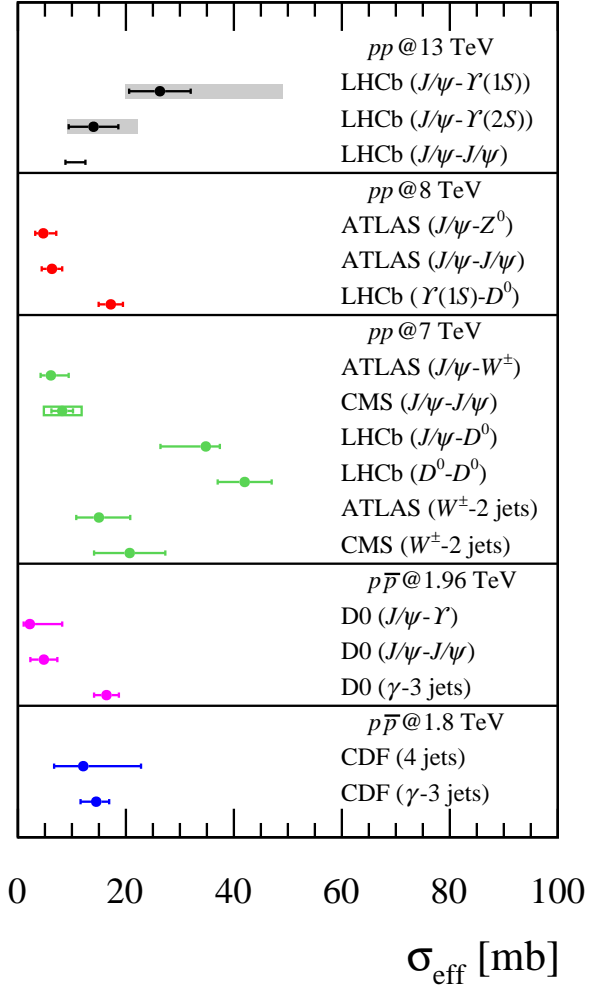
where the first uncertainty is statistical and the second systematic. The result is consistent with the measurement of $\Upsilon(1S, 2S)$ production [76] and of the production of $\Upsilon(1S, 2S)$ mesons associated with an open charm hadron [38], as is expected by the DPS assumption.

Using the DPS cross-section of the J/ψ - Υ associated production and the prompt-production cross-sections of single J/ψ and Υ mesons, the effective cross-section is calculated according to Eq. 1. The DPS cross-sections are estimated by subtracting the SPS cross-sections, $20_{-15}^{+52} \text{ pb}$ for J/ψ - $\Upsilon(1S)$ and 8_{-6}^{+22} pb for J/ψ - $\Upsilon(2S)$, from the associated-production cross-sections. The SPS cross-sections are adapted from the calculations with the NRQCD framework in Ref. [20]. The prompt-production cross-sections of J/ψ and Υ are taken from Ref. [73] and Ref. [76], respectively. The effective cross-section is

$$\sigma_{\text{eff}}(J/\psi\text{-}\Upsilon(1S)) = 26 \pm 5 \pm 2_{-3}^{+22} \text{ mb},$$

$$\sigma_{\text{eff}}(J/\psi\text{-}\Upsilon(2S)) = 14 \pm 5 \pm 1_{-1}^{+7} \text{ mb},$$

Figure 3: Effective cross-sections measured in different particle production by various experiments. For the LHCb measurements of $J/\psi-\Upsilon(1S)$ and $J/\psi-\Upsilon(2S)$ effective cross-sections, the error bars (grey boxes) represent the experimental (total) uncertainties. The result for $J/\psi-J/\psi$ production at LHCb is given as a range covering several model-dependent measurements [46]. Results from other analyses are reproduced from Refs. [1, 38].



where the first uncertainties are statistical, the second uncertainties are systematic, and the last terms are uncertainties due to theory calculations. The results of σ_{eff} are broadly compatible with measurements using hadroproduction of other particles, as shown in Fig. 3. The effective cross-sections for $J/\psi-\Upsilon(1S)$ and $J/\psi-\Upsilon(2S)$ production are consistent.

The distributions of some observables related to both J/ψ and $\Upsilon(1S)$ mesons are studied to probe the kinematic correlation between the two mesons. These variables include the $J/\psi-\Upsilon(1S)$ invariant mass, the transverse momentum of the $J/\psi-\Upsilon(1S)$ system, the relative azimuthal angle, and the rapidity difference between J/ψ and $\Upsilon(1S)$ mesons. The distributions of these variables and the transverse momentum distributions of the J/ψ and $\Upsilon(1S)$ mesons are presented in Fig. 4, after correcting for the total detection efficiency and subtracting the background contribution. The large uncertainties in the correlation distributions are due to the small size of the signal data sample, which dominate over systematic uncertainties. These distributions are compared with pseudoexperiments corresponding to different contributions of the DPS and SPS processes. Since the J/ψ and Υ mesons are produced independently from two different parton-parton scatterings in the DPS processes, the kinematic distribution of each meson in the associated production

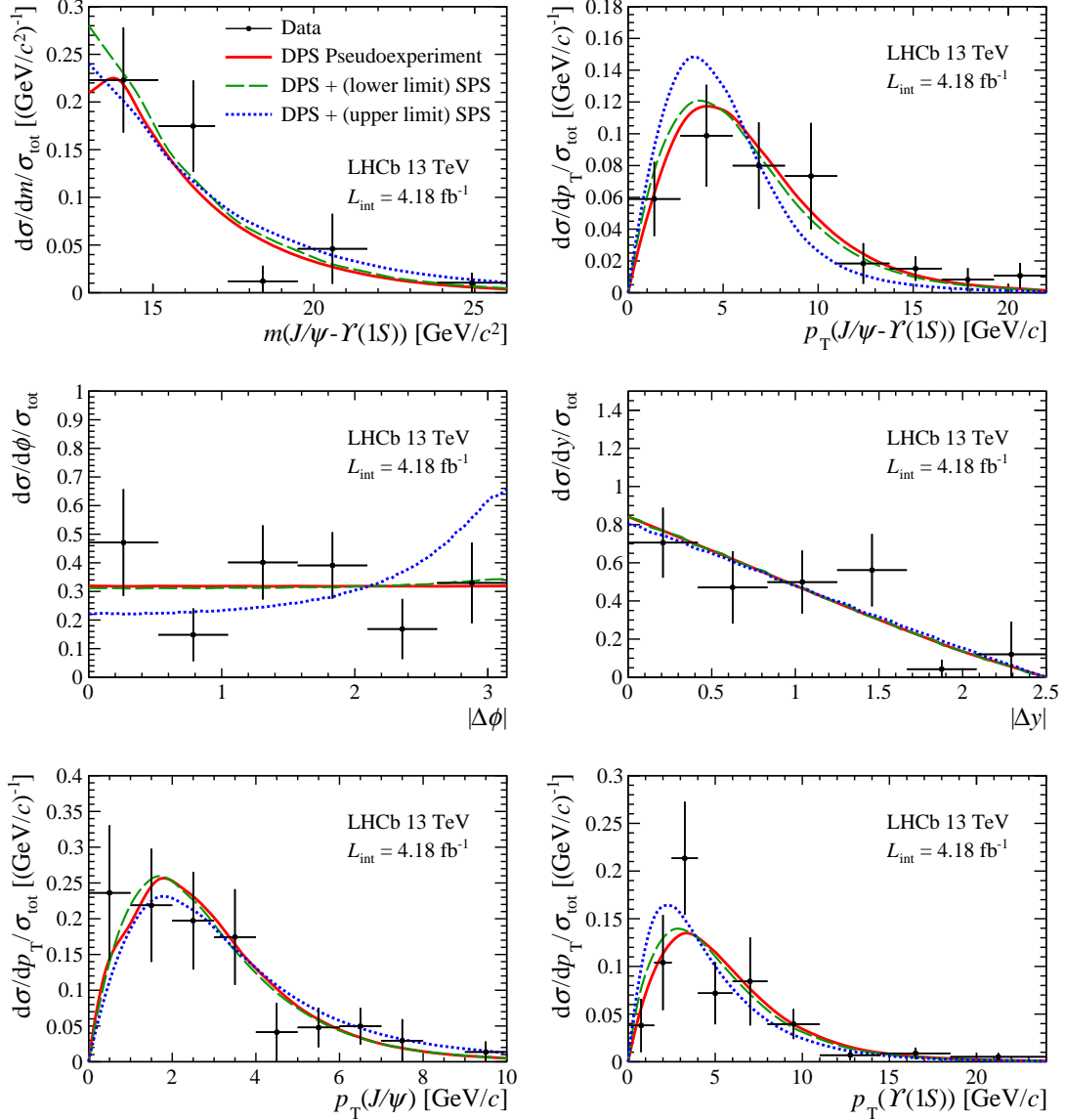


Figure 4: Distributions of (top left) invariant mass $m(J/\psi-\Upsilon(1S))$, (top right) transverse momentum $p_T(J/\psi-\Upsilon(1S))$, (middle left) azimuthal angle difference $|\Delta\phi|$, (middle right) rapidity difference $|\Delta y|$ of $J/\psi-\Upsilon(1S)$, and (bottom) p_T of the J/ψ and $\Upsilon(1S)$ mesons for data and the pseudodata modelled from previous measurements [73, 76]. Black points with error bars represent the data distributions with statistical uncertainties. Red solid lines represent distributions of the DPS pseudodata. Green dashed lines and blue dotted lines represent the DPS distribution together with the lower limit and the upper limit of the SPS distributions, respectively.

is expected to be similar to that in the single meson production. As a result, using the measured p_T and y distributions in single- J/ψ and $-\Upsilon(1S)$ production [73, 76], the DPS distributions of J/ψ and $\Upsilon(1S)$ kinematic variables in the associated production can be modelled. The distributions for the SPS production are taken from calculations in Ref. [20]. Three samples of pseudodata are generated, differing in the relative SPS to DPS fractions. For one sample, only DPS production is considered. For the other two samples, the SPS fraction is calculated using either the upper or lower limit of the

predicted cross-section in Ref. [20], and the DPS cross-section is the LHCb measurement of the total cross-section with the SPS cross-section subtracted. As shown in Fig. 4, the J/ψ and $\Upsilon(1S)$ p_T distributions and the kinematic correlations between the J/ψ and $\Upsilon(1S)$ mesons in the three pseudodata samples are all found to be consistent with measurements.

6 Summary

Using pp collision data collected by the LHCb experiment at a centre-of-mass energy of 13 TeV corresponding to an integrated luminosity of $4.18 \pm 0.08 \text{ fb}^{-1}$, a signal for $J/\psi\text{-}\Upsilon(1S)$ production is observed with a significance of 7.9σ , and evidence is found for $J/\psi\text{-}\Upsilon(2S)$ production. Within the fiducial region $2.0 < y < 4.5$ and $p_T < 10$ (30) GeV/ c for J/ψ (Υ) mesons, the cross-section for $J/\psi\text{-}\Upsilon(1S)$ production is measured to be 133 ± 22 (stat) ± 7 (syst) ± 3 (\mathcal{B}) pb and that for $J/\psi\text{-}\Upsilon(2S)$ production 76 ± 21 (stat) ± 4 (syst) ± 7 (\mathcal{B}) pb. The effective cross-sections for $J/\psi\text{-}\Upsilon(1S)$ and $J/\psi\text{-}\Upsilon(2S)$ production are calculated and found to be compatible with previous measurements in various processes. Kinematic correlations between the J/ψ and $\Upsilon(1S)$ mesons are studied, showing results consistent with both the hypotheses that the associated production is dominated by the DPS process or has DPS and SPS contributions. In the future, further data from LHCb combined with improved theory calculations will help constrain the associated quarkonium production mechanism.

Acknowledgements

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MICINN (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), Polish WLCG (Poland) and NERSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from ARC and ARDC (Australia); Minciencias (Colombia); AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); A*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and Sci. & Tech. Program of Guangzhou (China); GVA, XuntaGal, GENCAT and Prog. Atracción Talento, CM (Spain); SRC (Sweden); the Leverhulme Trust, the Royal Society and UKRI (United Kingdom).

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
















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


























































LHCb collaboration

R. Aaij³² , A.S.W. Abdelmotteleb⁵⁰ , C. Abellan Beteta⁴⁴ , F. Abudinén⁵⁰ ,
T. Ackernley⁵⁴ , B. Adeva⁴⁰ , M. Adinolfi⁴⁸ , P. Adlarson⁷⁷ , H. Afsharnia⁹,
C. Agapopoulou¹³ , C.A. Aidala⁷⁸ , Z. Ajaltouni⁹, S. Akar⁵⁹ , K. Akiba³² ,
P. Albicocco²³ , J. Albrecht¹⁵ , F. Alessio⁴² , M. Alexander⁵³ , A. Alfonso Albero³⁹ ,
Z. Aliouche⁵⁶ , P. Alvarez Cartelle⁴⁹ , R. Amalric¹³ , S. Amato² , J.L. Amey⁴⁸ ,
Y. Amhis^{11,42} , L. An⁴² , L. Anderlini²² , M. Andersson⁴⁴ , A. Andreianov³⁸ ,
M. Andreotti²¹ , D. Andreou⁶² , D. Ao⁶ , F. Archilli^{31,t} , A. Artamonov³⁸ ,
M. Artuso⁶² , E. Aslanides¹⁰ , M. Atzeni⁴⁴ , B. Audurier¹² , I.B. Bachiller Perea⁸ ,
S. Bachmann¹⁷ , M. Bachmayer⁴³ , J.J. Back⁵⁰ , A. Bailly-reyre¹³,
P. Baladron Rodriguez⁴⁰ , V. Balagura¹² , W. Baldini^{21,42} , J. Baptista de Souza Leite¹ ,
M. Barbetti^{22,j} , R.J. Barlow⁵⁶ , S. Barsuk¹¹ , W. Barter⁵² , M. Bartolini⁴⁹ ,
F. Baryshnikov³⁸ , J.M. Basels¹⁴ , G. Bassi^{29,q} , V. Batozskaya³⁶ , B. Batsukh⁴ ,
A. Battig¹⁵ , A. Bay⁴³ , A. Beck⁵⁰ , M. Becker¹⁵ , F. Bedeschi²⁹ , I.B. Bediaga¹ ,
A. Beiter⁶², S. Belin⁴⁰ , V. Bellee⁴⁴ , K. Belous³⁸ , I. Belov³⁸ , I. Belyaev³⁸ ,
G. Benane¹⁰ , G. Bencivenni²³ , E. Ben-Haim¹³ , A. Bereznoy³⁸ , R. Bernet⁴⁴ ,
S. Bernet Andres⁷⁶ , D. Berninghoff¹⁷, H.C. Bernstein⁶², C. Bertella⁵⁶ , A. Bertolin²⁸ ,
C. Betancourt⁴⁴ , F. Betti⁴² , Ia. Bezshyiko⁴⁴ , J. Bhom³⁵ , L. Bian⁶⁸ ,
M.S. Bieker¹⁵ , N.V. Biesuz²¹ , P. Billoir¹³ , A. Biolchini³² , M. Birch⁵⁵ ,
F.C.R. Bishop⁴⁹ , A. Bitadze⁵⁶ , A. Bizzeti , M.P. Blago⁴⁹ , T. Blake⁵⁰ , F. Blanc⁴³ ,
J.E. Blank¹⁵ , S. Blusk⁶² , D. Bobulska⁵³ , J.A. Boelhauve¹⁵ , O. Boente Garcia¹² ,
T. Boettcher⁵⁹ , A. Boldyrev³⁸ , C.S. Bolognani⁷⁴ , R. Bolzonella^{21,i} , N. Bondar^{38,42} ,
F. Borgato²⁸ , S. Borghi⁵⁶ , M. Borsato¹⁷ , J.T. Borsuk³⁵ , S.A. Bouchiba⁴³ ,
T.J.V. Bowcock⁵⁴ , A. Boyer⁴² , C. Bozzi²¹ , M.J. Bradley⁵⁵, S. Braun⁶⁰ ,
A. Brea Rodriguez⁴⁰ , J. Brodzicka³⁵ , A. Brossa Gonzalo⁴⁰ , J. Brown⁵⁴ ,
D. Brundu²⁷ , A. Buonauro⁴⁴ , L. Buonincontri²⁸ , A.T. Burke⁵⁶ , C. Burr⁴² ,
A. Bursche⁶⁶, A. Butkevich³⁸ , J.S. Butter³² , J. Buytaert⁴² , W. Byczynski⁴² ,
S. Cadeddu²⁷ , H. Cai⁶⁸, R. Calabrese^{21,i} , L. Calefice¹⁵ , S. Cali²³ , M. Calvi^{26,m} ,
M. Calvo Gomez⁷⁶ , P. Campana²³ , D.H. Campora Perez⁷⁴ ,
A.F. Campoverde Quezada⁶ , S. Capelli^{26,m} , L. Capriotti²⁰ , A. Carbone^{20,g} ,
R. Cardinale^{24,k} , A. Cardini²⁷ , P. Carniti^{26,m} , L. Carus¹⁴, A. Casais Vidal⁴⁰ ,
R. Caspary¹⁷ , G. Casse⁵⁴ , M. Cattaneo⁴² , G. Cavallero^{55,42} , V. Cavallini^{21,i} ,
S. Celani⁴³ , J. Cerasoli¹⁰ , D. Cervenkov⁵⁷ , A.J. Chadwick⁵⁴ , I.C. Chahrouh⁷⁸ ,
M.G. Chapman⁴⁸, M. Charles¹³ , Ph. Charpentier⁴² , C.A. Chavez Barajas⁵⁴ ,
M. Chefdeville⁸ , C. Chen¹⁰ , S. Chen⁴ , A. Chernov³⁵ , S. Chernyshenko⁴⁶ ,
V. Chobanova⁴⁰ , S. Cholak⁴³ , M. Chrzaszcz³⁵ , A. Chubykin³⁸ , V. Chulikov³⁸ ,
P. Ciambrone²³ , M.F. Cicala⁵⁰ , X. Cid Vidal⁴⁰ , G. Ciezarek⁴² , P. Cifra⁴² ,
G. Ciullo^{i,21} , P.E.L. Clarke⁵² , M. Clemencic⁴² , H.V. Cliff⁴⁹ , J. Closier⁴² ,
J.L. Cobbledick⁵⁶ , V. Coco⁴² , J. Cogan¹⁰ , E. Cogneras⁹ , L. Cojocariu³⁷ ,
P. Collins⁴² , T. Colombo⁴² , L. Congedo¹⁹ , A. Contu²⁷ , N. Cooke⁴⁷ ,
I. Corredoira⁴⁰ , G. Corti⁴² , B. Couturier⁴² , D.C. Craik⁴⁴ , M. Cruz Torres^{1,e} ,
R. Currie⁵² , C.L. Da Silva⁶¹ , S. Dadabaev³⁸ , L. Dai⁶⁵ , X. Dai⁵ , E. Dall’Occo¹⁵ ,
J. Dalseno⁴⁰ , C. D’Ambrosio⁴² , J. Daniel⁹ , A. Danilina³⁸ , P. d’Argent¹⁹ ,
J.E. Davies⁵⁶ , A. Davis⁵⁶ , O. De Aguiar Francisco⁵⁶ , J. de Boer⁴² , K. De Bruyn⁷³ ,
S. De Capua⁵⁶ , M. De Cian⁴³ , U. De Freitas Carneiro Da Graca¹ , E. De Lucia²³ ,
J.M. De Miranda¹ , L. De Paula² , M. De Serio^{19,f} , D. De Simone⁴⁴ , P. De Simone²³ ,
F. De Vellis¹⁵ , J.A. de Vries⁷⁴ , C.T. Dean⁶¹ , F. Debernardis^{19,f} , D. Decamp⁸ ,
V. Dedu¹⁰ , L. Del Buono¹³ , B. Delaney⁵⁸ , H.-P. Dembinski¹⁵ , V. Denysenko⁴⁴ ,
O. Deschamps⁹ , F. Dettori^{27,h} , B. Dey⁷¹ , P. Di Nezza²³ , I. Diachkov³⁸ 

S. Didenko³⁸ , L. Dieste Maronas⁴⁰, S. Ding⁶² , V. Dobishuk⁴⁶ , A. Dolmatov³⁸,
 C. Dong³ , A.M. Donohoe¹⁸ , F. Dordei²⁷ , A.C. dos Reis¹ , L. Douglas⁵³,
 A.G. Downes⁸ , P. Duda⁷⁵ , M.W. Dudek³⁵ , L. Dufour⁴² , V. Duk⁷² , P. Durante⁴² ,
 M. M. Duras⁷⁵ , J.M. Durham⁶¹ , D. Dutta⁵⁶ , A. Dziurda³⁵ , A. Dzyuba³⁸ ,
 S. Easo⁵¹ , U. Egede⁶³ , V. Egorychev³⁸ , C. Eirea Orro⁴⁰, S. Eisenhardt⁵² ,
 E. Ejopu⁵⁶ , S. Ek-In⁴³ , L. Eklund⁷⁷ , M.E. Elashri⁵⁹ , J. Ellbracht¹⁵ , S. Ely⁵⁵ ,
 A. Ene³⁷ , E. Epple⁵⁹ , S. Escher¹⁴ , J. Eschle⁴⁴ , S. Esen⁴⁴ , T. Evans⁵⁶ ,
 F. Fabiano^{27,h} , L.N. Falcao¹ , Y. Fan⁶ , B. Fang^{11,68} , L. Fantini^{72,p} , M. Faria⁴³ ,
 S. Farry⁵⁴ , D. Fazzini^{26,m} , L.F. Felkowski⁷⁵ , M. Feo⁴² , M. Fernandez Gomez⁴⁰ ,
 A.D. Fernez⁶⁰ , F. Ferrari²⁰ , L. Ferreira Lopes⁴³ , F. Ferreira Rodrigues² ,
 S. Ferreres Sole³² , M. Ferrillo⁴⁴ , M. Ferro-Luzzi⁴² , S. Filippov³⁸ , R.A. Fini¹⁹ ,
 M. Fiorini^{21,i} , M. Firlej³⁴ , K.M. Fischer⁵⁷ , D.S. Fitzgerald⁷⁸ , C. Fitzpatrick⁵⁶ ,
 T. Fiutowski³⁴ , F. Fleuret¹² , M. Fontana¹³ , F. Fontanelli^{24,k} , R. Forty⁴² ,
 D. Foulds-Holt⁴⁹ , V. Franco Lima⁵⁴ , M. Franco Sevilla⁶⁰ , M. Frank⁴² ,
 E. Franzoso^{21,i} , G. Frau¹⁷ , C. Frei⁴² , D.A. Friday⁵⁶ , L.F. Frontini^{25,l} , J. Fu⁶ ,
 Q. Fuehring¹⁵ , T. Fulghesu¹³ , E. Gabriel³² , G. Galati^{19,f} , M.D. Galati³² ,
 A. Gallas Torreira⁴⁰ , D. Galli^{20,g} , S. Gambetta^{52,42} , M. Gandelman² , P. Gandini²⁵ ,
 H.G. Gao⁶ , Y. Gao⁷ , Y. Gao⁵ , M. Garau^{27,h} , L.M. Garcia Martin⁵⁰ ,
 P. Garcia Moreno³⁹ , J. García Pardiñas⁴² , B. Garcia Plana⁴⁰, F.A. Garcia Rosales¹² ,
 L. Garrido³⁹ , C. Gaspar⁴² , R.E. Geertsema³² , D. Gerick¹⁷, L.L. Gerken¹⁵ ,
 E. Gersabeck⁵⁶ , M. Gersabeck⁵⁶ , T. Gershon⁵⁰ , L. Giambastiani²⁸ , V. Gibson⁴⁹ ,
 H.K. Giemza³⁶ , A.L. Gilman⁵⁷ , M. Giovannetti²³ , A. Gioventù⁴⁰ ,
 P. Gironella Gironell³⁹ , C. Giugliano^{21,i} , M.A. Giza³⁵ , K. Gizdov⁵² ,
 E.L. Gkougkousis⁴² , V.V. Gligorov^{13,42} , C. Göbel⁶⁴ , E. Golobardes⁷⁶ ,
 D. Golubkov³⁸ , A. Golutvin^{55,38} , A. Gomes^{1,a} , S. Gomez Fernandez³⁹ ,
 F. Goncalves Abrantes⁵⁷ , M. Goncerz³⁵ , G. Gong³ , I.V. Gorelov³⁸ , C. Gotti²⁶ ,
 J.P. Grabowski⁷⁰ , T. Grammatico¹³ , L.A. Granada Cardoso⁴² , E. Graugés³⁹ ,
 E. Graverini⁴³ , G. Graziani , A. T. Grecu³⁷ , L.M. Greeven³² , N.A. Grieser⁵⁹ ,
 L. Grillo⁵³ , S. Gromov³⁸ , B.R. Gruberg Cazon⁵⁷ , C. Gu³ , M. Guarise^{21,i} ,
 M. Guittiere¹¹ , P. A. Günther¹⁷ , E. Gushchin³⁸ , A. Guth¹⁴, Y. Guz^{5,38,42} , T. Gys⁴² ,
 T. Hadavizadeh⁶³ , C. Hadjivasiliou⁶⁰ , G. Haefeli⁴³ , C. Haen⁴² , J. Haimberger⁴² ,
 S.C. Haines⁴⁹ , T. Halewood-leagas⁵⁴ , M.M. Halvorsen⁴² , P.M. Hamilton⁶⁰ ,
 J. Hammerich⁵⁴ , Q. Han⁷ , X. Han¹⁷ , S. Hansmann-Menzemer¹⁷ , L. Hao⁶ ,
 N. Harnew⁵⁷ , T. Harrison⁵⁴ , C. Hasse⁴² , M. Hatch⁴² , J. He^{6,c} , K. Heijhoff³² ,
 F.H. Hemmer⁴² , C. Henderson⁵⁹ , R.D.L. Henderson^{63,50} , A.M. Hennequin⁵⁸ ,
 K. Hennessy⁵⁴ , L. Henry⁴² , J.H. Herd⁵⁵ , J. Heuel¹⁴ , A. Hicheur² , D. Hill⁴³ ,
 M. Hilton⁵⁶ , S.E. Hollitt¹⁵ , J. Horswill⁵⁶ , R. Hou⁷ , Y. Hou⁸ , J. Hu¹⁷, J. Hu⁶⁶ ,
 W. Hu⁵ , X. Hu³ , W. Huang⁶ , X. Huang⁶⁸, W. Hulsbergen³² , R.J. Hunter⁵⁰ ,
 M. Hushchyn³⁸ , D. Hutchcroft⁵⁴ , P. Ibis¹⁵ , M. Idzik³⁴ , D. Ilin³⁸ , P. Ilten⁵⁹ ,
 A. Inglese³⁸ , A. Injukhin³⁸ , A. Ishteev³⁸ , K. Ivshin³⁸ , R. Jacobsson⁴² , H. Jage¹⁴ ,
 S.J. Jaimes Elles⁴¹ , S. Jakobsen⁴² , E. Jans³² , B.K. Jashal⁴¹ , A. Jawahery⁶⁰ ,
 V. Jevtic¹⁵ , E. Jiang⁶⁰ , X. Jiang^{4,6} , Y. Jiang⁶ , M. John⁵⁷ , D. Johnson⁵⁸ ,
 C.R. Jones⁴⁹ , T.P. Jones⁵⁰ , S.J. Joshi³⁶ , B. Jost⁴² , N. Jurik⁴² , I. Juszczak³⁵ ,
 S. Kandybei⁴⁵ , Y. Kang³ , M. Karacson⁴² , D. Karpenkov³⁸ , M. Karpov³⁸ ,
 J.W. Kautz⁵⁹ , F. Keizer⁴² , D.M. Keller⁶² , M. Kenzie⁵⁰ , T. Ketel³² , B. Khanji¹⁵ ,
 A. Kharisova³⁸ , S. Kholodenko³⁸ , G. Khreich¹¹ , T. Kirn¹⁴ , V.S. Kirsebom⁴³ ,
 O. Kitouni⁵⁸ , S. Klaver³³ , N. Kleijne^{29,q} , K. Klimaszewski³⁶ , M.R. Kmieć³⁶ ,
 S. Koliiev⁴⁶ , L. Kolk¹⁵ , A. Kondybayeva³⁸ , A. Konoplyannikov³⁸ , P. Kopciwicz³⁴ ,
 R. Kopecna¹⁷, P. Koppenburg³² , M. Korolev³⁸ , I. Kostiuk³² , O. Kot⁴⁶,
 S. Kotriakhova , A. Kozachuk³⁸ , P. Kravchenko³⁸ , L. Kravchuk³⁸ , R.D. Krawczyk⁴² ,

M. Kreps⁵⁰ , S. Kretzschmar¹⁴ , P. Krokovny³⁸ , W. Krupa³⁴ , W. Krzemien³⁶ ,
J. Kubat¹⁷ , S. Kubis⁷⁵ , W. Kucewicz³⁵ , M. Kucharczyk³⁵ , V. Kudryavtsev³⁸ ,
E.K Kulikova³⁸ , A. Kupsc⁷⁷ , D. Lacarrere⁴² , G. Lafferty⁵⁶ , A. Lai²⁷ ,
A. Lampis^{27,h} , D. Lancierini⁴⁴ , C. Landesa Gomez⁴⁰ , J.J. Lane⁵⁶ , R. Lane⁴⁸ ,
C. Langenbruch¹⁴ , J. Langer¹⁵ , O. Lantwin³⁸ , T. Latham⁵⁰ , F. Lazzari^{29,r} ,
M. Lazzaroni²⁵ , C. Lazzeroni⁴⁷ , R. Le Gac¹⁰ , S.H. Lee⁷⁸ , R. Lefèvre⁹ , A. Leflat³⁸ ,
S. Legotin³⁸ , P. Lenisa^{i,21} , O. Leroy¹⁰ , T. Lesiak³⁵ , B. Leverington¹⁷ , A. Li³ ,
H. Li⁶⁶ , K. Li⁷ , P. Li⁴² , P.-R. Li⁶⁷ , S. Li⁷ , T. Li⁴ , T. Li⁶⁶ , Y. Li⁴ , Z. Li⁶² ,
X. Liang⁶² , C. Lin⁶ , T. Lin⁵¹ , R. Lindner⁴² , V. Lisovskyi¹⁵ , R. Litvinov^{27,h} ,
G. Liu⁶⁶ , H. Liu⁶ , K. Liu⁶⁷ , Q. Liu⁶ , S. Liu^{4,6} , A. Lobo Salvia³⁹ , A. Loi²⁷ ,
R. Lollini⁷² , J. Lomba Castro⁴⁰ , I. Longstaff⁵³ , J.H. Lopes² , A. Lopez Huertas³⁹ ,
S. López Soliño⁴⁰ , G.H. Lovell⁴⁹ , Y. Lu^{4,b} , C. Lucarelli^{22,j} , D. Lucchesi^{28,o} ,
S. Luchuk³⁸ , M. Lucio Martinez⁷⁴ , V. Lukashenko^{32,46} , Y. Luo³ , A. Lupato⁵⁶ ,
E. Luppi^{21,i} , A. Lusiani^{29,q} , K. Lynch¹⁸ , X.-R. Lyu⁶ , R. Ma⁶ , S. Maccolini¹⁵ ,
F. Machefert¹¹ , F. Maciuc³⁷ , I. Mackay⁵⁷ , V. Macko⁴³ , L.R. Madhan Mohan⁴⁹ ,
A. Maeviskiy³⁸ , D. Maisuzenko³⁸ , M.W. Majewski³⁴ , J.J. Malczewski³⁵ , S. Malde⁵⁷ ,
B. Malecki^{35,42} , A. Malinin³⁸ , T. Maltsev³⁸ , G. Manca^{27,h} , G. Mancinelli¹⁰ ,
C. Mancuso^{11,25,l} , R. Manera Escalero³⁹ , D. Manuzzi²⁰ , C.A. Manzari⁴⁴ ,
D. Marangotto^{25,l} , J.M. Maratas^{9,v} , J.F. Marchand⁸ , U. Marconi²⁰ , S. Mariani⁴² ,
C. Marin Benito³⁹ , J. Marks¹⁷ , A.M. Marshall⁴⁸ , P.J. Marshall⁵⁴ , G. Martelli^{72,p} ,
G. Martellotti³⁰ , L. Martinazzoli^{42,m} , M. Martinelli^{26,m} , D. Martinez Santos⁴⁰ ,
F. Martinez Vidal⁴¹ , A. Massafferri¹ , M. Materok¹⁴ , R. Matev⁴² , A. Mathad⁴⁴ ,
V. Matiunin³⁸ , C. Matteuzzi²⁶ , K.R. Mattioli¹² , A. Mauri⁵⁵ , E. Maurice¹² ,
J. Mauricio³⁹ , M. Mazurek⁴² , M. McCann⁵⁵ , L. McConnell¹⁸ , T.H. McGrath⁵⁶ ,
N.T. McHugh⁵³ , A. McNab⁵⁶ , R. McNulty¹⁸ , B. Meadows⁵⁹ , G. Meier¹⁵ ,
D. Melnychuk³⁶ , S. Meloni^{26,m} , M. Merk^{32,74} , A. Merli²⁵ , L. Meyer Garcia² ,
D. Miao^{4,6} , H. Miao⁶ , M. Mikhasenko^{70,d} , D.A. Milanese⁶⁹ , E. Millard⁵⁰ ,
M. Milovanovic⁴² , M.-N. Minard^{8,†} , A. Minotti^{26,m} , T. Miralles⁹ , S.E. Mitchell⁵² ,
B. Mitreska¹⁵ , D.S. Mittel¹⁵ , A. Modak⁵¹ , A. Mödden¹⁵ , R.A. Mohammed⁵⁷ ,
R.D. Moise¹⁴ , S. Mokhnenko³⁸ , T. Mombächer⁴⁰ , M. Monk^{50,63} , I.A. Monroy⁶⁹ ,
S. Monteil⁹ , G. Morello²³ , M.J. Morello^{29,q} , M.P. Morgenthaler¹⁷ , J. Moron³⁴ ,
A.B. Morris⁴² , A.G. Morris¹⁰ , R. Mountain⁶² , H. Mu³ , E. Muhammad⁵⁰ ,
F. Muheim⁵² , M. Mulder⁷³ , K. Müller⁴⁴ , C.H. Murphy⁵⁷ , D. Murray⁵⁶ ,
R. Murta⁵⁵ , P. Muzzetto^{27,h} , P. Naik⁴⁸ , T. Nakada⁴³ , R. Nandakumar⁵¹ ,
T. Nanut⁴² , I. Nasteva² , M. Needham⁵² , N. Neri^{25,l} , S. Neubert⁷⁰ , N. Neufeld⁴² ,
P. Neustroev³⁸ , R. Newcombe⁵⁵ , J. Nicolini^{15,11} , D. Nicotra⁷⁴ , E.M. Niel⁴³ ,
S. Nieswand¹⁴ , N. Nikitin³⁸ , N.S. Nolte⁵⁸ , C. Normand^{8,h,27} , J. Novoa Fernandez⁴⁰ ,
G.N Nowak⁵⁹ , C. Nunez⁷⁸ , A. Oblakowska-Mucha³⁴ , V. Obratsov³⁸ , T. Oeser¹⁴ ,
S. Okamura^{21,i} , R. Oldeman^{27,h} , F. Oliva⁵² , C.J.G. Onderwater⁷³ , R.H. O'Neil⁵² ,
J.M. Otalora Goicochea² , T. Ovsianikova³⁸ , P. Owen⁴⁴ , A. Oyanguren⁴¹ ,
O. Ozcelik⁵² , K.O. Padeken⁷⁰ , B. Pagare⁵⁰ , P.R. Pais⁴² , T. Pajero⁵⁷ , A. Palano¹⁹ ,
M. Palutan²³ , G. Panshin³⁸ , L. Paolucci⁵⁰ , A. Papanestis⁵¹ , M. Pappagallo^{19,f} ,
L.L. Pappalardo^{21,i} , C. Pappenheimer⁵⁹ , W. Parker⁶⁰ , C. Parkes⁵⁶ ,
B. Passalacqua^{21,i} , G. Passaleva²² , A. Pastore¹⁹ , M. Patel⁵⁵ , C. Patrignani^{20,g} ,
C.J. Pawley⁷⁴ , A. Pellegrino³² , M. Pepe Altarelli⁴² , S. Perazzini²⁰ , D. Pereima³⁸ ,
A. Pereiro Castro⁴⁰ , P. Perret⁹ , K. Petridis⁴⁸ , A. Petrolini^{24,k} , S. Petrucci⁵² ,
M. Petruzzo²⁵ , H. Pham⁶² , A. Philippov³⁸ , R. Piandani⁶ , L. Pica^{29,q} ,
M. Piccini⁷² , B. Pietrzyk⁸ , G. Pietrzyk¹¹ , M. Pili⁵⁷ , D. Pinci³⁰ , F. Pisani⁴² ,
M. Pizzichemi^{26,m,42} , V. Placinta³⁷ , J. Plews⁴⁷ , M. Plo Casaus⁴⁰ , F. Polci^{13,42} ,
M. Poli Lener²³ , A. Poluektov¹⁰ , N. Polukhina³⁸ , I. Polyakov⁴² , E. Polycarpo² ,

S. Ponce⁴², D. Popov^{6,42}, S. Poslavskii³⁸, K. Prasanth³⁵, L. Promberger¹⁷,
C. Prouve⁴⁰, V. Pugatch⁴⁶, V. Puill¹¹, G. Punzi^{29,r}, H.R. Qi³, W. Qian⁶,
N. Qin³, S. Qu³, R. Quagliani⁴³, N.V. Raab¹⁸, B. Rachwal³⁴,
J.H. Rademacker⁴⁸, R. Rajagopalan⁶², M. Rama²⁹, M. Ramos Pernas⁵⁰,
M.S. Rangel², F. Ratnikov³⁸, G. Raven³³, M. Rebollo De Miguel⁴¹, F. Redi⁴²,
J. Reich⁴⁸, F. Reiss⁵⁶, C. Remon Alepuz⁴¹, Z. Ren³, P.K. Resmi⁵⁷, R. Ribatti^{29,q},
A.M. Ricci²⁷, S. Ricciardi⁵¹, K. Richardson⁵⁸, M. Richardson-Slipper⁵²,
K. Rinnert⁵⁴, P. Robbe¹¹, G. Robertson⁵², E. Rodrigues^{54,42},
E. Rodriguez Fernandez⁴⁰, J.A. Rodriguez Lopez⁶⁹, E. Rodriguez Rodriguez⁴⁰,
D.L. Rolf⁴², A. Rollings⁵⁷, P. Roloff⁴², V. Romanovskiy³⁸, M. Romero Lamas⁴⁰,
A. Romero Vidal⁴⁰, J.D. Roth^{78,†}, M. Rotondo²³, M.S. Rudolph⁶², T. Ruf⁴²,
R.A. Ruiz Fernandez⁴⁰, J. Ruiz Vidal⁴¹, A. Ryzhikov³⁸, J. Ryzka³⁴,
J.J. Saborido Silva⁴⁰, N. Sagidova³⁸, N. Sahoo⁴⁷, B. Saitta^{27,h}, M. Salomoni⁴²,
C. Sanchez Gras³², I. Sanderswood⁴¹, R. Santacesaria³⁰, C. Santamarina Rios⁴⁰,
M. Santimaria²³, E. Santovetti^{31,t}, D. Saranin³⁸, G. Sarpis¹⁴, M. Sarpis⁷⁰,
A. Sarti³⁰, C. Satriano^{30,s}, A. Satta³¹, M. Saur¹⁵, D. Savrina³⁸, H. Sazak⁹,
L.G. Scantlebury Smead⁵⁷, A. Scarabotto¹³, S. Schael¹⁴, S. Scherl⁵⁴, M. Schiller⁵³,
H. Schindler⁴², M. Schmelling¹⁶, B. Schmidt⁴², S. Schmitt¹⁴, O. Schneider⁴³,
A. Schopper⁴², M. Schubiger³², S. Schulte⁴³, M.H. Schune¹¹, R. Schwemmer⁴²,
B. Sciascia²³, A. Sciuccati⁴², S. Sellam⁴⁰, A. Semennikov³⁸, M. Senghi Soares³³,
A. Sergi^{24,k}, N. Serra⁴⁴, L. Sestini²⁸, A. Seuthe¹⁵, Y. Shang⁵, D.M. Shangase⁷⁸,
M. Shapkin³⁸, I. Shchemerov³⁸, L. Shchutska⁴³, T. Shears⁵⁴, L. Shekhtman³⁸,
Z. Shen⁵, S. Sheng^{4,6}, V. Shevchenko³⁸, B. Shi⁶, E.B. Shields^{26,m}, Y. Shimizu¹¹,
E. Shmanin³⁸, R. Shorkin³⁸, J.D. Shupperd⁶², B.G. Siddi^{21,i}, R. Silva Coutinho⁶²,
G. Simi²⁸, S. Simone^{19,f}, M. Singla⁶³, N. Skidmore⁵⁶, R. Skuza¹⁷,
T. Skwarnicki⁶², M.W. Slater⁴⁷, J.C. Smallwood⁵⁷, J.G. Smeaton⁴⁹, E. Smith⁴⁴,
K. Smith⁶¹, M. Smith⁵⁵, A. Snoch³², L. Soares Lavra⁹, M.D. Sokoloff⁵⁹,
F.J.P. Soler⁵³, A. Solomin^{38,48}, A. Solovev³⁸, I. Solovyev³⁸, R. Song⁶³,
F.L. Souza De Almeida², B. Souza De Paula², B. Spaan^{15,†}, E. Spadaro Norella^{25,l},
E. Spedicato²⁰, J.G. Speer¹⁵, E. Spiridenkov³⁸, P. Spradlin⁵³, V. Sriskaran⁴²,
F. Stagni⁴², M. Stahl⁴², S. Stahl⁴², S. Stanislaus⁵⁷, E.N. Stein⁴², O. Steinkamp⁴⁴,
O. Stenyakin³⁸, H. Stevens¹⁵, D. Strelakina³⁸, Y.S. Su⁶, F. Suljik⁵⁷, J. Sun²⁷,
L. Sun⁶⁸, Y. Sun⁶⁰, P.N. Swallow⁴⁷, K. Swientek³⁴, A. Szabelski³⁶, T. Szumlak³⁴,
M. Szymanski⁴², Y. Tan³, S. Taneja⁵⁶, M.D. Tat⁵⁷, A. Terentev⁴⁴, F. Teubert⁴²,
E. Thomas⁴², D.J.D. Thompson⁴⁷, K.A. Thomson⁵⁴, H. Tilquin⁵⁵, V. Tisserand⁹,
S. T'Jampens⁸, M. Tobin⁴, L. Tomassetti^{21,i}, G. Tonani^{25,l}, X. Tong⁵,
D. Torres Machado¹, D.Y. Tou³, C. Trippl⁴³, G. Tuci⁶, N. Tuning³², A. Ukleja³⁶,
D.J. Unverzagt¹⁷, A. Usachov³³, A. Ustyuzhanin³⁸, U. Uwer¹⁷, V. Vagnoni²⁰,
A. Valassi⁴², G. Valenti²⁰, N. Valls Canudas⁷⁶, M. Van Dijk⁴³, H. Van Hecke⁶¹,
E. van Herwijnen⁵⁵, C.B. Van Hulse^{40,w}, M. van Veghel³², R. Vazquez Gomez³⁹,
P. Vazquez Regueiro⁴⁰, C. Vázquez Sierra⁴², S. Vecchi²¹, J.J. Velthuis⁴⁸,
M. Veltri^{22,u}, A. Venkateswaran⁴³, M. Veronesi³², M. Vesterinen⁵⁰, D. Vieira⁵⁹,
M. Vieites Diaz⁴³, X. Vilasis-Cardona⁷⁶, E. Vilella Figueras⁵⁴, A. Villa²⁰,
P. Vincent¹³, F.C. Volle¹¹, D. vom Bruch¹⁰, A. Vorobyev³⁸, V. Vorobyev³⁸,
N. Voropaev³⁸, K. Vos⁷⁴, C. Vrahas⁵², J. Walsh²⁹, E.J. Walton⁶³, G. Wan⁵,
C. Wang¹⁷, G. Wang⁷, J. Wang⁵, J. Wang⁴, J. Wang³, J. Wang⁶⁸, M. Wang²⁵,
R. Wang⁴⁸, X. Wang⁶⁶, Y. Wang⁷, Z. Wang⁴⁴, Z. Wang³, Z. Wang⁶,
J.A. Ward^{50,63}, N.K. Watson⁴⁷, D. Websdale⁵⁵, Y. Wei⁵, B.D.C. Westhenry⁴⁸,
D.J. White⁵⁶, M. Whitehead⁵³, A.R. Wiederhold⁵⁰, D. Wiedner¹⁵, G. Wilkinson⁵⁷,
M.K. Wilkinson⁵⁹, I. Williams⁴⁹, M. Williams⁵⁸, M.R.J. Williams⁵², R. Williams⁴⁹,

F.F. Wilson⁵¹ , W. Wislicki³⁶ , M. Witek³⁵ , L. Witola¹⁷ , C.P. Wong⁶¹ ,
G. Wormser¹¹ , S.A. Wotton⁴⁹ , H. Wu⁶² , J. Wu⁷ , K. Wyllie⁴² , Z. Xiang⁶ ,
Y. Xie⁷ , A. Xu⁵ , J. Xu⁶ , L. Xu³ , L. Xu³ , M. Xu⁵⁰ , Q. Xu⁶ , Z. Xu⁹ , Z. Xu⁶ ,
D. Yang³ , S. Yang⁶ , X. Yang⁵ , Y. Yang⁶ , Z. Yang⁵ , Z. Yang⁶⁰ ,
L.E. Yeomans⁵⁴ , V. Yeroshenko¹¹ , H. Yeung⁵⁶ , H. Yin⁷ , J. Yu⁶⁵ , X. Yuan⁶² ,
E. Zaffaroni⁴³ , M. Zavertyaev¹⁶ , M. Zdybal³⁵ , M. Zeng³ , C. Zhang⁵ , D. Zhang⁷ ,
L. Zhang³ , S. Zhang⁶⁵ , S. Zhang⁵ , Y. Zhang⁵ , Y. Zhang⁵⁷ , Y. Zhao¹⁷ ,
A. Zharkova³⁸ , A. Zhelezov¹⁷ , Y. Zheng⁶ , T. Zhou⁵ , X. Zhou⁷ , Y. Zhou⁶ ,
V. Zhovkovska¹¹ , X. Zhu³ , X. Zhu⁷ , Z. Zhu⁶ , V. Zhukov^{14,38} , Q. Zou^{4,6} ,
S. Zucchelli^{20,g} , D. Zuliani²⁸ , G. Zunica⁵⁶ .

¹Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil

²Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

³Center for High Energy Physics, Tsinghua University, Beijing, China

⁴Institute Of High Energy Physics (IHEP), Beijing, China

⁵School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

⁶University of Chinese Academy of Sciences, Beijing, China

⁷Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China

⁸Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France

⁹Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France

¹⁰Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

¹¹Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France

¹²Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

¹³LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France

¹⁴I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany

¹⁵Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany

¹⁶Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany

¹⁷Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

¹⁸School of Physics, University College Dublin, Dublin, Ireland

¹⁹INFN Sezione di Bari, Bari, Italy

²⁰INFN Sezione di Bologna, Bologna, Italy

²¹INFN Sezione di Ferrara, Ferrara, Italy

²²INFN Sezione di Firenze, Firenze, Italy

²³INFN Laboratori Nazionali di Frascati, Frascati, Italy

²⁴INFN Sezione di Genova, Genova, Italy

²⁵INFN Sezione di Milano, Milano, Italy

²⁶INFN Sezione di Milano-Bicocca, Milano, Italy

²⁷INFN Sezione di Cagliari, Monserrato, Italy

²⁸Università degli Studi di Padova, Università e INFN, Padova, Padova, Italy

²⁹INFN Sezione di Pisa, Pisa, Italy

³⁰INFN Sezione di Roma La Sapienza, Roma, Italy

³¹INFN Sezione di Roma Tor Vergata, Roma, Italy

³²Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands

³³Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands

³⁴AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland

³⁵Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland

³⁶National Center for Nuclear Research (NCBJ), Warsaw, Poland

³⁷Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania

³⁸Affiliated with an institute covered by a cooperation agreement with CERN

³⁹ICCUB, Universitat de Barcelona, Barcelona, Spain

⁴⁰Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain

- ⁴¹ *Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
- ⁴² *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
- ⁴³ *Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
- ⁴⁴ *Physik-Institut, Universität Zürich, Zürich, Switzerland*
- ⁴⁵ *NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
- ⁴⁶ *Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
- ⁴⁷ *University of Birmingham, Birmingham, United Kingdom*
- ⁴⁸ *H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- ⁴⁹ *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ⁵⁰ *Department of Physics, University of Warwick, Coventry, United Kingdom*
- ⁵¹ *STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ⁵² *School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵³ *School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵⁴ *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁵⁵ *Imperial College London, London, United Kingdom*
- ⁵⁶ *Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁵⁷ *Department of Physics, University of Oxford, Oxford, United Kingdom*
- ⁵⁸ *Massachusetts Institute of Technology, Cambridge, MA, United States*
- ⁵⁹ *University of Cincinnati, Cincinnati, OH, United States*
- ⁶⁰ *University of Maryland, College Park, MD, United States*
- ⁶¹ *Los Alamos National Laboratory (LANL), Los Alamos, NM, United States*
- ⁶² *Syracuse University, Syracuse, NY, United States*
- ⁶³ *School of Physics and Astronomy, Monash University, Melbourne, Australia, associated to ⁵⁰*
- ⁶⁴ *Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to ²*
- ⁶⁵ *Physics and Micro Electronic College, Hunan University, Changsha City, China, associated to ⁷*
- ⁶⁶ *Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Institute of Quantum Matter, South China Normal University, Guangzhou, China, associated to ³*
- ⁶⁷ *Lanzhou University, Lanzhou, China, associated to ⁴*
- ⁶⁸ *School of Physics and Technology, Wuhan University, Wuhan, China, associated to ³*
- ⁶⁹ *Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia, associated to ¹³*
- ⁷⁰ *Universität Bonn - Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany, associated to ¹⁷*
- ⁷¹ *Eotvos Lorand University, Budapest, Hungary, associated to ⁴²*
- ⁷² *INFN Sezione di Perugia, Perugia, Italy, associated to ²¹*
- ⁷³ *Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to ³²*
- ⁷⁴ *Universiteit Maastricht, Maastricht, Netherlands, associated to ³²*
- ⁷⁵ *Faculty of Material Engineering and Physics, Cracow, Poland, associated to ³⁵*
- ⁷⁶ *DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain, associated to ³⁹*
- ⁷⁷ *Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden, associated to ⁵³*
- ⁷⁸ *University of Michigan, Ann Arbor, MI, United States, associated to ⁶²*

^a *Universidade de Brasília, Brasília, Brazil*

^b *Central South U., Changsha, China*

^c *Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China*

^d *Excellence Cluster ORIGINS, Munich, Germany*

^e *Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras*

^f *Università di Bari, Bari, Italy*

^g *Università di Bologna, Bologna, Italy*

^h *Università di Cagliari, Cagliari, Italy*

ⁱ *Università di Ferrara, Ferrara, Italy*

^j *Università di Firenze, Firenze, Italy*

^k *Università di Genova, Genova, Italy*

^l *Università degli Studi di Milano, Milano, Italy*

^m *Università di Milano Bicocca, Milano, Italy*

ⁿ *Università di Modena e Reggio Emilia, Modena, Italy*

^o *Università di Padova, Padova, Italy*

^p *Università di Perugia, Perugia, Italy*

^q *Scuola Normale Superiore, Pisa, Italy*

^r *Università di Pisa, Pisa, Italy*

^s *Università della Basilicata, Potenza, Italy*

^t *Università di Roma Tor Vergata, Roma, Italy*

^u *Università di Urbino, Urbino, Italy*

^v *MSU - Iligan Institute of Technology (MSU-IIT), Iligan, Philippines*

^w *Universidad de Alcalá, Alcalá de Henares, Spain*

[†] *Deceased*