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Charged-particle distributions at low transverse momentum in $\sqrt{s} = 13$ TeV pp interactions measured with the ATLAS detector at the LHC

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Abstract Measurements of distributions of charged particles produced in proton–proton collisions with a centre-of-mass energy of 13 TeV are presented. The data were recorded by the ATLAS detector at the LHC and correspond to an integrated luminosity of 151 μb^{-1}. The particles are required to have a transverse momentum greater than 100 MeV and an absolute pseudorapidity less than 2.5. The charged-particle multiplicity, its dependence on transverse momentum and pseudorapidity and the dependence of the mean transverse momentum on multiplicity are measured in events containing at least two charged particles satisfying the above kinematic criteria. The results are corrected for detector effects and compared to the predictions from several Monte Carlo event generators.

1 Introduction

Measurements of charged-particle distributions in proton–proton (pp) collisions probe the strong interaction in the low-momentum transfer, non-perturbative region of quantum chromodynamics (QCD). In this region, charged-particle interactions are typically described by QCD-inspired models implemented in Monte Carlo (MC) event generators. Measurements are used to constrain the free parameters of these models. An accurate description of low-energy strong interaction processes is essential for simulating single pp interactions and the effects of multiple pp interactions in the same bunch crossing at high instantaneous luminosity in hadron colliders. Charged-particle distributions have been measured previously in hadronic collisions at various centre-of-mass energies [1–11].

The measurements presented in this paper use data from pp collisions at a centre-of-mass energy $\sqrt{s} = 13$ TeV recorded by the ATLAS experiment [12] at the Large Hadron Collider (LHC) [13] in 2015, corresponding to an integrated luminosity of 151 μb^{-1}. The data were recorded during special fills with low beam currents and reduced focusing to give a mean number of interactions per bunch crossing of 0.005. The same dataset and a similar analysis strategy were used to measure distributions of charged particles with transverse momentum p_T greater than 500 MeV [9]. This paper extends the measurements to the low-p_T regime of $p_T > 100$ MeV. While this nearly doubles the overall number of particles in the kinematic acceptance, the measurements are rendered more difficult due to multiple scattering and imprecise knowledge of the material in the detector. Measurements in the low-momentum regime provide important information for the description of the strong interaction in the low-momentum-transfer, non-perturbative region of QCD.

These measurements use tracks from primary charged particles, corrected for detector effects to the particle level, and are presented as inclusive distributions in a fiducial phase space region. Primary charged particles are defined in the same way as in Refs. [2,9] as charged particles with a mean lifetime $\tau > 300$ ps, either directly produced in pp interactions or from subsequent decays of directly produced particles with $\tau < 30$ ps; particles produced from decays of particles with $\tau > 30$ ps, denoted secondary particles, are excluded. Earlier analyses also included charged particles with a mean lifetime of $30 < \tau < 300$ ps. These are charged strange baryons and have been removed for the present analysis due to their low reconstruction efficiency. For comparison to the earlier measurements, the measured multiplicity at $\eta = 0$ is extrapolated to include charged strange baryons. All primary charged particles are required to have a momentum component transverse to the beam direction $p_T > 100$ MeV and absolute pseudorapidity[1] $|\eta| < 2.5$ to be within the geo-

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[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 upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the

metrical acceptance of the tracking detector. Each event is required to have at least two primary charged particles. The following observables are measured:

$$\frac{1}{N_{\mathrm{ev}}}\cdot\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta},\quad \frac{1}{N_{\mathrm{ev}}}\cdot\frac{1}{2\pi p_{\mathrm{T}}}\cdot\frac{\mathrm{d}^2N_{\mathrm{ch}}}{\mathrm{d}\eta\mathrm{d}p_{\mathrm{T}}},\quad \frac{1}{N_{\mathrm{ev}}}\cdot\frac{\mathrm{d}N_{\mathrm{ev}}}{\mathrm{d}n_{\mathrm{ch}}}$$
$$\text{and}\quad \langle p_{\mathrm{T}}\rangle \text{ vs. } n_{\mathrm{ch}}.$$

Here n_{ch} is the number of primary charged particles within the kinematic acceptance in an event, N_{ev} is the number of events with $n_{\mathrm{ch}} \geq 2$, and N_{ch} is the total number of primary charged particles in the kinematic acceptance.

The PYTHIA 8 [14], EPOS [15] and QGSJET- II [16] MC generators are used to correct the data for detector effects and to compare with particle-level corrected data. PYTHIA 8 and EPOS both model the effects of colour coherence, which is important in dense parton environments and effectively reduces the number of particles produced in multiple parton-parton interactions. In PYTHIA 8, the simulation is split into non-diffractive and diffractive processes, the former dominated by t-channel gluon exchange and amounting to approximately 80 % of the selected events, and the latter described by a pomeron-based approach [17]. In contrast, EPOS implements a parton-based Gribov–Regge [18] theory, an effective field theory describing both hard and soft scattering at the same time. QGSJET- II is based upon the Reggeon field theory framework [19]. The latter two generators do not rely on parton distribution functions (PDFs), as used in PYTHIA 8. Different parameter settings in the models are used in the simulation to reproduce existing experimental data and are referred to as tunes. For PYTHIA 8, the A2 [20] tune is based on the MSTW2008LO PDF [21] while the MONASH [22] underlying-event tune uses the NNPDF2.3LO PDF [23] and incorporates updated fragmentation parameters, as well as SPS and Tevatron data to constrain the energy scaling. For EPOS, the LHC [24] tune is used, while for QGSJET- II the default settings of the generator are applied. Details of the MC generator versions and settings are shown in Table 1. Detector effects are simulated using the GEANT4-based [25] ATLAS simulation framework [26].

2 ATLAS detector

The ATLAS detector covers nearly the whole solid angle around the collision point and includes tracking detectors, calorimeters and muon chambers. This measurement uses information from the inner detector and the trigger system, relying on the minimum-bias trigger scintillators (MBTS).

The inner detector covers the full range in ϕ and $|\eta| < 2.5$. It consists of the silicon pixel detector (pixel), the silicon microstrip detector (SCT) and the transition radiation straw-tube tracker (TRT). These are located around the interaction point spanning radial distances of 33–150, 299–560 and 563–1066 mm respectively. The barrel (each end-cap) consists of four (three) pixel layers, four (nine) double-layers of silicon microstrips and 73 (160) layers of TRT straws. During the LHC long shutdown 2013–2014, a new innermost pixel layer, the insertable B-layer (IBL) [27,28], was installed around a new smaller beam-pipe. The smaller radius of 33 mm and the reduced pixel size of the IBL result in improvements of both the transverse and longitudinal impact parameter resolutions. Requirements on an innermost pixel-layer hit and on impact parameters strongly suppress the number of tracks from secondary particles. A track from a charged particle passing through the barrel typically has 12 measurement points (hits) in the pixel and SCT detectors. The inner detector is located within a solenoid that provides an axial 2 T magnetic field.

A two-stage trigger system is used: a hardware-based level-1 trigger (L1) and a software-based high-level trigger (HLT). The L1 decision provided by the MBTS detector is used for this measurement. The scintillators are installed on either side of the interaction point in front of the liquid-argon end-cap calorimeter cryostats at $z = \pm 3.56$ m and segmented into two rings in pseudorapidity ($2.07 < |\eta| < 2.76$ and $2.76 < |\eta| < 3.86$). The inner (outer) ring consists of eight (four) azimuthal sectors, giving a total of 12 sectors on each side. The trigger used in this measurement requires at least one signal in a scintillator on one side to be above threshold.

Footnote 1 continued
beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

Table 1 Summary of MC generators used to compare to the corrected data. The generator, its version, the corresponding tune and the parton distribution function are given

Generator	Version	Tune	PDF
PYTHIA 8	8.185	A2	MSTW2008LO
PYTHIA 8	8.186	MONASH	NNPDF2.3LO
EPOS	LHCv3400	LHC	–
QGSJET- II	II- 04	Default	–

3 Analysis

The analysis closely follows the strategy described in Ref. [9], but modifications for the low-p_{T} region are applied where relevant.

3.1 Event and track selection

Events are selected from colliding proton bunches using the MBTS trigger described above. Each event is required to contain a primary vertex [29], reconstructed from at least two tracks with a minimum p_{T} of 100 MeV. To reduce contamination from events with more than one interaction in a bunch crossing, events with a second vertex containing four or more tracks are removed. The contributions from non-collision background events and the fraction of events where two interactions are reconstructed as a single vertex have been studied in data and are found to be negligible.

Track candidates are reconstructed in the pixel and SCT detectors and extended to include measurements in the TRT [30,31]. A special configuration of the track reconstruction algorithms was used for this analysis to reconstruct low-momentum tracks with good efficiency and purity. The purity is defined as the fraction of selected tracks that are also primary tracks with a transverse momentum of at least 100 MeV and an absolute pseudorapidity less than 2.5. The most critical change with respect to the 500 MeV analysis [9], besides lowering the p_T threshold to 100 MeV, is reducing the requirement on the minimum number of silicon hits from 7 to 5. All tracks, irrespective of their transverse momentum, are reconstructed in a single pass of the track reconstruction algorithm. Details of the performance of the track reconstruction in the 13 TeV data and its simulation can be found in Ref. [32]. Figure 1 shows the comparison between data and simulation in the distribution of the number of pixel hits associated with a track for the low-momentum region. Data and simulation agree reasonably well given the known imperfections in the simulation of inactive pixel modules. These differences are taken into account in the systematic uncertainty on the tracking efficiency by comparing the efficiency of the pixel hit requirements in data and simulation after applying all other track selection requirements.

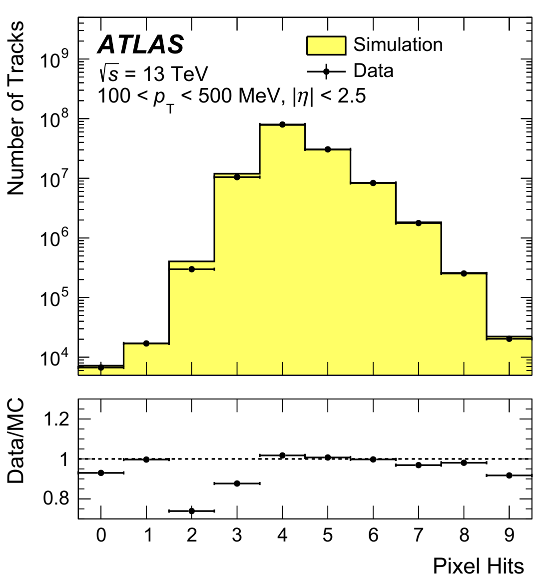

Fig. 1 Comparison between data and PYTHIA 8 A2 simulation for the distribution of the number of pixel hits associated with a track. The distribution is shown before the requirement on the number of pixel hits is applied, for tracks with $100 < p_T < 500$ MeV and $|\eta| < 2.5$. The *error bars* on the *points* are the statistical uncertainties of the data. The *lower panel* shows the ratio of data to MC prediction

Events are required to contain at least two selected tracks satisfying the following criteria: $p_T > 100$ MeV and $|\eta| < 2.5$; at least one pixel hit and an innermost pixel-layer hit if expected;[2] at least two, four or six SCT hits for $p_T < 300$ MeV, <400 MeV or >400 MeV respectively, in order to account for the dependence of track length on p_T; $|d_0^{BL}| < 1.5$ mm, where the transverse impact parameter d_0^{BL} is calculated with respect to the measured beam line (BL); and $|z_0^{BL} \times \sin\theta| < 1.5$ mm, where z_0^{BL} is the difference between the longitudinal position of the track along the beam line at the point where d_0^{BL} is measured and the longitudinal position of the primary vertex and θ is the polar angle of the track. High-momentum tracks with mismeasured p_T are removed by requiring the track-fit χ^2 probability to be larger than 0.01 for tracks with $p_T > 10$ GeV. In total 9.3×10^6 events pass the selection, containing a total of 3.2×10^8 selected tracks.

3.2 Background estimation

Background contributions to the tracks from primary particles include fake tracks (those formed by a random combination of hits), strange baryons and secondary particles. These contributions are subtracted on a statistical basis from the number of reconstructed tracks before correcting for other detector effects. The contribution of fake tracks, estimated from simulation, is at most 1 % for all p_T and η intervals with a relative uncertainty of ±50 % determined from dedicated comparisons of data with simulation [33]. Charged strange baryons with a mean lifetime $30 < \tau < 300$ ps are treated as background, because these particles and their decay products have a very low reconstruction efficiency. Their contribution is estimated from EPOS, where the best description of this strange baryon contribution is expected [9], to be below 0.01 % on average, with the fraction increasing with track p_T to be (3 ± 1) % above 20 GeV. The fraction is much smaller at low p_T due to the extremely low track reconstruction efficiency. The contribution from secondary particles is estimated by performing a template fit to the distribution of the track transverse impact parameter d_0^{BL}, using templates for primary and secondary particles created from PYTHIA 8 A2 simulation. All selection requirements are applied except that on the transverse impact parameter. The shape of the transverse impact parameter distribution differs for electron and non-electron secondary particles, as the d_0^{BL} reflects the radial location at which the secondaries were produced. The processes for conversions and hadronic interactions are rather different, which leads to differences in the radial distributions. The electrons are more often produced from conversions in the beam pipe. Furthermore, the fraction of electrons increases as p_T decreases. Therefore, separate

[2] A hit is expected if the extrapolated track crosses an known active region of a pixel module. If an innermost pixel-layer hit is not expected, a next-to-innermost pixel-layer hit is required if expected.

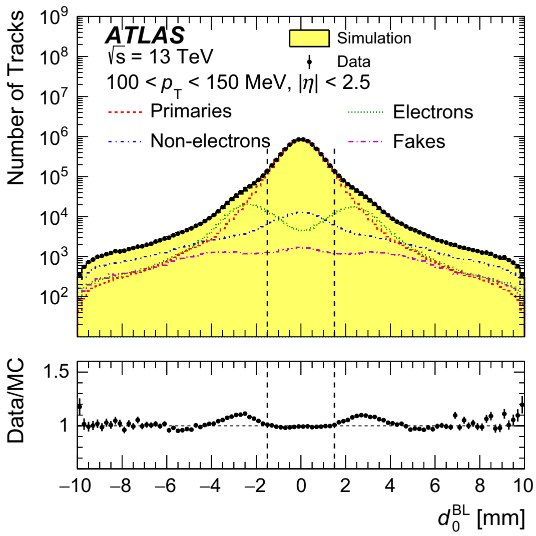

Fig. 2 Comparison between data and PYTHIA 8 A2 simulation for the transverse impact parameter d_0^{BL} distribution. The d_0^{BL} distribution is shown for $100 < p_{\mathrm{T}} < 150\,\mathrm{MeV}$ without applying the cut on the transverse impact parameter. The position where the cut is applied is shown as *dashed black lines* at $\pm 1.5\,\mathrm{mm}$. The simulated d_0^{BL} distribution is normalised to the number of tracks in data and the separate contributions from primary, fake, electron and non-electron tracks are shown as *lines* using various combinations of *dots* and *dashes*. The secondary particles are scaled by the fitted fractions as described in the text. The *error bars* on the *points* are the statistical uncertainties of the data. The *lower panel* shows the ratio of data to MC prediction

templates are used for electrons and non-electron secondary particles in the region $p_{\mathrm{T}} < 500\,\mathrm{MeV}$. The rate of secondary tracks is the sum of these two contributions and is measured with the fit. The background normalisation for fake tracks and strange baryons is determined from the prediction of the simulation. The fit is performed in nine p_{T} intervals, each of width 50 MeV, in the region $4 < |d_0^{\mathrm{BL}}| < 9.5$ mm. The fitted distribution for $100 < p_{\mathrm{T}} < 150\,\mathrm{MeV}$ is shown in Fig. 2. For this p_{T} interval, the fraction of secondary tracks within the region $|d_0^{\mathrm{BL}}| < 1.5\,\mathrm{mm}$ is measured to be (3.6 ± 0.7) %, equally distributed between electrons and non-electrons. For tracks with $p_{\mathrm{T}} > 500\,\mathrm{MeV}$, the fraction of secondary particles is measured to be (2.3 ± 0.6) %; these are mostly non-electron secondary particles. The uncertainties are evaluated by using different generators to estimate the interpolation from the fit region to $|d_0^{\mathrm{BL}}| < 1.5$ mm, changing the fit range and checking the η dependence of the fraction of tracks originating from secondaries. This last study is performed by fits integrated over different η ranges, because the η dependence could be different in data and simulation, as most of the secondary particles are produced in the material of the detector. The systematic uncertainties arising from imperfect knowledge of the passive material in the detector are also included; these are estimated using the same material variations as used in the estimation of the uncertainty on the tracking efficiency, described in Sect. 3.4.

3.3 Trigger and vertex reconstruction efficiency

The trigger efficiency $\varepsilon_{\mathrm{trig}}$ is measured in a data sample recorded using a control trigger which selected events randomly at L1 only requiring that the beams are colliding in the ATLAS detector. The events are then filtered at the HLT by requiring at least one reconstructed track with $p_{\mathrm{T}} >$ 200 MeV. The efficiency $\varepsilon_{\mathrm{trig}}$ is defined as the ratio of events that are accepted by both the control and the MBTS trigger to all events accepted by the control trigger. It is measured as a function of the number of selected tracks with the requirement on the longitudinal impact parameter removed, $n_{\mathrm{sel}}^{\mathrm{no\text{-}z}}$. The trigger efficiency increases from $96.5^{+0.4}_{-0.7}$ % for events with $n_{\mathrm{sel}}^{\mathrm{no\text{-}z}} = 2$, to (99.3 ± 0.2) % for events with $n_{\mathrm{sel}}^{\mathrm{no\text{-}z}} \geq 4$. The quoted uncertainties include statistical and systematic uncertainties. The systematic uncertainties are estimated from the difference between the trigger efficiencies measured on the two sides of the detector, and the impact of beam-induced background; the latter is estimated using events recorded when only one beam was present at the interaction point, as described in Ref. [9].

The vertex reconstruction efficiency $\varepsilon_{\mathrm{vtx}}$ is determined from data by calculating the ratio of the number of triggered events with a reconstructed vertex to the total number of all triggered events. The efficiency, measured as a function of $n_{\mathrm{sel}}^{\mathrm{no\text{-}z}}$, is approximately 87 % for events with $n_{\mathrm{sel}}^{\mathrm{no\text{-}z}} = 2$ and rapidly rises to 100 % for events with $n_{\mathrm{sel}}^{\mathrm{no\text{-}z}} > 4$. For events with $n_{\mathrm{sel}}^{\mathrm{no\text{-}z}} = 2$, the efficiency is also parameterised as a function of the difference between the longitudinal impact parameter of the two tracks ($\Delta z_{\mathrm{tracks}}$). This efficiency decreases roughly linearly from 91 % at $\Delta z_{\mathrm{tracks}} = 0\,\mathrm{mm}$ to 32 % at $\Delta z_{\mathrm{tracks}} = 10\,\mathrm{mm}$. The systematic uncertainty is estimated from the difference between the vertex reconstruction efficiency measured before and after beam-background removal and found to be negligible.

3.4 Track reconstruction efficiency

The primary-track reconstruction efficiency $\varepsilon_{\mathrm{trk}}$ is determined from simulation. The efficiency is parameterised in two-dimensional bins of p_{T} and η, and is defined as:

$$\varepsilon_{\mathrm{trk}}(p_{\mathrm{T}}, \eta) = \frac{N_{\mathrm{rec}}^{\mathrm{matched}}(p_{\mathrm{T}}, \eta)}{N_{\mathrm{gen}}(p_{\mathrm{T}}, \eta)},$$

where p_{T} and η are generated particle properties, $N_{\mathrm{rec}}^{\mathrm{matched}}$ (p_{T}, η) is the number of reconstructed tracks matched to generated primary charged particles and $N_{\mathrm{gen}}(p_{\mathrm{T}}, \eta)$ is the number of generated primary charged particles in that kinematic region. A track is matched to a generated particle if the weighted fraction of track hits originating from that particle exceeds 50 %. The hits are weighted such that hits in all subdetectors have the same weight in the sum, based on the number of expected hits and the resolution of the individual

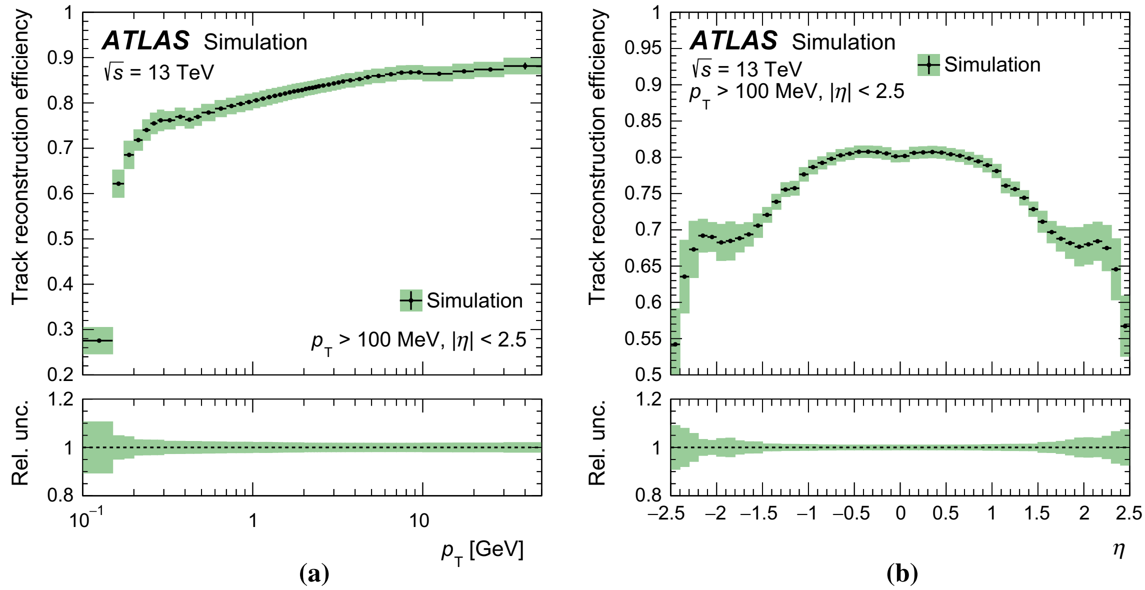

Fig. 3 Track reconstruction efficiency as a function of **a** transverse momentum p_T and of **b** pseudorapidity η for selected tracks with p_T >100 MeV and $|\eta| < 2.5$ as predicted by PYTHIA 8 A2 and single-particle simulation. The statistical uncertainties are shown as *vertical bars*, the sum in quadrature of statistical and systematic uncertainties as *shaded areas*

subdetector. For $100 < p_T < 125$ MeV and integrated over η, the primary-track reconstruction efficiency is 27.5 %. In the analysis using tracks with $p_T > 500$ MeV [9], a data-driven correction to the efficiency was evaluated in order to account for material effects in the $|\eta| > 1.5$ region. This correction to the efficiency is not applied in this analysis due to the large uncertainties of this method for low-momentum tracks, which are larger than the uncertainties in the material description.

The dominant uncertainty in the track reconstruction efficiency arises from imprecise knowledge of the passive material in the detector. This is estimated by evaluating the track reconstruction efficiency in dedicated simulation samples with increased detector material. The total uncertainty in the track reconstruction efficiency due to the amount of material is calculated as the linear sum of the contributions of 5 % additional material in the entire inner detector, 10 % additional material in the IBL and 50 % additional material in the pixel services region at $|\eta| > 1.5$. The sizes of the variations are estimated from studies of the rate of photon conversions, of hadronic interactions, and of tracks lost due to interactions in the pixel services [34]. The resulting uncertainty in the track reconstruction efficiency is 1 % at low $|\eta|$ and high p_T and up to 10 % for higher $|\eta|$ or for lower p_T. The systematic uncertainty arising from the track selection requirements is studied by comparing the efficiency of each requirement in data and simulation. This results in an uncertainty of 0.5 % for all p_T and η. The total uncertainty in the track reconstruction efficiency is obtained by adding all effects in quadrature. The track reconstruction efficiency is shown as function of p_T and η in Fig. 3, including all systematic uncertainties. The efficiency is calculated using the PYTHIA 8 A2 and single-particle simulation. Effectively identical results are obtained when using the prediction from EPOS or PYTHIA 8 MONASH.

3.5 Correction procedure and systematic uncertainties

The data are corrected to obtain inclusive spectra for primary charged particles satisfying the particle-level phase space requirement. The inefficiencies due to the trigger selection and vertex reconstruction are applied to all distributions as event weights:

$$w_{\mathrm{ev}}(n_{\mathrm{sel}}^{\text{no-z}}, \Delta z_{\mathrm{tracks}}) = \frac{1}{\varepsilon_{\mathrm{trig}}(n_{\mathrm{sel}}^{\text{no-z}})} \cdot \frac{1}{\varepsilon_{\mathrm{vtx}}(n_{\mathrm{sel}}^{\text{no-z}}, \Delta z_{\mathrm{tracks}})}. \tag{1}$$

Distributions of the selected tracks are corrected for inefficiencies in the track reconstruction with a track weight using the tracking efficiency ($\varepsilon_{\mathrm{trk}}$) and after subtracting the fractions of fake tracks (f_{fake}), of strange baryons (f_{sb}), of secondary particles (f_{sec}) and of particles outside the kinematic range (f_{okr}):

$$w_{\mathrm{trk}}(p_T, \eta) = \frac{1}{\varepsilon_{\mathrm{trk}}(p_T, \eta)} \cdot [1 - f_{\mathrm{fake}}(p_T, \eta) - f_{\mathrm{sb}}(p_T, \eta) - f_{\mathrm{sec}}(p_T, \eta) - f_{\mathrm{okr}}(p_T, \eta)]. \tag{2}$$

These distributions are estimated as described in Sect. 3.2 except that the fraction of particles outside the kinematic range whose reconstructed tracks enter the kinematic range is estimated from simulation. This fraction is largest at low p_T and high $|\eta|$. At $p_T = 100$ MeV and $|\eta| = 2.5$, 11 %

Table 2 Summary of the systematic uncertainties in the η, p_T, n_{ch} and $\langle p_T \rangle$ vs. n_{ch} observables. The uncertainties are given at the minimum and the maximum of the phase space

Distribution	$\frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\|\eta\|}$	$\frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2 N_{ch}}{d\eta d p_T}$	$\frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}$	$\langle p_T \rangle$ vs. n_{ch}
Range	0–2.5	0.1–50 GeV	2–250	0–160 GeV
Track reconstruction	1 %–7 %	1 %–6 %	0 %–$^{+38\,\%}_{-20\,\%}$	0 %–0.7 %
Track background	0.5 %	0.5 %–1 %	0 %–$^{+7\,\%}_{-1\,\%}$	0 %–0.1 %
p_T spectrum	–	–	0 %–$^{+3\,\%}_{-9\,\%}$	0 %–$^{+0.3\,\%}_{-0.1\,\%}$
Non-closure	0.4 %–1 %	1 %–3 %	0 %–4 %	0.5 %–2 %

of the particles enter the kinematic range and are subtracted as described in Formula 2 with a relative uncertainty of ± 4.5 %.

The p_T and η distributions are corrected by the event and track weights, as discussed above. In order to correct for resolution effects, an iterative Bayesian unfolding [35] is additionally applied to the p_T distribution. The response matrix used to unfold the data is calculated from PYTHIA 8 A2 simulation, and six iterations are used; this is the smallest number of iterations after which the process is stable. The statistical uncertainty is obtained using pseudo-experiments. For the η distribution, the resolution is smaller than the bin width and an unfolding is therefore unnecessary. After applying the event weight, the Bayesian unfolding is applied to the multiplicity distribution in order to correct from the observed track multiplicity to the multiplicity of primary charged particles, and therefore the track reconstruction efficiency weight does not need to be applied. The total number of events, N_{ev}, is defined as the integral of the multiplicity distribution after all corrections are applied and is used to normalise the distributions. The dependence of $\langle p_T \rangle$ on n_{ch} is obtained by first separately correcting the total number of tracks and $\sum_i p_T(i)$ (the scalar sum of the track p_T of all tracks with $p_T > 100$ MeV in one event), both versus the number of primary charged particles. After applying the correction to all events using the event and track weights, both distributions are unfolded separately. The ratio of the two unfolded distributions gives the dependence of $\langle p_T \rangle$ on n_{ch}.

A summary of the systematic uncertainties is given in Table 2 for all observables. The dominant uncertainty is due to material effects on the track reconstruction efficiency. Uncertainties due to imperfect detector alignment are taken into account and are less than 5 % at the highest track p_T values. In addition, resolution effects on the transverse momentum can result in low-p_T particles being reconstructed as high-p_T tracks. All these effects are considered as systematic uncertainty on the track reconstruction. The track background uncertainty is dominated by systematic effects in the estimation of the contribution from secondary particles. The track reconstruction efficiency determined in simulation can differ from the one in data if the p_T spectrum is different for data and simulation, as the efficiency depends strongly on the track p_T. This effect can alter the number of primary charged particles and is taken into account as a systematic uncertainty on the multiplicity distribution and $\langle p_T \rangle$ vs n_{ch}. The non-closure systematic uncertainty is estimated from differences in the unfolding results using PYTHIA 8 A2 and EPOS simulations. For this, all combinations of these MC generators are used to simulate the distribution and the input to the unfolding.

4 Results

The measured charged-particle multiplicities in events containing at least two charged particles with $p_T > 100$ MeV and $|\eta| < 2.5$ are shown in Fig. 4. The corrected data are compared to predictions from various generators. In general, the systematic uncertainties are larger than the statistical uncertainties.

Figure 4a shows the charged-particle multiplicity as a function of the pseudorapidity η. PYTHIA 8 MONASH, EPOS and QGSJET- II give a good description for $|\eta| < 1.5$. The prediction from PYTHIA 8 A2 has the same shape as predictions from the other generators, but lies below the data.

The charged-particle transverse momentum is shown in Fig. 4b. EPOS describes the data well for $p_T > 300$ MeV. For $p_T < 300$ MeV, the data are underestimated by up to 15 %. The other generators show similar mismodelling at low momentum but with larger discrepancies up to 35 % for QGSJET- II. In addition, they mostly overestimate the charged-particle multiplicity for $p_T > 400$ MeV; PYTHIA 8 A2 overestimates only in the intermediate p_T region and underestimates the data slightly for $p_T > 800$ MeV.

Figure 4c shows the charged-particle multiplicity. Overall, the form of the measured distribution is reproduced reasonably by all models. PYTHIA 8 A2 describes the data well for $30 < n_{ch} < 80$, but underestimates it for higher n_{ch}. For $30 < n_{ch} < 80$, PYTHIA 8 MONASH, EPOS and QGSJET- II underestimate the data by up to 20 %. PYTHIA 8 MONASH and EPOS overestimate the data for $n_{ch} > 80$ and drop below the measurement in the high-n_{ch} region, starting from $n_{ch} > 130$ and $n_{ch} > 200$ respectively. QGSJET- II overestimates the data significantly for $n_{ch} > 100$.

The mean transverse momentum versus the primary charged-particle multiplicity is shown in Fig. 4d. It increases towards higher n_{ch}, as modelled by a colour reconnection

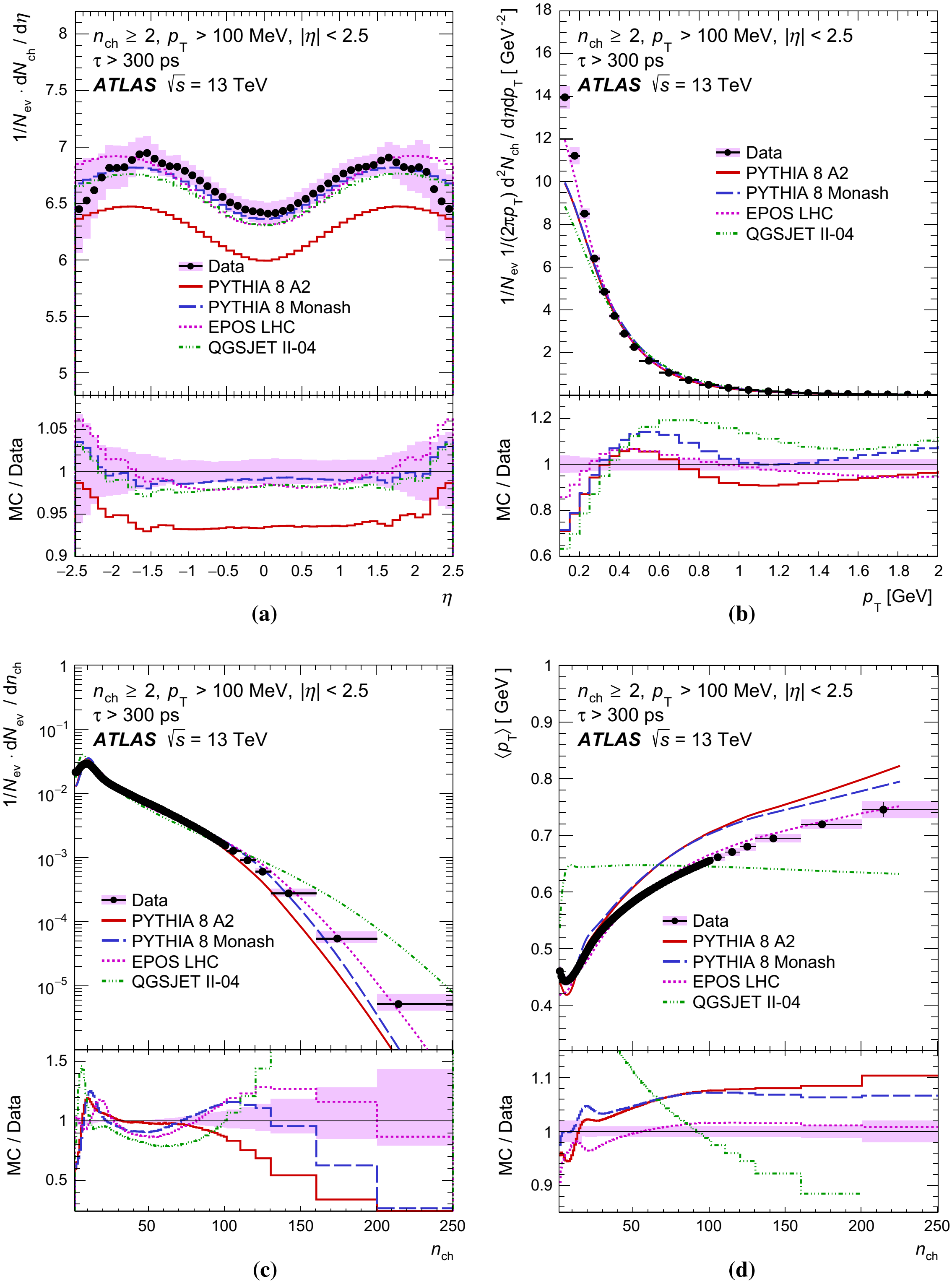

Fig. 4 Primary charged-particle multiplicities as a function of **a** pseudorapidity η and **b** transverse momentum p_T, **c** the primary charged-particle multiplicity n_{ch} and **d** the mean transverse momentum $\langle p_T \rangle$ versus n_{ch} for events with at least two primary charged particles with $p_T > 100$ MeV and $|\eta| < 2.5$, each with a lifetime $\tau > 300$ ps. The *black dots* represent the data and the *coloured curves* the different MC model predictions. The *vertical bars* represent the statistical uncertainties, while the *shaded areas* show statistical and systematic uncertainties added in quadrature. The *lower panel* in *each figure* shows the ratio of the MC simulation to data. As the bin centroid is different for data and simulation, the values of the ratio correspond to the averages of the bin content

mechanism in PYTHIA 8 and by the hydrodynamical evolution model in EPOS. The QGSJET- II generator, which has no model for colour coherence effects, describes the data poorly. For low n_{ch}, PYTHIA 8 A2 and EPOS underestimate the data, where PYTHIA 8 MONASH agrees within the uncertainties. For higher n_{ch} all generators overestimate the data, but for $n_{ch} > 40$, there is a constant offset for both PYTHIA 8 tunes, which describe the data to within 10 %. EPOS describes the data reasonably well and to within 2 %.

The mean number of primary charged particles per unit pseudorapidity in the central η region is measured to be 6.422 ± 0.096, by averaging over $|\eta| < 0.2$; the quoted error is the systematic uncertainty, the statistical uncertainty is negligible. In order to compare with other measurements, it is corrected for the contribution from strange baryons (and therefore extrapolated to primary charged particles with $\tau > 30$ ps) by a correction factor of 1.0121 ± 0.0035. The central value is taken from EPOS; the systematic uncertainty is taken from the difference between EPOS and PYTHIA 8 A2 (the largest difference was observed between EPOS and PYTHIA 8 A2) and the statistical uncertainty is negligible. The mean number of primary charged particles after the correction is 6.500 ± 0.099. This result is compared to previous measurements [1,2,9] at different $\sqrt{s}$ values in Fig. 5. The predictions from EPOS and PYTHIA 8 MONASH match the data well. For PYTHIA 8 A2, the match is not as good as was observed when measuring particles with $p_T > 500$ MeV [9].

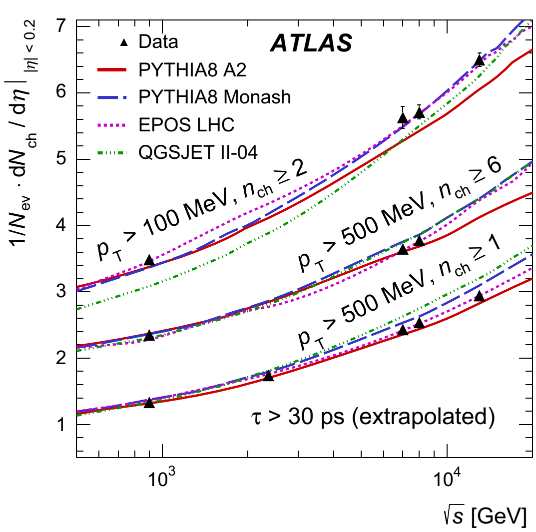

Fig. 5 The average primary charged-particle multiplicity in *pp* interactions per unit of pseudorapidity η for $|\eta| < 0.2$ as a function of the centre-of-mass energy $\sqrt{s}$. The values for the other *pp* centre-of-mass energies are taken from previous ATLAS analyses [1,2]. The value for particles with $p_T > 500$ MeV for a $\sqrt{s} = 13$ TeV is taken from Ref. [9]. The results have been extrapolated to include charged strange baryons (charged particles with a mean lifetime of $30 < \tau < 300$ ps). The data are shown as *black triangles* with *vertical errors bars* representing the total uncertainty. They are compared to various MC predictions which are shown as *coloured lines*

5 Conclusion

Primary charged-particle multiplicity measurements with the ATLAS detector using proton–proton collisions delivered by the LHC at $\sqrt{s} = 13$ TeV are presented for events with at least two primary charged particles with $|\eta| < 2.5$ and $p_T > 100$ MeV using a specialised track reconstruction algorithm. A data sample corresponding to an integrated luminosity of 151 μb^{-1} is analysed. The mean number of charged particles per unit pseudorapidity in the region $|\eta| < 0.2$ is measured to be 6.422 ± 0.096 with a negligible statistical uncertainty. Significant differences are observed between the measured distributions and the Monte Carlo predictions tested. Amongst the models considered, EPOS has the best overall description of the data as was seen in a previous ATLAS measurement at $\sqrt{s} = 13$ TeV using tracks with $p_T > 500$ MeV. PYTHIA 8 A2 and PYTHIA 8 MONASH provide a reasonable overall description, whereas QGSJET- II does not describe $\langle p_T \rangle$ vs. n_{ch} well but provides a reasonable level of agreement for other distributions.

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ATLAS Collaboration

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Cherkaoui El Moursli[135e], V. Chernyatin[27,*], E. Cheu[7], L. Chevalier[136], V. Chiarella[49], G. Chiarelli[124a,124b], G. Chiodini[74a], A. S. Chisholm[19], A. Chitan[28b], M. V. Chizhov[66], K. Choi[62], A. R. Chomont[36], S. Chouridou[9], B. K. B. Chow[100], V. Christodoulou[79], D. Chromek-Burckhart[32], J. Chudoba[127], A. J. Chuinard[88], J. J. Chwastowski[41], L. Chytka[115], G. Ciapetti[132a,132b], A. K. Ciftci[4a], D. Cinca[45], V. Cindro[76], I. A. Cioara[23], C. Ciocca[22a,22b], A. Ciocio[16], F. Cirotto[104a,104b], Z. H. Citron[171], M. Citterio[92a], M. Ciubancan[28b], A. Clark[51], B. L. Clark[58], M. R. Clark[37], P. J. Clark[48], R. N. Clarke[16], C. Clement[146a,146b], Y. Coadou[86], M. Cobal[163a,163c], A. Coccaro[51], J. Cochran[65], L. Coffey[25], L. Colasurdo[106], B. Cole[37], A. P. Colijn[107], J. Collot[57], T. Colombo[32], G. Compostella[101], P. Conde Muiño[126a,126b], E. Coniavitis[50], S. H. Connell[145b], I. A. Connelly[78], V. Consorti[50], S. Constantinescu[28b], G. Conti[32], F. Conventi[104a,k], M. Cooke[16], B. D. Cooper[79], A. M. Cooper-Sarkar[120], K. J. R. Cormier[158], T. Cornelissen[174], M. Corradi[132a,132b], F. Corriveau[88,l], A. Corso-Radu[162], A. Cortes-Gonzalez[13], G. Cortiana[101], G. Costa[92a], M. J. Costa[166], D. Costanzo[139], G. Cottin[30], G. Cowan[78], B. E. Cox[85], K. Cranmer[110], S. J. Crawley[55], G. Cree[31], S. Crépé-Renaudin[57], F. Crescioli[81], W. A. Cribbs[146a,146b], M. Crispin Ortuzar[120], M. Cristinziani[23], V. Croft[106], G. Crosetti[39a,39b], T. Cuhadar Donszelmann[139], J. Cummings[175], M. Curatolo[49], J. Cúth[84], C. Cuthbert[150], H. Czirr[141], P. Czodrowski[3], G. D'amen[22a,22b], S. D'Auria[55], M. D'Onofrio[75], M. J. Da Cunha Sargedas De Sousa[126a,126b], C. Da Via[85], W. Dabrowski[40a], T. Dado[144a], T. Dai[90], O. Dale[15], F. Dallaire[95], C. Dallapiccola[87], M. Dam[38], J. R. Dandoy[33], N. P. Dang[50], A. C. Daniells[19], N. S. Dann[85], M. Danninger[167], M. Dano Hoffmann[136], V. Dao[50], G. Darbo[52a], S. Darmora[8], J. Dassoulas[3], A. Dattagupta[62], W. Davey[23], C. David[168], T. Davidek[129], M. Davies[153], P. Davison[79], E. Dawe[89], I. Dawson[139], R. K. Daya-Ishmukhametova[87], K. De[8], R. de Asmundis[104a], A. De Benedetti[113], S. De Castro[22a,22b], S. De Cecco[81], N. De Groot[106], P. de Jong[107], H. De la Torre[83], F. De Lorenzi[65], A. De Maria[56], D. De Pedis[132a], A. De Salvo[132a], U. De Sanctis[149], A. De Santo[149], J. B. De Vivie De Regie[117], W. J. Dearnaley[73], R. Debbe[27], C. Debenedetti[137], D. V. Dedovich[66], N. Dehghanian[3], I. Deigaard[107], M. Del Gaudio[39a,39b], J. Del Peso[83], T. Del Prete[124a,124b], D. Delgove[117], F. Deliot[136], C. M. Delitzsch[51], M. Deliyergiyev[76], A. Dell'Acqua[32], L. Dell'Asta[24], M. Dell'Orso[124a,124b], M. Della Pietra[104a,k], D. della Volpe[51], M. Delmastro[5], P. A. Delsart[57], D. A. DeMarco[158], S. Demers[175], M. Demichev[66], A. Demilly[81], S. P. Denisov[130], D. Denysiuk[136], D. Derendarz[41], J. E. Derkaoui[135d], F. Derue[81], P. Dervan[75], K. Desch[23], C. Deterre[44], K. Dette[45], M. R. Devesa[29], P. O. Deviveiros[32], A. Dewhurst[131], S. Dhaliwal[25], A. Di Ciaccio[133a,133b], L. Di Ciaccio[5], W. K. Di Clemente[122], C. Di Donato[132a,132b], A. Di Girolamo[32], B. Di Girolamo[32], B. Di Micco[134a,134b], R. Di Nardo[32], A. Di Simone[50], R. Di Sipio[158], D. Di Valentino[31], C. Diaconu[86], M. Diamond[158], F. A. Dias[48], M. A. Diaz[34a], E. B. Diehl[90], J. Dietrich[17], S. Diglio[86], A. Dimitrievska[14], J. Dingfelder[23], P. Dita[28b], S. Dita[28b], F. Dittus[32], F. Djama[86], T. Djobava[53b], J. I. Djuvsland[59a], M. A. B. do Vale[26c], D. Dobos[32], M. Dobre[28b], C. Doglioni[82], T. Dohmae[155], J. Dolejsi[129], Z. Dolezal[129], B. A. Dolgoshein[98,*], M. Donadelli[26d], S. Donati[124a,124b], P. Dondero[121a,121b], J. Donini[36], J. Dopke[131], A. Doria[104a], M. T. Dova[72], A. T. Doyle[55], E. Drechsler[56], M. Dris[10], Y. Du[35d], J. Duarte-Campderros[153], E. Duchovni[171], G. Duckeck[100], O. A. Ducu[95,m], D. Duda[107], A. Dudarev[32], E. M. Duffield[16], L. Duflot[117], L. Duguid[78], M. Dührssen[32], M. Dumancic[171], M. Dunford[59a], H. Duran Yildiz[4a], M. Düren[54], A. Durglishvili[53b], D. Duschinger[46], B. Dutta[44], M. Dyndal[44], C. Eckardt[44], K. M. Ecker[101], R. C. Edgar[90], N. C. Edwards[48], T. Eifert[32], G. Eigen[15], K. Einsweiler[16], T. Ekelof[164], M. El Kacimi[135c], V. Ellajosyula[86], M. Ellert[164], S. Elles[5], F. Ellinghaus[174], A. A. Elliot[168], N. Ellis[32], J. Elmsheuser[27], M. Elsing[32], D. Emeliyanov[131], Y. Enari[155], O. C. Endner[84], M. Endo[118], J. S. Ennis[169], J. Erdmann[45], A. Ereditato[18], G. Ernis[174], J. Ernst[2], M. Ernst[27], S. Errede[165], E. Ertel[84], M. Escalier[117], H. Esch[45], C. Escobar[125], B. Esposito[49], A. I. Etienvre[136], E. Etzion[153], H. Evans[62],

A. Ezhilov[123], F. Fabbri[22a,22b], L. Fabbri[22a,22b], G. Facini[33], R. M. Fakhrutdinov[130], S. Falciano[132a], R. J. Falla[79], J. Faltova[129], Y. Fang[35a], M. Fanti[92a,92b], A. Farbin[8], A. Farilla[134a], C. Farina[125], E. M. Farina[121a,121b], T. Farooque[13], S. Farrell[16], S. M. Farrington[169], P. Farthouat[32], F. Fassi[135e], P. Fassnacht[32], D. Fassouliotis[9], M. Faucci Giannelli[78], A. Favareto[52a,52b], W. J. Fawcett[120], L. Fayard[117], O. L. Fedin[123,n], W. Fedorko[167], S. Feigl[119], L. Feligioni[86], C. Feng[35d], E. J. Feng[32], H. Feng[90], A. B. Fenyuk[130], L. Feremenga[8], P. Fernandez Martinez[166], S. Fernandez Perez[13], J. Ferrando[55], A. Ferrari[164], P. Ferrari[107], R. Ferrari[121a], D. E. Ferreira de Lima[59b], A. Ferrer[166], D. Ferrere[51], C. Ferretti[90], A. Ferretto Parodi[52a,52b], F. Fiedler[84], A. Filipčič[76], M. Filipuzzi[44], F. Filthaut[106], M. Fincke-Keeler[168], K. D. Finelli[150], M. C. N. Fiolhais[126a,126c], L. Fiorini[166], A. Firan[42], A. Fischer[2], C. Fischer[13], J. Fischer[174], W. C. Fisher[91], N. Flaschel[44], I. Fleck[141], P. Fleischmann[90], G. T. Fletcher[139], R. R. M. Fletcher[122], T. Flick[174], A. Floderus[82], L. R. Flores Castillo[61a], M. J. Flowerdew[101], G. T. Forcolin[85], A. Formica[136], A. Forti[85], A. G. Foster[19], D. Fournier[117], H. Fox[73], S. Fracchia[13], P. Francavilla[81], M. Franchini[22a,22b], D. Francis[32], L. Franconi[119], M. Franklin[58], M. Frate[162], M. Fraternali[121a,121b], D. Freeborn[79], S. M. Fressard-Batraneanu[32], F. Friedrich[46], D. Froidevaux[32], J. A. Frost[120], C. Fukunaga[156], E. Fullana Torregrosa[84], T. Fusayasu[102], J. Fuster[166], C. Gabaldon[57], O. Gabizon[174], A. Gabrielli[22a,22b], A. Gabrielli[16], G. P. Gach[40a], S. Gadatsch[32], S. Gadomski[51], G. Gagliardi[52a,52b], L. G. Gagnon[95], P. Gagnon[62], C. Galea[106], B. Galhardo[126a,126c], E. J. Gallas[120], B. J. Gallop[131], P. Gallus[128], G. Galster[38], K. K. Gan[111], J. Gao[35b,86], Y. Gao[48], Y. S. Gao[143,f], F. M. Garay Walls[48], C. García[166], J. E. García Navarro[166], M. Garcia-Sciveres[16], R. W. Gardner[33], N. Garelli[143], V. Garonne[119], A. Gascon Bravo[44], C. Gatti[49], A. Gaudiello[52a,52b], G. Gaudio[121a], B. Gaur[141], L. Gauthier[95], I. L. Gavrilenko[96], C. Gay[167], G. Gaycken[23], E. N. Gazis[10], Z. Gecse[167], C. N. P. Gee[131], Ch. Geich-Gimbel[23], M. Geisen[84], M. P. Geisler[59a], C. Gemme[52a], M. H. Genest[57], C. Geng[35b,o], S. Gentile[132a,132b], C. Gentsos[154], S. George[78], D. Gerbaudo[13], A. Gershon[153], S. Ghasemi[141], H. Ghazlane[135b], M. Ghneimat[23], B. Giacobbe[22a], S. Giagu[132a,132b], P. Giannetti[124a,124b], B. Gibbard[27], S. M. Gibson[78], M. Gignac[167], M. Gilchriese[16], T. P. S. Gillam[30], D. Gillberg[31], G. Gilles[174], D. M. Gingrich[3,d], N. Giokaris[9], M. P. Giordani[163a,163c], F. M. Giorgi[22a], F. M. Giorgi[17], P. F. Giraud[136], P. Giromini[58], D. Giugni[92a], F. Giuli[120], C. Giuliani[101], M. Giulini[59b], B. K. Gjelsten[119], S. Gkaitatzis[154], I. Gkialas[154], E. L. Gkougkousis[117], L. K. Gladilin[99], C. Glasman[83], J. Glatzer[32], P. C. F. Glaysher[48], A. Glazov[44], M. Goblirsch-Kolb[25], J. Godlewski[41], S. Goldfarb[89], T. Golling[51], D. Golubkov[130], A. Gomes[126a,126b,126d], R. Gonçalo[126a], J. Goncalves Pinto Firmino Da Costa[136], G. Gonella[50], L. Gonella[19], A. Gongadze[66], S. González de la Hoz[166], G. Gonzalez Parra[13], S. Gonzalez-Sevilla[51], L. Goossens[32], P. A. Gorbounov[97], H. A. Gordon[27], I. Gorelov[105], B. Gorini[32], E. Gorini[74a,74b], A. Gorišek[76], E. Gornicki[41], A. T. Goshaw[47], C. Gössling[45], M. I. Gostkin[66], C. R. Goudet[117], D. Goujdami[135c], A. G. Goussiou[138], N. Govender[145b,p], E. Gozani[152], L. Graber[56], I. Grabowska-Bold[40a], P. O. J. Gradin[57], P. Grafström[22a,22b], J. Gramling[51], E. Gramstad[119], S. Grancagnolo[17], V. Gratchev[123], P. M. Gravila[28e], H. M. Gray[32], E. Graziani[134a], Z. D. Greenwood[80,q], C. Grefe[23], K. Gregersen[79], I. M. Gregor[44], P. Grenier[143], K. Grevtsov[5], J. Griffiths[8], A. A. Grillo[137], K. Grimm[73], S. Grinstein[13,r], Ph. Gris[36], J.-F. Grivaz[117], S. Groh[84], J. P. Grohs[46], E. Gross[171], J. Grosse-Knetter[56], G. C. Grossi[80], Z. J. Grout[149], L. Guan[90], W. Guan[172], J. Guenther[63], F. Guescini[51], D. Guest[162], O. Gueta[153], E. Guido[52a,52b], T. Guillemin[5], S. Guindon[2], U. Gul[55], C. Gumpert[32], J. Guo[35e], Y. Guo[35b,o], R. Gupta[42], S. Gupta[120], G. Gustavino[132a,132b], P. Gutierrez[113], N. G. Gutierrez Ortiz[79], C. Gutschow[46], C. Guyot[136], C. Gwenlan[120], C. B. Gwilliam[75], A. Haas[110], C. Haber[16], H. K. Hadavand[8], N. Haddad[135e], A. Hadef[86], P. Haefner[23], S. Hageböck[23], Z. Hajduk[41], H. Hakobyan[176,*], M. Haleem[44], J. Haley[114], G. Halladjian[91], G. D. Hallewell[86], K. Hamacher[174], P. Hamal[115], K. Hamano[168], A. Hamilton[145a], G. N. Hamity[139], P. G. Hamnett[44], L. Han[35b], K. Hanagaki[67,s], K. Hanawa[155], M. Hance[137], B. Haney[122], S. Hanisch[32], P. Hanke[59a], R. Hanna[136], J. B. Hansen[38], J. D. Hansen[38], M. C. Hansen[23], P. H. Hansen[38], K. Hara[160], A. S. Hard[172], T. Harenberg[174], F. Hariri[117], S. Harkusha[93], R. D. Harrington[48], P. F. Harrison[169], F. Hartjes[107], N. M. Hartmann[100], M. Hasegawa[68], Y. Hasegawa[140], A. Hasib[113], S. Hassani[136], S. Haug[18], R. Hauser[91], L. Hauswald[46], M. Havranek[127], C. M. Hawkes[19], R. J. Hawkings[32], D. Hayden[91], C. P. Hays[120], J. M. Hays[77], H. S. Hayward[75], S. J. Haywood[131], S. J. Head[19], T. Heck[84], V. Hedberg[82], L. Heelan[8], S. Heim[122], T. Heim[16], B. Heinemann[16], J. J. Heinrich[100], L. Heinrich[110], C. Heinz[54], J. Hejbal[127], L. Helary[24], S. Hellman[146a,146b], C. Helsens[32], J. Henderson[120], R. C. W. Henderson[73], Y. Heng[172], S. Henkelmann[167], A. M. Henriques Correia[32], S. Henrot-Versille[117], G. H. Herbert[17], Y. Hernández Jiménez[166], G. Herten[50], R. Hertenberger[100], L. Hervas[32], G. G. Hesketh[79], N. P. Hessey[107], J. W. Hetherly[42], R. Hickling[77], E. Higón-Rodriguez[166], E. Hill[168], J. C. Hill[30], K. H. Hiller[44], S. J. Hillier[19], I. Hinchliffe[16], E. Hines[122], R. R. Hinman[16], M. Hirose[50], D. Hirschbuehl[174], J. Hobbs[148], N. Hod[159a], M. C. Hodgkinson[139], P. Hodgson[139], A. Hoecker[32], M. R. Hoeferkamp[105], F. Hoenig[100], D. Hohn[23], T. R. Holmes[16], M. Homann[45], T. M. Hong[125], B. H. Hooberman[165], W. H. Hopkins[116], Y. Horii[103], A. J. Horton[142], J-Y. Hostachy[57], S. Hou[151], A. Hoummada[135a], J. Howarth[44], M. Hrabovsky[115], I. Hristova[17], J. Hrivnac[117], T. Hryn'ova[5], A. Hrynevich[94], C. Hsu[145c], P. J. Hsu[151,t], S.-C. Hsu[138], D. Hu[37], Q. Hu[35b], Y. Huang[44], Z. Hubacek[128], F. Hubaut[86], F. Huegging[23], T. B. Huffman[120], E. W. Hughes[37], G. Hughes[73], M. Huhtinen[32], P. Huo[148], N. Huseynov[66,b], J. Huston[91], J. Huth[58], G. Iacobucci[51],

G. Iakovidis[27], I. Ibragimov[141], L. Iconomidou-Fayard[117], E. Ideal[175], Z. Idrissi[135e], P. Iengo[32], O. Igonkina[107,u], T. Iizawa[170], Y. Ikegami[67], M. Ikeno[67], Y. Ilchenko[11,v], D. Iliadis[154], N. Ilic[143], T. Ince[101], G. Introzzi[121a,121b], P. Ioannou[9,*], M. Iodice[134a], K. Iordanidou[37], V. Ippolito[58], N. Ishijima[118], M. Ishino[69], M. Ishitsuka[157], R. Ishmukhametov[111], C. Issever[120], S. Istin[20a], F. Ito[160], J. M. Iturbe Ponce[85], R. Iuppa[133a,133b], W. Iwanski[41], H. Iwasaki[67], J. M. Izen[43], V. Izzo[104a], S. Jabbar[3], B. Jackson[122], M. Jackson[75], P. Jackson[1], V. Jain[2], K. B. Jakobi[84], K. Jakobs[50], S. Jakobsen[32], T. Jakoubek[127], D. O. Jamin[114], D. K. Jana[80], E. Jansen[79], R. Jansky[63], J. Janssen[23], M. Janus[56], G. Jarlskog[82], N. Javadov[66,b], T. Javůrek[50], F. Jeanneau[136], L. Jeanty[16], J. Jejelava[53a,w], G.-Y. Jeng[150], D. Jennens[89], P. Jenni[50,x], J. Jentzsch[45], C. Jeske[169], S. Jézéquel[5], H. Ji[172], J. Jia[148], H. Jiang[65], Y. Jiang[35b], S. Jiggins[79], J. Jimenez Pena[166], S. Jin[35a], A. Jinaru[28b], O. Jinnouchi[157], P. Johansson[139], K. A. Johns[7], W. J. Johnson[138], K. Jon-And[146a,146b], G. Jones[169], R. W. L. Jones[73], S. Jones[7], T. J. Jones[75], J. Jongmanns[59a], P. M. Jorge[126a,126b], J. Jovicevic[159a], X. Ju[172], A. Juste Rozas[13,r], M. K. Köhler[171], A. Kaczmarska[41], M. Kado[117], H. Kagan[111], M. Kagan[143], S. J. Kahn[86], E. Kajomovitz[47], C. W. Kalderon[120], A. Kaluza[84], S. Kama[42], A. Kamenshchikov[130], N. Kanaya[155], S. Kaneti[30], L. Kanjir[76], V. A. Kantserov[98], J. Kanzaki[67], B. Kaplan[110], L. S. Kaplan[172], A. Kapliy[33], D. Kar[145c], K. Karakostas[10], A. Karamaoun[3], N. Karastathis[10], M. J. Kareem[56], E. Karentzos[10], M. Karnevskiy[84], S. N. Karpov[66], Z. M. Karpova[66], K. Karthik[110], V. Kartvelishvili[73], A. N. Karyukhin[130], K. Kasahara[160], L. Kashif[172], R. D. Kass[111], A. Kastanas[15], Y. Kataoka[155], C. Kato[155], A. Katre[51], J. Katzy[44], K. Kawagoe[71], T. Kawamoto[155], G. Kawamura[56], S. Kazama[155], V. F. Kazanin[109,c], R. Keeler[168], R. Kehoe[42], J. S. Keller[44], J. J. Kempster[78], K Kentaro[103], H. Keoshkerian[158], O. Kepka[127], B. P. Kerševan[76], S. Kersten[174], R. A. Keyes[88], M. Khader[165], F. Khalil-zada[12], A. Khanov[114], A. G. Kharlamov[109,c], T. J. Khoo[51], V. Khovanskiy[97], E. Khramov[66], J. Khubua[53b,y], S. Kido[68], H. Y. Kim[8], S. H. Kim[160], Y. K. Kim[33], N. Kimura[154], O. M. Kind[17], B. T. King[75], M. King[166], S. B. King[167], J. Kirk[131], A. E. Kiryunin[101], T. Kishimoto[68], D. Kisielewska[40a], F. Kiss[50], K. Kiuchi[160], O. Kivernyk[136], E. Kladiva[144b], M. H. Klein[37], M. Klein[75], U. Klein[75], K. Kleinknecht[84], P. Klimek[108], A. Klimentov[27], R. Klingenberg[45], J. A. Klinger[139], T. Klioutchnikova[32], E.-E. Kluge[59a], P. Kluit[107], S. Kluth[101], J. Knapik[41], E. Kneringer[63], E. B. F. G. Knoops[86], A. Knue[55], A. Kobayashi[155], D. Kobayashi[157], T. Kobayashi[155], M. Kobel[46], M. Kocian[143], P. Kodys[129], T. Koffas[31], E. Koffeman[107], T. Koi[143], H. Kolanoski[17], M. Kolb[59b], I. Koletsou[5], A. A. Komar[96,*], Y. Komori[155], T. Kondo[67], N. Kondrashova[44], K. Köneke[50], A. C. König[106], T. Kono[67,z], R. Konoplich[110,aa], N. Konstantinidis[79], R. Kopeliansky[62], S. Koperny[40a], L. Köpke[84], A. K. Kopp[50], K. Korcyl[41], K. Kordas[154], A. Korn[79], A. A. Korol[109,c], I. Korolkov[13], E. V. Korolkova[139], O. Kortner[101], S. Kortner[101], T. Kosek[129], V. V. Kostyukhin[23], A. Kotwal[47], A. Kourkoumeli-Charalampidi[154], C. Kourkoumelis[9], V. Kouskoura[27], A. B. Kowalewska[41], R. Kowalewski[168], T. Z. Kowalski[40a], C. Kozakai[155], W. Kozanecki[136], A. S. Kozhin[130], V. A. Kramarenko[99], G. Kramberger[76], D. Krasnopevtsev[98], M. W. Krasny[81], A. Krasznahorkay[32], J. K. Kraus[23], A. Kravchenko[27], M. 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Longo[74a,74b], K. A. Looper[111], L. Lopes[126a], D. Lopez Mateos[58],

B. Lopez Paredes[139], I. Lopez Paz[13], A. Lopez Solis[81], J. Lorenz[100], N. Lorenzo Martinez[62], M. Losada[21], P. J. Lösel[100], X. Lou[35a], A. Lounis[117], J. Love[6], P. A. Love[73], H. Lu[61a], N. Lu[90], H. J. Lubatti[138], C. Luci[132a,132b], A. Lucotte[57], C. Luedtke[50], F. Luehring[62], W. Lukas[63], L. Luminari[132a], O. Lundberg[146a,146b], B. Lund-Jensen[147], P. M. Luzi[81], D. Lynn[27], R. Lysak[127], E. Lytken[82], V. Lyubushkin[66], H. Ma[27], L. L. Ma[35d], Y. Ma[35d], G. Maccarrone[49], A. Macchiolo[101], C. M. Macdonald[139], B. Maček[76], J. Machado Miguens[122,126b], D. Madaffari[86], R. Madar[36], H. J. Maddocks[164], W. F. Mader[46], A. Madsen[44], J. Maeda[68], S. Maeland[15], T. Maeno[27], A. Maevskiy[99], E. Magradze[56], J. Mahlstedt[107], C. Maiani[117], C. Maidantchik[26a], A. A. Maier[101], T. Maier[100], A. Maio[126a,126b,126d], S. Majewski[116], Y. Makida[67], N. Makovec[117], B. Malaescu[81], Pa. Malecki[41], gnmV. P. Maleev[123], F. 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Mikuž[76], M. Milesi[89], A. Milic[63], D. W. Miller[33], C. Mills[48], A. Milov[171], D. A. Milstead[146a,146b], A. A. Minaenko[130], Y. Minami[155], I. A. Minashvili[66], A. I. Mincer[110], B. Mindur[40a], M. Mineev[66], Y. Ming[172], L. M. Mir[13], K. P. Mistry[122], T. Mitani[170], J. Mitrevski[100], V. A. Mitsou[166], A. Miucci[51], P. S. Miyagawa[139], J. U. Mjörnmark[82], T. Moa[146a,146b], K. Mochizuki[95], S. Mohapatra[37], S. Molander[146a,146b], R. Moles-Valls[23], R. Monden[69], M. C. Mondragon[91], K. Mönig[44], J. Monk[38], E. Monnier[86], A. Montalbano[148], J. Montejo Berlingen[32], F. Monticelli[72], S. Monzani[92a,92b], R. W. Moore[3], N. Morange[117], D. Moreno[21], M. Moreno Llácer[56], P. Morettini[52a], D. Mori[142], T. Mori[155], M. Morii[58], M. Morinaga[155], V. Morisbak[119], S. Moritz[84], A. K. Morley[150], G. Mornacchi[32], J. D. Morris[77], S. S. Mortensen[38], L. Morvaj[148], M. Mosidze[53b], J. Moss[143], K. Motohashi[157], R. Mount[143], E. Mountricha[27], S. V. Mouraviev[96,*], E. J. W. Moyse[87], S. Muanza[86], R. D. Mudd[19], F. Mueller[101], J. Mueller[125], R. S. P. Mueller[100], T. Mueller[30], D. Muenstermann[73], P. Mullen[55], G. A. Mullier[18], F. J. Munoz Sanchez[85], J. A. Murillo Quijada[19], W. J. Murray[169,131], H. Musheghyan[56], M. Muškinja[76], A. G. Myagkov[130,ae], M. Myska[128], B. P. Nachman[143], O. Nackenhorst[51], K. Nagai[120], R. Nagai[67,z], K. Nagano[67], Y. Nagasaka[60], K. Nagata[160], M. Nagel[50], E. Nagy[86], A. M. Nairz[32], Y. Nakahama[32], K. Nakamura[67], T. Nakamura[155], I. Nakano[112], H. Namasivayam[43], R. F. Naranjo Garcia[44], R. Narayan[11], D. I. Narrias Villar[59a], I. Naryshkin[123], T. Naumann[44], G. Navarro[21], R. Nayyar[7], H. A. Neal[90], P. Yu. Nechaeva[96], T. J. Neep[85], P. D. Nef[143], A. Negri[121a,121b], M. Negrini[22a], S. Nektarijevic[106], C. Nellist[117], A. Nelson[162], S. Nemecek[127], P. Nemethy[110], A. A. Nepomuceno[26a], M. Nessi[32,af], M. S. Neubauer[165], M. Neumann[174], R. M. Neves[110], P. Nevski[27], P. R. Newman[19], D. H. Nguyen[6], T. Nguyen Manh[95], R. B. Nickerson[120], R. Nicolaidou[136], J. Nielsen[137], A. Nikiforov[17], V. Nikolaenko[130,ae], I. Nikolic-Audit[81], K. Nikolopoulos[19], J. K. Nilsen[119], P. Nilsson[27], Y. Ninomiya[155], A. Nisati[132a], R. Nisius[101], T. Nobe[155], M. Nomachi[118], I. Nomidis[31], T. Nooney[77], S. Norberg[113], M. Nordberg[32], N. Norjoharuddeen[120], O. Novgorodova[46], S. Nowak[101], M. Nozaki[67], L. Nozka[115], K. Ntekas[10], E. Nurse[79], F. Nuti[89], F. O'grady[7], D. C. O'Neil[142], A. A. O'Rourke[44], V. O'Shea[55], F. G. Oakham[31,d], H. Oberlack[101], T. Obermann[23], J. Ocariz[81], A. Ochi[68], I. Ochoa[37], J. P. Ochoa-Ricoux[34a], S. Oda[71], S. Odaka[67], H. Ogren[62], A. Oh[85], S. H. Oh[47], C. C. Ohm[16], H. Ohman[164], H. Oide[32], H. Okawa[160], Y. Okumura[33], T. Okuyama[67], A. Olariu[28b], L. F. Oleiro Seabra[126a], S. A. Olivares Pino[48], D. Oliveira Damazio[27], A. Olszewski[41], J. Olszowska[41], A. Onofre[126a,126e], K. Onogi[103], P. U. E. Onyisi[11,v], M. J. Oreglia[33], Y. Oren[153], D. Orestano[134a,134b], N. Orlando[61b], R. S. Orr[158], B. Osculati[52a,52b], R. Ospanov[85], G. Otero y Garzon[29], H. Otono[71], M. Ouchrif[135d], F. Ould-Saada[119], A. Ouraou[136], K. P. Oussoren[107], Q. Ouyang[35a], M. Owen[55], R. E. Owen[19], V. E. Ozcan[20a], N. Ozturk[8], K. Pachal[142], A. Pacheco Pages[13], L. Pacheco Rodriguez[136], C. Padilla Aranda[13], M. Pagáčová[50], S. Pagan Griso[16], F. Paige[27], P. Pais[87], K. Pajchel[119], G. Palacino[159b], S. Palestini[32], M. Palka[40b], D. Pallin[36], A. Palma[126a,126b], E. St. Panagiotopoulou[10], C. E. Pandini[81], J. G. Panduro Vazquez[78], P. Pani[146a,146b], S. Panitkin[27], D. Pantea[28b], L. Paolozzi[51], Th. D. Papadopoulou[10],

K. Papageorgiou[154], A. Paramonov[6], D. Paredes Hernandez[175], A. J. Parker[73], M. A. Parker[30], K. A. Parker[139], F. Parodi[52a,52b], J. A. Parsons[37], U. Parzefall[50], V. R. Pascuzzi[158], E. Pasqualucci[132a], S. Passaggio[52a], Fr. Pastore[78], G. Pásztor[31,ag], S. Pataraia[174], J. R. Pater[85], T. Pauly[32], J. Pearce[168], B. Pearson[113], L. E. Pedersen[38], M. Pedersen[119], S. Pedraza Lopez[166], R. Pedro[126a,126b], S. V. Peleganchuk[109,c], D. Pelikan[164], O. Penc[127], C. Peng[35a], H. Peng[35b], J. Penwell[62], B. S. Peralva[26b], M. M. Perego[136], D. V. Perepelitsa[27], E. Perez Codina[159a], L. Perini[92a,92b], H. Pernegger[32], S. Perrella[104a,104b], R. Peschke[44], V. D. Peshekhonov[66], K. Peters[44], R. F. Y. Peters[85], B. A. Petersen[32], T. C. Petersen[38], E. Petit[57], A. Petridis[1], C. Petridou[154], P. Petroff[117], E. Petrolo[132a], M. Petrov[120], F. Petrucci[134a,134b], N. E. Pettersson[87], A. Peyaud[136], R. Pezoa[34b], P. W. Phillips[131], G. Piacquadio[143], E. Pianori[169], A. Picazio[87], E. Piccaro[77], M. Piccinini[22a,22b], M. A. Pickering[120], R. Piegaia[29], J. E. Pilcher[33], A. D. Pilkington[85], A. W. J. Pin[85], M. Pinamonti[163a163c,ah], J. L. Pinfold[3], A. Pingel[38], S. Pires[81], H. Pirumov[44], M. Pitt[171], L. Plazak[144a], M.-A. Pleier[27], V. Pleskot[84], E. Plotnikova[66], P. Plucinski[91], D. Pluth[65], R. Poettgen[146a,146b], L. Poggioli[117], D. Pohl[23], G. Polesello[121a], A. Poley[44], A. Policicchio[39a,39b], R. Polifka[158], A. Polini[22a], C. S. Pollard[55], V. Polychronakos[27], K. Pommès[32], L. Pontecorvo[132a], B. G. Pope[91], G. A. Popeneciu[28c], D. S. Popovic[14], A. Poppleton[32], S. Pospisil[128], K. Potamianos[16], I. N. Potrap[66], C. J. Potter[30], C. T. Potter[116], G. Poulard[32], J. Poveda[32], V. Pozdnyakov[66], M. E. Pozo Astigarraga[32], P. Pralavorio[86], A. Pranko[16], S. Prell[65], D. Price[85], L. E. Price[6], M. Primavera[74a], S. Prince[88], M. Proissl[48], K. Prokofiev[61c], F. Prokoshin[34b], S. Protopopescu[27], J. Proudfoot[6], M. Przybycien[40a], D. Puddu[134a,134b], M. Purohit[27,ai], P. Puzo[117], J. Qian[90], G. Qin[55], Y. Qin[85], A. Quadt[56], W. B. Quayle[163a,163b], M. Queitsch-Maitland[85], D. Quilty[55], S. Raddum[119], V. Radeka[27], V. Radescu[59b], S. K. Radhakrishnan[148], P. Radloff[116], P. Rados[89], F. Ragusa[92a,92b], G. Rahal[177], J. A. Raine[85], S. Rajagopalan[27], M. Rammensee[32], C. Rangel-Smith[164], M. G. Ratti[92a,92b], F. Rauscher[100], S. Rave[84], T. Ravenscroft[55], I. Ravinovich[171], M. Raymond[32], A. L. Read[119], N. P. Readioff[75], M. Reale[74a,74b], D. M. Rebuzzi[121a,121b], A. Redelbach[173], G. Redlinger[27], R. Reece[137], K. Reeves[43], L. Rehnisch[17], J. Reichert[122], H. Reisin[29], C. Rembser[32], H. Ren[35a], M. Rescigno[132a], S. Resconi[92a], O. L. Rezanova[109,c], P. Reznicek[129], R. Rezvani[95], R. Richter[101], S. Richter[79], E. Richter-Was[40b], O. Ricken[23], M. Ridel[81], P. Rieck[17], C. J. Riegel[174], J. Rieger[56], O. Rifki[113], M. Rijssenbeek[148], A. Rimoldi[121a,121b], M. Rimoldi[18], L. Rinaldi[22a], B. Ristić[51], E. Ritsch[32], I. Riu[13], F. Rizatdinova[114], E. Rizvi[77], C. Rizzi[13], S. H. Robertson[88,l], A. Robichaud-Veronneau[88], D. Robinson[30], J. E. M. Robinson[44], A. Robson[55], C. Roda[124a,124b], Y. Rodina[86], A. Rodriguez Perez[13], D. Rodriguez Rodriguez[166], S. Roe[32], C. S. Rogan[58], O. Røhne[119], A. Romaniouk[98], M. Romano[22a,22b], S. M. Romano Saez[36], E. Romero Adam[166], N. Rompotis[138], M. Ronzani[50], L. Roos[81], E. Ros[166], S. Rosati[132a], K. Rosbach[50], P. Rose[137], O. Rosenthal[141], N.-A. Rosien[56], V. Rossetti[146a,146b], E. Rossi[104a,104b], L. P. Rossi[52a], J. H. N. Rosten[30], R. Rosten[138], M. Rotaru[28b], I. Roth[171], J. Rothberg[138], D. Rousseau[117], C. R. Royon[136], A. Rozanov[86], Y. Rozen[152], X. Ruan[145c], F. Rubbo[143], M. S. Rudolph[158], F. Rühr[50], A. Ruiz-Martinez[31], Z. Rurikova[50], N. A. Rusakovich[66], A. Ruschke[100], H. L. Russell[138], J. P. Rutherfoord[7], N. Ruthmann[32], Y. F. Ryabov[123], M. Rybar[165], G. Rybkin[117], S. Ryu[6], A. Ryzhov[130], G. F. Rzehorz[56], A. F. Saavedra[150], G. Sabato[107], S. Sacerdoti[29], H. F-W. Sadrozinski[137], R. Sadykov[66], F. Safai Tehrani[132a], P. Saha[108], M. Sahinsoy[59a], M. Saimpert[136], T. Saito[155], H. Sakamoto[155], Y. Sakurai[170], G. Salamanna[134a,134b], A. Salamon[133a,133b], J. E. Salazar Loyola[34b], D. Salek[107], P. H. Sales De Bruin[138], D. Salihagic[101], A. Salnikov[143], J. Salt[166], D. Salvatore[39a,39b], F. Salvatore[149], A. Salvucci[61a], A. Salzburger[32], D. Sammel[50], D. Sampsonidis[154], A. Sanchez[104a,104b], J. Sánchez[166], V. Sanchez Martinez[166], H. Sandaker[119], R. L. Sandbach[77], H. G. Sander[84], M. Sandhoff[174], C. Sandoval[21], R. Sandstroem[101], D. P. C. Sankey[131], M. Sannino[52a,52b], A. Sansoni[49], C. Santoni[36], R. 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Tyndel[131], G. Ucchielli[22a,22b], I. Ueda[155], M. Ughetto[146a,146b], F. Ukegawa[160], G. Unal[32], A. Undrus[27], G. Unel[162], F. C. Ungaro[89], Y. Unno[67], C. Unverdorben[100], J. Urban[144b], P. Urquijo[89], P. Urrejola[84], G. Usai[8], A. Usanova[63], L. Vacavant[86], V. Vacek[128], B. Vachon[88], C. Valderanis[100], E. Valdes Santurio[146a,146b], N. Valencic[107], S. Valentinetti[22a,22b], A. Valero[166], L. Valery[13], S. Valkar[129], S. Vallecorsa[51], J. A. Valls Ferrer[166], W. Van Den Wollenberg[107], P. C. Van Der Deijl[107], R. van der Geer[107], H. van der Graaf[107], N. van Eldik[152], P. van Gemmeren[6], J. Van Nieuwkoop[142], I. van Vulpen[107], M. C. van Woerden[32], M. Vanadia[132a,132b], W. Vandelli[32], R. Vanguri[122], A. Vaniachine[130], P. Vankov[107], G. Vardanyan[176], R. Vari[132a], E. W. Varnes[7], T. Varol[42], D. Varouchas[81], A. Vartapetian[8], K. E. Varvell[150], J. G. Vasquez[175], F. Vazeille[36], T. Vazquez Schroeder[88], J. Veatch[56], L. M. Veloce[158], F. Veloso[126a,126c], S. Veneziano[132a], A. Ventura[74a,74b], M. Venturi[168], N. Venturi[158], A. Venturini[25], V. Vercesi[121a], M. Verducci[132a,132b], W. Verkerke[107], J. C. Vermeulen[107], A. Vest[46,aq], M. C. Vetterli[142,d], O. Viazlo[82], I. Vichou[165], T. Vickey[139], O. E. Vickey Boeriu[139], G. H. A. Viehhauser[120], S. Viel[16], L. Vigani[120], R. Vigne[63], M. Villa[22a,22b], M. Villaplana Perez[92a,92b], E. Vilucchi[49], M. G. Vincter[31], V. B. Vinogradov[66], C. Vittori[22a,22b], I. Vivarelli[149], S. Vlachos[10], M. Vlasak[128], M. Vogel[174], P. Vokac[128], G. Volpi[124a,124b], M. Volpi[89], H. von der Schmitt[101], E. von Toerne[23], V. Vorobel[129], K. Vorobev[98], M. Vos[166], R. Voss[32], J. H. Vossebeld[75], N. Vranjes[14], M. Vranjes Milosavljevic[14], V. Vrba[127], M. Vreeswijk[107], R. Vuillermet[32], I. Vukotic[33], Z. Vykydal[128], P. Wagner[23], W. Wagner[174], H. Wahlberg[72], S. Wahrmund[46], J. Wakabayashi[103], J. Walder[73], R. Walker[100], W. Walkowiak[141], V. Wallangen[146a,146b], C. Wang[35c], C. Wang[35d,86],

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