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ATLAS Collaboration

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Letter

Measurements of Lund subjet multiplicities in 13 TeV proton-proton collisions with the ATLAS detector

The ATLAS Collaboration *

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ABSTRACT

This Letter presents a differential cross-section measurement of Lund subjet multiplicities, suitable for testing current and future parton shower Monte Carlo algorithms. This measurement is made in dijet events in 140 fb^{-1} of $\sqrt{s} = 13$ TeV proton–proton collision data collected with the ATLAS detector at CERN's Large Hadron Collider. The data are unfolded to account for acceptance and detector-related effects, and are then compared with several Monte Carlo models and to recent resummed analytical calculations. The experimental precision achieved in the measurement allows tests of higher-order effects in QCD predictions. Most predictions fail to accurately describe the measured data, particularly at large values of jet transverse momentum accessible at the Large Hadron Collider, indicating the measurement's utility as an input to future parton shower developments and other studies probing fundamental properties of QCD and the production of hadronic final states up to the TeV-scale.

1. Introduction

At particle colliders such as the Large Hadron Collider (LHC) at CERN, the high-energy quarks and gluons that are produced in hard-scattering (HS) processes fragment and hadronise, producing collimated *jets* of hadrons in the final state [1]. Jets are complex objects; and jet substructure (JSS) probes a wide range of energy scales, providing a multi-faceted setting for tests of quantum chromodynamics (QCD) in the colinear limit [2]. Parton Shower Monte Carlo (PSMC) programs model the evolution of quarks and gluons produced in the HS into the low-energy hadrons that are observed experimentally, and are among the most widely-used theoretical tools in particle physics [3]. Modern PSMCs can adequately describe the bulk of LHC data, but predictions from different algorithms can disagree significantly for certain topologies or processes. Their formal accuracy is also limited in cases where subsequent emissions within the shower have commensurate energies or angles [4]: in such configurations, emissions beyond the initial one must be considered to obtain an accurate result. This lack of accuracy affects the precision of data analysis, either through *ad hoc* comparisons of discrepant algorithms (*e.g.* Refs. [5–8]) or due to increased reliance on particle-level correlations in simulation (*e.g.* with supervised Machine Learning techniques [9]).

There has been progress toward improved understanding of higher-order QCD effects in PSMCs and the development of more accurate algorithms [4,10–19]. A necessary advancement for this effort is the incorporation of 'double-soft' splittings [20,21], which describe the emission of two soft gluons or a quark-antiquark pair, beyond tree-level in QCD [22–24]. These processes have been implemented in some existing PSMC programs [25–34], and are now being implemented in PSMCs with higher logarithmic accuracy [4]. The 'Lund' subjet multiplicity, or 'Lund multiplicity,' is a JSS observable used to test for the inclusion of double-soft splittings [4]. For this purpose, it was calculated with analytical resummation at next-to-next-to-double-logarithmic (NNDL) accuracy in QCD in Refs. [35,36]. These predictions were used to assess the implementation of these higher-order contributions within the general-purpose PanGlobal PSMC [11].

The Lund multiplicity counts the number of subjets in a jet's angle-ordered clustering history [35] above a specified requirement on the subjet's transvese momentum relative to the jet core. This angular-ordered clustering history is obtained by reclustering the jet's con-

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

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

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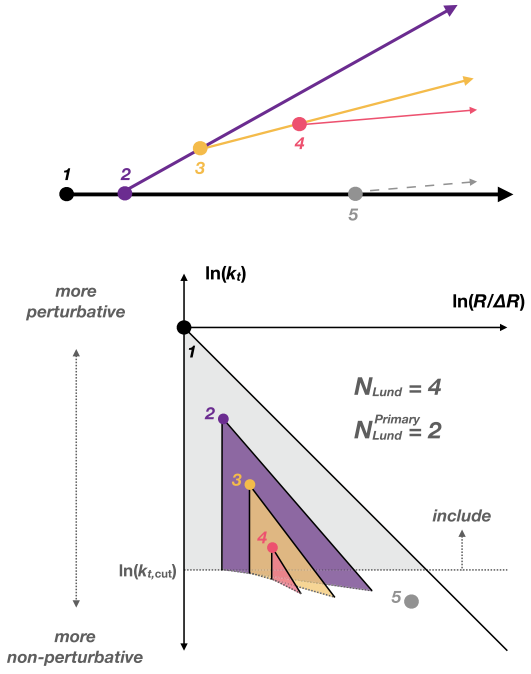

Fig. 1. Schematic representation of a jet's angle-ordered clustering history and the calculation of N_{Lund} and $N_{\text{Lund}}^{\text{Primary}}$. The emission labelled '5,' drawn with a dashed line, fails the k_t requirement and is not counted in the multiplicity calculation.

stituents with the Cambridge-Aachen (C/A) algorithm [37,38].[1] The branches of the clustering history with lower and higher relative transverse momentum at each step are respectively referred to as the 'emission' and 'core' of the jet, such that the transverse momentum of an emission relative to the jet core may be written as

$$k_t = p_{\text{T}}^{\text{emission}} \cdot \Delta R(p^{\text{emission}}, p^{\text{core}}).$$

The Lund multiplicity is built from the picture of JSS based on the Lund jet plane [39,40], which has proved to be a powerful experimental tool: the Primary Lund jet plane was measured by the ATLAS, ALICE and CMS collaborations [41–43], was used to develop new identification and calibration algorithms for boosted hadronically-decaying resonances [44,45], and was used by the ALICE Collaboration to observe the dead-cone effect in QCD [46]. The Lund multiplicity may be counted either in the full, fractal Lund jet plane (N_{Lund}) by following each branch of the clustering history, or along only the primary clustering sequence ($N_{\text{Lund}}^{\text{Primary}}$). These schemes provide observables with different levels of sensitivity to perturbative and non-perturbative effects. A schematic representation of this procedure for a jet with $N_{\text{Lund}} = 4$ and $N_{\text{Lund}}^{\text{Primary}} = 2$ is provided in Fig. 1. No measurement of the Lund multiplicity has been performed to-date. However, the related Cambridge multiplicity has an alternative definition of k_t that is suitable for e^+e^- annihilation, and was measured at LEP by the OPAL Collaboration [47]. New, precise measurements of observables used to assess progress in PSMC development are also an important component of the collective effort to understand QCD in the colinear limit at the level necessary to fully exploit the LHC data [48].

This Letter presents a differential cross-section measurement of the Lund subjet multiplicity in dijet events using 140 fb^{-1} of $\sqrt{s} = 13$ TeV proton–proton (pp) collision data collected by the ATLAS detector during Run 2. The N_{Lund} and $N_{\text{Lund}}^{\text{Primary}}$ distributions are measured differentially in up to five bins of jet p_{T} between 300 GeV–4500 GeV, and in relative-rapidity bins that separate in each event the more-forward and more-central of the two selected jets. These distributions are corrected for detector effects using a regularized, iterative unfolding procedure [49]. N_{Lund} and $N_{\text{Lund}}^{\text{Primary}}$ are measured for eight different emission k_t requirements (where k_t is required to be above 0.5 GeV, 1 GeV, 2 GeV, 5 GeV, 10 GeV, 20 GeV, 50 GeV and 100 GeV), resulting in sixteen differential measurements. The measured differential cross-sections as a function of N_{Lund} and $N_{\text{Lund}}^{\text{Primary}}$, along with their extracted mean values, are compared with state-of-the-art PSMCs. The average value of N_{Lund} is also compared with the recent next-to-leading-order (NLO) plus NNDL analytic prediction from Ref. [36]. Selected results are presented in the body of this Letter, but the complete differential measurement may be found as Supplemental Material, and digitally on the HepData platform [50,51].

2. The ATLAS detector

The ATLAS detector [52–54] is a general-purpose particle detector which provides nearly 4π coverage in solid angle. The inner tracking detector (ID) is inside a 2 T magnetic field and measures charged-particle trajectories up to $|\eta| = 2.5$. The innermost component of the ID is a pixelated silicon detector with fine granularity capable of resolving ambiguities inside the dense hit environment of jet cores [55], surrounded by silicon microstrip and transition radiation detectors. Beyond the ID are electromagnetic and hadronic calorimeters, from which topologically connected clusters of cells [56] are formed into particle-flow objects [57] using extrapolated measurements of charged ID particles. A muon spectrometer incorporating three superconducting air-core toroidal magnets systems surrounds the calorimetry systems. An extensive software suite is used in the reconstruction and analysis of real and simulated data, detector operations, and in the ATLAS trigger and data acquisition systems [58].

3. Reconstruction and event selection

Data passing the single-jet trigger selection [59,60] are recorded, and must satisfy the quality criteria described in Ref. [61]. The thresholds of these triggers varied depending on the data-taking period during Run 2, and some triggers are prescaled during data-taking. All triggers used to select data for this analysis are fully efficient in the regions where they are used. Events in data are reweighted by the appropriate prescale factor to recover a smoothly falling jet p_{T} spectrum in the analysis.

Jets are reconstructed from particle-flow objects [57] using the anti-k_t algorithm with radius parameter $R = 0.4$ [62,63]. Jets are calibrated such that the average detector-level jet energy scale (JES) matches that of the corresponding particle-level jets [7]. Both leading and subleading jets must have at least $p_{\text{T}} > 120$ GeV and be within the ID acceptance ($|y_{\text{jet}}| < 2.1$). They must also satisfy a dijet balance requirement of

$$p_{\text{T}}^{\text{leading}} < 1.5 \times p_{\text{T}}^{\text{subleading}},$$

suppressing possible background contributions and simplifying interpretations of the final state in terms of a $2 \to 2$ process. Only the leading and subleading jets in selected events are included in this measurement.

ID tracks are used for this measurement to precisely reconstruct the trajectories of individual particles. This approach follows methodology of earlier measurements by ATLAS [41,64,65] and CMS [66,67], providing good experimental resolution of colinear splittings within the dense jet core where relevant angular scales are much smaller than the ATLAS calorimeter granularity. Tracks are required to have $p_{\text{T}} > 500$ MeV and to be matched to the reconstructed primary vertex with the largest sum of track p_{T}^2 in the event [68]. All tracks within $\Delta R = 0.4$ of selected anti-k_t jets are reclustered using the C/A algorithm. The clustering history of the jet is then iteratively declustered to obtain the Lund multiplicities, counting the splittings within the C/A sequence that satisfy the emission k_t requirement. Once a splitting is encountered that fails the emission k_t requirement, no additional splittings are considered for that branch. To account for contributions from neutral particles, the emission k_t reconstructed from stable charged particles is rescaled by the ratio of

the jet p_{T} measured from stable charged and neutral constituents over the value of the jet p_{T} measured only from its charged constituents:

$$k_t = (p_{\mathrm{T}}^{\mathrm{all}} / p_{\mathrm{T}}^{\mathrm{charged}}) k_t^{\mathrm{charged}}.$$

As isospin is an approximate symmetry of the strong force, once the k_t value has been rescaled, the average difference between multiplicities constructed using all interacting particles and only stable charged hadrons is expected to be smaller [41,67,69]. All multiplicities presented in this analysis, at detector- and particle-level, are computed in this way.

4. Simulated event samples

Dijet events were simulated to perform the unfolding and to compare with the measured cross-sections.

Pythia 8.230 [70,71] is used as the nominal MC generator for this analysis, and is also referred to here as the 'nominal' simulation. Samples of $2 \to 2$ dijet events were simulated using the A14 tune [72], the Lund string hadronisation model and the NNPDF2.3lo [73] leading-order (LO) parton distribution function (PDF) set. The Pythia parton shower (PS) algorithm uses a dipole-style p_{T}-ordered evolution, and its renormalisation and factorisation scales were set to the geometric mean of the squared transverse masses of the outgoing particles. EvtGen [74] was used to model decays of heavy-flavour hadrons.

Two sets of Sherpa 2.2.5 [75] dijet events were simulated with the default AHADIC cluster hadronisation model [76] or with the Sherpa interface to the Lund string hadronisation model as implemented in Pythia 6.4, and its decay tables. These samples include LO matrix element calculations for $2 \to 2$ processes, and use the Sherpa parton shower algorithm based on Catani–Seymour dipole subtraction [77]. The CT14nnlo next-to-next-to-leading-order (NNLO) PDF [78] set is used for matrix element calculations and CT10 is used for multi-parton interactions (MPI) [79].

Two additional sets of Sherpa 2.2.11 samples were generated using $2 \to 2$ MEs and the CT10 PDF set, with either the default p_{T}-ordered [77] or the alternative Dire [80] PS algorithms. These samples use an updated set of tuned parameters for the cluster hadronisation model [81]. The Dire sample is of particular interest in the context of this analysis, as it incorporates some aspects of higher-order splitting functions in QCD [32], although not at the level of NLL accuracy [11].

A sample of Herwig 7.1.3 [82–84] multijet events was generated with the MMHT2014nlo PDF set [85], default cluster hadronisation model and the default angle-ordered PS. This sample models $2 \to 2$ matrix elements with NLO accuracy and $2 \to 3$ matrix elements with LO accuracy. The parton shower was matched to the matrix element calculation using the MC@NLO matching scheme [86,87], and the p_{T} of the leading jet is taken as the renormalisation scale.

A sample of dijet events with NLO matrix element accuracy were produced with Powheg v2 [88–90] using the dijet process implemented in Powheg Box v2 [91], matched to the Pythia 8 parton showers configured similarly to the corresponding sample described above. The renormalisation and factorisation scales in these samples were set to the p_{T} of the underlying Born-level configuration.

An additional Sherpa 3 prediction was provided by the authors of Ref. [18] using LO $2 \to 2$ MEs and the Alaric PS [18,92], extended to cover initial-state radiation. This sample uses CT14NNLO PDFs and Lund string hadronisation *via* an interface to Pythia 8. The Alaric PS is the successor to the Dire algorithm, and replaces explicit angle-ordering with a differentially-accurate simulation of the dependence of soft gluon splitting functions on azimuthal angles that is NLL-accurate.

All generated events used in the unfolding and its associated uncertainties were passed through a full detector simulation [93] based on Geant4 [94] and overlaid with simulated minimum-bias interactions generated using Pythia 8 with the A3 tune [95] and NNPDF2.3lo PDF set [73] to represent the effect of multiple pp interactions in the same and neighbouring bunch crossings ('pile-up'). The distribution of the average number of pile-up interactions in simulation was reweighted during data analysis to match that observed in Run 2 data. Additional details of the MC samples used in this measurement may be found in Ref. [96].

5. Unfolding procedure

Data are unfolded to correct for detector biases, resolution, and acceptance effects by applying iterative Bayesian unfolding [49], as implemented in RooUnfold [97], with four iterations. The number of iterations was selected based on a comparison of the modelling, statistical and data-driven non-closure uncertainties (described later, in Section 6) to minimise the total uncertainty in the measured cross-sections. The nominal Pythia MC sample is used to unfold the data. Unfolding corrects the multiplicities reconstructed from detector-level objects to charged-particle level. Charged particles and jets at the particle level are defined similarly to those at the detector level. Particle-level jets are reconstructed using all stable particles with a lifetime τ in the laboratory frame such that $c\tau > 10$ mm and the same anti-k_t algorithm. The same kinematic requirements as for detector-level jets are imposed on these jets; charged particles with $p_{\mathrm{T}} > 500$ MeV within $\Delta R = 0.4$ of the cores of particle-level jets are used to calculate N_{Lund} and $N_{\mathrm{Lund}}^{\mathrm{Primary}}$, and the emission k_t is also scaled by the ratio of the jet p_{T} computed with charged and neutral particles to that computed with only charged particles.

Jets at detector-level and particle-level that are uniquely matched based on their geometrical proximity (*via* a matching based on ΔR) are used to construct a *response matrix*, mapping migrations of the measured observables between detector- and particle-level. Unmatched jets are accounted for with purity and efficiency corrections, respectively applied before and after the regularized inversion of the response matrix. For each multiplicity observable measured in this analysis, this matrix is constructed differentially in the observable itself, and also in bins of jet p_{T} and two bins of relative jet rapidity ordering that contain the more-central and more-forward jet of each dijet system. This separation in rapidity is performed to allow the unfolding to properly account for underlying differences between the jet energy scale and fragmentation modelling caused by the different fractions of quark- and gluon-initiated jets in the more-central and more-forward rapidity bins. An additional p_{T} bin from 240–300 GeV is included in the unfolding to reduce the size of the purity and efficiency corrections in the fiducial region, such that they are below 10%. Unfolded distributions are normalized to the number of selected jets in a given p_{T} and relative-rapidity bin, rendering the analysis insensitive to the total jet cross-section and therefore enabling a more precise measurement of the multiplicity distribution's shape.

Since the multiplicity is an integer observable: N_{Lund} and $N_{\mathrm{Lund}}^{\mathrm{Primary}}$ distributions are unfolded using unit-width bins to simplify the calculation of the average values for different emission k_t requirements. After unfolding, the distributions are rebinned (by grouping unit-width bins) based on the detector resolution to obtain the measured differential cross-sections. Rebinning regularizes the reported distributions, ensuring that they are insensitive to sub-detector-resolution effects and unfolding biases from the steeply-falling distribution in wide bins [98]. The mean values of $\langle N_{\mathrm{Lund}} \rangle$ and $\langle N_{\mathrm{Lund}}^{\mathrm{Primary}} \rangle$ are computed from the finely-binned distributions; averaging the distribution is another form of regularisation. Studies using alternative methods, such as unfolding with the coarse measurement bins, or fitting the coarsely-binned distributions and applying a binning correction to determine the mean, showed that no significant differences in either the measured values or their uncertainties occur from using the rebinning approach selected for this analysis.

6. Uncertainties

Experimental systematic uncertainties are evaluated by independently propagating variations from each source through unfolding

(defining new purity and efficiency corrections and a new response matrix), then comparing the varied and nominal results. JES uncertainties [99] cause migrations between jet p_{T} bins and multiplicity bins due to the charged-to-all particles scaling applied to the emission k_t, typically amounting to $2-4\%$. Track reconstruction uncertainties are considered by modifying the measured track p_{T} or removing them completely [55,100]. Additional uncertainties are also included to account for differences in the tracking efficiency in the dense core of jets [55]. These uncertainties are typically below 2% but increase for smaller k_t requirements. Other experimental uncertainties related to the modelling of pile-up and the stability of the measurement across data-taking periods are negligible. A data-driven non-closure uncertainty that accounts in-part for possible bias due to regularisation in the unfolding procedure (labelled 'Unfolding' in Figs. 2 and 3) is determined by unfolding the simulated detector-level distribution following a reweighting based on a comparison of this distribution with the data [101]; this uncertainty is smaller than 2% and never dominant.

The choice of the parton shower and hadronisation models used for the unfolding procedure can affect the efficiency/purity corrections, response matrix, and unfolding prior. These contributions are estimated by unfolding with response matrices constructed with the SHERPA 2.2.11 AHADIC and HERWIG 7.1 angle-ordered samples. The component of this uncertainty related to modelling of the unfolding prior is omitted in this procedure, as it is estimated in a data-driven way when estimating the non-closure uncertainty. As the correlation between these uncertainty sources is unknown, the effect of changing the nominal model on each is assessed separately, then added in quadrature for each MC. An envelope constructed from the uncertainties determined using these alternative samples is taken as the final uncertainty; the contribution from HERWIG is usually the largest. To avoid double-counting of modelling effects related to the JES, which are accounted for separately, the JES of these samples is re-calibrated to match that of the nominal PYTHIA sample. This correction is applied separately for quark- and gluon-initiated jets in simulation, as labelled by the highest-energy parton that is associated to the particle-level jet [102]. The uncertainty due to the choice of nominal MC model ranges from $2-10\%$, and is the largest source of uncertainty in the measurement for both the differential cross-sections and extracted average multiplicities.

Statistical uncertainties due to the finite size of the data and MC samples are evaluated with Poissonian pseudo-experiments [103] respectively for the data prior or response matrix, purity and efficiency factors during unfolding. They are less than 1% throughout the measurement except in the tails of multiplicities.

7. Results

A representative selection of the measured differential cross-section as a function of N_{Lund} and $N_{\mathrm{Lund}}^{\mathrm{Primary}}$ is presented in Fig. 2, where the unfolded data are compared with several PSMCs. Most of the studied MC models do not describe the shape of the measured data well, showing two patterns of disagreement from small to large multiplicity values. For multiplicities with small k_t requirements, significant data-to-MC disagreements are generally observed at both low and high multiplicities. The total uncertainty on the measured differential cross-sections decreases with increasing k_t, and depends on the jet p_{T} bin. It is typically between $2-5\%$ in the bulk and $5-30\%$ in the tails of the multiplicity distributions.

The HERWIG angle-ordered PS provides the best overall description of both of the observables, once the emission k_t is perturbative (≥ 1 GeV) and for all configurations in the bulk of the multiplicity distributions. For smaller k_t requirements ($k_t \leq 1$ GeV), the SHERPA 2.2.11 and DIRE setups do best in the high-multiplicity tail, where non-perturbative contributions can be significant (Figs. 2(a) and 2(b)). With larger k_t requirements, most models show a similar decreasing pattern (Figs. 2(c) and 2(d)). In these cases, the best performing model tends to change from the SHERPA samples to the HERWIG sample as the multiplicity increases. The SHERPA sample using the ALARIC PS is found to behave similarly to the other SHERPA models in this region, where non-perturbative contributions are not significant.

Even for the largest k_t requirements that can be best-probed in high-p_{T} jets, such as the $k_t \geq 50$ GeV results from the bin of jet p_{T} between 1000 GeV and 1250 GeV shown in Fig. 2(e) and 2(f), the HERWIG sample performs best.

The distributions of $\langle N_{\mathrm{Lund}} \rangle$ and $\langle N_{\mathrm{Lund}}^{\mathrm{Primary}} \rangle$ are shown in Fig. 3 as a function of the emission k_t requirement, for jets with p_{T} above 300 GeV. The agreement between the unfolded data and MC models is qualitatively similar for both observables. The uncertainty on the measured average multiplicity values as a function of emission k_t is between $0.5-2\%$ for $\langle N_{\mathrm{Lund}} \rangle$ and $0.5-4\%$ for $\langle N_{\mathrm{Lund}}^{\mathrm{Primary}} \rangle$, increasing with jet p_{T}. The level of precision for $\langle N_{\mathrm{Lund}} \rangle$ is sufficient, for instance, to distinguish the next-to-double-logarithm (NDL) and NNDL predictions of Ref. [36].

Regions of the observable sensitive to non-perturbative effects can be determined by studying the relative separation of the SHERPA predictions with cluster- and string-based hadronisation models [41]: they disagree for $k_t \leq 5$ GeV and are compatible elsewhere. The PYTHIA and POWHEG+PYTHIA PSMCs are found to underestimate the measured $\langle N_{\mathrm{Lund}} \rangle$ data in the perturbative region. The SHERPA DIRE model, which includes some treatment of higher-order splitting functions, performs best among the SHERPA setups here, but also underestimates the average value in data. The HERWIG sample has the best overall agreement for both observables, and is found to be compatible with the unfolded data's uncertainty throughout both the perturbative and non-perturbative regions of the measurement. The PYTHIA, POWHEG+PYTHIA and SHERPA ALARIC samples overestimate the average multiplicity at low k_t ($<$ 1 GeV), although the SHERPA 2.2.5 Lund sample shows good agreement in this region.

The analytic prediction from Ref. [36] at NLO matched to NNDL resummation (labelled 'NLO+NNDL+NP') was provided by the authors, and is also compared with the $\langle N_{\mathrm{Lund}} \rangle$ values shown as a function of k_t in Fig. 3(a), 3(c), and 3(e). This prediction includes non-perturbative corrections computed by taking the ratio of the prediction in MC simulations at hadron-level with multi-parton interactions, and at parton-level without multi-parton interactions, following the prescription in Ref. [69]. This introduces an additional source of theoretical uncertainty that accounts for the experimental use of charged particles. Both the non-perturbative correction and its associated uncertainty are small for $k_t > 2$ GeV, but grow rapidly for smaller values where non-perturbative effects become more important.

Agreement between the central value of this prediction and the unfolded data is good in the region where perturbative effects are most relevant ($k_t \geq 5$ GeV), and is competitive with the best PSMC models in the lowest bins of jet p_{T}. The uncertainty on the prediction, dominated by the contribution from theoretical scale variations for emission $k_t \geq 5$ GeV, covers the difference between the prediction's central value and the measured data. As the jet p_{T} increases, the central value of the NLO+NNDL+NP prediction increasingly underestimates the $\langle N_{\mathrm{Lund}} \rangle$ distribution; this is most pronounced for low k_t requirements ($k_t \leq 10$ GeV). In this region, while they are still compatible within the theoretical uncertainty, the difference between the measured data and the prediction's central value approaches 10%: this is larger than the observed disagreement between the measured data and PSMC samples.

8. Summary

In summary, this Letter presents a differential cross-section measurement of Lund subjet multiplicities in dijet events with 140 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data collected with the ATLAS detector at the Large Hadron Collider. Multiplicities are calculated by reclustering the jets' constituents with the C/A algorithm, then counting the emissions above a specified k_t requirement in the full clustering tree or its primary branch. These observables are reconstructed using ID tracks within jets

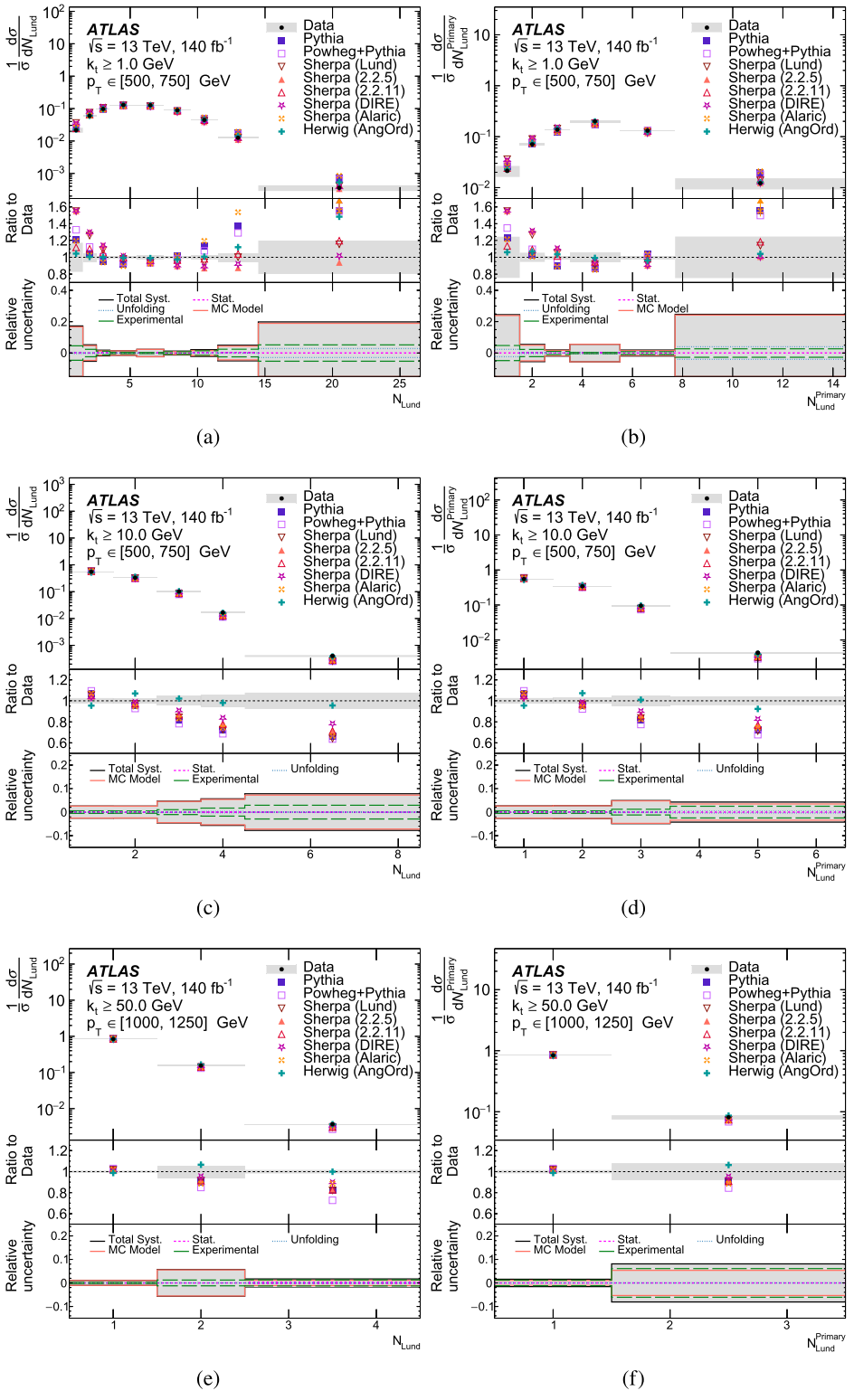

Fig. 2. A representative measured differential cross-section of (a,c,e) N_{Lund} and (b,d,f) $N_{\text{Lund}}^{\text{Primary}}$ for an emission k_t requirement of (a,b) 1 GeV, (c,d) 10 GeV and (e,f) 50 GeV. The data are shown in an inclusive bin of jet rapidity and a bin of jet p_{T} between either (a-d) 500-750 GeV or (e,f) 1000-1250 GeV. The unfolded data are compared with several MC predictions, and the total uncertainty on the data is indicated by a shaded grey region. The middle panel shows a ratio of the predictions to the measured data, and the bottom panel summarizes the various systematic uncertainties in each bin.

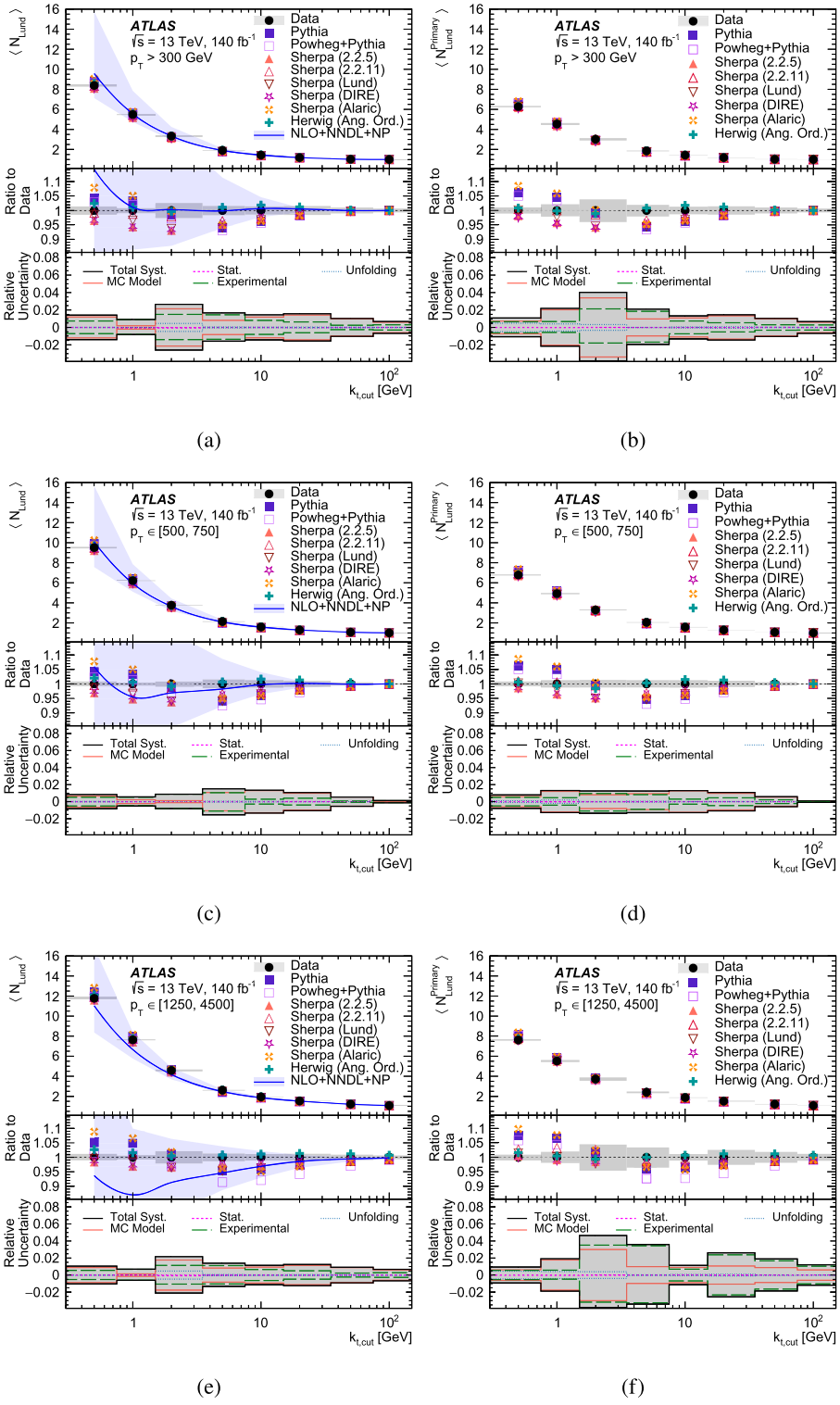

Fig. 3. (left) $\langle N_{\text{Lund}} \rangle$ and (right) $\langle N_{\text{Lund}}^{\text{Primary}} \rangle$ are shown as a function of the emission k_t requirement, $k_{t,\text{cut}}$. The unfolded data are compared with several MC predictions in (a,b) an inclusive p_{T} bin above 300 GeV, (c,d) a p_{T} bin between 500 GeV and 750 GeV and (e,f) a p_{T} bin between 1250 GeV and 4500 GeV. The $\langle N_{\text{Lund}} \rangle$ distribution is also compared with an analytic NLO+NNDL+NP prediction with additional non-perturbative corrections, depicted as a solid line, provided by the authors of Ref. [36]. The total uncertainty on the data and the NLO+NNDL+NP prediction are indicated as shaded regions. The middle panel shows a ratio of the predictions to the measured data, and the bottom panel summarizes the various systematic uncertainties in each bin.

to probe finer angular scales. Acceptance and detector effects are accounted for using an iterative Bayesian unfolding procedure.

The measurement is made for increasing requirements on the subjet k_t, and the average multiplicity value for each k_t requirement is also extracted for comparison with PSMC and analytic predictions. Out of many PSMC setups that were studied, a HERWIG sample generated with the default angle-ordered PS is found to agree best overall with the measured data for both the multiplicity distributions and their extracted average values. Several recent SHERPA setups describe the differential multiplicity distributions best when more non-perturbative emissions are allowed ($k_t < 2$ GeV). Other PSMC models often fail to accurately describe the measured data, indicating the utility of this measurement as an input to future parton shower developments.

The resummed analytic prediction presented in Ref. [36] was found to be in good agreement with the measured data in the perturbative region of the measurement ($k_t > 2$ GeV), particularly for jets with low p_{T} (*e.g.* between 300 GeV and 500 GeV). In this region, the performance of this prediction matches that of the best PSMC models that were studied. As the jet p_{T} increases, the performance of this prediction deteriorates, and it is found to underestimate the measured data in the highest p_{T} bins. This illustrates the important role of JSS measurements targeting such effects at the LHC, where access to high-energy jets provides a complement to existing fragmentation measurements made at lower-energy facilities such as LEP and HERA.

A Rivet routine is available for this measurement [104], and the measured data points have been made publicly available [50] as an input to future parton shower developments and other studies probing fundamental properties of QCD and jet formation at the TeV-scale.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data for this manuscript are not available. The values in the plots and tables associated to this article are stored in HEPDATA (https://hepdata.cedar.ac.uk).

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G. Aad [103], E. Aakvaag [16], B. Abbott [121], K. Abeling [55], N.J. Abicht [49], S.H. Abidi [29], M. Aboelela [44], A. Aboulhorma [35e], H. Abramowicz [152], H. Abreu [151], Y. Abulaiti [118], B.S. Acharya [69a,69b,l], A. Ackermann [63a], C. Adam Bourdarios [4], L. Adamczyk [86a], S.V. Addepalli [26], M.J. Addison [102], J. Adelman [116], A. Adiguzel [21c], T. Adye [135], A.A. Affolder [137], Y. Afik [39], M.N. Agaras [13], J. Agarwala [73a,73b], A. Aggarwal [101], C. Agheorghiesei [27c], A. Ahmad [36], F. Ahmadov [38,z], W.S. Ahmed [105], S. Ahuja [96], X. Ai [62e], G. Aielli [76a,76b], A. Aikot [164], M. Ait Tamlihat [35e], B. Aitbenchikh [35a], I. Aizenberg [170], M. Akbiyik [101], T.P.A. Åkesson [99], A.V. Akimov [37], D. Akiyama [169], N.N. Akolkar [24], S. Aktas [21a], K. Al Khoury [41], G.L. Alberghi [23b], J. Albert [166], P. Albicocco [53], G.L. Albouy [60], S. Alderweireldt [52], Z.L. Alegria [122], M. Aleksa [36], I.N. Aleksandrov [38], C. Alexa [27b], T. Alexopoulos [10], F. Alfonsi [23b], M. Algren [56], M. Alhroob [142], B. Ali [133], H.M.J. Ali [92], S. Ali [149], S.W. Alibocus [93], M. Aliev [33c], G. Alimonti [71a], W. Alkakhi [55], C. Allaire [66], B.M.M. Allbrooke [147], J.F. Allen [52], C.A. Allendes Flores [138f], P.P. Allport [20], A. Aloisio [72a,72b], F. Alonso [91], C. Alpigiani [139], M. Alvarez Estevez [100], A. Alvarez Fernandez [101], M. Alves Cardoso [56], M.G. Alviggi [72a,72b], M. Aly [102], Y. Amaral Coutinho [83b], A. Ambler [105], C. Amelung [36], M. Amerl [102], C.G. Ames [110], D. Amidei [107], K.J. Amirie [156], S.P. Amor Dos Santos [131a], K.R. Amos [164], S. An [84], V. Ananiev [126], C. Anastopoulos [140], T. Andeen [11], J.K. Anders [36], S.Y. Andrean [47a,47b], A. Andreazza [71a,71b], S. Angelidakis [9], A. Angerami [41,ab], A.V. Anisenkov [37], A. Annovi [74a], C. Antel [56], M.T. Anthony [140], E. Antipov [146], M. Antonelli [53], F. Anulli [75a], M. Aoki [84], T. Aoki [154], J.A. Aparisi Pozo [164], M.A. Aparo [147], L. Aperio Bella [48], C. Appelt [18], A. Apyan [26], S.J. Arbiol Val [87], C. Arcangeletti [53], A.T.H. Arce [51], E. Arena [93], J-F. Arguin [109],

S. Argyropoulos [54], J.-H. Arling [48], O. Arnaez [4], H. Arnold [115], G. Artoni [75a,75b], H. Asada [112], K. Asai [119], S. Asai [154], N.A. Asbah [36], K. Assamagan [29], R. Astalos [28a], K.S.V. Astrand [99], S. Atashi [160], R.J. Atkin [33a], M. Atkinson [163], H. Atmani [35f], P.A. Atmasiddha [129], K. Augsten [133], S. Auricchio [72a,72b], A.D. Auriol [20], V.A. Austrup [102], G. Avolio [36], K. Axiotis [56], G. Azuelos [109,af], D. Babal [28b], H. Bachacou [136], K. Bachas [153,p], A. Bachiu [34], F. Backman [47a,47b], A. Badea [39], T.M. Baer [107], P. Bagnaia [75a,75b], M. Bahmani [18], D. Bahner [54], K. Bai [124], J.T. Baines [135], L. Baines [95], O.K. Baker [173], E. Bakos [15], D. Bakshi Gupta [8], V. Balakrishnan [121], R. Balasubramanian [115], E.M. Baldin [37], P. Balek [86a], E. Ballabene [23b,23a], F. Balli [136], L.M. Baltes [63a], W.K. Balunas [32], J. Balz [101], E. Banas [87], M. Bandieramonte [130], A. Bandyopadhyay [24], S. Bansal [24], L. Barak [152], M. Barakat [48], E.L. Barberio [106], D. Barberis [57b,57a], M. Barbero [103], M.Z. Barel [115], K.N. Barends [33a], T. Barillari [111], M-S. Barisits [36], T. Barklow [144], P. Baron [123], D.A. Baron Moreno [102], A. Baroncelli [62a], G. Barone [29], A.J. Barr [127], J.D. Barr [97], F. Barreiro [100], J. Barreiro Guimarães da Costa [14a], U. Barron [152], M.G. Barros Teixeira [131a], S. Barsov [37], F. Bartels [63a], R. Bartoldus [144], A.E. Barton [92], P. Bartos [28a], A. Basan [101], M. Baselga [49], A. Bassalat [66,b], M.J. Basso [157a], R. Bate [165], R.L. Bates [59], S. Batlamous [35e], B. Batool [142], M. Battaglia [137], D. Battulga [18], M. Bauce [75a,75b], M. Bauer [36], P. Bauer [24], L.T. Bazzano Hurrell [30], J.B. Beacham [51], T. Beau [128], J.Y. Beaucamp [91], P.H. Beauchemin [159], P. Bechtle [24], H.P. Beck [19,o], K. Becker [168], A.J. Beddall [82], V.A. Bednyakov [38], C.P. Bee [146], L.J. Beemster [15], T.A. Beermann [36], M. Begalli [83d], M. Begel [29], A. Behera [146], J.K. Behr [48], J.F. Beirer [36], F. Beisiegel [24], M. Belfkir [117b], G. Bella [152], L. Bellagamba [23b], A. Bellerive [34], P. Bellos [20], K. Beloborodov [37], D. Benchekroun [35a], F. Bendebba [35a], Y. Benhammou [152], K.C. Benkendorfer [61], L. Beresford [48], M. Beretta [53], E. Bergeaas Kuutmann [162], N. Berger [4], B. Bergmann [133], J. Beringer [17a], G. Bernardi [5], C. Bernius [144], F.U. Bernlochner [24], F. Bernon [36,103], A. Berrocal Guardia [13], T. Berry [96], P. Berta [134], A. Berthold [50], S. Bethke [111], A. Betti [75a,75b], A.J. Bevan [95], N.K. Bhalla [54], M. Bhamjee [33c], S. Bhatta [146], D.S. Bhattacharya [167], P. Bhattarai [144], K.D. Bhide [54], V.S. Bhopatkar [122], R.M. Bianchi [130], G. Bianco [23b,23a], O. Biebel [110], R. Bielski [124], M. Biglietti [77a], C.S. Billingsley [44], M. Bindi [55], A. Bingul [21b], C. Bini [75a,75b], A. Biondini [93], C.J. Birch-sykes [102], G.A. Bird [32], M. Birman [170], M. Biros [134], S. Biryukov [147], T. Bisanz [49], E. Bisceglie [43b,43a], J.P. Biswal [135], D. Biswas [142], K. Bjørke [126], I. Bloch [48], A. Blue [59], U. Blumenschein [95], J. Blumenthal [101], V.S. Bobrovnikov [37], M. Boehler [54], B. Boehm [167], D. Bogavac [36], A.G. Bogdanchikov [37], C. Bohm [47a], V. Boisvert [96], P. Bokan [36], T. Bold [86a], M. Bomben [5], M. Bona [95], M. Boonekamp [136], C.D. Booth [96], A.G. Borbély [59], I.S. Bordulev [37], H.M. Borecka-Bielska [109], G. Borissov [92], D. Bortoletto [127], D. Boscherini [23b], M. Bosman [13], J.D. Bossio Sola [36], K. Bouaouda [35a], N. Bouchhar [164], J. Boudreau [130], E.V. Bouhova-Thacker [92], D. Boumediene [40], R. Bouquet [57b,57a], A. Boveia [120], J. Boyd [36], D. Boye [29], I.R. Boyko [38], J. Bracinik [20], N. Brahimi [4], G. Brandt [172], O. Brandt [32], F. Braren [48], B. Brau [104], J.E. Brau [124], R. Brener [170], L. Brenner [115], R. Brenner [162], S. Bressler [170], D. Britton [59], D. Britzger [111], I. Brock [24], R. Brock [108], G. Brooijmans [41], E. Brost [29], L.M. Brown [166], L.E. Bruce [61], T.L. Bruckler [127], P.A. Bruckman de Renstrom [87], B. Brüers [48], A. Bruni [23b], G. Bruni [23b], M. Bruschi [23b], N. Bruscino [75a,75b], T. Buanes [16], Q. Buat [139], D. Buchin [111], A.G. Buckley [59], O. Bulekov [37], B.A. Bullard [144], S. Burdin [93], C.D. Burgard [49], A.M. Burger [36], B. Burghgrave [8], O. Burlayenko [54], J.T.P. Burr [32], C.D. Burton [11], J.C. Burzynski [143], E.L. Busch [41], V. Büscher [101], P.J. Bussey [59], J.M. Butler [25], C.M. Buttar [59], J.M. Butterworth [97], W. Buttinger [135],

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D.R. Tovey [140], A. Traeet [16], I.S. Trandafir [27b], T. Trefzger [167], A. Tricoli [29], I.M. Trigger [157a], S. Trincaz-Duvoid [128], D.A. Trischuk [26], B. Trocmé [60], L. Truong [33c], M. Trzebinski [87], A. Trzupek [87], F. Tsai [146], M. Tsai [107], A. Tsiamis [153,e], P.V. Tsiareshka [37], S. Tsigaridas [157a], A. Tsirigotis [153,s], V. Tsiskaridze [156], E.G. Tskhadadze [150a], M. Tsopoulou [153], Y. Tsujikawa [88], I.I. Tsukerman [37], V. Tsulaia [17a], S. Tsuno [84], K. Tsuri [119], D. Tsybychev [146], Y. Tu [64b], A. Tudorache [27b], V. Tudorache [27b], A.N. Tuna [61], S. Turchikhin [57b,57a], I. Turk Cakir [3a], R. Turra [71a], T. Turtuvshin [38,y], P.M. Tuts [41], S. Tzamarias [153,e], E. Tzovara [101], F. Ukegawa [158], P.A. Ulloa Poblete [138c,138b], E.N. Umaka [29], G. Unal [36], A. Undrus [29], G. Unel [160], J. Urban [28b], P. Urquijo [106], P. Urrejola [138a], G. Usai [8], R. Ushioda [155], M. Usman [109], Z. Uysal [82], V. Vacek [133], B. Vachon [105], K.O.H. Vadla [126], T. Vafeiadis [36], A. Vaitkus [97], C. Valderanis [110], E. Valdes Santurio [47a,47b], M. Valente [157a], S. Valentinetti [23b,23a], A. Valero [164], E. Valiente Moreno [164], A. Vallier [90], J.A. Valls Ferrer [164], D.R. Van Arneman [115], T.R. Van Daalen [139], A. Van Der Graaf [49], P. Van Gemmeren [6], M. Van Rijnbach [126], S. Van Stroud [97], I. Van Vulpen [115], P. Vana [134], M. Vanadia [76a,76b], W. Vandelli [36], E.R. Vandewall [122], D. Vannicola [152], L. Vannoli [53], R. Vari [75a], E.W. Varnes [7], C. Varni [17b], T. Varol [149], D. Varouchas [66], L. Varriale [164], K.E. Varvell [148], M.E. Vasile [27b], L. Vaslin [84], G.A. Vasquez [166], A. Vasyukov [38], R. Vavricka [101], F. Vazeille [40], T. Vazquez Schroeder [36], J. Veatch [31], V. Vecchio [102], M.J. Veen [104], I. Veliscek [29], L.M. Veloce [156], F. Veloso [131a,131c], S. Veneziano [75a], A. Ventura [70a,70b], S. Ventura Gonzalez [136], A. Verbytskyi [111], M. Verducci [74a,74b], C. Vergis [95], M. Verissimo De Araujo [83b], W. Verkerke [115], J.C. Vermeulen [115], C. Vernieri [144], M. Vessella [104], M.C. Vetterli [143,af], A. Vgenopoulos [153,e], N. Viaux Maira [138f], T. Vickey [140], O.E. Vickey Boeriu [140], G.H.A. Viehhauser [127], L. Vigani [63b], M. Villa [23b,23a], M. Villaplana Perez [164], E.M. Villhauer [52], E. Vilucchi [53], M.G. Vincter [34], G.S. Virdee [20], A. Visibile [115], C. Vittori [36], I. Vivarelli [23b,23a], E. Voevodina [111], F. Vogel [110], J.C. Voigt [50], P. Vokac [133], Yu. Volkotrub [86b], J. Von Ahnen [48], E. Von Toerne [24], B. Vormwald [36], V. Vorobel [134], K. Vorobev [37], M. Vos [164], K. Voss [142], M. Vozak [115], L. Vozdecky [121], N. Vranjes [15], M. Vranjes Milosavljevic [15], M. Vreeswijk [115], N.K. Vu [62d,62c], R. Vuillermet [36], O. Vujinovic [101], I. Vukotic [39], S. Wada [158], C. Wagner [104], J.M. Wagner [17a], W. Wagner [172], S. Wahdan [172], H. Wahlberg [91], M. Wakida [112], J. Walder [135], R. Walker [110], W. Walkowiak [142], A. Wall [129], E.J. Wallin [99], T. Wamorkar [6], A.Z. Wang [137], C. Wang [101], C. Wang [11], H. Wang [17a], J. Wang [64c], R.-J. Wang [101], R. Wang [61], R. Wang [6], S.M. Wang [149], S. Wang [62b], T. Wang [62a], W.T. Wang [80], W. Wang [14a], X. Wang [14c], X. Wang [163], X. Wang [62c], Y. Wang [62d], Y. Wang [14c], Z. Wang [107], Z. Wang [62d,51,62c], Z. Wang [107], A. Warburton [105], R.J. Ward [20], N. Warrack [59], S. Waterhouse [96], A.T. Watson [20], H. Watson [59], M.F. Watson [20], E. Watton [59,135], G. Watts [139], B.M. Waugh [97], J.M. Webb [54], C. Weber [29], H.A. Weber [18], M.S. Weber [19], S.M. Weber [63a], C. Wei [62a], Y. Wei [127], A.R. Weidberg [127], E.J. Weik [118], J. Weingarten [49], M. Weirich [101], C. Weiser [54], C.J. Wells [48], T. Wenaus [29], B. Wendland [49], T. Wengler [36], N.S. Wenke [111], N. Wermes [24], M. Wessels [63a], A.M. Wharton [92], A.S. White [61], A. White [8], M.J. White [1], D. Whiteson [160], L. Wickremasinghe [125], W. Wiedenmann [171], M. Wielers [135], C. Wiglesworth [42], D.J. Wilbern [121], H.G. Wilkens [36], J.J.H. Wilkinson [32], D.M. Williams [41], H.H. Williams [129], S. Williams [32], S. Willocq [104], B.J. Wilson [102], P.J. Windischhofer [39], F.I. Winkel [30], F. Winklmeier [124], B.T. Winter [54], J.K. Winter [102], M. Wittgen [144], M. Wobisch [98], T. Wojtkowski [60], Z. Wolffs [115], J. Wollrath [160], M.W. Wolter [87], H. Wolters [131a,131c], M.C. Wong [137], E.L. Woodward [41], S.D. Worm [48], B.K. Wosiek [87],

K.W. Woźniak [87], S. Wozniewski [55], K. Wraight [59], C. Wu [20], M. Wu [14d], M. Wu [114], S.L. Wu [171], X. Wu [56], Y. Wu [62a], Z. Wu [4], J. Wuerzinger [111,ad], T.R. Wyatt [102], B.M. Wynne [52], S. Xella [42], L. Xia [14c], M. Xia [14b], J. Xiang [64c], M. Xie [62a], X. Xie [62a], S. Xin [14a,14e], A. Xiong [124], J. Xiong [17a], D. Xu [14a], H. Xu [62a], L. Xu [62a], R. Xu [129], T. Xu [107], Y. Xu [14b], Z. Xu [52], Z. Xu [14c], B. Yabsley [148], S. Yacoob [33a], Y. Yamaguchi [155], E. Yamashita [154], H. Yamauchi [158], T. Yamazaki [17a], Y. Yamazaki [85], J. Yan [62c], S. Yan [59], Z. Yan [104], H.J. Yang [62c,62d], H.T. Yang [62a], S. Yang [62a], T. Yang [64c], X. Yang [36], X. Yang [14a], Y. Yang [44], Y. Yang [62a], Z. Yang [62a], W-M. Yao [17a], H. Ye [14c], H. Ye [55], J. Ye [14a], S. Ye [29], X. Ye [62a], Y. Yeh [97], I. Yeletskikh [38], B. Yeo [17b], M.R. Yexley [97], T.P. Yildirim [127], P. Yin [41], K. Yorita [169], S. Younas [27b], C.J.S. Young [36], C. Young [144], C. Yu [14a,14e], Y. Yu [62a], M. Yuan [107], R. Yuan [62d], L. Yue [97], M. Zaazoua [62a], B. Zabinski [87], E. Zaid [52], Z.K. Zak [87], T. Zakareishvili [164], N. Zakharchuk [34], S. Zambito [56], J.A. Zamora Saa [138d,138b], J. Zang [154], D. Zanzi [54], O. Zaplatilek [133], C. Zeitnitz [172], H. Zeng [14a], J.C. Zeng [163], D.T. Zenger Jr [26], O. Zenin [37], T. Ženiš [28a], S. Zenz [95], S. Zerradi [35a], D. Zerwas [66], M. Zhai [14a,14e], D.F. Zhang [140], J. Zhang [62b], J. Zhang [6], K. Zhang [14a,14e], L. Zhang [62a], L. Zhang [14c], P. Zhang [14a,14e], R. Zhang [171], S. Zhang [107], S. Zhang [44], T. Zhang [154], X. Zhang [62c], X. Zhang [62b], Y. Zhang [62c,5], Y. Zhang [97], Y. Zhang [14c], Z. Zhang [17a], Z. Zhang [66], H. Zhao [139], T. Zhao [62b], Y. Zhao [137], Z. Zhao [62a], Z. Zhao [62a], A. Zhemchugov [38], J. Zheng [14c], K. Zheng [163], X. Zheng [62a], Z. Zheng [144], D. Zhong [163], B. Zhou [107], H. Zhou [7], N. Zhou [62c], Y. Zhou [14c], Y. Zhou [7], C.G. Zhu [62b], J. Zhu [107], Y. Zhu [62c], Y. Zhu [62a], X. Zhuang [14a], K. Zhukov [37], N.I. Zimine [38], J. Zinsser [63b], M. Ziolkowski [142], L. Živković [15], A. Zoccoli [23b,23a], K. Zoch [61], T.G. Zorbas [140], O. Zormpa [46], W. Zou [41], L. Zwalinski [36]

[1] *Department of Physics, University of Adelaide, Adelaide; Australia*
[2] *Department of Physics, University of Alberta, Edmonton AB; Canada*
[3] *(a) Department of Physics, Ankara University, Ankara; (b) Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye*
[4] *LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France*
[5] *APC, Université Paris Cité, CNRS/IN2P3, Paris; France*
[6] *High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America*
[7] *Department of Physics, University of Arizona, Tucson AZ; United States of America*
[8] *Department of Physics, University of Texas at Arlington, Arlington TX; United States of America*
[9] *Physics Department, National and Kapodistrian University of Athens, Athens; Greece*
[10] *Physics Department, National Technical University of Athens, Zografou; Greece*
[11] *Department of Physics, University of Texas at Austin, Austin TX; United States of America*
[12] *Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan*
[13] *Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain*
[14] *(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Physics Department, Tsinghua University, Beijing; (c) Department of Physics, Nanjing University, Nanjing; (d) School of Science, Shenzhen Campus of Sun Yat-sen University; (e) University of Chinese Academy of Science (UCAS), Beijing; China*
[15] *Institute of Physics, University of Belgrade, Belgrade; Serbia*
[16] *Department for Physics and Technology, University of Bergen, Bergen; Norway*
[17] *(a) Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; (b) University of California, Berkeley CA; United States of America*
[18] *Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany*
[19] *Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland*
[20] *School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom*
[21] *(a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Department of Physics, Istanbul University, Istanbul; Türkiye*
[22] *(a) Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá; (b) Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia*
[23] *(a) Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; (b) INFN Sezione di Bologna; Italy*
[24] *Physikalisches Institut, Universität Bonn, Bonn; Germany*
[25] *Department of Physics, Boston University, Boston MA; United States of America*
[26] *Department of Physics, Brandeis University, Waltham MA; United States of America*
[27] *(a) Transilvania University of Brasov, Brasov; (b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (e) National University of Science and Technology Politechnica, Bucharest; (f) West University in Timisoara, Timisoara; (g) Faculty of Physics, University of Bucharest, Bucharest; Romania*
[28] *(a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic*
[29] *Physics Department, Brookhaven National Laboratory, Upton NY; United States of America*
[30] *Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina*
[31] *California State University, CA; United States of America*
[32] *Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom*
[33] *(a) Department of Physics, University of Cape Town, Cape Town; (b) iThemba Labs, Western Cape; (c) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; (d) National Institute of Physics, University of the Philippines Diliman (Philippines); (e) University of South Africa, Department of Physics, Pretoria; (f) University of Zululand, KwaDlangezwa; (g) School of Physics, University of the Witwatersrand, Johannesburg; South Africa*
[34] *Department of Physics, Carleton University, Ottawa ON; Canada*

[35] [(a)] Faculté des Sciences Ain Chock, Université Hassan II de Casablanca; [(b)] Faculté des Sciences, Université Ibn-Tofail, Kénitra; [(c)] Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; [(d)] LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; [(e)] Faculté des sciences, Université Mohammed V, Rabat; [(f)] Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco
[36] CERN, Geneva; Switzerland
[37] Affiliated with an institute covered by a cooperation agreement with CERN
[38] Affiliated with an international laboratory covered by a cooperation agreement with CERN
[39] Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America
[40] LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France
[41] Nevis Laboratory, Columbia University, Irvington NY; United States of America
[42] Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark
[43] [(a)] Dipartimento di Fisica, Università della Calabria, Rende; [(b)] INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy
[44] Physics Department, Southern Methodist University, Dallas TX; United States of America
[45] Physics Department, University of Texas at Dallas, Richardson TX; United States of America
[46] National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece
[47] [(a)] Department of Physics, Stockholm University; [(b)] Oskar Klein Centre, Stockholm; Sweden
[48] Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
[49] Fakultät Physik , Technische Universität Dortmund, Dortmund; Germany
[50] Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany
[51] Department of Physics, Duke University, Durham NC; United States of America
[52] SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom
[53] INFN e Laboratori Nazionali di Frascati, Frascati; Italy
[54] Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
[55] II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
[56] Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
[57] [(a)] Dipartimento di Fisica, Università di Genova, Genova; [(b)] INFN Sezione di Genova; Italy
[58] II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany
[59] SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
[60] LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France
[61] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America
[62] [(a)] Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; [(b)] Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; [(c)] School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; [(d)] Tsung-Dao Lee Institute, Shanghai; [(e)] School of Physics and Microelectronics, Zhengzhou University; China
[63] [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany
[64] [(a)] Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; [(b)] Department of Physics, University of Hong Kong, Hong Kong; [(c)] Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China
[65] Department of Physics, National Tsing Hua University, Hsinchu; Taiwan
[66] IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France
[67] Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain
[68] Department of Physics, Indiana University, Bloomington IN; United States of America
[69] [(a)] INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; [(b)] ICTP, Trieste; [(c)] Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy
[70] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
[71] [(a)] INFN Sezione di Milano; [(b)] Dipartimento di Fisica, Università di Milano, Milano; Italy
[72] [(a)] INFN Sezione di Napoli; [(b)] Dipartimento di Fisica, Università di Napoli, Napoli; Italy
[73] [(a)] INFN Sezione di Pavia; [(b)] Dipartimento di Fisica, Università di Pavia, Pavia; Italy
[74] [(a)] INFN Sezione di Pisa; [(b)] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
[75] [(a)] INFN Sezione di Roma; [(b)] Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
[76] [(a)] INFN Sezione di Roma Tor Vergata; [(b)] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
[77] [(a)] INFN Sezione di Roma Tre; [(b)] Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
[78] [(a)] INFN-TIFPA; [(b)] Università degli Studi di Trento, Trento; Italy
[79] Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria
[80] University of Iowa, Iowa City IA; United States of America
[81] Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
[82] Istinye University, Sariyer, Istanbul; Türkiye
[83] [(a)] Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; [(b)] Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(c)] Instituto de Física, Universidade de São Paulo, São Paulo; [(d)] Rio de Janeiro State University, Rio de Janeiro; [(e)] Federal University of Bahia, Bahia; Brazil
[84] KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
[85] Graduate School of Science, Kobe University, Kobe; Japan
[86] [(a)] AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow; [(b)] Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland
[87] Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
[88] Faculty of Science, Kyoto University, Kyoto; Japan
[89] Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan
[90] L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France
[91] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina
[92] Physics Department, Lancaster University, Lancaster; United Kingdom
[93] Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom
[94] Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia
[95] School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom
[96] Department of Physics, Royal Holloway University of London, Egham; United Kingdom
[97] Department of Physics and Astronomy, University College London, London; United Kingdom
[98] Louisiana Tech University, Ruston LA; United States of America
[99] Fysiska institutionen, Lunds universitet, Lund; Sweden
[100] Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain
[101] Institut für Physik, Universität Mainz, Mainz; Germany
[102] School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom
[103] CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France
[104] Department of Physics, University of Massachusetts, Amherst MA; United States of America
[105] Department of Physics, McGill University, Montreal QC; Canada
[106] School of Physics, University of Melbourne, Victoria; Australia
[107] Department of Physics, University of Michigan, Ann Arbor MI; United States of America

[108] Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
[109] Group of Particle Physics, University of Montreal, Montreal QC; Canada
[110] Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany
[111] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany
[112] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan
[113] Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America
[114] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands
[115] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands
[116] Department of Physics, Northern Illinois University, DeKalb IL; United States of America
[117] [(a)] New York University Abu Dhabi, Abu Dhabi; [(b)] United Arab Emirates University, Al Ain; United Arab Emirates
[118] Department of Physics, New York University, New York NY; United States of America
[119] Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan
[120] Ohio State University, Columbus OH; United States of America
[121] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America
[122] Department of Physics, Oklahoma State University, Stillwater OK; United States of America
[123] Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic
[124] Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America
[125] Graduate School of Science, Osaka University, Osaka; Japan
[126] Department of Physics, University of Oslo, Oslo; Norway
[127] Department of Physics, Oxford University, Oxford; United Kingdom
[128] LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France
[129] Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America
[130] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America
[131] [(a)] Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; [(b)] Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; [(c)] Departamento de Física, Universidade de Coimbra, Coimbra; [(d)] Centro de Física Nuclear da Universidade de Lisboa, Lisboa; [(e)] Departamento de Física, Universidade do Minho, Braga; [(f)] Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); [(g)] Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal
[132] Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic
[133] Czech Technical University in Prague, Prague; Czech Republic
[134] Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic
[135] Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom
[136] IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France
[137] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America
[138] [(a)] Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; [(b)] Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago; [(c)] Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena; [(d)] Universidad Andres Bello, Department of Physics, Santiago; [(e)] Instituto de Alta Investigación, Universidad de Tarapacá, Arica; [(f)] Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile
[139] Department of Physics, University of Washington, Seattle WA; United States of America
[140] Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
[141] Department of Physics, Shinshu University, Nagano; Japan
[142] Department Physik, Universität Siegen, Siegen; Germany
[143] Department of Physics, Simon Fraser University, Burnaby BC; Canada
[144] SLAC National Accelerator Laboratory, Stanford CA; United States of America
[145] Department of Physics, Royal Institute of Technology, Stockholm; Sweden
[146] Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America
[147] Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom
[148] School of Physics, University of Sydney, Sydney; Australia
[149] Institute of Physics, Academia Sinica, Taipei; Taiwan
[150] [(a)] E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; [(b)] High Energy Physics Institute, Tbilisi State University, Tbilisi; [(c)] University of Georgia, Tbilisi; Georgia
[151] Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel
[152] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel
[153] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece
[154] International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan
[155] Department of Physics, Tokyo Institute of Technology, Tokyo; Japan
[156] Department of Physics, University of Toronto, Toronto ON; Canada
[157] [(a)] TRIUMF, Vancouver BC; [(b)] Department of Physics and Astronomy, York University, Toronto ON; Canada
[158] Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan
[159] Department of Physics and Astronomy, Tufts University, Medford MA; United States of America
[160] Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
[161] University of Sharjah, Sharjah; United Arab Emirates
[162] Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
[163] Department of Physics, University of Illinois, Urbana IL; United States of America
[164] Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain
[165] Department of Physics, University of British Columbia, Vancouver BC; Canada
[166] Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
[167] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
[168] Department of Physics, University of Warwick, Coventry; United Kingdom
[169] Waseda University, Tokyo; Japan
[170] Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel
[171] Department of Physics, University of Wisconsin, Madison WI; United States of America
[172] Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
[173] Department of Physics, Yale University, New Haven CT; United States of America

[a] Also Affiliated with an institute covered by a cooperation agreement with CERN.
[b] Also at An-Najah National University, Nablus; Palestine.
[c] Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
[d] Also at Center for High Energy Physics, Peking University; China.
[e] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
[f] Also at Centro Studi e Ricerche Enrico Fermi; Italy.
[g] Also at CERN, Geneva; Switzerland.
[h] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.

[i] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[j] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[k] Also at Department of Physics, California State University, Sacramento; United States of America.
[l] Also at Department of Physics, King's College London, London; United Kingdom.
[m] Also at Department of Physics, Stanford University, Stanford CA; United States of America.
[n] Also at Department of Physics, Stellenbosch University; South Africa.
[o] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[p] Also at Department of Physics, University of Thessaly; Greece.
[q] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
[r] Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia; Bulgaria.
[s] Also at Hellenic Open University, Patras; Greece.
[t] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[u] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[v] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
[w] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
[x] Also at Institute of Particle Physics (IPP); Canada.
[y] Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.
[z] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[aa] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[ab] Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
[ac] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
[ad] Also at Technical University of Munich, Munich; Germany.
[ae] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[af] Also at TRIUMF, Vancouver BC; Canada.
[ag] Also at Università di Napoli Parthenope, Napoli; Italy.
[ah] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[ai] Also at Washington College, Chestertown, MD; United States of America.
[aj] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
[*] Deceased.