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Dielectron and heavy-quark production in inelastic and high-multiplicity proton–proton collisions at $\sqrt{s} = 13$ TeV

ALICE Collaboration *

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ABSTRACT

The measurement of dielectron production is presented as a function of invariant mass and transverse momentum (p_{T}) at midrapidity ($|y_{\mathrm{e}}| < 0.8$) in proton–proton (pp) collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. The contributions from light-hadron decays are calculated from their measured cross sections in pp collisions at $\sqrt{s} = 7$ TeV or 13 TeV. The remaining continuum stems from correlated semileptonic decays of heavy-flavour hadrons. Fitting the data with templates from two different MC event generators, PYTHIA and POWHEG, the charm and beauty cross sections at midrapidity are extracted for the first time at this collision energy: $\mathrm{d}\sigma_{\mathrm{c\bar{c}}}/\mathrm{d}y|_{y=0} = 974 \pm 138\,(\mathrm{stat.}) \pm 140\,(\mathrm{syst.}) \pm 214(\mathrm{BR})$ µb and $\mathrm{d}\sigma_{\mathrm{b\bar{b}}}/\mathrm{d}y|_{y=0} = 79 \pm 14\,(\mathrm{stat.}) \pm 11\,(\mathrm{syst.}) \pm 5(\mathrm{BR})$ µb using PYTHIA simulations and $\mathrm{d}\sigma_{\mathrm{c\bar{c}}}/\mathrm{d}y|_{y=0} = 1417 \pm 184\,(\mathrm{stat.}) \pm 204\,(\mathrm{syst.}) \pm 312(\mathrm{BR})$ µb and $\mathrm{d}\sigma_{\mathrm{b\bar{b}}}/\mathrm{d}y|_{y=0} = 48 \pm 14\,(\mathrm{stat.}) \pm 7\,(\mathrm{syst.}) \pm 3(\mathrm{BR})$ µb for POWHEG. These values, whose uncertainties are fully correlated between the two generators, are consistent with extrapolations from lower energies. The different results obtained with POWHEG and PYTHIA imply different kinematic correlations of the heavy-quark pairs in these two generators. Furthermore, comparisons of dielectron spectra in inelastic events and in events collected with a trigger on high charged-particle multiplicities are presented in various p_{T} intervals. The differences are consistent with the already measured scaling of light-hadron and open-charm production at high charged-particle multiplicity as a function of p_{T}. Upper limits for the contribution of virtual direct photons are extracted at 90% confidence level and found to be in agreement with pQCD calculations.

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1. Introduction

Heavy-flavour quarks (charm and beauty) are copiously produced by inelastic partonic scatterings in high-energy proton–proton (pp) collisions at the CERN Large Hadron Collider (LHC). Their large masses (m_{Q}) make it possible to calculate their production cross sections with perturbative quantum chromodynamics (pQCD) [1–3]. Hence, experimental measurements of heavy-quark production provide an excellent test of pQCD in this energy regime. Flavour conservation allows heavy quarks to be only produced in pairs. Charm hadrons and their decay products reflect the initial angular correlation of the heavy-quark pairs, whereas in the case of decays of beauty hadrons the correlation is weakened due to their large masses. The contribution from the simultaneous semileptonic decays of the corresponding heavy-flavour hadron pairs dominates the dilepton yield in the intermediate mass region (IMR) $1 < m_{\ell\ell} < 3$ GeV/c^2. Hence, dielectron measurements can be used to study charm and beauty production.

The ALICE Collaboration has reported charm and beauty production cross section measurements at midrapidity ($|y| < 0.5$) in pp collisions at centre-of-mass energies of $\sqrt{s} = 2.76$ and 7 TeV [4–10]. The charm measurement at $\sqrt{s} = 7$ TeV is complemented by ATLAS data extending to higher transverse momentum (p_{T}) and $|y| < 2.1$ [11]. Furthermore, the CMS Collaboration has provided a variety of charm and bottom measurements at midrapidity at $\sqrt{s} = 2.76$, 5 and 7 TeV [12–20]. At forward rapidity ($2 < y < 5$), the LHCb Collaboration has measured charm and beauty production cross sections in pp collisions at $\sqrt{s} = 5$, 7, 8 and 13 TeV [21–24]. These results are generally in good agreement with pQCD calculations at next-to-leading order (NLO) in the strong coupling constant (α_{s}) with all-order resummation of the logarithms of $p_{\mathrm{T}}/m_{\mathrm{Q}}$ (FONLL) [1–3]. Though the measured charm production cross sections consistently lie on the upper edge of the systematic uncertainties of the theory calculations. Recently, the ALICE Collaboration has measured the charm and beauty production cross sections in pp collisions at $\sqrt{s} = 7$ TeV using electron–positron pairs (dielectrons) from correlated semileptonic decays of heavy-flavour hadrons [25]. Such an approach was first performed by the PHENIX Collaboration in pp and d–Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV at the Relativistic Heavy Ion Collider

* *E-mail address:* alice-publications@cern.ch.

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(RHIC) [26–28]. These measurements have the advantage that they probe the full p_{T} range of heavy-quark pairs and contain complementary information about the initial correlation of charm quarks, i.e. the underlying production mechanism, which is not accessible in conventional single heavy-flavour measurements.

The measurement of direct photons, i.e. those produced in hard scatterings between incoming partons in hadronic collisions, provides another important test of pQCD. Furthermore, at $p_{\mathrm{T}} < 3$ GeV/c, where the applicability of perturbation theory may be questionable, experimental data of direct-photon production in pp collisions serve as a crucial reference to establish the presence of thermal radiation from the hot and dense medium created in heavy-ion collisions [29–32]. The measurement of real (massless) direct photons at low p_{T} is challenging because of the large background of hadron decay photons. This background can be largely reduced by measuring the contribution of virtual direct photons, i.e. direct $\mathrm{e}^+\mathrm{e}^-$ pairs, to the dielectron invariant-mass spectrum above the π^0 mass [29,30].

Proton–proton collisions in which a large number of charged particles are produced have recently attracted the interest of the heavy-ion community [33,34]. These events exhibit features that are similar to those observed in heavy-ion collisions, e.g. collective effects, such as long-range angular correlations [35–40] or enhanced strangeness production [41]. Charged-hadron p_{T} spectra in pp collisions at $\sqrt{s} = 13$ TeV show a hardening with increasing multiplicity, an effect that arises naturally from jets [42]. Also, heavy-quark production is found to scale faster than linearly with the charged-particle multiplicity in pp collisions at $\sqrt{s} = 7$ TeV [43,44]. This motivates the study of dielectron production in high-multiplicity pp collisions. In the low mass region ($m_{\mathrm{ee}} < 1$ GeV/c^2), dielectron measurements provide further insight into possible modifications of the light vector and pseudoscalar meson production via their resonance and/or Dalitz decays, whereas in the IMR they allow for complementary studies of the heavy-flavour production. At LHC energies, the contribution from open charm already dominates the dielectron continuum at $m_{\mathrm{ee}} \approx 0.5$ GeV/c^2. Moreover, if a thermalised system were created in such high-multiplicity pp collisions, a signal of thermal (virtual) photons should be present.

In this letter, first results of charm and beauty production cross sections at midrapidity in inelastic (INEL) and high-multiplicity (HM) pp collisions at $\sqrt{s} = 13$ TeV are reported. The paper is organised as follows: the ALICE apparatus and the data samples used in the analysis are described in Section 2, the data analysis is discussed in Section 3, Section 4 introduces the cocktail of known hadronic sources, and the results are presented and discussed in Section 5.

2. The ALICE detector and data samples

A detailed description of the ALICE apparatus and its performance can be found in [45–48]. The detectors used in this analysis are briefly described below.

Trajectories of charged particles are reconstructed in the ALICE central barrel with the Inner Tracking System (ITS) and the Time Projection Chamber (TPC) that reside within a solenoid, which provides a homogeneous magnetic field of 0.5 T along the beam direction. The ITS consists of six cylindrical layers of silicon detectors, with radial distances from the beam axis between 3.9 cm and 43 cm. The two innermost layers are equipped with Silicon Pixel Detectors (SPD), the two intermediate layers are composed of Silicon Drift Detectors, and the two outermost layers are made of Silicon Strip Detectors. The TPC, main tracking device in the ALICE central barrel, is a 5 m long cylindrical gaseous detector extending from 85 cm to 247 cm in radial direction. It provides up to 159 spacial points per track for charged-particle reconstruction and particle identification (PID) through the measurement of the specific ionisation energy loss $\mathrm{d}E/\mathrm{d}x$ in the gas volume.

The PID is complemented by the Time-Of-Flight (TOF) system located at a radial distance of 3.7 m from the nominal interaction point. It measures the arrival time of particles relative to the event collision time provided by the TOF detector itself or by the T0 detectors, two arrays of Cherenkov counters located at forward rapidities [49].

Collision events are triggered by the V0 detector that comprises two plastic scintillator arrays placed on both sides of the interaction point at pseudorapidities $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$. The V0 is also used to reject background events like beam-gas interactions, collisions with de-bunched protons or with mechanical structures of the beam line.

The data samples used in this letter were recorded with ALICE in 2016 during the LHC pp run at $\sqrt{s} = 13$ TeV. For the minimum-bias event trigger that is used to define the data sample for the analysis of inelastic pp collisions, coincident signals in both V0 scintillators are required to be synchronous with the beam crossing time defined by the LHC clock. Events with high charged-particle multiplicities are triggered on by additionally requiring the total signal amplitude measured in the V0 detector to exceed a certain threshold. At the analysis level, the 0.036 percentile of inelastic events with the highest V0 multiplicity (V0M) is selected to define the high-multiplicity event class. This value is low enough to avoid inefficiencies due to trigger threshold variations during data taking. Track segments reconstructed in the SPD are extrapolated back to the beam line to define the interaction vertex. Events with multiple vertices identified with the SPD are tagged as pile-up and removed from the analysis [48]. The vertex information may be improved based on the information provided by tracks reconstructed in the ITS and TPC. To assure a uniform detector coverage within $|\eta| < 0.8$, the vertex position along the beam direction is restricted to ± 10 cm around the nominal interaction point. A total of 455×10^6 minimum-bias (MB) pp events and 79.2×10^6 high-multiplicity pp events are considered for further analysis, which corresponds to an integrated luminosity of $\mathscr{L}_{\mathrm{int}}^{\mathrm{MB}} = 7.87 \pm 0.40$ nb^{-1} and $\mathscr{L}_{\mathrm{int}}^{\mathrm{HM}} = 2.79 \pm 0.15$ pb^{-1}, respectively. The luminosity determination is based on the visible cross section for the V0-based minimum-bias trigger, measured in a van der Meer scan carried out in 2015 [50]. A conservative uncertainty of 5% is assigned to this measurement, to account for possible variations of the cross section between the two data-taking periods.

3. Data analysis

Electron[1] candidates are selected from charged-particle tracks reconstructed in the ITS and TPC in the kinematic range $|\eta_{\mathrm{e}}| < 0.8$ and $p_{\mathrm{T,e}} > 0.2$ GeV/c. Basic track quality criteria are applied, e.g. a sufficient number of space points measured in the TPC and ITS as well as a good track fit. The contribution from secondary tracks is reduced by requiring a maximum distance of closest approach (DCA) to the primary vertex in the transverse plane ($\mathrm{DCA_{xy}} < 1.0$ cm) and in the longitudinal direction ($\mathrm{DCA_z} < 3.0$ cm). To further suppress the contribution from photon conversions in the detector material, electron candidates are required to have a hit in the first SPD layer and no ITS clusters shared with other reconstructed tracks.

The electron identification is based on the complementary information provided by the TPC and TOF. The detector PID response,

[1] The term 'electron' is used for both electrons and positrons if not stated otherwise.

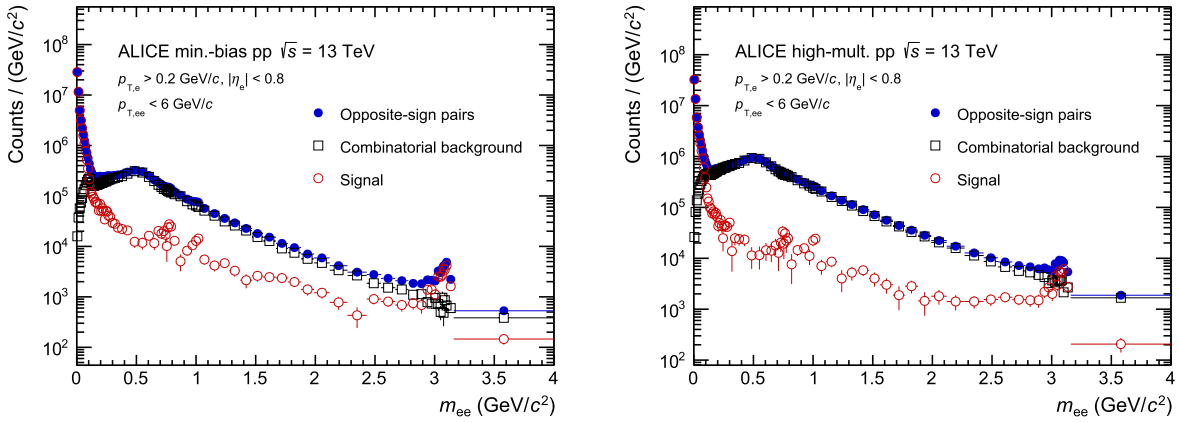


Fig. 1. Opposite-sign spectrum N_{+-}, the combinatorial background B and the signal S in minimum-bias (left) and high-multiplicity (right) events. Only statistical uncertainties are shown.

Table 1
Sources of systematic uncertainties.

Source	Minimum bias	High multiplicity
Track reconstruction	13%	13%
Electron identification	2%	2%
Conversion rejection ($m_{ee} < 0.14$ GeV/c^2)	2%	2%
Acceptance correction factor (R)	2%	2%
Vertex distribution bias	–	6%
Multiplicity dependence of tracking and PID	–	6%
Total	14%	15%

$n(\sigma_i^{\mathrm{DET}})$, is expressed in terms of the deviation between the measured and expected value of the specific ionisation energy loss in the TPC or time-of-flight in the TOF for a given particle hypothesis i and momentum, normalised by the detector resolution (σ^{DET}). In the TPC, electrons are selected in the range $\left|n\left(\sigma_{\mathrm{e}}^{\mathrm{TPC}}\right)\right| < 3$ and pions are rejected by requiring $n\left(\sigma_{\pi}^{\mathrm{TPC}}\right) > 4$. Furthermore, kaons and protons are rejected with $\left|n\left(\sigma_{\mathrm{K}}^{\mathrm{TPC}}\right)\right| > 4$ and $\left|n\left(\sigma_{\mathrm{p}}^{\mathrm{TPC}}\right)\right| > 4$, unless the candidate is positively identified as an electron in the TOF, i.e. fulfilling $\left|n\left(\sigma_{\mathrm{e}}^{\mathrm{TOF}}\right)\right| < 3$. For particles that are outside $\left|n\left(\sigma_{\mathrm{K}}^{\mathrm{TPC}}\right)\right| < 4$ and $\left|n\left(\sigma_{\mathrm{p}}^{\mathrm{TPC}}\right)\right| < 4$ the TOF information is only used to select electron candidates with $\left|n\left(\sigma_{\mathrm{e}}^{\mathrm{TOF}}\right)\right| < 3$ if the track has an associated hit in the TOF detector.

Since experimentally the origin of each electron or positron is unknown, all electron candidates are paired considering combinations with opposite (N_{+-}) but also same-sign charge ($N_{\pm\pm}$). Most of the electron pairs arise from the combination of two electrons originating from different mother particles. These pairs give rise to the combinatorial background B that is estimated via the geometric mean of same-sign pairs $\sqrt{N_{++}N_{--}}$ within the same event. Opposite- and same-sign pairs include correlated background, e.g. originating from π^0 decays with two $\mathrm{e^+e^-}$ pairs in the final state ($\pi^0 \to \gamma^{(*)}\gamma^{(*)} \to \mathrm{e^+e^-e^+e^-}$), which includes decay channels with real photons and their subsequent conversion in detector material. Such processes lead to opposite and same-sign pairs at equal rate. The background estimate needs to be corrected for the different detector acceptance of opposite and same-sign pairs. This correction factor is determined by dividing the yields of uncorrelated opposite (M_{+-}) and same-sign pairs ($M_{\pm\pm}$) in mixed events: $R = M_{+-}/(2\sqrt{M_{++}M_{--}})$. The dielectron signal is then obtained as $S = N_{+-} - B = N_{+-} - 2R\sqrt{N_{++}N_{--}}$. The signal S is shown together with the opposite-sign spectrum N_{+-} and the combinatorial background B in Fig. 1 for minimum-bias and high-multiplicity events. In the mass interval $0.2 < m_{ee} < 3$ GeV/c^2, the signal-to-background ratio varies in MB events between 0.3 and 0.04 with a minimum around $m_{ee} \approx 0.5$ GeV/c^2 and is roughly constant at 0.2 in the IMR [51]. In HM events, the minimum reaches 0.01 and is about 0.08 in the IMR.

Electron–positron pairs from photon conversion in the detector material, contributing to the low mass spectrum below 0.14 GeV/c^2, are removed by using their distinct orientation relative to the magnetic field [25].

The data are corrected for the reconstruction efficiencies using detailed Monte Carlo (MC) simulations. For this, pp events are generated with the Monash 2013 tune of Pythia 8 [52] for light-hadron decays and the Perugia 2011 tune of Pythia 6.4 for heavy-flavour decays [53] and the resulting particles are propagated through a detector simulation using Geant 3 [54]. The choice of the different Pythia versions is motivated by the fact that the Perugia 2011 tune describes reasonably well the transverse momentum spectra of heavy-flavour hadrons while the Monash 2013 tune reproduces many of the relevant light-hadron multiplicities [55,56]. The signal reconstruction efficiencies were studied as a function of m_{ee} and pair transverse momentum $p_{T,ee}$ separately for the different $\mathrm{e^+e^-}$ sources: resonance and Dalitz decays of relevant mesons as well as correlated semileptonic decays of charm and beauty hadrons. The total signal reconstruction efficiency is obtained by weighting the efficiency of each dielectron source by its expected contribution and is found to be about 20% in $0.7 < m_{ee} < 1.2$ GeV/c^2 and approaches 30% at lower and higher masses.

Different aspects of the analysis are considered as possible sources of systematic uncertainties, which are summarised in Table 1. The systematic uncertainties due to the track reconstruction are estimated by comparing the efficiency of the ITS–TPC matching, the requirement of a hit in the first SPD layer, and the requirement of no shared ITS clusters in MC simulations and data. The residual disagreements between data and MC add to a 6.5% uncertainty on the single track level, which leads to a 13% uncertainty for pairs. The MC simulations were also checked to reproduce all details of the PID selection within a systematic uncertainty of 2% for $\mathrm{e^+e^-}$ pairs. The purity of the electron sample is estimated to be >93% over the relevant p_{T} range, with a p_{T}-integrated hadron contamination of about 4%. The resulting hadron contamination on the dielectron signal is found to be negligible. For $m_{ee} < 0.14$ GeV/c^2, a 2% uncertainty on the conversion rejection was estimated from the yield change when tightening the selection to reject photon conversions. A 2% uncertainty on the signal yield due to the correction factor R is obtained by repeating the event mixing in different event classes, defined by the position of the reconstructed primary

vertex and by the charged-particle multiplicity. The efficiency of the minimum-bias trigger to select inelastic events with an e^+e^- pair in the ALICE acceptance ($|\eta_e| < 0.8$ and $p_{T,e} > 0.2$ GeV/c) is estimated to be (99 ± 1)% from the Monash 2013 tune of PYTHIA 8. This and the luminosity uncertainty of 5% [50] are global uncertainties, which are not included in the point-to-point uncertainties. No significant variation of systematic uncertainties on mass or $p_{T,ee}$ is observed in the analysis, and the same total uncertainty of 14% is assigned as point-to-point correlated uncertainties on the differential dielectron cross section in inelastic pp collisions.

The analysis of the high-multiplicity data has additional systematic uncertainties. First, no dedicated high-multiplicity MC simulation was performed. In such events the vertex distribution is biased more than in MB events by the asymmetric pseudorapidity coverage of the two V0 detectors. The change of the detector acceptance with vertex position could lead to a difference in the number of reconstructed electrons of up to 3%, which results in an uncertainty of 6% for e^+e^- pairs. Second, a possible multiplicity dependence of the reconstruction and PID efficiency is covered by an uncertainty of 6% [57]. Added in quadrature, this amounts to a total uncertainty of 15%.

4. Cocktail of known hadronic sources

The dielectron spectrum measured in pp collisions at $\sqrt{s} =$ 13 TeV is compared with the expectations from all known hadron sources, i.e. the hadronic cocktail, contributing to the dielectron spectrum in the ALICE central barrel acceptance ($|\eta_e| < 0.8$ and $p_{T,e} > 0.2$ GeV/c). A fast MC simulation is used to estimate the contribution from π^0, η, η', ρ, ω and ϕ decays in pp collisions, as detailed in [25].

Following the approach outlined in [58], the pion p_T-spectrum at $\sqrt{s} = 13$ TeV is approximated by scaling the p_T-spectrum of charged hadrons [42] by the pion-to-hadron ratio measured at $\sqrt{s} = 7$ TeV [59,60]. The difference with respect to the same procedure based on the pion-to-hadron ratio measured at $\sqrt{s} =$ 2.76 TeV [59,61] is smaller than 1% at low p_T and reaches 5% at high p_T. The charged hadron p_T-spectra at $\sqrt{s} = 13$ TeV are normalised to INEL>0 events, i.e. inelastic collisions that produce at least one charged particle in $|\eta| < 1$, rather than INEL events. This is corrected taking the 21% difference in the p_T integrated $\mathrm{d}N_{ch}/\mathrm{d}\eta$ values for these two event classes [42]. A conservative uncertainty of 10% is assigned on this extrapolation.

A fit of the obtained charged-pion p_T-spectrum with a modified Hagedorn function is then taken as proxy for the neutral-pion p_T-distribution. The simulated cross section per unit rapidity of the π^0 is $\mathrm{d}\sigma/\mathrm{d}y|_{y=0} = 155.2$ mb. For the η meson a fit of the measured η/π^0 ratio in pp collisions at $\sqrt{s} = 7$ TeV is used [62]. The Monash 2013 tune of PYTHIA 8 describes the ρ/π^0 and ω/π^0 ratios measured in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV, respectively [55,56]. Therefore, MC simulations obtained with this tune at $\sqrt{s} = 13$ TeV are used to obtain the ρ/π^0 and ω/π^0 ratios. Based on the η/π^0, ρ/π^0 and ω/π^0 data, the ratios at high p_T are 0.5 ± 0.1, 1.0 ± 0.2 and 0.85 ± 0.17, respectively. The η' and ϕ mesons are generated assuming m_T scaling, replacing p_T with $\sqrt{m^2 - m_\pi^2 + (p_T/c)^2}$ [63]. For the m_T scaling, particle yields are normalised at high p_T relative to the π^0 yield: 0.40 ± 0.08 for η' (from PYTHIA 6 calculations) and 0.13 ± 0.04 for ϕ [64]. The detector response, including momentum and angular resolutions, as well as Bremsstrahlung effects obtained from full MC simulations, is applied to the decay electrons as a function of $p_{T,e}$, η_e and the azimuth φ_e. This results in a mass resolution of approximately 1%. The following sources of systematic uncertainties were evaluated: the input parameterisations of the measured spectra as a function of p_T ($\pi^\pm$, η/π^0 and ω/π^0), the branching fractions of all included decay modes, the m_T scaling parameters and the resolution smearing. For the high-multiplicity cocktail, the input hadron p_T-distributions are adjusted according to the measured modifications of the charged-hadron p_T spectra [42]. The uncertainties of the cocktail from light-hadron decays are about ±15%, reaching up to +50% in the region dominated by the η meson due to uncertainties in the extrapolation to low p_T. The multiplicity dependence has an uncertainty that varies between about 12% at low p_T and 40% at high p_T.

The Perugia 2011 tune of PYTHIA 6.4, which includes NLO parton showering processes, is used to estimate the contributions of correlated semileptonic decays of open charm and beauty hadrons [53,65]. As an alternative, the NLO event generator POWHEG is also considered [66–69]. The resulting same-sign spectrum is subtracted from the opposite-sign distribution as in the data analysis. Detector effects are implemented as for the light-hadron cocktail. The spectra are normalised to cross sections at midrapidity that are based on FONLL [1–3] extrapolations of the ALICE measurements at 7 TeV [8–10]. Following the description in [70], this leads to cross sections per unit rapidity of $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y|_{y=0} = 1296^{+172}_{-162}$ μb and $\mathrm{d}\sigma_{b\bar{b}}/\mathrm{d}y|_{y=0} = 68^{+15}_{-16}$ μb at $\sqrt{s} = 13$ TeV. The quoted uncertainties take into account both the measured uncertainty and the FONLL extrapolation uncertainties. The latter (dominated by scale uncertainties but also including PDF and mass uncertainties) are considered to be fully correlated between the two energies [71]. For the high-multiplicity cocktail, the open charm contribution is weighted as a function of p_T according to the measured enhancement of D mesons with $p_T > 1$ GeV/c at $\sqrt{s} = 7$ TeV [43]. The same weights are applied to the open beauty contribution as no significant difference between the production of D mesons and J/ψ from beauty-hadron decays is observed [43]. For electrons originating from charm or beauty hadrons with $p_T < 1$ GeV/c, the same weight as for $1 < p_T < 2$ GeV/c is assumed in the absence of a measurement. This leads to an uncertainty on the multiplicity dependence of about 40% at low p_T decreasing to 20% at high p_T.

The J/ψ contribution is simulated with PYTHIA 6.4 and normalised to the cross section at $\sqrt{s} = 13$ TeV, extrapolated with FONLL [9] from the measurement at $\sqrt{s} = 7$ TeV by the ALICE Collaboration [72]. In the high-multiplicity cocktail, the J/ψ is scaled according to a dedicated, p_T-integrated measurement [44]. The $\psi(2S)$ contribution is normalised to the J/ψ based on a cross section ratio of $\sigma_{\psi(2S)\to e^+e^-}/\sigma_{J/\psi\to e^+e^-} = (1.59 \pm 0.17)$% [73].

5. Results

The dielectron cross sections are reported within the ALICE central barrel acceptance $|\eta_e| < 0.8$ and $p_{T,e} > 0.2$ GeV/c, i.e. without correction to full phase space. The result, integrated over $p_{T,ee} < 6$ GeV/c, is shown as a function of m_{ee} in the left panel of Fig. 2. The data are compared with the expectation from the hadronic decay cocktail, using PYTHIA for the heavy-flavour components, and found to be in agreement within uncertainties. Good agreement between data and cocktail calculations is also found as a function of $p_{T,ee}$, which is shown for three m_{ee} intervals in the right panel of Fig. 2.

Figs. 3 and 4 show the ratios of the dielectron spectra in high-multiplicity over inelastic events as a function of m_{ee} for different $p_{T,ee}$ intervals. To account for the trivial scaling with charged-particle multiplicity, the ratio is scaled by the factor $\mathrm{d}N_{ch}/\mathrm{d}\eta(\mathrm{HM})/\langle \mathrm{d}N_{ch}/\mathrm{d}\eta(\mathrm{INEL})\rangle = 6.27 \pm 0.22$, where $\mathrm{d}N_{ch}/\mathrm{d}\eta(\mathrm{HM}) = 33.29 \pm 0.39$ and $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta(\mathrm{INEL})\rangle = 5.31 \pm 0.18$ are the charged-particle multiplicities in $|\eta_{ch}| < 0.5$ measured in high-multiplicity and inelastic pp collisions, respectively [42]. In this ratio, the multiplicity-independent uncertainties cancel and the total

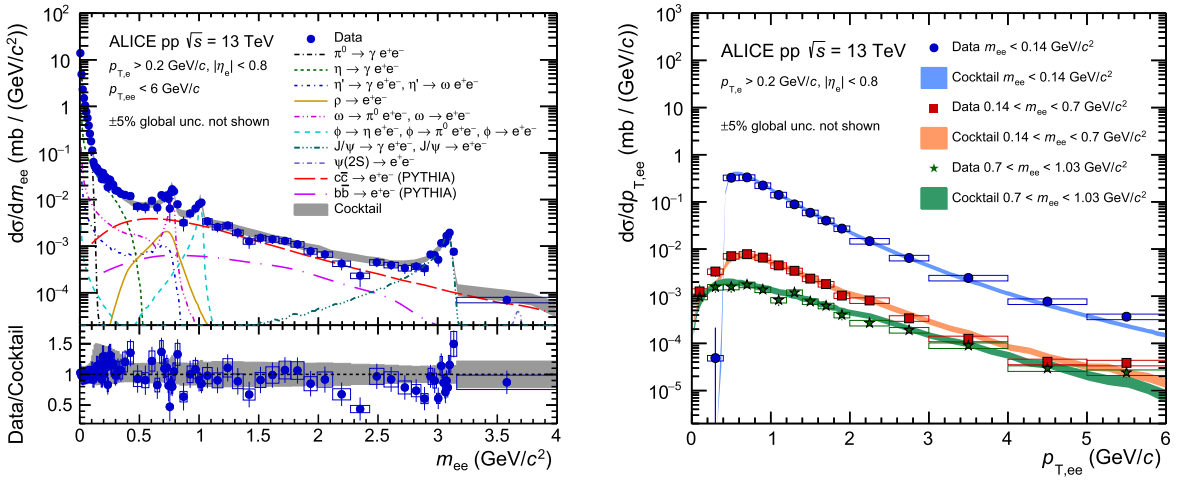


Fig. 2. The dielectron cross section in inelastic pp collisions at $\sqrt{s} = 13$ TeV as a function of invariant mass (left) and of pair transverse momentum in different mass intervals (right). The global scale uncertainty on the pp luminosity (5%) is not shown. The statistical and systematic uncertainties of the data are shown as vertical bars and boxes. The expectation from the hadronic decay cocktail is shown as a band, and the bottom left plot shows the ratio data to cocktail together with the cocktail uncertainty.

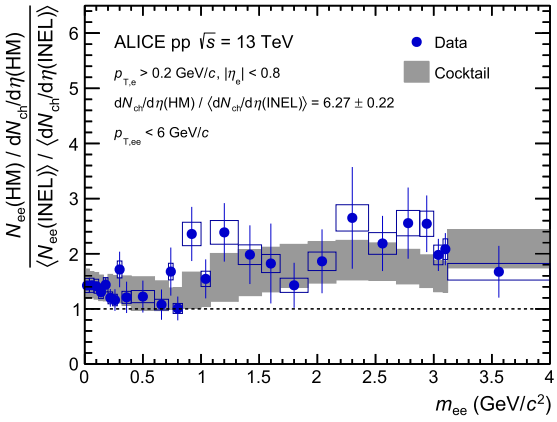


Fig. 3. Ratio of dielectron spectra in HM and INEL events scaled by the charged-particle multiplicity. The statistical and systematic uncertainties of the data are shown as vertical bars and boxes. The expectation from the hadronic decay cocktail calculation is shown as a grey band.

systematic uncertainty reduces to 9%. The ratio is in good agreement with the hadronic decay cocktail calculations over the whole measured m_{ee} and $p_{T,ee}$ range. This is the first measurement sensitive to the production of π^0, η, ω and ϕ in high-multiplicity pp collisions. The result confirms the hypothesis that these light mesons have the same multiplicity dependence as a function of m_T, which was used in the construction of the high-multiplicity hadron cocktail. From the agreement between data and cocktail in the high-p_T range ($3 < p_{T,ee} < 6$ GeV/c), which is dominated by open beauty, it can be also concluded for the first time that the open beauty production has a multiplicity dependence similar to that of open charm. This puts additional constraints on mechanisms used to describe heavy-flavour production in high-multiplicity pp collisions, such as multiple parton interactions, percolation or hydrodynamic models.

In the intermediate mass region ($1.03 < m_{ee} < 2.86$ GeV/c^2), which is dominated by open heavy-flavour decays, the data are fitted simultaneously in m_{ee} and $p_{T,ee}$ (for $p_{T,ee} < 6$ GeV/c) with PYTHIA and POWHEG templates of open charm and beauty production, keeping the light-flavour and J/ψ contributions fixed, which introduces negligible uncertainties on the heavy-flavour cross section. The PYTHIA and POWHEG least-square fits of dielectron spectra in inelastic events projected over $p_{T,ee}$ and m_{ee} are shown in the left and right panels of Fig. 5, respectively. The resulting cross sections are summarised in Table 2. The first uncertainty is the statistical uncertainty resulting from the fits and the second is the systematic uncertainty, which is determined by moving the data points coherently upward and downward by their systematic uncertainties and repeating the fits. The branching fraction of charm-hadron decays to electrons is taken as $(9.6 \pm 0.4)\%$ [74]. An additional uncertainty of 9.3% is added in quadrature to account for differences in the Λ_c/D^0 ratio measured by ALICE in pp collisions at $\sqrt{s} = 7$ TeV, which is 0.543 ± 0.061 (stat.) ± 0.160 (syst.) for $p_T > 1$ GeV/c [75], and the LEP average of $0.113 \pm 0.013 \pm 0.006$ [76]. This translates into a 22% uncertainty at the pair level. The branching fraction of beauty hadrons decaying into electrons, including via intermediate charm hadrons, is $(21.53 \pm 0.63)\%$ [74], which leads to a 6% uncertainty on the dielectron-based cross section measurement. Like the statistical and systematic uncertainties, these branching fraction uncertainties are fully correlated between the PYTHIA and POWHEG based results.

The results are consistent with extrapolations from lower energies based on pQCD calculations discussed in the previous section. There is a strong anti-correlation between the fitted charm and beauty cross sections. The sizeable difference in the cross sections between the two MC event generators are comparable to what is observed at $\sqrt{s} = 7$ TeV [25]. The different cross sections obtained from fits with PYTHIA and POWHEG simulations are caused by acceptance differences of e^+e^- pairs from heavy-flavour hadron decays in these two event generators because of different kinematic correlations of the heavy quark pairs, in particular in rapidity. The fraction of e^+e^- pairs that fall into the ALICE acceptance and the intermediate mass region originating from $c\bar{c}$ pairs at midrapidity is 14% in PYTHIA and 10% in POWHEG. This points to important differences in the heavy quark production mechanisms between the two generators. It should be stressed that single heavy-flavour measurements appear insensitive to these differences as the cross sections obtained from such measurements agree between PYTHIA and POWHEG based extrapolations [7,11,22]. Therefore, dielectrons provide complementary information on heavy-flavour production that, if properly modelled, should lead to consistent cross sections with PYTHIA and POWHEG.

Table 2 also summarises the corresponding cross sections for the high-multiplicity data. In case of PYTHIA, the measured charm cross section translates into an enhancement of 1.86 ± 0.40 (stat.) $\pm$ 0.40 (syst.) relative to the charged-particle multiplicity increase. This is consistent with the modelled multiplicity dependence used

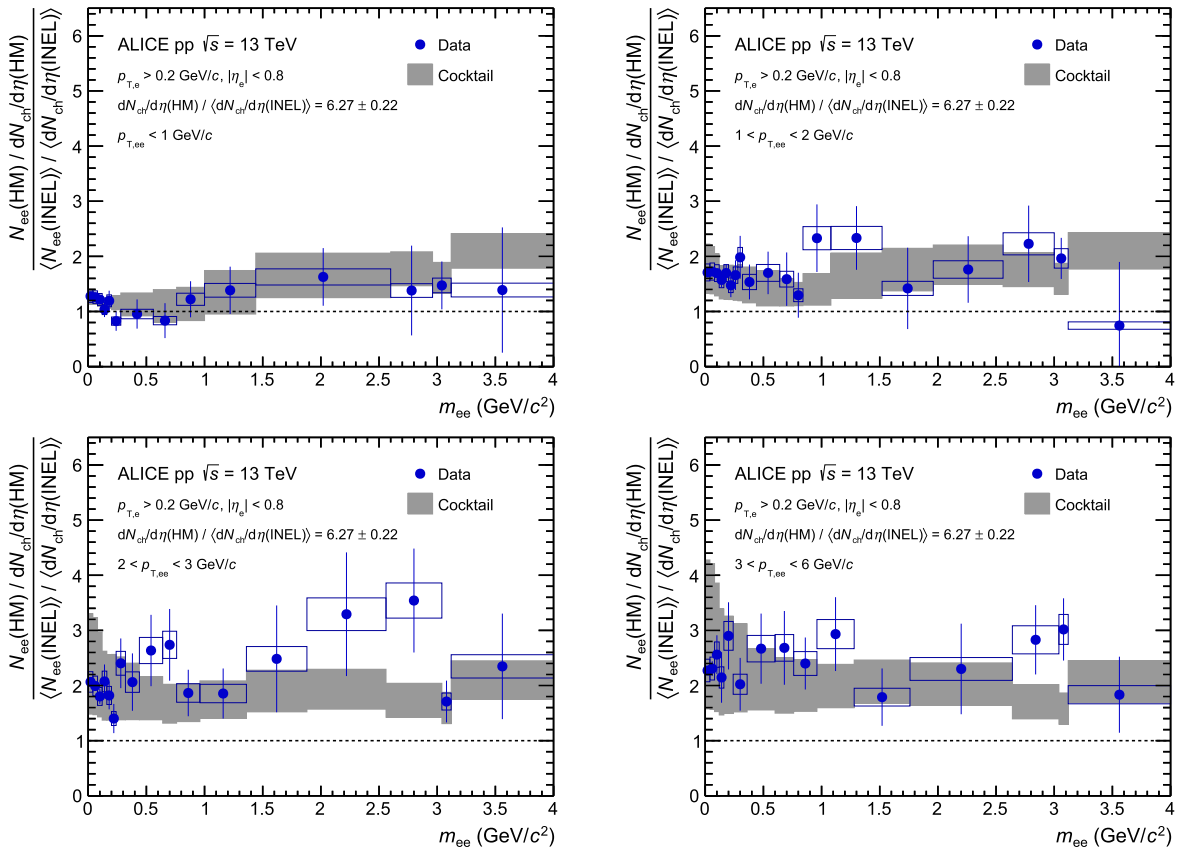


Fig. 4. Ratio of dielectron spectra in HM and INEL events scaled by the charged-particle multiplicity in different $p_{\mathrm{T,ee}}$ intervals. The statistical and systematic uncertainties of the data are shown as vertical bars and boxes. The expectation from the hadronic decay cocktail calculation is shown as a grey band.

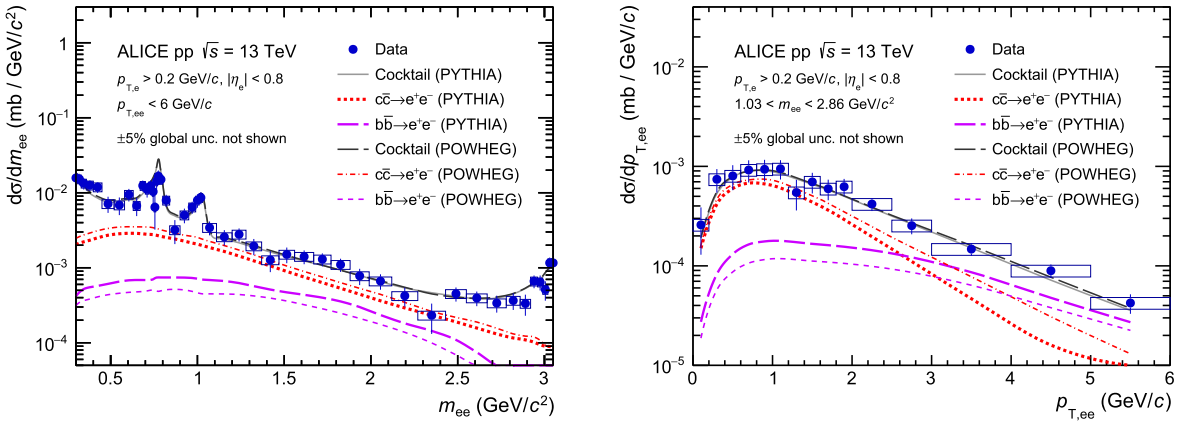


Fig. 5. Projection of the heavy-flavour dielectron fit (grey line) in inelastic pp collisions at $\sqrt{s} = 13$ TeV onto the dielectron mass (left) and $p_{\mathrm{T,ee}}$ (right) using the PYTHIA and POWHEG event generators. The lines show the charm (red) and beauty (magenta) contributions after the fit. The global scale uncertainty on the pp luminosity (5%) is not shown. The statistical and systematic uncertainties of the data are shown as vertical bars and boxes. The fits with PYTHIA and POWHEG result in a χ^2/ndf of 57.8/66 and 52.6/66, respectively.

as input for the cocktail in Figs. 3 and 4. For the beauty cross section the observed enhancement is $1.63 \pm 0.50\,(\mathrm{stat.}) \pm 0.35\,(\mathrm{syst.})$. This is consistent with the multiplicity dependence observed for open charm, but a scaling with charged-particle multiplicity cannot be excluded.

The fraction of real direct photons to inclusive photons can be extracted from the dielectron spectrum at small invariant masses assuming the equivalence between this fraction and the ratio of virtual direct photons to inclusive photons. The data are fitted minimising the χ^2, in bins of $p_{\mathrm{T,ee}}$, with the sum of the light-flavour cocktail ($f_{\mathrm{LF}}(m_{\mathrm{ee}})$), open heavy-flavour contribution ($f_{\mathrm{HF}}(m_{\mathrm{ee}})$) and a virtual direct photon component ($f_{\mathrm{direct}}(m_{\mathrm{ee}})$), whose shape is described by the Kroll–Wada equation [77,78] in the quasi-real virtual photon regime ($p_{\mathrm{T,ee}} \gg m_{\mathrm{ee}}$). The normalisation of the open heavy-flavour component is fixed to the measured open charm and beauty cross sections presented above, using the PYTHIA simulations for the nominal fit. As systematic uncertainty estimate, the POWHEG simulation is used instead. The light-flavour cocktail and virtual direct photon templates are normalised independently to the data in $m_{\mathrm{ee}} < 0.04$ GeV/c^2, i.e. in a mass window in which both Dalitz decays and direct photons have the same $1/m_{\mathrm{ee}}$ dependence. The direct-photon frac-

Table 2
Heavy-flavour cross sections in inelastic and high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV. The 22% (6%) branching fraction uncertainty for charm (beauty) decays into electrons is not listed. Like statistical and systematic uncertainties, it is fully correlated between the PYTHIA and POWHEG based results.

	PYTHIA	POWHEG
$\mathrm{d}\sigma_{\mathrm{c\bar{c}}}/\mathrm{d}y\|_{y=0}$	$974 \pm 138\,(\mathrm{stat.}) \pm 140\,(\mathrm{syst.})$ µb	$1417 \pm 184\,(\mathrm{stat.}) \pm 204\,(\mathrm{syst.})$ µb
$\mathrm{d}\sigma_{\mathrm{b\bar{b}}}/\mathrm{d}y\|_{y=0}$	$79 \pm 14\,(\mathrm{stat.}) \pm 11\,(\mathrm{syst.})$ µb	$48 \pm 14\,(\mathrm{stat.}) \pm 7\,(\mathrm{syst.})$ µb
$\mathrm{d}\sigma_{\mathrm{c\bar{c}}}/\mathrm{d}y\|^{\mathrm{HM}}_{y=0}$	$4.14 \pm 0.67\,(\mathrm{stat.}) \pm 0.66\,(\mathrm{syst.})$ µb	$5.95 \pm 0.91\,(\mathrm{stat.}) \pm 0.95\,(\mathrm{syst.})$ µb
$\mathrm{d}\sigma_{\mathrm{b\bar{b}}}/\mathrm{d}y\|^{\mathrm{HM}}_{y=0}$	$0.29 \pm 0.07\,(\mathrm{stat.}) \pm 0.05\,(\mathrm{syst.})$ µb	$0.17 \pm 0.07\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.})$ µb

Table 3
Upper limits at 90% C.L. on the direct-photon fractions in comparison with the expectation in inelastic pp collisions based on a NLO pQCD calculation for a factorisation and renormalisation scale choice of $\mu = p_{\mathrm{T}}$ [80].

Data sample	$1 < p_{\mathrm{T,ee}} < 2$ GeV/c	$2 < p_{\mathrm{T,ee}} < 3$ GeV/c	$3 < p_{\mathrm{T,ee}} < 6$ GeV/c
Minimum bias	0.057	0.072	0.023
High multiplicity	0.060	0.083	0.055
pQCD	0.003	0.007	0.013

tion r is then extracted by fitting the data in the mass interval $0.14 < m_{\mathrm{ee}} < 0.32$ GeV/c^2, i.e. above the π^0 mass to suppress the most dominant hadron background, with the following expression: $\mathrm{d}\sigma/\mathrm{d}m_{\mathrm{ee}} = r f_{\mathrm{dir}}(m_{\mathrm{ee}}) + (1-r) f_{\mathrm{LF}}(m_{\mathrm{ee}}) + f_{\mathrm{HF}}(m_{\mathrm{ee}})$.

No significant direct photon contribution is observed in neither the inelastic nor the high-multiplicity events [51]. Upper limits at 90% confidence level (C.L.) are extracted with the Feldman–Cousins method [79] and summarised in Table 3 together with predictions from perturbative QCD calculations for inelastic events [80]. The current uncertainties prevent any conclusions on the scaling of direct-photon production with charged-particle multiplicity.

6. Summary and conclusion

We have presented the first measurement of dielectron production at midrapidity ($|y_{\mathrm{e}}| < 0.8$) in proton–proton collisions at $\sqrt{s} = 13$ TeV. The dielectron continuum can be well described by the expected contributions from decays of light- and heavy-flavour hadrons. The charm and beauty cross sections are extracted for the first time at midrapidity at $\sqrt{s} = 13$ TeV and are consistent with extrapolations from lower energies based on pQCD calculations. The differences observed between POWHEG and PYTHIA imply different kinematic correlations of the heavy-quark pairs in these two event generators. Therefore dielectrons are uniquely sensitive to the heavy quark production mechanisms. The comparison of the dielectron spectra in inelastic events and in events with high charged-particle multiplicities does not reveal modifications of the spectrum beyond the already established ones of light and open charm hadrons. The upper limits on the direct-photon fractions are consistent with predictions from perturbative quantum chromodynamics calculations.

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Saini [139], S. Sakai [131], M.A. Saleh [141], S. Sambyal [99], V. Samsonov [96,91], A. Sandoval [72], A. Sarkar [73], D. Sarkar [139], N. Sarkar [139], P. Sarma [41], M.H.P. Sas [63], E. Scapparone [53], F. Scarlassara [29], B. Schaefer [94],

H.S. Scheid [69], C. Schiaua [47], R. Schicker [102], C. Schmidt [104], H.R. Schmidt [101], M.O. Schmidt [102], M. Schmidt [101], N.V. Schmidt [94,69], J. Schukraft [34], Y. Schutz [34,134], K. Schwarz [104], K. Schweda [104], G. Scioli [27], E. Scomparin [58], M. Šefčík [38], J.E. Seger [16], Y. Sekiguchi [130], D. Sekihata [45], I. Selyuzhenkov [104,91], S. Senyukov [134], E. Serradilla [72], P. Sett [48], A. Sevcenco [68], A. Shabanov [62], A. Shabetai [113], R. Shahoyan [34], W. Shaikh [107], A. Shangaraev [90], A. Sharma [98], A. Sharma [99], M. Sharma [99], N. Sharma [98], A.I. Sheikh [139], K. Shigaki [45], M. Shimomura [82], S. Shirinkin [64], Q. Shou [6,110], K. Shtejer [26], Y. Sibiriak [87], S. Siddhanta [54], K.M. Sielewicz [34], T. Siemiarczuk [84], D. Silvermyr [80], G. Simatovic [89], G. Simonetti [34,103], R. Singaraju [139], R. Singh [85], R. Singh [99], V. Singhal [139], T. Sinha [107], B. Sitar [14], M. Sitta [32], T.B. Skaali [21], M. Slupecki [126], N. Smirnov [144], R.J.M. Snellings [63], T.W. Snellman [126], J. Song [18], F. Soramel [29], S. Sorensen [128], F. Sozzi [104], I. Sputowska [117], J. Stachel [102], I. Stan [68], P. Stankus [94], E. Stenlund [80], D. Stocco [113], M.M. Storetvedt [36], P. Strmen [14], A.A.P. Suaide [120], T. Sugitate [45], C. Suire [61], M. Suleymanov [15], M. Suljic [34,25], R. Sultanov [64], M. Šumbera [93], S. Sumowidagdo [50], K. Suzuki [112], S. Swain [66], A. Szabo [14], I. Szarka [14], U. Tabassam [15], J. Takahashi [121], G.J. Tambave [22], N. Tanaka [131], M. Tarhini [113], M. Tariq [17], M.G. Tarzila [47], A. Tauro [34], G. Tejeda Muñoz [44], A. Telesca [34], C. Terrevoli [29], B. Teyssier [133], D. Thakur [49], S. Thakur [139], D. Thomas [118], F. Thoresen [88], R. Tieulent [133], A. Tikhonov [62], A.R. Timmins [125], A. Toia [69], N. Topilskaya [62], M. Toppi [51], S.R. Torres [119], S. Tripathy [49], S. Trogolo [26], G. Trombetta [33], L. Tropp [38], V. Trubnikov [2], W.H. Trzaska [126], T.P. Trzcinski [140], B.A. Trzeciak [63], T. Tsuji [130], A. Tumkin [106], R. Turrisi [56], T.S. Tveter [21], K. Ullaland [22], E.N. Umaka [125], A. Uras [133], G.L. Usai [24], A. Utrobicic [97], M. Vala [115], J.W. Van Hoorne [34], M. van Leeuwen [63], P. Vande Vyvre [34], D. Varga [143], A. Vargas [44], M. Vargyas [126], R. Varma [48], M. Vasileiou [83], A. Vasiliev [87], A. Vauthier [78], O. Vázquez Doce [103,116], V. Vechernin [111], A.M. Veen [63], E. Vercellin [26], S. Vergara Limón [44], L. Vermunt [63], R. Vernet [7], R. Vértesi [143], L. Vickovic [35], J. Viinikainen [126], Z. Vilakazi [129], O. Villalobos Baillie [108], A. Villatoro Tello [44], A. Vinogradov [87], T. Virgili [30], V. Vislavicius [88,80], A. Vodopyanov [75], M.A. Völkl [101], K. Voloshin [64], S.A. Voloshin [141], G. Volpe [33], B. von Haller [34], I. Vorobyev [116,103], D. Voscek [115], D. Vranic [104,34], J. Vrláková [38], B. Wagner [22], H. Wang [63], M. Wang [6], Y. Watanabe [131], M. Weber [112], S.G. Weber [104], A. Wegrzynek [34], D.F. Weiser [102], S.C. Wenzel [34], J.P. Wessels [142], U. Westerhoff [142], A.M. Whitehead [124], J. Wiechula [69], J. Wikne [21], G. Wilk [84], J. Wilkinson [53], G.A. Willems [142,34], M.C.S. Williams [53], E. Willsher [108], B. Windelband [102], W.E. Witt [128], R. Xu [6], S. Yalcin [77], K. Yamakawa [45], S. Yano [45], Z. Yin [6], H. Yokoyama [78,131], I.-K. Yoo [18], J.H. Yoon [60], V. Yurchenko [2], V. Zaccolo [58], A. Zaman [15], C. Zampolli [34], H.J.C. Zanoli [120], N. Zardoshti [108], A. Zarochentsev [111], P. Závada [67], N. Zaviyalov [106], H. Zbroszczyk [140], M. Zhalov [96], X. Zhang [6], Y. Zhang [6], Z. Zhang [6,132], C. Zhao [21], V. Zherebchevskii [111], N. Zhigareva [64], D. Zhou [6], Y. Zhou [88], Z. Zhou [22], H. Zhu [6], J. Zhu [6], Y. Zhu [6], A. Zichichi [27,10], M.B. Zimmermann [34], G. Zinovjev [2], J. Zmeskal [112], S. Zou [6]

[1] *A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia*
[2] *Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine*
[3] *Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India*
[4] *Budker Institute for Nuclear Physics, Novosibirsk, Russia*
[5] *California Polytechnic State University, San Luis Obispo, CA, United States*
[6] *Central China Normal University, Wuhan, China*
[7] *Centre de Calcul de l'IN2P3, Villeurbanne, Lyon, France*
[8] *Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba*
[9] *Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico*
[10] *Centro Fermi – Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Rome, Italy*
[11] *Chicago State University, Chicago, IL, United States*
[12] *China Institute of Atomic Energy, Beijing, China*
[13] *Chonbuk National University, Jeonju, Republic of Korea*
[14] *Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia*
[15] *COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan*
[16] *Creighton University, Omaha, NE, United States*
[17] *Department of Physics, Aligarh Muslim University, Aligarh, India*
[18] *Department of Physics, Pusan National University, Pusan, Republic of Korea*
[19] *Department of Physics, Sejong University, Seoul, Republic of Korea*
[20] *Department of Physics, University of California, Berkeley, CA, United States*
[21] *Department of Physics, University of Oslo, Oslo, Norway*
[22] *Department of Physics and Technology, University of Bergen, Bergen, Norway*
[23] *Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy*
[24] *Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy*
[25] *Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy*
[26] *Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy*
[27] *Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy*
[28] *Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy*

[29] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
[30] Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
[31] Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
[32] Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy
[33] Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
[34] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[35] Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
[36] Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway
[37] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[38] Faculty of Science, P.J. Šafárik University, Košice, Slovakia
[39] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[40] Gangneung-Wonju National University, Gangneung, Republic of Korea
[41] Gauhati University, Department of Physics, Guwahati, India
[42] Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
[43] Helsinki Institute of Physics (HIP), Helsinki, Finland
[44] High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
[45] Hiroshima University, Hiroshima, Japan
[46] Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT), Worms, Germany
[47] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[48] Indian Institute of Technology Bombay (IIT), Mumbai, India
[49] Indian Institute of Technology Indore, Indore, India
[50] Indonesian Institute of Sciences, Jakarta, Indonesia
[51] INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[52] INFN, Sezione di Bari, Bari, Italy
[53] INFN, Sezione di Bologna, Bologna, Italy
[54] INFN, Sezione di Cagliari, Cagliari, Italy
[55] INFN, Sezione di Catania, Catania, Italy
[56] INFN, Sezione di Padova, Padova, Italy
[57] INFN, Sezione di Roma, Rome, Italy
[58] INFN, Sezione di Torino, Turin, Italy
[59] INFN, Sezione di Trieste, Trieste, Italy
[60] Inha University, Incheon, Republic of Korea
[61] Institut de Physique Nucléaire d'Orsay (IPNO), Institut National de Physique Nucléaire et de Physique des Particules (IN2P3/CNRS), Université de Paris-Sud, Université Paris-Saclay, Orsay, France
[62] Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
[63] Institute for Subatomic Physics, Utrecht University/Nikhef, Utrecht, Netherlands
[64] Institute for Theoretical and Experimental Physics, Moscow, Russia
[65] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
[66] Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
[67] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[68] Institute of Space Science (ISS), Bucharest, Romania
[69] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[70] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
[71] Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
[72] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[73] iThemba LABS, National Research Foundation, Somerset West, South Africa
[74] Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany
[75] Joint Institute for Nuclear Research (JINR), Dubna, Russia
[76] Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
[77] KTO Karatay University, Konya, Turkey
[78] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
[79] Lawrence Berkeley National Laboratory, Berkeley, CA, United States
[80] Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
[81] Nagasaki Institute of Applied Science, Nagasaki, Japan
[82] Nara Women's University (NWU), Nara, Japan
[83] National and Kapodistrian University of Athens, School of Science, Department of Physics, Athens, Greece
[84] National Centre for Nuclear Research, Warsaw, Poland
[85] National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India
[86] National Nuclear Research Center, Baku, Azerbaijan
[87] National Research Centre Kurchatov Institute, Moscow, Russia
[88] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[89] Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands
[90] NRC Kurchatov Institute IHEP, Protvino, Russia
[91] NRNU Moscow Engineering Physics Institute, Moscow, Russia
[92] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
[93] Nuclear Physics Institute of the Czech Academy of Sciences, Řež u Prahy, Czech Republic
[94] Oak Ridge National Laboratory, Oak Ridge, TN, United States
[95] Ohio State University, Columbus, OH, United States
[96] Petersburg Nuclear Physics Institute, Gatchina, Russia
[97] Physics Department, Faculty of science, University of Zagreb, Zagreb, Croatia
[98] Physics Department, Panjab University, Chandigarh, India
[99] Physics Department, University of Jammu, Jammu, India
[100] Physics Department, University of Rajasthan, Jaipur, India
[101] Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
[102] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[103] Physik Department, Technische Universität München, Munich, Germany
[104] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[105] Rudjer Bošković Institute, Zagreb, Croatia
[106] Russian Federal Nuclear Center (VNIIEF), Sarov, Russia

[107] Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
[108] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[109] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[110] Shanghai Institute of Applied Physics, Shanghai, China
[111] St. Petersburg State University, St. Petersburg, Russia
[112] Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
[113] SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France
[114] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[115] Technical University of Košice, Košice, Slovakia
[116] Technische Universität München, Excellence Cluster 'Universe', Munich, Germany
[117] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[118] The University of Texas at Austin, Austin, TX, United States
[119] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[120] Universidade de São Paulo (USP), São Paulo, Brazil
[121] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[122] Universidade Federal do ABC, Santo Andre, Brazil
[123] University College of Southeast Norway, Tonsberg, Norway
[124] University of Cape Town, Cape Town, South Africa
[125] University of Houston, Houston, TX, United States
[126] University of Jyväskylä, Jyväskylä, Finland
[127] University of Liverpool, Liverpool, United Kingdom
[128] University of Tennessee, Knoxville, TN, United States
[129] University of the Witwatersrand, Johannesburg, South Africa
[130] University of Tokyo, Tokyo, Japan
[131] University of Tsukuba, Tsukuba, Japan
[132] Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[133] Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, Lyon, France
[134] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France
[135] Université Paris-Saclay Centre dÉtudes de Saclay (CEA), IRFU, Department de Physique Nucléaire (DPhN), Saclay, France
[136] Università degli Studi di Foggia, Foggia, Italy
[137] Università degli Studi di Pavia, Pavia, Italy
[138] Università di Brescia, Brescia, Italy
[139] Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India
[140] Warsaw University of Technology, Warsaw, Poland
[141] Wayne State University, Detroit, MI, United States
[142] Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany
[143] Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary
[144] Yale University, New Haven, CT, United States
[145] Yonsei University, Seoul, Republic of Korea

[i] Deceased.
[ii] Dipartimento DET del Politecnico di Torino, Turin, Italy.
[iii] M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear, Physics, Moscow, Russia.
[iv] Department of Applied Physics, Aligarh Muslim University, Aligarh, India.
[v] Institute of Theoretical Physics, University of Wroclaw, Poland.