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Authors

Collaboration, ATLAS
Aad, G
Abbott, B
et al.

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Measurement of the dependence of transverse energy production at large pseudorapidity on the hard-scattering kinematics of proton–proton collisions at $\sqrt{s} = 2.76$ TeV with ATLAS

ATLAS Collaboration[*]

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ABSTRACT

The relationship between jet production in the central region and the underlying-event activity in a pseudorapidity-separated region is studied in 4.0 pb^{-1} of $\sqrt{s} = 2.76$ TeV pp collision data recorded with the ATLAS detector at the LHC. The underlying event is characterised through measurements of the average value of the sum of the transverse energy at large pseudorapidity downstream of one of the protons, which are reported here as a function of hard-scattering kinematic variables. The hard scattering is characterised by the average transverse momentum and pseudorapidity of the two highest transverse momentum jets in the event. The dijet kinematics are used to estimate, on an event-by-event basis, the scaled longitudinal momenta of the hard-scattered partons in the target and projectile beam-protons moving toward and away from the region measuring transverse energy, respectively. Transverse energy production at large pseudorapidity is observed to decrease with a linear dependence on the longitudinal momentum fraction in the target proton and to depend only weakly on that in the projectile proton. The results are compared to the predictions of various Monte Carlo event generators, which qualitatively reproduce the trends observed in data but generally underpredict the overall level of transverse energy at forward pseudorapidity.

1. Introduction

Properties of the underlying event at large rapidity in proton–proton (pp) collisions in the presence of a hard parton–parton scattering are sensitive to many features of hadronic interactions. Previous studies of the underlying event mainly focused on probing the region transverse to final-state jets at mid-rapidity [1–4]. This Letter presents a study of the transverse energy produced at small angles with respect to the proton beam, a region where particle production may be particularly sensitive to the colour connections between the hard partons and the beam remnants. Such measurements are needed to constrain particle production models, which systematically underpredict the total transverse energy at forward rapidities in hard-scattering events [4].

Measurements of transverse energy production at large rapidity are also needed to aid in the interpretation of recent results on jet production in proton–lead ($p+\text{Pb}$) collisions [5,6]. In these collisions, hard scattering rates are expected to grow with the increasing degree of geometric overlap between the proton and the nucleus. Simultaneously, the level of overlap is traditionally thought to be reflected in the rate of soft particle production, particularly at large pseudorapidity in the nucleus-going direction. The recent results found that single and dijet production rates in the proton-going (forward, or projectile) direction are related to the underlying-event activity in the nucleus-going (backward, or target) direction in a way that contradicts the models of how jet and underlying-event production should correlate. Specifically, the average transverse energy produced in the backward direction was found to systematically decrease, relative to that for low-energy jet events, with increasing jet energy. This decrease resulted in an apparent enhancement of the jet rate in low-activity, or peripheral, events and a suppression of the jet rate in high-activity, or central, events.

These results have several competing interpretations. For example, they are taken as evidence that proton configurations with a parton carrying a large fraction x of the proton longitudinal momentum interact with nucleons in the nucleus with a significantly smaller than average cross-section [7]. Alternatively, other authors have argued that in the constituent nucleon–nucleon (NN) collisions, energy production at backward rapidities naturally decreases with increasing x in the forward-going proton, either through the suppression of soft gluons available for particle production [8] or from a rapidity-separated energy-momentum conservation be-

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

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tween the hard process and soft production [9]. More generally, the modification of soft particle production in NN collisions in the presence of a hard process is expected to affect estimates of the collision geometry of $p+\mathrm{Pb}$ collisions with a hard scatter [10–12]. Thus a control measurement in pp collisions to determine how soft particle production at negative pseudorapidities varies with the x in the projectile (target) beam-proton headed towards positive (negative) rapidity can provide insight into the relevance of these various scenarios.

This Letter presents a measurement of the average of the sum of the transverse energy at large pseudorapidity,[1] $\langle\sum E_{\mathrm{T}}\rangle$, downstream of one of the protons in pp collisions, as a function of the hard-scattering kinematics in dijet events. For each kinematic selection, $\langle\sum E_{\mathrm{T}}\rangle$ is the average of the $\sum E_{\mathrm{T}}$ distribution in the selected events. The $\sum E_{\mathrm{T}}$ measurement was deliberately made in only one of the two forward calorimeter modules on either side of the interaction point. This was done in analogy with the centrality definition in $p+\mathrm{Pb}$ collisions [5,13], which is characterised by the $\sum E_{\mathrm{T}}$ in the forward calorimeter module situated at $-4.9<\eta<-3.2$, in the nucleus-going direction. In pp collisions the asymmetric choice of the $\sum E_{\mathrm{T}}$-measuring region means that the target proton plays the role of one of the nucleons in the Pb nucleus.

The value of $\sum E_{\mathrm{T}}$ was measured by summing the transverse energy in the forward calorimeter cells and correcting for the detector response. The average value, $\langle\sum E_{\mathrm{T}}\rangle$, is reported as a function of the average dijet transverse momentum, $p_{\mathrm{T}}^{\mathrm{avg}}=(p_{\mathrm{T},1}+p_{\mathrm{T},2})/2$, and pseudorapidity, $\eta^{\mathrm{dijet}}=(\eta_1+\eta_2)/2$. In these quantities, $p_{\mathrm{T},1}$ and η_1 are the transverse momentum and pseudorapidity of the leading (highest-p_{T}) jet in the event, while $p_{\mathrm{T},2}$ and η_2 are those for the subleading (second highest-p_{T}) jet. Results are also reported as a function of two kinematic quantities x_{proj} and x_{targ} defined by

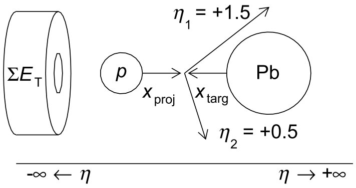
$$x_{\mathrm{proj}}=p_{\mathrm{T}}^{\mathrm{avg}}(e^{+\eta_1}+e^{+\eta_2})/\sqrt{s}, \tag{1}$$

$$x_{\mathrm{targ}}=p_{\mathrm{T}}^{\mathrm{avg}}(e^{-\eta_1}+e^{-\eta_2})/\sqrt{s}. \tag{2}$$

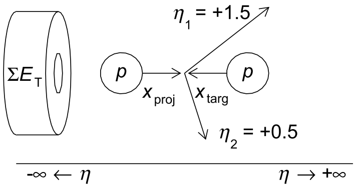
In a perturbative approach, at leading order, x_{proj} (x_{targ}) corresponds approximately to the Bjorken-x of the hard-scattered parton in the beam-proton with positive (negative) rapidity. Estimates of the initial parton–parton kinematics through jet-level variables have been used previously in dijet measurements at the CERN $Sp\bar{p}S$ collider [14,15] and in measurements of dihadrons in $d+\mathrm{Au}$ collisions at RHIC [16]. Finally, to better reveal the relative dependence of $\langle\sum E_{\mathrm{T}}\rangle$ on the hard-scattering kinematics, results are also reported as a ratio to a reference value $\langle\sum E_{\mathrm{T}}\rangle^{\mathrm{ref}}$, which is the $\langle\sum E_{\mathrm{T}}\rangle$ evaluated at a fixed choice of dijet kinematics, $50\ \mathrm{GeV}<p_{\mathrm{T}}^{\mathrm{avg}}<63\ \mathrm{GeV}$ and $|\eta^{\mathrm{dijet}}|<0.3$.

Fig. 1 schematically illustrates the meaning of the kinematic variables utilised in this measurement. The top panel in Fig. 1 shows the convention used in $p+\mathrm{Pb}$ collisions at ATLAS, in which the proton beam is the "projectile" and has positive rapidity, while the nuclear beam is the "target" and has negative rapidity. The centrality of the $p+\mathrm{Pb}$ collision, an experimental quantity sensitive to the collision geometry, is characterised by the $\sum E_{\mathrm{T}}$ in the forward calorimeter situated in the nucleus-going direction. The middle panel in Fig. 1 illustrates the measurement in pp collisions reported in this Letter, in which the proton beam with positive rapidity is considered to be the analogue of the projectile proton in $p+\mathrm{Pb}$ collisions, while the target proton with negative rapidity is the analogue of a single nucleon within the Pb nucleus, and the $\sum E_{\mathrm{T}}$ is measured in the forward calorimeter downstream of the target proton. Due to the symmetric nature of pp collisions, each event can also be interpreted by exchanging the roles of the target and projectile between the two protons, and measuring the $\sum E_{\mathrm{T}}$ in the opposite forward calorimeter module. To keep the same convention in this case, the z-axis (and thus the pseudorapidity) is inverted and the kinematic variables are determined within this new coordinate system as shown in the bottom panel of Fig. 1. The full analysis was performed separately using each forward calorimeter side, one at a time, and the final results were obtained by averaging the $\langle\sum E_{\mathrm{T}}\rangle$ measurements from each side. This increased the number of $\sum E_{\mathrm{T}}$ measurements by a factor of two and also provided an important cross-check on the detector energy scale. For simplicity, all η values in the selection cuts and η^{dijet} values in the results described below are always presented according to the convention where $\sum E_{\mathrm{T}}$ is measured at negative pseudorapidity.

(a) p+Pb collision



(b) pp collision



(c) same pp collision, inverted pseudorapidity

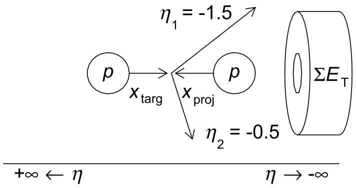


Fig. 1. Schematic illustration of the kinematic variables in the measurement. Panel (a) illustrates the convention in $p+\mathrm{Pb}$ collisions. Panels (b) and (c) illustrate how a single pp event provides a measurement of $\sum E_{\mathrm{T}}$ at two values of $\eta^{\mathrm{dijet}}=(\eta_1+\eta_2)/2$, in this case for $\eta^{\mathrm{dijet}}=+1$ and for $\eta^{\mathrm{dijet}}=-1$, respectively.

The dataset used in this measurement was collected during the $\sqrt{s}=2.76$ TeV pp collision data-taking in February 2013 at the Large Hadron Collider, with an integrated luminosity corresponding to $4.0\ \mathrm{pb}^{-1}$. During data-taking, the mean number of pp interactions per bunch crossing varied from 0.1 to 0.5. This dataset is particularly suitable for the measurement because the small mean interaction rate per crossing allows rejection of dijet-producing pp events with additional pp interactions in the same bunch crossing (pileup) with good systematic control while simultaneously having enough integrated luminosity to measure dijet production over a wide kinematic range with good statistical precision.

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

2. Experimental setup

The ATLAS detector is described in detail in Ref. [17]. This analysis uses primarily the tracking detectors, the calorimeter, and the trigger system. Charged-particle tracks were measured over the range $|\eta| < 2.5$ using the inner detector, which is composed of silicon pixel detectors in the innermost layers, silicon microstrip detectors, and a straw-tube transition-radiation tracker ($|\eta| < 2.0$) in the outer layer, all immersed in a 2 T axial magnetic field. The calorimeter system consists of a liquid argon (LAr) electromagnetic calorimeter ($|\eta| < 3.2$), a steel/scintillator sampling hadronic calorimeter ($|\eta| < 1.7$), a LAr hadronic calorimeter ($1.5 < |\eta| < 3.2$), and a forward calorimeter ($3.2 < |\eta| < 4.9$). The forward calorimeter is composed of two modules situated at opposite sides of the interaction region and provides the $\sum E_{\mathrm{T}}$ measurement. The modules consist of tungsten and copper absorbers with LAr as the active medium, which together provide ten interaction lengths of material, and are segmented into one electromagnetic and two hadronic sections longitudinal in the shower direction. The 1782 cells in each forward calorimeter module are aligned parallel to the beam axis and therefore are not projective, but have a segmentation corresponding to approximately 0.2×0.2 in η and ϕ.

Data were acquired for this analysis using a series of central-jet triggers covering $|\eta| < 3.2$ with different (increasing) jet-p_{T} thresholds, ranging from 40 GeV to 75 GeV [18]. Each trigger was prescaled, meaning that only a fraction of events passing the trigger criteria were ultimately selected, and these fractions varied with time to accommodate the evolution of the luminosity within an LHC fill. This fraction increased for triggers with increasing jet p_{T} threshold and the highest-threshold trigger, which dominates the kinematic range studied in this Letter, sampled the full integrated luminosity.

3. Monte Carlo simulation

Monte Carlo (MC) simulations of $\sqrt{s} = 2.76$ TeV pp hard-scattering events were used to understand the performance of the ATLAS detector, to correct the measured $\sum E_{\mathrm{T}}$ and dijet kinematic variables for detector effects, and to determine the systematic uncertainties in the measurement. Three MC programs were used to generate event samples with the leading-jet p_{T} in the range from 20 GeV to 1 TeV: the Pythia 6 generator [19] with parameter values chosen to reproduce data according to the `AUET2B` set of tuned parameters (tune) [20] and `CTEQ6L1` parton distribution function (PDF) set [21]; the Pythia 8 generator [22] with the `AU2` tune [23] and `CT10` PDF set [24]; and the Herwig++ generator [25] with the `UE-EE-3` tune [26] and `CTEQ6L1` PDF set. The generated events were passed through a full Geant 4 simulation [27, 28] of the ATLAS detector under the same conditions present during data-taking. The simulated events included contributions from pileup similar to that in data.

At the particle level, jets are defined by applying the anti-k_t algorithm [29] with radius parameter R of 0.4 to primary particles[2] within $|\eta| < 4.9$, excluding muons and neutrinos. $\sum E_{\mathrm{T}}$ is defined at the particle level as the sum of the transverse energy of all primary particles within $-4.9 < \eta < -3.2$, including muons and neutrinos, and with no additional kinematic selection.

4. Event reconstruction and calibration

The vertex reconstruction, jet reconstruction and calibration, and $\sum E_{\mathrm{T}}$ measurement and calibration procedures are described in this section. They were applied identically to the experimental data and the simulated events.

4.1. Track and vertex reconstruction

In the offline analysis, charged-particle tracks were reconstructed in the inner detector with an algorithm used in previous measurements of charged-particle multiplicities in minimum-bias pp interactions [30]. Analysed events were required to contain a reconstructed vertex, formed by at least two tracks with $p_{\mathrm{T}} > 0.1$ GeV [31]. The contribution from pileup interactions was suppressed by rejecting events containing more than one reconstructed vertex with five or more associated charged-particle tracks. This requirement rejected approximately 8% of events.

4.2. Jet reconstruction and calibration

The jet reconstruction and associated background determination procedures closely follow those developed within ATLAS for jet measurements in heavy-ion and pp collisions [5,32–34]. This procedure is summarised in the following and is described in more detail in Ref. [32]. Jets were reconstructed by applying the anti-k_t algorithm with $R = 0.4$ to calorimeter cells grouped into towers of size $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. The procedure provided an η- and sampling layer-dependent estimate of the small energy density deposited by the soft underlying event from pileup interactions in each crossing. The energies of the cells in each jet were corrected for this estimate of the soft pileup contribution. The p_{T} of the resulting jets was corrected for the calorimeter energy response through a simulation-derived calibration, with an additional *in situ* correction, typically at the percent level, derived through comparisons of boson–jet and dijet p_{T} balance in collision data and simulation [35].

4.3. Forward transverse energy measurement and calibration

The $\sum E_{\mathrm{T}}$ quantity was evaluated by measuring the sum of the transverse energy in the cells in one forward calorimeter module ($\sum E_{\mathrm{T}}^{\mathrm{raw}}$). The energy signals from the cells were included in the sum without any energy threshold requirement. This quantity was corrected event-by-event to account for the detector response, using a calibration procedure derived in simulation, to give an estimate of the full energy deposited in the calorimeter ($\sum E_{\mathrm{T}}^{\mathrm{calib}}$). Pythia 8 was found to give the best overall description of $\sum E_{\mathrm{T}}$ production and of its dependence on dijet kinematics in data. Thus, a subset of Pythia 8 events with good kinematic overlap with the data and a wide range of $\sum E_{\mathrm{T}}$ values was used to calibrate $\sum E_{\mathrm{T}}^{\mathrm{raw}}$. The calibration was derived by requiring that for each subset of simulated events with a narrow range of particle-level $\sum E_{\mathrm{T}}$ values ($\sum E_{\mathrm{T}}^{\mathrm{gen}}$), the mean value of the $\sum E_{\mathrm{T}}^{\mathrm{calib}}$ distribution in those events corresponded to the mean value of $\sum E_{\mathrm{T}}^{\mathrm{gen}}$. First, to determine the average offset in the response (Δ), the average $\sum E_{\mathrm{T}}^{\mathrm{raw}}$ as a function of $\sum E_{\mathrm{T}}^{\mathrm{gen}}$ was extrapolated with a linear fit to zero $\sum E_{\mathrm{T}}^{\mathrm{gen}}$. This additive offset, which described the average net effect of energy inflow from outside and energy outflow from inside the fiducial pseudorapidity acceptance of $-4.9 < \eta < -3.2$, was found to be approximately $\Delta \approx -0.7$ GeV. It also reflected the residual contribution from pileup interactions and the average distortion of the signal from energy deposited by collisions in previous bunch crossings. Second, the average response (C) was determined by the ratio of the mean offset-corrected $\sum E_{\mathrm{T}}^{\mathrm{raw}}$ to each corresponding value of $\sum E_{\mathrm{T}}^{\mathrm{gen}}$, $C = \langle \sum E_{\mathrm{T}}^{\mathrm{raw}} - \Delta \rangle / \sum E_{\mathrm{T}}^{\mathrm{gen}}$. C was found to be approximately 0.7 and varied only weakly with $\sum E_{\mathrm{T}}^{\mathrm{gen}}$ after the offset correction. This residual dependence was modelled by evaluating C in narrow bins of $\sum E_{\mathrm{T}}^{\mathrm{raw}}$ and fitting

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[2] Primary particles are defined as final-state particles with a proper lifetime greater than 30 ps.

the results with a smooth function to produce a continuous interpolation, $C(\sum E_{\mathrm{T}}^{\mathrm{raw}})$. The calibrated quantity in each event was determined by correcting the raw quantity for the offset and average response, $\sum E_{\mathrm{T}}^{\mathrm{calib}} = (\sum E_{\mathrm{T}}^{\mathrm{raw}} - \Delta)/C(\sum E_{\mathrm{T}}^{\mathrm{raw}})$.

The closure of this calibration, defined as the ratio $\langle \sum E_{\mathrm{T}}^{\mathrm{calib}} \rangle / \sum E_{\mathrm{T}}^{\mathrm{gen}}$ as a function of $\sum E_{\mathrm{T}}^{\mathrm{gen}}$, was within 1% of unity. The closure was also checked for different selections on the dijet kinematics, which have a variety of $\mathrm{d}N/\mathrm{d}\sum E_{\mathrm{T}}$ and $\mathrm{d}\sum E_{\mathrm{T}}/\mathrm{d}\eta$ distributions, by comparing the mean $\sum E_{\mathrm{T}}^{\mathrm{calib}}$ to the mean of the $\sum E_{\mathrm{T}}^{\mathrm{gen}}$ distribution in these events. For the selections on dijet kinematics in which the closure was statistically meaningful, it was within a few percent of unity and the non-closure was accounted for in the systematic uncertainty described below.

5. Event selection and data analysis

In the offline analysis, the leading jet in each jet-triggered event was required to match to a jet reconstructed at the trigger stage. Only one trigger was used for each leading-jet p_{T} interval. This trigger was chosen to be the one with the highest integrated luminosity that was simultaneously $> 99\%$ efficient within the interval. The contribution from each event to the $\sum E_{\mathrm{T}}$ measurement was weighted by the inverse of the luminosity of the trigger used to select it, such that the underlying dijet kinematic distributions in the measurement correspond to the full two-jet cross-section.

Events with two jets were selected, where the transverse momenta of the jets were $p_{\mathrm{T},1} > 50$ GeV, $p_{\mathrm{T},2} > 20$ GeV, and $p_{\mathrm{T}}^{\mathrm{avg}} > 50$ GeV. Both jets were required to have $\eta_{1,2} > -2.8$ to separate them by 0.4 units in pseudorapidity from the $\sum E_{\mathrm{T}}$-measuring region. Furthermore, the leading jet was also required to have $\eta_1 < 3.2$ to match the acceptance of the central-jet trigger.

For each selection on dijet kinematics, either as a function of $p_{\mathrm{T}}^{\mathrm{avg}}$ and η^{dijet} or as a function of x_{proj} and x_{targ}, $\langle \sum E_{\mathrm{T}} \rangle$ was determined from the mean value of the $\sum E_{\mathrm{T}}^{\mathrm{calib}}$ distribution. The two values of $\langle \sum E_{\mathrm{T}} \rangle$ as measured in the forward calorimeter at negative pseudorapidity and in the forward calorimeter at positive pseudorapidity under the inverted-sign convention (see Fig. 1) were averaged to yield the presented results.

The resolution on $p_{\mathrm{T},1}$ and $p_{\mathrm{T},2}$ and the splitting of particle-level jets in the reconstruction resulted in a migration of some events to adjacent $p_{\mathrm{T}}^{\mathrm{avg}}$, x_{proj} and x_{targ} bins. This migration was corrected by applying a multiplicative factor to the results. This factor was determined in simulation by taking the ratio of the $\langle \sum E_{\mathrm{T}}^{\mathrm{gen}} \rangle$ evaluated as a function of reconstructed dijet variables to that evaluated with the jets at the particle level. Since Pythia 6 was found to best describe the jet spectra and various jet-event-topology variables, it was used to derive this bin-by-bin correction, which was typically only a few percent from unity.

6. Systematic uncertainties

The results presented in this Letter are susceptible to several sources of systematic uncertainty. The uncertainty from each source was evaluated by analysing the data or deriving the corrections with a corresponding variation in the procedure, averaging the $\langle \sum E_{\mathrm{T}} \rangle$ results from each forward calorimeter side, and observing the changes from the nominal results. The uncertainties from different sources were treated as uncorrelated and added in quadrature to determine the total uncertainty.

The $\sum E_{\mathrm{T}}$ calibration procedure is susceptible to uncertainties in the overall energy scale of the forward calorimeter, in the amount of material upstream of the calorimeter, in the physics model used to derive it, and in the modelling of pileup in simulation. These uncertainties were determined by deriving a new $\sum E_{\mathrm{T}}$ calibration for each variation corresponding to a systematic uncertainty and applying it to the data. To evaluate the energy scale uncertainty, the calorimeter response in simulation was varied in an η-dependent manner by an uncertainty derived from previous studies of $\pi^0 \to \gamma\gamma$ candidates in $\sqrt{s} = 7$ TeV collision data and simulation [4], and from comparisons of beam-test data with simulation [36]. The resulting changes in $\langle \sum E_{\mathrm{T}} \rangle$ from negative and positive variations of the response were $+4\%$ and -8% respectively. To account for the uncertainty in the amount of material upstream of the forward calorimeter, the analysis described in Ref. [4], which evaluated the response in simulations with increased material in these regions for $\sqrt{s} = 7$ TeV events, was adapted to the conditions of this analysis. Those results were used to vary the response in this analysis, which resulted in changes of $\langle \sum E_{\mathrm{T}} \rangle$ by $\pm 2\%$.

To evaluate the sensitivity to the physics model, $\sum E_{\mathrm{T}}$ calibrations were derived using simulated Pythia 6 and Herwig++ events and compared to that derived using Pythia 8. The variations among the three generators in distributions relevant to the $\sum E_{\mathrm{T}}$ measurement, such as the distribution of $\sum E_{\mathrm{T}}$ values, $\mathrm{d}N/\mathrm{d}\sum E_{\mathrm{T}}$, or the pseudorapidity distribution, $\mathrm{d}\sum E_{\mathrm{T}}/\mathrm{d}\eta$, were found to reasonably span those in data. Thus, the largest difference in the results when using the calibrations derived from any two generators, 5%, was symmetrised and assigned as the uncertainty associated with the sensitivity to the physics model.

The uncertainty in the modelling of the pileup within the simulation was determined to be $\pm 2\%$ by investigating the sensitivity of the $\sum E_{\mathrm{T}}$ calibration to several factors. These included varying the mean number of pp interactions per crossing, varying the pileup rejection requirement, and accounting for possible mismodelling in the simulation of the residual contribution to $\sum E_{\mathrm{T}}$ from unrejected pileup vertices.

An additional uncertainty arising from possible defects in the performance of the $\sum E_{\mathrm{T}}$ calibration was obtained from checking the closure of the calibration procedure. The $\sum E_{\mathrm{T}}$ calibration, derived from a Pythia 8 event sample with a wide kinematic range, was found to differ from unity when evaluated for subsets of the sample with narrower selections on the dijet kinematics. In the simulation, this behaviour results from a number of effects, such as the dependence of the mean E_{T} per generator particle and the shape of the $\mathrm{d}\sum E_{\mathrm{T}}/\mathrm{d}\eta$ distribution on the selected dijet kinematics, both of which affect the average response. A conservative symmetric uncertainty of 5% was chosen to account for the potential differences of the closure values from unity observed in simulation.

The uncertainty in the correction for bin migration effects, evaluated by considering the sensitivity of the corrections to alternative generators (Pythia 8 and Herwig++) and to variations in the jet energy scale and resolution, was found to be smaller than $\pm 1\%$. Additional internal cross-checks on the $\langle \sum E_{\mathrm{T}} \rangle$ results were investigated in the data. The nominal results were compared to an alternative analysis in which the cells were combined into topological clusters [37] and a new calibration was derived for the detector-level $\sum E_{\mathrm{T}}^{\mathrm{raw}}$ constructed from the sum of cluster transverse energies. An uncertainty of $\pm 1\%$ in the $\langle \sum E_{\mathrm{T}} \rangle$ was assigned from this cross-check. Results determined using each side of the forward calorimeter separately were compared and found to be consistent. Additional potential sources of systematic uncertainty, such as that in the energy resolution of the forward calorimeter, were found to be negligible.

For most of the kinematic range except at high $p_{\mathrm{T}}^{\mathrm{avg}}$, or when x_{proj} or x_{targ} is large, the statistical uncertainties are negligible compared to the systematic ones. The dominant uncertainties in the $\langle \sum E_{\mathrm{T}} \rangle$ measurement are from the energy scale, the physics model, and the variation of the $\sum E_{\mathrm{T}}$ response with dijet kinematics. The total uncertainty is $+9\%/-11\%$ and varies only

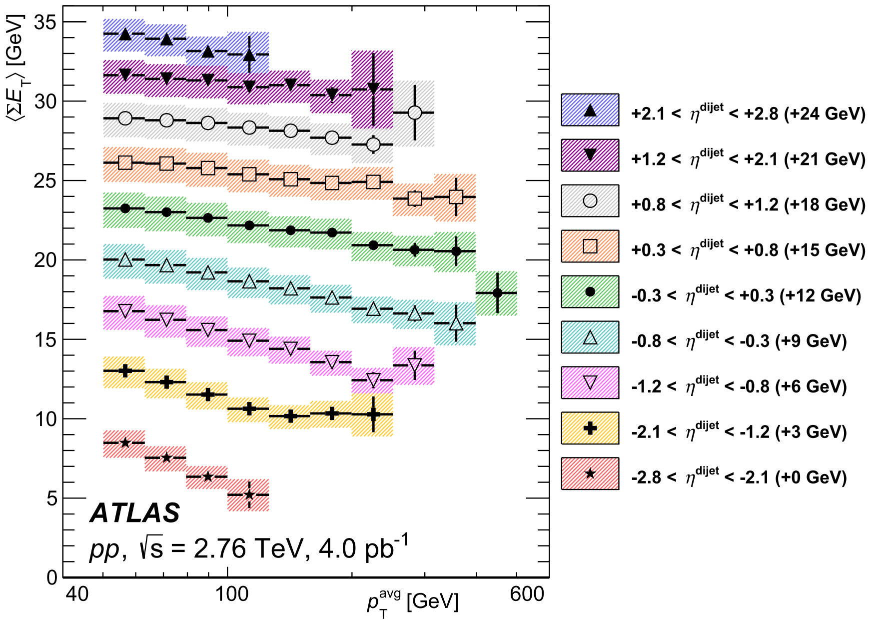

Fig. 2. Measured average sum of the transverse energy at large pseudorapidity $\langle \sum E_T \rangle$ in hard-scatter pp collisions, shown as a function of the average dijet momentum p_T^{avg}. Each series depicts a different range of the average dijet pseudorapidity η^{dijet} and the series are displaced vertically for clarity by the amount given in round brackets in the legend. The vertical shaded bands represent the total systematic and statistical uncertainties on the data in quadrature while the vertical bars represent statistical uncertainties only.

Table 1
Relative systematic uncertainties for the measurements of $\langle \sum E_T \rangle$ and $\langle \sum E_T \rangle / \langle \sum E_T \rangle^{ref}$, shown for each individual source of uncertainty. An entry of "–" means that the source was found to be negligible.

Source	Typical uncertainty in	
	$\langle \sum E_T \rangle$	$\langle \sum E_T \rangle / \langle \sum E_T \rangle^{ref}$
$\sum E_T$ calibration		
Forward calorimeter response	+4%/−8%	–
Extra material	±2%	–
Physics model	±5%	±1%
Pileup modelling	±2%	–
$\sum E_T$ calibration closure	±5%	±5%
Dijet kinematics bin migration	±1%	±1%
Calorimeter cluster cross-check	±1%	±1%
Total uncertainty	+9%/−11%	±5%

weakly with selections on dijet kinematics. The uncertainty in the $\langle \sum E_T \rangle / \langle \sum E_T \rangle^{ref}$ quantity was determined by varying the numerator and denominator according to each source simultaneously to properly account for their cancellation in the ratio. The resulting uncertainty is ±5%, dominated by the variation of the $\sum E_T$ response with kinematics, which by its nature does not cancel in the ratio of $\langle \sum E_T \rangle$ for different kinematic selections. The total systematic uncertainty is summarised in Table 1 for the $\langle \sum E_T \rangle$ and $\langle \sum E_T \rangle / \langle \sum E_T \rangle^{ref}$ quantities.

A further cross-check was performed to determine the average contribution to the mean $\sum E_T$ from any additional jet in the events. This contribution was estimated by repeating the analysis and rejecting events with a $p_T > 15$ GeV jet in $\eta < -2.8$, and was found to be smaller than 2%. Since the $\sum E_T$ definition includes this energy, no uncertainty is assigned or correction applied.

7. Results

This section shows the $\langle \sum E_T \rangle$ and $\langle \sum E_T \rangle / \langle \sum E_T \rangle^{ref}$ results, corrected to the particle level. In all distributions the events are required to contain two particle-level jets with $p_{T,1} > 50$ GeV, $p_{T,2} > 20$ GeV, and $p_T^{avg} > 50$ GeV. Both jets are required to have $\eta_{1,2} > -2.8$ and the leading jet is also required to have $\eta_1 < 3.2$.

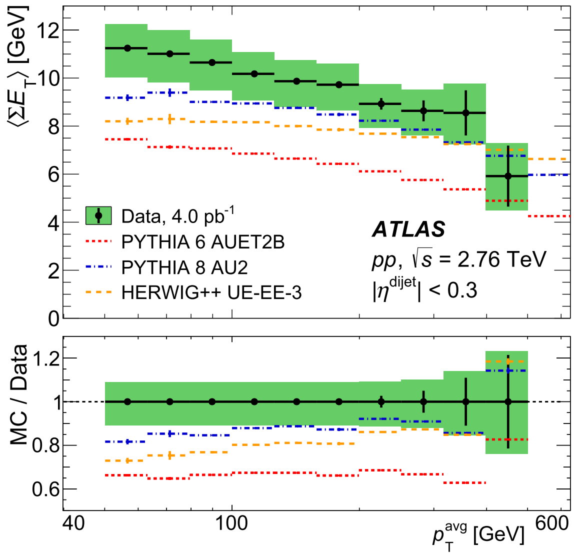

Fig. 3. Measured $\langle \sum E_T \rangle$ in hard-scatter pp collisions, shown as a function of p_T^{avg} for $|\eta^{dijet}| < 0.3$ and in comparison with the predictions of three MC event generators. The vertical shaded bands represent total systematic and statistical uncertainties in the data in quadrature while the vertical bars represent statistical uncertainties only. The bottom panel shows the ratio of the predictions of the three MC generators to the data.

Fig. 2 shows an overview of the measured $\langle \sum E_T \rangle$ values as a function of p_T^{avg} for each range of η^{dijet} and summarises the range of dijet kinematics accessed in the measurement. Fig. 3 shows the $\langle \sum E_T \rangle$ as a function of p_T^{avg} for central jet pairs ($|\eta^{dijet}| < 0.3$) in more detail. The $\langle \sum E_T \rangle$ is anti-correlated with the dijet p_T^{avg}, decreasing by 25% as p_T^{avg} varies from 50 GeV to 500 GeV. The bottom panel of Fig. 3 shows the ratio of the $\langle \sum E_T \rangle$ in these generators to that in the data. Pythia 8 best reproduces $\langle \sum E_T \rangle$ in data, typically agreeing within one and a half times the uncertainty of

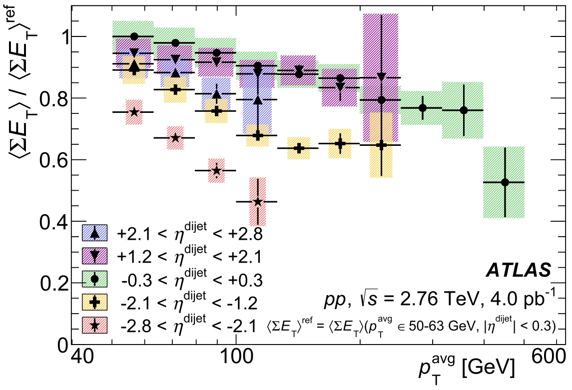

Fig. 4. Measured ratio $\langle \sum E_{\mathrm{T}} \rangle / \langle \sum E_{\mathrm{T}} \rangle^{\mathrm{ref}}$ in hard-scatter *pp* collisions, shown as a function of $p_{\mathrm{T}}^{\mathrm{avg}}$ for different selections on η^{dijet}. The vertical shaded bands represent the total systematic and statistical uncertainties in quadrature while the vertical error bars represent statistical uncertainties only. When two error bands overlap vertically, their horizontal widths have been adjusted so that the edges of both are visible.

the data in the kinematic selections shown here and in most other selections analysed. While the generators systematically underpredict the overall scale of the $\sum E_{\mathrm{T}}$ production, the $\langle \sum E_{\mathrm{T}} \rangle$ is generally anticorrelated with $p_{\mathrm{T}}^{\mathrm{avg}}$ in each one just as it is in the data. The observation of an anticorrelation with $p_{\mathrm{T}}^{\mathrm{avg}}$ at mid-rapidity in *pp* collisions is important for interpreting the $p+\mathrm{Pb}$ results, since it indicates a non-trivial correlation between hard-scattering kinematics and $\sum E_{\mathrm{T}}$ production, but the $p_{\mathrm{T}}^{\mathrm{avg}}$ quantity offers only an indirect relationship to the underlying Bjorken-*x* values. The first point in the upper panel of Fig. 3 shows the reference value for data of $\langle \sum E_{\mathrm{T}} \rangle^{\mathrm{ref}} = 11.2^{+1.0}_{-1.2}$ GeV. For the generators considered in this analysis, the value of $\langle \sum E_{\mathrm{T}} \rangle^{\mathrm{ref}}$ in simulation is 7.5 GeV in Pythia 6, 9.2 GeV in Pythia 8, and 8.2 GeV in Herwig++.

To further explore the variation of the results with the Bjorken-*x* of the hard-scattered partons, the dependence on the average pseudorapidity of the dijet was investigated. At fixed $p_{\mathrm{T}}^{\mathrm{avg}}$, dijets with large positive or negative η^{dijet} arise from parton–parton configurations with large *x* in the projectile or target proton, respectively. Fig. 4 shows the ratio $\langle \sum E_{\mathrm{T}} \rangle / \langle \sum E_{\mathrm{T}} \rangle^{\mathrm{ref}}$ as a function of $p_{\mathrm{T}}^{\mathrm{avg}}$ for different ranges of η^{dijet}. In the ratio $\langle \sum E_{\mathrm{T}} \rangle / \langle \sum E_{\mathrm{T}} \rangle^{\mathrm{ref}}$, much of the uncertainty in the data and the overall scale difference between data and the generators cancels, allowing a precise measurement of the relative dependence of $\langle \sum E_{\mathrm{T}} \rangle$ on dijet kinematics and comparison to generators. When the dijet pair is at positive pseudorapidity (in the direction of the projectile proton), the relationship between the $\langle \sum E_{\mathrm{T}} \rangle$ and $p_{\mathrm{T}}^{\mathrm{avg}}$ is similar to that for mid-rapidity dijets. However, as the dijet pair pseudorapidity moves to negative rapidities close to the $\sum E_{\mathrm{T}}$-measuring region (in the direction of the target proton), this anti-correlation becomes stronger and the overall level of the $\sum E_{\mathrm{T}}$ decreases. For the η^{dijet} selection nearest to the region in which the $\sum E_{\mathrm{T}}$ is measured ($-2.8 < \eta^{\mathrm{dijet}} < -2.1$), $\langle \sum E_{\mathrm{T}} \rangle$ decreases by 40% as $p_{\mathrm{T}}^{\mathrm{avg}}$ increases by a factor of two from 50 GeV to 100 GeV.

Finally, the pattern of how the $\langle \sum E_{\mathrm{T}} \rangle$ values for dijets at all $p_{\mathrm{T}}^{\mathrm{avg}}$ and η^{dijet} depend on the underlying hard scattering kinematics can be explored more directly by plotting them as a function of the kinematic variables x_{proj} and x_{targ}. Fig. 5 shows the ratio $\langle \sum E_{\mathrm{T}} \rangle / \langle \sum E_{\mathrm{T}} \rangle^{\mathrm{ref}}$ as a function of each variable, while integrating over the other. The value of $\langle \sum E_{\mathrm{T}} \rangle$ is largely insensitive to x_{proj} (which corresponds to the Bjorken-*x* in the proton moving to positive rapidity), changing by only 10% over the entire range $0 < x_{\mathrm{proj}} < 1$. On the other hand, $\langle \sum E_{\mathrm{T}} \rangle$ varies strongly with x_{targ} (which corresponds to the Bjorken-*x* in the proton moving to negative rapidity), decreasing by more than a factor of two between $x_{\mathrm{targ}} = 0$ and 0.9 in an approximately linear fashion.

Since x_{proj} and x_{targ} are generally anti-correlated in dijet events, the data were also analysed by fixing each variable in a narrow range and testing the dependence of $\langle \sum E_{\mathrm{T}} \rangle$ on the other, and this gave results quantitatively similar to those in Fig. 5. The generators considered here have qualitatively similar behaviour. They describe the x_{proj} dependence well, but Pythia 6 and Pythia 8 show a slightly stronger dependence on x_{targ}, while Herwig++ shows a much weaker one. The observed dependence admits a simple interpretation: when the hard scattering involves a parton with large x_{targ}, the beam remnant has less longitudinal energy and transverse energy production at large pseudorapidity is substantially reduced.

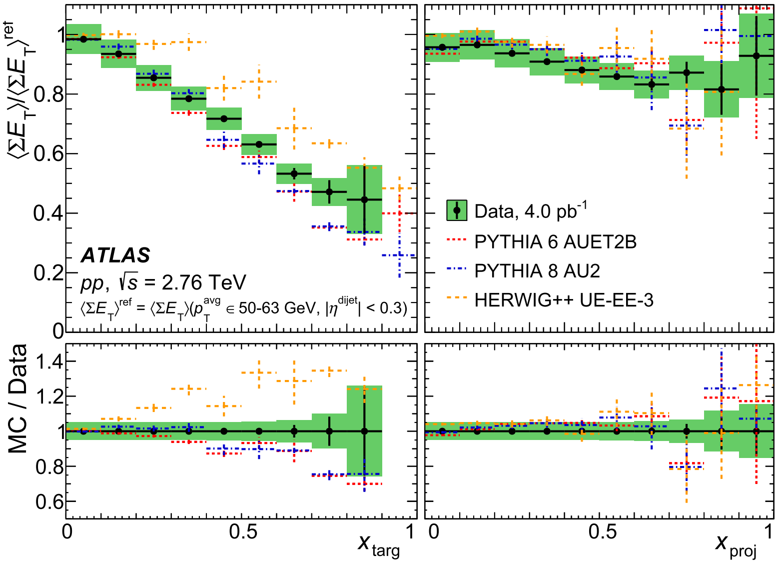

Fig. 5. Measured ratio $\langle \sum E_{\mathrm{T}} \rangle / \langle \sum E_{\mathrm{T}} \rangle^{\mathrm{ref}}$ in hard-scatter *pp* collisions, shown as a function of x_{targ} (left) and x_{proj} (right). The vertical shaded bands represent total systematic and statistical uncertainties in the data in quadrature while the vertical bars represent statistical uncertainties only. The bottom panel shows the ratio of the predictions of three MC event generators to the data.

8. Conclusions

This Letter presents measurements of the dependence of transverse energy production at large rapidity on hard-scattering kinematics in 4.0 pb^{-1} of $\sqrt{s} = 2.76$ TeV pp collision data with the ATLAS detector at the LHC. The results have a number of implications. They demonstrate that the average level of transverse energy production at large pseudorapidity is sensitive mainly to the Bjorken-x of the parton originating in the beam-proton which is headed towards the energy-measuring region, and is largely insensitive to x in the other proton. Specifically, the decrease in the mean transverse energy downstream of a beam-proton is approximately linear in the longitudinal energy carried away from that beam-proton in the hard scattering. Monte Carlo event generators generally underpredict the overall value of the transverse energy but properly model with varying accuracy the trend in how this quantity depends on hard-scattering kinematics.

These results provide counter-evidence to claims that the observed centrality-dependence of the jet rate in $p+\text{Pb}$ collisions simply arises from the suppression of transverse energy production at negative rapidity in the hard-scattered NN sub-collision. In the $p+\text{Pb}$ data, the deviations from the expected centrality dependence are observed to depend only on, and increase with, x in the proton. Therefore, for this effect to be consistent with arising from a feature of NN collisions, transverse energy production at small angles should decrease strongly and continuously with increasing x in the proton headed in the opposite direction (corresponding to x_{proj} in this measurement). The results presented in this Letter do not obviously support such a scenario.

In conclusion, the measurements presented in this Letter seek to reveal the correlation between hard-process kinematics and transverse energy production at large pseudorapidity which is present in individual nucleon–nucleon collisions. As a $p+\text{Pb}$ collision can be understood as a superposition of such interactions, the measurements presented here may serve as a limiting case against which to test descriptions of the underlying physics of hard and soft particle production in $p+\text{Pb}$ collisions.

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Soldatov[98], U. Soldevila[167], A.A. Solodkov[130], A. Soloshenko[65], O.V. Solovyanov[130], V. Solovyev[123], P. Sommer[48], H.Y. Song[33b,z], N. Soni[1], A. Sood[15], A. Sopczak[128], B. Sopko[128], V. Sopko[128], V. Sorin[12], D. Sosa[58b], M. Sosebee[8], C.L. Sotiropoulou[124a,124b], R. Soualah[164a,164c], A.M. Soukharev[109,c], D. South[42], B.C. Sowden[77], S. Spagnolo[73a,73b], M. Spalla[124a,124b], M. Spangenberg[170], F. Spanò[77], W.R. Spearman[57], D. Sperlich[16], F. Spettel[101], R. Spighi[20a], G. Spigo[30], L.A. Spiller[88], M. Spousta[129], T. Spreitzer[158], R.D. St. Denis[53,∗], A. Stabile[91a], S. Staerz[44], J. Stahlman[122], R. Stamen[58a], S. Stamm[16], E. Stanecka[39], R.W. Stanek[6], C. Stanescu[134a], M. Stanescu-Bellu[42], M.M. Stanitzki[42], S. Stapnes[119], E.A. Starchenko[130], J. Stark[55], P. Staroba[127], P. Starovoitov[58a], R. Staszewski[39], P. Steinberg[25], B. Stelzer[142], H.J. Stelzer[30], O. Stelzer-Chilton[159a], H. Stenzel[52], G.A. Stewart[53], J.A. Stillings[21], M.C. Stockton[87], M. Stoebe[87], G. Stoicea[26a], P. Stolte[54], S. Stonjek[101], A.R. Stradling[8], A. Straessner[44], M.E. Stramaglia[17], J. Strandberg[147], S. Strandberg[146a,146b], A. Strandlie[119], E. Strauss[143], M. Strauss[113], P. Strizenec[144b], R. Ströhmer[174], D.M. Strom[116], R. Stroynowski[40], A. Strubig[106], S.A. Stucci[17], B. Stugu[14], N.A. Styles[42], D. Su[143], J. Su[125], R. Subramaniam[79], A. Succurro[12], S. Suchek[58a], Y. Sugaya[118], M. Suk[128], V.V. Sulin[96], S. Sultansoy[4c], T. Sumida[68], S. Sun[57], X. Sun[33a], J.E. Sundermann[48], K. Suruliz[149], G. Susinno[37a,37b], M.R. Sutton[149], S. Suzuki[66], M. Svatos[127], M. Swiatlowski[143], I. Sykora[144a], T. Sykora[129], D. Ta[48], C. Taccini[134a,134b], K. Tackmann[42], J. Taenzer[158], A. Taffard[163], R. Tafirout[159a], N. Taiblum[153], H. Takai[25], R. Takashima[69], H. Takeda[67], T. Takeshita[140], Y. Takubo[66], M. Talby[85], A.A. Talyshev[109,c], J.Y.C. Tam[174], K.G. Tan[88], J. Tanaka[155], R. Tanaka[117], S. Tanaka[66], B.B. Tannenwald[111], N. Tannoury[21], S. Tapprogge[83], S. Tarem[152], F. Tarrade[29], G.F. Tartarelli[91a], P. Tas[129], M. Tasevsky[127], T. Tashiro[68], E. Tassi[37a,37b], A. Tavares Delgado[126a,126b], Y. Tayalati[135d], F.E. Taylor[94], G.N. Taylor[88], P.T.E. Taylor[88], W. Taylor[159b], F.A. Teischinger[30], P. Teixeira-Dias[77], K.K. Temming[48], D. Temple[142], H. Ten Kate[30], P.K. Teng[151], J.J. Teoh[118], F. Tepel[175], S. Terada[66], K. Terashi[155], J. Terron[82], S. Terzo[101], M. Testa[47], R.J. Teuscher[158,k], T. Theveneaux-Pelzer[34], J.P. Thomas[18], J. Thomas-Wilsker[77], E.N. Thompson[35], P.D. Thompson[18], R.J. Thompson[84], A.S. Thompson[53], L.A. Thomsen[176], E. Thomson[122], M. Thomson[28], R.P. Thun[89,∗], M.J. Tibbetts[15], R.E. Ticse Torres[85], V.O. Tikhomirov[96,aj], Yu.A. Tikhonov[109,c], S. Timoshenko[98], E. Tiouchichine[85], P. Tipton[176], S. Tisserant[85], K. Todome[157], T. Todorov[5,∗], S. Todorova-Nova[129], J. Tojo[70], S. Tokár[144a], K. Tokushuku[66], K. Tollefson[90], E. Tolley[57], L. Tomlinson[84], M. Tomoto[103], L. Tompkins[143,ak], K. Toms[105], E. Torrence[116], H. Torres[142], E. Torró Pastor[138], J. Toth[85,al], F. Touchard[85], D.R. Tovey[139], T. Trefzger[174], L. Tremblet[30], A. Tricoli[30], I.M. Trigger[159a], S. Trincaz-Duvoid[80], M.F. Tripiana[12], W. Trischuk[158], B. Trocmé[55], C. Troncon[91a], M. Trottier-McDonald[15], M. Trovatelli[169], P. True[90], L. Truong[164a,164c], M. Trzebinski[39], A. Trzupek[39], C. Tsarouchas[30], J.C-L. Tseng[120], P.V. Tsiareshka[92], D. Tsionou[154], G. Tsipolitis[10], N. Tsirintanis[9], S. Tsiskaridze[12], V. Tsiskaridze[48], E.G. Tskhadadze[51a], I.I. Tsukerman[97], V. Tsulaia[15], S. Tsuno[66], D. Tsybychev[148], A. Tudorache[26a], V. Tudorache[26a], A.N. Tuna[57], S.A. Tupputi[20a,20b], S. Turchikhin[99,ai], D. Turecek[128], R. Turra[91a,91b], A.J. 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J. Yu[114], L. Yuan[67], S.P.Y. Yuen[21], A. Yurkewicz[108], I. Yusuff[28,an], B. Zabinski[39], R. Zaidan[63],
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L. Zhou[35], L. Zhou[40], M. Zhou[148], N. Zhou[33f], C.G. Zhu[33d], H. Zhu[33a], J. Zhu[89], Y. Zhu[33b], X. Zhuang[33a],
K. Zhukov[96], A. Zibell[174], D. Zieminska[61], N.I. Zimine[65], C. Zimmermann[83], S. Zimmermann[48],
Z. Zinonos[54], M. Zinser[83], M. Ziolkowski[141], L. Živković[13], G. Zobernig[173], A. Zoccoli[20a,20b],
M. zur Nedden[16], G. Zurzolo[104a,104b], L. Zwalinski[30]

[1] Department of Physics, University of Adelaide, Adelaide, Australia
[2] Physics Department, SUNY Albany, Albany, NY, United States
[3] Department of Physics, University of Alberta, Edmonton, AB, Canada
[4] (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
[5] LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
[6] High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
[7] Department of Physics, University of Arizona, Tucson, AZ, United States
[8] Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
[9] Physics Department, University of Athens, Athens, Greece
[10] Physics Department, National Technical University of Athens, Zografou, Greece
[11] Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[12] Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
[13] Institute of Physics, University of Belgrade, Belgrade, Serbia
[14] Department for Physics and Technology, University of Bergen, Bergen, Norway
[15] Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
[16] Department of Physics, Humboldt University, Berlin, Germany
[17] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[18] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[19] (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Department of Physics, Dogus University, Istanbul, Turkey
[20] (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
[21] Physikalisches Institut, University of Bonn, Bonn, Germany

[22] *Department of Physics, Boston University, Boston, MA, United States*
[23] *Department of Physics, Brandeis University, Waltham, MA, United States*
[24] *(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*
[25] *Physics Department, Brookhaven National Laboratory, Upton, NY, United States*
[26] *(a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania*
[27] *Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
[28] *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[29] *Department of Physics, Carleton University, Ottawa, ON, Canada*
[30] *CERN, Geneva, Switzerland*
[31] *Enrico Fermi Institute, University of Chicago, Chicago, IL, United States*
[32] *(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[33] *(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China*
[34] *Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France*
[35] *Nevis Laboratory, Columbia University, Irvington, NY, United States*
[36] *Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*
[37] *(a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy*
[38] *(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
[39] *Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
[40] *Physics Department, Southern Methodist University, Dallas, TX, United States*
[41] *Physics Department, University of Texas at Dallas, Richardson, TX, United States*
[42] *DESY, Hamburg and Zeuthen, Germany*
[43] *Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
[44] *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
[45] *Department of Physics, Duke University, Durham, NC, United States*
[46] *SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[47] *INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[48] *Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany*
[49] *Section de Physique, Université de Genève, Geneva, Switzerland*
[50] *(a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy*
[51] *(a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
[52] *II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
[53] *SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[54] *II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany*
[55] *Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France*
[56] *Department of Physics, Hampton University, Hampton, VA, United States*
[57] *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States*
[58] *(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany*
[59] *Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
[60] *(a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
[61] *Department of Physics, Indiana University, Bloomington, IN, United States*
[62] *Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
[63] *University of Iowa, Iowa City, IA, United States*
[64] *Department of Physics and Astronomy, Iowa State University, Ames, IA, United States*
[65] *Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia*
[66] *KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
[67] *Graduate School of Science, Kobe University, Kobe, Japan*
[68] *Faculty of Science, Kyoto University, Kyoto, Japan*
[69] *Kyoto University of Education, Kyoto, Japan*
[70] *Department of Physics, Kyushu University, Fukuoka, Japan*
[71] *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
[72] *Physics Department, Lancaster University, Lancaster, United Kingdom*
[73] *(a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
[74] *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[75] *Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia*
[76] *School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
[77] *Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
[78] *Department of Physics and Astronomy, University College London, London, United Kingdom*
[79] *Louisiana Tech University, Ruston, LA, United States*
[80] *Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
[81] *Fysiska institutionen, Lunds universitet, Lund, Sweden*
[82] *Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain*
[83] *Institut für Physik, Universität Mainz, Mainz, Germany*
[84] *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[85] *CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
[86] *Department of Physics, University of Massachusetts, Amherst, MA, United States*
[87] *Department of Physics, McGill University, Montreal, QC, Canada*
[88] *School of Physics, University of Melbourne, Victoria, Australia*
[89] *Department of Physics, The University of Michigan, Ann Arbor, MI, United States*
[90] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States*
[91] *(a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy*
[92] *B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
[93] *National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus*

[94] *Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States*
[95] *Group of Particle Physics, University of Montreal, Montreal, QC, Canada*
[96] *P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
[97] *Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
[98] *National Research Nuclear University MEPhI, Moscow, Russia*
[99] *D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
[100] *Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
[101] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
[102] *Nagasaki Institute of Applied Science, Nagasaki, Japan*
[103] *Graduate School of Science and Kobayashi–Maskawa Institute, Nagoya University, Nagoya, Japan*
[104] *(a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
[105] *Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States*
[106] *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
[107] *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
[108] *Department of Physics, Northern Illinois University, DeKalb, IL, United States*
[109] *Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*
[110] *Department of Physics, New York University, New York, NY, United States*
[111] *Ohio State University, Columbus, OH, United States*
[112] *Faculty of Science, Okayama University, Okayama, Japan*
[113] *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States*
[114] *Department of Physics, Oklahoma State University, Stillwater, OK, United States*
[115] *Palacký University, RCPTM, Olomouc, Czech Republic*
[116] *Center for High Energy Physics, University of Oregon, Eugene, OR, United States*
[117] *LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
[118] *Graduate School of Science, Osaka University, Osaka, Japan*
[119] *Department of Physics, University of Oslo, Oslo, Norway*
[120] *Department of Physics, Oxford University, Oxford, United Kingdom*
[121] *(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[122] *Department of Physics, University of Pennsylvania, Philadelphia, PA, United States*
[123] *National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
[124] *(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[125] *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States*
[126] *(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Fisica, Universidade do Minho, Braga; (f) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); (g) Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal*
[127] *Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
[128] *Czech Technical University in Prague, Praha, Czech Republic*
[129] *Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*
[130] *State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia*
[131] *Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
[132] *(a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
[133] *(a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
[134] *(a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
[135] *(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; (b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco*
[136] *DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France*
[137] *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States*
[138] *Department of Physics, University of Washington, Seattle, WA, United States*
[139] *Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
[140] *Department of Physics, Shinshu University, Nagano, Japan*
[141] *Fachbereich Physik, Universität Siegen, Siegen, Germany*
[142] *Department of Physics, Simon Fraser University, Burnaby, BC, Canada*
[143] *SLAC National Accelerator Laboratory, Stanford, CA, United States*
[144] *(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
[145] *(a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
[146] *(a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden*
[147] *Physics Department, Royal Institute of Technology, Stockholm, Sweden*
[148] *Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States*
[149] *Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
[150] *School of Physics, University of Sydney, Sydney, Australia*
[151] *Institute of Physics, Academia Sinica, Taipei, Taiwan*
[152] *Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel*
[153] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
[154] *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[155] *International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*
[156] *Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
[157] *Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
[158] *Department of Physics, University of Toronto, Toronto, ON, Canada*
[159] *(a) TRIUMF, Vancouver, BC; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada*
[160] *Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan*
[161] *Department of Physics and Astronomy, Tufts University, Medford, MA, United States*
[162] *Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*
[163] *Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States*
[164] *(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
[165] *Department of Physics, University of Illinois, Urbana, IL, United States*
[166] *Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*

[167] *Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain*
[168] *Department of Physics, University of British Columbia, Vancouver, BC, Canada*
[169] *Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada*
[170] *Department of Physics, University of Warwick, Coventry, United Kingdom*
[171] *Waseda University, Tokyo, Japan*
[172] *Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*
[173] *Department of Physics, University of Wisconsin, Madison, WI, United States*
[174] *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*
[175] *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[176] *Department of Physics, Yale University, New Haven, CT, United States*
[177] *Yerevan Physics Institute, Yerevan, Armenia*
[178] *Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*

[a] Also at Department of Physics, King's College London, London, United Kingdom.
[b] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[c] Also at Novosibirsk State University, Novosibirsk, Russia.
[d] Also at TRIUMF, Vancouver, BC, Canada.
[e] Also at Department of Physics, California State University, Fresno, CA, United States.
[f] Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
[g] Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.
[h] Also at Tomsk State University, Tomsk, Russia.
[i] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[j] Also at Universita di Napoli Parthenope, Napoli, Italy.
[k] Also at Institute of Particle Physics (IPP), Canada.
[l] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
[m] Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[n] Also at Louisiana Tech University, Ruston, LA, United States.
[o] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[p] Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
[q] Also at Graduate School of Science, Osaka University, Osaka, Japan.
[r] Also at Department of Physics, National Tsing Hua University, Taiwan.
[s] Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.
[t] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
[u] Also at CERN, Geneva, Switzerland.
[v] Also at Georgian Technical University (GTU),Tbilisi, Georgia.
[w] Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
[x] Also at Manhattan College, New York, NY, United States.
[y] Also at Hellenic Open University, Patras, Greece.
[z] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
[aa] Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
[ab] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[ac] Also at School of Physics, Shandong University, Shandong, China.
[ad] Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
[ae] Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[af] Also at International School for Advanced Studies (SISSA), Trieste, Italy.
[ag] Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
[ah] Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
[ai] Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
[aj] Also at National Research Nuclear University MEPhI, Moscow, Russia.
[ak] Also at Department of Physics, Stanford University, Stanford, CA, United States.
[al] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[am] Also at Flensburg University of Applied Sciences, Flensburg, Germany.
[an] Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
* Deceased.