EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: EPJ C

CERN-EP-2023-193
29th September 2023

Measurement of the production cross-section of J/ψ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Measurements of the differential production cross-sections of prompt and non-prompt J/ψ and $\psi(2S)$ mesons with transverse momenta between 8 and 360 GeV and rapidity in the range $|y| < 2$ are reported. Furthermore, measurements of the non-prompt fractions of J/ψ and $\psi(2S)$, and the prompt and non-prompt $\psi(2S)$-to-J/ψ production ratios, are presented. The analysis is performed using 140 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data recorded by the ATLAS detector at the LHC during the years 2015–2018.

1 Introduction

Studies involving heavy quarkonia provide a unique insight into the nature of quantum chromodynamics (QCD) near the boundary of the perturbative and non-perturbative regimes. However, despite a long history of research, quarkonium production in hadronic collisions still presents significant challenges to both theory and experiment.

In high-energy hadronic collisions, charmonium states can be produced either from short-lived QCD sources (referred to as 'prompt' production) or from long-lived sources – decays of beauty hadrons ('non-prompt' production). These sources can be distinguished experimentally by measuring the distance between the production and decay vertices of the charmonium state. Feed-down decays of higher charmonium states contribute to the production of J/ψ mesons, whereas they do not contribute significantly to $\psi(2S)$ production. While calculations within the framework of perturbative QCD (see e.g. Refs. [1, 2]) have been reasonably successful in describing the non-prompt contributions, a satisfactory understanding of the prompt production mechanisms is still to be achieved.

Methods developed within the non-relativistic QCD (NRQCD) approach provide a framework for describing quarkonium production processes, leading to a variety of models differing in their accuracy and predictive power. In particular, Ref. [3] introduced a number of phenomenological parameters – long-distance matrix elements (LDMEs) – which can be extracted from fits to the experimental data, and are expected to describe the cross-sections and differential spectra reasonably well [4–7]. However, various attempts to build a universal 'library' of LDMEs to be used to describe a wider range of measurements such as the polarisation of quarkonia [8–11], their associated production [12, 13] or the production of quarkonium in a wider range of processes (e.g. photo- and electro-production) have not been particularly successful [14–18]. A combination of ATLAS results with cross-section and polarisation measurements from CMS [7, 19, 20], LHCb [6, 21–25] and ALICE [11, 26–32] now includes a variety of charmonium production characteristics in a wide kinematic range, thus providing a wealth of information for a new generation of theoretical models.

One way to add qualitatively new information is to extend the kinematic range of quarkonium production measurements. ATLAS has previously measured the inclusive differential cross-section for J/ψ production in pp collisions at $\sqrt{s} = 7$ and 8 TeV [4], as well as the differential cross-sections for the production of χ_c states [33], and for $\psi(2S)$ production [5]. In most of these measurements, ATLAS exploited a dimuon trigger with a muon transverse momentum (p_T) threshold of 4 GeV, with the high-p_T reach limited mainly by the dimuon trigger's performance to about 100 GeV: at higher p_T values the angular resolution of the muon trigger system is not sufficient to separate the two almost collinear muons. This paper describes a measurement of J/ψ ($\psi(2S)$) meson production and decay in the dimuon channel, at $\sqrt{s} = 13$ TeV and for meson transverse momenta of 8–360 GeV (8–140 GeV), which is a much broader range than in previous measurements. This was made possible by the use of two different triggers. Production of J/ψ and $\psi(2S)$ at low p_T, between 8 and 60 GeV, is measured using a dimuon trigger requiring a pair of muons to each pass a p_T threshold of 4 GeV, while at high p_T a single-muon trigger with a p_T threshold of 50 GeV was used. This allowed measurements to be performed for transverse momenta as high as 360 GeV for J/ψ and 140 GeV for $\psi(2S)$. The measurements include the double-differential cross-sections for production of the two vector charmonium states (separately for the prompt and non-prompt production mechanisms), the non-prompt fraction for each state, and the prompt and non-prompt $\psi(2S)$-to-J/ψ production ratios.

The paper is organised as follows. A brief description of the ATLAS detector is given in Section 2. The event selection and the analysis strategy are explained in Section 3, followed by a description of the systematic uncertainties affecting the measurement in Section 4. Results and comparisons with theoretical calculations are presented in Section 5, followed by a summary in Section 6.

2 The ATLAS detector

The ATLAS experiment [34] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Metal/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer has a system of precision chambers for tracking and fast detectors for triggering. A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. An extensive software suite [35] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Analysis strategy

3.1 Event selection

Data for this analysis were taken during the LHC proton–proton collision runs at $\sqrt{s} = 13$ TeV in the years 2015 to 2018. For lower values of the transverse momentum p_{T} of the dimuon system, between 8 and 60 GeV, a dimuon trigger was used, requiring a pair of muons to each pass a p_{T} threshold of 4 GeV. This trigger ran unprescaled during 2015 data-taking, with an integrated luminosity of 2.6 fb^{-1}. In the high p_{T} range between 60 and 360 GeV, a single-muon trigger with a p_{T} threshold of 50 GeV was used, unprescaled throughout the full Run 2 data-taking, with a total integrated luminosity of 140 fb^{-1}. The selected events were required to contain a pair of oppositely charged muons of high quality (using the ‘tight’ identification requirements defined in Ref. [36]), with $p_{\mathrm{T}} > 4$ GeV and $|\eta| < 2.4$. In the low p_{T} range the two muons were required to match the two trigger objects of the dimuon trigger, while in the high p_{T} range at least one of the muons was required to have $p_{\mathrm{T}} > 52.5$ GeV and match the trigger object. The two ID tracks attributed to the muons were fitted to a common vertex, and the dimuon invariant mass $m_{\mu\mu}$

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

was required to satisfy $2.6 < m_{\mu\mu} < 4.2$ GeV. The transverse distance L_{xy} between the primary vertex and the dimuon vertex was used to calculate the meson's pseudo-proper decay time

$$\tau = \frac{m_{\mu\mu}}{p_{\mathrm{T}}} \frac{L_{xy}}{c},$$

where p_{T} is the reconstructed transverse momentum of the dimuon system, and c is the speed of light. The primary vertex is chosen as the reconstructed collision interaction vertex whose z coordinate is nearest to the point of closest approach of the dimuon system's trajectory to the beam axis. If an event has more than one selected dimuon candidate, all candidates are retained and treated independently.

3.2 Cross-section determination

The phase space of the measurement is divided into 34 intervals in dimuon p_{T} covering the range from 8 to 360 GeV, and 3 intervals in absolute rapidity[2] $|y|$ with boundaries at 0, 0.75, 1.5 and 2.0, thus producing 102 'analysis bins' overall. In each (p_{T}, y) bin, a two-dimensional unbinned maximum-likelihood fit to the distribution of dimuon candidates in invariant mass $m_{\mu\mu}$ and pseudo-proper decay time τ of the ψ meson is performed to obtain the raw yields $N_{\psi}^{\mathrm{P,NP}}$ for prompt (P) and non-prompt (NP) ψ mesons, where $\psi = J/\psi,\ \psi(2S)$. The raw yields are then corrected to account for the geometrical acceptance $\mathcal{A}(\psi)$, the trigger and reconstruction efficiencies ϵ_{trig} and ϵ_{reco}, and the trigger and reconstruction correction scale factors $\epsilon_{\mathrm{trigSF}}$ and $\epsilon_{\mathrm{recoSF}}$, averaged over that bin. Several low p_{T} bins are divided into narrower sub-bins to obtain raw yields in finer granularity, which are then corrected and summed to give the final yield in the corresponding analysis bin. This procedure helps to reduce measurement biases due to modelling assumptions in the regions of phase space with large statistical power.

The prompt (P) and non-prompt (NP) double-differential production cross-sections for $\psi = J/\psi,\ \psi(2S)$ in each analysis bin are calculated as

$$\frac{\mathrm{d}^2\sigma^{\mathrm{P,NP}}(pp \to \psi)}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \times \mathcal{B}(\psi \to \mu^+\mu^-) = \frac{1}{\mathcal{A}(\psi)\epsilon_{\mathrm{trig}}\epsilon_{\mathrm{trigSF}}\epsilon_{\mathrm{reco}}\epsilon_{\mathrm{recoSF}}} \frac{N_{\psi}^{\mathrm{P,NP}}}{\Delta p_{\mathrm{T}}\ \Delta y\ \int \mathcal{L}\mathrm{d}t}, \quad (1)$$

where Δp_{T} and Δy are bin widths in p_{T} and rapidity, and $\int \mathcal{L}\mathrm{d}t$ is the corresponding integrated luminosity. Bin migration effects are discussed in Section 3.4. The acceptance $\mathcal{A}(\psi)$ is defined as the probability that a ψ state with (true) momentum within an analysis bin survives the following acceptance cuts imposed on the two muons (assuming $p_{\mathrm{T}}(\mu1) > p_{\mathrm{T}}(\mu2)$) in the two ψ p_{T} ranges:

- low p_{T} range, $p_{\mathrm{T}}(\psi) < 60$ GeV: $p_{\mathrm{T}}(\mu_1) > 4$ GeV, $p_{\mathrm{T}}(\mu_2) > 4$ GeV, $|\eta(\mu_1)|, |\eta(\mu_2)| < 2.4$;
- high p_{T} range, $p_{\mathrm{T}}(\psi) \geq 60$ GeV: $p_{\mathrm{T}}(\mu_1) > 52.5$ GeV, $p_{\mathrm{T}}(\mu_2) > 4$ GeV, $|\eta(\mu_1)|, |\eta(\mu_2)| < 2.4$.

The acceptance calculation is performed using Monte Carlo (MC) generator-level kinematic variables, with resolution effects taken into account at the efficiency correction stage. An isotropic angular distribution of muons in the ψ decay frame is assumed. Since the spin alignment of the ψ states may affect the acceptance, a number of non-isotropic spin-alignment scenarios are used to calculate correction factors for the measured cross-sections (see Appendix). For a given spin-alignment scenario, systematic uncertainties due to the acceptance calculation are small (see Section 4). Changing to a different spin-alignment scenario, however,

[2] Rapidity y of a particle of energy E and longitudinal momentum p_z is defined as $y = \frac{1}{2}\log\frac{E+p_z}{E-p_z}$.

can lead to noticeable changes in the cross-sections and other measured quantities, including variations as a function of p_{T} (see Section 5).

The reconstruction efficiency ϵ_{reco} and trigger efficiency ϵ_{trig} are calculated using samples of fully simulated J/ψ and $\psi(2\mathrm{S})$ events, including appropriate trigger information (see Section 3.4 for more details). Correction scale factors $\epsilon_{\mathrm{recoSF}}$ and $\epsilon_{\mathrm{trigSF}}$ account for the differences between simulated and real data.

The non-prompt fractions for $\psi = J/\psi, \psi(2\mathrm{S})$ are defined as

$$F_{\psi}^{\mathrm{NP}}(p_{\mathrm{T}}, y) \quad = \quad \frac{\mathrm{d}^2\sigma^{\mathrm{NP}}(pp \to \psi)}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \times \left[\frac{\mathrm{d}^2\sigma^{\mathrm{P}}(pp \to \psi)}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} + \frac{\mathrm{d}^2\sigma^{\mathrm{NP}}(pp \to \psi)}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \right]^{-1} . \qquad (2)$$

Finally, $\psi(2\mathrm{S})$-to-J/ψ production ratios are defined separately for the prompt and non-prompt production mechanisms as

$$\begin{aligned} R^{\mathrm{P,NP}}(p_{\mathrm{T}}, y) \quad = \quad & \frac{\mathrm{d}^2\sigma^{\mathrm{P,NP}}(pp \to \psi(2\mathrm{S}))}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \times \mathcal{B}(\psi(2\mathrm{S}) \to \mu^+\mu^-) \\ & \times \left[\frac{\mathrm{d}^2\sigma^{\mathrm{P,NP}}(pp \to J/\psi)}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \times \mathcal{B}(J/\psi \to \mu^+\mu^-) \right]^{-1} . \qquad (3) \end{aligned}$$

In calculating these quantities, the event yields, efficiencies, and acceptance corrections are used in accord with Eq. (1); uncertainties in the fraction and ratio measurements partially cancel out.

3.3 Fit model

The fit model's probability distribution function $F(m_{\mu\mu}, \tau)$ contains seven terms,

$$F(m_{\mu\mu}, \tau) = \sum_{i=1}^{7} \kappa_i P_i(m_{\mu\mu}, \tau),$$

with fractions κ_i, describing four signal contributions and three types of background. Terms $i = 1, 2$ describe prompt and non-prompt J/ψ signal respectively; terms $i = 3, 4$ correspond to prompt and non-prompt $\psi(2\mathrm{S})$ signal. Term $i = 5$ describes the prompt background, where non-resonant dimuons are produced at the primary vertex (e.g. Drell–Yan pairs). Term $i = 6$ describes 'single-sided' non-prompt background, mainly for dimuon continuum events where the two muons originate from the (cascade) decay of a single b-hadron, while term $i = 7$ describes the 'double-sided' part of the non-prompt continuum, where the two muons originate from different b-hadrons, yielding a secondary vertex which may appear on either side of the beamline. For $i = 2$–7, each term is factorised into a function $f_i(m_{\mu\mu})$ of dimuon mass $m_{\mu\mu}$ and a function $h_i(\tau)$ of pseudo-proper decay time τ, where the latter is convolved with a decay time resolution function $R(\tau)$:

$$P_i(m_{\mu\mu}, \tau) = f_i(m_{\mu\mu}) \cdot [h_i(\tau) \otimes R(\tau)] .$$

The term with $i = 1$, which describes the prompt J/ψ peak, has a similar structure but allows for some correlations between $m_{\mu\mu}$ and τ, as described below.

The decay time resolution function $R(\tau)$ is parameterised as a sum of three Gaussian functions, $G_{\mathrm{A}}, G_{\mathrm{B}}$ and G_{C}, with the relative weights of the first two, ω_{A} and ω_{B}, treated as free parameters:

$$R(\tau) = \omega_{\mathrm{A}} G_{\mathrm{A}}(\tau) + \omega_{\mathrm{B}} G_{\mathrm{B}}(\tau) + (1 - \omega_{\mathrm{A}} - \omega_{\mathrm{B}}) G_{\mathrm{C}}(\tau).$$

Based on MC studies with fully simulated signal samples, the means of the three Gaussian functions are fixed to zero, and the widths are linked by $\sigma_{\mathrm{B}} = 2\sigma_{\mathrm{A}}$ and $\sigma_{\mathrm{C}} = 4\sigma_{\mathrm{A}}$, where $\sigma_{\mathrm{A}} = 0.04$ ps is fixed to the smallest value found in test fits.

The parameterisations of the functions $f_i(m_{\mu\mu})$ and $h_i(\tau)$ are summarised in Table 1. The mass lineshapes of the J/ψ and ψ(2S) peaks, $f_i(m_{\mu\mu})$ for $i = 1$ to 4, are parameterised as weighted sums of two Gaussian functions and a Crystal Ball function [37], which are the same for the prompt and non-prompt components. Based on MC studies, the weights are common to J/ψ and ψ(2S), while the ratios of the peak positions and the widths are fixed to the ratio β of the masses [38] of the two states. The lifetime distributions $h_1(\tau)$ and $h_3(\tau)$ of prompt J/ψ and ψ(2S), respectively, are parameterised as delta functions, while for non-prompt ψ(2S), a single-sided exponential function is used for $h_4(\tau)$. Since the non-prompt J/ψ sample is larger and has a wider observed τ range, its decay time distribution $h_2(\tau)$ is described by a superposition of two single-sided exponential functions with slopes related by $\gamma_1 = b\gamma_2$, where the constant $b = 1.4$ is obtained from test fits. All these exponential functions are convolved with the resolution function $R(\tau)$.

In the $i = 1$ term, describing the prompt J/ψ peak, the product of the narrowest Gaussian term in $f_1(m_{\mu\mu})$ and the narrowest Gaussian term in $R(\tau)$ was replaced by a bivariate Gaussian function in $m_{\mu\mu}$ and τ with a correlation coefficient $\rho = 0.3$,

$$\omega_0 G_1(m_{\mu\mu};\sigma_1) \cdot f_{\mathrm{A}} G_{\mathrm{A}}(\tau;\sigma_{\mathrm{A}}) \mapsto \omega_0 f_{\mathrm{A}} G_{\mathrm{BV}}(m_{\mu\mu},\tau;\sigma_1,\sigma_{\mathrm{A}},\rho), \tag{4}$$

to take into account the observed correlation between the measured values of these quantities.

Parameterisations for the background terms are selected using both the experience gained from similar analyses at lower energies [4] and physics considerations. In the prompt background term, $i = 5$, the mass distribution is modelled by a second-order polynomial, while the non-prompt mass distributions for $i = 6$ and 7 are parameterised as exponential functions, with independent parameters. The decay time distribution is a delta function for the prompt term $i = 5$, a single-sided exponential function for the main non-prompt term $i = 6$, and a symmetric double-sided exponential function for the last term, $i = 7$. Each of these is also convolved with the decay time resolution function $R(\tau)$.

Table 1: Parameterisation of the fit model. Here G, CB, E and P denote Gaussian, Crystal Ball, exponential and second-order polynomial functions, respectively, with different indices corresponding to different parameters. The parameterisation of the $i = 1$ term is modified as described in the text and shown in Eq. (4).

i	Type	P/NP	$f_i(m)$	$h_i(\tau)$
1	J/ψ	P	$\omega_0 G_1(m) + (1-\omega_0)[\omega_1 CB(m) + (1-\omega_1)G_2(m)]$	$\delta(\tau)$
2	J/ψ	NP	$\omega_0 G_1(m) + (1-\omega_0)[\omega_1 CB(m) + (1-\omega_1)G_2(m)]$	$\omega_2 E_1(\tau) + (1-\omega_2)E_1(b\tau)$
3	$\psi(2S)$	P	$\omega_0 G_1(\beta m) + (1-\omega_0)[\omega_1 CB(\beta m) + (1-\omega_1)G_2(\beta m)]$	$\delta(\tau)$
4	$\psi(2S)$	NP	$\omega_0 G_1(\beta m) + (1-\omega_0)[\omega_1 CB(\beta m) + (1-\omega_1)G_2(\beta m)]$	$E_2(\tau)$
5	Bkg	P	P	$\delta(\tau)$
6	Bkg	NP	$E_3(m)$	$E_4(\tau)$
7	Bkg	NP	$E_5(m)$	$E_6(\lvert\tau\rvert)$

Fits are performed in each (sub-)bin using an unbinned maximum-likelihood method, in the dimuon mass range from 2.7 to 4.1 GeV and the decay time range between −1 and 11 ps. Twenty of the 29 parameters are determined from the fit, with the rest fixed to predetermined values obtained from test fits using samples of MC simulated J/ψ and ψ(2S) signal events. Uncertainties due to variations of the fit model and assumptions about the fixed parameters are estimated during the studies of systematic uncertainties described in Section 4. In particular, it is found that a reliable determination of the cross-sections for prompt and non-prompt production of the $\psi(2S)$ meson is only possible up to $p_T = 140$ GeV, mainly due poorer mass resolution and a lower signal-to-background ratio at higher p_T. For $p_T > 140$ GeV the yield of $\psi(2S)$ was fixed to a constant fraction (0.07) of the yield of J/ψ, by extrapolating the results from the fits at lower transverse momenta.

Figure 1 shows the mass and pseudo-proper decay time projections of the fits in several sample bins, together with the associated pull distributions. The quality of the fits, assessed by calculating a two-dimensional χ^2 value, is found to be good in all (sub-)bins.

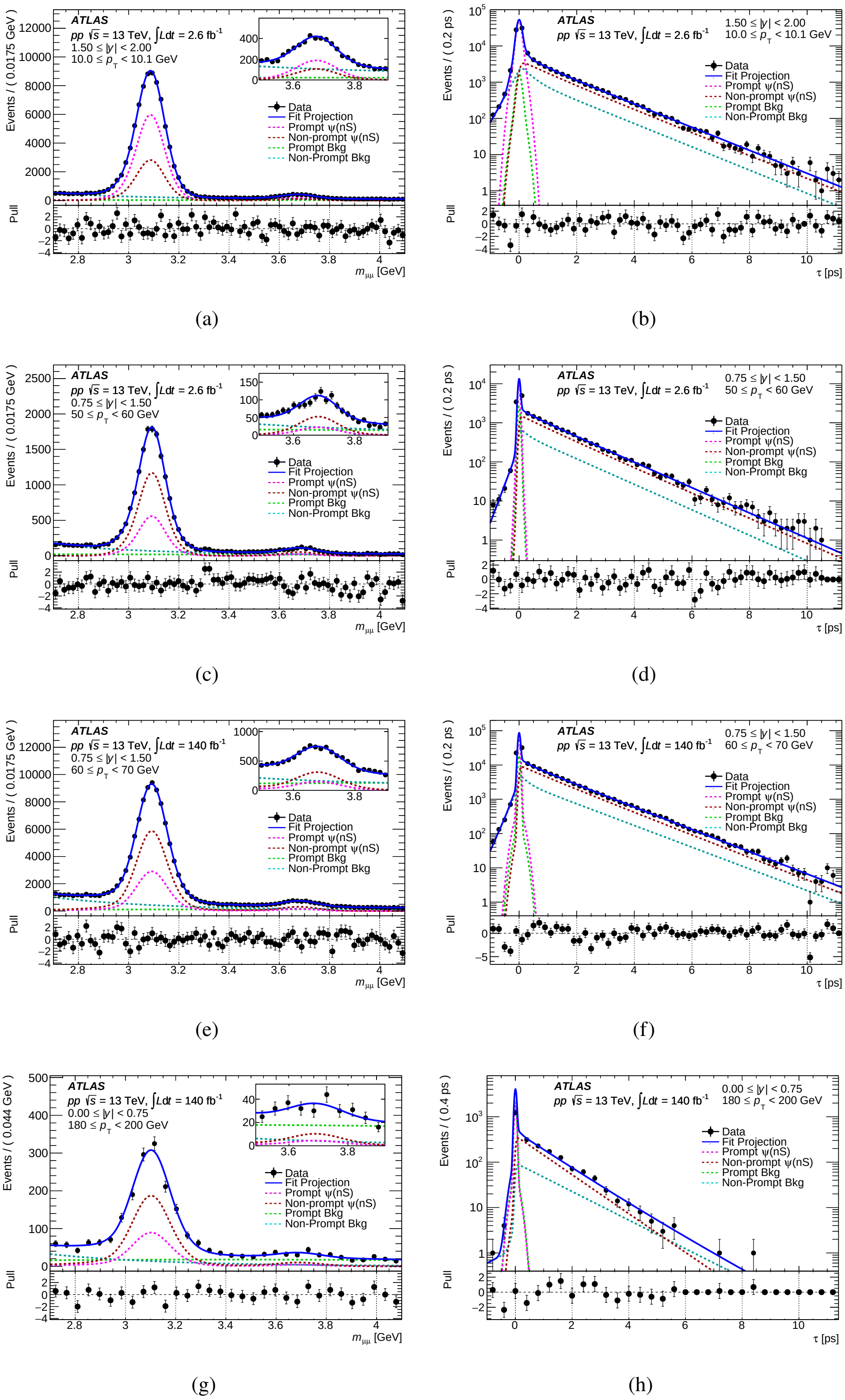


Figure 1: Mass (left) and pseudo-proper decay time (right) projections of the fit result for selected analysis (sub-)bins.

The main parameters determined from the fits are the prompt and non-prompt yields of J/ψ and $\psi(2S)$ states. The cross-sections, non-prompt fractions and production ratios were then calculated using Eqs. (1)–(3). The results for all measured quantities are presented in Section 5.

3.4 Efficiency corrections

As shown in Eq. (1), the yields obtained from two-dimensional maximum-likelihood fits in each (sub-)bin are subject to acceptance corrections, followed by the corrections for reconstruction and trigger efficiencies obtained from J/ψ and $\psi(2S)$ MC simulations, and by the correction scale factors that account for differences between data and MC simulation.

MC samples used for efficiency determinations were produced either by the Pythia 8 generator [39] with the A14 set of tuned parameters [40], or by a custom 'particle gun' generator producing single ψ states with a given distribution, followed by their decay into a dimuon final state. The generated events were passed through the full ATLAS detector simulation [41] based on Geant4 [42], and were reconstructed using the same software as the real data. The reconstruction efficiency ϵ_{reco} in each analysis (sub-)bin is defined as the ratio

$$\epsilon_{\text{reco}} = \frac{N_{\text{reco}}}{N_{\text{true}}},$$

where N_{reco} is the reconstructed yield within the bin boundaries defined in terms of reconstructed variables, with fiducial cuts applied to reconstructed variables, while N_{true} is the true (generated) yield within the bin boundaries defined in terms of true variable values, with fiducial cuts applied to the true variable values. This definition takes into account detector resolution smearing of the kinematic variables used to define the fiducial cuts and bin boundaries, and hence includes 'bin migration' effects between neighbouring bins.

The trigger efficiency ϵ_{trig}, also obtained using MC simulations, is defined fully in terms of reconstructed variables as

$$\epsilon_{\text{trig}} = \frac{N_{\text{trig}}}{N_{\text{reco}}},$$

where N_{trig} is the number of triggered events among the reconstructed events. Since this measurement used two different triggers, the trigger efficiency was calculated accordingly. Further correction scale factors, ϵ_{recoSF} and ϵ_{trigSF}, are applied to account for any differences between data and MC events at reconstruction level and trigger level (see Eq. (1)). These are evaluated in dedicated 'tag-and-probe' studies with auxiliary triggers, using a mixture of $J/\psi \to \mu^+\mu^-$ and $Z \to \mu^+\mu^-$ decays (see Ref. [36] for details).

4 Systematic uncertainties

Systematic effects from a variety of sources were studied, and appropriate corrections and uncertainties were assigned. The systematic uncertainties can be broadly grouped into those related to reconstruction, trigger, and acceptance corrections, and those related to the fit model.

In order to assess the systematic uncertainties related to the fit model, the fit model was varied in several ways. As mentioned in Section 3.3, in the nominal fits some of the parameters describing the lineshapes of the signal peaks in the mass and lifetime domains were fixed to the values obtained from signal MC studies. These include the values of parameters α and n of the Crystal Ball function, the constant β linking the positions of the J/ψ and $\psi(2S)$ mass peaks, and the factor b relating the slopes of the two exponential functions describing the distribution of J/ψ decay times, τ. These parameters were allowed to float, one at a time, and the fits were repeated. Some variations covered changes in the decay time resolution parameterisation, with widths of the three Gaussian functions changed independently. In other variations, alternative parameterisations were chosen for the mass dependence of the background terms, and the fits were repeated. Finally, in the highest p_{T} bins, $p_{\mathrm{T}} > 140$ GeV, the fixed fraction 0.07, relating the $\psi(2\mathrm{S})$ and J/ψ yields, was varied by 0.01 to cover the observed range at lower p_{T} values, and the fits were run again. After each rerun, changes in the measured yields were recorded. The outcome of this process, in each analysis bin, was a number of measurements of each yield, scattered around the result of the nominal fit for that yield. It was assumed that the probability distribution of these variations around the nominal value was uniform between the smallest and largest measured values, and, therefore, the corresponding systematic uncertainty was evaluated as the standard deviation of this uniform distribution.

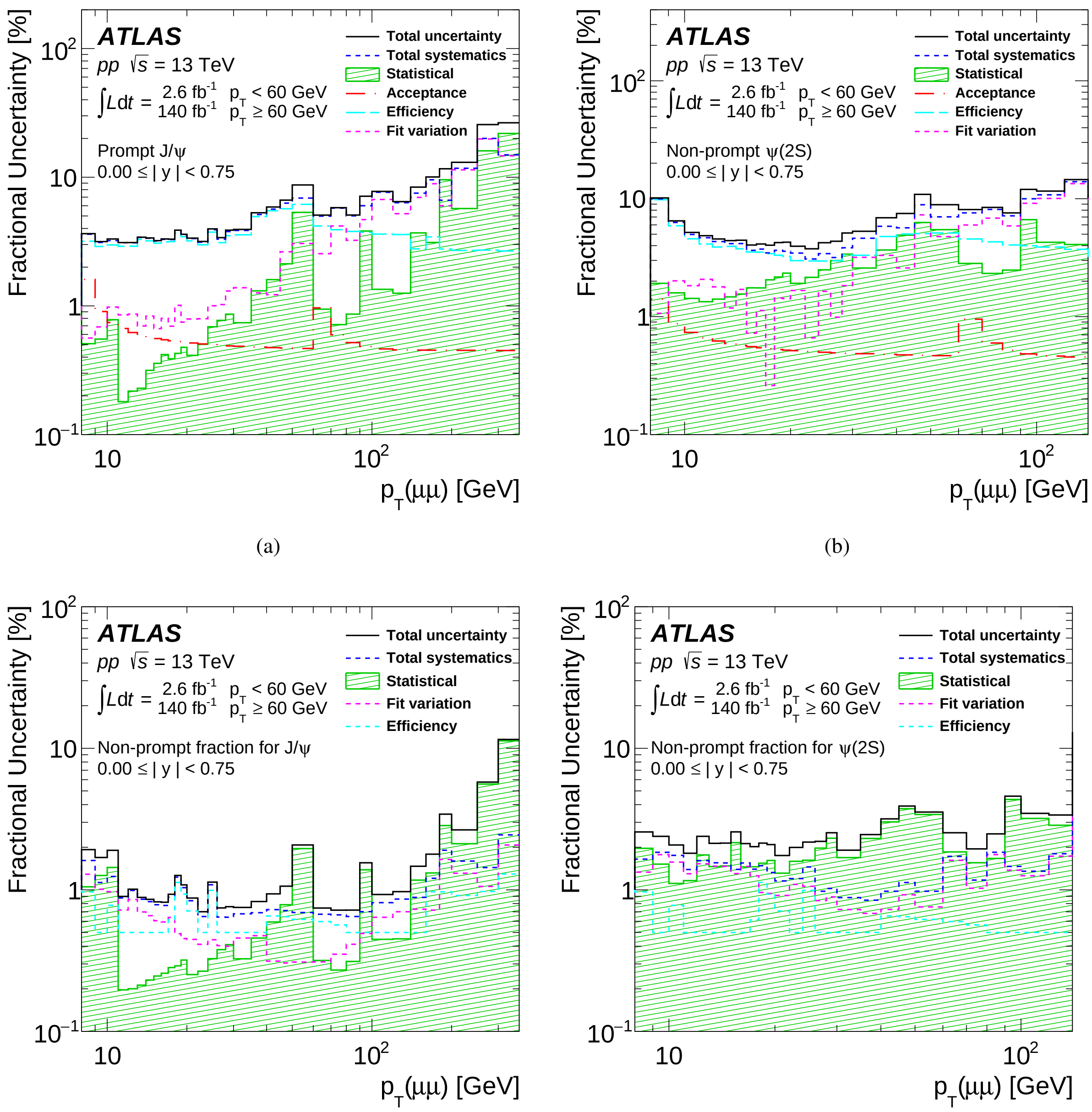
Acceptance-related systematic uncertainties are governed by the size of the samples used to generate the corresponding acceptance maps. The chosen size ensured that these uncertainties are small relative to the total systematic uncertainties. Changes in acceptance due to different spin-alignment hypotheses were treated separately (see Appendix).

Systematic uncertainties due to trigger and reconstruction efficiency corrections have a number of components, including the size of the MC samples and the scale factors' systematic uncertainties [36], and these were added in quadrature.

The total systematic uncertainty in each bin is calculated by summing in quadrature the uncertainties from the above-mentioned sources. The total uncertainty is calculated as the sum in quadrature of the total systematic and statistical uncertainties.

An additional systematic uncertainty comes from the determination of the integrated luminosity. In the $p_{\mathrm{T}} < 60$ GeV region, where only 2015 data contributes to this measurement, the integrated luminosity has a 1.13% uncertainty [43], while for $p_{\mathrm{T}} \geq 60$ GeV the uncertainty in the combined 2015–2018 integrated luminosity is 0.83%, as obtained using the LUCID-2 detector [44].

As an illustration, in Figure 2 the total, statistical, and systematic uncertainties, together with the main individual contributions to the systematic uncertainty, are shown for the central rapidity slice for the differential cross-sections of prompt J/ψ and non-prompt $\psi(2\mathrm{S})$ mesons, as well as for the non-prompt fractions of J/ψ and $\psi(2\mathrm{S})$ mesons, as functions of p_{T}. For the cross-sections, apart from a few high p_{T} bins, the uncertainties are largely systematic, while for the non-prompt fractions and $\psi(2\mathrm{S})$-to-J/ψ production ratios, statistical errors dominate in many bins because the systematic uncertainties partially cancel out. Similar results are obtained in other rapidity slices.

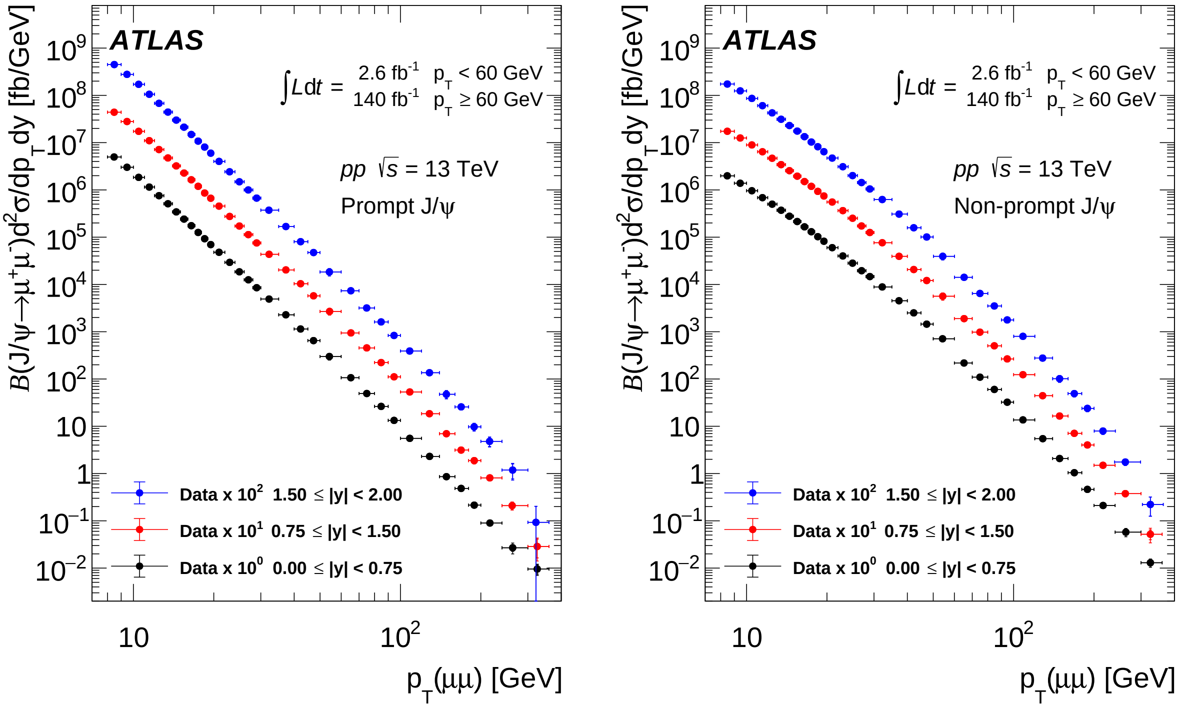


(a) (b) (c) (d)

Figure 2: Total, statistical, and systematic uncertainties (in %) as functions of p_{T} for the differential (a) prompt J/ψ and (b) non-prompt $\psi(2S)$ cross-sections, and for the non-prompt fractions of (c) J/ψ and (d) $\psi(2S)$, in the rapidity slice $0.00 \leq |y| < 0.75$. The main components of the systematic uncertainties are also shown.

5 Results

The measured double-differential cross-sections for prompt and non-prompt J/ψ production in the nominal isotropic spin-alignment scenario are presented in Figures 3(a) and 3(b), respectively. The same quantities for $\psi(2S)$ are shown in Figures 4(a) and 4(b). The non-prompt production fractions for J/ψ and $\psi(2S)$ are



(a) (b)

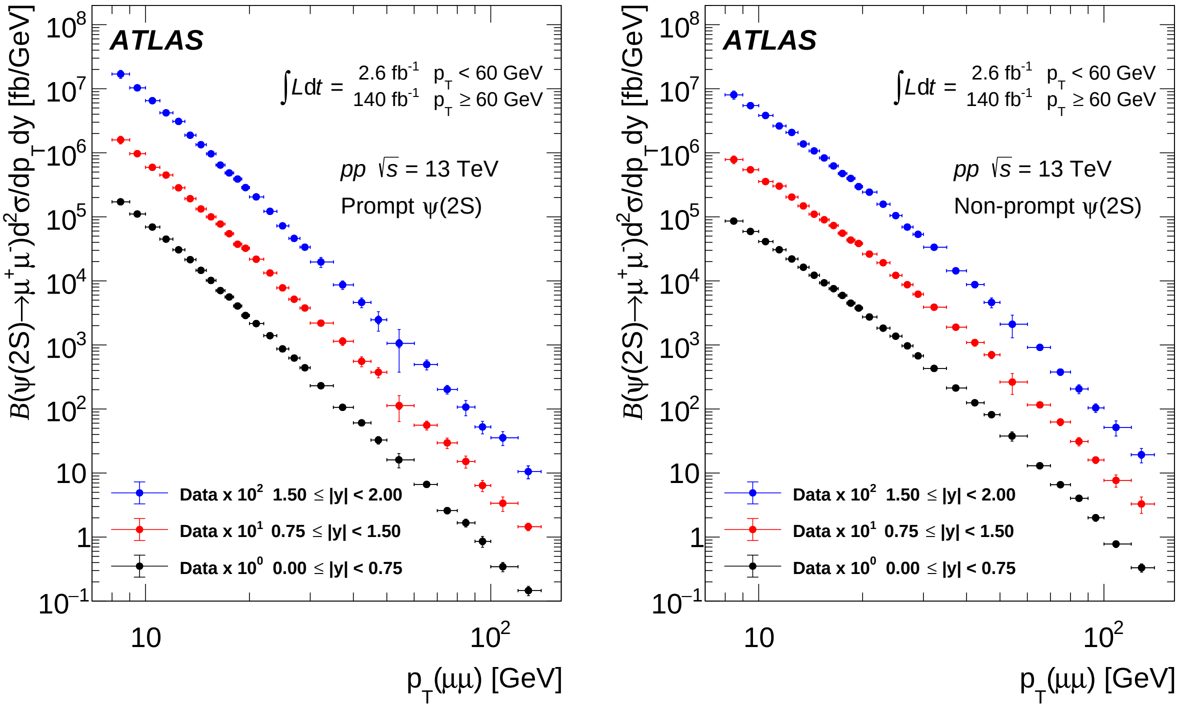
Figure 3: Differential cross-sections for (a) prompt and (b) non-prompt production of J/ψ mesons. For visual clarity, a scaling factor of 1, 10, or 100 is applied to the rapidity slices $0.00 \leq |y| < 0.75$, $0.75 \leq |y| < 1.5$, and $1.5 \leq |y| < 2.0$, respectively. For each data point, the horizontal bar spans the p_T range covered by that bin, with the horizontal position of each point representing the mean p_T in that bin. The vertical uncertainty range (obscured by the marker for some values) combines both the statistical (the inner bar) and total uncertainty. Uncertainties related to spin alignment or integrated luminosity are not included. Data up to 60 GeV were taken with a dimuon trigger with integrated luminosity 2.6 fb^{-1}; data above 60 GeV were taken with a single-muon trigger with integrated luminosity 140 fb^{-1}.

presented in Figures 5(a) and 5(b). Finally, the $\psi(2S)$-to-J/ψ production ratios are presented in Figures 6(a) and 6(b) for the prompt and non-prompt production mechanisms, respectively.

While the non-prompt fractions shown in Figure 5 increase steadily with p_T up to about 100 GeV, they are almost constant for both J/ψ and $\psi(2S)$ in the high p_T range, which suggests similar p_T-dependences for the prompt and non-prompt differential cross-sections at very high transverse momenta.

The transition between the low-p_T dimuon trigger and the high-p_T single-muon trigger at p_T = 60 GeV presents a particular challenge because of the sharp change in event kinematics. The corresponding changes in the acceptance and efficiency correction factors are significant and could lead to discontinuities in the measured distributions.

Since the spin alignment of ψ states may be different for the prompt and non-prompt production mechanisms, additional correction factors may be needed for all measured distributions. In order to quantitatively assess the possible impact of ψ spin alignment, correction factors are calculated for a variety of scenarios. It was found that the dependence on the polar angle θ in the helicity frame of the ψ state causes the largest variation,

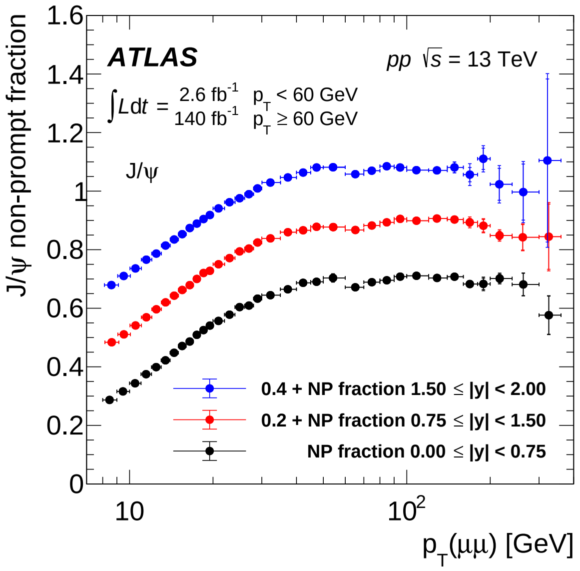


(a) (b)

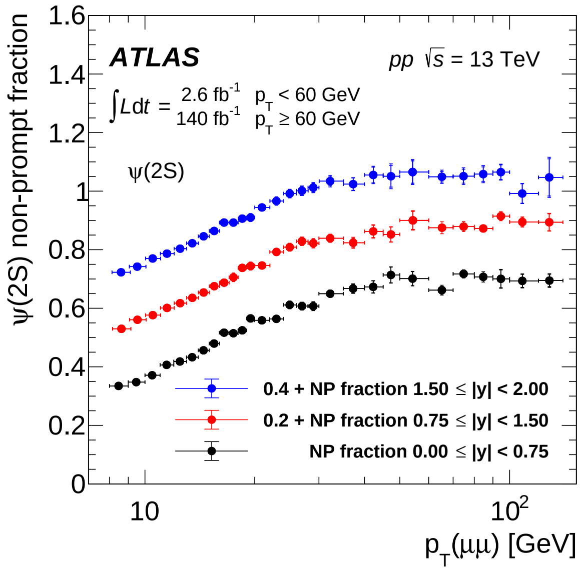
Figure 4: Differential cross-sections for (a) prompt and (b) non-prompt production of $\psi(2S)$ mesons. For visual clarity, a scaling factor of 1, 10, or 100 is applied to the rapidity slices $0.00 \leq |y| < 0.75$, $0.75 \leq |y| < 1.5$, and $1.5 \leq |y| < 2.0$, respectively. For each data point, the horizontal bar spans the p_{T} range covered by that bin, with the horizontal position of each point representing the mean p_{T} in that bin. The vertical uncertainty range (obscured by the marker for some values) combines both the statistical (the inner bar) and total uncertainty. Uncertainties related to spin alignment or integrated luminosity are not included. Data up to 60 GeV were taken with a dimuon trigger with integrated luminosity 2.6 fb^{-1}; data above 60 GeV were taken with a single-muon trigger with integrated luminosity 140 fb^{-1}.

so the angular dependence of $\psi \to \mu^+\mu^-$ decays is assumed to be $\propto (1 + \lambda_\theta \cos^2\theta)$. The correction factors are shown in Figures 7(a) and 7(b) for the differential cross-sections and non-prompt fractions respectively, where the values $\lambda_\theta = \pm 0.20$ are chosen to reflect the approximate level of experimental knowledge [7, 32, 45] and theoretical understanding [46–48] of this parameter. The correction factors are shown for prompt J/ψ in the central rapidity range, but were found to be essentially the same for J/ψ and $\psi(2S)$, for the prompt and non-prompt production mechanisms, and also for the three rapidity regions.

The potential bias due to the spin-alignment assumption is especially noticeable at the $p_{\mathrm{T}} = 60$ GeV transition, and indeed a step can be seen at this point in the J/ψ non-prompt fraction in Figure 5(a), reflecting a possible issue in the spin-alignment modelling. Correction factors for some other values of λ_θ are presented in the Appendix. These can be used for further studies, if more precise spin-alignment data and/or improved modelling become available in the future.



(a)



(b)

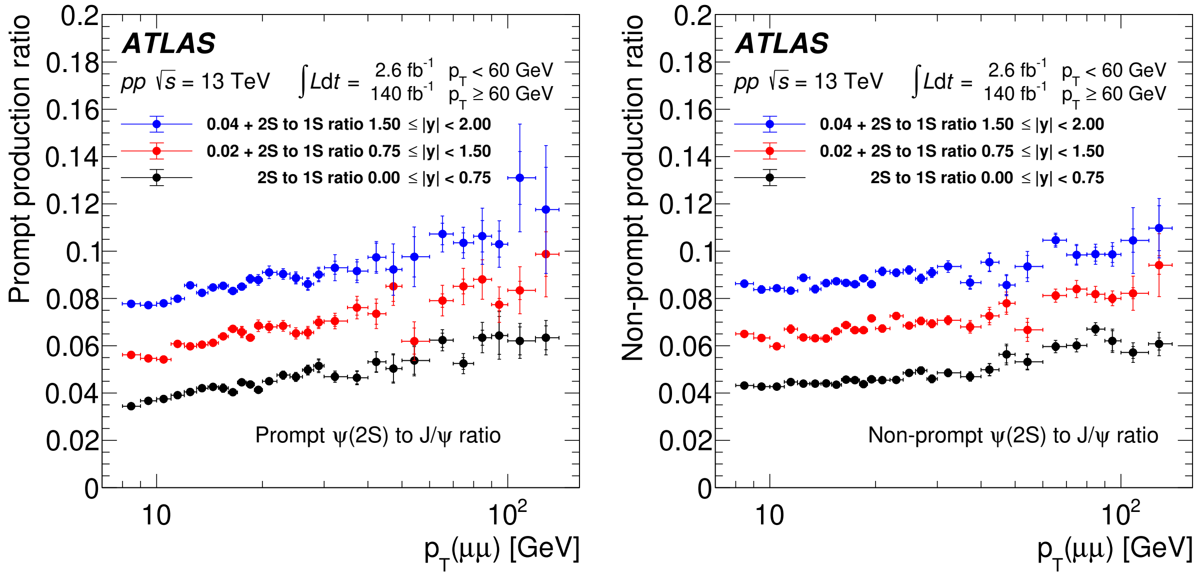
Figure 5: Non-prompt production fraction of (a) J/ψ and (b) $\psi(2S)$ mesons. For visual clarity, a vertical shift of 0, 0.2, or 0.4 is applied to the rapidity slices $0.00 \leq |y| < 0.75$, $0.75 \leq |y| < 1.5$, and $1.5 \leq |y| < 2.0$, respectively. For each data point, the horizontal bar spans the p_T range covered by that bin, with the horizontal position of each point representing the mean p_T in that bin. The vertical uncertainty range (obscured by the marker for some values) combines both the statistical (the inner bar) and total uncertainty. Uncertainties related to spin alignment or integrated luminosity are not included. Data up to 60 GeV were taken with a dimuon trigger with integrated luminosity 2.6 fb^{-1}; data above 60 GeV were taken with a single-muon trigger with integrated luminosity 140 fb^{-1}.

5.1 Theory comparison: prompt production

Model calculations of prompt production of charmonium are usually based on perturbative QCD for the production of the $c\bar{c}$ pair, and differ in the mechanism of formation of the bound state with specific quantum numbers.

The predictions of a model using the non-relativistic QCD approach to charmonium production cross-sections at next-to-leading order (NLO NRQCD) [49], using predetermined LDMEs [50, 51], are shown in comparison with our measurements of the J/ψ and $\psi(2S)$ production cross-sections in the top panels of Figures 8(a) and 8(b) respectively. The predictions of the model largely overlap with the data points within the theoretical uncertainties, which include variations of the renormalisation, factorisation and NRQCD scales. However, the predictions seem to overestimate the cross-sections at high p_T.

One generalisation of the NRQCD approach is a model which aims to improve the description by taking into account the transverse degrees of freedom of the initial gluons in the colliding protons (k_T-factorisation model) [52, 53]. The predictions of this model, obtained with the PEGASUS event generator [54] using the LDMEs determined in Ref. [55], are compared with our measured results as shown in the middle panels of Figures 8(a) and 8(b) for J/ψ and $\psi(2S)$ respectively, where the theoretical uncertainties only account for variations of the renormalisation scale. The range of comparison is limited by the availability of the transverse-momentum-dependent parton distribution function (PDF) of the gluon [56]. Where this PDF is



(a) (b)

Figure 6: The $\psi(2S)$-to-J/ψ production ratio for the (a) prompt and (b) non-prompt production mechanisms. For visual clarity, a vertical shift of 0, 0.02, or 0.04 is applied to the rapidity slices $0.00 \leq |y| < 0.75$, $0.75 \leq |y| < 1.5$, and $1.5 \leq |y| < 2.0$, respectively. For each data point, the horizontal bar spans the p_T range covered by that bin, with the horizontal position of each point representing the mean p_T in that bin. The vertical uncertainty range (hidden by the marker for some values) combines both the statistical (the inner bar) and total uncertainty. Uncertainties related to spin alignment or integrated luminosity are not included. Data up to 60 GeV were taken with a dimuon trigger with integrated luminosity 2.6 fb^{-1}; data above 60 GeV were taken with a single-muon trigger with integrated luminosity 140 fb^{-1}.

available, the predictions of the model reproduce the shapes of the measured p_T distributions reasonably well, but tend to underestimate the cross-sections at low p_T.

A different approach is used by the 'improved colour evaporation model' (ICEM) [57], which assigns a fixed fraction of the $c\bar{c}$ production cross-section below the open charm threshold to individual charmonium states. Comparisons of ICEM predictions with the parameter values and their uncertainties previously determined from fits to LHCb data at 7 TeV [10, 58] are shown in the bottom panels of Figures 8(a) and 8(b) for J/ψ and $\psi(2S)$ respectively. The model seems to predict somewhat harder p_T spectra than observed in the data for both J/ψ and $\psi(2S)$, and tends to underestimate the cross-section for $\psi(2S)$.

5.2 Theory comparison: non-prompt production

Theoretical calculations of non-prompt charmonium production are based on perturbative QCD for the production of a $b\bar{b}$ quark pair, their hadronisation into a pair of b-hadrons, and their subsequent decay into a charmonium state with specific quantum numbers. Predictions from one such model, based on fixed-order–next-to-leading-log (FONLL) QCD calculations [1, 2] were obtained using the web-based tool [59] with default parameter values, and are shown in comparison with our measurements in the top panels of Figures 9(a) and 9(b) for J/ψ and $\psi(2S)$ respectively. Here the uncertainties cover variations of

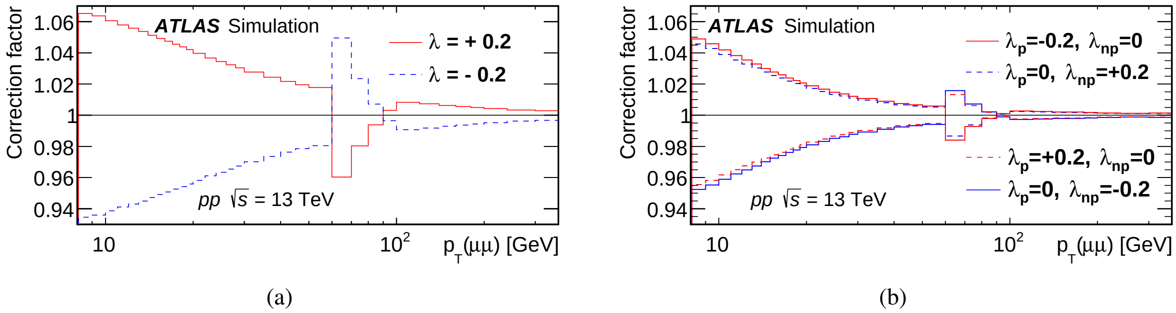


Figure 7: Spin-alignment hypothesis correction factors for the J/ψ (a) differential cross-section and (b) non-prompt production fraction, for a number of spin-alignment scenarios. The correction factors are approximately the same for J/ψ and $\psi(2S)$, for the prompt and non-prompt production mechanisms, and also for the three rapidity regions. The discontinuities at $p_T = 60$ GeV are due to the transition from a low-p_T dimuon trigger to a high-p_T single-muon trigger, and the corresponding change in event acceptance.

both the renormalisation scale and the charm quark mass. Agreement is good at lower p_T values, but the FONLL model predicts somewhat higher cross-sections for J/ψ at the high p_T end.

Another set of predictions, based on the next-to-leading-order QCD calculation in the general-mass–variable-flavour-number scheme (GM–VFNS) [60] are shown in the middle panels of Figures 9(a) and 9(b). Parameter values were determined in Ref. [50, 61], with uncertainties originating from renormalisation scale dependence. These predictions lead to similar results, but the deviation from data at the highest p_T values is somewhat more pronounced, especially in the J/ψ case.

Finally, the NRQCD model with k_T-factorisation can also be used to predict the p_T distributions of vector charmonia through the non-prompt production mechanisms [54, 62] (see bottom panels of Figures 9(a) and 9(b)), but here the limitations of the transverse-momentum-dependent model for the gluon PDF show up at even lower charmonium p_T values. Also, in this model the cross-section for $\psi(2S)$ non-prompt production at low p_T is somewhat underestimated.

Overall, none of the models considered here is able to describe the data over the whole measured range of transverse momenta. The general trend shown by all theoretical models is a slower-than-observed decrease of the cross-section with p_T, which could be related to insufficiently accounting for PDF evolution and/or possible dependence of LDMEs on transverse momentum. In any case, these measurements should help refine theoretical models of hadronic production of quarkonium at the highest available energies and at transverse momenta well beyond 100 GeV.

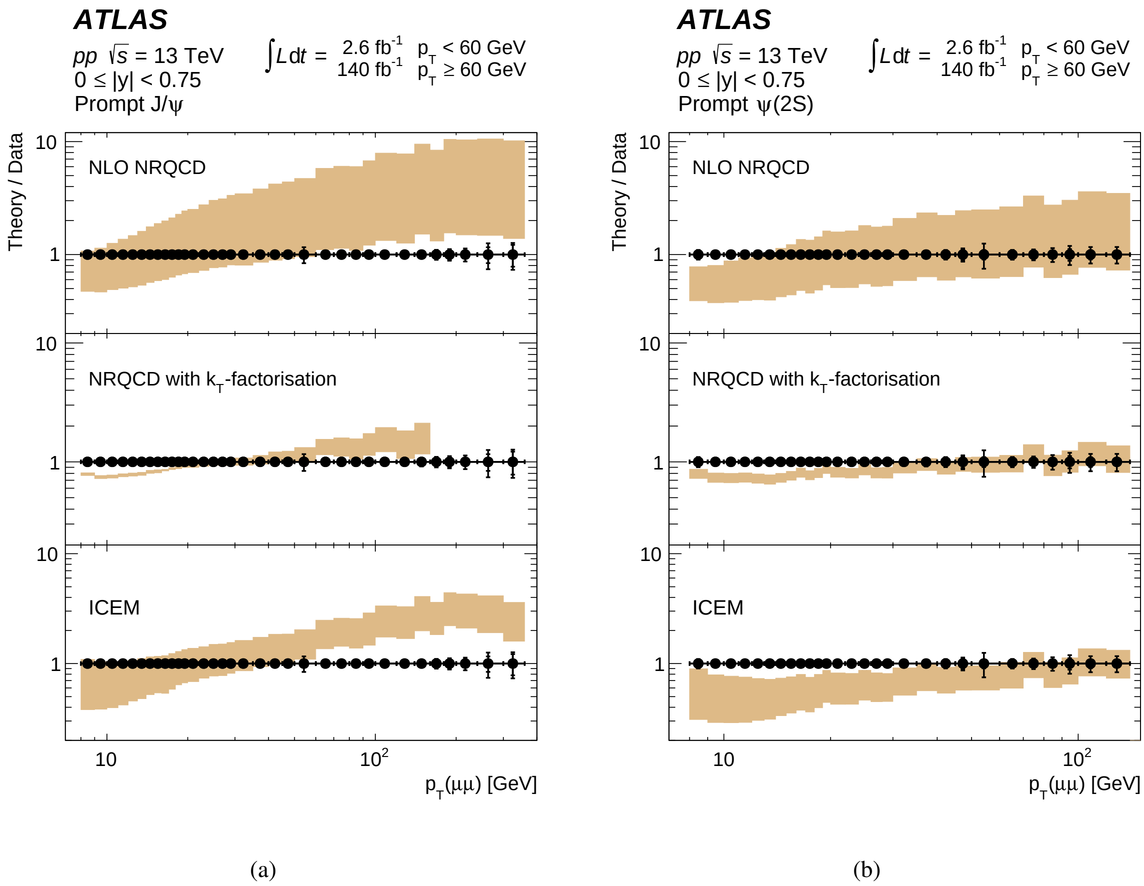


Figure 8: Ratios of various theoretical predictions (described in the text) to the data points from this measurement, for the prompt production of (a) J/ψ and (b) $\psi(2S)$ in the central rapidity region. In each p_T bin, the shaded area represents the ratio of the theoretical prediction to the measured value, with the vertical spread showing the uncertainties of the respective model. Error bars on the black dots show fractional uncertainties of this measurement.

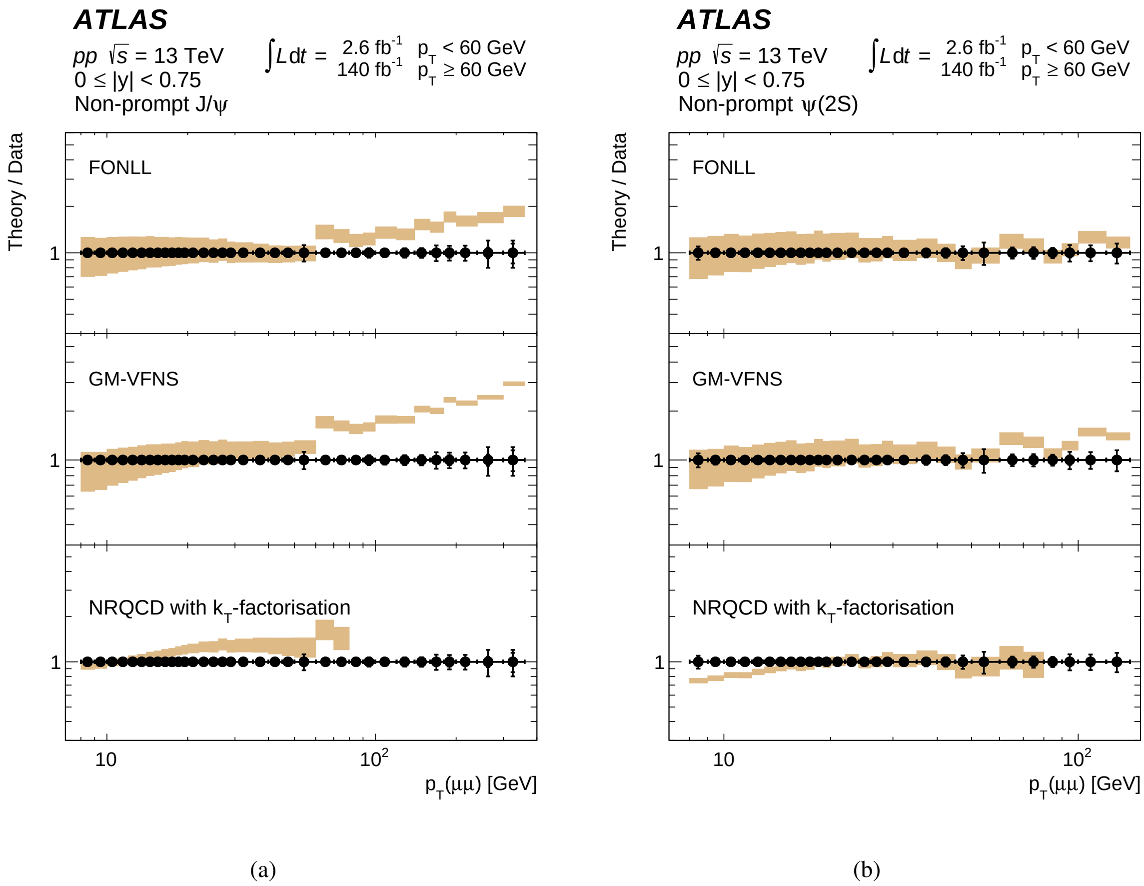


Figure 9: Ratios of various theoretical predictions (described in the text) to the data points from this measurement, for non-prompt production of (a) J/ψ and (b) $\psi(2S)$ in the central rapidity region. In each p_T bin, the shaded area represents the ratio of the theoretical prediction to the measured value, with the vertical spread showing the uncertainties of the respective model. Error bars on the black dots show fractional uncertainties of this measurement.

6 Summary

This paper describes a measurement of the double-differential production cross-sections of J/ψ and $\psi(2S)$ charmonium states in pp collisions at $\sqrt{s} = 13$ TeV, performed through their decays into dimuons and using 140 fb^{-1} of data collected by the ATLAS detector at the LHC during Run 2. The cross-sections for each of the two states are measured separately for prompt and non-prompt production mechanisms. The non-prompt fractions for each state are also measured, along with the $\psi(2S)$-to-J/ψ production ratios. The rapidity range of the measurement is $|y| < 2$. For $\psi(2S)$ the transverse momentum range is 8−140 GeV, while for J/ψ the results cover a much wider transverse momentum range, from 8 GeV to 360 GeV, extending well beyond the range of previous measurements. In the high p_T range the results show similar p_T-dependences for the prompt and non-prompt differential cross-sections, with the non-prompt fractions being nearly constant for both J/ψ and $\psi(2S)$.

The results are compared with a number of theoretical predictions, which describe the data with varying degrees of success. The extended p_T reach of this measurement provides important fresh input for future tuning of theoretical models.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEiN, Poland; FCT, Portugal; MNE/IFA, Romania; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; PRIMUS 21/SCI/017 and UNCE SCI/013, Czech Republic; COST, ERC, ERDF, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; Norwegian Financial Mechanism 2014-2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [63].

Appendix

The ψ meson's acceptance depends on its spin alignment. The nominal results presented in this paper assume an isotropic angular distribution, corresponding to the 'unpolarised' case. In order to assess the dependence of the cross-section on the spin alignment, the acceptance maps were reweighted for a variety of spin-alignment scenarios, and for each analysis bin the correction factors were determined relative to the nominal values. The correction factors calculated for several values of the parameter λ_θ, assuming the angular dependence in the ψ helicity frame to be $\propto (1 + \lambda_\theta \cos^2\theta)$, are shown in Table 2. The factors are shown for prompt J/ψ in the central rapidity range, but were found to be the same for J/ψ and $\psi(2S)$ within 1%–2%, with the variation over the other rapidity ranges also within 1%–2%. For $\lambda_\theta \neq 0$ the nominal value of the measured cross-section should be multiplied by the appropriate correction factor from Table 2.

Table 2: Correction factors for an assumed angular dependence $\propto 1 + \lambda_\theta \cos^2\theta$ in the helicity frame, for several values of the parameter λ_θ. The correction factors were found to be the same (within 1%–2%) for J/ψ and $\psi(2S)$ mesons, for prompt and non-prompt production mechanisms, and for the three rapidity intervals considered in this paper.

p_T	$\lambda_\theta = -1$	$\lambda_\theta = -0.2$	$\lambda_\theta = +0.2$	$\lambda_\theta = +1$
8– 9 [GeV]	0.69	0.93	1.07	1.29
9– 10 [GeV]	0.69	0.94	1.06	1.28
10– 11 [GeV]	0.70	0.94	1.06	1.27
11– 12 [GeV]	0.70	0.94	1.06	1.26
12– 13 [GeV]	0.71	0.94	1.06	1.25
13– 14 [GeV]	0.72	0.94	1.05	1.24
14– 15 [GeV]	0.73	0.95	1.05	1.24
15– 16 [GeV]	0.73	0.95	1.05	1.22
16– 17 [GeV]	0.74	0.95	1.05	1.21
17– 18 [GeV]	0.75	0.95	1.05	1.20
18– 19 [GeV]	0.75	0.95	1.04	1.20
19– 20 [GeV]	0.76	0.96	1.04	1.19
20– 22 [GeV]	0.77	0.96	1.04	1.18
22– 24 [GeV]	0.78	0.96	1.04	1.17
24– 26 [GeV]	0.79	0.96	1.03	1.15
26– 28 [GeV]	0.80	0.97	1.03	1.14
28– 30 [GeV]	0.81	0.97	1.03	1.13
30– 35 [GeV]	0.82	0.97	1.03	1.12
35– 40 [GeV]	0.84	0.97	1.02	1.10
40– 45 [GeV]	0.86	0.98	1.02	1.09
45– 50 [GeV]	0.87	0.98	1.02	1.08
50– 60 [GeV]	0.88	0.98	1.02	1.07
60– 70 [GeV]	1.48	1.05	0.96	0.86
70– 80 [GeV]	1.19	1.02	0.98	0.93
80– 90 [GeV]	1.05	1.01	0.99	0.98
90–100 [GeV]	0.98	1.00	1.00	1.01
100–120 [GeV]	0.94	0.99	1.01	1.03
120–140 [GeV]	0.94	0.99	1.01	1.03
140–160 [GeV]	0.95	0.99	1.01	1.03
160–180 [GeV]	0.96	0.99	1.01	1.02
180–200 [GeV]	0.96	0.99	1.00	1.02
200–240 [GeV]	0.97	1.00	1.00	1.02
240–300 [GeV]	0.97	1.00	1.00	1.01
300–360 [GeV]	0.98	1.00	1.00	1.01

References

[1] M. Cacciari, S. Frixione and P. Nason, *The p_T spectrum in heavy flavor photoproduction*, JHEP **03** (2001) 006, arXiv: hep-ph/0102134.

[2] M. Cacciari et al., *Theoretical predictions for charm and bottom production at the LHC*, JHEP **10** (2012) 137, arXiv: 1205.6344 [hep-ph].

[3] G. T. Bodwin, E. Braaten and G. P. Lepage, *Rigorous QCD analysis of inclusive annihilation and production of heavy quarkonium*, Phys. Rev. D **51** (1995) 1125, arXiv: hep-ph/9407339 [hep-ph], [Erratum: Phys. Rev. D **55** (1997)].

[4] ATLAS Collaboration, *Measurement of the differential cross-sections of prompt and non-prompt production of J/ψ and $\psi(2S)$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector*, Eur. Phys. J. C **76** (2016) 283, arXiv: 1512.03657 [hep-ex].

[5] ATLAS Collaboration, *Measurement of the production cross-section of $\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$ in pp collisions at $\sqrt{s} = 7$ TeV at ATLAS*, JHEP **09** (2014) 079, arXiv: 1407.5532 [hep-ex].

[6] LHCb Collaboration, *Measurement of $\psi(2S)$ meson production in pp collisions at $\sqrt{s}$=7 TeV*, Eur. Phys. J. C **72** (2012) 2100, arXiv: 1204.1258 [hep-ex].

[7] CMS Collaboration, *J/ψ and $\psi(2S)$ production in pp collisions at $\sqrt{s} = 7$ TeV*, JHEP **02** (2012) 011, arXiv: 1111.1557 [hep-ex].

[8] ALICE Collaboration, *J/ψ polarization in pp collisions at $\sqrt{s} = 7$ TeV*, Phys. Rev. Lett. **108** (2012) 082001, arXiv: 1111.1630 [hep-ex].

[9] CMS Collaboration, *Measurement of the prompt J/ψ and $\psi(2S)$ polarizations in pp collisions at $\sqrt{s} = 7$ TeV*, Phys. Lett. B **727** (2013) 381, arXiv: 1307.6070 [hep-ex].

[10] LHCb Collaboration, *Measurement of $\psi(2S)$ polarisation in pp collisions at $\sqrt{s} = 7$ TeV*, Eur. Phys. J. C **74** (2014) 2872, arXiv: 1403.1339 [hep-ex].

[11] ALICE Collaboration, *Measurement of the inclusive J/ψ polarization at forward rapidity in pp collisions at $\sqrt{\mathbf{s}} = \mathbf{8}$ TeV*, Eur. Phys. J. C **78** (2018) 562, arXiv: 1805.04374 [hep-ex].

[12] ATLAS Collaboration, *Measurement of the production cross section of prompt J/ψ mesons in association with a $W^\pm$ boson in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, JHEP **04** (2014) 172, arXiv: 1401.2831 [hep-ex].

[13] ATLAS Collaboration, *Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Eur. Phys. J. C **75** (2015) 229, arXiv: 1412.6428 [hep-ex].

[14] G. Li, M. Song, R.-Y. Zhang and W.-G. Ma, *QCD corrections to J/ψ production in association with a W-boson at the LHC*, Phys. Rev. D **83** (2011) 014001, arXiv: 1012.3798 [hep-ph].

[15] J. P. Lansberg and C. Lorce, *Reassessing the importance of the colour-singlet contributions to direct $J/\psi + W$ production at the LHC and the Tevatron*, Phys. Lett. B **726** (2013) 218, arXiv: 1303.5327 [hep-ph], [Erratum: Phys. Lett. B **738** (2014) 529].

[16] B. Gong, J.-P. Lansberg, C. Lorce and J. Wang, *Next-to-leading-order QCD corrections to the yields and polarisations of J/ψ and Υ directly produced in association with a Z boson at the LHC*, JHEP **03** (2013) 115, arXiv: 1210.2430 [hep-ph].

[17] M. Song, W.-G. Ma, G. Li, R.-Y. Zhang and L. Guo, *QCD corrections to J/ψ plus Z^0-boson production at the LHC*, JHEP **02** (2011) 071, arXiv: 1102.0398 [hep-ph], [Erratum: JHEP **12** (2012) 010].

[18] M. Butenschoen and B. A. Kniehl, *J/ψ production in NRQCD: A global analysis of yield and polarization*, Nucl. Phys. Proc. Suppl. **222-224** (2012) 151, arXiv: 1201.3862 [hep-ph].

[19] CMS Collaboration, *Measurement of J/ψ and $\psi(2S)$ Prompt Double-Differential Cross Sections in pp Collisions at $\sqrt{s} = 7$ TeV*, Phys. Rev. Lett. **114** (2015) 191802, arXiv: 1502.04155 [hep-ex].

[20] CMS Collaboration, *Measurement of quarkonium production cross sections in pp collisions at $\sqrt{s} = 13$ TeV*, Phys. Lett. B **780** (2018) 251, arXiv: 1710.11002 [hep-ex].

[21] LHCb Collaboration, *Exclusive J/ψ and ψ(2S) production in pp collisions at $\sqrt{s} = 7$ TeV*, J. Phys. G **40** (2013) 045001, arXiv: 1301.7084 [hep-ex].

[22] LHCb Collaboration, *Measurement of J/ψ polarization in pp collisions at $\sqrt{s} = 7$ TeV*, Eur. Phys. J. C **73** (2013) 2631, arXiv: 1307.6379 [hep-ex].

[23] LHCb Collaboration, *Updated measurements of exclusive J/ψ and ψ(2S) production cross-sections in pp collisions at $\sqrt{s} = 7$ TeV*, J. Phys. G **41** (2014) 055002, arXiv: 1401.3288 [hep-ex].

[24] LHCb Collaboration, *Measurement of forward J/ψ production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV*, JHEP **10** (2015) 172, arXiv: 1509.00771 [hep-ex], [Erratum: JHEP **05** (2017) 063].

[25] LHCb Collaboration, *Central exclusive production of J/ψ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV*, JHEP **10** (2018) 167, arXiv: 1806.04079 [hep-ex].

[26] ALICE Collaboration, *Measurement of quarkonium production at forward rapidity in pp collisions at $\sqrt{s} = 7$ TeV*, Eur. Phys. J. C **74** (2014) 2974, arXiv: 1403.3648 [nucl-ex].

[27] ALICE Collaboration, *Prompt and non-prompt J/ψ production cross sections at midrapidity in proton-proton collisions at $\sqrt{s} = 5.02$ and 13 TeV*, JHEP **03** (2022) 190, arXiv: 2108.02523 [nucl-ex].

[28] ALICE Collaboration, *Prompt and non-prompt J/ψ production cross sections at midrapidity in proton-proton collisions at $\sqrt{s} = 5.02$ and 13 TeV*, JHEP **03** (2022) 190, arXiv: 2108.02523 [nucl-ex].

[29] ALICE Collaboration, *Inclusive J/ψ production at midrapidity in pp collisions at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **81** (2021) 1121, arXiv: 2108.01906 [nucl-ex].

[30] ALICE Collaboration, *Energy dependence of forward-rapidity* J/ψ *and* $\psi(2\mathrm{S})$ *production in pp collisions at the LHC*, Eur. Phys. J. C **77** (2017) 392, arXiv: 1702.00557 [hep-ex].

[31] ALICE Collaboration, *Measurement of prompt J/ψ and beauty hadron production cross sections at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV*, JHEP **11** (2012) 065, arXiv: 1205.5880 [hep-ex].

[32] ALICE Collaboration, *J/ψ polarization in pp collisions at $\sqrt{s} = 7$ TeV*, Phys. Rev. Lett. **108** (2012) 082001, arXiv: 1111.1630 [hep-ex].

[33] ATLAS Collaboration,
Measurement of χ_{c1} and χ_{c2} production with $\sqrt{s} = 7$ TeV pp collisions at ATLAS,
JHEP **07** (2014) 154, arXiv: 1404.7035 [hep-ex].

[34] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*,
JINST **3** (2008) S08003.

[35] ATLAS Collaboration, *The ATLAS Collaboration Software and Firmware*, tech. rep., CERN, 2021,
URL: https://cds.cern.ch/record/2767187.

[36] ATLAS Collaboration, *Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **76** (2016) 292, arXiv: 1603.05598 [hep-ex].

[37] M. Oreglia, *A Study of the Reactions $\psi' \to \gamma\gamma\psi$*, PhD thesis, Stanford University, 1980,
SLAC-R-236.

[38] Particle Data Group, P. Zyla et al., *Review of Particle Physics*, PTEP **2020** (2020) 083C01.

[39] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, Comput. Phys. Commun. **191** (2015) 159,
arXiv: 1410.3012 [hep-ph].

[40] ATLAS Collaboration, *ATLAS Pythia 8 tunes to 7 TeV data*, tech. rep., CERN, 2014,
URL: https://cds.cern.ch/record/1966419.

[41] ATLAS Collaboration, *The ATLAS Simulation Infrastructure*, Eur. Phys. J. C **70** (2010) 823,
arXiv: 1005.4568 [physics.ins-det].

[42] S. Agostinelli et al., *GEANT4 – a simulation toolkit*, Nucl. Instrum. Meth. A **506** (2003) 250.

[43] ATLAS Collaboration,
Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC,
(2022), arXiv: 2212.09379 [hep-ex].

[44] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS*,
JINST **13** (2018) P07017.

[45] CDF Collaboration, *Measurement of J/ψ and $\psi(2S)$ Polarization in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$TeV*,
Phys. Rev. Lett. **85** (2000) 2886.

[46] Y.-Q. Ma, T. Stebel and R. Venugopalan, *J/ψ polarization in the CGC+NRQCD approach*,
JHEP **12** (2018) 057, arXiv: 1809.03573 [hep-ph].

[47] Y. Feng, B. Gong, C.-H. Chang and J.-X. Wang,
Remaining parts of the long-standing J/ψ polarization puzzle, Phys. Rev. D **99** (2019) 014044,
arXiv: 1810.08989 [hep-ph].

[48] P. Faccioli and C. Lourenço,
On the polarization of the non-prompt contribution to inclusive J/ψ production in pp collisions,
JHEP **10** (2022) 005, arXiv: 2206.14686 [hep-ph].

[49] M. Butenschön and B. A. Kniehl, *Reconciling J/ψ Production at HERA, RHIC, Tevatron, and LHC with Nonrelativistic QCD Factorization at Next-to-Leading Order*,
Phys. Rev. Lett. **106** (2011) 022003.

[50] M. Butenschoen and B. A. Kniehl, *World data of J/ψ production consolidate nonrelativistic QCD factorization at next-to-leading order*, Phys. Rev. D **84** (2011) 051501.

[51] M. Butenschoen and B. A. Kniehl, *Global analysis of ψ(2S) inclusive hadroproduction at next-to-leading order in nonrelativistic-QCD factorization*, Phys. Rev. D **107** (2023) 034003,
arXiv: 2207.09346 [hep-ph].

[52] S. P. Baranov, A. V. Lipatov and N. P. Zotov, *Prompt charmonia production and polarization at LHC in the NRQCD with k_T -factorization. Part I: $\psi(2S)$ meson*, Eur. Phys. J. C **75** (2015) 455, arXiv: 1508.05480 [hep-ph].

[53] S. P. Baranov and A. V. Lipatov, *Prompt charmonia production and polarization at the LHC in the NRQCD with k_T-factorization. III. J/ψ meson*, Phys. Rev. D **96** (2017) 034019.

[54] A. V. Lipatov, M. A. Malyshev and S. P. Baranov, *Particle Event Generator: A Simple-in-Use System PEGASUS version 1.0*, Eur. Phys. J. C **80** (2020) 330, arXiv: 1912.04204 [hep-ph].

[55] S. P. Baranov and A. V. Lipatov, *Are there any challenges in the charmonia production and polarization at the LHC?*, Phys. Rev. D **100** (2019) 114021.

[56] H. Jung, 'Un-integrated PDFs in CCFM', *12th International Workshop on Deep Inelastic Scattering (DIS 2004)*, 2004 299, arXiv: hep-ph/0411287.

[57] V. Cheung and R. Vogt, *Production and polarization of direct J/ψ to $O(\alpha_s^3)$ in the improved color evaporation model in collinear factorization*, Phys. Rev. D **104** (2021) 094026.

[58] LHCb Collaboration, *Measurement of J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV*, Eur. Phys. J. C **71** (2011) 1645, arXiv: 1103.0423 [hep-ex].

[59] M. Cacciari, *FONLL Heavy Quark Production*, http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html, Accessed: 2019-09-03.

[60] P. Bolzoni, B. A. Kniehl and G. Kramer, *Inclusive J/ψ and $\psi(2S)$ production from b-hadron decay in $p\overline{p}$ and pp collisions*, Phys. Rev. D **88** (2013) 074035.

[61] B. A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, *Cross sections of inclusive $\psi(2S)$ and $X(3872)$ production from b-hadron decays in pp collisions and comparison with ATLAS, CMS, and LHCb data*, Phys. Rev. D **103** (2021) 094002.

[62] S. P. Baranov, A. V. Lipatov and M. A. Malyshev, *Associated non-prompt $J/\psi + \mu$ and $J/\psi + J/\psi$ production at LHC as a test for TMD gluon density*, Eur. Phys. J. C **78** (2018) 820, arXiv: 1808.06233 [hep-ph].

[63] ATLAS Collaboration, *ATLAS Computing Acknowledgements*, ATL-SOFT-PUB-2023-001, 2023, URL: https://cds.cern.ch/record/2869272.

The ATLAS Collaboration

G. Aad[102], B. Abbott[120], K. Abeling[55], N.J. Abicht[49], S.H. Abidi[29], A. Aboulhorma[35e], H. Abramowicz[151], H. Abreu[150], Y. Abulaiti[117], B.S. Acharya[69a,69b,q], C. Adam Bourdarios[4], L. Adamczyk[86a], S.V. Addepalli[26], M.J. Addison[101], J. Adelman[115], A. Adiguzel[21c], T. Adye[134], A.A. Affolder[136], Y. Afik[36], M.N. Agaras[13], J. Agarwala[73a,73b], A. Aggarwal[100], C. Agheorghiesei[27c], A. Ahmad[36], F. Ahmadov[38,ak], W.S. Ahmed[104], S. Ahuja[95], X. Ai[62a], G. Aielli[76a,76b], A. Aikot[163], M. Ait Tamlihat[35e], B. Aitbenchikh[35a], I. Aizenberg[169], M. Akbiyik[100], T.P.A. Åkesson[98], A.V. Akimov[37], D. Akiyama[168], N.N. Akolkar[24], K. Al Khoury[41], G.L. Alberghi[23b], J. Albert[165], P. Albicocco[53], G.L. Albouy[60], S. Alderweireldt[52], M. Aleksa[36], I.N. Aleksandrov[38], C. Alexa[27b], T. Alexopoulos[10], F. Alfonsi[23b], M. Algren[56], M. Alhroob[120], B. Ali[132], H.M.J. Ali[91], S. Ali[148], S.W. Alibocus[92], M. Aliev[145], G. Alimonti[71a], W. Alkakhi[55], C. Allaire[66], B.M.M. Allbrooke[146], J.F. Allen[52], C.A. Allendes Flores[137f], P.P. Allport[20], A. Aloisio[72a,72b], F. Alonso[90], C. Alpigiani[138], M. Alvarez Estevez[99], A. Alvarez Fernandez[100], M. Alves Cardoso[56], M.G. Alviggi[72a,72b], M. Aly[101], Y. Amaral Coutinho[83b], A. Ambler[104], C. Amelung[36], M. Amerl[101], C.G. Ames[109], D. Amidei[106], S.P. Amor Dos Santos[130a], K.R. Amos[163], V. Ananiev[125], C. Anastopoulos[139], T. Andeen[11], J.K. Anders[36], S.Y. Andrean[47a,47b], A. Andreazza[71a,71b], S. Angelidakis[9], A. Angerami[41,ao], A.V. Anisenkov[37], A. Annovi[74a], C. Antel[56], M.T. Anthony[139], E. Antipov[145], M. Antonelli[53], F. Anulli[75a], M. Aoki[84], T. Aoki[153], J.A. Aparisi Pozo[163], M.A. Aparo[146], L. Aperio Bella[48], C. Appelt[18], A. Apyan[26], N. Aranzabal[36], S.J. Arbiol Val[87], C. Arcangeletti[53], A.T.H. Arce[51], E. Arena[92], J-F. Arguin[108], S. Argyropoulos[54], J.-H. Arling[48], O. Arnaez[4], H. Arnold[114], G. Artoni[75a,75b], H. Asada[111], K. Asai[118], S. Asai[153], N.A. Asbah[61], J. Assahsah[35d], K. Assamagan[29], R. Astalos[28a], S. Atashi[160], R.J. Atkin[33a], M. Atkinson[162], H. Atmani[35f], P.A. Atmasiddha[106], K. Augsten[132], S. Auricchio[72a,72b], A.D. Auriol[20], V.A. Austrup[101], G. Avolio[36], K. Axiotis[56], G. Azuelos[108,aw], D. Babal[28b], H. Bachacou[135], K. Bachas[152,w], A. Bachiu[34], F. Backman[47a,47b], A. Badea[61], T.M. Baer[106], P. Bagnaia[75a,75b], M. Bahmani[18], A.J. Bailey[163], V.R. Bailey[162], J.T. Baines[134], L. Baines[94], O.K. Baker[172], E. Bakos[15], D. Bakshi Gupta[8], V. Balakrishnan[120], R. Balasubramanian[114], E.M. Baldin[37], P. Balek[86a], E. Ballabene[23b,23a], F. Balli[135], L.M. Baltes[63a], W.K. Balunas[32], J. Balz[100], E. Banas[87], M. Bandieramonte[129], A. Bandyopadhyay[24], S. Bansal[24], L. Barak[151], M. Barakat[48], E.L. Barberio[105], D. Barberis[57b,57a], M. Barbero[102], M.Z. Barel[114], K.N. Barends[33a], T. Barillari[110], M-S. Barisits[36], T. Barklow[143], P. Baron[122], D.A. Baron Moreno[101], A. Baroncelli[62a], G. Barone[29], A.J. Barr[126], J.D. Barr[96], L. Barranco Navarro[47a,47b], F. Barreiro[99], J. Barreiro Guimarães da Costa[14a], U. Barron[151], M.G. Barros Teixeira[130a], S. Barsov[37], F. Bartels[63a], R. Bartoldus[143], A.E. Barton[91], P. Bartos[28a], A. Basan[100,af], M. Baselga[49], A. Bassalat[66,b], M.J. Basso[156a], C.R. Basson[101], R.L. Bates[59], S. Batlamous[35e], J.R. Batley[32], B. Batool[141], M. Battaglia[136], D. Battulga[18], M. Bauce[75a,75b], M. Bauer[36], P. Bauer[24], L.T. Bazzano Hurrell[30], J.B. Beacham[51], T. Beau[127], J.Y. Beaucamp[90], P.H. Beauchemin[158], F. Becherer[54], P. Bechtle[24], H.P. Beck[19,u], K. Becker[167], A.J. Beddall[82], V.A. Bednyakov[38], C.P. Bee[145], L.J. Beemster[15], T.A. Beermann[36], M. Begalli[83d], M. Begel[29], A. Behera[145], J.K. Behr[48], J.F. Beirer[55], F. Beisiegel[24], M. Belfkir[159], G. Bella[151], L. Bellagamba[23b], A. Bellerive[34], P. Bellos[20], K. Beloborodov[37], D. Benchekroun[35a], F. Bendebba[35a], Y. Benhammou[151], M. Benoit[29], J.R. Bensinger[26], S. Bentvelsen[114], L. Beresford[48],

M. Beretta [53], E. Bergeaas Kuutmann [161], N. Berger [4], B. Bergmann [132], J. Beringer [17a], G. Bernardi [5], C. Bernius [143], F.U. Bernlochner [24], F. Bernon [36,102], A. Berrocal Guardia [13], T. Berry [95], P. Berta [133], A. Berthold [50], I.A. Bertram [91], S. Bethke [110], A. Betti [75a,75b], A.J. Bevan [94], N.K. Bhalla [54], M. Bhamjee [33c], S. Bhatta [145], D.S. Bhattacharya [166], P. Bhattarai [143], V.S. Bhopatkar [121], R. Bi [29,az], R.M. Bianchi [129], G. Bianco [23b,23a], O. Biebel [109], R. Bielski [123], M. Biglietti [77a], M. Bindi [55], A. Bingul [21b], C. Bini [75a,75b], A. Biondini [92], C.J. Birch-sykes [101], G.A. Bird [20,134], M. Birman [169], M. Biros [133], S. Biryukov [146], T. Bisanz [49], E. Bisceglie [43b,43a], J.P. Biswal [134], D. Biswas [141], A. Bitadze [101], K. Bjørke [125], I. Bloch [48], C. Blocker [26], A. Blue [59], U. Blumenschein [94], J. Blumenthal [100], G.J. Bobbink [114], V.S. Bobrovnikov [37], M. Boehler [54], B. Boehm [166], D. Bogavac [36], A.G. Bogdanchikov [37], C. Bohm [47a], V. Boisvert [95], P. Bokan [48], T. Bold [86a], M. Bomben [5], M. Bona [94], M. Boonekamp [135], C.D. Booth [95], A.G. Borbély [59,at], I.S. Bordulev [37], H.M. Borecka-Bielska [108], G. Borissov [91], D. Bortoletto [126], D. Boscherini [23b], M. Bosman [13], J.D. Bossio Sola [36], K. Bouaouda [35a], N. Bouchhar [163], J. Boudreau [129], E.V. Bouhova-Thacker [91], D. Boumediene [40], R. Bouquet [165], A. Boveia [119], J. Boyd [36], D. Boye [29], I.R. Boyko [38], J. Bracinik [20], N. Brahimi [62d], G. Brandt [171], O. Brandt [32], F. Braren [48], B. Brau [103], J.E. Brau [123], R. Brener [169], L. Brenner [114], R. Brenner [161], S. Bressler [169], D. Britton [59], D. Britzger [110], I. Brock [24], G. Brooijmans [41], W.K. Brooks [137f], E. Brost [29], L.M. Brown [165,n], L.E. Bruce [61], T.L. Bruckler [126], P.A. Bruckman de Renstrom [87], B. Brüers [48], A. Bruni [23b], G. Bruni [23b], M. Bruschi [23b], N. Bruscino [75a,75b], T. Buanes [16], Q. Buat [138], D. Buchin [110], A.G. Buckley [59], O. Bulekov [37], B.A. Bullard [143], S. Burdin [92], C.D. Burgard [49], A.M. Burger [40], B. Burghgrave [8], O. Burlayenko [54], J.T.P. Burr [32], C.D. Burton [11], J.C. Burzynski [142], E.L. Busch [41], V. Büscher [100], P.J. Bussey [59], J.M. Butler [25], C.M. Buttar [59], J.M. Butterworth [96], W. Buttinger [134], C.J. Buxo Vazquez [107], A.R. Buzykaev [37], S. Cabrera Urbán [163], L. Cadamuro [66], D. Caforio [58], H. Cai [129], Y. Cai [14a,14e], Y. Cai [14c], V.M.M. Cairo [36], O. Cakir [3a], N. Calace [36], P. Calafiura [17a], G. Calderini [127], P. Calfayan [68], G. Callea [59], L.P. Caloba [83b], D. Calvet [40], S. Calvet [40], T.P. Calvet [102], M. Calvetti [74a,74b], R. Camacho Toro [127], S. Camarda [36], D. Camarero Munoz [26], P. Camarri [76a,76b], M.T. Camerlingo [72a,72b], D. Cameron [36,h], C. Camincher [165], M. Campanelli [96], A. Camplani [42], V. Canale [72a,72b], A. Canesse [104], J. Cantero [163], Y. Cao [162], F. Capocasa [26], M. Capua [43b,43a], A. Carbone [71a,71b], R. Cardarelli [76a], J.C.J. Cardenas [8], F. Cardillo [163], G. Carducci [43b,43a], T. Carli [36], G. Carlino [72a], J.I. Carlotto [13], B.T. Carlson [129,x], E.M. Carlson [165,156a], L. Carminati [71a,71b], A. Carnelli [135], M. Carnesale [75a,75b], S. Caron [113], E. Carquin [137f], S. Carrá [71a,71b], G. Carratta [23b,23a], F. Carrio Argos [33g], J.W.S. Carter [155], T.M. Carter [52], M.P. Casado [13,k], M. Caspar [48], F.L. Castillo [4], L. Castillo Garcia [13], V. Castillo Gimenez [163], N.F. Castro [130a,130e], A. Catinaccio [36], J.R. Catmore [125], V. Cavaliere [29], N. Cavalli [23b,23a], V. Cavasinni [74a,74b], Y.C. Cekmecelioglu [48], E. Celebi [21a], F. Celli [126], M.S. Centonze [70a,70b], V. Cepaitis [56], K. Cerny [122], A.S. Cerqueira [83a], A. Cerri [146], L. Cerrito [76a,76b], F. Cerutti [17a], B. Cervato [141], A. Cervelli [23b], G. Cesarini [53], S.A. Cetin [82], Z. Chadi [35a], D. Chakraborty [115], J. Chan [170], W.Y. Chan [153], J.D. Chapman [32], E. Chapon [135], B. Chargeishvili [149b], D.G. Charlton [20], T.P. Charman [94], M. Chatterjee [19], C. Chauhan [133], S. Chekanov [6], S.V. Chekulaev [156a], G.A. Chelkov [38,a], A. Chen [106], B. Chen [151], B. Chen [165], H. Chen [14c], H. Chen [29], J. Chen [62c], J. Chen [142], M. Chen [126], S. Chen [153], S.J. Chen [14c], X. Chen [62c,135], X. Chen [14b,av], Y. Chen [62a], C.L. Cheng [170], H.C. Cheng [64a], S. Cheong [143], A. Cheplakov [38], E. Cheremushkina [48], E. Cherepanova [114], R. Cherkaoui El Moursli [35e], E. Cheu [7], K. Cheung [65], L. Chevalier [135], V. Chiarella [53], G. Chiarelli [74a], N. Chiedde [102], G. Chiodini [70a], A.S. Chisholm [20], A. Chitan [27b], M. Chitishvili [163], M.V. Chizhov [38],

K. Choi[11], A.R. Chomont[75a,75b], Y. Chou[103], E.Y.S. Chow[113], T. Chowdhury[33g], K.L. Chu[169], M.C. Chu[64a], X. Chu[14a,14e], J. Chudoba[131], J.J. Chwastowski[87], D. Cieri[110], K.M. Ciesla[86a], V. Cindro[93], A. Ciocio[17a], F. Cirotto[72a,72b], Z.H. Citron[169,o], M. Citterio[71a], D.A. Ciubotaru[27b], B.M. Ciungu[155], A. Clark[56], P.J. Clark[52], C. Clarry[155], J.M. Clavijo Columbie[48], S.E. Clawson[48], C. Clement[47a,47b], J. Clercx[48], L. Clissa[23b,23a], Y. Coadou[102], M. Cobal[69a,69c], A. Coccaro[57b], R.F. Coelho Barrue[130a], R. Coelho Lopes De Sa[103], S. Coelli[71a], H. Cohen[151], A.E.C. Coimbra[71a,71b], B. Cole[41], J. Collot[60], P. Conde Muiño[130a,130g], M.P. Connell[33c], S.H. Connell[33c], I.A. Connelly[59], E.I. Conroy[126], F. Conventi[72a,ax], H.G. Cooke[20], A.M. Cooper-Sarkar[126], A. Cordeiro Oudot Choi[127], L.D. Corpe[40], M. Corradi[75a,75b], F. Corriveau[104,ai], A. Cortes-Gonzalez[18], M.J. Costa[163], F. Costanza[4], D. Costanzo[139], B.M. Cote[119], G. Cowan[95], K. Cranmer[170], D. Cremonini[23b,23a], S. Crépé-Renaudin[60], F. Crescioli[127], M. Cristinziani[141], M. Cristoforetti[78a,78b], V. Croft[114], J.E. Crosby[121], G. Crosetti[43b,43a], A. Cueto[99], T. Cuhadar Donszelmann[160], H. Cui[14a,14e], Z. Cui[7], W.R. Cunningham[59], F. Curcio[43b,43a], P. Czodrowski[36], M.M. Czurylo[63b], M.J. Da Cunha Sargedas De Sousa[57b,57a], J.V. Da Fonseca Pinto[83b], C. Da Via[101], W. Dabrowski[86a], T. Dado[49], S. Dahbi[33g], T. Dai[106], D. Dal Santo[19], C. Dallapiccola[103], M. Dam[42], G. D'amen[29], V. D'Amico[109], J. Damp[100], J.R. Dandoy[128], M.F. Daneri[30], M. Danninger[142], V. Dao[36], G. Darbo[57b], S. Darmora[6], S.J. Das[29,az], S. D'Auria[71a,71b], C. David[156b], T. Davidek[133], B. Davis-Purcell[34], I. Dawson[94], H.A. Day-hall[132], K. De[8], R. De Asmundis[72a], N. De Biase[48], S. De Castro[23b,23a], N. De Groot[113], P. de Jong[114], H. De la Torre[115], A. De Maria[14c], A. De Salvo[75a], U. De Sanctis[76a,76b], A. De Santo[146], J.B. De Vivie De Regie[60], D.V. Dedovich[38], J. Degens[114], A.M. Deiana[44], F. Del Corso[23b,23a], J. Del Peso[99], F. Del Rio[63a], F. Deliot[135], C.M. Delitzsch[49], M. Della Pietra[72a,72b], D. Della Volpe[56], A. Dell'Acqua[36], L. Dell'Asta[71a,71b], M. Delmastro[4], P.A. Delsart[60], S. Demers[172], M. Demichev[38], S.P. Denisov[37], L. D'Eramo[40], D. Derendarz[87], F. Derue[127], P. Dervan[92], K. Desch[24], C. Deutsch[24], F.A. Di Bello[57b,57a], A. Di Ciaccio[76a,76b], L. Di Ciaccio[4], A. Di Domenico[75a,75b], C. Di Donato[72a,72b], A. Di Girolamo[36], G. Di Gregorio[36], A. Di Luca[78a,78b], B. Di Micco[77a,77b], R. Di Nardo[77a,77b], C. Diaconu[102], M. Diamantopoulou[34], F.A. Dias[114], T. Dias Do Vale[142], M.A. Diaz[137a,137b], F.G. Diaz Capriles[24], M. Didenko[163], E.B. Diehl[106], L. Diehl[54], S. Díez Cornell[48], C. Diez Pardos[141], C. Dimitriadi[161,24,161], A. Dimitrievska[17a], J. Dingfelder[24], I-M. Dinu[27b], S.J. Dittmeier[63b], F. Dittus[36], F. Djama[102], T. Djobava[149b], J.I. Djuvsland[16], C. Doglioni[101,98], A. Dohnalova[28a], J. Dolejsi[133], Z. Dolezal[133], K.M. Dona[39], M. Donadelli[83c], B. Dong[107], J. Donini[40], A. D'Onofrio[77a,77b], M. D'Onofrio[92], J. Dopke[134], A. Doria[72a], N. Dos Santos Fernandes[130a], P. Dougan[101], M.T. Dova[90], A.T. Doyle[59], M.A. Draguet[126], E. Dreyer[169], I. Drivas-koulouris[10], M. Drnevich[117], A.S. Drobac[158], M. Drozdova[56], D. Du[62a], T.A. du Pree[114], F. Dubinin[37], M. Dubovsky[28a], E. Duchovni[169], G. Duckeck[109], O.A. Ducu[27b], D. Duda[52], A. Dudarev[36], E.R. Duden[26], M. D'uffizi[101], L. Duflot[66], M. Dührssen[36], C. Dülsen[171], A.E. Dumitriu[27b], M. Dunford[63a], S. Dungs[49], K. Dunne[47a,47b], A. Duperrin[102], H. Duran Yildiz[3a], M. Düren[58], A. Durglishvili[149b], B.L. Dwyer[115], G.I. Dyckes[17a], M. Dyndal[86a], B.S. Dziedzic[87], Z.O. Earnshaw[146], G.H. Eberwein[126], B. Eckerova[28a], S. Eggebrecht[55], E. Egidio Purcino De Souza[127], L.F. Ehrke[56], G. Eigen[16], K. Einsweiler[17a], T. Ekelof[161], P.A. Ekman[98], S. El Farkh[35b], Y. El Ghazali[35b], H. El Jarrari[35e,148], A. El Moussaouy[108,ab], V. Ellajosyula[161], M. Ellert[161], F. Ellinghaus[171], N. Ellis[36], J. Elmsheuser[29], M. Elsing[36], D. Emeliyanov[134], Y. Enari[153], I. Ene[17a], S. Epari[13], J. Erdmann[49], P.A. Erland[87],

M. Errenst[171], M. Escalier[66], C. Escobar[163], E. Etzion[151], G. Evans[130a], H. Evans[68], L.S. Evans[95], M.O. Evans[146], A. Ezhilov[37], S. Ezzarqtouni[35a], F. Fabbri[59], L. Fabbri[23b,23a], G. Facini[96], V. Fadeyev[136], R.M. Fakhrutdinov[37], S. Falciano[75a], L.F. Falda Ulhoa Coelho[36], P.J. Falke[24], J. Faltova[133], C. Fan[162], Y. Fan[14a], Y. Fang[14a,14e], M. Fanti[71a,71b], M. Faraj[69a,69b], Z. Farazpay[97], A. Farbin[8], A. Farilla[77a], T. Farooque[107], S.M. Farrington[52], F. Fassi[35e], D. Fassouliotis[9], M. Faucci Giannelli[76a,76b], W.J. Fawcett[32], L. Fayard[66], P. Federic[133], P. Federicova[131], O.L. Fedin[37,a], G. Fedotov[37], M. Feickert[170], L. Feligioni[102], D.E. Fellers[123], C. Feng[62b], M. Feng[14b], Z. Feng[114], M.J. Fenton[160], A.B. Fenyuk[37], L. Ferencz[48], R.A.M. Ferguson[91], S.I. Fernandez Luengo[137f], P. Fernandez Martinez[13], M.J.V. Fernoux[102], J. Ferrando[48], A. Ferrari[161], P. Ferrari[114,113], R. Ferrari[73a], D. Ferrere[56], C. Ferretti[106], F. Fiedler[100], P. Fiedler[132], A. Filipčič[93], E.K. Filmer[1], F. Filthaut[113], M.C.N. Fiolhais[130a,130c,d], L. Fiorini[163], W.C. Fisher[107], T. Fitschen[101], P.M. Fitzhugh[135], I. Fleck[141], P. Fleischmann[106], T. Flick[171], M. Flores[33d,ap], L.R. Flores Castillo[64a], L. Flores Sanz De Acedo[36], F.M. Follega[78a,78b], N. Fomin[16], J.H. Foo[155], B.C. Forland[68], A. Formica[135], A.C. Forti[101], E. Fortin[36], A.W. Fortman[61], M.G. Foti[17a], L. Fountas[9,l], D. Fournier[66], H. Fox[91], P. Francavilla[74a,74b], S. Francescato[61], S. Franchellucci[56], M. Franchini[23b,23a], S. Franchino[63a], D. Francis[36], L. Franco[113], V. Franco Lima[36], L. Franconi[48], M. Franklin[61], G. Frattari[26], A.C. Freegard[94], W.S. Freund[83b], Y.Y. Frid[151], J. Friend[59], N. Fritzsche[50], A. Froch[54], D. Froidevaux[36], J.A. Frost[126], Y. Fu[62a], S. Fuenzalida Garrido[137f], M. Fujimoto[118,aq], E. Fullana Torregrosa[163,*], K.Y. Fung[64a], E. Furtado De Simas Filho[83b], M. Furukawa[153], J. Fuster[163], A. Gabrielli[23b,23a], A. Gabrielli[155], P. Gadow[36], G. Gagliardi[57b,57a], L.G. Gagnon[17a], E.J. Gallas[126], B.J. Gallop[134], K.K. Gan[119], S. Ganguly[153], Y. Gao[52], F.M. Garay Walls[137a,137b], B. Garcia[29,az], C. García[163], A. Garcia Alonso[114], A.G. Garcia Caffaro[172], J.E. García Navarro[163], M. Garcia-Sciveres[17a], G.L. Gardner[128], R.W. Gardner[39], N. Garelli[158], D. Garg[80], R.B. Garg[143,t], J.M. Gargan[52], C.A. Garner[155], C.M. Garvey[33a], P. Gaspar[83b], V.K. Gassmann[158], G. Gaudio[73a], V. Gautam[13], P. Gauzzi[75a,75b], I.L. Gavrilenko[37], A. Gavrilyuk[37], C. Gay[164], G. Gaycken[48], E.N. Gazis[10], A.A. Geanta[27b], C.M. Gee[136], C. Gemme[57b], M.H. Genest[60], S. Gentile[75a,75b], A.D. Gentry[112], S. George[95], W.F. George[20], T. Geralis[46], P. Gessinger-Befurt[36], M.E. Geyik[171], M. Ghani[167], M. Ghneimat[141], K. Ghorbanian[94], A. Ghosal[141], A. Ghosh[160], A. Ghosh[7], B. Giacobbe[23b], S. Giagu[75a,75b], T. Giani[114], P. Giannetti[74a], A. Giannini[62a], S.M. Gibson[95], M. Gignac[136], D.T. Gil[86b], A.K. Gilbert[86a], B.J. Gilbert[41], D. Gillberg[34], G. Gilles[114], N.E.K. Gillwald[48], L. Ginabat[127], D.M. Gingrich[2,aw], M.P. Giordani[69a,69c], P.F. Giraud[135], G. Giugliarelli[69a,69c], D. Giugni[71a], F. Giuli[36], I. Gkialas[9,l], L.K. Gladilin[37], C. Glasman[99], G.R. Gledhill[123], G. Glemža[48], M. Glisic[123], I. Gnesi[43b,g], Y. Go[29,az], M. Goblirsch-Kolb[36], B. Gocke[49], D. Godin[108], B. Gokturk[21a], S. Goldfarb[105], T. Golling[56], M.G.D. Gololo[33g], D. Golubkov[37], J.P. Gombas[107], A. Gomes[130a,130b], G. Gomes Da Silva[141], A.J. Gomez Delegido[163], R. Gonçalo[130a,130c], G. Gonella[123], L. Gonella[20], A. Gongadze[149c], F. Gonnella[20], J.L. Gonski[41], R.Y. González Andana[52], S. González de la Hoz[163], S. Gonzalez Fernandez[13], R. Gonzalez Lopez[92], C. Gonzalez Renteria[17a], M.V. Gonzalez Rodrigues[48], R. Gonzalez Suarez[161], S. Gonzalez-Sevilla[56], G.R. Gonzalvo Rodriguez[163], L. Goossens[36], B. Gorini[36], E. Gorini[70a,70b], A. Gorišek[93], T.C. Gosart[128], A.T. Goshaw[51], M.I. Gostkin[38], S. Goswami[121], C.A. Gottardo[36], S.A. Gotz[109], M. Gouighri[35b], V. Goumarre[48], A.G. Goussiou[138], N. Govender[33c], I. Grabowska-Bold[86a], K. Graham[34], E. Gramstad[125], S. Grancagnolo[70a,70b], M. Grandi[146], C.M. Grant[1,135], P.M. Gravila[27f], F.G. Gravili[70a,70b], H.M. Gray[17a], M. Greco[70a,70b], C. Grefe[24], I.M. Gregor[48], P. Grenier[143], S.G. Grewe[110],

C. Grieco[13], A.A. Grillo[136], K. Grimm[31], S. Grinstein[13,ad], J.-F. Grivaz[66], E. Gross[169], J. Grosse-Knetter[55], C. Grud[106], J.C. Grundy[126], L. Guan[106], W. Guan[29], C. Gubbels[164], J.G.R. Guerrero Rojas[163], G. Guerrieri[69a,69c], F. Guescini[110], R. Gugel[100], J.A.M. Guhit[106], A. Guida[18], T. Guillemin[4], E. Guilloton[167,134], S. Guindon[36], F. Guo[14a,14e], J. Guo[62c], L. Guo[48], Y. Guo[106], R. Gupta[48], R. Gupta[129], S. Gurbuz[24], S.S. Gurdasani[54], G. Gustavino[36], M. Guth[56], P. Gutierrez[120], L.F. Gutierrez Zagazeta[128], M. Gutsche[50], C. Gutschow[96], C. Gwenlan[126], C.B. Gwilliam[92], E.S. Haaland[125], A. Haas[117], M. Habedank[48], C. Haber[17a], H.K. Hadavand[8], A. Hadef[100], S. Hadzic[110], A.I. Hagan[91], J.J. Hahn[141], E.H. Haines[96], M. Haleem[166], J. Haley[121], J.J. Hall[139], G.D. Hallewell[102], L. Halser[19], K. Hamano[165], M. Hamer[24], G.N. Hamity[52], E.J. Hampshire[95], J. Han[62b], K. Han[62a], L. Han[14c], L. Han[62a], S. Han[17a], Y.F. Han[155], K. Hanagaki[84], M. Hance[136], D.A. Hangal[41,ao], H. Hanif[142], M.D. Hank[128], R. Hankache[101], J.B. Hansen[42], J.D. Hansen[42], P.H. Hansen[42], K. Hara[157], D. Harada[56], T. Harenberg[171], S. Harkusha[37], M.L. Harris[103], Y.T. Harris[126], J. Harrison[13], N.M. Harrison[119], P.F. Harrison[167], N.M. Hartman[110], N.M. Hartmann[109], Y. Hasegawa[140], R. Hauser[107], C.M. Hawkes[20], R.J. Hawkings[36], Y. Hayashi[153], S. Hayashida[111], D. Hayden[107], C. Hayes[106], R.L. Hayes[114], C.P. Hays[126], J.M. Hays[94], H.S. Hayward[92], F. He[62a], M. He[14a,14e], Y. He[154], Y. He[48], N.B. Heatley[94], V. Hedberg[98], A.L. Heggelund[125], N.D. Hehir[94], C. Heidegger[54], K.K. Heidegger[54], W.D. Heidorn[81], J. Heilman[34], S. Heim[48], T. Heim[17a], J.G. Heinlein[128], J.J. Heinrich[123], L. Heinrich[110,au], J. Hejbal[131], L. Helary[48], A. Held[170], S. Hellesund[16], C.M. Helling[164], S. Hellman[47a,47b], R.C.W. Henderson[91], L. Henkelmann[32], A.M. Henriques Correia[36], H. Herde[98], Y. Hernández Jiménez[145], L.M. Herrmann[24], T. Herrmann[50], G. Herten[54], R. Hertenberger[109], L. Hervas[36], M.E. Hesping[100], N.P. Hessey[156a], H. Hibi[85], E. Hill[155], S.J. Hillier[20], J.R. Hinds[107], F. Hinterkeuser[24], M. Hirose[124], S. Hirose[157], D. Hirschbuehl[171], T.G. Hitchings[101], B. Hiti[93], J. Hobbs[145], R. Hobincu[27e], N. Hod[169], M.C. Hodgkinson[139], B.H. Hodkinson[32], A. Hoecker[36], D.D. Hofer[106], J. Hofer[48], T. Holm[24], M. Holzbock[110], L.B.A.H. Hommels[32], B.P. Honan[101], J. Hong[62c], T.M. Hong[129], B.H. Hooberman[162], W.H. Hopkins[6], Y. Horii[111], S. Hou[148], A.S. Howard[93], J. Howarth[59], J. Hoya[6], M. Hrabovsky[122], A. Hrynevich[48], T. Hryn'ova[4], P.J. Hsu[65], S.-C. Hsu[138], Q. Hu[62a], Y.F. Hu[14a,14e], S. Huang[64b], X. Huang[14c], X. Huang[14a,14e], Y. Huang[139,m], Y. Huang[14a], Z. Huang[101], Z. Hubacek[132], M. Huebner[24], F. Huegging[24], T.B. Huffman[126], C.A. Hugli[48], M. Huhtinen[36], S.K. Huiberts[16], R. Hulsken[104], N. Huseynov[12], J. Huston[107], J. Huth[61], R. Hyneman[143], G. Iacobucci[56], G. Iakovidis[29], I. Ibragimov[141], L. Iconomidou-Fayard[66], P. Iengo[72a,72b], R. Iguchi[153], T. Iizawa[126,r], Y. Ikegami[84], N. Ilic[155], H. Imam[35a], M. Ince Lezki[56], T. Ingebretsen Carlson[47a,47b], G. Introzzi[73a,73b], M. Iodice[77a], V. Ippolito[75a,75b], R.K. Irwin[92], M. Ishino[153], W. Islam[170], C. Issever[18,48], S. Istin[21a,bb], H. Ito[168], J.M. Iturbe Ponce[64a], R. Iuppa[78a,78b], A. Ivina[169], J.M. Izen[45], V. Izzo[72a], P. Jacka[131,132], P. Jackson[1], R.M. Jacobs[48], B.P. Jaeger[142], C.S. Jagfeld[109], G. Jain[156a], P. Jain[54], K. Jakobs[54], T. Jakoubek[169], J. Jamieson[59], K.W. Janas[86a], M. Javurkova[103], F. Jeanneau[135], L. Jeanty[123], J. Jejelava[149a,al], P. Jenni[54,i], C.E. Jessiman[34], S. Jézéquel[4], C. Jia[62b], J. Jia[145], X. Jia[61], X. Jia[14a,14e], Z. Jia[14c], S. Jiggins[48], J. Jimenez Pena[13], S. Jin[14c], A. Jinaru[27b], O. Jinnouchi[154], P. Johansson[139], K.A. Johns[7], J.W. Johnson[136], D.M. Jones[32], E. Jones[48], P. Jones[32], R.W.L. Jones[91], T.J. Jones[92], H.L. Joos[55,36], R. Joshi[119], J. Jovicevic[15], X. Ju[17a], J.J. Junggeburth[103,v], T. Junkermann[63a], A. Juste Rozas[13,ad], M.K. Juzek[87], S. Kabana[137e], A. Kaczmarska[87], M. Kado[110], H. Kagan[119], M. Kagan[143], A. Kahn[41], A. Kahn[128], C. Kahra[100], T. Kaji[153], E. Kajomovitz[150], N. Kakati[169], I. Kalaitzidou[54], C.W. Kalderon[29], A. Kamenshchikov[155], N.J. Kang[136], D. Kar[33g], K. Karava[126], M.J. Kareem[156b], E. Karentzos[54], I. Karkanias[152], O. Karkout[114], S.N. Karpov[38], Z.M. Karpova[38], V. Kartvelishvili[91], A.N. Karyukhin[37], E. Kasimi[152], J. Katzy[48], S. Kaur[34], K. Kawade[140], M.P. Kawale[120], C. Kawamoto[88], T. Kawamoto[135], E.F. Kay[36], F.I. Kaya[158], S. Kazakos[107], V.F. Kazanin[37], Y. Ke[145], J.M. Keaveney[33a], R. Keeler[165], G.V. Kehris[61], J.S. Keller[34], A.S. Kelly[96], J.J. Kempster[146], K.E. Kennedy[41], P.D. Kennedy[100], O. Kepka[131], B.P. Kerridge[167], S. Kersten[171], B.P. Kerševan[93], S. Keshri[66], L. Keszeghova[28a], S. Ketabchi Haghighat[155], R.A. Khan[129], M. Khandoga[127], A. Khanov[121], A.G. Kharlamov[37], T. Kharlamova[37], E.E. Khoda[138], M. Kholodenko[37], T.J. Khoo[18], G. Khoriauli[166], J. Khubua[149b], Y.A.R. Khwaira[66], A. Kilgallon[123], D.W. Kim[47a,47b], Y.K. Kim[39], N. Kimura[96], M.K. Kingston[55], A. Kirchhoff[55], C. Kirfel[24], F. Kirfel[24], J. Kirk[134], A.E. Kiryunin[110], C. Kitsaki[10], O. Kivernyk[24], M. Klassen[63a], C. Klein[34], L. Klein[166], M.H. Klein[106], M. Klein[92], S.B. Klein[56], U. Klein[92], P. Klimek[36], A. Klimentov[29], T. Klioutchnikova[36], P. Kluit[114], S. Kluth[110], E. Kneringer[79], T.M. Knight[155], A. Knue[49], R. Kobayashi[88], D. Kobylianskii[169], S.F. Koch[126], M. Kocian[143], P. Kodyš[133], D.M. Koeck[123], P.T. Koenig[24], T. Koffas[34], O. Kolay[50], M. Kolb[135], I. Koletsou[4], T. Komarek[122], K. Köneke[54], A.X.Y. Kong[1], T. Kono[118], N. Konstantinidis[96], P. Kontaxakis[56], B. Konya[98], R. Kopeliansky[68], S. Koperny[86a], K. Korcyl[87], K. Kordas[152,f], G. Koren[151], A. Korn[96], S. Korn[55], I. Korolkov[13], N. Korotkova[37], B. Kortman[114], O. Kortner[110], S. Kortner[110], W.H. Kostecka[115], V.V. Kostyukhin[141], A. Kotsokechagia[135], A. Kotwal[51], A. Koulouris[36], A. Kourkoumeli-Charalampidi[73a,73b], C. Kourkoumelis[9], E. Kourlitis[110,au], O. Kovanda[146], R. Kowalewski[165], W. Kozanecki[135], A.S. Kozhin[37], V.A. Kramarenko[37], G. Kramberger[93], P. Kramer[100], M.W. Krasny[127], A. Krasznahorkay[36], J.W. Kraus[171], J.A. Kremer[48], T. Kresse[50], J. Kretzschmar[92], K. Kreul[18], P. Krieger[155], S. Krishnamurthy[103], M. Krivos[133], K. Krizka[20], K. Kroeninger[49], H. Kroha[110], J. Kroll[131], J. Kroll[128], K.S. Krowpman[107], U. Kruchonak[38], H. Krüger[24], N. Krumnack[81], M.C. Kruse[51], J.A. Krzysiak[87], O. Kuchinskaia[37], S. Kuday[3a], S. Kuehn[36], R. Kuesters[54], T. Kuhl[48], V. Kukhtin[38], Y. Kulchitsky[37,a], S. Kuleshov[137d,137b], M. Kumar[33g], N. Kumari[48], A. Kupco[131], T. Kupfer[49], A. Kupich[37], O. Kuprash[54], H. Kurashige[85], L.L. Kurchaninov[156a], O. Kurdysh[66], Y.A. Kurochkin[37], A. Kurova[37], M. Kuze[154], A.K. Kvam[103], J. Kvita[122], T. Kwan[104], N.G. Kyriacou[106], L.A.O. Laatu[102], C. Lacasta[163], F. Lacava[75a,75b], H. Lacker[18], D. Lacour[127], N.N. Lad[96], E. Ladygin[38], B. Laforge[127], T. Lagouri[137e], F.Z. Lahbabi[35a], S. Lai[55], I.K. Lakomiec[86a], N. Lalloue[60], J.E. Lambert[165,n], S. Lammers[68], W. Lampl[7], C. Lampoudis[152,f], A.N. Lancaster[115], E. Lançon[29], U. Landgraf[54], M.P.J. Landon[94], V.S. Lang[54], R.J. Langenberg[103], O.K.B. Langrekken[125], A.J. Lankford[160], F. Lanni[36], K. Lantzsch[24], A. Lanza[73a], A. Lapertosa[57b,57a], J.F. Laporte[135], T. Lari[71a], F. Lasagni Manghi[23b], M. Lassnig[36], V. Latonova[131], A. Laudrain[100], A. Laurier[150], S.D. Lawlor[139], Z. Lawrence[101], M. Lazzaroni[71a,71b], B. Le[101], E.M. Le Boulicaut[51], B. Leban[93], A. Lebedev[81], M. LeBlanc[101,as], F. Ledroit-Guillon[60], A.C.A. Lee[96], S.C. Lee[148], S. Lee[47a,47b], T.F. Lee[92], L.L. Leeuw[33c], H.P. Lefebvre[95], M. Lefebvre[165], C. Leggett[17a], G. Lehmann Miotto[36], M. Leigh[56], W.A. Leight[103], W. Leinonen[113], A. Leisos[152,ac], M.A.L. Leite[83c], C.E. Leitgeb[48], R. Leitner[133], K.J.C. Leney[44], T. Lenz[24], S. Leone[74a], C. Leonidopoulos[52], A. Leopold[144], C. Leroy[108], R. Les[107], C.G. Lester[32], M. Levchenko[37], J. Levêque[4], D. Levin[106], L.J. Levinson[169], M.P. Lewicki[87], D.J. Lewis[4], A. Li[5], B. Li[62b], C. Li[62a], C-Q. Li[62c], H. Li[62a], H. Li[62b], H. Li[14c], H. Li[14b], H. Li[62b], J. Li[62c], K. Li[138], L. Li[62c], M. Li[14a,14e], Q.Y. Li[62a], S. Li[14a,14e], S. Li[62d,62c,e], T. Li[5,c], X. Li[104], Z. Li[126], Z. Li[104], Z. Li[92], Z. Li[14a,14e], S. Liang[14a,14e], Z. Liang[14a], M. Liberatore[135,am], B. Liberti[76a],

K. Lie[64c], J. Lieber Marin[83b], H. Lien[68], K. Lin[107], R.E. Lindley[7], J.H. Lindon[2], E. Lipeles[128], A. Lipniacka[16], A. Lister[164], J.D. Little[4], B. Liu[14a], B.X. Liu[142], D. Liu[62d,62c], J.B. Liu[62a], J.K.K. Liu[32], K. Liu[62d,62c], M. Liu[62a], M.Y. Liu[62a], P. Liu[14a], Q. Liu[62d,138,62c], X. Liu[62a], Y. Liu[14d,14e], Y.L. Liu[62b], Y.W. Liu[62a], J. Llorente Merino[142], S.L. Lloyd[94], E.M. Lobodzinska[48], P. Loch[7], T. Lohse[18], K. Lohwasser[139], E. Loiacono[48], M. Lokajicek[131,*], J.D. Lomas[20], J.D. Long[162], I. Longarini[160], L. Longo[70a,70b], R. Longo[162], I. Lopez Paz[67], A. Lopez Solis[48], J. Lorenz[109], N. Lorenzo Martinez[4], A.M. Lory[109], O. Loseva[37], X. Lou[47a,47b], X. Lou[14a,14e], A. Lounis[66], J. Love[6], P.A. Love[91], G. Lu[14a,14e], M. Lu[80], S. Lu[128], Y.J. Lu[65], H.J. Lubatti[138], C. Luci[75a,75b], F.L. Lucio Alves[14c], A. Lucotte[60], F. Luehring[68], I. Luise[145], O. Lukianchuk[66], O. Lundberg[144], B. Lund-Jensen[144], N.A. Luongo[123], M.S. Lutz[151], A.B. Lux[25], D. Lynn[29], H. Lyons[92], R. Lysak[131], E. Lytken[98], V. Lyubushkin[38], T. Lyubushkina[38], M.M. Lyukova[145], H. Ma[29], K. Ma[62a], L.L. Ma[62b], Y. Ma[121], D.M. Mac Donell[165], G. Maccarrone[53], J.C. MacDonald[100], P.C. Machado De Abreu Farias[83b], R. Madar[40], W.F. Mader[50], T. Madula[96], J. Maeda[85], T. Maeno[29], H. Maguire[139], V. Maiboroda[135], A. Maio[130a,130b,130d], K. Maj[86a], O. Majersky[48], S. Majewski[123], N. Makovec[66], V. Maksimovic[15], B. Malaescu[127], Pa. Malecki[87], V.P. Maleev[37], F. Malek[60], M. Mali[93], D. Malito[95,s], U. Mallik[80], S. Maltezos[10], S. Malyukov[38], J. Mamuzic[13], G. Mancini[53], G. Manco[73a,73b], J.P. Mandalia[94], I. Mandić[93], L. Manhaes de Andrade Filho[83a], I.M. Maniatis[169], J. Manjarres Ramos[102,an], D.C. Mankad[169], A. Mann[109], B. Mansoulie[135], S. Manzoni[36], X. Mapekula[33c], A. Marantis[152,ac], G. Marchiori[5], M. Marcisovsky[131], C. Marcon[71a,71b], M. Marinescu[20], M. Marjanovic[120], E.J. Marshall[91], Z. Marshall[17a], S. Marti-Garcia[163], T.A. Martin[167], V.J. Martin[52], B. Martin dit Latour[16], L. Martinelli[75a,75b], M. Martinez[13,ad], P. Martinez Agullo[163], V.I. Martinez Outschoorn[103], P. Martinez Suarez[13], S. Martin-Haugh[134], V.S. Martoiu[27b], A.C. Martyniuk[96], A. Marzin[36], D. Mascione[78a,78b], L. Masetti[100], T. Mashimo[153], J. Masik[101], A.L. Maslennikov[37], L. Massa[23b], P. Massarotti[72a,72b], P. Mastrandrea[74a,74b], A. Mastroberardino[43b,43a], T. Masubuchi[153], T. Mathisen[161], J. Matousek[133], N. Matsuzawa[153], J. Maurer[27b], B. Maček[93], D.A. Maximov[37], R. Mazini[148], I. Maznas[152], M. Mazza[107], S.M. Mazza[136], E. Mazzeo[71a,71b], C. Mc Ginn[29], J.P. Mc Gowan[104], S.P. Mc Kee[106], E.F. McDonald[105], A.E. McDougall[114], J.A. Mcfayden[146], R.P. McGovern[128], G. Mchedlidze[149b], R.P. Mckenzie[33g], T.C. Mclachlan[48], D.J. Mclaughlin[96], S.J. McMahon[134], C.M. Mcpartland[92], R.A. McPherson[165,ai], S. Mehlhase[109], A. Mehta[92], D. Melini[150], B.R. Mellado Garcia[33g], A.H. Melo[55], F. Meloni[48], A.M. Mendes Jacques Da Costa[101], H.Y. Meng[155], L. Meng[91], S. Menke[110], M. Mentink[36], E. Meoni[43b,43a], C. Merlassino[126], L. Merola[72a,72b], C. Meroni[71a,71b], G. Merz[106], O. Meshkov[37], J. Metcalfe[6], A.S. Mete[6], C. Meyer[68], J-P. Meyer[135], R.P. Middleton[134], L. Mijović[52], G. Mikenberg[169], M. Mikestikova[131], M. Mikuž[93], H. Mildner[100], A. Milic[36], C.D. Milke[44], D.W. Miller[39], L.S. Miller[34], A. Milov[169], D.A. Milstead[47a,47b], T. Min[14c], A.A. Minaenko[37], I.A. Minashvili[149b], L. Mince[59], A.I. Mincer[117], B. Mindur[86a], M. Mineev[38], Y. Mino[88], L.M. Mir[13], M. Miralles Lopez[163], M. Mironova[17a], A. Mishima[153], M.C. Missio[113], A. Mitra[167], V.A. Mitsou[163], Y. Mitsumori[111], O. Miu[155], P.S. Miyagawa[94], T. Mkrtchyan[63a], M. Mlinarevic[96], T. Mlinarevic[96], M. Mlynarikova[36], S. Mobius[19], P. Moder[48], P. Mogg[109], A.F. Mohammed[14a,14e], S. Mohapatra[41], G. Mokgatitswane[33g], L. Moleri[169], B. Mondal[141], S. Mondal[132], G. Monig[146], K. Mönig[48], E. Monnier[102], L. Monsonis Romero[163], J. Montejo Berlingen[13], M. Montella[119], F. Montereali[77a,77b], F. Monticelli[90], S. Monzani[69a,69c], N. Morange[66], A.L. Moreira De Carvalho[130a],

M. Moreno Llácer [163], C. Moreno Martinez [56], P. Morettini [57b], S. Morgenstern [36], M. Morii [61], M. Morinaga [153], A.K. Morley [36], F. Morodei [75a,75b], L. Morvaj [36], P. Moschovakos [36], B. Moser [36], M. Mosidze[149b], T. Moskalets [54], P. Moskvitina [113], J. Moss [31,p], E.J.W. Moyse [103], O. Mtintsilana [33g], S. Muanza [102], J. Mueller [129], D. Muenstermann [91], R. Müller [19], G.A. Mullier [161], A.J. Mullin[32], J.J. Mullin[128], D.P. Mungo [155], D. Munoz Perez [163], F.J. Munoz Sanchez [101], M. Murin [101], W.J. Murray [167,134], A. Murrone [71a,71b], M. Muškinja [17a], C. Mwewa [29], A.G. Myagkov [37,a], A.J. Myers [8], G. Myers [68], M. Myska [132], B.P. Nachman [17a], O. Nackenhorst [49], A. Nag [50], K. Nagai [126], K. Nagano [84], J.L. Nagle [29,az], E. Nagy [102], A.M. Nairz [36], Y. Nakahama [84], K. Nakamura [84], K. Nakkalil [5], H. Nanjo [124], R. Narayan [44], E.A. Narayanan [112], I. Naryshkin [37], M. Naseri [34], S. Nasri [159], C. Nass [24], G. Navarro [22a], J. Navarro-Gonzalez [163], R. Nayak [151], A. Nayaz [18], P.Y. Nechaeva [37], F. Nechansky [48], L. Nedic [126], T.J. Neep [20], A. Negri [73a,73b], M. Negrini [23b], C. Nellist [114], C. Nelson [104], K. Nelson [106], S. Nemecek [131], M. Nessi [36,j], M.S. Neubauer [162], F. Neuhaus [100], J. Neundorf [48], R. Newhouse [164], P.R. Newman [20], C.W. Ng [129], Y.W.Y. Ng [48], B. Ngair [35e], H.D.N. Nguyen [108], R.B. Nickerson [126], R. Nicolaidou [135], J. Nielsen [136], M. Niemeyer [55], J. Niermann [55,36], N. Nikiforou [36], V. Nikolaenko [37,a], I. Nikolic-Audit [127], K. Nikolopoulos [20], P. Nilsson [29], I. Ninca [48], H.R. Nindhito [56], G. Ninio [151], A. Nisati [75a], N. Nishu [2], R. Nisius [110], J-E. Nitschke [50], E.K. Nkadimeng [33g], T. Nobe [153], D.L. Noel [32], T. Nommensen [147], M.B. Norfolk [139], R.R.B. Norisam [96], B.J. Norman [34], J. Novak [93], T. Novak [48], L. Novotny [132], R. Novotny [112], L. Nozka [122], K. Ntekas [160], N.M.J. Nunes De Moura Junior [83b], E. Nurse[96], J. Ocariz [127], A. Ochi [85], I. Ochoa [130a], S. Oerdek [48,y], J.T. Offermann [39], A. Ogrodnik [133], A. Oh [101], C.C. Ohm [144], H. Oide [84], R. Oishi [153], M.L. Ojeda [48], M.W. O'Keefe[92], Y. Okumura [153], L.F. Oleiro Seabra [130a], S.A. Olivares Pino [137d], D. Oliveira Damazio [29], D. Oliveira Goncalves [83a], J.L. Oliver [160], Ö.O. Öncel [54], A.P. O'Neill [19], A. Onofre [130a,130e], P.U.E. Onyisi [11], M.J. Oreglia [39], G.E. Orellana [90], D. Orestano [77a,77b], N. Orlando [13], R.S. Orr [155], V. O'Shea [59], L.M. Osojnak [128], R. Ospanov [62a], G. Otero y Garzon [30], H. Otono [89], P.S. Ott [63a], G.J. Ottino [17a], M. Ouchrif [35d], J. Ouellette [29], F. Ould-Saada [125], M. Owen [59], R.E. Owen [134], K.Y. Oyulmaz [21a], V.E. Ozcan [21a], F. Ozturk [87], N. Ozturk [8], S. Ozturk [82], H.A. Pacey [126], A. Pacheco Pages [13], C. Padilla Aranda [13], G. Padovano [75a,75b], S. Pagan Griso [17a], G. Palacino [68], A. Palazzo [70a,70b], S. Palestini [36], J. Pan [172], T. Pan [64a], D.K. Panchal [11], C.E. Pandini [114], J.G. Panduro Vazquez [95], H.D. Pandya [1], H. Pang [14b], P. Pani [48], G. Panizzo [69a,69c], L. Paolozzi [56], C. Papadatos [108], S. Parajuli [44], A. Paramonov [6], C. Paraskevopoulos [10], D. Paredes Hernandez [64b], K.R. Park [41], T.H. Park [155], M.A. Parker [32], F. Parodi [57b,57a], E.W. Parrish [115], V.A. Parrish [52], J.A. Parsons [41], U. Parzefall [54], B. Pascual Dias [108], L. Pascual Dominguez [151], E. Pasqualucci [75a], S. Passaggio [57b], F. Pastore [95], P. Pasuwan [47a,47b], P. Patel [87], U.M. Patel [51], J.R. Pater [101], T. Pauly [36], J. Pearkes [143], M. Pedersen [125], R. Pedro [130a], S.V. Peleganchuk [37], O. Penc [36], E.A. Pender [52], K.E. Penski [109], M. Penzin [37], B.S. Peralva [83d], A.P. Pereira Peixoto [60], L. Pereira Sanchez [47a,47b], D.V. Perepelitsa [29,az], E. Perez Codina [156a], M. Perganti [10], L. Perini [71a,71b,*], H. Pernegger [36], O. Perrin [40], K. Peters [48], R.F.Y. Peters [101], B.A. Petersen [36], T.C. Petersen [42], E. Petit [102], V. Petousis [132], C. Petridou [152,f], A. Petrukhin [141], M. Pettee [17a], N.E. Pettersson [36], A. Petukhov [37], K. Petukhova [133], R. Pezoa [137f], L. Pezzotti [36], G. Pezzullo [172], T.M. Pham [170], T. Pham [105], P.W. Phillips [134], G. Piacquadio [145], E. Pianori [17a], F. Piazza [123], R. Piegaia [30], D. Pietreanu [27b], A.D. Pilkington [101], M. Pinamonti [69a,69c], J.L. Pinfold [2], B.C. Pinheiro Pereira [130a], A.E. Pinto Pinoargote [100,135], L. Pintucci [69a,69c], K.M. Piper [146], A. Pirttikoski [56], D.A. Pizzi [34], L. Pizzimento [64b], A. Pizzini [114], M.-A. Pleier [29], V. Plesanovs[54],

V. Pleskot [133], E. Plotnikova[38], G. Poddar [4], R. Poettgen [98], L. Poggioli [127], I. Pokharel [55], S. Polacek [133], G. Polesello [73a], A. Poley [142,156a], R. Polifka [132], A. Polini [23b], C.S. Pollard [167], Z.B. Pollock [119], V. Polychronakos [29], E. Pompa Pacchi [75a,75b], D. Ponomarenko [113], L. Pontecorvo [36], S. Popa [27a], G.A. Popeneciu [27d], A. Poreba [36], D.M. Portillo Quintero [156a], S. Pospisil [132], M.A. Postill [139], P. Postolache [27c], K. Potamianos [167], P.A. Potepa [86a], I.N. Potrap [38], C.J. Potter [32], H. Potti [1], T. Poulsen [48], J. Poveda [163], M.E. Pozo Astigarraga [36], A. Prades Ibanez [163], J. Pretel [54], D. Price [101], M. Primavera [70a], M.A. Principe Martin [99], R. Privara [122], T. Procter [59], M.L. Proffitt [138], N. Proklova [128], K. Prokofiev [64c], G. Proto [110], S. Protopopescu [29], J. Proudfoot [6], M. Przybycien [86a], W.W. Przygoda [86b], J.E. Puddefoot [139], D. Pudzha [37], D. Pyatiizbyantseva [37], J. Qian [106], D. Qichen [101], Y. Qin [101], T. Qiu [52], A. Quadt [55], M. Queitsch-Maitland [101], G. Quetant [56], R.P. Quinn [164], G. Rabanal Bolanos [61], D. Rafanoharana [54], F. Ragusa [71a,71b], J.L. Rainbolt [39], J.A. Raine [56], S. Rajagopalan [29], E. Ramakoti [37], I.A. Ramirez-Berend [34], K. Ran [48,14e], N.P. Rapheeha [33g], H. Rasheed [27b], V. Raskina [127], D.F. Rassloff [63a], S. Rave [100], B. Ravina [55], I. Ravinovich [169], M. Raymond [36], A.L. Read [125], N.P. Readioff [139], D.M. Rebuzzi [73a,73b], G. Redlinger [29], A.S. Reed [110], K. Reeves [26], J.A. Reidelsturz [171,aa], D. Reikher [151], A. Rej [49,z], C. Rembser [36], A. Renardi [48], M. Renda [27b], M.B. Rendel[110], F. Renner [48], A.G. Rennie [160], A.L. Rescia [48], S. Resconi [71a], M. Ressegotti [57b,57a], S. Rettie [36], J.G. Reyes Rivera [107], E. Reynolds [17a], O.L. Rezanova [37], P. Reznicek [133], N. Ribaric [91], E. Ricci [78a,78b], R. Richter [110], S. Richter [47a,47b], E. Richter-Was [86b], M. Ridel [127], S. Ridouani [35d], P. Rieck [117], P. Riedler [36], E.M. Riefel [47a,47b], J.O. Rieger[114], M. Rijssenbeek [145], A. Rimoldi [73a,73b], M. Rimoldi [36], L. Rinaldi [23b,23a], T.T. Rinn [29], M.P. Rinnagel [109], G. Ripellino [161], I. Riu [13], P. Rivadeneira [48], J.C. Rivera Vergara [165], F. Rizatdinova [121], E. Rizvi [94], B.A. Roberts [167], B.R. Roberts [17a], S.H. Robertson [104,ai], D. Robinson [32], C.M. Robles Gajardo[137f], M. Robles Manzano [100], A. Robson [59], A. Rocchi [76a,76b], C. Roda [74a,74b], S. Rodriguez Bosca [63a], Y. Rodriguez Garcia [22a], A. Rodriguez Rodriguez [54], A.M. Rodríguez Vera [156b], S. Roe[36], J.T. Roemer [160], A.R. Roepe-Gier [136], J. Roggel [171], O. Røhne [125], R.A. Rojas [103], C.P.A. Roland [127], J. Roloff [29], A. Romaniouk [37], E. Romano [73a,73b], M. Romano [23b], A.C. Romero Hernandez [162], N. Rompotis [92], L. Roos [127], S. Rosati [75a], B.J. Rosser [39], E. Rossi [126], E. Rossi [72a,72b], L.P. Rossi [57b], L. Rossini [54], R. Rosten [119], M. Rotaru [27b], B. Rottler [54], C. Rougier [102,an], D. Rousseau [66], D. Rousso [32], A. Roy [162], S. Roy-Garand [155], A. Rozanov [102], Y. Rozen [150], X. Ruan [33g], A. Rubio Jimenez [163], A.J. Ruby [92], V.H. Ruelas Rivera [18], T.A. Ruggeri [1], A. Ruggiero [126], A. Ruiz-Martinez [163], A. Rummler [36], Z. Rurikova [54], N.A. Rusakovich [38], H.L. Russell [165], G. Russo [75a,75b], J.P. Rutherfoord [7], S. Rutherford Colmenares [32], K. Rybacki[91], M. Rybar [133], E.B. Rye [125], A. Ryzhov [44], J.A. Sabater Iglesias [56], P. Sabatini [163], L. Sabetta [75a,75b], H.F-W. Sadrozinski [136], F. Safai Tehrani [75a], B. Safarzadeh Samani [134], M. Safdari [143], S. Saha [165], M. Sahinsoy [110], M. Saimpert [135], M. Saito [153], T. Saito [153], D. Salamani [36], A. Salnikov [143], J. Salt [163], A. Salvador Salas [151], D. Salvatore [43b,43a], F. Salvatore [146], A. Salzburger [36], D. Sammel [54], D. Sampsonidis [152,f], D. Sampsonidou [123], J. Sánchez [163], A. Sanchez Pineda [4], V. Sanchez Sebastian [163], H. Sandaker [125], C.O. Sander [48], J.A. Sandesara [103], M. Sandhoff [171], C. Sandoval [22b], D.P.C. Sankey [134], T. Sano [88], A. Sansoni [53], L. Santi [75a,75b], C. Santoni [40], H. Santos [130a,130b], S.N. Santpur [17a], A. Santra [169], K.A. Saoucha [116b], J.G. Saraiva [130a,130d], J. Sardain [7], O. Sasaki [84], K. Sato [157], C. Sauer[63b], F. Sauerburger [54], E. Sauvan [4], P. Savard [155,aw], R. Sawada [153], C. Sawyer [134], L. Sawyer [97], I. Sayago Galvan[163], C. Sbarra [23b], A. Sbrizzi [23b,23a], T. Scanlon [96], J. Schaarschmidt [138], P. Schacht [110], U. Schäfer [100], A.C. Schaffer [66,44], D. Schaile [109], R.D. Schamberger [145], C. Scharf [18], M.M. Schefer [19], V.A. Schegelsky [37], D. Scheirich [133], F. Schenck [18],

M. Schernau[160], C. Scheulen[55], C. Schiavi[57b,57a], E.J. Schioppa[70a,70b], M. Schioppa[43b,43a], B. Schlag[143,t], K.E. Schleicher[54], S. Schlenker[36], J. Schmeing[171], M.A. Schmidt[171], K. Schmieden[100], C. Schmitt[100], N. Schmitt[100], S. Schmitt[48], L. Schoeffel[135], A. Schoening[63b], P.G. Scholer[54], E. Schopf[126], M. Schott[100], J. Schovancova[36], S. Schramm[56], F. Schroeder[171], T. Schroer[56], H-C. Schultz-Coulon[63a], M. Schumacher[54], B.A. Schumm[136], Ph. Schune[135], A.J. Schuy[138], H.R. Schwartz[136], A. Schwartzman[143], T.A. Schwarz[106], Ph. Schwemling[135], R. Schwienhorst[107], A. Sciandra[136], G. Sciolla[26], F. Scuri[74a], C.D. Sebastiani[92], K. Sedlaczek[115], P. Seema[18], S.C. Seidel[112], A. Seiden[136], B.D. Seidlitz[41], C. Seitz[48], J.M. Seixas[83b], G. Sekhniaidze[72a], S.J. Sekula[44], L. Selem[60], N. Semprini-Cesari[23b,23a], D. Sengupta[56], V. Senthilkumar[163], L. Serin[66], L. Serkin[69a,69b], M. Sessa[76a,76b], H. Severini[120], F. Sforza[57b,57a], A. Sfyrla[56], E. Shabalina[55], R. Shaheen[144], J.D. Shahinian[128], D. Shaked Renous[169], L.Y. Shan[14a], M. Shapiro[17a], A. Sharma[36], A.S. Sharma[164], P. Sharma[80], S. Sharma[48], P.B. Shatalov[37], K. Shaw[146], S.M. Shaw[101], A. Shcherbakova[37], Q. Shen[62c,5], P. Sherwood[96], L. Shi[96], X. Shi[14a], C.O. Shimmin[172], J.D. Shinner[95], I.P.J. Shipsey[126], S. Shirabe[56,j], M. Shiyakova[38,ag], J. Shlomi[169], M.J. Shochet[39], J. Shojaii[105], D.R. Shope[125], B. Shrestha[120], S. Shrestha[119,ba], E.M. Shrif[33g], M.J. Shroff[165], P. Sicho[131], A.M. Sickles[162], E. Sideras Haddad[33g], A. Sidoti[23b], F. Siegert[50], Dj. Sijacki[15], R. Sikora[86a], F. Sili[90], J.M. Silva[20], M.V. Silva Oliveira[29], S.B. Silverstein[47a], S. Simion[66], R. Simoniello[36], E.L. Simpson[59], H. Simpson[146], L.R. Simpson[106], N.D. Simpson[98], S. Simsek[82], S. Sindhu[55], P. Sinervo[155], S. Singh[155], S. Sinha[48], S. Sinha[101], M. Sioli[23b,23a], I. Siral[36], E. Sitnikova[48], S.Yu. Sivoklokov[37,*], J. Sjölin[47a,47b], A. Skaf[55], E. Skorda[20,ar], P. Skubic[120], M. Slawinska[87], V. Smakhtin[169], B.H. Smart[134], J. Smiesko[36], S.Yu. Smirnov[37], Y. Smirnov[37], L.N. Smirnova[37,a], O. Smirnova[98], A.C. Smith[41], E.A. Smith[39], H.A. Smith[126], J.L. Smith[92], R. Smith[143], M. Smizanska[91], K. Smolek[132], A.A. Snesarev[37], S.R. Snider[155], H.L. Snoek[114], S. Snyder[29], R. Sobie[165,ai], A. Soffer[151], C.A. Solans Sanchez[36], E.Yu. Soldatov[37], U. Soldevila[163], A.A. Solodkov[37], S. Solomon[26], A. Soloshenko[38], K. Solovieva[54], O.V. Solovyanov[40], V. Solovyev[37], P. Sommer[36], A. Sonay[13], W.Y. Song[156b], J.M. Sonneveld[114], A. Sopczak[132], A.L. Sopio[96], F. Sopkova[28b], I.R. Sotarriva Alvarez[154], V. Sothilingam[63a], S. Sottocornola[68], R. Soualah[116b], Z. Soumaimi[35e], D. South[48], N. Soybelman[169], S. Spagnolo[70a,70b], M. Spalla[110], D. Sperlich[54], G. Spigo[36], S. Spinali[91], D.P. Spiteri[59], M. Spousta[133], E.J. Staats[34], A. Stabile[71a,71b], R. Stamen[63a], A. Stampekis[20], M. Standke[24], E. Stanecka[87], M.V. Stange[50], B. Stanislaus[17a], M.M. Stanitzki[48], B. Stapf[48], E.A. Starchenko[37], G.H. Stark[136], J. Stark[102,an], D.M. Starko[156b], P. Staroba[131], P. Starovoitov[63a], S. Stärz[104], R. Staszewski[87], G. Stavropoulos[46], J. Steentoft[161], P. Steinberg[29], B. Stelzer[142,156a], H.J. Stelzer[129], O. Stelzer-Chilton[156a], H. Stenzel[58], T.J. Stevenson[146], G.A. Stewart[36], J.R. Stewart[121], M.C. Stockton[36], G. Stoicea[27b], M. Stolarski[130a], S. Stonjek[110], A. Straessner[50], J. Strandberg[144], S. Strandberg[47a,47b], M. Stratmann[171], M. Strauss[120], T. Strebler[102], P. Strizenec[28b], R. Ströhmer[166], D.M. Strom[123], L.R. Strom[48], R. Stroynowski[44], A. Strubig[47a,47b], S.A. Stucci[29], B. Stugu[16], J. Stupak[120], N.A. Styles[48], D. Su[143], S. Su[62a], W. Su[62d], X. Su[62a,66], K. Sugizaki[153], V.V. Sulin[37], M.J. Sullivan[92], D.M.S. Sultan[78a,78b], L. Sultanaliyeva[37], S. Sultansoy[3b], T. Sumida[88], S. Sun[106], S. Sun[170], O. Sunneborn Gudnadottir[161], N. Sur[102], M.R. Sutton[146], H. Suzuki[157], M. Svatos[131], M. Swiatlowski[156a], T. Swirski[166], I. Sykora[28a], M. Sykora[133], T. Sykora[133], D. Ta[100], K. Tackmann[48,ae], A. Taffard[160], R. Tafirout[156a], J.S. Tafoya Vargas[66], E.P. Takeva[52], Y. Takubo[84], M. Talby[102], A.A. Talyshev[37], K.C. Tam[64b], N.M. Tamir[151], A. Tanaka[153],

J. Tanaka[153], R. Tanaka[66], M. Tanasini[57b,57a], Z. Tao[164], S. Tapia Araya[137f], S. Tapprogge[100], A. Tarek Abouelfadl Mohamed[107], S. Tarem[150], K. Tariq[14a], G. Tarna[102,27b], G.F. Tartarelli[71a], P. Tas[133], M. Tasevsky[131], E. Tassi[43b,43a], A.C. Tate[162], G. Tateno[153], Y. Tayalati[35e,ah], G.N. Taylor[105], W. Taylor[156b], A.S. Tee[170], R. Teixeira De Lima[143], P. Teixeira-Dias[95], J.J. Teoh[155], K. Terashi[153], J. Terron[99], S. Terzo[13], M. Testa[53], R.J. Teuscher[155,ai], A. Thaler[79], O. Theiner[56], N. Themistokleous[52], T. Theveneaux-Pelzer[102], O. Thielmann[171], D.W. Thomas[95], J.P. Thomas[20], E.A. Thompson[17a], P.D. Thompson[20], E. Thomson[128], Y. Tian[55], V. Tikhomirov[37,a], Yu.A. Tikhonov[37], S. Timoshenko[37], D. Timoshyn[133], E.X.L. Ting[1], P. Tipton[172], S.H. Tlou[33g], A. Tnourji[40], K. Todome[154], S. Todorova-Nova[133], S. Todt[50], M. Togawa[84], J. Tojo[89], S. Tokár[28a], K. Tokushuku[84], O. Toldaiev[68], R. Tombs[32], M. Tomoto[84,111], L. Tompkins[143,t], K.W. Topolnicki[86b], E. Torrence[123], H. Torres[102,an], E. Torró Pastor[163], M. Toscani[30], C. Tosciri[39], M. Tost[11], D.R. Tovey[139], A. Traeet[16], I.S. Trandafir[27b], T. Trefzger[166], A. Tricoli[29], I.M. Trigger[156a], S. Trincaz-Duvoid[127], D.A. Trischuk[26], B. Trocmé[60], C. Troncon[71a], L. Truong[33c], M. Trzebinski[87], A. Trzupek[87], F. Tsai[145], M. Tsai[106], A. Tsiamis[152,f], P.V. Tsiareshka[37], S. Tsigaridas[156a], A. Tsirigotis[152,ac], V. Tsiskaridze[155], E.G. Tskhadadze[149a], M. Tsopoulou[152,f], Y. Tsujikawa[88], I.I. Tsukerman[37], V. Tsulaia[17a], S. Tsuno[84], O. Tsur[150], K. Tsuri[118], D. Tsybychev[145], Y. Tu[64b], A. Tudorache[27b], V. Tudorache[27b], A.N. Tuna[36], S. Turchikhin[57b,57a], I. Turk Cakir[3a], R. Turra[71a], T. Turtuvshin[38,aj], P.M. Tuts[41], S. Tzamarias[152,f], P. Tzanis[10], E. Tzovara[100], F. Ukegawa[157], P.A. Ulloa Poblete[137c,137b], E.N. Umaka[29], G. Unal[36], M. Unal[11], A. Undrus[29], G. Unel[160], J. Urban[28b], P. Urquijo[105], P. Urrejola[137a], G. Usai[8], R. Ushioda[154], M. Usman[108], Z. Uysal[21b], V. Vacek[132], B. Vachon[104], K.O.H. Vadla[125], T. Vafeiadis[36], A. Vaitkus[96], C. Valderanis[109], E. Valdes Santurio[47a,47b], M. Valente[156a], S. Valentinetti[23b,23a], A. Valero[163], E. Valiente Moreno[163], A. Vallier[102,an], J.A. Valls Ferrer[163], D.R. Van Arneman[114], T.R. Van Daalen[138], A. Van Der Graaf[49], P. Van Gemmeren[6], M. Van Rijnbach[125,36], S. Van Stroud[96], I. Van Vulpen[114], M. Vanadia[76a,76b], W. Vandelli[36], M. Vandenbroucke[135], E.R. Vandewall[121], D. Vannicola[151], L. Vannoli[57b,57a], R. Vari[75a], E.W. Varnes[7], C. Varni[17b], T. Varol[148], D. Varouchas[66], L. Varriale[163], K.E. Varvell[147], M.E. Vasile[27b], L. Vaslin[84], G.A. Vasquez[165], A. Vasyukov[38], F. Vazeille[40], T. Vazquez Schroeder[36], J. Veatch[31], V. Vecchio[101], M.J. Veen[103], I. Veliscek[126], L.M. Veloce[155], F. Veloso[130a,130c], S. Veneziano[75a], A. Ventura[70a,70b], S. Ventura Gonzalez[135], A. Verbytskyi[110], M. Verducci[74a,74b], C. Vergis[24], M. Verissimo De Araujo[83b], W. Verkerke[114], J.C. Vermeulen[114], C. Vernieri[143], M. Vessella[103], M.C. Vetterli[142,aw], A. Vgenopoulos[152,f], N. Viaux Maira[137f], T. Vickey[139], O.E. Vickey Boeriu[139], G.H.A. Viehhauser[126], L. Vigani[63b], M. Villa[23b,23a], M. Villaplana Perez[163], E.M. Villhauer[52], E. Vilucchi[53], M.G. Vincter[34], G.S. Virdee[20], A. Vishwakarma[52], A. Visibile[114], C. Vittori[36], I. Vivarelli[146], E. Voevodina[110], F. Vogel[109], J.C. Voigt[50], P. Vokac[132], Yu. Volkotrub[86a], J. Von Ahnen[48], E. Von Toerne[24], B. Vormwald[36], V. Vorobel[133], K. Vorobev[37], M. Vos[163], K. Voss[141], J.H. Vossebeld[92], M. Vozak[114], L. Vozdecky[94], N. Vranjes[15], M. Vranjes Milosavljevic[15], M. Vreeswijk[114], R. Vuillermet[36], O. Vujinovic[100], I. Vukotic[39], S. Wada[157], C. Wagner[103], J.M. Wagner[17a], W. Wagner[171], S. Wahdan[171], H. Wahlberg[90], M. Wakida[111], J. Walder[134], R. Walker[109], W. Walkowiak[141], A. Wall[128], T. Wamorkar[6], A.Z. Wang[136], C. Wang[100], C. Wang[62c], H. Wang[17a], J. Wang[64a], R.-J. Wang[100], R. Wang[61], R. Wang[6], S.M. Wang[148], S. Wang[62b], T. Wang[62a], W.T. Wang[80], W. Wang[14a], X. Wang[14c], X. Wang[162], X. Wang[62c], Y. Wang[62d], Y. Wang[14c], Z. Wang[106], Z. Wang[62d,51,62c], Z. Wang[106], A. Warburton[104], R.J. Ward[20], N. Warrack[59], A.T. Watson[20], H. Watson[59], M.F. Watson [20], E. Watton [59,134], G. Watts [138], B.M. Waugh [96], C. Weber [29], H.A. Weber [18], M.S. Weber [19], S.M. Weber [63a], C. Wei[62a], Y. Wei [126], A.R. Weidberg [126], E.J. Weik [117], J. Weingarten [49], M. Weirich [100], C. Weiser [54], C.J. Wells [48], T. Wenaus [29], B. Wendland [49], T. Wengler [36], N.S. Wenke[110], N. Wermes [24], M. Wessels [63a], A.M. Wharton [91], A.S. White [61], A. White [8], M.J. White [1], D. Whiteson [160], L. Wickremasinghe [124], W. Wiedenmann [170], C. Wiel [50], M. Wielers [134], C. Wiglesworth [42], D.J. Wilbern[120], H.G. Wilkens [36], D.M. Williams [41], H.H. Williams[128], S. Williams [32], S. Willocq [103], B.J. Wilson [101], P.J. Windischhofer [39], F.I. Winkel [30], F. Winklmeier [123], B.T. Winter [54], J.K. Winter [101], M. Wittgen[143], M. Wobisch [97], Z. Wolffs [114], J. Wollrath[160], M.W. Wolter [87], H. Wolters [130a,130c], A.F. Wongel [48], E.L. Woodward [41], S.D. Worm [48], B.K. Wosiek [87], K.W. Woźniak [87], S. Wozniewski [55], K. Wraight [59], C. Wu [20], J. Wu [14a,14e], M. Wu [64a], M. Wu [113], S.L. Wu [170], X. Wu [56], Y. Wu [62a], Z. Wu [135], J. Wuerzinger [110,au], T.R. Wyatt [101], B.M. Wynne [52], S. Xella [42], L. Xia [14c], M. Xia [14b], J. Xiang [64c], M. Xie [62a], X. Xie [62a], S. Xin [14a,14e], A. Xiong [123], J. Xiong [17a], D. Xu [14a], H. Xu [62a], L. Xu [62a], R. Xu [128], T. Xu [106], Y. Xu [14b], Z. Xu [52], Z. Xu [14a], Z. Xu[14c], B. Yabsley [147], S. Yacoob [33a], Y. Yamaguchi [154], E. Yamashita [153], H. Yamauchi [157], T. Yamazaki [17a], Y. Yamazaki [85], J. Yan[62c], S. Yan [126], Z. Yan [25], H.J. Yang [62c,62d], H.T. Yang [62a], S. Yang [62a], T. Yang [64c], X. Yang [36], X. Yang [14a], Y. Yang [44], Y. Yang[62a], Z. Yang [62a], W-M. Yao [17a], Y.C. Yap [48], H. Ye [14c], H. Ye [55], J. Ye [14a], S. Ye [29], X. Ye [62a], Y. Yeh [96], I. Yeletskikh [38], B.K. Yeo [17b], M.R. Yexley [96], P. Yin [41], K. Yorita [168], S. Younas [27b], C.J.S. Young [36], C. Young [143], C. Yu [14a,14e,ay], Y. Yu [62a], M. Yuan [106], R. Yuan [62b], L. Yue [96], M. Zaazoua [62a], B. Zabinski [87], E. Zaid[52], T. Zakareishvili [149b], N. Zakharchuk [34], S. Zambito [56], J.A. Zamora Saa [137d,137b], J. Zang [153], D. Zanzi [54], O. Zaplatilek [132], C. Zeitnitz [171], H. Zeng [14a], J.C. Zeng [162], D.T. Zenger Jr [26], O. Zenin [37], T. Ženiš [28a], S. Zenz [94], S. Zerradi [35a], D. Zerwas [66], M. Zhai [14a,14e], B. Zhang [14c], D.F. Zhang [139], J. Zhang [62b], J. Zhang [6], K. Zhang [14a,14e], L. Zhang [14c], P. Zhang[14a,14e], R. Zhang [170], S. Zhang [106], S. Zhang [44], T. Zhang [153], X. Zhang [62c], X. Zhang [62b], Y. Zhang [62c,5], Y. Zhang [96], Y. Zhang [14c], Z. Zhang [17a], Z. Zhang [66], H. Zhao [138], P. Zhao [51], T. Zhao [62b], Y. Zhao [136], Z. Zhao [62a], A. Zhemchugov [38], J. Zheng [14c], K. Zheng [162], X. Zheng [62a], Z. Zheng [143], D. Zhong [162], B. Zhou[106], H. Zhou [7], N. Zhou [62c], Y. Zhou[7], C.G. Zhu [62b], J. Zhu [106], Y. Zhu [62c], Y. Zhu [62a], X. Zhuang [14a], K. Zhukov [37], V. Zhulanov [37], N.I. Zimine [38], J. Zinsser [63b], M. Ziolkowski [141], L. Živković [15], A. Zoccoli [23b,23a], K. Zoch [61], T.G. Zorbas [139], O. Zormpa [46], W. Zou [41], L. Zwalinski [36].

[1]Department of Physics, University of Adelaide, Adelaide; Australia.
[2]Department of Physics, University of Alberta, Edmonton AB; Canada.
[3(a)]Department of Physics, Ankara University, Ankara;[(b)]Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye.
[4]LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.
[5]APC, Université Paris Cité, CNRS/IN2P3, Paris; France.
[6]High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.
[7]Department of Physics, University of Arizona, Tucson AZ; United States of America.
[8]Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.
[9]Physics Department, National and Kapodistrian University of Athens, Athens; Greece.
[10]Physics Department, National Technical University of Athens, Zografou; Greece.
[11]Department of Physics, University of Texas at Austin, Austin TX; United States of America.
[12]Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[13]Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona;

Spain.
[14(a)]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;[(b)]Physics Department, Tsinghua University, Beijing;[(c)]Department of Physics, Nanjing University, Nanjing;[(d)]School of Science, Shenzhen Campus of Sun Yat-sen University;[(e)]University of Chinese Academy of Science (UCAS), Beijing; China.
[15]Institute of Physics, University of Belgrade, Belgrade; Serbia.
[16]Department for Physics and Technology, University of Bergen, Bergen; Norway.
[17(a)]Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA;[(b)]University of California, Berkeley CA; United States of America.
[18]Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
[19]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
[20]School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
[21(a)]Department of Physics, Bogazici University, Istanbul;[(b)]Department of Physics Engineering, Gaziantep University, Gaziantep;[(c)]Department of Physics, Istanbul University, Istanbul; Türkiye.
[22(a)]Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá;[(b)]Departamento de Física, Universidad Nacional de Colombia, Bogotá;[(c)]Pontificia Universidad Javeriana, Bogota; Colombia.
[23(a)]Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna;[(b)]INFN Sezione di Bologna; Italy.
[24]Physikalisches Institut, Universität Bonn, Bonn; Germany.
[25]Department of Physics, Boston University, Boston MA; United States of America.
[26]Department of Physics, Brandeis University, Waltham MA; United States of America.
[27(a)]Transilvania University of Brasov, Brasov;[(b)]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;[(c)]Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;[(d)]National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;[(e)]University Politehnica Bucharest, Bucharest;[(f)]West University in Timisoara, Timisoara;[(g)]Faculty of Physics, University of Bucharest, Bucharest; Romania.
[28(a)]Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;[(b)]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
[29]Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
[30]Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina.
[31]California State University, CA; United States of America.
[32]Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
[33(a)]Department of Physics, University of Cape Town, Cape Town;[(b)]iThemba Labs, Western Cape;[(c)]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;[(d)]National Institute of Physics, University of the Philippines Diliman (Philippines);[(e)]University of South Africa, Department of Physics, Pretoria;[(f)]University of Zululand, KwaDlangezwa;[(g)]School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
[34]Department of Physics, Carleton University, Ottawa ON; Canada.
[35(a)]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;[(b)]Faculté des Sciences, Université Ibn-Tofail, Kénitra;[(c)]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;[(d)]LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda;[(e)]Faculté des sciences, Université Mohammed V, Rabat;[(f)]Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.

[36]CERN, Geneva; Switzerland.
[37]Affiliated with an institute covered by a cooperation agreement with CERN.
[38]Affiliated with an international laboratory covered by a cooperation agreement with CERN.
[39]Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
[40]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
[41]Nevis Laboratory, Columbia University, Irvington NY; United States of America.
[42]Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
[43][(a)]Dipartimento di Fisica, Università della Calabria, Rende;[(b)]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
[44]Physics Department, Southern Methodist University, Dallas TX; United States of America.
[45]Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
[46]National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
[47][(a)]Department of Physics, Stockholm University;[(b)]Oskar Klein Centre, Stockholm; Sweden.
[48]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
[49]Fakultät Physik , Technische Universität Dortmund, Dortmund; Germany.
[50]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
[51]Department of Physics, Duke University, Durham NC; United States of America.
[52]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
[53]INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
[54]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
[55]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
[56]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[57][(a)]Dipartimento di Fisica, Università di Genova, Genova;[(b)]INFN Sezione di Genova; Italy.
[58]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
[59]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
[60]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
[61]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
[62][(a)]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;[(b)]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;[(c)]School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai;[(d)]Tsung-Dao Lee Institute, Shanghai; China.
[63][(a)]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;[(b)]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
[64][(a)]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;[(b)]Department of Physics, University of Hong Kong, Hong Kong;[(c)]Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.
[65]Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
[66]IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
[67]Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain.
[68]Department of Physics, Indiana University, Bloomington IN; United States of America.
[69][(a)]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;[(b)]ICTP, Trieste;[(c)]Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.
[70][(a)]INFN Sezione di Lecce;[(b)]Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
[71][(a)]INFN Sezione di Milano;[(b)]Dipartimento di Fisica, Università di Milano, Milano; Italy.
[72][(a)]INFN Sezione di Napoli;[(b)]Dipartimento di Fisica, Università di Napoli, Napoli; Italy.

[73](a)INFN Sezione di Pavia;(b)Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
[74](a)INFN Sezione di Pisa;(b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
[75](a)INFN Sezione di Roma;(b)Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
[76](a)INFN Sezione di Roma Tor Vergata;(b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
[77](a)INFN Sezione di Roma Tre;(b)Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
[78](a)INFN-TIFPA;(b)Università degli Studi di Trento, Trento; Italy.
[79]Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.
[80]University of Iowa, Iowa City IA; United States of America.
[81]Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
[82]Istinye University, Sariyer, Istanbul; Türkiye.
[83](a)Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;(b)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;(c)Instituto de Física, Universidade de São Paulo, São Paulo;(d)Rio de Janeiro State University, Rio de Janeiro; Brazil.
[84]KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
[85]Graduate School of Science, Kobe University, Kobe; Japan.
[86](a)AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow;(b)Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
[87]Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
[88]Faculty of Science, Kyoto University, Kyoto; Japan.
[89]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
[90]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
[91]Physics Department, Lancaster University, Lancaster; United Kingdom.
[92]Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
[93]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
[94]School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
[95]Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
[96]Department of Physics and Astronomy, University College London, London; United Kingdom.
[97]Louisiana Tech University, Ruston LA; United States of America.
[98]Fysiska institutionen, Lunds universitet, Lund; Sweden.
[99]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
[100]Institut für Physik, Universität Mainz, Mainz; Germany.
[101]School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
[102]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
[103]Department of Physics, University of Massachusetts, Amherst MA; United States of America.
[104]Department of Physics, McGill University, Montreal QC; Canada.
[105]School of Physics, University of Melbourne, Victoria; Australia.
[106]Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
[107]Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[108]Group of Particle Physics, University of Montreal, Montreal QC; Canada.
[109]Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
[110]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
[111]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.

[112]Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
[113]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.
[114]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
[115]Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
[116(a)]New York University Abu Dhabi, Abu Dhabi;[(b)]University of Sharjah, Sharjah; United Arab Emirates.
[117]Department of Physics, New York University, New York NY; United States of America.
[118]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
[119]Ohio State University, Columbus OH; United States of America.
[120]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
[121]Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
[122]Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.
[123]Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.
[124]Graduate School of Science, Osaka University, Osaka; Japan.
[125]Department of Physics, University of Oslo, Oslo; Norway.
[126]Department of Physics, Oxford University, Oxford; United Kingdom.
[127]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.
[128]Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
[129]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
[130(a)]Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;[(b)]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;[(c)]Departamento de Física, Universidade de Coimbra, Coimbra;[(d)]Centro de Física Nuclear da Universidade de Lisboa, Lisboa;[(e)]Departamento de Física, Universidade do Minho, Braga;[(f)]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);[(g)]Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.
[131]Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.
[132]Czech Technical University in Prague, Prague; Czech Republic.
[133]Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
[134]Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
[135]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
[136]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.
[137(a)]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;[(b)]Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago;[(c)]Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena;[(d)]Universidad Andres Bello, Department of Physics, Santiago;[(e)]Instituto de Alta Investigación, Universidad de Tarapacá, Arica;[(f)]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.
[138]Department of Physics, University of Washington, Seattle WA; United States of America.
[139]Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
[140]Department of Physics, Shinshu University, Nagano; Japan.
[141]Department Physik, Universität Siegen, Siegen; Germany.

[142]Department of Physics, Simon Fraser University, Burnaby BC; Canada.
[143]SLAC National Accelerator Laboratory, Stanford CA; United States of America.
[144]Department of Physics, Royal Institute of Technology, Stockholm; Sweden.
[145]Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.
[146]Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
[147]School of Physics, University of Sydney, Sydney; Australia.
[148]Institute of Physics, Academia Sinica, Taipei; Taiwan.
[149(a)]E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;[(b)]High Energy Physics Institute, Tbilisi State University, Tbilisi;[(c)]University of Georgia, Tbilisi; Georgia.
[150]Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
[151]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
[152]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
[153]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
[154]Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.
[155]Department of Physics, University of Toronto, Toronto ON; Canada.
[156(a)]TRIUMF, Vancouver BC;[(b)]Department of Physics and Astronomy, York University, Toronto ON; Canada.
[157]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.
[158]Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
[159]United Arab Emirates University, Al Ain; United Arab Emirates.
[160]Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.
[161]Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
[162]Department of Physics, University of Illinois, Urbana IL; United States of America.
[163]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
[164]Department of Physics, University of British Columbia, Vancouver BC; Canada.
[165]Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
[166]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
[167]Department of Physics, University of Warwick, Coventry; United Kingdom.
[168]Waseda University, Tokyo; Japan.
[169]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.
[170]Department of Physics, University of Wisconsin, Madison WI; United States of America.
[171]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
[172]Department of Physics, Yale University, New Haven CT; United States of America.
[a] Also Affiliated with an institute covered by a cooperation agreement with CERN.
[b] Also at An-Najah National University, Nablus; Palestine.
[c] Also at APC, Université Paris Cité, CNRS/IN2P3, Paris; France.
[d] Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
[e] Also at Center for High Energy Physics, Peking University; China.
[f] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
[g] Also at Centro Studi e Ricerche Enrico Fermi; Italy.
[h] Also at CERN Tier-0; Switzerland.

[i] Also at CERN, Geneva; Switzerland.
[j] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[k] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[l] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[m] Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
[n] Also at Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
[o] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
[p] Also at Department of Physics, California State University, Sacramento; United States of America.
[q] Also at Department of Physics, King's College London, London; United Kingdom.
[r] Also at Department of Physics, Oxford University, Oxford; United Kingdom.
[s] Also at Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
[t] Also at Department of Physics, Stanford University, Stanford CA; United States of America.
[u] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[v] Also at Department of Physics, University of Massachusetts, Amherst MA; United States of America.
[w] Also at Department of Physics, University of Thessaly; Greece.
[x] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
[y] Also at Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
[z] Also at Fakultät Physik , Technische Universität Dortmund, Dortmund; Germany.
[aa] Also at Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
[ab] Also at Group of Particle Physics, University of Montreal, Montreal QC; Canada.
[ac] Also at Hellenic Open University, Patras; Greece.
[ad] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[ae] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[af] Also at Institut für Physik, Universität Mainz, Mainz; Germany.
[ag] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
[ah] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
[ai] Also at Institute of Particle Physics (IPP); Canada.
[aj] Also at Institute of Physics and Technology, Ulaanbaatar; Mongolia.
[ak] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[al] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[am] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
[an] Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
[ao] Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
[ap] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
[aq] Also at Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
[ar] Also at School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
[as] Also at School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
[at] Also at SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
[au] Also at Technical University of Munich, Munich; Germany.
[av] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[aw] Also at TRIUMF, Vancouver BC; Canada.
[ax] Also at Università di Napoli Parthenope, Napoli; Italy.
[ay] Also at University of Chinese Academy of Sciences (UCAS), Beijing; China.
[az] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.

[ba] Also at Washington College, Chestertown, MD; United States of America.
[bb] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
[*] Deceased