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Search for emerging jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS experiment

The ATLAS Collaboration

A search is presented for emerging jets using 140 fb^{-1} of proton–proton collision data at $\sqrt{s} = 13$ TeV, collected by the ATLAS experiment between 2015 and 2018. The search looks for the existence of a dark sector with symmetries similar to those in quantum chromodynamics. This dark sector is populated with dark quarks, which undergo showering similar to quarks in the Standard Model, leading to a high multiplicity of long-lived dark hadrons within a dark jet. These dark hadrons subsequently decay to Standard Model particles via a new heavy scalar mediating particle ϕ. This results in jets which contain multiple displaced vertices, known as emerging jets. This analysis targets four-jet topologies, with two emerging jets and two Standard Model jets, resulting from the decay of pair-produced scalar mediators. No significant excess above the Standard Model background is observed. For dark pion proper decay lengths of 20 mm, mediator masses are excluded between 1 TeV and 2 TeV assuming a dark pion mass of 20 GeV.

Contents

1 Introduction

Although there is a vast body of evidence for the existence of Dark Matter (DM) [1–3], its nature is one of the major unanswered questions in fundamental physics. Many theoretical models of particle DM have been proposed, each with corresponding interactions with the Standard Model (SM). However, after years of searching, no experiment has yet provided evidence of the particle nature of DM [4–12]. This drought of experimental confirmations has prompted the search for more exotic models of DM, including the existence of a *dark sector* (DS). The DS is an extension of the SM which contains new particles that are uncharged under the symmetries of the SM, instead having interactions governed by a new confining DS gauge group [13–15]. Although the DS and SM cannot communicate directly, interactions between DS and SM particles can be mediated by new particles that are charged under both SM and DS symmetries.

Several models propose new DS interactions which resemble quantum chromodynamics (QCD) in the SM, colloquially known as *dark QCD* [16–18]. These DS models contain quark-like particles, with N_f flavours and N_c colours, which transform under a non-Abelian gauge group SU(N_c). This new interaction is characterized by a confining scale (Λ_d) below which dark quarks (Q_d) hadronize, analogously to QCD, to form dark baryons and mesons. The lightest dark baryon could be stable, providing a DM candidate which conforms to the astrophysical evidence, while the lightest dark mesons, *dark pions* (π_d), would be unstable and decay to into SM particles via an exchange of a virtual mediator particle. Depending on the lifetimes of the dark pions, the resulting decay topology can differ greatly, giving rise to three general categories of detector signatures in collider experiments. If some of the dark particles are stable, while others decay promptly, the result is called a *semi-visible jet* [19], where the stable dark particles carry transverse momentum which goes undetected, resulting in missing transverse momentum aligned with the hadronic jets. Conversely, if the dark hadrons decay promptly, the resulting *dark jet* [20] tends to be wider and contain a larger number of charged particles than SM hadronic jets. For lifetimes in the intermediate regime, the dark pions decay within the detector volume but displaced from the initial collision, giving rise to *emerging jets* (EJs) [21] with multiple displaced vertices (DVs) contained in the jet cone. Due to the exponential distribution of the π_d decay times, these DVs occur at varying radial distances, giving rise to the emerging quality of the EJ.

Using the proton–proton (pp) collisions of the LHC, both ATLAS and CMS collaborations have carried out dedicated searches for different dark-QCD scenarios, characterized by various production modes and decay topologies. Both ATLAS and CMS have searched for semi-visible jets in Run 2 data [22–24]. ATLAS has set limits on a search for promptly decaying dark hadrons from the resonant production of dark jets [25]. In Run 1, ATLAS performed a search for hadronic decays of long-lived particles which give a displaced jet signature [26]. In Run 2, CMS performed two searches specifically targeting EJ signatures by looking for pair-produced, *bifundamental*[1], scalar mediators (ϕ) resulting in a four-jet topology [27, 28]. In Run 3 ATLAS produced a search for EJs that focused on the resonant production of a vector mediator (Z') resulting in a two-jet topology [29]. The Run 3 analysis also included an interpretation using t−channel production of the bifundamental scalar mediator with two, three, or four jets in the final state, which causes the production cross-section to be dependent on the Yukawa coupling of the mediator. For dark pions with proper decay length of 10 mm and mass of 10 GeV, the CMS search produced limits which excluded scalar mediator masses up to 1.95 TeV, and the ATLAS search produced limits which excluded vector mediator masses up to 2.55 TeV.

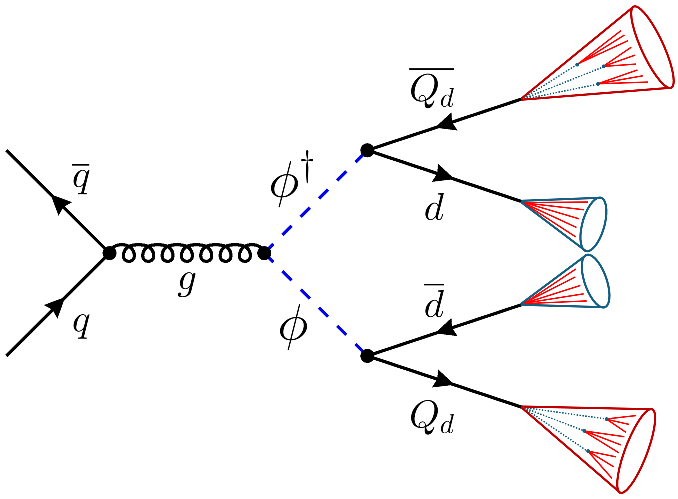


Figure 1: Feynman diagram of the pair-production of dark scalar mediators, ϕ, via quark–antiquark annihilation. The resulting four jets are shown as cones for illustrative purposes. Dashed lines within the cones represent the trajectories of dark pions, solid lines within the cones represent the trajectories of SM particles.

This search looks for pair-produced dark scalar mediators in pp collisions at $\sqrt{s}$ = 13 TeV. The two production modes considered are $q\overline{q}$ annihilation (shown in Figure 1) and gluon–gluon fusion. These

[1] Bifundamental means that it is charged under both the symmetries of Dark QCD and Standard Model QCD as $SU(3)_{QCD} = 3$ and $SU(N_c)_{Dark} = N_c$. Note that the bifundamental scalar is labeled X_d in Ref. [21] and X_{dark} in Ref. [27, 28].

production modes are expected to dominate over $t-$channel production used in the Run 3 search [21]. Both modes proceed via a virtual gluon which produces a pair of dark mediators ($\phi^\dagger\phi$). Each dark mediator immediately decays into a dark quark and a SM quark, both of which hadronize in their corresponding sectors, resulting in a SM jet and an EJ. The final topology is a four jet final state, with two emerging jets and two SM jets. The Yukawa coupling (κ) is assumed to be sufficiently small, that diagrams proportional to κ^4 are ignored.

An *unflavoured* model (similar to the most-minimal model in Ref. [30]) is considered, where the Yukawa coupling between the dark mediator and the SM quark is only non-zero for SM down quarks[2], giving only light SM jets in the final state. The choice of ϕ coupling only to SM down quarks or SM up quarks is arbitrary in the unflavoured model, as both will give only light SM jets in the final state; the down-type coupling is chosen following Ref. [21]. The Run 3 search considered a *flavour-aligned* model of the bifundamental scalar, where the scalar mediator can couple to any down-type standard model quark. This allows for heavy-flavour jets in the final state when kinematically allowed.

A two-stage machine learning (ML) based classifier is used to separate EJ-like events from the dominant QCD multijet background. The contribution from this background is estimated using a data-driven approach based on the ABCD method. Other background processes, such as top quark pair-production, were considered, but their contributions are suppressed to a negligible level by analysis preselections.

The paper is structured in the following way: Section 2 gives a description of the Run 2 configuration of the ATLAS detector, while Section 3 gives an overview of the collected dataset, and the simulated samples produced for this analysis. Sections 4 and 5 detail how the various physics objects are reconstructed, and how events are selected for the analysis. The ML classifier is described in Section 6. Then, Section 7 outlines the background estimation method and Section 8 documents the systematic uncertainties. Finally, the results of the analysis are presented in Section 9 with conclusions given in Section 10.

2 ATLAS detector

The ATLAS detector [31] at the LHC covers nearly the entire solid angle around the collision point.[3] It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets.

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, the first hit generally being in the insertable B-layer (IBL) installed before Run 2 [32, 33]. It is followed by the SemiConductor Tracker (SCT), which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$. The TRT also provides

[2] In addition to $SU(3)_{QCD} = 3$ charge, the mediator has SM $U(1) = \frac{1}{3}$ charge, since it couples to down quarks.

[3] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Polar 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 $\eta = -\ln\tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

electron identification information based on the fraction of hits (typically 30 in total) above a higher energy-deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic energy measurements, respectively.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, cover the region $|\eta| < 2.7$, complemented by cathode-strip chambers in the forward region, where the background is highest. The muon trigger system covers the range $|\eta| < 2.4$ with resistive-plate chambers in the barrel, and thin-gap chambers in the endcap regions.

The luminosity is measured mainly by the LUCID–2 [34] detector that records Cherenkov light produced in the quartz windows of photomultipliers located close to the beampipe.

Events were selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger [35]. The first-level trigger accepted events from the 40 MHz bunch crossings at a rate close to 100 kHz, which the high-level trigger further reduced in order to record complete events to disk at about 1.25 kHz.

A software suite [36] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Data and Simulated Events

This analysis uses 140 fb^{-1} of pp collision data collected at $\sqrt{s} = 13$ TeV by the ATLAS experiment between the years of 2015 and 2018, corresponding to Run 2 of the LHC. The dataset contains only those events recorded during stable beam conditions, with all detector subsystems operating properly. Standard data-quality requirements are used to ensure reliable reconstruction of the physics objects [37].

Monte Carlo (MC) simulation events, generated with Pythia 8.230 [38], are used to optimise the analysis strategy, evaluate the signal efficiency, and test the background estimation methods. Matrix element generation of the hard scattering process and subsequent showering uses the NNPDF2.3lo [39] parton distribution function (PDF) set, with the A14 set of tuned parameters [40]. Pile-up, the effect of multiple interactions in the same and neighbouring bunch crossings, is modelled by combining the results of the simulated hard-scattering event with simulated inelastic pp events generated with Pythia 8.186 [41] and the A3 set of tuned parameters [42]. The interaction of the collision products with the ATLAS detector, and subsequent detector response [36], are modelled by passing MC events through a detailed map of the detector material implemented into Geant4 [43]. MC events then are reconstructed using the same algorithms applied to the data.

3.1 Signal Simulation

Samples of $pp \rightarrow \phi^{\dagger}\phi \rightarrow \overline{Q}_d q Q_d \overline{q}$ are produced at leading-order (LO) using the Hidden Valley [44] implementation in Pythia 8.230, which handles the showering and hadronization of the dark quarks within the DS. Mediator masses ranging from 1 TeV to 2.2 TeV are used, with the corresponding pair-production cross-sections estimated using calculations from Supersymmetry, where stop–antistop pairs are used as a proxy for the dark mediators. The cross-sections are calculated at approximate next-to-next leading-order and next-to-next leading-logarithm (NNLOapprox + NNLL) using NNLL-Fast [45, 46]. Cross-section values are multiplied by a factor of N_c, for the $N_c = 3$ model this gives values in the range from 20.5 fb at $M_\phi = 1$ TeV to 0.015 fb at $M_\phi = 2.2$ TeV. Theoretical uncertainties corresponding to parton distribution functions, QCD scale, and resummation of Coulomb corrections are also produced using NNLL-Fast for each mediator mass.

Benchmark signal models are produced with $N_c = 3, N_f = 7$, following Ref. [21] to ensure a QCD-like DS. For a given N_c, there are a range of values for N_f, such that the running of the dark strong coupling (α_d) is still asymptotically free, $N_f = 7$ is the centre of that range.

The dark confinement scale is used to set the masses of the DS particles with the following scheme: $\Lambda_d = m_{Q_d} = 2\, m_{\pi_d} = \frac{m_{\rho_d}}{2}$. This forces the heavier dark mesons such as the dark rho to decay into dark pions ($\rho_d \rightarrow \pi_d \pi_d$), which occurs within the DS and therefore proceeds quickly. The subsequent dark pion decay to SM down quarks ($\pi_d \rightarrow d\bar{d}$) proceeds via t-channel exchange of a dark mediator. The decay is slow due to the large mass difference between the ϕ and π_d, giving rise to the macroscopic lifetimes of the dark pions. The production of dark baryons, which are suppressed by a factor of $1/N_c^2$ [19], or dark mesons other than the ρ_d and π_d, is not considered.

Three choices of Λ_d are used, corresponding to m_{π_d} values of 5, 10, and 20 GeV. These values ensure that the decay of the dark pion into jets is valid, since lower mass π_d would decay to distinct hadronic final states [47, 48]. For dark pion masses much larger than $O(10)$ GeV, the reduced phase space for dark pion production leads to a more diffuse spray of few dark pions giving a displaced jet signature, while this analysis targets the emerging jets signature with a collimated spray of many dark pions.

The dark pion lifetime ($c\tau_{\pi_d}$), as a function of the other phenomenological parameters of the model, is given by [21]:

$$c\tau = \frac{80\text{ mm}}{\kappa^4}\left(\frac{2\text{ GeV}}{f_{\pi_d}}\right)^2\left(\frac{100\text{ MeV}}{m_q^{\text{SM}}}\right)^2\left(\frac{2\text{ GeV}}{m_{\pi_d}}\right)\left(\frac{M_\phi}{1\text{ TeV}}\right)^4 \quad (1)$$

where κ is the Yukawa coupling between the dark mediator and the quarks, f_{π_d} is the dark pion decay constant (analogous to the pion decay constant in the SM), and m_q^{SM} is the mass of the SM quark which the mediator couples to (in this case the SM down quark). A consistent set of dark pion lifetimes can be set for each choice of M_ϕ or m_{π_d} by varying the Yukawa coupling. Samples are produced for proper decay lengths between 1 mm and 1000 mm, such that the majority of the dark pions decay within the tracking detectors. Table 1 gives a summary of the model parameters used in the signal MC samples for this analysis.

Table 1: Signal model parameters used to give the model grid for the analysis.

M_ϕ [TeV]	1.0, 1.4, 1.6, 1.8, 2.0, 2.2
m_{π_d} [GeV]	5, 10, 20
$c\tau_{\pi_d}$ [mm]	1, 2, 5, 20, 75, 150, 300, 500, 1000

3.2 Background Simulation

While the background estimation strategy described in Section 7 is fully data-driven, background MC samples are produced to optimise the analysis methodology.

The multijet QCD background [49] was generated using Pythia 8.230 with dijet production matrix elements calculated at LO. The NNPDF2.3lo PDF set is used for matrix element generation, showering, and multi-parton interactions, with the A14 set of parameters.

Samples of $t\bar{t}$ events were used to determine their contribution to the background. These were produced at next-to-leading-order (NLO) with Powheg Box v2 [50–52] using $h_{\text{damp}} = 1.5\, m_t$ [53], then interfaced with Pythia 8.230 for parton showering and hadronization. The decays of hadrons containing b and c quarks common in $t\bar{t}$ decays are performed by EvtGen 1.6.0 [54]. The contribution of $t\bar{t}$ events are negligible after the analysis selections (described in Section 5), and therefore are not considered in the background estimate.

4 Event Reconstruction

The standard ATLAS track reconstruction in Run 2 uses a combinatorial Kalman filter [55] to create tracks from energy deposits in the ID. It is optimised for reconstructing tracks from prompt charged particles with $p_{\text{T}} > 500$ MeV and transverse impact parameters (d_0) less than 10 mm, but is largely insensitive to tracks which are displaced from the interaction point (IP) as a result of the decay of neutral long-lived particles. In order to increase the tracking acceptance to displaced signatures, a secondary reconstruction for large impact parameter tracks is performed on hits in the ID not associated with tracks from the standard track reconstruction. This dedicated Large Radius Tracking (LRT) [56] greatly relaxes the impact parameter selection to $|d_0| < 300$ mm, with a stricter momentum requirement of $p_{\text{T}} > 900$ MeV.

Events are required to have a primary vertex, associated to the hard scatter interaction, which must have at least two tracks associated with it [57]. Because there may be several interaction vertices within the event, the primary interaction vertex is selected as the one with the largest $\sum p_{\text{T}}^2$ of all associated standard tracks.

Secondary displaced vertices (DVs) are reconstructed using a dedicated algorithm seeded with tracks from both the standard and LRT track collections [58]. In order to mitigate the contribution of background DVs from SM processes, material interactions, and fakes, a series of analysis-specific requirements were defined which apply successive selections to the DVs. These aim to reject background DVs while maintaining high efficiency of selecting signal DVs. The first selections are on the radial and longitudinal position of the DV, restricting DVs to where the LRT tracking is efficient, $r_{\text{DV}} < 300$ mm and $|z_{\text{DV}}| < 300$ mm. Next, to reduce the contribution from long-lived neutral kaons (K_S^0), the DVs are required to have $m_{\text{DV}} > 0.7$ GeV, where the mass is computed as the invariant mass of the sum of the four-momenta of all tracks associated to the DV, where each track is assumed to be from a SM charged pion. The effect of random track crossings being reconstructed as DVs is limited by applying requirements on the minimum of the impact parameters of all tracks matched to the DV ($\min|d_0| < 10$ mm, $\min|z_0| < 100$ mm), and the transverse momenta ($p_{\text{T}}^{\text{DV}} > 2.5$ GeV) of the reconstructed DVs. Selections on the associated uncertainties of the impact parameters ($\sigma_{d_0} < 0.25$ mm, $\sigma_{z_0} < 2.25$ mm) help to remove DVs reconstructed from LRT fakes. Finally, a map of the ID material obtained with Run 2 data [59] is used to veto DVs which are located in regions of known detector material.

Jets are reconstructed using energy deposits in the calorimeters. Topological clusters [60, 61] are reconstructed into jets using the anti-k_t algorithm using a distance parameter of $R = 0.4$, and are calibrated at the electromagnetic scale. In order to be counted in the jet collection, jets are required to have $p_{\mathrm{T}} > 50$ GeV and $|\eta| < 2.7$.

Additionally, jets containing b-hadrons (b-jets) are tagged using the DL1r algorithm [62], passing the 85% efficiency working point, and are used to estimate the contribution of heavy-flavour within the multijet QCD background. In order to keep jets with associated displaced tracks, which are expected with the emerging jets topology, no attempt is made to match jets to the primary vertex.

5 Event Selection

Events are selected using an unprescaled trigger which requires at least 4 jets with a p_{T} threshold of 120 GeV [63]. The trigger has a Level 1 requirement of three jets that each deposit at least 50 GeV of transverse energy, within a region of 0.8×0.8 in $\eta - \phi$ space [64, 65] in the calorimeters. As described above, the analysis uses a set of reconstruction techniques which were non-standard and computationally expensive in Run 2. Thus, this special reconstruction was only run on events which passed the baseline topology requirements of at least four jets, each with transverse momentum $p_{\mathrm{T}} > 120$ GeV and $|\eta| < 2.4$. Events matching this topology are selected using jets before calibration, which is applied after reconstruction.

A dedicated emerging jets trigger was implemented in Run 3, which allowed for the analysis in Ref. [29] to increase their sensitivities to lower jet multiplicity topologies. However, in Run 2, only the 4-jet trigger provided sufficient background rejection to allow for sensitivity to the emerging jets models.

Requirements are imposed on the four highest p_{T} jets within the event to ensure an emerging jet-like topology. The scalar sum p_{T} of these jets (H_{T}) is required to be greater than 1 TeV. At least one of the four highest p_{T} jets is also required to have a well-defined prompt track fraction (PTF):

$$\mathrm{PTF} = \frac{1}{p_{\mathrm{T}}^{\mathrm{Jet}}} \sum_{i \in \mathrm{tracks}} \left(p_{\mathrm{T},i} \middle| \frac{|d_{0,i}|}{\sigma_{d_{0},i}} < 3 \right). \tag{2}$$

For jets within $|\eta| < 2$, the PTF is computed if at least one standard track with $p_{\mathrm{T}}^{\mathrm{Track}} \geq 2$ GeV can be matched within $\Delta R < 0.4$, even if it does not meet the promptness criterion of the d_0 significance.

Finally, events are required to have at least one displaced vertex, passing all the selections defined above, which is matched to a reconstructed jet. Jet-matching for DVs is done using a loosened angular distance criterion of $\Delta R < 0.6$. This is done to account for the potential of jet-splitting within the EJs, where certain combinations of model parameters result in more diffuse sprays of high energy dark pions, which can potentially be reconstructed as individual jets, rather than a single emerging jet. This effect both inflates the jet multiplicity (N_{Jet}) of the event and decreases the displaced vertex multiplicity of the reconstructed jets.

6 Machine Learning Classifier

The analysis uses a two-stage ML approach using boosted decision trees (BDTs) implemented with the Toolkit for Multivariate Analysis (`TMVA`) [66]. The first step trains a BDT on jet-level information to select

EJ candidates, while the second step uses a BDT trained on event-level information, including the BDT scores of the four highest p_T jets, to separate EJ signal events from SM multijet background. A cut-based version of the analysis, which is not optimized to the same degree as the ML strategy, is described in Appendix A and included in HEPData to aid with reinterpretation of the results.

In order to avoid biasing the results, both signal and background events which pass the selections defined in Section 5 are separated into two equal sets. The first set is used only for training both stages of the BDT and the second is used for testing. While the two sets are statistically independent, their BDT response distributions are consistent within the MC statistical uncertainties, showing the classifier is not overtrained. Both the jet- and event-level BDTs are trained on all of the signal MC samples mixed together, with background events sampled equally from across the full p_T spectrum of the multijet MC. The full training set comprises over 9 million events.

The jet-level BDT is trained on each of the four highest p_T jets in the event, using the jet-level observables given in Table 2. After training, the individual jet-level BDT responses (R_{Jet}) of the four highest p_T jets are used as inputs to the event-level BDT.

Table 2: List of variables used in training for the jet-level boosted decision tree.

Observable	Description
E_{Jet}	Jet energy, measured directly from calorimeter deposits
$m_{\text{Jet}} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i\right)^2}$	Jet mass, invariant mass from the sum of topological clusters
$W_{\text{Jet}} = \frac{1}{p_T^{\text{Jet}}} \sum_i p_{T,i} \Delta R_i$	Jet width, p_T-weighted angular spread of topological clusters
η_{Jet}	Jet pseudorapidity

In addition to the four highest p_T jet BDT responses, the event-level BDT takes several observables which are used to help separate signal and background. The full list is summarized in Table 3. One of the observables, transverse sphericity (S_T), is an isotropy measure [67], which characterizes the shape of the event. Background events, for which the majority of the event activity is concentrated in the two highest p_T jets (often balanced in the transverse plane), are expected to have values of S_T close to 0. On the other hand, signal events tend to have a larger multiplicity of jets arranged more isotropically, leading to transverse sphericity values closer to 1.

Table 3: List of variables used in training for the event-level boosted decision tree.

Observable	Description
R_{Jet}^{1-4}	BDT response of the four highest p_T jets, individually
$H_T = \sum_{j=1}^{4} p_{T,j}$	Scalar sum of the four highest p_T jet transverse momenta
minPTF	The minimum PTF value in the four highest p_T jets
N_{Jet}	Reconstructed jet multiplicity
S_T	Transverse Sphericity

Figure 2 shows the event-level BDT response observable (R) evaluated on background MC and a selection of signal models. In general, models with higher M_ϕ and intermediate $c\tau_{\pi_d}$ are better separated from multijet background. The BDT is largely insensitive to m_{π_d}, with the 10 and 20 GeV models being only slightly better separated than the 5 GeV models.

An additional selection of $R > -0.2$ is applied to improve the background estimation discussed in Section 7. This requirement removes mainly background events, with at most 0.1‰ impact on the signal efficiency.

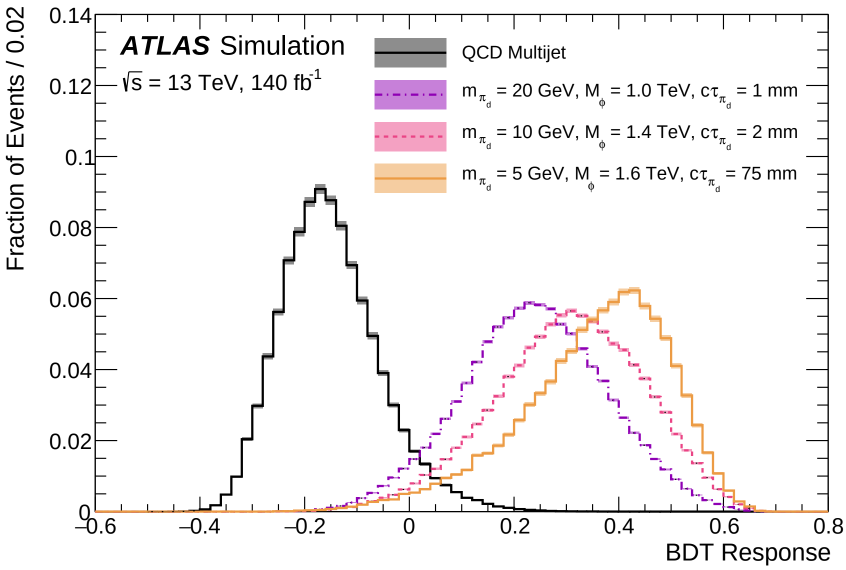


Figure 2: Normalized event-level BDT response distribution for the QCD multijet background, with three selected signal samples for comparison.

7 Background Estimation

The dominant background for this analysis is QCD multijet production. However, these processes are difficult to properly model in simulation, thus the background estimate is produced using a data driven technique modified from the ABCD method.

The ABCD method employs a 2D parameter space divided into four regions (labelled A, B, C, and D) by applying selection criteria on each of the two variables. If the background distributions of these variables are independent, the ratios of expected background yields are related by: $\frac{N_A}{N_B} = \frac{N_C}{N_D}$. If the plane is designed such that the background primarily populates regions B, C, and D (labelled control regions, CRs), while the signal is concentrated in region A (labelled signal region, SR), the background yield in the SR can be estimated as:

$$N_A = N_B \times \frac{N_C}{N_D} \tag{3}$$

When performing the final statistical analysis, any signal contamination in the CRs is accounted for using a simultaneous fit, as described in Section 9.

The ABCD plane is defined using the event-level BDT response and the number of jet-matched displaced vertices in the event (N_{DV}). The distributions of events in the ABCD plane are shown for data and an example signal model in Figure 3. The SR is defined by $R \geq 0.2$ and $N_{\mathrm{DV}} \geq 2$. Control regions B and C are defined by inverting one of the two selections, and region D is defined by inverting both selections. For signal models with $M_\phi = 1.6$ TeV and $m_{\pi_d} = 10$ GeV, the full set of SR selections have efficiencies which vary between 1.4% for $c\tau_{\pi_d} = 1000$ mm and 72% for $c\tau_{\pi_d} = 20$ mm.

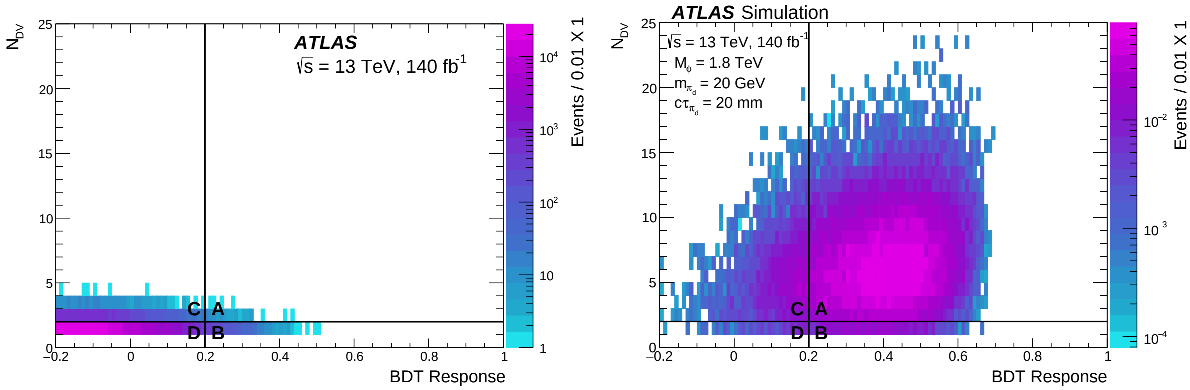


Figure 3: Distributions of events in the ABCD plane for (left) Run 2 data and (right) an example signal model with parameters: $m_{\pi_d} = 20$ GeV, $M_\phi = 1.8$ TeV, and $c\tau_{\pi_d} = 20$ mm. The signal events are scaled to the pair-production cross-section for $pp \to \phi^\dagger\phi$ at $M_\phi = 1.8$ TeV, and normalized to the integrated luminosity of the dataset.

To account for non-negligible correlations between the two variables, CRs C and D are subdivided and the ratio $\frac{N_C}{N_D}$ is calculated in each subdivision. This is then fit with a two-parameter linear function which can be extrapolated into the SR. This function then replaces the ratio in Equation 3, to become:

$$N_A = (p_0 \cdot R_B + p_1) \times N_B \tag{4}$$

where p_0 and p_1 are the slope and y-intercept of the linear function, respectively, and R_B is the event-weighted mean BDT response value within region B. The statistical uncertainty on the background estimation is a combination of the propagated statistical uncertainties from the fit parameters and the statistical uncertainty from the counts in region B. This corresponds to an uncertainty of 5% on the final background estimate.

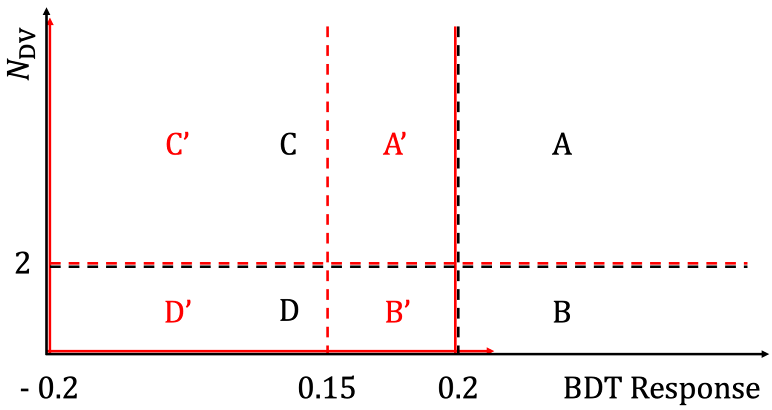


Figure 4: Schematic diagram of the Shifted-ABCD VR constructed in CRs C and D. The four new regions are shown in red, and labeled A', B', C', and D'. The actual ABCD plane regions are shown in black for comparison.

In order to validate the background estimation method, two validation regions (VRs) are constructed. The Low-H_T VR is defined by inverting the H_T requirement used in the event selection to be $H_T < 1$ TeV, while keeping the other selections in place. This allowed for the construction of another ABCD plane using a background enriched region where data could be analysed without biasing the method. The Low-H_T VR is further restricted to be between 775 GeV $\leq H_T <$ 1000 GeV to ensure good modelling, which rapidly deteriorates at lower H_T values. Since the H_T requirement is inverted, signal contamination in the Low-H_T VR is below 0.001% for all signal models.

The second VR is constructed using CRs C and D from the ABCD plane, which have the largest contribution of background events, and the smallest signal contamination. The Shifted-ABCD VR, shown in Figure 4, is defined with an additional selection on the BDT response, along with the same selection on N_{DV} used in the actual ABCD plane, to define four new regions. The pseudo-signal region A' is defined for $0.15 \leq R < 0.2$ and $N_{DV} \geq 2$, with the corresponding primed CRs defined by inverting one or both of the selections. Since it is much closer to the actual SR, signal contamination is slightly higher in region A' than in the Low-H_T VR, however, all models still contribute less than 10% of the total MC event yield.

The predicted and observed counts in the SRs of both the Low-H_T VR and the Shifted-ABCD VR are given in Table 4. The modified ABCD method is shown to predict background contributions which agree with the observed yields within their respective uncertainties.

Table 4: Predicted and observed counts in the A' regions of the Low-H_T VR and the Shifted-ABCD VR, using the modified ABCD method. Quoted uncertainties are statistical only.

Region	Low-H_T VR	Shifted-ABCD VR
Predicted Counts	25 ± 3	215 ± 8
Observed Counts	24	209

The relative difference of 3% between the predicted and observed background yields in region A' of the Shifted-ABCD VR is used as a systematic uncertainty for potential non-closure of the modifed ABCD method in the actual SR. Both the statistical uncertainty and the systematic uncertainty on the background estimation method are included separately in the statistical analysis (discussed in Section 9).

The closure of the modified ABCD method was also tested using QCD multijet simulation. Good agreement of the predicted and observed event yields in the SR was found, both inclusively, and when tested on heavy-flavour QCD production by selecting events where at least one of the four highest p_T jets is b-tagged using either the DL1r classifier or truth-level information.

8 Signal Systematic Uncertainties

Experimental uncertainties relating to instrumentation or reconstruction are assigned to the modelling of simulated signal samples. These systematic uncertainties include contributions from jets, tracks and displaced vertices, luminosity, as well as a dedicated uncertainty for the prompt track fraction.

The systematic associated with jets has contributions from the jet energy scale (JES), jet energy resolution (JER) [68], and jet mass scale (JMS) [69]. Jets are varied within the uncertainties for each of these contributions and the effects are propagated to the final signal yield. The resulting uncertainty depends primarily on the mediator mass of the signal sample, with dark pion lifetime having a larger effect at smaller mediator masses. The combined systematic varies between 1% for $M_\phi = 2.2$ TeV and 13% for $M_\phi = 1$ TeV.

Uncertainties from tracks and displaced vertices are derived from a combination of sources to account for both the standard and large-radius tracks. The uncertainty from LRT is derived from comparisons of events consistent with $K^0_S \rightarrow \pi^+\pi^-$ between simulation and data, and follows a prescription defined in Ref. [70]. To assess the impact, the track collection is varied according to these differences, summed in quadrature with the 1.7% systematic uncertainty associated with standard tracking [71], and then vertex reconstruction is repeated using the altered set of tracks. These changes are eventually propagated to track and DV observables, in particular N_{DV}, which gives the dominant source of uncertainty. In this case, the dark pion lifetime has the biggest impact on the size of the uncertainty, which varies between 0.5% for $c\tau_{\pi_d} = 2$ mm and 39% for $c\tau_{\pi_d} = 1000$ mm. The mediator mass also has an impact on the systematic uncertainty, since lower M_ϕ result in lower multiplicities of dark pions.

The dedicated systematic uncertainty to cover the modelling of PTF is determined by comparing the distribution of minPTF in data and background MC using the Low-H_{T} VR region. Per-event weights are created based on the differences, which are then used to reweight the signal samples. The final uncertainty is taken as the difference in the signal yield and varies between 1% and 12%, where the combination of lower M_ϕ and $c\tau_{\pi_d}$ result in larger uncertainties.

Pile-up conditions during different data-taking periods are modelled by reweighting simulated events, such that the average number of interactions per bunch crossing matches the observed distribution in data. These contributions depend on the inelastic pp cross-section, so the difference between predicted and measured values [72] are propagated as a systematic variation to reweighted events. The pile-up uncertainty varies between 0.3% for $M_\phi = 1$ TeV and 5% for $M_\phi = 2$ TeV.

Signal MC events are scaled to the integrated luminosity of the dataset, and are therefore subject to the uncertainty associated with the measurement of the total luminosity. For the full Run 2 dataset, the uncertainty is 0.8% [73], obtained using the LUCID-2 detector [34].

Theoretical uncertainties relating to the production of the dark mediators are applied to the theoretical cross-sections used for limit-setting in Section 9. These uncertainties are produced using NNLL-Fast [45, 46] along with the corresponding cross-sections, and are roughly proportional to the mediator mass. Values range from 11% at $M_\phi = 1$ TeV to 27% for $M_\phi = 2$ TeV.

The dominant source of uncertainty varies between the different signal models, but in most cases the tracking and vertexing systematic is the leading contribution.

9 Results

The predicted background yield in the SR, determined from the extrapolated fit of the modified ABCD method (described in Section 7), and corresponding observed yield is given in Table 5. No excess above the data-driven background estimate is observed.

In the absence of excess data events, a hypothesis test is performed using a simultaneous likelihood fit which incorporates the methodology of the modified ABCD method, and accounts for any signal leakage into the CRs. Signal and background systematic uncertainties are included in the fit as Gaussian nuisance parameters.

Table 5: Predicted number of background events, including statistical and systematic uncertainties, and observed event yield in the SR.

Event Yield in the SR	
Prediction	112 ± 6 (stat.) ± 4 (syst.)
Observed Yield	103

The likelihood fit is constructed with the product of Poisson probabilities of observing the event yield in each region $i \in \{A, B, C, D\}$ of the ABCD plane, subdivided into j bins across the BDT response ($N^{\text{Obs}}_{i,j}$) in order to perform the linear fit across regions C and D, which is then extrapolated into the regions A and B. The CRs C and D are divided into 8 bins across the BDT response, while the SR and CR B are divided into 4-5 bins, where the number of bins is adjusted to ensure there are sufficient data events in each bin of region B. The expected number of events in a given bin of region A ($N^{\text{Exp}}_{A,j}$) is then given by:

$$N^{\text{Exp}}_{A,j} = (p_0 \cdot R_j + p_1) \times N^{\text{Exp}}_{B,j} + \mu \cdot N^{\text{Sig}}_{A,j} \quad (5)$$

where p_0 and p_1 are again the slope and y-intercept, respectively, of the linear fit extracted from the subdivided regions C and D. R_j is the event weighted mean value of the BDT response within the j bin of region B. The signal strength parameter, μ, is fit simultaneously across the entire ABCD plane, and $N^{\text{Sig}}_{A,j}$ is the expected signal contribution in each bin of A, taken from signal MC. The agreement between the extrapolated background estimate, as determined by the likelihood fit, and the observed data in the SR is shown in Figure 5. Only data and MC from the SR and region C are shown, since events are required to have $N_{\text{DV}} > 1$.

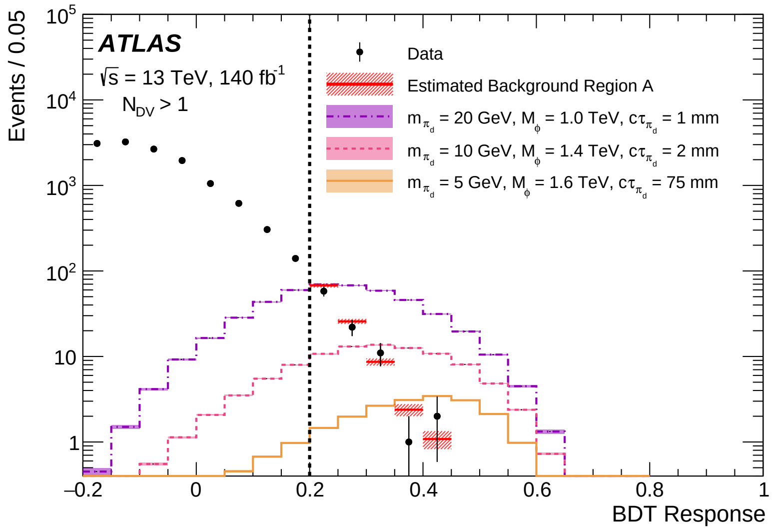


Figure 5: Comparison of the data with $N_{\text{DV}} > 1$ and the estimated background in the SR using the modified ABCD method. The division between the SR and CR is shown by the vertical dashed line. In the final fit, the bins with $R > 0.4$ are combined into a single bin. Three selected signal samples are included for comparison.

The full likelihood function is give by:

$$\mathcal{L}(\mu, \theta) = \prod_{i \in \{A,B,C,D\}} \left(\prod_{j \in i} P\left(N^{\text{Obs}}_{i,j} | N^{\text{Exp}}_{i,j}(p_0, p_1, \mu)\right) \right) \left(G\left(\alpha^{\text{Sig}}_i, \sigma^{\text{Sig}} | 0, 1\right) \right) \times \prod_{k=1}^{3} G\left(\alpha_k, \sigma_k | 0, 1\right) \quad (6)$$

where P represents the Poisson probabilities, and G are the Gaussian constraints on the systematic uncertainties, with α and σ the mean and standard deviations, respectively. The set of free parameters, other than the signal strength, is given by $\theta = \{p_0, p_1, N_{B,j}^{\text{Exp}}, N_{D,j}^{\text{Exp}}, \alpha_i^{\text{Sig}}, \alpha_k\}$.

The four signal systematic uncertainties (jet, track and vertex, pile-up, and PTF) are combined, but kept decorrelated across the four ABCD regions; the standard deviation of the Gaussian constraint (σ^{Sig}) is set to the same value across the four regions (set by the combined systematic uncertainty), but the mean (α^{Sig}) is allowed to float independently in each region. This allows for different systematic uncertainty values in each region of the ABCD plane. The three other systematic uncertainties, one for the luminosity uncertainty, and two for the background estimate uncertainty (which are applied only to region A), are included as individual nuisance parameters. In these cases, the Gaussian terms are correlated across the full ABCD plane giving only a single value for the mean of each term, while the standard deviations are set by the corresponding systematic uncertainties.

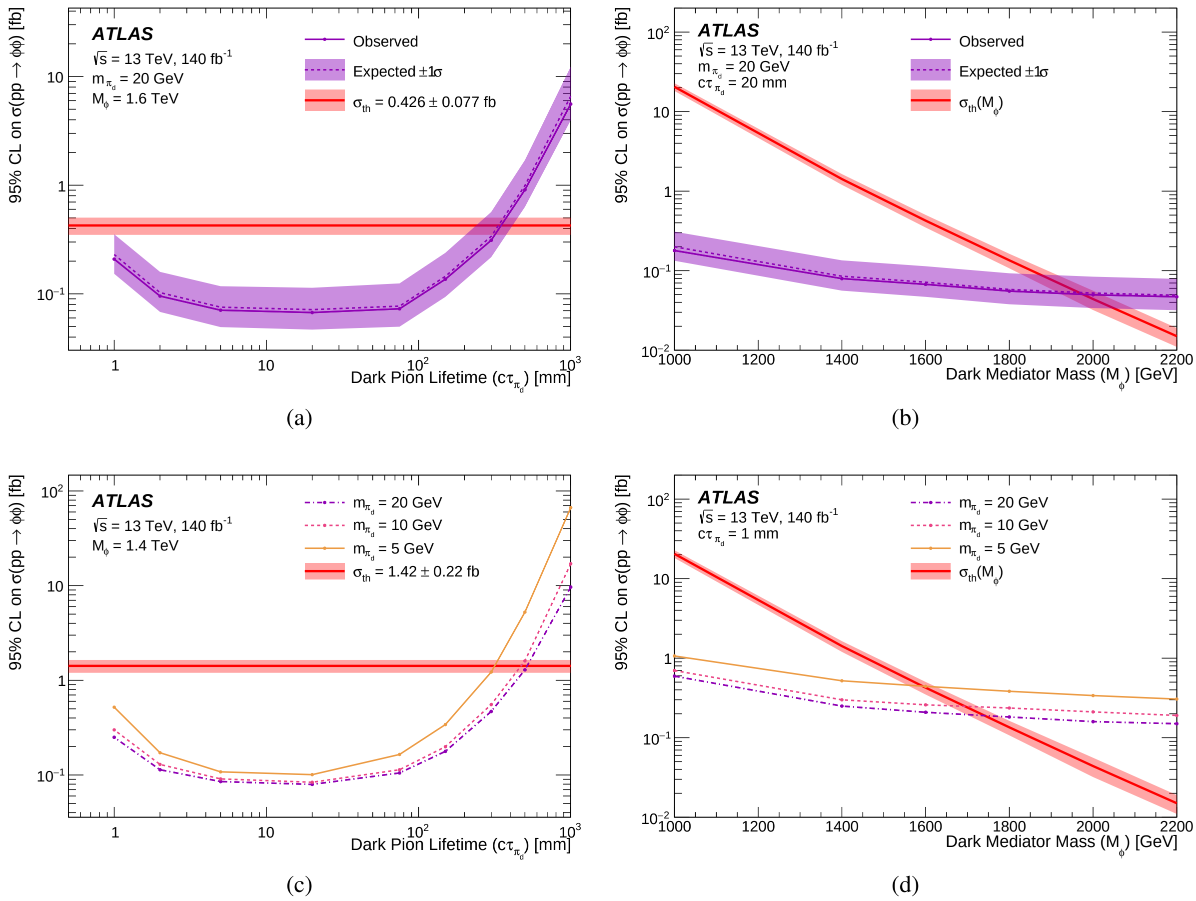


Figure 6: 95% CL upper limits as a function of (left) $c\tau_{\pi_d}$ and (right) M_ϕ. The upper plots show the expected and observed limits on $\sigma(pp \to \phi^\dagger\phi)$ for m_{π_d} = 20 GeV: (a) using M_ϕ = 1.6 TeV and (b) using $c\tau_{\pi_d}$ = 20 mm. The lower plots show a comparison of the observed limits for all three dark pion masses: (c) using M_ϕ = 1.4 TeV, and (d) using $c\tau_{\pi_d}$ = 1 mm. The mediator mass-dependent theoretical cross-section is given with the band corresponding to the uncertainty from NNLL-Fast.

The test statistic is defined using the profile likelihood ratio whose probability distribution is determined with the asymptotic approximation [74], and which gives a signal strength that is strictly positive. The likelihood implementation is handled by the `xRooFit` package.

Upper limits at the 95% confidence level (CL) are set on the pair-production cross-section for each signal hypothesis using the CL_s method [75]. Figure 6 shows the upper limit on $\sigma(pp \to \phi^\dagger\phi)$ at 95% confidence level as either a function of $c\tau_{\pi_d}$ or M_ϕ. In general, for a given combination of M_ϕ and $c\tau_{\pi_d}$, the sensitivity improves slightly with increasing m_{π_d}, as can be seen in Figures 6(c) and 6(d). The limits are strictest for intermediate dark pion lifetimes in the range 2 mm $< c\tau_{\pi_d} <$ 100 mm, but sensitivity decreases for $c\tau_{\pi_d} >$ 100 mm due to the reduction in tracking and vertexing efficiency at large radii. Similarly, the limits weaken for $c\tau_{\pi_d} <$ 2 mm due to the strict requirements on reconstructed DVs, and dark pions producing jets with larger prompt track fractions. This results in more Standard Model-like minPTF distributions, which is the strongest variable in the event-level BDT. The limits have only a weak dependence on M_ϕ, getting stronger at higher mediator masses. The cutoff in the exclusion contours at $M_\phi >$ 2 TeV is due to the rapidly falling theoretical cross-sections, which become inaccessible with the current dataset.

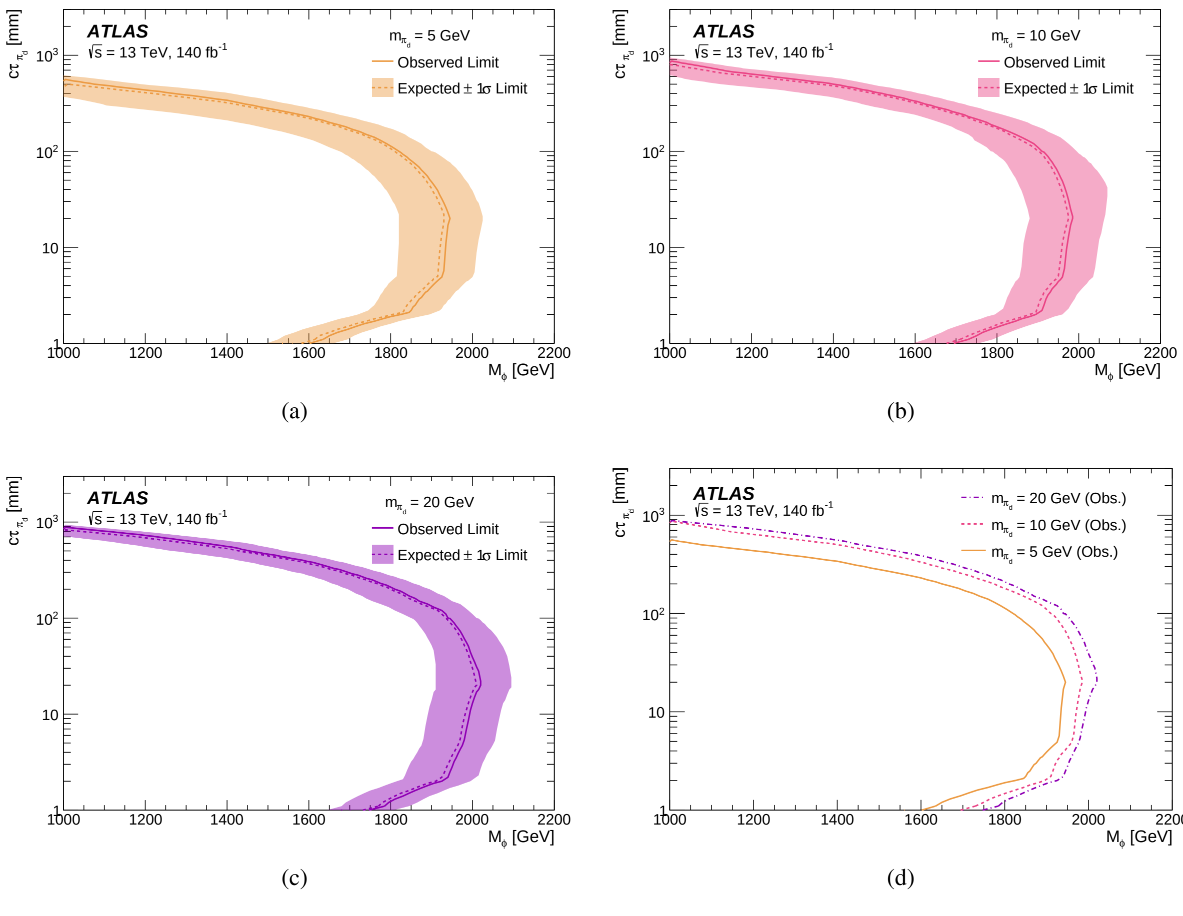
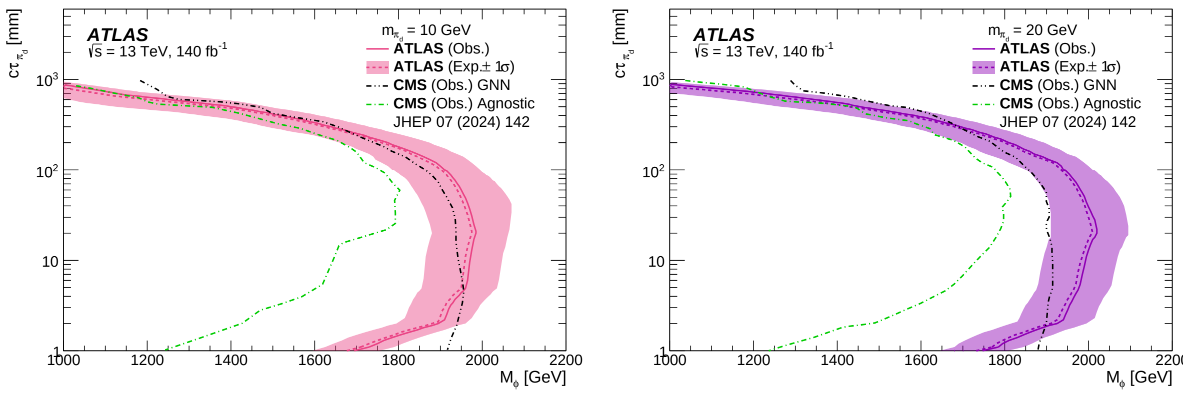


Figure 7: 95% CL exclusion contours as a function of M_ϕ and $c\tau_{\pi_d}$. The expected and observed limits on $\sigma(pp \to \phi^\dagger\phi)$ are shown for (a) m_{π_d} = 5 GeV, (b) m_{π_d} = 10 GeV, and (c) m_{π_d} = 20 GeV. A comparison of the observed limits is given in (d) for each of the three dark pion masses.

Exclusion contours based on the expected and observed limits on $\sigma(pp \to \phi^\dagger\phi)$ as a function of M_ϕ and $c\tau_{\pi_d}$ are shown for m_{π_d} = 5, 10 and 20 GeV in Figures 7(a), 7(b), and 7(c) respectively. Figure 7(d) gives a comparison of the exclusion contours based on the observed limits for the three dark pion masses. For models with $c\tau_{\pi_d} = 20$ mm, the production cross-section is excluded for ϕ masses up to $M_\phi = 1.95$ TeV, 1.99 TeV, and 2.00 TeV for $m_{\pi_d} = 5,\ 10,\ 20$ GeV, respectively. For $M_\phi = 1$ TeV, dark pion lifetimes up to about 880 mm are excluded for $m_{\pi_d} = 10, 20$ GeV and up to about 530 mm for $m_{\pi_d} = 5$ GeV.

This analysis is able to probe cross-sections that are a factor of two smaller than those in the four jet topology of the bifundamental scalar interpretation in the ATLAS Run 3 search [29], which is more optimised for the Z' scenario.



(a) (b)

Figure 8: Comparison of the 95% CL exclusion contours between ATLAS and CMS [28] for (a) models with $m_{\pi_d} = 10$ GeV and (b) models with $m_{\pi_d} = 20$ GeV. The expected and observed limits are shown for ATLAS, while only the observed limits in both the model agnostic and GNN cases are included for CMS. The expected limits from the CMS result are omitted, but are, in general, very close to the CMS observed limits.

Figure 8 shows the comparison between the results of this analysis, with those from the corresponding CMS search [28]. CMS included two methods of tagging emerging jets: a *model agnostic* version based on track displacement variables, and an ML-based Graph Neural Network (GNN) tagger. The GNN sets stricter limits at very low and very high proper lifetimes, while this search is more sensitive for intermediate lifetimes (2 – 300 mm).

10 Conclusion

This paper presents a search for emerging jets, a detector signature arising from a strongly self-interacting dark sector, using 140 fb^{-1} of data from proton–proton collisions at $\sqrt{s} = 13$ TeV, collected by the ATLAS detector at the LHC between 2015 and 2018. The search uses a two-stage boosted decision tree: the first trained on jet-level variables, and the second using event-level observables to select emerging-jet-like events from a wide model space. The Standard Model background is estimated using a fully data-driven approach. No excess above this estimate is observed.

Upper limits on the pair-production cross-section of heavy scalar mediators are set at the 95% confidence level. Mediator masses up to 2 TeV are excluded for dark pions with proper decay lengths of 20 mm and a dark pion mass of 20 GeV. This search complements the larger experimental efforts of the ATLAS collaboration looking for dark QCD, and is competitive with the recent results from both CMS and ATLAS, in some cases setting the strictest limits to date on the pair-production of a new scalar mediator.

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JSPS KAKENHI JP22KK0227, JSPS KAKENHI JP24K23939, JSPS KAKENHI JP24KK0251, JSPS KAKENHI JP25H00650, JSPS KAKENHI JP25H01291, JSPS KAKENHI JP25K01023); Norway: Research Council of Norway (RCN-314472); Poland: Ministry of Science and Higher Education (IDUB AGH, POB8, D4 no 9722), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS 2023/51/B/ST2/02507, NCN UMO-2019/34/E/ST2/00393, UMO-2022/47/O/ST2/00148, UMO-2023/49/B/ST2/04085, UMO-2023/51/B/ST2/00920, UMO-2024/53/N/ST2/00869); Portugal: Foundation for Science and Technology (FCT); Spain: Ministry of Science and Innovation (MCIN & NextGenEU PCI2022-135018-2, MICIN & FEDER PID2021-125273NB, RYC2019-028510-I, RYC2020-030254-I, RYC2021-031273-I, RYC2022-038164-I); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS 22:2312), Swedish Research Council (Swedish Research Council 2023-04654, VR 2021-03651, VR 2022-03845, VR 2022-04683, VR 2023-03403, VR 2024-05451), Knut and Alice Wallenberg Foundation (KAW 2018.0458, KAW 2022.0358, KAW 2023.0366); Switzerland: Swiss National Science Foundation (SNSF - PCEFP2_194658); United Kingdom: Royal Society (NIF-R1-231091); United States of America: U.S. Department of Energy (ECA DE-AC02-76SF00515), Neubauer Family Foundation.

A Cut-Based Analysis

A cut-based version of the analysis was performed, but not optimized to the same degree as the BDT-based analysis. As such, it does not achieve the same sensitivity as the BDT, but it does provide results which are easier for theorists to reinterpret.

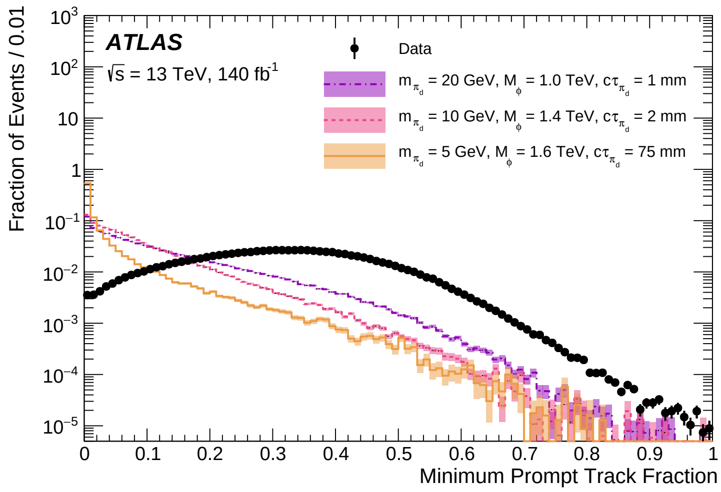


Figure 9: Normalized minPTF distribution in data, with three selected signal samples for comparison

The analysis requires the same event selections as described in Section 5, and only differs in the choice of variables used in the ABCD plane for the background estimation. Instead of using the BDT response, the cut-based analysis uses the minimum prompt track fraction of the four highest p_T jets (minPTF), which is one of the best separating variables used in the BDT training. A comparison of the minPTF between Data and three example signal samples is shown in Figure 9.

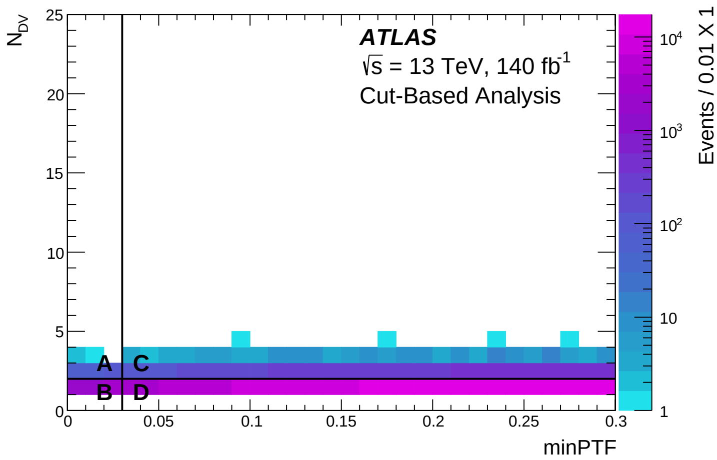


Figure 10: Distribution of data events in the ABCD plane defined for the Cut-Based analysis, using the minimum prompt track fraction (minPTF) of the four highest p_T jets on the x-axis, and the displaced vertex multiplicity on the y-axis. The cuts used to define the four regions are at minPTF = 0.03 and $N_{\mathrm{DV}} = 2$. The four regions are labeled accordingly.

The ABCD plane is constructed using minPTF and the number of jet-matched displaced vertices in the event (N_{DV}). The cuts used to define the signal region are minPTF ≤ 0.03 and $N_{\mathrm{DV}} \geq 2$. In order to aid the background estimation method, which is the same as described in Section 7, minPTF is restricted to the region less than 0.3. The distribution of data events within the ABCD plane are shown in Figure 10.

Table 6: Predicted number of background events, including statistical and systematic uncertainties, and observed event yield in the Cut-Based SR.

Cut-Based Analysis: Event Yield in the SR	
Prediction	227 ± 10 (stat.) ± 1 (syst.)
Observed Yield	219

An extrapolated linear fit based on the modified ABCD method was used to produce a prediction of the background contribution in the SR. The predicted and observed yield in region A are given in Table 6. No excess above the SM background prediction is observed

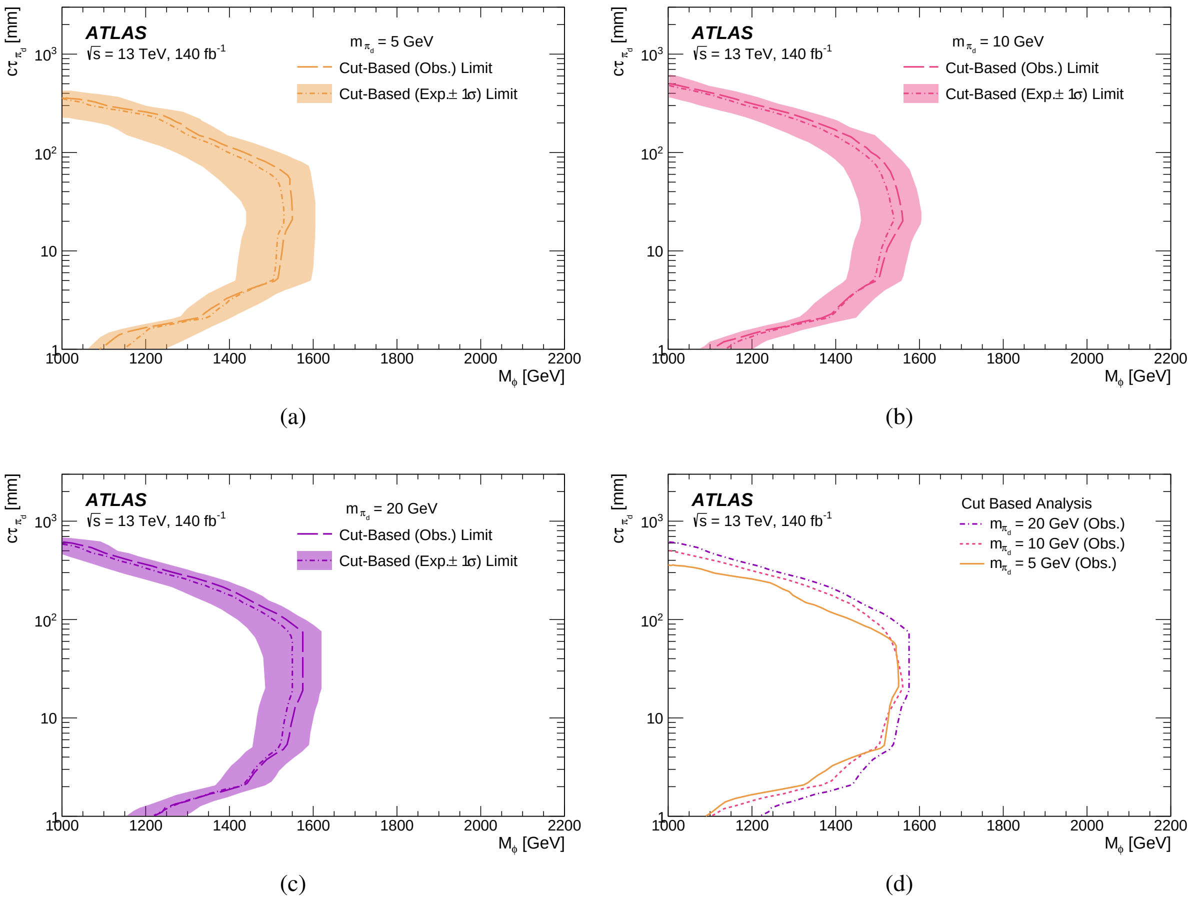
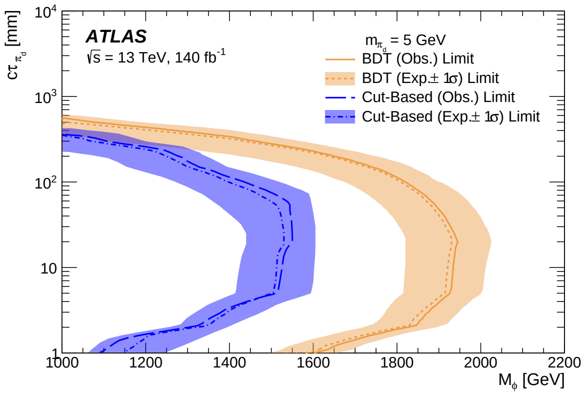
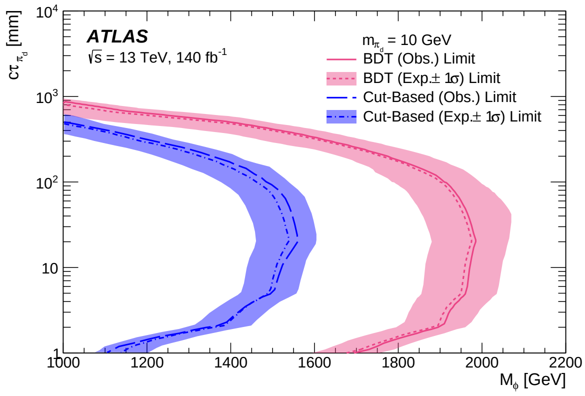


Figure 11: 95% CL exclusion contours as a function of M_ϕ and $c\tau_{\pi_d}$ for the Cut-Based analysis. The expected and observed limits on $\sigma(pp \to \phi^\dagger\phi)$ are shown for (a) m_{π_d} = 5 GeV, (b) m_{π_d} = 10 GeV, and (c) m_{π_d} = 20 GeV. A comparison of the observed limits is given in (d) for each of the three dark pion masses.

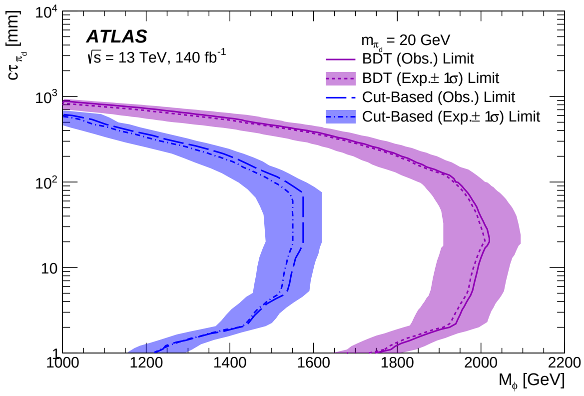
Using the same statistical machinery as described in Section 9, limits at the 95% confidence level are produced for the Cut-Based analysis. Exclusion contours as a function of M_ϕ and $c\tau_{\pi_d}$ are shown for m_{π_d} = 5, 10 and 20 GeV in Figures 11(a), 11(b), and 11(c) respectively. A comparison of the observed limits for all three dark pion masses is shown in Figure 11(d). Similar to the BDT-based analysis, the m_{π_d} = 20 GeV models set the strictest limits of the three. Mediator masses are excluded up to 1.57 TeV for 20 GeV dark pions with proper lifetimes between 20 mm and 75 mm.



(a)



(b)



(c)

Figure 12: Comparison of observed and expected 95% CL limits of the Cut-Based analysis against the corresponding BDT-based analysis. Limits on $\sigma(pp \to \phi^\dagger\phi)$ are shown as a function of M_ϕ and $c\tau_{\pi_d}$ for (a) m_{π_d} = 5 GeV, (b) m_{π_d} = 10 GeV, and (c) m_{π_d} = 20 GeV.

The Cut-Based analysis excludes a much smaller region of phase-space as compared to the BDT-based analysis, which speaks to the enhanced separating power that the BDT response has over any of the individual training variables. Comparisons between the Cut-Based and BDT-based analyses are shown in Figure 12 for each of the dark pion masses individually.

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A.D. Gentry [114], S. George [96], T. Geralis [46], A.A. Gerwin [122], P. Gessinger-Befurt [37],
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M.P. Giordani [69a,69c], P.F. Giraud [137], G. Giugliarelli [69a,69c], D. Giugni [71a], F. Giuli [76a,76b],
I. Gkialas [9,i], L.K. Gladilin [38], C. Glasman [100], M. Glazewska [20], R.M. Gleason [164],
G. Glemža [48], M. Glisic [125], I. Gnesi [44b], Y. Go [30], M. Goblirsch-Kolb [37], B. Gocke [49],
D. Godin [109], B. Gokturk [22a], S. Goldfarb [106], T. Golling [56], M.G.D. Gololo [34c], A. Golub [141],
D. Golubkov [38], J.P. Gombas [108], A. Gomes [132a,132b], G. Gomes Da Silva [146],
A.J. Gomez Delegido [37], R. Gonçalo [132a], L. Gonella [21], A. Gongadze [154c], F. Gonnella [21],
J.L. Gonski [148], R.Y. González Andana [52], S. González de la Hoz [168], M.V. Gonzalez Rodrigues [48],
R. Gonzalez Suarez [166], S. Gonzalez-Sevilla [56], L. Goossens [37], B. Gorini [37], E. Gorini [70a,70b],
A. Gorišek [94], T.C. Gosart [130], A.T. Goshaw [51], M.I. Gostkin [39], S. Goswami [123],
C.A. Gottardo [37], S.A. Gotz [110], M. Gouighri [36b], A.G. Goussiou [141], N. Govender [34c],
R.P. Grabarczyk [128], I. Grabowska-Bold [86a], K. Graham [35], E. Gramstad [127],
S. Grancagnolo [70a,70b], C.M. Grant [1], P.M. Gravila [28f], F.G. Gravili [70a,70b], H.M. Gray [18a],
M. Greco [111], M.J. Green [1], C. Grefe [25], A.S. Grefsrud [17], I.M. Gregor [48], K.T. Greif [164],
P. Grenier [148], S.G. Grewe [111], A.A. Grillo [138], K. Grimm [32], S. Grinstein [13,x], J.-F. Grivaz [66],
E. Gross [174], J. Grosse-Knetter [55], L.H. Grossman [18b], L. Guan [107], G. Guerrieri [37],

R. Guevara[127], R. Gugel[101], J.A.M. Guhit[107], A. Guida[19], E. Guilloton[172], S. Guindon[37], F. Guo[14,113c], J. Guo[143a], L. Guo[48], L. Guo[113b,v], Y. Guo[107], Y. Guo[42], A. Gupta[49], R. Gupta[131], S. Gupta[27], S. Gurbuz[25], S.S. Gurdasani[48], G. Gustavino[75a,75b], P. Gutierrez[122], L.F. Gutierrez Zagazeta[130], M. Gutsche[50], C. Gutschow[97], C. Gwenlan[128], C.B. Gwilliam[93], E.S. Haaland[127], A. Haas[119], M. Habedank[59], C. Haber[18a], H.K. Hadavand[8], A. Haddad[41], A. Hadef[50], A.I. Hagan[92], J.J. Hahn[146], E.H. Haines[97], M. Haleem[171], J. Haley[123], G.D. Hallewell[103], J.A. Hallford[48], K. Hamano[170], H. Hamdaoui[166], M. Hamer[25], S.E.D. Hammoud[66], E.J. Hampshire[96], J. Han[142a], L. Han[113a], L. Han[62], S. Han[14], K. Hanagaki[83], M. Hance[138], D.A. Hangal[42], H. Hanif[147], M.D. Hank[130], J.B. Hansen[43], P.H. Hansen[43], T. Harenberg[176], S. Harkusha[178], M.L. Harris[104], Y.T. Harris[25], J. Harrison[13], P.F. Harrison[172], M.L.E. Hart[97], N.M. Hartman[111], N.M. Hartmann[110], R.Z. Hasan[96,136], Y. Hasegawa[145], F. Haslbeck[128], S. Hassan[17], R. Hauser[108], M. Haviernik[135], C.M. Hawkes[21], R.J. Hawkings[37], Y. Hayashi[158], D. Hayden[108], C. Hayes[107], R.L. Hayes[116], C.P. Hays[128], J.M. Hays[95], H.S. Hayward[93], M. He[14,113c], Y. He[48], Y. He[97], N.B. Heatley[95], V. Hedberg[99], J. Heilman[35], S. Heim[48], T. Heim[18a], J.J. Heinrich[125], L. Heinrich[111], J. Hejbal[133], M. Helbig[50], A. Held[175], S. Hellesund[17], C.M. Helling[169], S. Hellman[47a,47b], A.M. Henriques Correia[37], H. Herde[99], Y. Hernández Jiménez[150], L.M. Herrmann[25], T. Herrmann[50], G. Herten[54], R. Hertenberger[110], L. Hervas[37], M.E. Hesping[101], N.P. Hessey[161a], J. Hessler[111], M. Hidaoui[36b], N. Hidic[135], E. Hill[160], T.S. Hillersoy[17], S.J. Hillier[21], J.R. Hinds[108], F. Hinterkeuser[25], M. Hirose[126], S. Hirose[162], D. Hirschbuehl[176], T.G. Hitchings[102], B. Hiti[94], J. Hobbs[150], R. Hobincu[28e], N. Hod[174], A.M. Hodges[167], M.C. Hodgkinson[144], B.H. Hodkinson[128], A. Hoecker[37], D.D. Hofer[107], J. Hofer[168], J. Hofner[101], M. Holzbock[37], L.B.A.H. Hommels[33], V. Homsak[128], J.J. Hong[68], T.M. Hong[131], B.H. Hooberman[167], W.H. Hopkins[6], M.C. Hoppesch[167], Y. Horii[112], M.E. Horstmann[111], S. Hou[153], M.R. Housenga[167], J. Howarth[59], J. Hoya[6], M. Hrabovsky[124], T. Hryn'ova[4], P.J. Hsu[65], S.-C. Hsu[141], T. Hsu[66], M. Hu[18a], Q. Hu[62], S. Huang[33], X. Huang[14,113c], Y. Huang[135], Y. Huang[113b], Y. Huang[14], Z. Huang[66], Z. Hubacek[134], F. Huegging[25], T.B. Huffman[128], M. Hufnagel Maranha De Faria[82a], C.A. Hugli[48], M. Huhtinen[37], S.K. Huiberts[127], R. Hulsken[105], C.E. Hultquist[18a], D.L. Humphreys[104], N. Huseynov[12], J. Huston[108], J. Huth[61], L. Huth[48], R. Hyneman[7], G. Iacobucci[56], G. Iakovidis[30], L. Iconomidou-Fayard[66], J.P. Iddon[37], P. Iengo[72a,72b], Y. Iiyama[158], T. Iizawa[158], Y. Ikegami[83], D. Iliadis[157], N. Ilic[160], H. Imam[36a], G. Inacio Goncalves[82d], S.A. Infante Cabanas[139c], T. Ingebretsen Carlson[47a,47b], J.M. Inglis[95], G. Introzzi[73a,73b], M. Iodice[77a], V. Ippolito[75a,75b], R.K. Irwin[93], M. Ishino[158], W. Islam[175], C. Issever[19], S. Istin[22a,ao], K. Itabashi[126], H. Ito[173], R. Iuppa[78a,78b], A. Ivina[174], S. Izumiyama[112], V. Izzo[72a], P. Jacka[134], P. Jackson[1], P. Jain[48], K. Jakobs[54], T. Jakoubek[174], J. Jamieson[59], W. Jang[158], S. Jankovych[135], M. Javurkova[104], P. Jawahar[102], L. Jeanty[125], J. Jejelava[154a,ae], P. Jenni[54,f], C.E. Jessiman[35], C. Jia[142a], H. Jia[169], J. Jia[150], X. Jia[111,113c], Z. Jia[113a], C. Jiang[52], Q. Jiang[64b], S. Jiggins[48], M. Jimenez Ortega[168], J. Jimenez Pena[13], S. Jin[113a], A. Jinaru[28b], O. Jinnouchi[140], P. Johansson[144], K.A. Johns[7], J.W. Johnson[138], F.A. Jolly[48], D.M. Jones[151], E. Jones[48], K.S. Jones[8], P. Jones[33], R.W.L. Jones[92], T.J. Jones[93], H.L. Joos[55], R. Joshi[121], J. Jovicevic[16], X. Ju[18a], J.J. Junggeburth[37], T. Junkermann[63a], A. Juste Rozas[13,x], M.K. Juzek[87], S. Kabana[139f], A. Kaczmarska[87], S.A. Kadir[148], M. Kado[111], H. Kagan[121], M. Kagan[148], A. Kahn[130], C. Kahra[101], T. Kaji[158], E. Kajomovitz[155], N. Kakati[174], N. Kakoty[13], I. Kalaitzidou[54], S. Kandel[8], N.J. Kang[138], D. Kar[34j], E. Karentzos[25], K. Karki[8], O. Karkout[116], S.N. Karpov [39], Z.M. Karpova [39], V. Kartvelishvili [92,154b], A.N. Karyukhin [38], E. Kasimi [157], J. Katzy [48], S. Kaur [35], K. Kawade [145], M.P. Kawale [122], C. Kawamoto [88], T. Kawamoto [62], E.F. Kay [37], S. Kazakos [108], V.F. Kazanin [38], J.M. Keaveney [34a], R. Keeler [170], G.V. Kehris [61], J.S. Keller [35], J.M. Kelly [170], J.J. Kempster [151], O. Kepka [133], J. Kerr [161b], B.P. Kerridge [136], B.P. Kerševan [94], L. Keszeghova [29a], R.A. Khan [131], A. Khanov [123], A.G. Kharlamov [38], T. Kharlamova [38], E.E. Khoda [141], M. Kholodenko [132a], T.J. Khoo [19], G. Khoriauli [171], Y. Khoulaki [36a], Y.A.R. Khwaira [129], B. Kibirige[34j], D. Kim [6], D.W. Kim [18b], Y.K. Kim [40], N. Kimura [97], M.K. Kingston [55], A. Kirchhoff [55], C. Kirfel [25], F. Kirfel [25], J. Kirk [136], A.E. Kiryunin [111], S. Kita [162], O. Kivernyk [25], M. Klassen [163], C. Klein [35], L. Klein [171], M.H. Klein [45], S.B. Klein [56], U. Klein [93], A. Klimentov [30], T. Klioutchnikova [37], P. Kluit [116], S. Kluth [111], E. Kneringer [79], T.M. Knight [160], A. Knue [49], M. Kobel [50], D. Kobylianskii [174], S.F. Koch [128], M. Kocian [148], P. Kodyš [135], D.M. Koeck [125], T. Koffas [35], O. Kolay [50], I. Koletsou [4], T. Komarek [87], K. Köneke [55], A.X.Y. Kong [1], T. Kono [120], N. Konstantinidis [97], P. Kontaxakis [56], B. Konya [99], R. Kopeliansky [42], S. Koperny [86a], R. Koppenhofer [54], K. Korcyl [87], K. Kordas [157,d], A. Korn [97], S. Korn [55], I. Korolkov [13], N. Korotkova [38], B. Kortman [116], O. Kortner [111], S. Kortner [111], W.H. Kostecka [117], M. Kostov [29a], V.V. Kostyukhin [146], A. Kotsokechagia [37], A. Kotwal [51], A. Koulouris [37], A. Kourkoumeli-Charalampidi [73a,73b], C. Kourkoumelis [9], E. Kourlitis [111], O. Kovanda [125], R. Kowalewski [170], W. Kozanecki [125], A.S. Kozhin [38], V.A. Kramarenko [38], G. Kramberger [94], P. Kramer [25], M.W. Krasny [129], A. Krasznahorkay [104], A.C. Kraus [117], J.W. Kraus [176], J.A. Kremer [48], N.B. Krengel [146], T. Kresse [50], L. Kretschmann [176], J. Kretzschmar [93], P. Krieger [160], K. Krizka [21], K. Kroeninger [49], H. Kroha [111], J. Kroll [133], J. Kroll [130], K.S. Krowpman [108], U. Kruchonak [39], H. Krüger [25], N. Krumnack[80], M.C. Kruse [51], O. Kuchinskaia [39], S. Kuday [3a], S. Kuehn [37], R. Kuesters [54], T. Kuhl [48], V. Kukhtin [39], Y. Kulchitsky [39], S. Kuleshov [139d,139b], J. Kull [1], E.V. Kumar [110], M. Kumar [34j], N. Kumari [48], P. Kumari [161b], A. Kupco [133], A. Kupich [38], O. Kuprash [54], H. Kurashige [85], L.L. Kurchaninov [161a], O. Kurdysh [4], A. Kurova [38], M. Kuze [140], A.K. Kvam [104], J. Kvita [124], N.G. Kyriacou [141], M. Laassiri [30], C. Lacasta [168], F. Lacava [75a,75b], H. Lacker [19], D. Lacour [129], N.N. Lad [97], E. Ladygin [39], A. Lafarge [41], B. Laforge [129], T. Lagouri [177], F.Z. Lahbabi [36a], S. Lai [55,37], W.S. Lai [97], I.K. Lakomiec [55], J.E. Lambert [170], S. Lammers [68], W. Lampl [7], C. Lampoudis [157,d], G. Lamprinoudis [101], A.N. Lancaster [117], E. Lançon [30], U. Landgraf [54], M.P.J. Landon [95], V.S. Lang [54], A.J. Lankford [164], F. Lanni [37], C.S. Lantz[167], K. Lantzsch [25], A. Lanza [73a], M. Lanzac Berrocal [168], J.F. Laporte [137], T. Lari [71a], D. Larsen [17], L. Larson [11], F. Lasagni Manghi [24b], M. Lassnig [37], S.D. Lawlor [144], R. Lazaridou[164], M. Lazzaroni [71a,71b], E.T.T. Le [164], H.D.M. Le [108], E.M. Le Boulicaut [177], L.T. Le Pottier [18a], B. Leban [24b,24a], F. Ledroit-Guillon [60], T.F. Lee [161b], L.L. Leeuw [34c], M. Lefebvre [170], C. Leggett [18a], G. Lehmann Miotto [37], M. Leigh [56], W.A. Leight [104], W. Leinonen [115], A. Leisos [157,u], M.A.L. Leite [82c], C.E. Leitgeb [19], R. Leitner [135], K.J.C. Leney [45], T. Lenz [25], S. Leone [74a], C. Leonidopoulos [52], A. Leopold [149], J.H. Lepage Bourbonnais [35], R. Les [108], C.G. Lester [33], M. Levchenko [38], J. Levêque [4], L.J. Levinson [174], G. Levrini [24b,24a], M.P. Lewicki [87], C. Lewis [141], D.J. Lewis [4], L. Lewitt [144], A. Li [30], B. Li [142a], C. Li[107], C-Q. Li [111], H. Li [142a], H. Li [102], H. Li [15], H. Li[62], H. Li [142a], J. Li [143a], K. Li [14], L. Li [143a], R. Li [177], S. Li [14,113c], S. Li [143b,143a], T. Li [5], X. Li [105], Y. Li[14], Z. Li [158], Z. Li [14,113c], Z. Li [62], S. Liang [14,113c], Z. Liang [14], M. Liberatore [137], B. Liberti [76a], G.B. Libotte [82d], K. Lie [64c], J. Lieber Marin [82e], H. Lien [68], H. Lin [107], S.F. Lin [150], L. Linden [110], R.E. Lindley [7], J.H. Lindon [37], J. Ling [61], E. Lipeles [130], A. Lipniacka [17], A. Lister [169], J.D. Little [68], B. Liu [14], B.X. Liu [113b], D. Liu [155], D. Liu [138], E.H.L. Liu [21], J.K.K. Liu [119], K. Liu [143b], K. Liu [143b,143a], M. Liu [62], M.Y. Liu [62], P. Liu [14], Q. Liu [148], S. Liu [150], X. Liu [142a], Y. Liu [113b,113c], Y. Liu [167], Y.L. Liu [142a], Y.W. Liu [62], Z. Liu [66,k], S.L. Lloyd [95], E.M. Lobodzinska [48], P. Loch [7], E. Lodhi [160], K. Lohwasser [144], E. Loiacono [48], J.D. Lomas [21], J.D. Long [42], I. Longarini [164], R. Longo [167], A. Lopez Solis [13], N.A. Lopez-canelas [7], N. Lorenzo Martinez [4], A.M. Lory [110], M. Losada [118a], G. Löschcke Centeno [4], X. Lou [47a,47b], X. Lou [14,113c], A. Lounis [66], P.A. Love [92], M. Lu [66], S. Lu [130], Y.J. Lu [153], H.J. Lubatti [141], C. Luci [75a,75b], F.L. Lucio Alves [113a], F. Luehring [68], B.S. Lunday [130], O. Lundberg [149], J. Lunde [37], N.A. Luongo [6], M.S. Lutz [37], A.B. Lux [26], D. Lynn [30], R. Lysak [133], V. Lysenko [134], E. Lytken [99], V. Lyubushkin [39], T. Lyubushkina [39], M.M. Lyukova [150], H. Ma [30], K. Ma [62], L.L. Ma [142a], W. Ma [62], Y. Ma [123], J.C. MacDonald [101], P.C. Machado De Abreu Farias [82e], D. Macina [37], R. Madar [41], T. Madula [97], J. Maeda [85], T. Maeno [30], P.T. Mafa [34c,j], H. Maguire [144], M. Maheshwari [33], V. Maiboroda [66], A. Maio [132a,132b,132d], K. Maj [86a], O. Majersky [48], S. Majewski [125], R. Makhmanazarov [38], N. Makovec [66], V. Maksimovic [16], B. Malaescu [129], J. Malamant[127], Pa. Malecki [87], V.P. Maleev [38], F. Malek [60,o], M. Mali [94], D. Malito [96], A. Maloizel [5], S. Maltezos[10], A. Malvezzi Lopes [82d], S. Malyukov[39], J. Mamuzic [94], G. Mancini [53], M.N. Mancini [27], G. Manco [73a,73b], J.P. Mandalia [95], S.S. Mandarry [151], I. Mandić [94], L. Manhaes de Andrade Filho [82a], I.M. Maniatis [174], J. Manjarres Ramos [90], D.C. Mankad [174], A. Mann [110], T. Manoussos [37], M.N. Mantinan [40], S. Manzoni [37], L. Mao [143a], X. Mapekula [34c], A. Marantis [157], R.R. Marcelo Gregorio [95], G. Marchiori [5], C. Marcon [71a], E. Maricic [16], M. Marinescu [48], S. Marium [48], M. Marjanovic [122], A. Markhoos [54], M. Markovitch [66], M.K. Maroun [104], M.C. Marr [147], G.T. Marsden[102], E.J. Marshall [92], Z. Marshall [18a], S. Marti-Garcia [168], J. Martin [97], T.A. Martin [136], V.J. Martin [52], B. Martin dit Latour [17], L. Martinelli [75a,75b], M. Martinez [13,x], P. Martinez Agullo [168], V.I. Martinez Outschoorn [104], P. Martinez Suarez [37], S. Martin-Haugh [136], G. Martinovicova [135], V.S. Martoiu [28b], A.C. Martyniuk [97], A. Marzin [37], D. Mascione [78a,78b], L. Masetti [101], J. Masik [102], A.L. Maslennikov [39], S.L. Mason [42], P. Massarotti [72a,72b], P. Mastrandrea [74a,74b], A. Mastroberardino [44b,44a], T. Masubuchi [126], T.T. Mathew [125], J. Matousek [135], D.M. Mattern [49], K. Mauer [48], J. Maurer [28b], T. Maurin [59], A.J. Maury [66], B. Maček [94], C. Mavungu Tsava [103], D.A. Maximov [38], A.E. May [102], E. Mayer [41], R. Mazini [34j], I. Maznas [117], S.M. Mazza [138], E. Mazzeo [37], J.P. Mc Gowan [170], S.P. Mc Kee [107], C.A. Mc Lean [6], C.C. McCracken [169], E.F. McDonald [106], A.E. McDougall [116], L.F. Mcelhinney [92], J.A. Mcfayden [151], R.P. McGovern [130], R.P. Mckenzie [34j], T.C. Mclachlan [48], D.J. Mclaughlin [97], S.J. McMahon [136], C.M. Mcpartland [93], R.A. McPherson [170,ab], S. Mehlhase [110], A. Mehta [93], D. Melini [168], B.R. Mellado Garcia [34j], A.H. Melo [55], F. Meloni [48], A.M. Mendes Jacques Da Costa [102], L. Meng [92], S. Menke [111], M. Mentink [37], E. Meoni [44b,44a], G. Mercado [117], S. Merianos [157], C. Merlassino [69a,69c], C. Meroni [71a,71b], J. Metcalfe [6], A.S. Mete [6], E. Meuser [101], C. Meyer [68], J-P. Meyer [137], Y. Miao[113a], R.P. Middleton [136], M. Mihovilovic [66], L. Mijović [52], G. Mikenberg [174], M. Mikestikova [133], M. Mikuž [94], H. Mildner [101], A. Milic [37], D.W. Miller [40], E.H. Miller [148], A. Milov [174], D.A. Milstead[47a,47b], T. Min[113a], A.A. Minaenko [38], I.A. Minashvili [154b], A.I. Mincer [119], B. Mindur [86a], M. Mineev [39], Y. Mino [88], L.M. Mir [13], M. Miralles Lopez [59], M. Mironova [18a], M. Missio [41], A. Mitra [172], V.A. Mitsou [168], Y. Mitsumori [112], O. Miu [160], P.S. Miyagawa [95], T. Mkrtchyan [37], M. Mlinarevic [97], T. Mlinarevic [97], M. Mlynarikova [135], L. Mlynarska [86a], C. Mo [143a], S. Mobius [20], M.H. Mohamed Farook [114], S. Mohapatra [42], M.F. Mohd Soberi [52], S. Mohiuddin [123], G. Mokgatitswane [34j], L. Moleri [174], U. Molinatti [128], L.G. Mollier [20], B. Mondal [133], S. Mondal [134], K. Mönig [48], E. Monnier [103], L. Monsonis Romero[168], J. Montejo Berlingen [13], A. Montella [47a,47b], M. Montella [121], F. Montereali [77a,77b],

F. Monticelli[91], S. Monzani[69a,69c], A. Morancho Tarda[43], N. Morange[66], A.L. Moreira De Carvalho[48], M. Moreno Llácer[168], C. Moreno Martinez[56], J.M. Moreno Perez[23b], P. Morettini[57b], S. Morgenstern[37], M. Morii[61], M. Morinaga[158], M. Moritsu[89], F. Morodei[75a,75b], P. Moschovakos[37], B. Moser[54], M. Mosidze[154b], T. Moskalets[45], P. Moskvitina[115], J. Moss[32], P. Moszkowicz[86a], A. Moussa[36d], Y. Moyal[174], H. Moyano Gomez[13], E.J.W. Moyse[104], T.G. Mroz[87], S. Muanza[103], M. Mucha[25], J. Mueller[131], R. Müller[37], G.A. Mullier[166], A.J. Mullin[33], J.J. Mullin[51], A.C. Mullins[45], A.E. Mulski[61], D.P. Mungo[160], D. Munoz Perez[168], F.J. Munoz Sanchez[102], W.J. Murray[172,136], M. Muškinja[94], C. Mwewa[48], A.G. Myagkov[38,a], A.J. Myers[8], G. Myers[107], M. Myska[134], B.P. Nachman[148], K. Nagai[128], K. Nagano[83], R. Nagasaka[158], J.L. Nagle[30,al], E. Nagy[103], A.M. Nairz[37], Y. Nakahama[83], K. Nakamura[83], K. Nakkalil[5], A. Nandi[63b], H. Nanjo[126], E.A. Narayanan[45], Y. Narukawa[158], I. Naryshkin[38], L. Nasella[71a,71b], S. Nasri[118b], C. Nass[25], G. Navarro[23a], A. Nayaz[19], P.Y. Nechaeva[38], S. Nechaeva[24b,24a], F. Nechansky[133], L. Nedic[128], T.J. Neep[21], A. Negri[73a,73b], M. Negrini[24b], C. Nellist[116], C. Nelson[105], K. Nelson[107], S. Nemecek[133], M. Nessi[37,g], M.S. Neubauer[167], J. Newell[93], P.R. Newman[21], Y.W.Y. Ng[167], B. Ngair[118a], H.D.N. Nguyen[109], J.D. Nichols[122], R.B. Nickerson[128], R. Nicolaidou[137], J. Nielsen[138], M. Niemeyer[55], J. Niermann[37], N. Nikiforou[37], V. Nikolaenko[38,a], I. Nikolic-Audit[129], P. Nilsson[30], I. Ninca[48], G. Ninio[156], A. Nisati[75a], R. Nisius[111], N. Nitika[174], E.K. Nkadimeng[34b], T. Nobe[158], D. Noll[148], T. Nommensen[152], M.B. Norfolk[144], B.J. Norman[35], L.C. Nosler[18a], M. Noury[36a], J. Novak[94], T. Novak[94], P. Novotny[174], R. Novotny[134], L. Nozka[124], K. Ntekas[164], D. Ntounis[148], N.M.J. Nunes De Moura Junior[82b], J. Ocariz[129], I. Ochoa[132a], A. Odella Rodriguez[13], S. Oerdek[48,y], J.T. Offermann[40], A. Ogrodnik[87], A. Oh[102], C.C. Ohm[149], H. Oide[83], M.L. Ojeda[37], Y. Okumura[158], L.F. Oleiro Seabra[132a], I. Oleksiyuk[56], G. Oliveira Correa[13], D. Oliveira Damazio[30], J.L. Oliver[164], R. Omar[68], Ö.O. Öncel[54], A.P. O'Neill[20], A. Onofre[132a,132e,e], P.U.E. Onyisi[11], M.J. Oreglia[40], D. Orestano[77a,77b], R. Orlandini[77a,77b], R.S. Orr[160], L.M. Osojnak[42], Y. Osumi[112], G. Otero y Garzon[31], H. Otono[89], M. Ouchrif[36d], F. Ould-Saada[127], T. Ovsiannikova[141], M. Owen[59], R.E. Owen[136], V.E. Ozcan[22a], F. Ozturk[87], N. Ozturk[8], S. Ozturk[81], H.A. Pacey[128], K. Pachal[161a], A. Pacheco Pages[13], C. Padilla Aranda[13], G. Padovano[75a,75b], S. Pagan Griso[18a], J. Pampel[25], J. Pan[177], D.K. Panchal[11], C.E. Pandini[60], J.G. Panduro Vazquez[136], H.D. Pandya[1], H. Pang[137], P. Pani[48], G. Panizzo[69a,69c], L. Panwar[129], L. Paolozzi[56], S. Parajuli[167], A. Paramonov[6], C. Paraskevopoulos[53], D. Paredes Hernandez[64b], S.R. Paredes Saenz[52], A. Pareti[73a,73b], K.R. Park[42], T.H. Park[111], F. Parodi[57b,57a], J.A. Parsons[42], U. Parzefall[54], B. Pascual Dias[41], L. Pascual Dominguez[100], E. Pasqualucci[75a], S. Passaggio[57b], F. Pastore[96], P. Patel[87], U.M. Patel[51], J.R. Pater[102], T. Pauly[37], F. Pauwels[135], C.I. Pazos[163], M. Pedersen[127], R. Pedro[132a], S.V. Peleganchuk[38], O. Penc[133], S. Peng[15], G.D. Penn[177], K.E. Penski[110], M. Penzin[38], B.S. Peralva[82d], A.P. Pereira Peixoto[141], L. Pereira Sanchez[148], D.V. Perepelitsa[30,al], G. Perera[104], E. Perez Codina[37], M. Perganti[10], H. Pernegger[37], S. Perrella[75a,75b], K. Peters[48], R.F.Y. Peters[102], B.A. Petersen[37], T.C. Petersen[43], E. Petit[103], V. Petousis[134], A.R. Petri[71a,71b], C. Petridou[157,d], T. Petru[135], M. Pettee[18a], A. Petukhov[81], K. Petukhova[37], R. Pezoa[139g], L. Pezzotti[24b,24a], G. Pezzullo[177], L. Pfaffenbichler[37], A.J. Pfleger[79], T.M. Pham[175], T. Pham[106], P.W. Phillips[136], G. Piacquadio[150], E. Pianori[18a], F. Piazza[125], R. Piegaia[31], D. Pietreanu[28b], A.D. Pilkington[102], M. Pinamonti[69a,69c], J.L. Pinfold[2], G. Pinheiro Matos[42], B.C. Pinheiro Pereira[132a], J. Pinol Bel[13], A.E. Pinto Pinoargote[129], L. Pintucci[69a,69c], K.M. Piper[151], A. Pirttikoski[56], D.A. Pizzi[35],

L. Pizzimento[64b], A. Plebani[33], M.-A. Pleier[30], V. Pleskot[135], E. Plotnikova[39], G. Poddar[95], R. Poettgen[99], L. Poggioli[129], S. Polacek[135], G. Polesello[73a], A. Poley[147], A. Polini[24b], C.S. Pollard[172], Z.B. Pollock[121], E. Pompa Pacchi[122], N.I. Pond[97], D. Ponomarenko[68], L. Pontecorvo[37], S. Popa[28a], G.A. Popeneciu[28d], A. Poreba[37], D.M. Portillo Quintero[161a], S. Pospisil[134], M.A. Postill[144], P. Postolache[28c], K. Potamianos[172], P.A. Potepa[86a], I.N. Potrap[39], C.J. Potter[33], H. Potti[152], J. Poveda[168], M.E. Pozo Astigarraga[37], R. Pozzi[37], A. Prades Ibanez[76a,76b], S.R. Pradhan[144], J. Pretel[170], D. Price[102], M. Primavera[70a], L. Primomo[69a,69c], M.A. Principe Martin[100], R. Privara[124], T. Procter[86b], M.L. Proffitt[141], N. Proklova[130], K. Prokofiev[64c], G. Proto[111], J. Proudfoot[6], M. Przybycien[86a], W.W. Przygoda[86b], A. Psallidas[46], J.E. Puddefoot[144], D. Pudzha[53], H.I. Purnell[1], D. Pyatiizbyantseva[115], J. Qian[107], R. Qian[108], D. Qichen[128], Y. Qin[13], T. Qiu[52], A. Quadt[55], M. Queitsch-Maitland[102], G. Quetant[56], R.P. Quinn[169], G. Rabanal Bolanos[61], D. Rafanoharana[111], F. Raffaeli[76a,76b], F. Ragusa[71a,71b], J.L. Rainbolt[40], S. Rajagopalan[30], E. Ramakoti[39], L. Rambelli[57b,57a], I.A. Ramirez-Berend[35], K. Ran[107,113c], D.S. Rankin[130], N.P. Rapheeha[34j], H. Rasheed[28b], A. Rastogi[18a], S. Rave[101], S. Ravera[57b,57a], B. Ravina[37], I. Ravinovich[174], M. Raymond[37], A.L. Read[127], N.P. Readioff[144], D.M. Rebuzzi[73a,73b], A.S. Reed[59], K. Reeves[27], D. Reikher[37], A. Rej[49], C. Rembser[37], H. Ren[62], M. Renda[28b], F. Renner[48], A.G. Rennie[59], M. Repik[56], A.L. Rescia[57b,57a], S. Resconi[71a], M. Ressegotti[57b,57a], S. Rettie[116], W.F. Rettie[35], M.M. Revering[33], E. Reynolds[18a], O.L. Rezanova[39], P. Reznicek[135], H. Riani[36d], N. Ribaric[51], B. Ricci[69a,69c], E. Ricci[78a,78b], R. Richter[111], S. Richter[47a,47b], E. Richter-Was[86b], M. Ridel[129], S. Ridouani[36d], P. Rieck[119], P. Riedler[37], E.M. Riefel[47a,47b], J.O. Rieger[116], M. Rijssenbeek[150], M. Rimoldi[34c], L. Rinaldi[24b,24a], P. Rincke[166,55], G. Ripellino[166], I. Riu[13], J.C. Rivera Vergara[170], F. Rizatdinova[123], E. Rizvi[95], B.R. Roberts[40], S.S. Roberts[138], D. Robinson[33], A. Robson[59], A. Rocchi[76a,76b], C. Roda[74a,74b], F.A. Rodriguez[117], S. Rodriguez Bosca[37], Y. Rodriguez Garcia[23a], A.M. Rodríguez Vera[117], S. Roe[37], J.T. Roemer[37], O. Røhne[127], R.A. Rojas[37], C.P.A. Roland[129], A. Romaniouk[79], E. Romano[73a,73b], M. Romano[24b], A.C. Romero Hernandez[167], N. Rompotis[93], L. Roos[129], S. Rosati[75a], B.J. Rosser[40], E. Rossi[128], E. Rossi[72a,72b], L.P. Rossi[61], L. Rossini[54], R. Rosten[121], M. Rotaru[28b], D. Rousseau[66], D. Rousso[48], S. Roy-Garand[160], A. Rozanov[103], Z.M.A. Rozario[59], Y. Rozen[155], A. Rubio Jimenez[168], V.H. Ruelas Rivera[19], T.A. Ruggeri[1], A. Ruggiero[128], A. Ruiz-Martinez[168], A. Rummler[37], G.B. Rupnik Boero[37], Z. Rurikova[54], N.A. Rusakovich[39], S. Ruscelli[49], H.L. Russell[170], G. Russo[75a,75b], J.P. Rutherfoord[7], S. Rutherford Colmenares[33], M. Rybar[135], P. Rybczynski[86a], A. Ryzhov[45], H.F-W. Sadrozinski[138], F. Safai Tehrani[75a], S. Saha[1], M. Sahinsoy[81], B. Sahoo[174], A. Saibel[168], B.T. Saifuddin[122], M. Saimpert[137], G.T. Saito[82c], M. Saito[158], T. Saito[158], A. Sala[71a,71b], A. Salnikov[148], J. Salt[168], A. Salvador Salas[156], F. Salvatore[151], A. Salzburger[37], D. Sammel[54], E. Sampson[92], D. Sampsonidis[157,d], D. Sampsonidou[125], M.A.A. Samy[59], J. Sánchez[168], V. Sanchez Sebastian[168], H. Sandaker[127], C.O. Sander[48], J.A. Sandesara[175], M. Sandhoff[176], C. Sandoval[23b], L. Sanfilippo[63a], D.P.C. Sankey[136], T. Sano[88], A. Sansoni[53], M. Santana Queiroz[18b], L. Santi[37], C. Santoni[41], H. Santos[132a,132b], A. Santra[174], E. Sanzani[24b,24a], K.A. Saoucha[84b], J.G. Saraiva[132a,132d], J. Sardain[7], O. Sasaki[83], K. Sato[162], C. Sauer[37], E. Sauvan[4], P. Savard[160,ai], R. Sawada[158], C. Sawyer[136], L. Sawyer[98], A.M. Sayed[27], C. Sbarra[24b], A. Sbrizzi[24b,24a], T. Scanlon[97], J. Schaarschmidt[141], U. Schäfer[101], A.C. Schaffer[66,45], D. Schaile[110], R.D. Schamberger[150], C. Scharf[19], M.M. Schefer[20], V.A. Schegelsky[38], D. Scheirich[135], M. Schernau[139f], C. Scheulen[56], C. Schiavi[57b,57a], M. Schioppa[44b,44a], B. Schlag[148], S. Schlenker[37],

J. Schmeing[176], E. Schmidt[111], M.A. Schmidt[176], K. Schmieden[25], C. Schmitt[101], N. Schmitt[101], S. Schmitt[48], N.A. Schneider[110], L. Schoeffel[137], A. Schoening[63b], P.G. Scholer[35], E. Schopf[146], M. Schott[25], S. Schramm[56], T. Schroer[56], H-C. Schultz-Coulon[63a], M. Schumacher[54], B.A. Schumm[138], Ph. Schune[137], H.R. Schwartz[7], A. Schwartzman[148], T.A. Schwarz[107], Ph. Schwemling[137], R. Schwienhorst[108], F.G. Sciacca[20], A. Sciandra[30], G. Sciolla[27], F. Scuri[74a], C.D. Sebastiani[37], K. Sedlaczek[117], S.C. Seidel[114], A. Seiden[138], B.D. Seidlitz[42], C. Seitz[48], J.M. Seixas[82b], G. Sekhniaidze[72a], L. Selem[60], N. Semprini-Cesari[24b,24a], A. Semushin[178], D. Sengupta[56], V. Senthilkumar[168], L. Serin[66], M. Sessa[72a,72b], H. Severini[122], F. Sforza[57b,57a], A. Sfyrla[56], Q. Sha[14], H. Shaddix[117], A.H. Shah[33], R. Shaheen[149], J.D. Shahinian[130], M. Shamim[37], L.Y. Shan[14], M. Shapiro[18a], A. Sharma[37], A.S. Sharma[169], P. Sharma[30], P.B. Shatalov[38], K. Shaw[151], S.M. Shaw[102], Q. Shen[14], D.J. Sheppard[147], P. Sherwood[97], L. Shi[97], X. Shi[14], S. Shimizu[83], I.P.J. Shipsey[128,*], S. Shirabe[89], M. Shiyakova[39,z], M.J. Shochet[40], D.R. Shope[127], B. Shrestha[122], S. Shrestha[121,an], I. Shreyber[39], M.J. Shroff[170], P. Sicho[133], A.M. Sickles[167], E. Sideras Haddad[34j,165], A.C. Sidley[116], A. Sidoti[24b], F. Siegert[50], Dj. Sijacki[16], F. Sili[62], J.M. Silva[52], I. Silva Ferreira[82b], M.V. Silva Oliveira[30], S.B. Silverstein[47a], S. Simion[66], R. Simoniello[37], E.L. Simpson[102], H. Simpson[151], L.R. Simpson[6], S. Simsek[81], S. Sindhu[55], S.N. Singh[27], S. Singh[30], S. Sinha[48], S. Sinha[102], M. Sioli[24b,24a], K. Sioulas[9], I. Siral[37], E. Sitnikova[48], J. Sjölin[47a,47b], A. Skaf[55], E. Skorda[21], P. Skubic[122], M. Slawinska[87], I. Slazyk[17], I. Sliusar[127], V. Smakhtin[174], B.H. Smart[136], S.Yu. Smirnov[139b], Y. Smirnov[34c], L.N. Smirnova[38,a], O. Smirnova[99], A.C. Smith[42], D.R. Smith[164], J.L. Smith[102], M.B. Smith[35], R. Smith[148], H. Smitmanns[101], M. Smizanska[92], K. Smolek[134], P. Smolyanskiy[134], A.A. Snesarev[39], H.L. Snoek[116], R.M. Snyder[51], S. Snyder[30], R. Sobie[170,ab], A. Soffer[156], C.A. Solans Sanchez[37], E.Yu. Soldatov[39], U. Soldevila[168], A.A. Solodkov[34j], S. Solomon[27], A. Soloshenko[39], K. Solovieva[54], O.V. Solovyanov[41], P. Sommer[50], A. Sonay[13], A. Sopczak[134], A.L. Sopio[52], F. Sopkova[29b], J.D. Sorenson[114], I.R. Sotarriva Alvarez[140], V. Sothilingam[63a], O.J. Soto Sandoval[139c,139b], S. Sottocornola[68], R. Soualah[84a], Z. Soumaimi[36e], D. South[48], N. Soybelman[174], S. Spagnolo[70a,70b], D. Sperlich[54], B. Spisso[72a,72b], D.P. Spiteri[59], L. Splendori[103], M. Spousta[135], E.J. Staats[35], R. Stamen[63a], E. Stanecka[87], W. Stanek-Maslouska[48], M.V. Stange[50], B. Stanislaus[18a], M.M. Stanitzki[48], E.A. Starchenko[38], G.H. Stark[138], J. Stark[90], P. Staroba[133], P. Starovoitov[84b], R. Staszewski[87], C. Stauch[110], G. Stavropoulos[46], A. Stefl[37], A. Stein[101], P. Steinberg[30], B. Stelzer[147,161a], H.J. Stelzer[131], O. Stelzer[161a], H. Stenzel[58], T.J. Stevenson[151], G.A. Stewart[37], J.R. Stewart[123], G. Stoicea[28b], M. Stolarski[132a], S. Stonjek[111], A. Straessner[50], J. Strandberg[149], S. Strandberg[47a,47b], M. Stratmann[176], M. Strauss[122], T. Strebler[103], P. Strizenec[29b], R. Ströhmer[171], D.M. Strom[125], R. Stroynowski[45], A. Strubig[47a,47b], S.A. Stucci[30], B. Stugu[17], J. Stupak[122], N.A. Styles[48], D. Su[148], S. Su[62], X. Su[62], D. Suchy[29a], A.D. Sudhakar Ponnu[55], L. Sudit[174], K. Sugizaki[130], V.V. Sulin[38], D.M.S. Sultan[128], L. Sultanaliyeva[25], S. Sultansoy[3b], S. Sun[175], W. Sun[14], N. Sur[99], N. Suri Jr[177], M.R. Sutton[151], M. Svatos[133], P.N. Swallow[33], M. Swiatlowski[161a], A. Swoboda[37], I. Sykora[29a], M. Sykora[135], T. Sykora[135], D. Ta[101], K. Tackmann[48,y], A. Taffard[164], R. Tafirout[161a], Y. Takubo[83], M. Talby[103], A.A. Talyshev[38], K.C. Tam[64b], N.M. Tamir[156], A. Tanaka[158], J. Tanaka[158], R. Tanaka[66], M. Tanasini[150], Z. Tao[169], S. Tapia Araya[139g], S. Tapprogge[101], A. Tarek Abouelfadl Mohamed[37], S. Tarem[155], K. Tariq[14], G. Tarna[37], G.F. Tartarelli[71a], M.J. Tartarin[90], P. Tas[135], M. Tasevsky[133], E. Tassi[44b,44a], A.C. Tate[167], Y. Tayalati[36e,aa], G.N. Taylor[106], W. Taylor[161b], R.J. Taylor Vara[168], A.S. Tegetmeier[90],

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Trzebinski [87], A. Trzupek [87], F. Tsai [150], M. Tsai [107], A. Tsiamis [157], P.V. Tsiareshka[39], S. Tsigaridas [161a], A. Tsirigotis [157,u], V. Tsiskaridze [154a], E.G. Tskhadadze [154a], Y. Tsujikawa [88], I.I. Tsukerman [38], V. Tsulaia [18a], S. Tsuno [83], K. Tsuri [120], D. Tsybychev [150], Y. Tu [64b], A. Tudorache [28b], V. Tudorache [28b], S.B. Tuncay [128], S. Turchikhin [57b,57a], I. Turk Cakir [3a], R. Turra [71a], T. Turtuvshin [39,ac], P.M. Tuts [42], S. Tzamarias [157,d], Y. Uematsu [83], F. Ukegawa [162], P.A. Ulloa Poblete [139c,139b], E.N. Umaka [30], G. Unal [37], A. Undrus [30], G. Unel [164], J. Urban [29b], P. Urrejola [139e], G. Usai [8], R. Ushioda [159], M. Usman [109], F. Ustuner [52], Z. Uysal [81], V. Vacek [134], B. Vachon [105], T. Vafeiadis [37], A. Vaitkus [97], C. Valderanis [110], E. Valdes Santurio [47a,47b], M. Valente [37], S. Valentinetti [24b,24a], A. Valero [168], E. Valiente Moreno [168], A. Vallier [90], J.A. Valls Ferrer [168], D.R. 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