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Measurement of exclusive pion pair production in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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Abstract The exclusive production of pion pairs in the process $pp \to pp\pi^+\pi^-$ has been measured at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC, using $80\,\mu\text{b}^{-1}$ of low-luminosity data. The pion pairs were detected in the ATLAS central detector while outgoing protons were measured in the forward ATLAS ALFA detector system. This represents the first use of proton tagging to measure an exclusive hadronic final state at the LHC. A cross-section measurement is performed in two kinematic regions defined by the proton momenta, the pion rapidities and transverse momenta, and the pion–pion invariant mass. Cross-section values of 4.8 ± 1.0 (stat) $^{+0.3}_{-0.2}$ (syst) μb and 9 ± 6 (stat) $^{+2}_{-2}$ (syst) μb are obtained in the two regions; they are compared with theoretical models and provide a demonstration of the feasibility of measurements of this type.

Contents

1 Introduction

A significant fraction of LHC proton–proton (pp) collisions are either elastic ($\approx$ 25%) or diffractive ($\approx$ 20% of the remaining inelastic collisions [1]). In many of these collisions the momentum transferred from the beam protons is too small ($<$ 1 GeV) for perturbative quantum chromodynamics (QCD) to be applicable, and instead Regge theory [2,3] is used. This involves the exchange of a non-perturbative Pomeron, a soft colour-singlet object originally introduced to keep the universality of the s-dependence of high energy total cross sections by Gribov [4], Chew and Frautschi [5] and later providing an explanation of the rise of hadronic collision cross-sections with increasing beam energy energy [6]. Since QCD is assumed to be universally valid, there should nevertheless be a 'mapping' between Regge theory and QCD in which the exchanged Pomeron is equivalent to the exchange of quarks and gluons, the fundamental quanta of QCD. In certain kinematic regions, the Pomeron can be treated approximately as a two-gluon colour-singlet state. Exclusive diffractive processes provide a clean environment to study the interactions of Pomerons, via the observation of final states involving only several hadrons and no beam-remnants except the outgoing protons.

This paper presents first measurements of the exclusive double-diffractive production of charged-pion pairs in the process $pp \to pp\pi^+\pi^-$, schematically shown in Fig. 1, using the ATLAS detector at the LHC.

The charged pions are measured with the ATLAS inner detector [7], while the outgoing protons are measured by the ALFA detector [8], comprising two tracking stations situated in the forward regions on either side of ATLAS at distances of approximately 240 m from the ATLAS interaction point (IP). The ALFA detector system was designed in the first place to determine the total pp cross section at LHC energies, as well as to measure the LHC luminosity via small-angle proton-scattering processes [9]. The use of the ALFA detectors is a distinctive feature of the present study, since the outgoing protons are directly measured, suppressing con-

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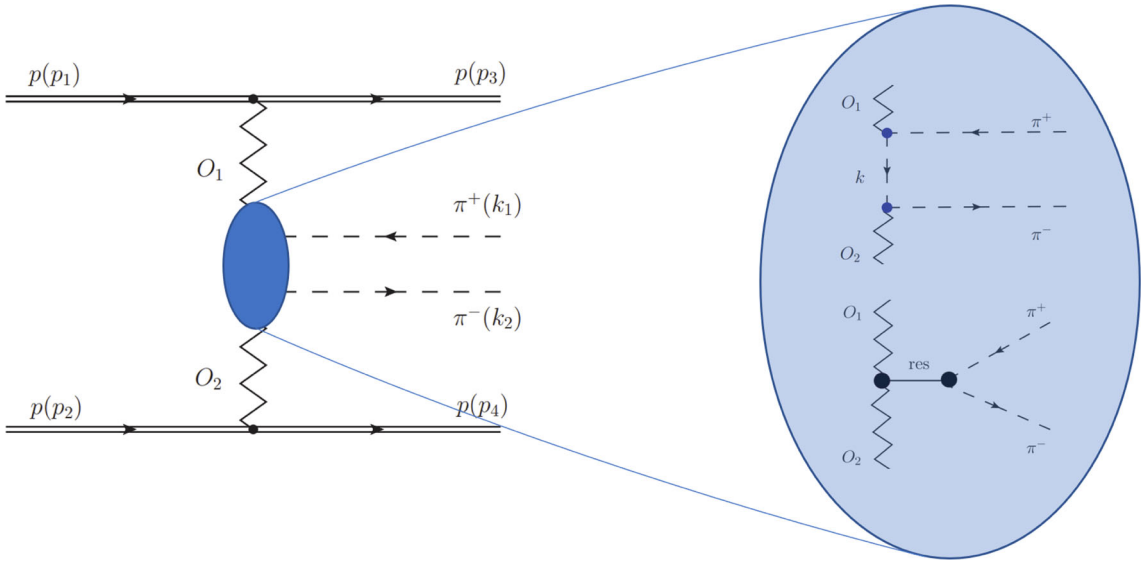


Fig. 1 A schematic Feynman diagram (left) describing the process of interest, in which two protons p with momenta p_1, p_2 interact to give a pion pair $\pi^+\pi^-$ with momenta k_1, k_2 accompanied by two outgoing protons with momenta p_3, p_4. The exchanged virtual objects O_1 and O_2 are not necessarily of the same type, but may be typified as Reggeons (e.g. the Pomeron) and must have all hadronic quantum numbers equal to zero. Two of the simplest examples of possible production mechanisms are shown in the bubble (right) – the upper one belonging to so-called continuum contributions and the lower one to resonance contributions

tamination from the remnants of excited scattered protons. The analysis benefits from procedures developed previously in the ALFA total cross section measurement [9].

The present results can be compared with existing measurements of the exclusive production of pion pairs using data from the ISR [10,11], SPS [12], RHIC [13] and LHC [14,15], where the CMS results [14,15] are not based on purely exclusive events but on a mixture of exclusive and semi-exclusive processes. Some recent theory predictions for the process considered here may be found in Refs. [16–26]. In addition to revealing general properties of Pomerons, these channels provide a rich potential harvest for a variety of final states, including the production of resonances and the possible production of the long-sought glueball states.

2 Experimental apparatus

ATLAS is a multipurpose apparatus covering almost the entire solid angle around its LHC interaction point (IP) [7].[1] The present analysis combines information from the ATLAS inner detector, the minimum-bias trigger scintillators, and the ALFA detector system.

The ATLAS inner detector (ID) [7,27] immediately surrounds the ATLAS IP and is composed of three tracker subsystems that provide high-precision track reconstruction: a silicon pixel detector (innermost), a silicon semiconductor tracker (SCT), and a transition-radiation tracker (outermost), which also helps to discriminate electrons from hadrons. The ID covers a range of $|\eta| < 2.5$. It is surrounded by a superconducting solenoid, which produces a 2 T axial field within the ID volume.

The minimum-bias trigger scintillators (MBTS) [28] are located on either side of ATLAS between the ID and the liquid-argon calorimeter at ± 3.6 m from the IP. Each of the two MBTS detectors is oriented perpendicularly to the beam direction and consists of 16 panels assembled in two concentric rings, the outer ring covering the range $2.1 < |\eta| < 2.8$ and the inner ring covering the range $2.8 < |\eta| < 3.8$.

The ALFA detector system [8], located at $z \approx \pm 240$ m, consists of four Roman pot stations, containing vertically movable detectors that can approach the outgoing beams to within one millimetre. A schematic diagram of the detector arrangement relative to the ATLAS IP is shown in Fig. 2.

Each station is equipped with two Roman pots, each of which hosts a nearly edgeless tracking detector composed of scintillating fibres, as depicted in Fig. 3.

The ALFA detector system has a limited radiation tolerance and takes data under conditions with low numbers (μ) of

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

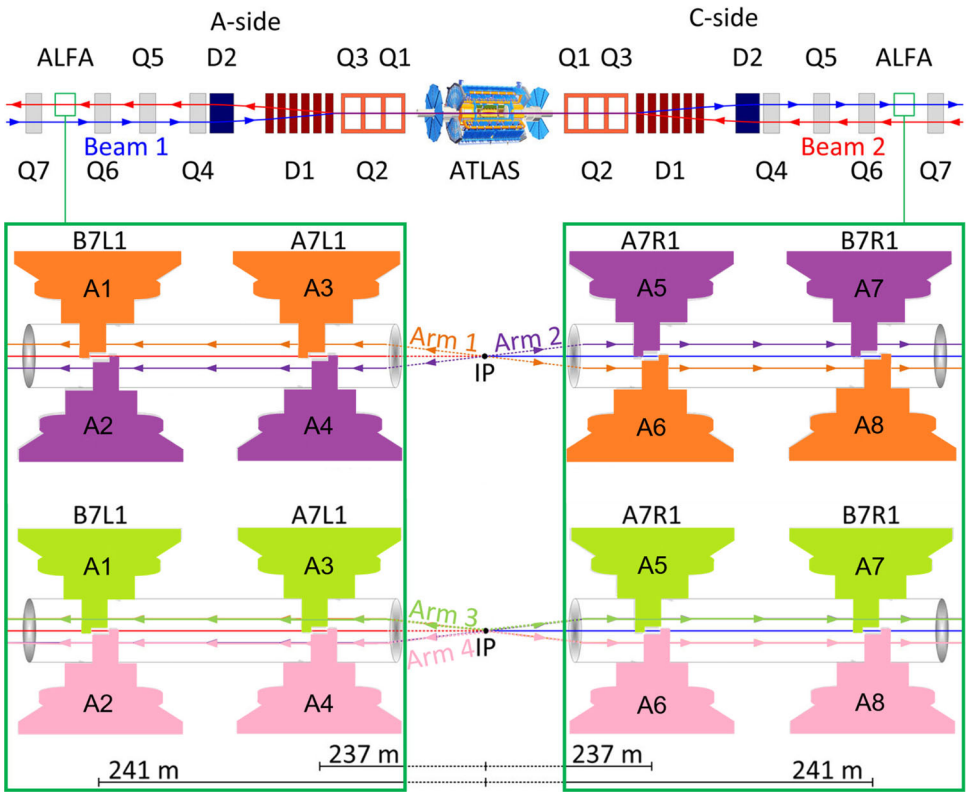


Fig. 2 A schematic depiction of the arrangement of ALFA in ATLAS, indicating the naming and numbering conventions used [8]. The upper part of the diagram gives a plan view that shows the dipole (D) and quadrupole (Q) magnets on either side of ATLAS whose settings are relevant for the beam optics. The proton beams that circulate anticlockwise and clockwise are depicted in this view, emerging into the A and C sides, respectively. The lower diagrams give side views that show the ALFA detector combinations (arms) used for the elastic measurement (Arm 1, orange, and Arm 2, purple) and the anti-elastic measurement (Arm 3, green, and Arm 4, pink). Each arm comprises two sections (armlets), consisting of two upper or lower detectors on a single side. The ALFA stations are numbered from A1 to A8 together with a more detailed designation. In these views the vertically deflected protons entering the different arms are indicated

simultaneous proton–proton collisions interactions per beam crossing (pile-up).

An extensive software suite [29] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Monte Carlo generators

The analysis makes use of two Monte Carlo (MC) signal generators: GenEx [30] and Dime [25].[2] The models are similar, but not identical, and provide different predictions. The GenEx generator is used for the baseline calculations of detection and reconstruction efficiency for the events, and for corrections to the data, while Dime is used for comparison and to estimate model uncertainties.

[2] Some other generators, also suitable for modelling the considered process, became available later, e.g. ExDiff [31] and SuperChic [32].

The generator GenEx (version May 2015) is based on a theoretical model from Lebiedowicz et al. [24] and calculates the exclusive continuum production of $\pi^+\pi^-$ and K^+K^- pairs. It is based on a Regge-exchange description. The parameter determining the meson form factor (in its exponential parameterization) is the only free parameter. The implemented model describes non-resonant production without an absorption correction and does not include a rapidity gap survival factor (see e.g. Ref. [33]). In the present analysis, pions were generated within a region of pseudorapidity $|\eta| < 2.7$, and with the off-shell-pion form-factor parameter set to $\Lambda_{\text{off}} = 1\,\text{GeV}$. Otherwise, default program settings were used.

The generator Dime (version 1.06) similarly generates exclusive continuum production of $\pi^+\pi^-$ and K^+K^- pairs, although other channels are also implemented, e.g. exclusive $\rho\rho$ or $\phi\phi$ production. Unlike GenEx, Dime includes wider possibilities for modelling absorption effects: four different models (parameter iin, 1 – the default value used in our analysis; see Table 12 in Ref. [34]) for absorption are available

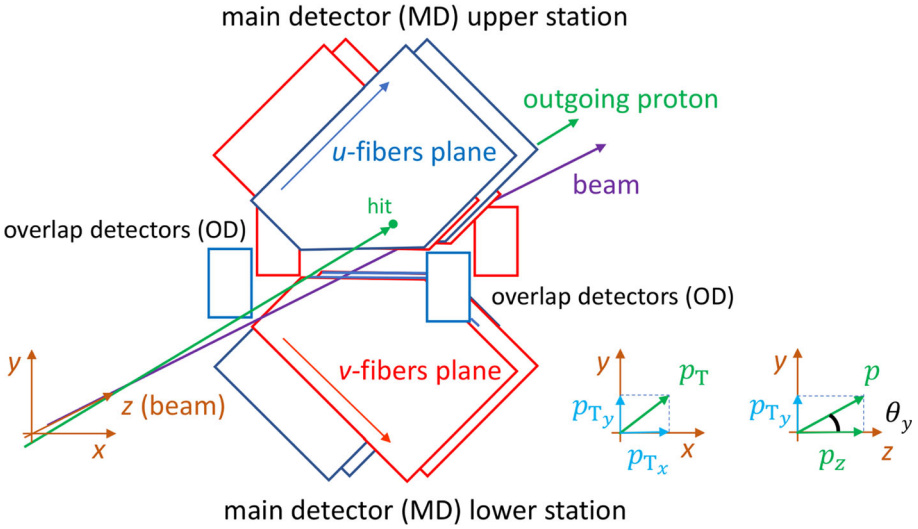


Fig. 3 A schematic drawing of the ALFA detectors in one station, here A5+A6 in Fig. 2. Each of the main detectors is made of ten u and ten v fibre layers; for more details see Ref. [8]. Only the first and last layers are drawn. For the overlap detectors, serving for the mutual positioning of the upper and lower detectors, only one of the three planes is drawn. The trigger planes are not drawn. The local coordinate system, relative to the beamline, is indicated together with the projections of the leading outgoing proton momentum p and the angle θ_y; the angle θ_x is defined similarly

with three different parameterizations of the meson form factor (exponential, 'Orear-like' – used in the present analysis, and power-like) [25].

The central diffractive background processes were generated by PYTHIA8 [35] (version 8.183), using the ATLAS A2 set of tuned parameters [36] and the MSTW2008LO PDF set [37]. PYTHIA8 employs a parton structure function approach and calculates the processes of central diffraction via double Pomeron exchange (DPE). The exclusive pion-pair process is removed from the dataset.

The GEANT4 [38] toolkit is implemented to simulate the response of the ATLAS central and forward detectors [39]. The leading outgoing protons are transported to the ALFA locations using the beam parameter values and ALFA detector positions corresponding to the data-taking period [9] in which a special high-beta* optics, referred to here as the nominal optics, was employed. The MC events were reconstructed using the same ATLAS software chain as used for the data.

4 Data taking

The data were recorded in October 2011 during a special four-hour run with high $\beta^\star = 90$ m and very low pile-up given by $\mu = 0.035$. Each beam of the LHC was filled with one circulating proton bunch containing $7{\cdot}10^{10}$ protons. The integrated delivered luminosity and its uncertainty were determined to be $L_{\text{int}} = 78.7 \pm 0.1(\text{stat}) \pm 1.9\ (\text{syst})\ \mu\text{b}^{-1}$ [9].

Two event topological configurations are used in this analysis, covering four regions of phase space. They are referred to as elastic and anti-elastic and are based on signals in different combinations of four ALFA detectors, as shown in Fig. 2. Each detector combination is designated as an arm (following the existing ALFA notation [9]), and includes detectors on side A and side C in order to measure forward protons on each side of ATLAS. The elastic configuration makes use of two arm combinations: Arm1 = arm_{1368} = A1+A3+A6+A8 (elastic arm 0) and Arm2 = arm_{2457} = A2+A4+A5+A7 (elastic arm 1), while the anti-elastic configuration uses Arm3 = arm_{1357} = A1+A3+A5+A7 (anti-elastic arm 0) and Arm4 = arm_{2468} = A2+A4+A6+A8 (anti-elastic arm 1). Each arm comprises two armlets, consisting of two ALFA stations on either the A side or C side of ATLAS. The two configurations measure different ranges of momentum transfer to the pion system and their events were recorded by different combinations of triggers during data taking. They correspond physically to different kinematic phase-space regions, and theoretical models can differ in their estimates of cross-sections.

5 Data analysis

5.1 Event selection

The event topology for exclusive pion-pair production consists of two oppositely charged pions detected by the ATLAS ID, accompanied by a leading outgoing proton entering each of the ATLAS forward regions and detected by the ALFA

Table 1 List of applied selections

Selection
Bunch selection
Lumi blocks selection
Trigger configuration
Pions:
Number of tracks
Primary vertex
ID track quality
MBTS veto
Protons:
ALFA track quality
ALFA *uv*-condition
ALFA clean track
ALFA geometry condition
Full system momentum balance in p_x and p_y
Fiducial region

Table 2 Data statistics for the two configurations after the successive selection conditions. Definitions of 'arm 0' and 'arm 1' (elastic and anti-elastic) are given in Sect. 4

Selection	Configuration	
	Elastic	Anti-elastic
Recorded ATLAS events	6 620 953	
Data quality and trigger preselections	1 106 855	397 683
ID selection (pion pair)	1 520	1 115
ALFA track selection (incl. clean track and *uv*-condition)	486	11
MBTS veto	136	5
ALFA geometry condition	96	5
Full system momentum balance in x and y	30	3
Fiducial region	28	3
Total selected (arm 0 + arm 1)	28 (18+10)	3 (2+1)

detector system. There should be no other activity in the ATLAS ID and in the inner cells of the MBTS, and the total three-momentum of the measured protons and pions must be consistent with zero.[3] The data selections are summarized in Table 1. The order in which the selections were applied to the data is given in Table 2.

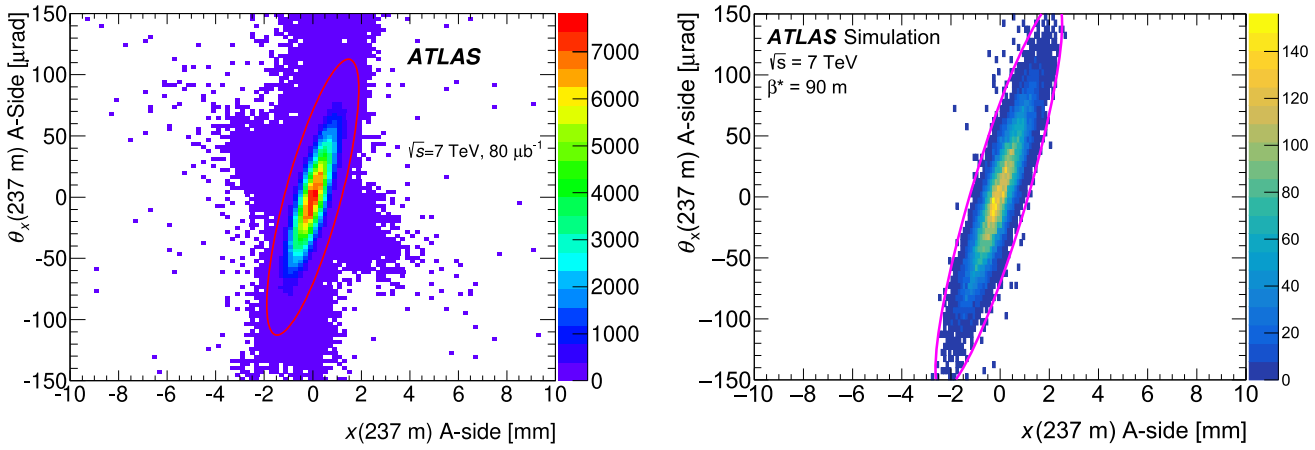
5.1.1 Description of selections

The description of the conditions that are applied to select a clean sample of $pp\pi^+\pi^-$ event candidates, as summarized in Table 1, is as follows.

- Bunch system and good lumi blocks. The data come from single colliding proton bunches in the LHC. The data-recording intervals that were used ('lumi blocks') are required to be longer than 60 s in duration and the dead time must be smaller than 5%.
- Trigger. For the elastic configuration, a coincidence in the upper A-side and lower C-side detectors or the lower A-side and upper C-side detectors was required [9] (see Fig. 2). The trigger efficiency within the geometrical acceptance of the detectors is measured to be $(99.96 \pm 0.10)\%$ [9]. For the anti-elastic configuration the relevant trigger (a signal in any of the eight ALFA detectors) was prescaled by a factor of 15, which resulted in a low numbers of recorded anti-elastic events. The trigger efficiency for each of the anti-elastic configurations is determined as the product of the measured single-diffractive trigger efficiencies on each side, leading to the value $(99.02 \pm 0.25)\%$ before prescaling.
- Pion system.
  - Charged tracks. Tracks in the ATLAS ID were reconstructed using a low-p_{T} tracking algorithm ($p_{\mathrm{T}} > 100$ MeV) as in Ref. [40], where p_{T} denotes the transverse momentum component. Each track must pass the following quality conditions:
    - Pixel detector: at least one hit is required,
    - Semiconductor tracker: a minimum number of hits in the SCT is required, depending on the track p_{T}: at least two hits for $p_{\mathrm{T}} > 100$ MeV, four hits for $p_{\mathrm{T}} > 200$ MeV and six hits for $p_{\mathrm{T}} > 300$ MeV.

    Events with at least two tracks are required. A primary vertex is required and must have exactly two accepted tracks with opposite-sign charges and small impact parameters relative to the beam axis. For the purposes of this analysis, all charged tracks are treated as pion tracks, since the numbers of electron, kaon and proton pairs are estimated to be small. The pions' transverse momenta are reconstructed [40] with an uncertainty of about 10 MeV independent of their charge.
- MBTS. To select events with no additional visible activity in the ATLAS ID, taking into consideration its limited η coverage, a MBTS veto criterion is applied: the total number of MBTS inner cells on the two ATLAS sides with a signal is required to be at most one, ignoring the outer cells. This criterion was chosen since it was robust against electronic noise in the MBTS detector.
- Proton system.

[3] The precise expectation value depends on the beam-crossing angle, which varied during the data taking and was at most 10 μ rad in the y projection and smaller in x. The full effect is safely ignored since its impact is less than those of the ALFA detector resolution.



(a) (b)

Fig. 4 The correlation between the reconstructed position of a proton at $|z| = 237$ m (A-side; a similar correlation is measured for the C-side) and its local angle projection on the horizontal direction. In **a** the proton candidates in elastic proton–proton data lie within the area of the indicated ellipse [9]. The ellipse shown in **b** is obtained using the selection criteria applied to the sample of exclusive pion-pair production generated by GENEX

– ALFA track reconstruction. The proton reconstruction criteria used in a previous analysis [9] – bunch group, data quality, selections on the reconstructed track and geometrical deflection, beam-screen and edge conditions (see Table 2 of Ref. [9]) – together with the detector alignment, are adopted for the current study.
– ALFA ***uv***-condition. This requirement is introduced to remove contributions from beam halo and showers (caused by interactions with material between the IP and the ALFA detectors). These contributions are absent in MC simulations. The purpose of the ALFA *uv*-condition is to differentiate between events with single particles and those with multi-particle showers entering the detectors, so as to filter out multi-particle signals, and in this way to allow good correspondence between MC simulations and real data samples.
  The *uv*-condition is based on the fibre multiplicities associated with a candidate proton. The first four *u* and first four *v* detector layers [8], closest to the IP, must satisfy the following:
  – at least two of these *u* layers, and at least two of these *v* layers, must have at least one hit, and
  – at most one *u* layer and one *v* layer may have more than three hits.
  The first condition identifies a well-measured track and is based on the estimate of the single-fibre efficiency and a requirement on the *uv*-condition efficiency. The second, allowing at most two cross-talk hits surrounding that of the signal, is based on observations made during beam tests of the ALFA detectors. It also rejects tracks that give rise to showers.
– ALFA clean track. Due to e.g. beam halo, pile-up or showers, more than one track may be reconstructed in a given ALFA detector [9], and it may not be possible to decide which of the tracks is the correct one. Therefore, only events with exactly one reconstructed track in each of the detectors that comprise an arm are considered in the present analysis, and a correction is evaluated for each of the configuration arms to compensate for the consequent loss of signal.
– ALFA geometric condition. In measuring leading protons, the ALFA detector system operates as a spectrometer in which a proton having a larger energy loss undergoes a larger deflection, corresponding to a larger x value of its track position measured in the horizontal direction in the coordinates of the ALFA station. In the case of exclusive pion-pair production, the energy loss of a leading proton is low and the expected distribution in the scatter plot of the reconstructed x-positions of the protons and corresponding local angles θ_x (see Fig. 3) should have a shape similar to that of elastically scattered protons. This is illustrated in Fig. 4 and allows a geometrical selection to be used to remove many protons not originating from the process of interest. Data and MC events were selected within the ellipse indicated in Fig. 4b, whose size is slightly larger than that from the elastically scattered protons shown in Fig. 4a. This covers the larger kinematic phase space occupied by the protons after losing energy to the pion system.

- Overall momentum balance. Because of the limited reconstruction of the proton kinematics, a selection criterion for overall four-momentum conservation is not possible; instead the momentum balance in the x and y projections is used.
  The methods used for the reconstruction of the proton kinematics from the tracks measured by the ALFA detector are based on knowledge of the accelerator optics. As the mass of the centrally produced pion-pair system is low, the 'lattice' method [9], originally used for elastically scattered protons, can be applied. Proton momentum projections p_x and p_y are used in the analysis, and are reconstructed with a resolution of about 40 MeV and 1 MeV respectively.
  The transverse momentum components of the full $pp\pi^+\pi^-$ system are determined with a resolution of approximately 60 MeV in p_x and 20 MeV in p_y, denoted by σ_x and σ_y respectively. The signal region is defined by $3.5\sigma_{x,y}$ intervals about zero in p_x and p_y.
- Fiducial condition. The exclusive production of pion pairs is studied within a fiducial region which is defined to be close to that which is allowed by the sub-detector acceptances. The data and Monte Carlo analyses use the same fiducial region, which is given in terms of the pseudorapidities $\eta(\pi)$ and transverse momenta $p_{\mathrm{T}}(\pi)$ of the individual pions, and the mass of the central pion system $m_{\pi\pi}$:

$$|\eta(\pi)| < 2.5, \;\; p_{\mathrm{T}}(\pi) > 0.1 \text{ GeV},$$
$$2m_\pi < m_{\pi\pi} < 2.0 \text{ GeV}.$$

  Additional conditions are applied to the y-components of the proton momenta $p_{\mathrm{y}}(\mathrm{A})$ and $p_{\mathrm{y}}(\mathrm{C})$, in both the elastic and anti-elastic configurations:

$$\mathrm{armlet}_{ij}^{\mathrm{low\_cut}} < p_{\mathrm{y}}(\mathrm{A}) < \mathrm{armlet}_{ij}^{\mathrm{up\_cut}} \quad \text{and}$$
$$\mathrm{armlet}_{kl}^{\mathrm{low\_cut}} < p_{\mathrm{y}}(\mathrm{C}) < \mathrm{armlet}_{kl}^{\mathrm{up\_cut}},$$

  where $ijkl \in \{1368, 2457, 1357, 2468\}$ and

$$\mathrm{armlet}_{13}^{\mathrm{up\_cut}} = 0.267 \text{ GeV}, \quad \mathrm{armlet}_{57}^{\mathrm{up\_cut}} = 0.246 \text{ GeV},$$
$$\mathrm{armlet}_{13}^{\mathrm{low\_cut}} = 0.080 \text{ GeV}, \quad \mathrm{armlet}_{57}^{\mathrm{low\_cut}} = 0.080 \text{ GeV},$$
$$\mathrm{armlet}_{24}^{\mathrm{up\_cut}} = -0.079 \text{ GeV}, \quad \mathrm{armlet}_{68}^{\mathrm{up\_cut}} = -0.082 \text{ GeV},$$
$$\mathrm{armlet}_{24}^{\mathrm{low\_cut}} = -0.250 \text{ GeV}, \quad \mathrm{armlet}_{68}^{\mathrm{low\_cut}} = -0.269 \text{ GeV}.$$

  These selections are evaluated in terms of the reconstructed ALFA proton kinematic parameters, calculated using the nominal beam optics and ALFA detector positions. The experimental uncertainties of these values translate into a systematic uncertainty that is common to the corrected data and the MC predictions.

5.1.2 Data selection statistics

The numbers of events after the successive selection conditions are shown in Table 2.

5.2 Background estimation

One source of background consists of centrally produced pion pairs that are accidentally accompanied by one or more beam-halo protons which are detected in ALFA. This background is suppressed by the event selections to a low level. This can be seen in Fig. 5, which shows (a) the total multiplicity distribution of the MBTS inner rings for events that satisfy the selection criteria listed in Table 1, except for those on MBTS and momentum balance, and (b) after all the selections in Table 1 are applied. A fit to the data is performed in terms of a model comprising generated signal events (GenEx) and backgrounds from (i) generated diffractive events (Pythia8) and (ii) an 'accidentals' event sample formed from data events with a pion pair that are combined with unrelated data events randomly found to have ALFA signals. For exclusive pion events, the MBTS multiplicity is at most one, while for other diffractive events it can be higher. Events with accidental coincidences can give both higher and lower MBTS multiplicities. Such events are contained in the event sample, but Fig. 5b shows that they contribute no contamination to the signal region $|p_a| < 3.5\sigma_a$, where $a = x, y$ (see Sect. 5.1.1), after all conditions listed in Table 1 are applied.

The very strong effect of the MBTS veto on background suppression is demonstrated also in Fig. 6, which shows that the summed vertical (y-axis) track momenta exhibit a clear signal peak in the total p_y of the event only after this veto is applied. Figure 6a includes events with selections up to those on the ID and ALFA tracks listed in Table 2, while Fig. 6b shows the same data and backgrounds but with the MBTS veto also applied. The background was fitted outside the signal region, which approximately covers the central three plotted intervals. The signal peak is now prominent.

Since the data were taken during the special run with very low pile-up, the remaining backgrounds, after applying the event selections of Sect. 5.1, presumably originate from other central diffraction processes. For both the elastic and anti-elastic event configurations, the backgrounds due to these diffraction processes are estimated using events satisfying the complete set of selections listed in Table 1 except for the requirement on the momentum balance in the x and y projections. They are evaluated from a fit to the p_y distribution of the data outside the signal region, using a model consisting of a background generated by Pythia8 and accidentals. This is shown in Fig. 7a, while Fig. 7b shows the distribution with all the selections applied.

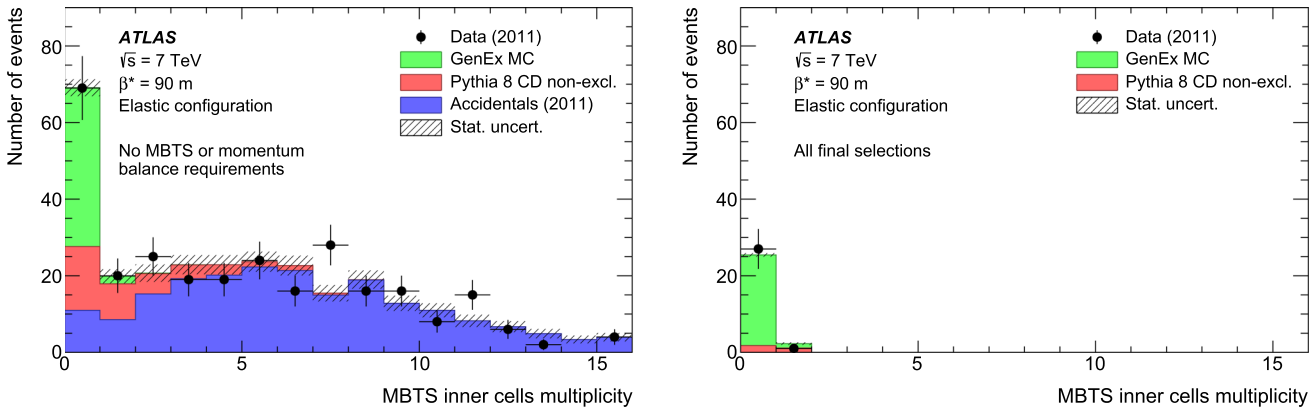


Fig. 5 Total multiplicity of the MBTS inner cells, comparing data with MC signal simulation (GenEx), MC background simulation (Pythia8 central diffraction (CD)), and accidental coincidences. In **a** the MBTS selection criteria and selections for momentum balance in the x and y projections are not applied; in **b** all the selections listed in Table 1 are applied. The MC and accidental coincidences histograms are stacked. Statistical uncertainties of MC events and accidentals are combined

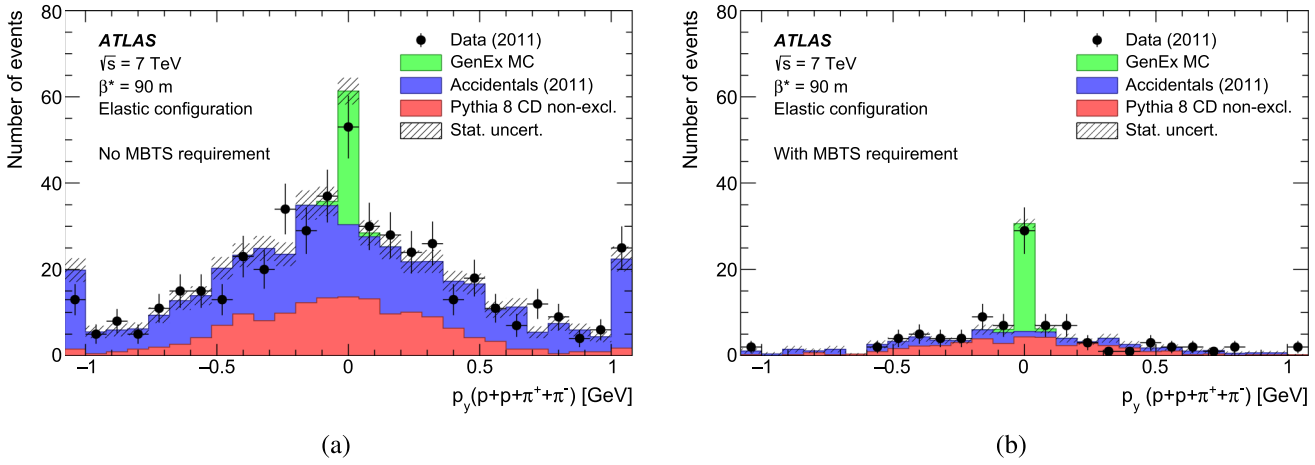


Fig. 6 The summed momentum values in p_y after the pion and proton system selection: **a** before and **b** after the MBTS veto is applied (see Table 2). The histograms of the MC predictions and the accidentals are stacked. Statistical uncertainties of MC events and accidentals are combined. The underflow and overflow bins ($|p_y| > 1$ GeV) are shown

5.3 Beam and ALFA modelling inefficiencies, correction procedure

The implementation of the ALFA detector in the ATLAS simulation framework has some limitations. The response can differ from that of the real detector, mainly due to imperfect implementation of signal and noise production mechanisms and the omission of electronic cross-talk between channels.

Since the simulation does not include the production of particle showers that are due to the interaction of forward-going particles with parts of the LHC (accelerator beam pipe, collimators, shielding of magnets, etc.), the *uv*-condition is introduced, effectively removing these showers from the data. This affects the signal, and the corresponding correction depends on the elastic or anti-elastic configuration ('conf') and the arm. A further correction is required for the clean track selection (Sect. 5.1).

If the MC description were perfect, the detector efficiency ε, for a given arm and configuration, would be written as

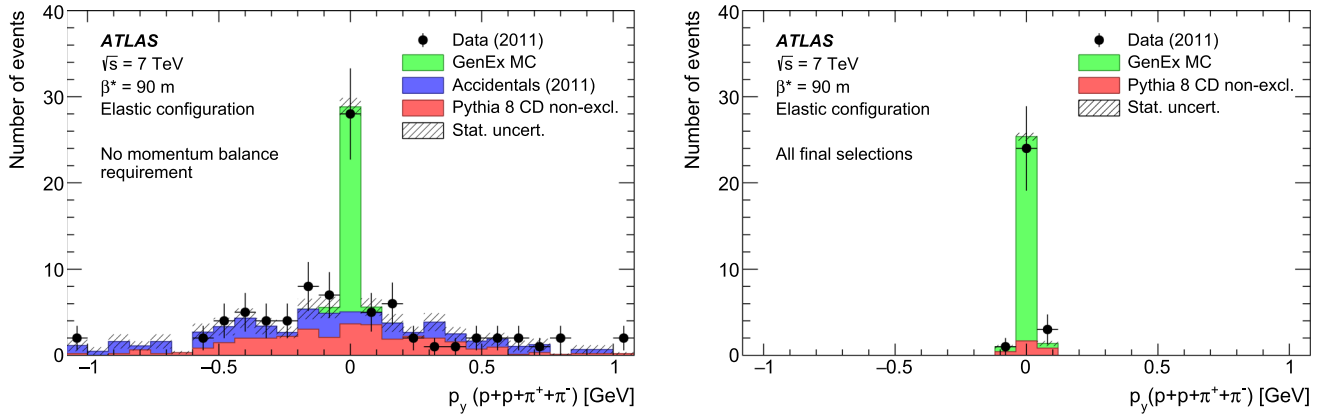


Fig. 7 Full final-state p_y momentum component of data, fitted to MC simulation and accidentals using GENEX for the signal component and a background consisting of accidentals and PYTHIA8 central diffraction (CD) without exclusive pion processes; in **a** all the final selections listed in Table 1 are applied except those on the momentum balance in the x and y projections, while in **b** all the final selections are applied. The histograms of the MC predictions and the accidentals are stacked. Statistical uncertainties of the MC events and accidentals are combined. The underflow and overflow bins ($|p_y| > 1$ GeV) are shown

$$(\varepsilon)^{\text{conf}}_{\text{arm}} = \left[\left(\frac{N_{\text{trk}}}{N_{\text{acc}}}\right)^{\text{MC}}\right]^{\text{conf}}_{\text{arm}}, \tag{1}$$

where N_{trk} is the number of generated MC signal events with at least one track reconstructed in each of the detectors in a given configuration and N_{acc} is the number of MC signal events within the acceptance of that configuration.

Since the MC simulation does not contain all relevant effects, the uv-condition and the clean track selection are introduced and Eq. (1) is now rewritten as

$$\begin{aligned}(\varepsilon')^{\text{conf}}_{\text{arm}} &= \left[\left(\frac{N_{\text{trk}}}{N_{\text{uv}}}\right)^{\text{data}} \times \left(\frac{N_{\text{uv}}}{N_{\text{acc}}}\right)^{\text{MC}}\right]^{\text{conf}}_{\text{arm}} \\ &\overset{\text{def}}{=} \left[r^{\text{data}} \times t^{\text{MC}}\right]^{\text{conf}}_{\text{arm}},\end{aligned} \tag{2}$$

where N_{uv} is the number of events which pass the uv-condition. The first factor in Eq. (2) is given by physics that can be mismodelled by generators, and the second factor takes account of the clean track selection.

Denoting $R^{\text{conf}}_{\text{arm}} = \left(o^{\text{MC}}/o^{\text{data}}\right)^{\text{conf}}_{\text{arm}}$, where the ratio $o^{\text{X}} = N^{\text{X, clean}}/N^{\text{X, any}}$ gives the ratio of the number of events with clean tracks to all events in a given track sample X (MC or data), the combined correction factor $f^{\text{s+}uv\text{,conf}}_{\text{arm}}$, where s+$uv$ denotes the combination of single tracks and uv-conditions, is written as

$$f^{\text{s+}uv\text{,conf}}_{\text{arm}} = \left(\varepsilon/\varepsilon' \times R\right)^{\text{conf}}_{\text{arm}}$$

which, using Eq. (2), can be re-written as

$$f^{\text{s+}uv\text{,conf}}_{\text{arm}} = \left(r^{\text{MC}}/r^{\text{data}} \times o^{\text{MC}}/o^{\text{data}}\right)^{\text{conf}}_{\text{arm}}.$$

Table 3 Correction factors for the single-track selection and uv-condition, and the correction factor for MC simulation based on the GENEX generator. Statistical uncertainties are quoted

Configuration	Arm	$f^{\text{s+}uv\text{,conf}}_{\text{arm}}$	$f^{\text{corr,conf}}_{\text{arm}}$
Elastic	0	1.097 ± 0.015	0.076 ± 0.001
	1	1.135 ± 0.016	0.070 ± 0.001
Anti-elastic	0	1.229 ± 0.115	0.069 ± 0.001
	1	1.126 ± 0.134	0.068 ± 0.001

Its values are given in Table 3.

The effects arising from detector efficiency and due to migrations across the fiducial phase-space boundary at particle and detector level are corrected for with a single factor for each configuration. This is adequate in view of the limited statistical precision of the data, given that the MC model describes the data well. The correction factor, $f^{\text{corr,conf}}_{\text{arm}}$, is based on the GENEX MC simulation, and for a given configuration it is defined as the ratio of the number of events, $N^{\text{passed}}_{\text{detector\_level}}$, that pass the event selection criteria at the detector level, to the number of events $N^{\text{passed}}_{\text{particle\_level}}$ that pass the fiducial region selection at the particle level, i.e. $f^{\text{corr,conf}}_{\text{arm}} = \left(N^{\text{passed}}_{\text{detector\_level}}/N^{\text{passed}}_{\text{particle\_level}}\right)^{\text{conf}}_{\text{arm}}$. The geometrical acceptance of each ALFA detector is ≈ 0.25, giving rise to the calculated combined values stated in Table 3.

The visible cross-section for a given elastic or anti-elastic configuration is then determined as

$$\sigma^{\text{vis, conf}}_{\pi^+\pi^-} = \frac{1}{L} \times \left[\left(N^{\text{conf}}_0 - B^{\text{conf}}_0\right) \times C^{\text{conf}}_0\right.$$

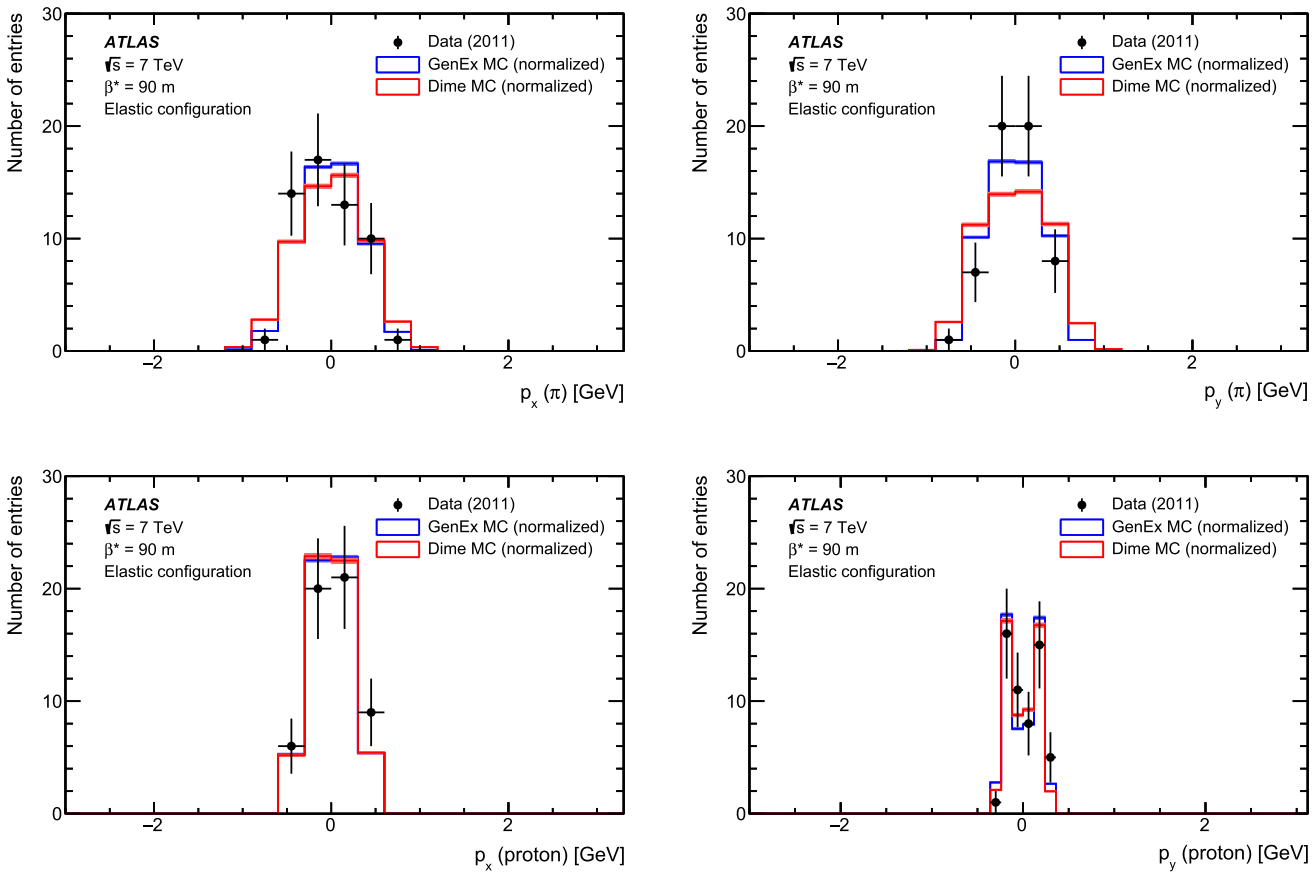


Fig. 8 Distributions, for the selected events, of p_x and p_y components of the pion tracks reconstructed in the ATLAS central detector (upper row), and p_x and p_y components of the proton tracks reconstructed in the ALFA detectors (lower row) for the data, GenEx MC and Dime MC simulations after applying all the event selections, but without a background subtraction applied to the data ($\approx 10\%$). Each of the MC samples is scaled to the data. Statistical uncertainties are shown only for the data; they are negligible for the MC predictions

$$+\left(N_1^{\text{conf}} - B_1^{\text{conf}}\right) \times C_1^{\text{conf}}\Big] \times \frac{1}{\epsilon_{\text{trig}}^{\text{conf}} \cdot \epsilon_{\text{DAQ}}}$$

where L represents the integrated luminosity used; $N_{\text{arm}}^{\text{conf}}$ and $B_{\text{arm}}^{\text{conf}}$ are the numbers of selected signal candidate events and calculated background events in each arm; $C_{\text{arm}}^{\text{conf}} = f_{\text{arm}}^{\text{s+}uv,\text{conf}} / f_{\text{arm}}^{\text{corr,conf}}$; $\epsilon_{\text{trig}}^{\text{conf}}$ is the trigger efficiency for the given configuration; ϵ_{DAQ} is the dead-time correction factor, as defined and determined in Ref. [9].

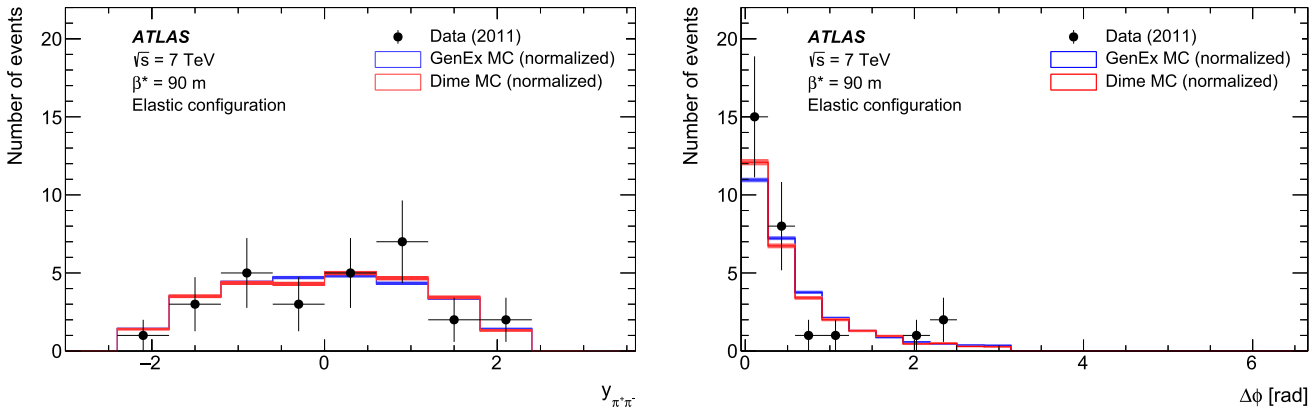
5.4 Kinematic distributions

Taking into account the precision of the reconstruction, the kinematic distributions of the pions and protons are well modelled by the MC simulations. Figures 8, 9 and 10 show comparisons of the distributions of the momentum components of the reconstructed pions and protons, and the pion-pair rapidity, acoplanarity, transverse momentum and invariant mass, for the data and the GenEx MC and Dime MC simulations. The distributions are presented after applying all the event selections, but without applying a background subtraction ($\approx 10\%$) to the data. In view of the low number of events for the anti-elastic configuration, only distributions for the elastic configuration are shown.

5.5 Systematic uncertainties

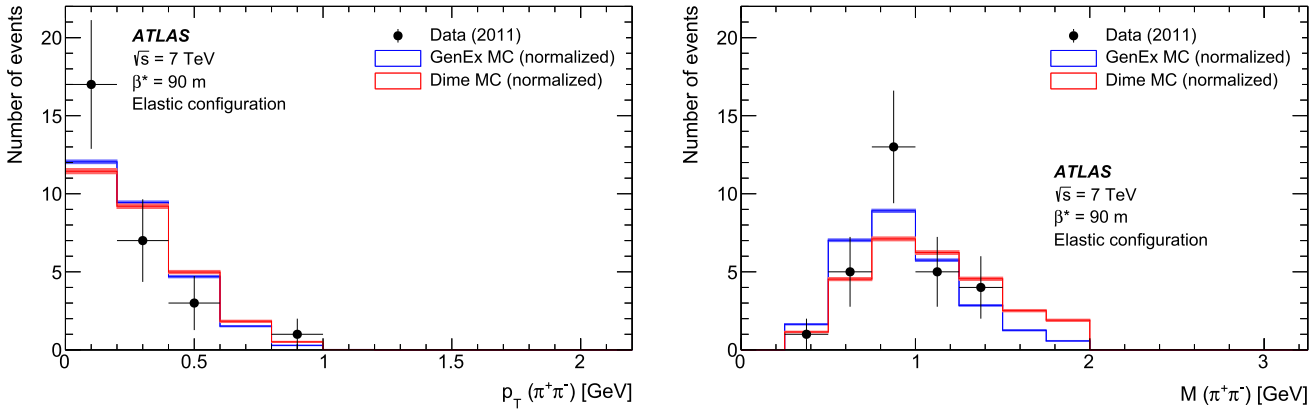
The overall systematic uncertainty on the exclusive pion-pair cross-section measurement is estimated as $^{+6.4}_{-4.2}\,\%$ for the elastic configuration and $^{+6.0}_{-4.4}\,\%$ for the anti-elastic configuration. Table 4 summarizes the main sources of systematic uncertainty. The difference between the relative uncertainties of the two configurations comes mainly from data-driven systematic uncertainties. Some of the MC studies made use of slightly enlarged fiducial region criteria to estimate systematic uncertainties.

Background determination. The systematic uncertainty is determined as half of the difference between the background estimates for the standard signal region, $3.5\sigma_{x,y}$ around zero



(a) (b)

Fig. 9 Distributions of **a** pion-pair rapidity and **b** pion-pair acoplanarity for the data, GenEx MC and Dime MC simulations after applying all event selections, but without a background subtraction applied to the data. Each of the MC samples is normalized to the data. Statistical uncertainties are shown only for the data; they are negligible for the MC predictions



(a) (b)

Fig. 10 Distributions of **a** pion-pair transverse momentum and **b** pion-pair invariant mass for the data, GenEx MC and Dime MC simulations after applying all event selections, but without a background subtraction applied to the data. Each of the MC samples is normalized to the data. Statistical uncertainties are shown only for the data; they are negligible for the MC predictions

in p_x and p_y, and for the case when the signal region is increased to $5\sigma_{x,y}$. It is symmetrized.

LHC beam energy. The systematic uncertainty due to that of the nominal beam energy is based on a beam energy variation of about $\pm 0.1\%$ [41].

Thicknesses of material. An uncertainty in the amount of material in the ID is calculated by changing this by $+5\%$ and $+10\%$ in the whole ID and by $+10\%$ in the pixel detector to determine the difference between the lowest and the highest value of the corrected exclusive pion-pair cross-section [40].

MBTS Veto. The MBTS veto uncertainty determination is based on the corresponding procedure used in the measurement of the inelastic proton–proton cross-section at $\sqrt{s}$ = 7 TeV [42].

Selection criteria. The uncertainty in the efficiency due to the selection criteria is determined from the fraction of lost signal. The overall uncertainty in the ALFA reconstruction efficiency is determined by varying the event selection criteria and summing the corresponding individual uncertainties in quadrature.

Correction factors. An uncertainty in the values of $f_{\text{arm}}^{\text{s}+uv,\text{conf}}$ arises from the restricted selection of data that is used to evaluate this factor in each arm. Although of statistical origin, this is treated as a systematic uncertainty.

Beam optics. This analysis uses data at a collision energy of 7 TeV and with high $\beta^\star = 90$ m beam optics, referred to as the nominal optics. Based on data measurements, an adjustment is made to the current-to-field calibration offset

Table 4 Summary of the exclusive pion-pair cross-section systematic uncertainties

Source of uncertainty	Uncertainty (%)	
	Elastic	Anti-elastic
Trigger efficiency ϵ_{trig}	±0.1	±0.3
Background determination	±3.5	±3.5
Signal and background corrections:		
Beam energy	±0.1	±0.1
ID material	+4.8	+4.1
Veto on MBTS signal	±1.3	±2.0
ALFA single-track selection	±0.9	±0.9
ALFA reconstruction efficiency	±0.9	±0.8
ALFA geometry selection	±0.5	±0.5
Optics	±1.1	±1.0
Overall systematic uncertainty	+6.4	+6.0
	−4.2	−4.4
Statistical uncertainty	±21.2	±61.6
Theoretical modelling	±2.8	±8.0
Luminosity	±1.2	±1.2

between the Q1Q3 and Q2 quadrupole magnets to derive the so-called effective optics [9]. Studies related to both optics are performed: the effective and the nominal optics are used in MC simulation to calculate all the corrections applied in reconstructing the data. The nominal optics is used as the baseline; the difference in the cross-section values is used to determine the systematic uncertainties.

Modelling. The analysis of the data uses the generator GenEx as the baseline for modelling the signal sample. The full analysis is repeated using the generator Dime, and the difference between the resulting cross-sections is taken as an uncertainty due to the modelling and is applied symmetrically.

Table 5 Exclusive pion-pair cross-section within the defined fiducial region for elastic and anti-elastic configurations, for the measurement and MC simulations. The statistical uncertainties of the MC simulations are negligible. The GenEx predictions have been multiplied by an absorptive correction factor of 0.22 suggested by the author of the generator

Exclusive $\pi^+\pi^-$ cross-section [μb]	
Elastic configuration	
Measurement	4.8 ± 1.0 (stat) $^{+0.3}_{-0.2}$ (syst) $\pm$ 0.1 (lumi) $\pm$ 0.1 (model)
GenEx ×0.22 (absorptive correction)	1.5
Dime	1.6
Anti-elastic configuration	
Measurement	9 ± 6 (stat) $^{+1}_{-1}$ (syst) $\pm$ 1 (lumi) $\pm$ 1 (model)
GenEx ×0.22 (absorptive correction)	2
Dime	3

6 Results and discussion

The cross-section for exclusive pion pair production is measured for two non-overlapping configurations, elastic and anti-elastic. The fiducial region is defined in Sect. 5.1.1 and the results are presented in Table 5.

There are 28 candidate signal events in the elastic configuration and 3 in the anti-elastic configuration (see Table 2). These include an estimated 2.9 background events in the elastic configuration (≈ 10%) and 0.2 background events (≈ 6%) in the anti-elastic configuration.

The results may be compared with cross-sections provided by MC generators using the same fiducial region definition: 1.5 μb (elastic configuration) and 2 μb (anti-elastic configuration) in the case of GenEx (these have been multiplied by an absorptive correction, abs. corr.), and 1.6 μb (elastic configuration) and 3 μb (anti-elastic configuration) in the case of Dime. The absorptive correction [25] applied here to GenEx covers possible rescatterings of the particles entering the process and complicates the simple picture in Fig. 1. The value used of 0.22 was communicated by its author; the correction is not included in GenEx itself and is, in general, kinematics and model dependent. It is not used in the experimental analysis, since the MC distributions are normalized to data, but only in the present comparison with the results. The measured anti-elastic cross-section has a large statistical uncertainty, and is not statistically different from zero, which prevents strong conclusions from being drawn.

7 Conclusion

A first measurement of the purely exclusive pion-pair cross-section at the LHC is presented, using $80\,\mu\text{b}^{-1}$ of $\sqrt{s} = 7$ TeV low-luminosity pp collision data collected by the ATLAS detector. The limited statistical precision obtained excludes the present possibility of tuning or excluding any of the existing physical models for the process, but the two models that are employed here, GenEx and Dime, evaluated with the parameters provided by their authors, provide preliminary theoretical estimates. The use of the forward ALFA detectors distinguishes the present measurement from others performed at comparable energies, since both outgoing protons have been measured directly, and used to suppress contamination from beam remnants. This measurement demonstrates the potential to measure exclusive diffractive hadronic processes using forward sub-detectors in combination with the ATLAS central detector.

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Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: "All ATLAS scientific output is published in journals, and preliminary results are made available in Conference Notes. All are openly available, without restriction on use by external parties beyond copyright law and the standard conditions agreed by CERN. Data associated with journal publications are also made available: tables and data from plots (e.g. cross section values, likelihood profiles, selection efficiencies, cross section limits, ...) are stored in appropriate repositories such as HEPDATA (https://www.hepdata.net/). ATLAS also strives to make additional material related to the paper available that allows a reinterpretation of the data in the context of new theoretical models. For example, an extended encapsulation of the analysis is often provided for measurements in the framework of RIVET (http://rivet.hepforge.org/)." This information is taken from the ATLAS Data Access Policy, which is a public document that can be downloaded from http://opendata.cern.ch/record/413 [opendata.cern.ch]. The data for this publication will be available at: https://doi.org/10.17182/hepdata.131222].

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ATLAS Collaboration[★]

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Allbrooke[145], P. P. Allport[20], A. Aloisio[71a,71b], F. Alonso[89], C. Alpigiani[137], E. Alunno Camelia[75a,75b], M. Alvarez Estevez[98], M. G. Alviggi[71a,71b], M. Aly[100], Y. Amaral Coutinho[81b], A. Ambler[103], C. Amelung[36], M. Amerl[1], C. G. Ames[108], D. Amidei[105], S. P. Amor Dos Santos[129a], S. Amoroso[48], K. R. Amos[162], V. Ananiev[124], C. Anastopoulos[138], T. Andeen[11], J. K. Anders[19], S. Y. Andrean[47a,47b], A. Andreazza[70a,70b], S. Angelidakis[9], A. Angerami[41,z], A. V. Anisenkov[37], A. Annovi[73a], C. Antel[56], M. T. Anthony[138], E. Antipov[120], M. Antonelli[53], D. J. A. Antrim[17a], F. Anulli[74a], M. Aoki[82], T. Aoki[152], J. A. Aparisi Pozo[162], M. A. Aparo[145], L. Aperio Bella[48], C. Appelt[18], N. Aranzabal[36], V. Araujo Ferraz[81a], C. Arcangeletti[53], A. T. H. Arce[51], E. Arena[91], J-F. Arguin[107], S. Argyropoulos[54], J.-H. Arling[48], A. J. Armbruster[36], O. Arnaez[154], H. Arnold[113], Z. P. Arrubarrena Tame[108], G. Artoni[74a,74b], H. Asada[110], K. Asai[117], S. Asai[152], N. A. Asbah[61], J. Assahsah[35d], K. Assamagan[29], R. Astalos[28a], R. J. Atkin[33a], M. Atkinson[161], N. B. Atlay[18], H. Atmani[62b], P. A. Atmasiddha[105], K. Augsten[131], S. Auricchio[71a,71b], A. D. Auriol[20], V. A. Austrup[170], G. Avner[149], G. Avolio[36], K. Axiotis[56], M. K. Ayoub[14c], G. Azuelos[107,ac], D. Babal[28a], H. Bachacou[134], K. Bachas[151,r], A. Bachiu[34], F. Backman[47a,47b], A. Badea[61], P. Bagnaia[74a,74b], M. Bahmani[18], A. J. Bailey[162], V. R. Bailey[161], J. T. Baines[133], C. Bakalis[10], O. K. Baker[171], P. J. Bakker[113], E. Bakos[15], D. Bakshi Gupta[8], S. Balaji[146], R. Balasubramanian[113], E. M. Baldin[37], P. Balek[132], E. Ballabene[70a,70b], F. Balli[134], L. M. Baltes[63a], W. K. Balunas[32], J. Balz[99], E. Banas[85], M. Bandieramonte[128], A. Bandyopadhyay[24], S. Bansal[24], L. Barak[150], E. L. Barberio[104], D. Barberis[57a,57b], M. Barbero[101], G. Barbour[95], K. N. Barends[33a], T. Barillari[109], M-S. Barisits[36], T. Barklow[142], R. M. Barnett[17a], P. Baron[121], D. A. Baron Moreno[100], A. Baroncelli[62a], G. Barone[29], A. J. Barr[125], L. Barranco Navarro[47a,47b], F. Barreiro[98], J. Barreiro Guimarães da Costa[14a], U. Barron[150], M. G. Barros Teixeira[129a], S. Barsov[37], F. Bartels[63a], R. Bartoldus[142], A. E. Barton[90], P. Bartos[28a], A. Basalaev[48], A. Basan[99], M. Baselga[49], I. Bashta[76a,76b], A. Bassalat[66,b], M. J. Basso[154], C. R. Basson[100], R. L. Bates[59], S. Batlamous[35e], J. R. Batley[32], B. Batool[140], M. Battaglia[135], D. Battulga[18], M. Bauce[74a,74b], P. Bauer[24], A. Bayirli[21a], J. B. Beacham[51], T. Beau[126], P. H. Beauchemin[157], F. Becherer[54], P. Bechtle[24], H. P. Beck[19,q], K. Becker[166], A. J. Beddall[21d], V. A. Bednyakov[38], C. P. Bee[144], L. J. Beemster[15], T. A. Beermann[36], M. Begalli[81d], M. Begel[29], A. Behera[144], J. K. Behr[48], C. Beirao Da Cruz E Silva[36], J. F. Beirer[36,55], F. Beisiegel[24], M. Belfkir[158], G. Bella[150], L. Bellagamba[23b], A. Bellerive[34], P. Bellos[20], K. Beloborodov[37], K. Belotskiy[37], N. L. Belyaev[37], D. Benchekroun[35a], F. Bendebba[35a], Y. Benhammou[150], D. P. Benjamin[29], M. Benoit[29], J. R. Bensinger[26], S. Bentvelsen[113], L. Beresford[36], M. Beretta[53], D. Berge[18], E. Bergeaas Kuutmann[160], N. Berger[4], B. Bergmann[131], J. Beringer[17a], S. Berlendis[7], G. Bernardi[5], C. Bernius[142], F. U. Bernlochner[24], T. Berry[94], P. Berta[132], A. Berthold[50], I. A. Bertram[90], S. Bethke[109], A. Betti[74a,74b], A. J. Bevan[93], M. Bhamjee[33c], S. Bhatta[144], D. S. Bhattacharya[165], P. Bhattarai[26], V. S. Bhopatkar[120], R. Bi[29,af], R. M. Bianchi[128], O. Biebel[108], R. Bielski[122], M. Biglietti[76a], T. R. V. Billoud[131], M. Bindi[55], A. Bingul[21b], C. Bini[74a,74b], S. Biondi[23a,23b], A. Biondini[91], C. J. Birch-sykes[100], G. A. Bird[20,133], M. Birman[168], T. Bisanz[36], E. Bisceglie[43a,43b], D. Biswas[169,l], A. Bitadze[100], K. Bjørke[124], I. Bloch[48], C. Blocker[26], A. Blue[59], U. Blumenschein[93], J. Blumenthal[99], G. J. Bobbink[113], V. S. Bobrovnikov[37], M. Boehler[54], D. Bogavac[36], A. G. Bogdanchikov[37], C. Bohm[47a], V. Boisvert[94], P. Bokan[48], T. Bold[84a], M. Bomben[5], M. Bona[93], M. Boonekamp[134], C. D. Booth[94], A. G. Borbély[59], H. M. Borecka-Bielska[107], L. S. Borgna[95], G. Borissov[90], D. Bortoletto[125], D. Boscherini[23b], M. Bosman[13], J. D. Bossio Sola[36], K. Bouaouda[35a], N. Bouchhar[162], J. Boudreau[128], E. V. Bouhova-Thacker[90], D. Boumediene[40], R. Bouquet[5], A. Boveia[118], J. Boyd[36], D. Boye[29], I. R. Boyko[38], J. Bracinik[20], N. Brahimi[62d], G. Brandt[170], O. Brandt[32], F. Braren[48], B. Brau[102],

J. E. Brau[122], K. Brendlinger[48], R. Brener[168], L. Brenner[113], R. Brenner[160], S. Bressler[168], B. Brickwedde[99], D. Britton[59], D. Britzger[109], I. Brock[24], G. Brooijmans[41], W. K. Brooks[136f], E. Brost[29], T. L. Bruckler[125], P. A. Bruckman de Renstrom[85], B. Brüers[48], D. Bruncko[28b,*], A. Bruni[23b], G. Bruni[23b], M. Bruschi[23b], N. Bruscino[74a,74b], L. Bryngemark[142], T. Buanes[16], Q. Buat[137], P. Buchholz[140], A. G. Buckley[59], I. A. Budagov[38,*], M. K. Bugge[124], O. Bulekov[37], B. A. Bullard[61], S. Burdin[91], C. D. Burgard[48], A. M. Burger[40], B. Burghgrave[8], J. T. P. Burr[32], C. D. Burton[11], J. C. Burzynski[141], E. L. Busch[41], V. Büscher[99], P. J. Bussey[59], J. M. Butler[25], C. M. Buttar[59], J. M. Butterworth[95], W. Buttinger[133], C. J. Buxo Vazquez[106], A. R. Buzykaev[37], G. Cabras[23b], S. Cabrera Urbán[162], D. Caforio[58], H. Cai[128], Y. Cai[14a,14d], V. M. M. Cairo[36], O. Cakir[3a], N. Calace[36], P. Calafiura[17a], G. Calderini[126], P. Calfayan[67], G. Callea[59], L. P. Caloba[81b], D. Calvet[40], S. Calvet[40], T. P. Calvet[101], M. Calvetti[73a,73b], R. Camacho Toro[126], S. Camarda[36], D. Camarero Munoz[26], P. Camarri[75a,75b], M. T. Camerlingo[76a,76b], D. Cameron[124], C. Camincher[164], M. Campanelli[95], A. Camplani[42], V. Canale[71a,71b], A. Canesse[103], M. Cano Bret[79], J. Cantero[162], Y. Cao[161], F. Capocasa[26], M. Capua[43a,43b], A. Carbone[70a,70b], R. Cardarelli[75a], J. C. J. Cardenas[8], F. Cardillo[162], T. Carli[36], G. Carlino[71a], J. I. Carlotto[13], B. T. Carlson[128,s], E. M. Carlson[155a,164], L. Carminati[70a,70b], M. Carnesale[74a,74b], S. Caron[112], E. Carquin[136f], S. Carrá[70a,70b], G. Carratta[23a,23b], F. Carrio Argos[33g], J. W. S. Carter[154], T. M. Carter[52], M. P. Casado[13,i], A. F. Casha[154], E. G. Castiglia[171], F. L. Castillo[63a], L. Castillo Garcia[13], V. Castillo Gimenez[162], N. F. Castro[129a,129e], A. Catinaccio[36], J. R. Catmore[124], V. Cavaliere[29], N. Cavalli[23a,23b], V. Cavasinni[73a,73b], E. Celebi[21a], F. Celli[125], M. S. Centonze[69a,69b], K. Cerny[121], A. S. Cerqueira[81a], A. Cerri[145], L. Cerrito[75a,75b], F. Cerutti[17a], A. Cervelli[23b], S. A. Cetin[21d], Z. Chadi[35a], D. Chakraborty[114], M. Chala[129f], J. Chan[169], W. Y. Chan[152], J. D. Chapman[32], B. Chargeishvili[148b], D. G. Charlton[20], T. P. Charman[93], M. Chatterjee[19], S. Chekanov[6], S. V. Chekulaev[155a], G. A. Chelkov[38,a], A. Chen[105], B. Chen[150], B. Chen[164], C. Chen[62a], H. Chen[14c], H. Chen[29], J. Chen[62c], J. Chen[26], S. Chen[152], S. J. Chen[14c], X. Chen[62c], X. Chen[14b,ab], Y. Chen[62a], C. L. Cheng[169], H. C. Cheng[64a], S. Cheong[142], A. Cheplakov[38], E. Cheremushkina[48], E. Cherepanova[113], R. Cherkaoui El Moursli[35e], E. Cheu[7], K. Cheung[65], L. Chevalier[134], V. Chiarella[53], G. Chiarelli[73a], N. Chiedde[101], G. Chiodini[69a], A. S. Chisholm[20], A. Chitan[27b], M. Chitishvili[162], Y. H. Chiu[164], M. V. Chizhov[38], K. Choi[11], A. R. Chomont[74a,74b], Y. Chou[102], E. Y. S. Chow[113], T. Chowdhury[33g], L. D. Christopher[33g], K. L. Chu[64a], M. C. Chu[64a], X. Chu[14a,14d], J. Chudoba[130], J. J. Chwastowski[85], D. Cieri[109], K. M. Ciesla[84a], V. Cindro[92], A. Ciocio[17a], F. Cirotto[71a,71b], Z. H. Citron[168,m], M. Citterio[70a], D. A. Ciubotaru[27b], B. M. Ciungu[154], A. Clark[56], P. J. Clark[52], J. M. Clavijo Columbie[48], S. E. Clawson[100], C. Clement[47a,47b], J. Clercx[48], L. Clissa[23a,23b], Y. Coadou[101], M. Cobal[68a,68c], A. Coccaro[57b], R. F. Coelho Barrue[129a], R. Coelho Lopes De Sa[102], S. Coelli[70a], H. Cohen[150], A. E. C. Coimbra[70a,70b], B. Cole[41], J. Collot[60], P. Conde Muiño[129a,129g], M. P. Connell[33c], S. H. Connell[33c], I. A. Connelly[59], E. I. Conroy[125], F. Conventi[71a,ad], H. G. Cooke[20], A. M. Cooper-Sarkar[125], F. Cormier[163], L. D. Corpe[36], M. Corradi[74a,74b], E. E. Corrigan[97], F. Corriveau[103,w], A. Cortes-Gonzalez[18], M. J. Costa[162], F. Costanza[4], D. Costanzo[138], B. M. Cote[118], G. Cowan[94], J. W. Cowley[32], K. Cranmer[116], S. Crépé-Renaudin[60], F. Crescioli[126], M. Cristinziani[140], M. Cristoforetti[77a,77b,d], V. Croft[157], G. Crosetti[43a,43b], A. Cueto[36], T. Cuhadar Donszelmann[159], H. Cui[14a,14d], Z. Cui[7], A. R. Cukierman[142], W. R. Cunningham[59], F. Curcio[43a,43b], P. Czodrowski[36], M. M. Czurylo[63b], M. J. Da Cunha Sargedas De Sousa[62a], J. V. Da Fonseca Pinto[81b], C. Da Via[100], W. Dabrowski[84a], T. Dado[49], S. Dahbi[33g], T. Dai[105], C. Dallapiccola[102], M. Dam[42], G. D'amen[29], V. D'Amico[108], J. Damp[99], J. R. Dandoy[127], M. F. Daneri[30], M. Danninger[141], V. Dao[36], G. Darbo[57b], S. Darmora[6], S. J. Das[29], S. D'Auria[70a,70b], C. David[155b], T. Davidek[132], D. R. Davis[51], B. Davis-Purcell[34], I. Dawson[93], K. De[8], R. De Asmundis[71a], M. De Beurs[113], N. De Biase[48], S. De Castro[23a,23b], N. De Groot[112], P. de Jong[113], H. De la Torre[106], A. De Maria[14c], A. De Salvo[74a], U. De Sanctis[75a,75b], A. De Santo[145], J. B. De Vivie De Regie[60], D. V. Dedovich[38], J. Degens[113], A. M. Deiana[44], F. Del Corso[23a,23b], J. Del Peso[98], F. Del Rio[63a], F. Deliot[134], C. M. Delitzsch[49], M. Della Pietra[71a,71b], D. Della Volpe[56], A. Dell'Acqua[36], L. Dell'Asta[70a,70b], M. Delmastro[4], P. A. Delsart[60], S. Demers[171], M. Demichev[38], S. P. Denisov[37], L. D'Eramo[114], D. Derendarz[85], F. Derue[126], P. Dervan[91], K. Desch[24], K. Dette[154], C. Deutsch[24], P. O. Deviveiros[36], F. A. Di Bello[74a,74b], A. Di Ciaccio[75a,75b], L. Di Ciaccio[4], A. Di Domenico[74a,74b], C. Di Donato[71a,71b], A. Di Girolamo[36], G. Di Gregorio[73a,73b], A. Di Luca[77a,77b], B. Di Micco[76a,76b], R. Di Nardo[76a,76b], C. Diaconu[101], F. A. Dias[113], T. Dias Do Vale[141], M. A. Diaz[136a,136b], F. G. Diaz Capriles[24], M. Didenko[162], E. B. Diehl[105], L. Diehl[54], S. Díez Cornell[48], C. Diez Pardos[140],

C. Dimitriadi[24,160], A. Dimitrievska[17a], W. Ding[14b], J. Dingfelder[24], I-M. Dinu[27b], S. J. Dittmeier[63b], F. Dittus[36], F. Djama[101], T. Djobava[148b], J. I. Djuvsland[16], C. Doglioni[97,100], J. Dolejsi[132], Z. Dolezal[132], M. Donadelli[81c], B. Dong[62c], J. Donini[40], A. D'Onofrio[14c], M. D'Onofrio[91], J. Dopke[133], A. Doria[71a], M. T. Dova[89], A. T. Doyle[59], M. A. Draguet[125], E. Drechsler[141], E. Dreyer[168], I. Drivas-koulouris[10], A. S. Drobac[157], M. Drozdova[56], D. Du[62a], T. A. du Pree[113], F. Dubinin[37], M. Dubovsky[28a], E. Duchovni[168], G. Duckeck[108], O. A. Ducu[27b], D. Duda[109], A. Dudarev[36], M. D'uffizi[100], L. Duflot[66], M. Dührssen[36], C. Dülsen[170], A. E. Dumitriu[27b], M. Dunford[63a], S. Dungs[49], K. Dunne[47a,47b], A. Duperrin[101], H. Duran Yildiz[3a], M. Düren[58], A. Durglishvili[148b], B. L. Dwyer[114], G. I. Dyckes[17a], M. Dyndal[84a], S. Dysch[100], B. S. Dziedzic[85], Z. O. Earnshaw[145], B. Eckerova[28a], M. G. Eggleston[51], E. Egidio Purcino De Souza[81b], L. F. Ehrke[56], G. Eigen[16], K. Einsweiler[17a], T. Ekelof[160], P. A. Ekman[97], Y. El Ghazali[35b], H. El Jarrari[35e,147], A. El Moussaouy[35a], V. Ellajosyula[160], M. Ellert[160], F. Ellinghaus[170], A. A. Elliot[93], N. Ellis[36], J. Elmsheuser[29], M. Elsing[36], D. Emeliyanov[133], A. Emerman[41], Y. Enari[152], I. Ene[17a], S. Epari[13], J. Erdmann[49,aa], A. Ereditato[19], P. A. Erland[85], M. Errenst[170], M. Escalier[66], C. Escobar[162], E. Etzion[150], G. Evans[129a], H. Evans[67], M. O. Evans[145], A. Ezhilov[37], S. Ezzarqtouni[35a], F. Fabbri[59], L. Fabbri[23a,23b], G. Facini[95], V. Fadeyev[135], R. M. Fakhrutdinov[37], S. Falciano[74a], P. J. Falke[24], S. Falke[36], J. Faltova[132], Y. Fan[14a], Y. Fang[14a,14d], G. Fanourakis[46], M. Fanti[70a,70b], M. Faraj[68a,68b], A. Farbin[8], A. Farilla[76a], T. Farooque[106], S. M. Farrington[52], F. Fassi[35e], D. Fassouliotis[9], M. Faucci Giannelli[75a,75b], W. J. Fawcett[32], L. Fayard[66], P. Federicova[130], O. L. Fedin[37,a], G. Fedotov[37], M. Feickert[161], L. Feligioni[101], A. Fell[138], D. E. Fellers[122], C. Feng[62b], M. Feng[14b], Z. Feng[113], M. J. Fenton[159], A. B. Fenyuk[37], L. Ferencz[48], S. W. Ferguson[45], J. Ferrando[48], A. Ferrari[160], P. Ferrari[112,113], R. Ferrari[72a], D. Ferrere[56], C. Ferretti[105], F. Fiedler[99], A. Filipčič[92], E. K. Filmer[1], F. Filthaut[112], M. C. N. Fiolhais[129a,129c,c], L. Fiorini[162], F. Fischer[140], W. C. Fisher[106], T. Fitschen[20], I. Fleck[140], P. Fleischmann[105], T. Flick[170], L. Flores[127], M. Flores[33d], L. R. Flores Castillo[64a], F. M. Follega[77a,77b], N. Fomin[16], J. H. Foo[154], B. C. Forland[67], A. Formica[134], A. C. Forti[100], E. Fortin[101], A. W. Fortman[61], M. G. Foti[17a], L. Fountas[9], D. Fournier[66], H. Fox[90], P. Francavilla[73a,73b], S. Francescato[61], M. Franchini[23a,23b], S. Franchino[63a], D. Francis[36], L. Franco[112], L. Franconi[19], M. Franklin[61], G. Frattari[26], A. C. Freegard[93], P. M. Freeman[20], W. S. Freund[81b], N. Fritzsche[50], A. Froch[54], D. Froidevaux[36], J. A. Frost[125], Y. Fu[62a], M. Fujimoto[117], E. Fullana Torregrosa[162,*], J. Fuster[162], A. Gabrielli[23a,23b], A. Gabrielli[154], P. Gadow[48], G. Gagliardi[57a,57b], L. G. Gagnon[17a], G. E. Gallardo[125], E. J. Gallas[125], B. J. Gallop[133], R. Gamboa Goni[93], K. K. Gan[118], S. Ganguly[152], J. Gao[62a], Y. Gao[52], F. M. Garay Walls[136a,136b], B. Garcia[29,af], C. García[162], J. E. García Navarro[162], J. A. García Pascual[14a], M. Garcia-Sciveres[17a], R. W. Gardner[39], D. Garg[79], R. B. Garg[142], S. Gargiulo[54], C. A. Garner[154], V. Garonne[29], S. J. Gasiorowski[137], P. Gaspar[81b], G. Gaudio[72a], V. Gautam[13], P. Gauzzi[74a,74b], I. L. Gavrilenko[37], A. Gavrilyuk[37], C. Gay[163], G. Gaycken[48], E. N. Gazis[10], A. A. Geanta[27b,27e], C. M. Gee[135], J. Geisen[97], M. Geisen[99], C. Gemme[57b], M. H. Genest[60], S. Gentile[74a,74b], S. George[94], W. F. George[20], T. Geralis[46], L. O. Gerlach[55], P. Gessinger-Befurt[36], M. Ghasemi Bostanabad[164], M. Ghneimat[140], K. Ghorbanian[93], A. Ghosal[140], A. Ghosh[159], A. Ghosh[7], B. Giacobbe[23b], S. Giagu[74a,74b], N. Giangiacomi[154], P. Giannetti[73a], A. Giannini[62a], S. M. Gibson[94], M. Gignac[135], D. T. Gil[84b], A. K. Gilbert[84a], B. J. Gilbert[41], D. Gillberg[34], G. Gilles[113], N. E. K. Gillwald[48], L. Ginabat[126], D. M. Gingrich[2,ac], M. P. Giordani[68a,68c], P. F. Giraud[134], G. Giugliarelli[68a,68c], D. Giugni[70a], F. Giuli[36], I. Gkialas[9,j], L. K. Gladilin[37], C. Glasman[98], G. R. Gledhill[122], M. Glisic[122], I. Gnesi[43b,f], Y. Go[29,af], M. Goblirsch-Kolb[26], D. Godin[107], S. Goldfarb[104], T. Golling[56], M. G. D. Gololo[33g], D. Golubkov[37], J. P. Gombas[106], A. Gomes[129a,129b], G. Gomes Da Silva[140], A. J. Gomez Delegido[162], R. Goncalves Gama[55], R. Gonçalo[129a,129c], G. Gonella[122], L. Gonella[20], A. Gongadze[38], F. Gonnella[20], J. L. Gonski[41], R. Y. González Andana[52], S. González de la Hoz[162], S. Gonzalez Fernandez[13], R. Gonzalez Lopez[91], C. Gonzalez Renteria[17a], R. Gonzalez Suarez[160], S. Gonzalez-Sevilla[56], G. R. Gonzalvo Rodriguez[162], L. Goossens[36], N. A. Gorasia[20], P. A. Gorbounov[37], B. Gorini[36], E. Gorini[69a,69b], A. Gorišek[92], A. T. Goshaw[51], M. I. Gostkin[38], C. A. Gottardo[36], M. Gouighri[35b], V. Goumarre[48], A. G. Goussiou[137], N. Govender[33c], C. Goy[4], I. Grabowska-Bold[84a], K. Graham[34], E. Gramstad[124], S. Grancagnolo[18], M. Grandi[145], V. Gratchev[37,*], P. M. Gravila[27f], F. G. Gravili[69a,69b], H. M. Gray[17a], M. Greco[69a,69b], C. Grefe[24], I. M. Gregor[48], P. Grenier[142], C. Grieco[13], A. A. Grillo[135], K. Grimm[31,n], S. Grinstein[13,u], J. -F. Grivaz[66], E. Gross[168], J. Grosse-Knetter[55], C. Grud[105], A. Grummer[111], J. C. Grundy[125], L. Guan[105], W. Guan[169], C. Gubbels[163], J. G. R. Guerrero Rojas[162], G. Guerrieri[68a,68b], F. Guescini[109], R. Gugel[99],

J. A. M. Guhit[105], A. Guida[48], T. Guillemin[4], E. Guilloton[133,166], S. Guindon[36], F. Guo[14a,14d], J. Guo[62c], L. Guo[66], Y. Guo[105], R. Gupta[48], S. Gurbuz[24], S. S. Gurdasani[54], G. Gustavino[36], M. Guth[56], P. Gutierrez[119], L. F. Gutierrez Zagazeta[127], C. Gutschow[95], C. Guyot[134], C. Gwenlan[125], C. B. Gwilliam[91], E. S. Haaland[124], A. Haas[116], M. Habedank[48], C. Haber[17a], H. K. Hadavand[8], A. Hadef[99], S. Hadzic[109], E. H. Haines[95], M. Haleem[165], J. Haley[120], J. J. Hall[138], G. D. Hallewell[101], L. Halser[19], P. Hamal[121], K. Hamano[164], H. Hamdaoui[35e], M. Hamer[24], G. N. Hamity[52], J. Han[62b], K. Han[62a], L. Han[14c], L. Han[62a], S. Han[17a], Y. F. Han[154], K. Hanagaki[82], M. Hance[135], D. A. Hangal[41,z], H. Hanif[141], M. D. Hank[39], R. Hankache[100], J. B. Hansen[42], J. D. Hansen[42], P. H. Hansen[42], K. Hara[156], D. Harada[56], T. Harenberg[170], S. Harkusha[37], Y. T. Harris[125], N. M. Harrison[118], P. F. Harrison[166], N. M. Hartman[142], N. M. Hartmann[108], Y. Hasegawa[139], A. Hasib[52], S. Haug[19], R. Hauser[106], M. Havranek[131], C. M. Hawkes[20], R. J. Hawkings[36], S. Hayashida[110], D. Hayden[106], C. Hayes[105], R. L. Hayes[163], C. P. Hays[125], J. M. Hays[93], H. S. Hayward[91], F. He[62a], Y. He[153], Y. He[126], M. P. Heath[52], V. Hedberg[97], A. L. Heggelund[124], N. D. Hehir[93], C. Heidegger[54], K. K. Heidegger[54], W. D. Heidorn[80], J. Heilman[34], S. Heim[48], T. Heim[17a], J. G. Heinlein[127], J. J. Heinrich[122], L. Heinrich[109], J. Hejbal[130], L. Helary[48], A. Held[169], S. Hellesund[124], C. M. Helling[163], S. Hellman[47a,47b], C. Helsens[36], R. C. W. Henderson[90], L. Henkelmann[32], A. M. Henriques Correia[36], H. Herde[97], Y. Hernández Jiménez[144], M. G. Herrmann[108], T. Herrmann[50], G. Herten[54], R. Hertenberger[108], L. Hervas[36], N. P. Hessey[155a], H. Hibi[83], E. Higón-Rodriguez[162], S. J. Hillier[20], I. Hinchliffe[17a], F. Hinterkeuser[24], M. Hirose[123], S. Hirose[156], D. Hirschbuehl[170], T. G. Hitchings[100], B. Hiti[92], J. Hobbs[144], R. Hobincu[27e], N. Hod[168], M. C. Hodgkinson[138], B. H. Hodkinson[32], A. Hoecker[36], J. Hofer[48], D. Hohn[54], T. Holm[24], M. Holzbock[109], L. B. A. H. Hommels[32], B. P. Honan[100], J. Hong[62c], T. M. Hong[128], Y. Hong[55], J. C. Honig[54], A. Hönle[109], B. H. Hooberman[161], W. H. Hopkins[6], Y. Horii[110], S. Hou[147], A. S. Howard[92], J. Howarth[59], J. Hoya[6], M. Hrabovsky[121], A. Hrynevich[48], T. Hryn'ova[4], P. J. Hsu[65], S. -C. Hsu[137], Q. Hu[41,z], Y. F. Hu[14a,14d,ae], D. P. Huang[95], S. Huang[64b], X. Huang[14c], Y. Huang[62a], Y. Huang[14a], Z. Huang[100], Z. Hubacek[131], M. Huebner[24], F. Huegging[24], T. B. Huffman[125], M. Huhtinen[36], S. K. Huiberts[16], R. Hulsken[103], N. Huseynov[12,a], J. Huston[106], J. Huth[61], R. Hyneman[142], S. Hyrych[28a], G. Iacobucci[56], G. Iakovidis[29], I. Ibragimov[140], L. Iconomidou-Fayard[66], P. Iengo[71a,71b], R. Iguchi[152], T. Iizawa[56], Y. Ikegami[82], A. Ilg[19], N. Ilic[154], H. Imam[35a], T. Ingebretsen Carlson[47a,47b], G. Introzzi[72a,72b], M. Iodice[76a], V. Ippolito[74a,74b], M. Ishino[152], W. Islam[169], C. Issever[18,48], S. Istin[21a,ah], H. Ito[167], J. M. Iturbe Ponce[64a], R. Iuppa[77a,77b], A. Ivina[168], J. M. Izen[45], V. Izzo[71a], P. Jacka[130,131], P. Jackson[1], R. M. Jacobs[48], B. P. Jaeger[141], C. S. Jagfeld[108], G. Jäkel[170], K. Jakobs[54], T. Jakoubek[168], J. Jamieson[59], K. W. Janas[84a], G. Jarlskog[97], A. E. Jaspan[91], M. Javurkova[102], F. Jeanneau[134], L. Jeanty[122], J. Jejelava[148a,y], P. Jenni[54,g], C. E. Jessiman[34], S. Jézéquel[4], J. Jia[144], X. Jia[61], X. Jia[14a,14d], Z. Jia[14c], Y. Jiang[62a], S. Jiggins[52], J. Jimenez Pena[109], S. Jin[14c], A. Jinaru[27b], O. Jinnouchi[153], P. Johansson[138], K. A. Johns[7], D. M. Jones[32], E. Jones[166], P. Jones[32], R. W. L. Jones[90], T. J. Jones[91], R. Joshi[118], J. Jovicevic[15], X. Ju[17a], J. J. Junggeburth[36], A. Juste Rozas[13,u], S. Kabana[136e], A. Kaczmarska[85], M. Kado[74a,74b], H. Kagan[118], M. Kagan[142], A. Kahn[41], A. Kahn[127], C. Kahra[99], T. Kaji[167], E. Kajomovitz[149], N. Kakati[168], C. W. Kalderon[29], A. Kamenshchikov[154], S. Kanayama[153], N. J. Kang[135], Y. Kano[110], D. Kar[33g], K. Karava[125], M. J. Kareem[155b], E. Karentzos[54], I. Karkanias[151], S. N. Karpov[38], Z. M. Karpova[38], V. Kartvelishvili[90], A. N. Karyukhin[37], E. Kasimi[151], C. Kato[62d], J. Katzy[48], S. Kaur[34], K. Kawade[139], K. Kawagoe[88], T. Kawamoto[134], G. Kawamura[55], E. F. Kay[164], F. I. Kaya[157], S. Kazakos[13], V. F. Kazanin[37], Y. Ke[144], J. M. Keaveney[33a], R. Keeler[164], G. V. Kehris[61], J. S. Keller[34], A. S. Kelly[95], D. Kelsey[145], J. J. Kempster[20], K. E. Kennedy[41], P. D. Kennedy[99], O. Kepka[130], B. P. Kerridge[166], S. Kersten[170], B. P. Kerševan[92], S. Keshri[66], L. Keszeghova[28a], S. Ketabchi Haghighat[154], M. Khandoga[126], A. Khanov[120], A. G. Kharlamov[37], T. Kharlamova[37], E. E. Khoda[137], T. J. Khoo[18], G. Khoriauli[165], J. Khubua[148b], Y. A. R. Khwaira[66], M. Kiehn[36], A. Kilgallon[122], D. W. Kim[47a,47b], E. Kim[153], Y. K. Kim[39], N. Kimura[95], A. Kirchhoff[55], D. Kirchmeier[50], C. Kirfel[24], J. Kirk[133], A. E. Kiryunin[109], T. Kishimoto[152], D. P. Kisliuk[154], C. Kitsaki[10], O. Kivernyk[24], M. Klassen[63a], C. Klein[34], L. Klein[165], M. H. Klein[105], M. Klein[91], S. B. Klein[56], U. Klein[91], P. Klimek[36], A. Klimentov[29], F. Klimpel[109], T. Klingl[24], T. Klioutchnikova[36], F. F. Klitzner[108], P. Kluit[113], S. Kluth[109], E. Kneringer[78], T. M. Knight[154], A. Knue[54], D. Kobayashi[88], R. Kobayashi[86], M. Kocian[142], P. Kodyš[132], D. M. Koeck[145], P. T. Koenig[24], T. Koffas[34], N. M. Köhler[36], M. Kolb[134], I. Koletsou[4], T. Komarek[121], K. Köneke[54], A. X. Y. Kong[1], T. Kono[117], N. Konstantinidis[95], B. Konya[97], R. Kopeliansky[67],

S. Koperny[84a], K. Korcyl[85], K. Kordas[151], G. Koren[150], A. Korn[95], S. Korn[55], I. Korolkov[13], N. Korotkova[37], B. Kortman[113], O. Kortner[109], S. Kortner[109], W. H. Kostecka[114], V. V. Kostyukhin[140], A. Kotsokechagia[134], A. Kotwal[51], A. Koulouris[36], A. Kourkoumeli-Charalampidi[72a,72b], C. Kourkoumelis[9], E. Kourlitis[6], O. Kovanda[145], R. Kowalewski[164], W. Kozanecki[134], A. S. Kozhin[37], V. A. Kramarenko[37], G. Kramberger[92], P. Kramer[99], M. W. Krasny[126], A. Krasznahorkay[36], J. A. Kremer[99], T. Kresse[50], J. Kretzschmar[91], K. Kreul[18], P. Krieger[154], F. Krieter[108], S. Krishnamurthy[102], A. Krishnan[63b], M. Krivos[132], K. Krizka[17a], K. Kroeninger[49], H. Kroha[109], J. Kroll[130], J. Kroll[127], K. S. Krowpman[106], U. Kruchonak[38], H. Krüger[24], N. Krumnack[80], M. C. Kruse[51], J. A. Krzysiak[85], A. Kubota[153], O. Kuchinskaia[37], S. Kuday[3a], D. Kuechler[48], J. T. Kuechler[48], S. Kuehn[36], T. Kuhl[48], V. Kukhtin[38], Y. Kulchitsky[37,a], S. Kuleshov[136b,136d], M. Kumar[33g], N. Kumari[101], A. Kupco[130], T. Kupfer[49], A. Kupich[37], O. Kuprash[54], H. Kurashige[83], L. L. Kurchaninov[155a], Y. A. Kurochkin[37], A. Kurova[37], M. Kuze[153], A. K. Kvam[102], J. Kvita[121], T. Kwan[103], K. W. Kwok[64a], N. G. Kyriacou[105], L. A. O. Laatu[101], C. Lacasta[162], F. Lacava[74a,74b], H. Lacker[18], D. Lacour[126], N. N. Lad[95], E. Ladygin[38], B. Laforge[126], T. Lagouri[136e], S. Lai[55], I. K. Lakomiec[84a], N. Lalloue[60], J. E. Lambert[119], S. Lammers[67], W. Lampl[7], C. Lampoudis[151], A. N. Lancaster[114], E. Lançon[29], U. Landgraf[54], M. P. J. Landon[93], V. S. Lang[54], R. J. Langenberg[102], A. J. Lankford[159], F. Lanni[36], K. Lantzsch[24], A. Lanza[72a], A. Lapertosa[57a,57b], J. F. Laporte[134], T. Lari[70a], F. Lasagni Manghi[23b], M. Lassnig[36], V. Latonova[130], T. S. Lau[64a], A. Laudrain[99], A. Laurier[34], S. D. Lawlor[94], Z. Lawrence[100], M. Lazzaroni[70a,70b], B. Le[100], B. Leban[92], A. Lebedev[80], M. LeBlanc[36], T. LeCompte[6], F. Ledroit-Guillon[60], A. C. A. Lee[95], G. R. Lee[16], L. Lee[61], S. C. Lee[147], S. Lee[47a,47b], T. F. Lee[91], L. L. Leeuw[33c], H. P. Lefebvre[94], M. Lefebvre[164], C. Leggett[17a], K. Lehmann[141], G. Lehmann Miotto[36], M. Leigh[56], W. A. Leight[102], A. Leisos[151,t], M. A. L. Leite[81c], C. E. Leitgeb[48], R. Leitner[132], K. J. C. Leney[44], T. Lenz[24], S. Leone[73a], C. Leonidopoulos[52], A. Leopold[143], C. Leroy[107], R. Les[106], C. G. Lester[32], M. Levchenko[37], J. Levêque[4], D. Levin[105], L. J. Levinson[168], M. P. Lewicki[85], D. J. Lewis[4], B. Li[14b], B. Li[62b], C. Li[62a], C-Q. Li[62c], H. Li[62a], H. Li[62b], H. Li[14c], H. Li[62b], J. Li[62c], K. Li[137], L. Li[62c], M. Li[14a,14d], Q. Y. Li[62a], S. Li[62c,62d,e], T. Li[62b], X. Li[103], Z. Li[62b], Z. Li[125], Z. Li[103], Z. Li[91], Z. Li[14a,14d], Z. Liang[14a], M. Liberatore[48], B. Liberti[75a], K. Lie[64c], J. Lieber Marin[81b], K. Lin[106], R. A. Linck[67], R. E. Lindley[7], J. H. Lindon[2], A. Linss[48], E. Lipeles[127], A. Lipniacka[16], A. Lister[163], J. D. Little[4], B. Liu[14a], B. X. Liu[141], D. Liu[62c,62d], J. B. Liu[62a], J. K. K. Liu[32], K. Liu[62c,62d], M. Liu[62a], M. Y. Liu[62a], P. Liu[14a], Q. Liu[62c,62d,137], X. Liu[62a], Y. Liu[48], Y. Liu[14c,14d], Y. L. Liu[105], Y. W. Liu[62a], M. Livan[72a,72b], J. Llorente Merino[141], S. L. Lloyd[93], E. M. Lobodzinska[48], P. Loch[7], S. Loffredo[75a,75b], T. Lohse[18], K. Lohwasser[138], M. Lokajicek[130], J. D. Long[161], I. Longarini[74a,74b], L. Longo[69a,69b], R. Longo[161], I. Lopez Paz[36], A. Lopez Solis[48], J. Lorenz[108], N. Lorenzo Martinez[4], A. M. Lory[108], A. Lösle[54], X. Lou[47a,47b], X. Lou[14a,14d], A. Lounis[66], J. Love[6], P. A. Love[90], J. J. Lozano Bahilo[162], G. Lu[14a,14d], M. Lu[79], S. Lu[127], Y. J. Lu[65], H. J. Lubatti[137], C. Luci[74a,74b], F. L. Lucio Alves[14c], A. Lucotte[60], F. Luehring[67], I. Luise[144], O. Lukianchuk[66], O. Lundberg[143], B. Lund-Jensen[143], N. A. Luongo[122], M. S. Lutz[150], D. Lynn[29], H. Lyons[91], R. Lysak[130], E. Lytken[97], F. Lyu[14a], V. Lyubushkin[38], T. Lyubushkina[38], H. Ma[29], L. L. Ma[62b], Y. Ma[95], D. M. Mac Donell[164], G. Maccarrone[53], J. C. MacDonald[138], R. Madar[40], W. F. Mader[50], J. Maeda[83], T. Maeno[29], M. Maerker[50], V. Magerl[54], J. Magro[68a,68c], H. Maguire[138], D. J. Mahon[41], C. Maidantchik[81b], A. Maio[129a,129b,129d], K. Maj[84a], O. Majersky[28a], S. Majewski[122], N. Makovec[66], V. Maksimovic[15], B. Malaescu[126], Pa. Malecki[85], V. P. Maleev[37], F. Malek[60], D. Malito[43a,43b], U. Mallik[79], C. Malone[32], S. Maltezos[10], S. Malyukov[38], J. Mamuzic[13], G. Mancini[53], G. Manco[72a,72b], J. P. Mandalia[93], I. Mandić[92], L. Manhaes de Andrade Filho[81a], I. M. Maniatis[151], M. Manisha[134], J. Manjarres Ramos[50], D. C. Mankad[168], A. Mann[108], B. Mansoulie[134], S. Manzoni[36], A. Marantis[151], G. Marchiori[5], M. Marcisovsky[130], L. Marcoccia[75a,75b], C. Marcon[70a,70b], M. Marinescu[20], M. Marjanovic[119], Z. Marshall[17a], S. Marti-Garcia[162], T. A. Martin[166], V. J. Martin[52], B. Martin dit Latour[16], L. Martinelli[74a,74b], M. Martinez[13,u], P. Martinez Agullo[162], V. I. Martinez Outschoorn[102], P. Martinez Suarez[13], S. Martin-Haugh[133], V. S. Martoiu[27b], A. C. Martyniuk[95], A. Marzin[36], S. R. Maschek[109], L. Masetti[99], T. Mashimo[152], J. Masik[100], A. L. Maslennikov[37], L. Massa[23b], P. Massarotti[71a,71b], P. Mastrandrea[73a,73b], A. Mastroberardino[43a,43b], T. Masubuchi[152], T. Mathisen[160], N. Matsuzawa[152], J. Maurer[27b], B. Maček[92], D. A. Maximov[37], R. Mazini[147], I. Maznas[151], M. Mazza[106], S. M. Mazza[135], C. Mc Ginn[29,af], J. P. Mc Gowan[103], S. P. Mc Kee[105], W. P. McCormack[17a], E. F. McDonald[104], A. E. McDougall[113], J. A. Mcfayden[145], G. Mchedlidze[148b], R. P. Mckenzie[33g], T. C. Mclachlan[48], D. J. Mclaughlin[95],

K. D. McLean[164], S. J. McMahon[133], P. C. McNamara[104], C. M. Mcpartland[91], R. A. McPherson[164,w], T. Megy[40], S. Mehlhase[108], A. Mehta[91], B. Meirose[45], D. Melini[149], B. R. Mellado Garcia[33g], A. H. Melo[55], F. Meloni[48], E. D. Mendes Gouveia[129a], A. M. Mendes Jacques Da Costa[20], H. Y. Meng[154], L. Meng[90], S. Menke[109], M. Mentink[36], E. Meoni[43a,43b], C. Merlassino[125], L. Merola[71a,71b], C. Meroni[70a], G. Merz[105], O. Meshkov[37], J. K. R. Meshreki[140], J. Metcalfe[6], A. S. Mete[6], C. Meyer[67], J-P. Meyer[134], M. Michetti[18], R. P. Middleton[133], L. Mijović[52], G. Mikenberg[168], M. Mikestikova[130], M. Mikuž[92], H. Mildner[138], A. Milic[36], C. D. Milke[44], D. W. Miller[39], L. S. Miller[34], A. Milov[168], D. A. Milstead[47a,47b], T. Min[14c], A. A. Minaenko[37], I. A. Minashvili[148b], L. Mince[59], A. I. Mincer[116], B. Mindur[84a], M. Mineev[38], Y. Mino[86], L. M. Mir[13], M. Miralles Lopez[162], M. Mironova[125], M. C. Missio[112], T. Mitani[167], A. Mitra[166], V. A. Mitsou[162], O. Miu[154], P. S. Miyagawa[93], Y. Miyazaki[88], A. Mizukami[82], J. U. Mjörnmark[97], T. Mkrtchyan[63a], T. Mlinarevic[95], M. Mlynarikova[36], T. Moa[47a,47b], S. Mobius[55], K. Mochizuki[107], P. Moder[48], P. Mogg[108], A. F. Mohammed[14a,14d], S. Mohapatra[41], G. Mokgatitswane[33g], B. Mondal[140], S. Mondal[131], K. Mönig[48], E. Monnier[101], L. Monsonis Romero[162], J. Montejo Berlingen[36], M. Montella[118], F. Monticelli[89], N. Morange[66], A. L. Moreira De Carvalho[129a], M. Moreno Llácer[162], C. Moreno Martinez[56], P. Morettini[57b], S. Morgenstern[166], M. Morii[61], M. Morinaga[152], V. Morisbak[124], A. K. Morley[36], F. Morodei[74a,74b], L. Morvaj[36], P. Moschovakos[36], B. Moser[36], M. Mosidze[148b], T. Moskalets[54], P. Moskvitina[112], J. Moss[31,o], E. J. W. Moyse[102], S. Muanza[101], J. Mueller[128], D. Muenstermann[90], R. Müller[19], G. A. Mullier[97], J. J. Mullin[127], D. P. Mungo[154], J. L. Munoz Martinez[13], D. Munoz Perez[162], F. J. Munoz Sanchez[100], M. Murin[100], W. J. Murray[133,166], A. Murrone[70a,70b], J. M. Muse[119], M. Muškinja[17a], C. Mwewa[29], A. G. Myagkov[37,a], A. J. Myers[8], A. A. Myers[128], G. Myers[67], M. Myska[131], B. P. Nachman[17a], O. Nackenhorst[49], A. Nag[50], K. Nagai[125], K. Nagano[82], J. L. Nagle[29,af], E. Nagy[101], A. M. Nairz[36], Y. Nakahama[82], K. Nakamura[82], H. Nanjo[123], R. Narayan[44], E. A. Narayanan[111], I. Naryshkin[37], M. Naseri[34], C. Nass[24], G. Navarro[22a], J. Navarro-Gonzalez[162], R. Nayak[150], A. Nayaz[18], P. Y. Nechaeva[37], F. Nechansky[48], L. Nedic[125], T. J. Neep[20], A. Negri[72a,72b], M. Negrini[23b], C. Nellist[112], C. Nelson[103], K. Nelson[105], S. Nemecek[130], M. Nessi[36,h], M. S. Neubauer[161], F. Neuhaus[99], J. Neundorf[48], R. Newhouse[163], P. R. Newman[20], C. W. Ng[128], Y. S. Ng[18], Y. W. Y. Ng[48], B. Ngair[35e], H. D. N. Nguyen[107], R. B. Nickerson[125], R. Nicolaidou[134], J. Nielsen[135], M. Niemeyer[55], N. Nikiforou[36], V. Nikolaenko[37,a], I. Nikolic-Audit[126], K. Nikolopoulos[20], P. Nilsson[29], H. R. Nindhito[56], A. Nisati[74a], N. Nishu[2], R. Nisius[109], J-E. Nitschke[50], E. K. Nkadimeng[33g], S. J. Noacco Rosende[89], T. Nobe[152], D. L. Noel[32], Y. Noguchi[86], T. Nommensen[146], M. A. Nomura[29], M. B. Norfolk[138], R. R. B. Norisam[95], B. J. Norman[34], J. Novak[92], T. Novak[48], O. Novgorodova[50], L. Novotny[131], R. Novotny[111], L. Nozka[121], K. Ntekas[159], N. M. J. Nunes De Moura Junior[81b], E. Nurse[95], F. G. Oakham[34,ac], J. Ocariz[126], A. Ochi[83], I. Ochoa[129a], S. Oerdek[160], A. Ogrodnik[84a], A. Oh[100], C. C. Ohm[143], H. Oide[153], R. Oishi[152], M. L. Ojeda[48], Y. Okazaki[86], M. W. O'Keefe[91], Y. Okumura[152], A. Olariu[27b], L. F. Oleiro Seabra[129a], S. A. Olivares Pino[136e], D. Oliveira Damazio[29], D. Oliveira Goncalves[81a], J. L. Oliver[159], M. J. R. Olsson[159], A. Olszewski[85], J. Olszowska[85,*], Ö. O. Öncel[54], D. C. O'Neil[141], A. P. O'Neill[19], A. Onofre[129a,129e], P. U. E. Onyisi[11], M. J. Oreglia[39], G. E. Orellana[89], D. Orestano[76a,76b], N. Orlando[13], R. S. Orr[154], V. O'Shea[59], R. Ospanov[62a], G. Otero y Garzon[30], H. Otono[88], P. S. Ott[63a], G. J. Ottino[17a], M. Ouchrif[35d], J. Ouellette[29,af], F. Ould-Saada[124], M. Owen[59], R. E. Owen[133], K. Y. Oyulmaz[21a], V. E. Ozcan[21a], N. Ozturk[8], S. Ozturk[21d], J. Pacalt[121], H. A. Pacey[32], K. Pachal[51], A. Pacheco Pages[13], C. Padilla Aranda[13], G. Padovano[74a,74b], S. Pagan Griso[17a], G. Palacino[67], A. Palazzo[69a,69b], S. Palazzo[52], S. Palestini[36], M. Palka[84b], J. Pan[171], T. Pan[64a], D. K. Panchal[11], C. E. Pandini[113], J. G. Panduro Vazquez[94], H. Pang[14b], P. Pani[48], G. Panizzo[68a,68c], L. Paolozzi[56], C. Papadatos[107], S. Parajuli[44], A. Paramonov[6], C. Paraskevopoulos[10], D. Paredes Hernandez[64b], T. H. Park[154], M. A. Parker[32], F. Parodi[57a,57b], E. W. Parrish[114], V. A. Parrish[52], J. A. Parsons[41], U. Parzefall[54], B. Pascual Dias[107], L. Pascual Dominguez[150], V. R. Pascuzzi[17a], F. Pasquali[113], E. Pasqualucci[74a], S. Passaggio[57b], F. Pastore[94], P. Pasuwan[47a,47b], P. Patel[85], J. R. Pater[100], J. Patton[91], T. Pauly[36], J. Pearkes[142], M. Pedersen[124], R. Pedro[129a], S. V. Peleganchuk[37], O. Penc[36], E. A. Pender[52], C. Peng[64b], H. Peng[62a], K. E. Penski[108], M. Penzin[37], B. S. Peralva[81d,81d], A. P. Pereira Peixoto[60], L. Pereira Sanchez[47a,47b], D. V. Perepelitsa[29,af], E. Perez Codina[155a], M. Perganti[10], L. Perini[70a,70b,*], H. Pernegger[36], S. Perrella[36], A. Perrevoort[112], O. Perrin[40], K. Peters[48], R. F. Y. Peters[100], B. A. Petersen[36], T. C. Petersen[42], E. Petit[101], V. Petousis[131], C. Petridou[151], A. Petrukhin[140], M. Pettee[17a], N. E. Pettersson[36], A. Petukhov[37], K. Petukhova[132], A. Peyaud[134], R. Pezoa[136f], L. Pezzotti[36],

G. Pezzullo[171], T. M. Pham[169], T. Pham[104], P. W. Phillips[133], M. W. Phipps[161], G. Piacquadio[144], E. Pianori[17a], F. Piazza[70a,70b], R. Piegaia[30], D. Pietreanu[27b], A. D. Pilkington[100], M. Pinamonti[68a,68c], J. L. Pinfold[2], B. C. Pinheiro Pereira[129a], C. Pitman Donaldson[95], D. A. Pizzi[34], L. Pizzimento[75a,75b], A. Pizzini[113], M. -A. Pleier[29], V. Plesanovs[54], V. Pleskot[132], E. Plotnikova[38], G. Poddar[4], R. Poettgen[97], L. Poggioli[126], I. Pogrebnyak[106], D. Pohl[24], I. Pokharel[55], S. Polacek[132], G. Polesello[72a], A. Poley[141,155a], R. Polifka[131], A. Polini[23b], C. S. Pollard[125], Z. B. Pollock[118], V. Polychronakos[29], E. Pompa Pacchi[74a,74b], D. Ponomarenko[37], L. Pontecorvo[36], S. Popa[27a], G. A. Popeneciu[27d], D. M. Portillo Quintero[155a], S. Pospisil[131], P. Postolache[27c], K. Potamianos[125], I. N. Potrap[38], C. J. Potter[32], H. Potti[1], T. Poulsen[48], J. Poveda[162], M. E. Pozo Astigarraga[36], A. Prades Ibanez[162], M. M. Prapa[46], J. Pretel[54], D. Price[100], M. Primavera[69a], M. A. Principe Martin[98], R. Privara[121], M. L. Proffitt[137], N. Proklova[127], K. Prokofiev[64c], G. Proto[75a,75b], S. Protopopescu[29], J. Proudfoot[6], M. Przybycien[84a], J. E. Puddefoot[138], D. Pudzha[37], P. Puzo[66], D. Pyatiizbyantseva[37], J. Qian[105], D. Qichen[100], Y. Qin[100], T. Qiu[93], A. Quadt[55], M. Queitsch-Maitland[100], G. Quetant[56], G. Rabanal Bolanos[61], D. Rafanoharana[54], F. Ragusa[70a,70b], J. L. Rainbolt[39], J. A. Raine[56], S. Rajagopalan[29], E. Ramakoti[37], K. Ran[48,14d], N. P. Rapheeha[33g], V. Raskina[126], D. F. Rassloff[63a], S. Rave[99], B. Ravina[55], I. Ravinovich[168], M. Raymond[36], A. L. Read[124], N. P. Readioff[138], D. M. Rebuzzi[72a,72b], G. Redlinger[29], K. Reeves[45], J. A. Reidelsturz[170], D. Reikher[150], A. Reiss[99], A. Rej[140], C. Rembser[36], A. Renardi[48], M. Renda[27b], M. B. Rendel[109], F. Renner[48], A. G. Rennie[59], S. Resconi[70a], M. Ressegotti[57a,57b], E. D. Resseguie[17a], S. Rettie[36], B. Reynolds[118], E. Reynolds[17a], M. Rezaei Estabragh[170], O. L. Rezanova[37], P. Reznicek[132], E. Ricci[77a,77b], R. Richter[109], S. Richter[47a,47b], E. Richter-Was[84b], M. Ridel[126], P. Rieck[116], P. Riedler[36], M. Rijssenbeek[144], A. Rimoldi[72a,72b], M. Rimoldi[48], L. Rinaldi[23a,23b], T. T. Rinn[29], M. P. Rinnagel[108], G. Ripellino[143], I. Riu[13], P. Rivadeneira[48], J. C. Rivera Vergara[164], F. Rizatdinova[120], E. Rizvi[93], C. Rizzi[56], B. A. Roberts[166], B. R. Roberts[17a], S. H. Robertson[103,w], M. Robin[48], D. Robinson[32], C. M. Robles Gajardo[136f], M. Robles Manzano[99], A. Robson[59], A. Rocchi[75a,75b], C. Roda[73a,73b], S. Rodriguez Bosca[63a], Y. Rodriguez Garcia[22a], A. Rodriguez Rodriguez[54], A. M. Rodríguez Vera[155b], S. Roe[36], J. T. Roemer[159], A. R. Roepe-Gier[119], J. Roggel[170], O. Røhne[124], R. A. Rojas[164], B. Roland[54], C. P. A. Roland[67], J. Roloff[29], A. Romaniouk[37], E. Romano[72a,72b], M. Romano[23b], A. C. Romero Hernandez[161], N. Rompotis[91], L. Roos[126], S. Rosati[74a], B. J. Rosser[39], E. Rossi[4], E. Rossi[71a,71b], L. P. Rossi[57b], L. Rossini[48], R. Rosten[118], M. Rotaru[27b], B. Rottler[54], D. Rousseau[66], D. Rousso[32], G. Rovelli[72a,72b], A. Roy[161], A. Rozanov[101], Y. Rozen[149], X. Ruan[33g], A. Rubio Jimenez[162], A. J. Ruby[91], V. H. Ruelas Rivera[18], T. A. Ruggeri[1], F. Rühr[54], A. Ruiz-Martinez[162], A. Rummler[36], Z. Rurikova[54], N. A. Rusakovich[38], H. L. Russell[164], J. P. Rutherfoord[7], K. Rybacki[90], M. Rybar[132], E. B. Rye[124], A. Ryzhov[37], J. A. Sabater Iglesias[56], P. Sabatini[162], L. Sabetta[74a,74b], H. F-W. Sadrozinski[135], F. Safai Tehrani[74a], B. Safarzadeh Samani[145], M. Safdari[142], S. Saha[103], M. Sahinsoy[109], M. Saimpert[134], M. Saito[152], T. Saito[152], D. Salamani[36], G. Salamanna[76a,76b], A. Salnikov[142], J. Salt[162], A. Salvador Salas[13], D. Salvatore[43a,43b], F. Salvatore[145], A. Salzburger[36], D. Sammel[54], D. Sampsonidis[151], D. Sampsonidou[62c,62d], J. Sánchez[162], A. Sanchez Pineda[4], V. Sanchez Sebastian[162], H. Sandaker[124], C. O. Sander[48], J. A. Sandesara[102], M. Sandhoff[170], C. Sandoval[22b], D. P. C. Sankey[133], A. Sansoni[53], L. Santi[74a,74b], C. Santoni[40], H. Santos[129a,129b], S. N. Santpur[17a], A. Santra[168], K. A. Saoucha[138], J. G. Saraiva[129a,129d], J. Sardain[7], O. Sasaki[82], K. Sato[156], C. Sauer[63b], F. Sauerburger[54], E. Sauvan[4], P. Savard[154,ac], R. Sawada[152], C. Sawyer[133], L. Sawyer[96], I. Sayago Galvan[162], C. Sbarra[23b], A. Sbrizzi[23a,23b], T. Scanlon[95], J. Schaarschmidt[137], P. Schacht[109], D. Schaefer[39], U. Schäfer[99], A. C. Schaffer[66], D. Schaile[108], R. D. Schamberger[144], E. Schanet[108], C. Scharf[18], M. M. Schefer[19], V. A. Schegelsky[37], D. Scheirich[132], F. Schenck[18], M. Schernau[159], C. Scheulen[55], C. Schiavi[57a,57b], Z. M. Schillaci[26], E. J. Schioppa[69a,69b], M. Schioppa[43a,43b], B. Schlag[99], K. E. Schleicher[54], S. Schlenker[36], M. A. Schmidt[170], K. Schmieden[99], C. Schmitt[99], S. Schmitt[48], L. Schoeffel[134], A. Schoening[63b], P. G. Scholer[54], E. Schopf[125], M. Schott[99], J. Schovancova[36], S. Schramm[56], F. Schroeder[170], H-C. Schultz-Coulon[63a], M. Schumacher[54], B. A. Schumm[135], Ph. Schune[134], A. Schwartzman[142], T. A. Schwarz[105], Ph. Schwemling[134], R. Schwienhorst[106], A. Sciandra[135], G. Sciolla[26], F. Scuri[73a], F. Scutti[104], C. D. Sebastiani[91], K. Sedlaczek[49], P. Seema[18], S. C. Seidel[111], A. Seiden[135], B. D. Seidlitz[41], T. Seiss[39], C. Seitz[48], J. M. Seixas[81b], G. Sekhniaidze[71a], S. J. Sekula[44], L. Selem[4], N. Semprini-Cesari[23a,23b], S. Sen[51], D. Sengupta[56], V. Senthilkumar[162], L. Serin[66], L. Serkin[68a,68b], M. Sessa[76a,76b], H. Severini[119], S. Sevova[142], F. Sforza[57a,57b], A. Sfyrla[56], E. Shabalina[55], R. Shaheen[143], J. D. Shahinian[127], N. W. Shaikh[47a,47b], D. Shaked Renous[168], L. Y. Shan[14a], M. Shapiro[17a], A. Sharma[36],

A. S. Sharma[163], P. Sharma[79], S. Sharma[48], P. B. Shatalov[37], K. Shaw[145], S. M. Shaw[100], Q. Shen[62c,5], P. Sherwood[95], L. Shi[95], C. O. Shimmin[171], Y. Shimogama[167], J. D. Shinner[94], I. P. J. Shipsey[125], S. Shirabe[60], M. Shiyakova[38], J. Shlomi[168], M. J. Shochet[39], J. Shojaii[104], D. R. Shope[124], S. Shrestha[118,ag], E. M. Shrif[33g], M. J. Shroff[164], P. Sicho[130], A. M. Sickles[161], E. Sideras Haddad[33g], A. Sidoti[23b], F. Siegert[50], Dj. Sijacki[15], R. Sikora[84a], F. Sili[89], J. M. Silva[20], M. V. Silva Oliveira[36], S. B. Silverstein[47a], S. Simion[66], R. Simoniello[36], E. L. Simpson[59], N. D. Simpson[97], S. Simsek[21d], S. Sindhu[55], P. Sinervo[154], V. Sinetckii[37], S. Singh[141], S. Singh[154], S. Sinha[48], S. Sinha[33g], M. Sioli[23a,23b], I. Siral[36], S. Yu. Sivoklokov[37,*], J. Sjölin[47a,47b], A. Skaf[55], E. Skorda[97], P. Skubic[119], M. Slawinska[85], V. Smakhtin[168], B. H. Smart[133], J. Smiesko[36], S. Yu. Smirnov[37], Y. Smirnov[37], L. N. Smirnova[37,a], O. Smirnova[97], A. C. Smith[41], E. A. Smith[39], H. A. Smith[125], J. L. Smith[91], R. Smith[142], M. Smizanska[90], K. Smolek[131], A. Smykiewicz[85], A. A. Snesarev[37], H. L. Snoek[113], S. Snyder[29], R. Sobie[164,w], A. Soffer[150], C. A. Solans Sanchez[36], E. Yu. Soldatov[37], U. Soldevila[162], A. A. Solodkov[37], S. Solomon[54], A. Soloshenko[38], K. Solovieva[54], O. V. Solovyanov[37], V. Solovyev[37], P. Sommer[36], A. Sonay[13], W. Y. Song[155b], A. Sopczak[131], A. L. Sopio[95], F. Sopkova[28b], V. Sothilingam[63a], S. Sottocornola[72a,72b], R. Soualah[115b], Z. Soumaimi[35e], D. South[48], S. Spagnolo[69a,69b], M. Spalla[109], F. Spanò[94], D. Sperlich[54], G. Spigo[36], M. Spina[145], S. Spinali[90], D. P. Spiteri[59], M. Spousta[132], E. J. Staats[34], A. Stabile[70a,70b], R. Stamen[63a], M. Stamenkovic[113], A. Stampekis[20], M. Standke[24], E. Stanecka[85], M. V. Stange[50], B. Stanislaus[17a], M. M. Stanitzki[48], M. Stankaityte[125], B. Stapf[48], E. A. Starchenko[37], G. H. Stark[135], J. Stark[101], D. M. Starko[155b], P. Staroba[130], P. Starovoitov[63a], S. Stärz[103], R. Staszewski[85], G. Stavropoulos[46], J. Steentoft[160], P. Steinberg[29], A. L. Steinhebel[122], B. Stelzer[141,155a], H. J. Stelzer[128], O. Stelzer-Chilton[155a], H. Stenzel[58], T. J. Stevenson[145], G. A. Stewart[36], M. C. Stockton[36], G. Stoicea[27b], M. Stolarski[129a], S. Stonjek[109], A. Straessner[50], J. Strandberg[143], S. Strandberg[47a,47b], M. Strauss[119], T. Strebler[101], P. Strizenec[28b], R. Ströhmer[165], D. M. Strom[122], L. R. Strom[48], R. Stroynowski[44], A. Strubig[47a,47b], S. A. Stucci[29], B. Stugu[16], J. Stupak[119], N. A. Styles[48], D. Su[142], S. Su[62a], W. Su[62c,62d,137], X. Su[62a,66], K. Sugizaki[152], V. V. Sulin[37], M. J. Sullivan[91], D. M. S. Sultan[77a,77b], L. Sultanaliyeva[37], S. Sultansoy[3b], T. Sumida[86], S. Sun[105], S. Sun[169], O. 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