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Editors' Suggestion

Centrality and pseudorapidity dependence of the transverse energy density in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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The almost hermetic coverage of the CMS detector is used to measure the distribution of transverse energy, E_{T}, over 13.2 units of pseudorapidity, η, for pPb collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The huge angular acceptance exploits the fact that the CASTOR calorimeter at $-6.6 < \eta < -5.2$ is effectively present on both sides of the colliding system because of a switch in the proton-going and lead-going beam directions. This wide acceptance enables the study of correlations between well-separated angular regions and makes the measurement a particularly powerful test of event generators. For minimum bias pPb collisions the maximum value of $dE_{\mathrm{T}}/d\eta$ is 22 GeV, which implies an E_{T} per participant nucleon pair comparable to that of peripheral PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The increase of $dE_{\mathrm{T}}/d\eta$ with centrality is much stronger for the lead-going side than for the proton-going side. The η dependence of $dE_{\mathrm{T}}/d\eta$ is sensitive to the η range in which the centrality variable is defined. Several modern generators are compared to these results but none is able to capture all aspects of the η and centrality dependence of the data and the correlations observed between different η regions.

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I. INTRODUCTION

In a heavy-ion or proton nucleus collision the total transverse energy, E_{T}, is a measure of the energy liberated by the deceleration, or "stopping power" of the colliding nucleons while dE_{T}/dy measures the total energy carried by the system of particles or medium, produced in the collision, which is moving with longitudinal rapidity y [1]. In heavy-ion collisions the energy density, ϵ_{BJ}, of this medium at proper time τ_0 shortly after the impact of the two nuclei can be estimated using the Bjorken formula,

$$\epsilon_{\mathrm{BJ}} = \frac{dE_{\mathrm{T}}}{dy}\frac{1}{\tau_0 A_{\perp}}, \tag{1}$$

where $A_{\perp}$ is the nuclear transverse area, i.e., the initial size of the medium [2]. The time τ_0 at which it is first appropriate to speak about an energy density is a model assumption. Some collaborations have chosen to report the product of energy density and proper time $\epsilon_{\mathrm{BJ}}\tau_0$ [2,3] while others have used $\tau_0 = 1$ fm/c as a reference value [4,5].

For the top 5% most central lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, this formula gives energy densities up to 14 GeV/fm^3 at a time $\tau_0 = 1$ fm/c [4]. This value is above the expected threshold of $\epsilon > 1$ GeV/fm^3 for the production of a quark-gluon plasma estimated from quantum chromodynamics (QCD) calculations performed on a lattice [6]. Collective phenomena such as azimuthal flow and strangeness enhancement have been observed in proton-lead (pPb) [7–9] and even high-multiplicity proton-proton (pp) collisions [10–15]. Given such evidence of collective motion and strangeness enhancement in small systems, it is relevant to study the energy densities achieved in pPb collisions to see if a quark-gluon plasma could be formed in pPb collisions.

The E_{T} spectra in proton-nucleus, pA, and deuteron-nucleus, dA, collisions have been measured at center-of-mass energies ranging from $\sqrt{s_{\mathrm{NN}}} = 5.5$ to 200 GeV with nuclei ranging from deuterium (atomic number $A = 2$) to uranium (U, $A = 238$) [16–19]. At $\sqrt{s_{\mathrm{NN}}} = 5.5$ GeV, only a weak correlation is observed between the total E_{T} and the charged-particle multiplicity in the forward region [17]. At $\sqrt{s_{\mathrm{NN}}} = 5.5$, 20, and 30 GeV, the mean pseudorapidity η moves backward, i.e., in the ion-going direction, and the pseudorapidity width of the $dE_{\mathrm{T}}/d\eta$ distribution decreases as the total E_{T} in the event increases [16–18].

In this paper, we report $dE_{\mathrm{T}}/d\eta$ distributions measured in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV by the CMS experiment at the CERN Large Hadron Collider (LHC). This beam energy is 25 times larger than that for the previous highest energy measurements at Relativistic Heavy Ion Collider [20]. The analysis combines measurements from both pPb and Pbp data taking to cover 13.2 units of η, i.e., $|\eta| < 6.6$, in the laboratory frame. Since the energy per nucleon of the proton beam is higher than that of the lead one, the nucleon-nucleon center-of-mass is at a pseudorapidity of $\eta_{\mathrm{lab}} = 0.465$ in the

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2469-9985/2019/100(2)/024902(20)

laboratory frame of reference. For symmetric heavy-ion collisions, the shape of $dE_T/d\eta$ vs. η has only a weak dependence on the η region, which is used to classify the centrality of the events [4]. To test whether this is the case for the much smaller system created in pPb collisions, events are classified according to the E_T or charged-particle multiplicity in several different η regions, and the $dE_T/d\eta$ distributions produced by the different classification procedures are compared to each other.

The comparison of these collider data with modern event generator calculations is a significant motivation for this work. The data presented here reach into the forward region that is crucial for understanding the development of cosmic ray air showers. A significant uncertainty in cosmic ray physics arises from the simulation of very high energy hadron-air collisions [21]. This uncertainty has an important effect on the modeling of air showers and the energy calibration of modern cosmic ray observatories. For a proper description of the development of cosmic ray air showers it is crucial to understand the rapidity region within four units of the rapidity of the incoming proton or nucleus [22]. The data are compared in detail to calculations from three event generators: HIJING v2.1, EPOS-LHC, and QGSJET II-04 [23–25].

II. THE CMS APPARATUS

The central feature of the CMS apparatus is a superconducting solenoid of 6-m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The silicon detectors provide tracking in the region $|\eta| < 2.5$, ECAL and HCAL cover the pseudorapidity interval $|\eta| < 3.0$, while the muon system covers the region $|\eta| < 2.4$. In the forward region, the hadron forward (HF) calorimeters cover the region $3.0 < |\eta| < 5.2$.

Each HF calorimeter consists of 432 readout towers, containing long and short quartz fibers running parallel to the beam. By reading out the two sets of fibers separately, it is possible to distinguish showers generated by electrons and photons from those generated by hadrons. Very forward angles are covered at one end of CMS ($-6.6 < \eta < -5.2$) by the CASTOR calorimeter and at both ends ($|\eta| > 8.3$) by the zero-degree calorimeters (ZDCs). Both CASTOR and the ZDCs consist of quartz plates or fibers embedded in tungsten absorbers. They are segmented longitudinally to allow the separation of electromagnetic and hadronic components of the showers produced by incoming particles. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [26].

Analysis in the midrapidity region is based on objects produced by the CMS particle-flow algorithm [27], which reconstructs and identifies each individual particle-flow candidate with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement, corrected for the effects of the zero-suppression algorithm. The zero-suppression algorithm both speeds up the readout and reduces the volume of data that must be recorded. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex, as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track, reconstructed using information from both tracker and muon stations. For $|\eta| < 2.5$ the energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching of ECAL and HCAL energy deposits. These energy deposits are corrected for the effects of the zero-suppression algorithm and the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

For the forward detectors, HF, CASTOR, and ZDC, there is no tracking information, therefore information from the calorimeter towers only is used for the analysis. The two HF calorimeters are each segmented into 13 rings in η. For this analysis, the first two rings, covering $3.00 < |\eta| < 3.15$, are excluded since they are partially located in the shadow of the endcap calorimeter. The subsequent 10 rings of width $\delta\eta = 0.175$ are grouped into 5 pairs of consecutive rings. The last ring has a width of $\delta\eta = 0.3$. In total, the transverse energy is measured in these six η bins in each HF calorimeter. The calibration of the HF calorimeter is derived from test beam data, and radioactive sources and has an accuracy of 10% [28]. The energy flow in the HF calorimeter is measured by summing all energy deposits above the threshold of 4 GeV in a given ring. Since CASTOR has no η segmentation, all energy deposits within it are summed together. The absolute calibration of the CASTOR calorimeter is achieved by a combination of extrapolation from the HF region for 7 TeV pp data and simulation-based corrections. The accuracy of the energy scale is estimated to be 22%. The calibration of the ZDCs is based on electromagnetic interactions that produce single neutrons in the calorimeters with the energy E_{beam}/A [29].

III. DATA TAKING AND EVENT SELECTION

The data for this analysis were recorded during the CERN LHC 2013 pPb and Pbp data taking. During these runs, 31 nb^{-1} of data were collected by CMS, of which 1.14 nb^{-1} are used for this analysis. For this luminosity the statistical uncertainties on the data are very small compared to the systematic ones. For this paper the proton-going direction is defined to be toward positive rapidity, which implies that negative η is in the lead-going direction. The switch in the proton and lead beam directions allows the use of CASTOR for measuring E_T on both the lead- and proton-going sides of the collision. For this analysis, events are selected with an unbiased hardware trigger requiring only the presence of proton and lead bunches in the CMS detector. These bunches are detected by induction counters placed 175 m from the interaction point on each side of the experiment. Furthermore, the presence of at least one single reconstructed charged-particle track with $|\eta| < 2.4$ and $p_T > 400$ MeV/c is required. An offline selection reduces events from beam-gas or electromagnetic interactions [30]. Events are required to have at least one HF calorimeter tower with more than 3 GeV of total energy on both the positive and negative sides of the interaction point and at least one reconstructed primary vertex with at least two associated tracks. The effect of noise on the E_T measurement is estimated from a sample of events collected with a random trigger when no beams are present.

IV. EVENT CENTRALITY

In heavy-ion collisions the activity or violence of a collision can be classified by several theoretical constructs [1]: the number of nucleons that participate in the collision, N_{part}, by the number of collisions between participants, N_{coll}, and by the closest distance between the centers of the colliding nuclei, which is called the impact parameter, b. The term centrality is used as an estimator of the impact parameter of the collisions. It is generally defined in terms of the multiplicity of charged particles or the E_T produced in a given η region. While in Monte Carlo (MC) simulations N_{part}, N_{coll}, and b are known, in data, these variables cannot be measured directly. These quantities are estimated using E_T or charged-particle multiplicity, which are both believed to scale monotonically with N_{part} or b.

The centrality of a particular event is defined to be the percentile of events with values of the estimator larger than for that particular event. A Glauber model is then used to relate the centrality to N_{part}, N_{coll}, and b [31].

For symmetric heavy-ion collisions the correlation of centrality with N_{part} is strong [4], but for the much smaller pPb system the fluctuations of N_{part} with a given experimental observable are large [32]. For this paper three different measures of centrality are investigated:

(i) HF-single: E_T deposited in the Pb-going side of HF, in $-5.0 < \eta < -4.0$,
(ii) HF-double: the sum of E_T deposited in both sides of HF, in $4.0 < |\eta| < 5.0$,
(iii) N_{track}: number of reconstructed tracks with $p_T > 400$ MeV/c and $|\eta| < 2.4$.

When using the charged-particle multiplicity or E_T in given η regions to define centrality there is an obvious autocorrelation between the centrality and the multiplicity or E_T in that region. It is not known, however, how far these correlations extend over larger η regions. The near hermetic coverage of the CMS calorimeters, 13.2 units of η, allow for the most complete picture of energy production yet performed for proton-lead collisions at the LHC. In order to understand the correlation that can arise from a choice of the centrality variable, a study needs to be made over a large pseudorapidity range for several centrality classes.

V. DATA ANALYSIS

The measured transverse energy densities are are presented for $|\eta| < 2.0$ in the tracker region, for $3.15 < |\eta| < 5.20$ in the HF calorimeter, and for $5.2 < |\eta| < 6.6$ in the CASTOR calorimeter. Because of a switch of the beam direction during the data taking, the CASTOR calorimeter can be used for both positive and negative η.

The transverse energy density is calculated using the following equation:

$$\frac{dE_T}{d\eta}(\eta) = \frac{C(\eta)}{N\Delta\eta}\sum_j E_T^j \left(\text{if } E_T^j > \text{noise}\right), \tag{2}$$

where N is the number of good events that pass the online and the offline event selection, $C(\eta)$ is a correction factor that accounts for the reconstruction and triggering inefficiencies, and the index j in the summation runs over all reconstructed particle-flow objects. The correction is deduced from simulations and is defined as

$$C(\eta) = \frac{\sum_k E_T^k(\text{generated})}{\sum_j E_T^j\left(\text{reconstructed}\right)\left(\text{if } E_T^j > \text{noise}\right)}, \tag{3}$$

where the index k in the top summation runs over all generated particles. Using this definition $C(\eta)$ corrects the data from the detector level of the data to the stable-particle level, i.e., those particles with lifetimes $c\tau > 1$ cm. This correction accounts for the nonlinearity of the calorimeter response and the noise thresholds. The correction factor depends on the particle mix and average transverse momentum of the particles. The EPOS-LHC, HIJING, and QGSJET II generators are used to estimate $C(\eta)$. For the analysis of the reconstructed simulated events, the event selection and noise reduction requirements are the same as for the data analysis. Events are selected by requiring at least one stable particle to be within the HF η range, $3.2 < |\eta| < 5.2$, on both sides.

In order to focus on the centrality dependence of the transverse energy as a function of η, the events are divided into 10 bins of centrality, 0–10%, 10–20%, etc. Here we consider 0–10% to be *central* and any other centrality to be *peripheral*. Using these definitions the ratio of peripheral to central $dE_T/d\eta$ is defined as

$$S_{\mathrm{PC}}(\eta) = \frac{\frac{dE_T}{d\eta}(\text{peripheral}, \eta)}{\frac{dE_T}{d\eta}(\text{central}, \eta)}. \tag{4}$$

This can be written as

$$S_{\mathrm{PC}}(\eta) = \frac{\sum_i E_T^i(\text{peripheral})}{\sum_i E_T^i(\text{central})}\frac{N_{\text{peripheral}}}{N_{\text{central}}}\frac{C(\text{peripheral}, \eta)}{C(\text{central}, \eta)}. \tag{5}$$

Since S_{PC} represents a ratio of results for two data samples multiplied by a ratio of two correction factors, correlated uncertainties tend to cancel, which is a major advantage of this approach. This method of studying the centrality dependence, rather than the more traditional ratio of central to peripheral events, exploits the fact that the 0–10% centrality class has the smallest fractional uncertainties and so minimizes the correlated uncertainties when comparing data from different centrality classes.

TABLE I. Systematic uncertainties in $dE_T/d\eta$ and S_{PC} for the tracker region, the HF region, and the CASTOR region as a function of centrality defined by HF-double. The S_{PC} ratio is by construction unity for 0–10% centrality and is not defined for minimum bias events.

Centrality	$dE_T/d\eta$ systematic (%)			S_{PC} systematic (%)		
	Tracker	HF	CASTOR	Tracker	HF	CASTOR
0–10%	3.7	10.1	22		…	
10–20%	3.8	10.1	22	1.0	1.1	1.3
20–30%	3.8	10.1	22	1.3	1.1	1.5
30–40%	3.8	10.1	22	1.3	1.2	4.1
40–50%	4.2	10.1	22	1.3	1.2	4.1
50–60%	4.5	10.1	22	1.3	1.2	4.1
60–70%	5.1	10.2	22	1.6	1.3	4.1
70–80%	7.0	10.4	23	3.5	1.3	4.1
Min. bias	4.2	10.1	22		…	

VI. SYSTEMATIC UNCERTAINTIES

In this analysis, there are several sources of systematic uncertainties on $dE_T/d\eta$:

(1) The differences in E_T spectra and particle composition between data and the MC simulation used to generate correction factors. The impact of these differences is estimated by generating MC samples with different particle mixes and E_T spectra. These effects are most important in the tracker, $|\eta| < 2.4$, and HF regions, $3.15 < |\eta| < 5.20$, and are less than 3%.

(2) Uncertainties in the calorimeter energy scale. These are estimated by the differences in calibration from various methods. These contribute less than 1% in the tracker region, 10% for HF, and 22% for CASTOR.

(3) Method of handling the noise in the calorimeters. These uncertainties are estimated by using different sets of noise reduction requirements in the analysis. These uncertainties are less than 3% in the tracker and HF regions and are negligible for CASTOR.

(4) Any asymmetries between the positive and negative sides of CMS, e.g., from dead channels, etc. The data from *p*Pb collisions at a given positive η are compared to those of Pb*p* events at the corresponding negative η. These uncertainties are up to 5.0% in the tracker region, and up to 3.5% in the HF region.

The uncertainties described above are evaluated separately in the tracker, HF, and CASTOR regions and summed in quadrature. For the CASTOR region the uncertainty in the energy scale dominates the total systematic uncertainty. Table I lists the systematic uncertainties on $dE_T/d\eta$ and S_{PC} for each η region as a function centrality as defined by HF-double. The systematic uncertainties are the smallest for the most central events. For S_{PC}, there is a high degree of cancellation between the uncertainties in different centrality classes. In particular the energy scale and forward/backward systematic uncertainties cancel almost completely while the uncertainties related to the simulation and noise reduction only partially cancel. The net result is that the systematic uncertainties in S_{PC} are considerably smaller than those in E_T.

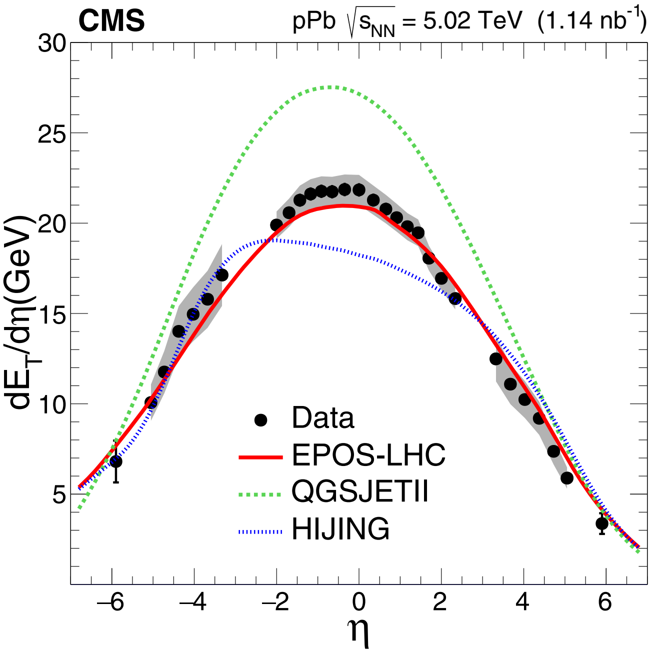

FIG. 1. Transverse energy density versus η from minimum bias *p*Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The proton is moving toward positive η. The statistical uncertainties are smaller than the size of the data points and the total errors are dominated by the systematics. The systematic uncertainties are largely correlated point to point within the central and with the HF regions and so shown by gray bands there. The systematic uncertainties for the most forward and backward data points, i.e., $\eta = \pm 5.9$ are uncorrelated with those of central and HF regions and so are shown as vertical bars. Predictions from the EPOS-LHC (red solid), QGSJET II (green dashed), and HIJING (blue dotted) event generators are also shown.

VII. RESULTS

The most basic measurement of E_T production is performed for the minimum bias selection as a function of η. Figure 1 shows the resulting $dE_T/d\eta$ versus η for data and for predictions from the EPOS-LHC, QGSJET II, and HIJING models. The HIJING event generator is based on a two-component model for hadron production in high-energy nucleon and nuclear collisions. Hard parton scattering is assumed to be described by perturbative QCD, and soft interactions are approximated by string excitations with an effective cross section. For heavy nuclei, initial parton distributions are modified with respect to those of free protons. Also, multiple scatterings inside a nucleus lead to transverse momentum (p_T) broadening of both initial- and final-state partons. Both the EPOS-LHC and QGSJET II models use Gribov-Regge theory to give a self-consistent quantum-mechanical treatment of the initial parton-level interactions without an arbitrary division into soft and hard interactions [33]. The EPOS-LHC generator also includes a phenomenological implementation of gluon saturation. After the initial interactions, this model uses a hydrodynamic approach to evolve regions of high energy density. The QGSJET II generator allows parton cascades to split and merge via pomeron-pomeron interactions but does not include a hydrodynamic component. Saturation effects are produced via higher-order pomeron-pomeron interactions.

From Fig. 1 it can be seen that $dE_T/d\eta|_{\eta=0} \approx 22$ GeV. This is 1/40 of the value observed for the 2.5% most central PbPb collisions [4]. However, since the cross-sectional area of a *p*Pb collision is much smaller than that of a central PbPb collision [34,35], this result implies that the maximum energy density in *p*Pb collisions is comparable to that achieved in PbPb collisions.

By comparing $dE_T/d\eta$ to $dN_{ch}/d\eta$, which was previously measured by our experiment in proton-lead collisions at the same energy [36], it is possible to calculate the transverse energy per charged particle. At the center-of-mass pseudorapidity we find $E_T/N_{ch} = 1.31 \pm 0.07$ GeV/particle for minimum bias *p*Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. This is somewhat higher than the value of 1.0 ± 0.1 GeV/particle reported by PHENIX for *d*Au collisions at $\sqrt{s_{NN}} = 200$ GeV [37].

Predictions from the EPOS-LHC model are close to the data over the entire pseudorapidity range while those from the HIJING model are consistent with the data for $\eta < -3$ and $\eta > 2$, but are significantly below the data at midrapidity, i.e., $|\eta| < 2$. Predictions from the QGSJET II generator are consistently above the data over the entire η range. The peak of the data distribution is around $\eta = -0.5$. Both EPOS-LHC and QGSJET II generators peak close to this value while HIJING has a maximum at $\eta = -2.5$.

Figure 2 shows the transverse energy density at midrapidity, $dE_T/d\eta|_{\eta=0}$, versus $\sqrt{s_{NN}}$ for minimum bias *pA* and *dA* collisions for several experiments [18,19,38]. The data are averaged over a small region around the center-of-mass pseudorapidity, with a typical $|\eta - \eta_{c.m.}| < 0.5$. To account for the different system sizes the $dE_T/d\eta$ values are normalized to the number of participating pairs of nucleons in the collisions. For the CMS data N_{part} was estimated to be 8.0 ± 0.2 using the method described in Ref. [31]. Figure 2 also shows a compilation of results for central *AA* collisions from Ref. [19] with the addition of a recent ALICE PbPb data point [3]. Although the geometries and lifetimes of *pA* and *AA* collisions are very different, it is interesting to note that the *p*Pb minimum bias value of 5.33 ± 0.25 GeV per participant pair is higher than the central AuAu result at $\sqrt{s_{NN}} = 200$ GeV [19] and consistent with the peripheral PbPb result at 2.76 TeV [4].

The rate of increase of $dE_T/d\eta|_{\eta=0}$ with $\sqrt{s_{NN}}$ is stronger for *AA* than for *pA* collisions. This is expected because of the increased stopping power, i.e., the ability to decelerate nucleons, of heavy nuclei compared to protons [47,48]. The stopping power controls the total amount of energy available for particle production. The rapidity shift of the incoming nucleons is proportional to the beam rapidity for energies up to $\sqrt{s_{NN}} = 63$ GeV but then seems to saturate [48–51]. This limit to the deceleration may be the reason for the change in slope of the *AA* data near $\sqrt{s_{NN}} \approx 10$ GeV. The *pA* data also seems to change slope in this region but unfortunately the sparsity of data with $\sqrt{s_{NN}}$ between 5 and 20 GeV make it difficult to determine where this change happens in *pA* collisions.

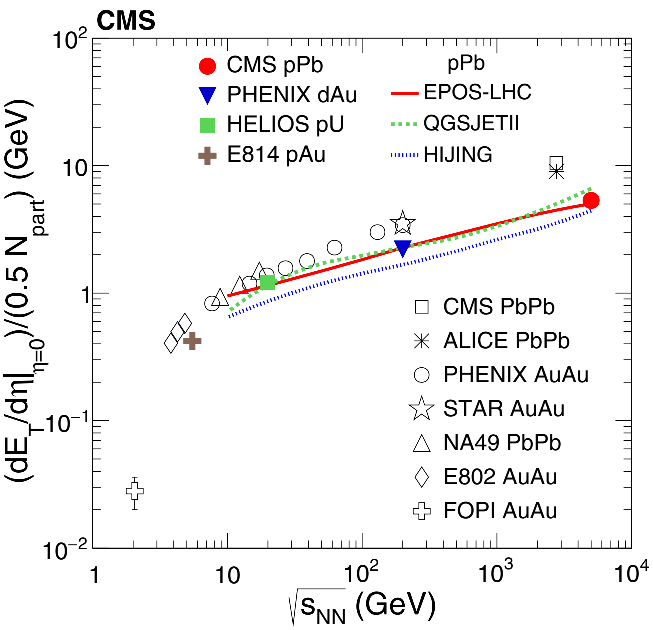

FIG. 2. Transverse energy density per participating nucleon-nucleon pair evaluated at $\eta_{c.m.}$ versus $\sqrt{s_{NN}}$ for minimum bias *p*Au, *p*U, *d*Au, and *p*Pb collisions. For the CMS *p*Pb data at $\sqrt{s_{NN}} = 5.02$ TeV, N_{part} was estimated to be 8.0 ± 0.2 using the method described in Ref. [31]. The uncertainties are generally smaller than the size of the data points. Also shown are the corresponding results for central AuAu and PbPb collisions, as well as simulation for minimum bias *p*Pb collisions from three event generators [3,4,18,37–46].

For energies above $\sqrt{s_{NN}} \approx 10$ GeV the scaled transverse energy density increases as a power law according to s_{NN}^{γ}. Such an energy dependence has been previously observed for the charged-particle multiplicity density, $dN^{\pm}/d\eta$, near $\eta = 0$ [3,19,36]. Table II lists the results of fitting the energy dependence of the scaled $dN^{\pm}/d\eta$ and $dE_T/d\eta$ for central events to a function of the form s_{NN}^{γ}. The E_T rises more rapidly with energy than the charged-particle multiplicity. Again this is expected because the mean transverse momentum is also increasing with beam energy [52]. This difference in the energy dependence of E_T and multiplicity production is stronger for *AA* than for *pA* collisions. This suggests that the mean transverse momentum rises faster with energy in *AA* than in *pA* collisions.

Figure 2 also shows simulations of *p*Pb interactions at various energies. Predictions from the EPOS-LHC model are consistent with the data from $\sqrt{s_{NN}} = 20$ GeV to 5.02 TeV. The QGSJET model is consistent with the 20 and 200 GeV data

TABLE II. Values of exponents from fitting the energy dependence of $dN^{\pm}/d\eta$ [36] and $dE_T/d\eta$ at midrapidity to a function of the form s_{NN}^{γ} for minimum bias proton-nucleus and central nucleus-nucleus collisions.

Collision	γ for N_{ch}	γ for E_T
pA	$0.103 \pm .005$	$0.135 \pm .003$
AA	$0.158 \pm .004$	$0.205 \pm .005$

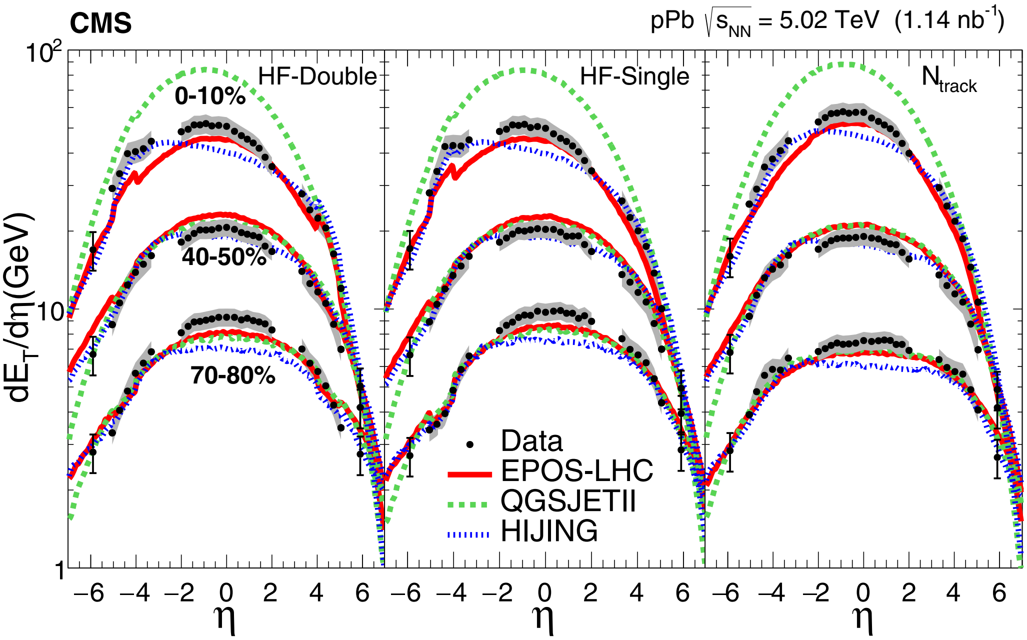

FIG. 3. Transverse energy density versus η and centrality from 5.02 TeV pPb collisions for the HF-double (left), HF-single (center), and N_{track} (right) centrality definitions for data and for predictions from the EPOS-LHC, QGSJET II, and HIJING event generators, for 0–10% (upper), 40–50% (middle), and 70–80% (lower) central collisions. The uncertainties are dominated by the systematic components, which are largely correlated point-to-point in the central region and in HF and which are shown by gray bands there.

but is somewhat higher than the data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The HIJING generator has a similar energy dependence of the data but is consistently below the experimental results.

Figure 3 shows $dE_{\mathrm{T}}/d\eta$ versus η for pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV for several centralities and for three different definitions of centrality for both data and simulations. For 0–10% most central collisions, $dE_{\mathrm{T}}/d\eta|_{\eta=0}$ exceeds 50 GeV. For the top 10% central pPb collisions it is reasonable to assume a complete overlap of the incoming proton with the lead nucleus. Thus, the transverse area $A_{\perp}$ corresponds to the total proton-proton (pp) cross section, $\sigma_{pp}^{\mathrm{tot}}$, at $\sqrt{s} = 5.02$ TeV. The TOTEM collaboration has measured $\sigma_{pp}^{\mathrm{tot}}$ at 2.76, 7, 8, and 13 TeV [53–56]. Based on these results we estimate $\sigma_{pp}^{\mathrm{tot}} = 94 \pm 1$ mb at $\sqrt{s} = 5.02$ TeV. Furthermore, the factor $dy/d\eta$ needed for Eq. (1) depends on the particle mix and p_{T} spectra. This factor is evaluated using simulated events from the three MC generators and is found to be 1.12 ± 0.03. With these considerations Eq. (1) implies an energy density at a time $\tau_0 = 1$ fm/c of the order of 4.5 GeV/fm^3 for the top 10% pPb collisions. This is above the expected threshold for the production of a quark-gluon plasma estimated from lattice QCD calculations [6].

For peripheral events the peak of $dE_{\mathrm{T}}/d\eta$ is close to the nucleon-nucleon center-of-mass pseudorapidity, $\eta_{\mathrm{c.m.}} = 0.465$. The peak moves toward the Pb side as the centrality increases, reflecting the increased momentum from the lead-going nucleons. For the most central events, the peak of $dE_{\mathrm{T}}/d\eta$ is at $\eta \approx -1.0$, i.e., 1.4 units below $\eta_{\mathrm{c.m.}}$. This is very close to the pseudorapidity shift observed for central pU collisions at $\sqrt{s_{\mathrm{NN}}} = 20$ GeV [18], suggesting that the stopping power of heavy nuclei for protons is almost independent of the center-of-mass energy for energies above 20 GeV. For AA collisions a similar energy independence of the stopping power has been observed for $\sqrt{s_{\mathrm{NN}}}$ greater than 63 GeV [49–51].

All three event generators show a large increase of $dE_{\mathrm{T}}/d\eta|_{\eta=0}$ and a shift of $\langle\eta\rangle$ toward the lead-going side as the centrality increases. However, for the 0–10%, centrality selection the HIJING distribution peaks at significantly lower η than the data. Predictions from the EPOS-LHC model are closest to the data for $|\eta| < 2$, whereas the HIJING generator gives a better description of the data in the lead-going region, i.e., $\eta < -3$. In the proton-going region, i.e., $\eta > 3$, the two generators are closer to each other and the data. The QGSJET II predictions significantly exceed the data at all rapidities for the 0–10% most central collisions but are close to the data for the 40–50% and 70–80% centrality classes. As the centrality increases, $dE_{\mathrm{T}}/d\eta|_{\eta=0}$ increases faster for the N_{track} centrality definition than for the HF-single or HF-double definitions. This effect results from the autocorrelation with the centrality definition.

Figure 4 shows $dE_{\mathrm{T}}/d\eta$ scaled by the number of participant nucleon pairs as a function of N_{part} for the far lead-going region $-6.6 < \eta < -5.2$, the midrapidity region $|\eta| < 0.8$, and the far proton-going region $5.2 < \eta < 6.6$. The centrality definition is based on the HF-single selection, i.e., $-5.0 < \eta < -4.0$. It is clear that the centrality dependence of E_{T} production varies strongly with η. For $N_{\mathrm{part}} > 3$ we find that $dE_{\mathrm{T}}/d\eta$ per participant nucleon pair rises with N_{part} in the lead-going and midrapidity regions but falls for the far proton-going region. This is consistent with the backward shift of the mean η with centrality observed in Fig. 3.

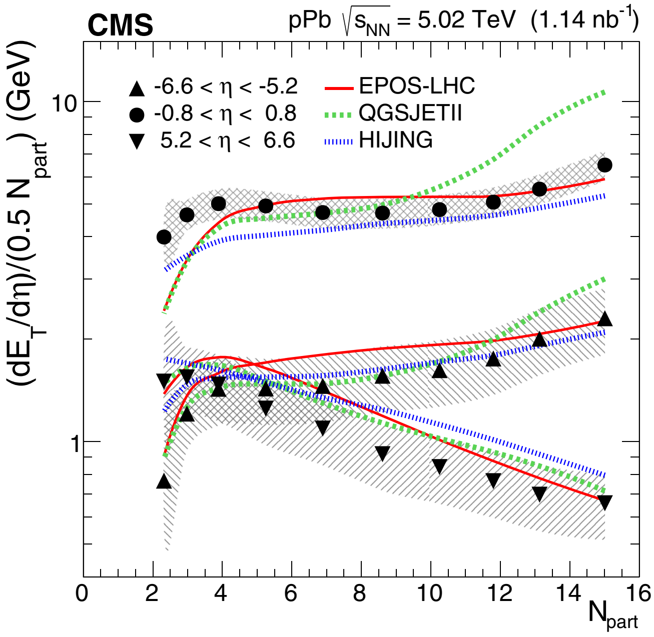

FIG. 4. Transverse energy density per participating nucleon-nucleon pair versus N_{part} for different η ranges. The N_{part} values are based on the method described in Ref. [31]. The HF-single method was used to define centrality. The total experimental uncertainties are shown by gray bands. The values of N_{part} were calculated using the method described in Ref. [31].

Figure 4 also shows model predictions from EPOS-LHC, QGSJET II, and HIJING. At midrapidity none of the generators is consistent with the data over the whole range of N_{part}. In particular, the QGSJET II model has a much stronger centrality dependence than the data. For the lead-going region all three generators are consistent with the data within errors. For the proton-going region, all three generators are above the data, but predictions from the QGSJET II model are closer to the data than those from either EPOS-LHC or HIJING.

Figure 5 shows S_{PC} as a function of η for three centrality ranges and for all three centrality definitions for data as well as for predictions from the EPOS-LHC, QGSJET II, and HIJING event generators. Note that as per the definition, for each centrality bin, say, 40–50%, S_{PC} shows the ratio of the $dE_{\text{T}}/d\eta$ in that "peripheral" bin to $dE_{\text{T}}/d\eta$ for the 0–10% most central events. As expected, S_{PC} increases with centrality for all centrality definitions. The S_{PC} value tends to rise with η since the centrality dependence of E_{T} production is stronger on the lead-going side than on the proton-going side. This is presumably because particles moving in the lead direction are more likely to have multiple interactions than particles moving in the proton-going region.

The autocorrelation between the centrality definition and the measure of $dE_{\text{T}}/d\eta$ suppresses $dE_{\text{T}}/d\eta$ for peripheral events and enhances it for central events in the η region that is used for the centrality determination. These two effects naturally induce a dip in the ratio of peripheral to central distributions in that particular η region. This effect is strongest for S_{PC} in the 70–80% centrality class for the HF-single and HF-double centrality definitions. While the HF centrality is based on $4 < |\eta| < 5$, the impact of the autocorrelations is very clearly visible over one to two more units of η. In contrast, the N_{track} centrality definition uses all tracks with $|\eta| < 2.4$, resulting in a much smoother S_{PC} as a function of η.

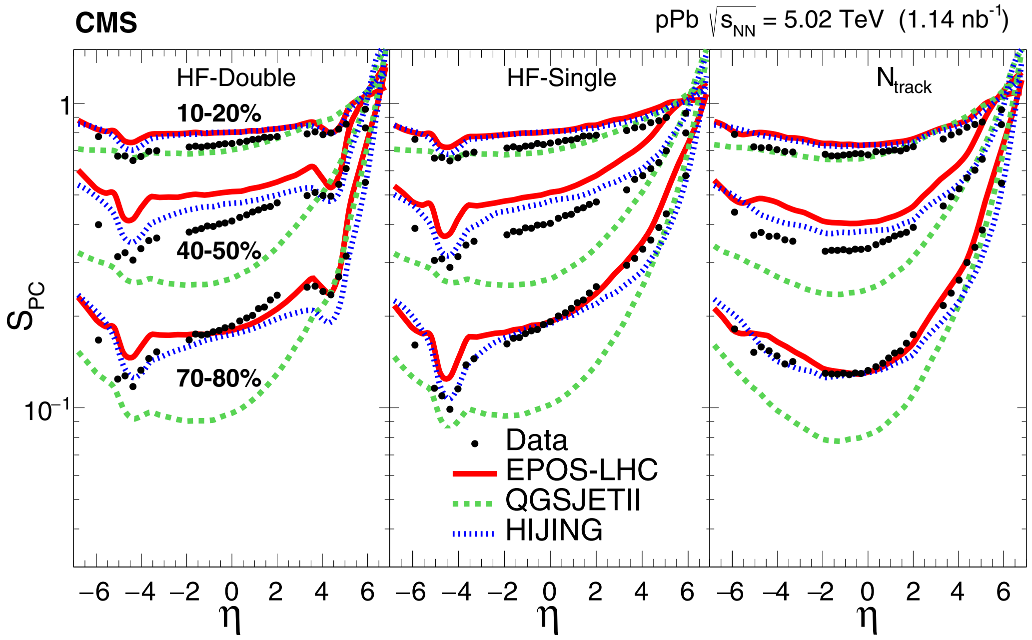

FIG. 5. Ratio of peripheral to central E_{T} production, S_{PC}, as a function of η for three centrality ranges for HF-double (left), HF-single (middle), and N_{track} (right) for data, and for the EPOS-LHC, QGSJET II, and HIJING event generators. The systematic uncertainties are dominant and are of comparable size to the data points.

The QGSJET II model gives the best description of S_{PC} in the 10–20% centrality range; however, it significantly underestimates the magnitude of S_{PC} in all other cases, implying that it significantly overestimates the increase of $dE_{\mathrm{T}}/d\eta$ with centrality. The HIJING and EPOS-LHC generators in general do a better job in describing the magnitude of S_{PC} with EPOS-LHC, giving the best description in the 70–80% centrality range. None of the models gives a complete description of the centrality dependence of the data.

The QGSJET II generator also underestimates the dips in S_{PC} as a function of η for both the HF-double and HF-single definitions of centrality. This is most clearly seen for the HF-double definition in the forward region where the data show significant dips but the QGSJET II distributions increase monotonically with η. The HIJING and EPOS-LHC models both produce dips in the same η regions as the data for both HF centrality definitions but neither generator is able to predict the shape of S_{PC} over the full η range. This failure to reproduce the η dependence of S_{PC} suggests that the generators do not correctly model the correlations present in proton-lead collisions.

VIII. SUMMARY

In this paper we report the centrality and pseudorapidity (η) dependence of transverse energy (E_{T}) production from pPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02$ TeV over 13.2 units of η. The E_{T} per participant pair in minimum bias pPb events at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02$ TeV is comparable to that of peripheral PbPb collisions at 2.76 TeV. At midrapidity the energy density at a proper time $\tau_0 = 1\ \mathrm{fm}/c$ is of order of $4.5\ \mathrm{GeV/fm^3}$ for the top 10% most central pPb collisions, which is comparable to those observed in PbPb collisions. As the centrality of the collision increases, the total E_{T} increases dramatically and the mean η of the E_{T} distribution moves toward the lead-going side of the collision. For central collisions, the peak of $dE_{\mathrm{T}}/d\eta$ is 1.4 units below the center-of-mass pseudorapidity. This pseudorapidity shift is almost the same as for pU collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 20$ GeV.

The EPOS-LHC event generator gives a good description of the minimum bias $dE_{\mathrm{T}}/d\eta$ distribution and peaks at an η value close to that of the data for all centralities. The centrality dependence of E_{T} production for QGSJET II is stronger than that of the data. This model is below the data for 70–80% peripheral events and almost a factor of two above the data for the 10% most central events. Near midrapidity the HIJING generator tends to underestimate the magnitude of $dE_{\mathrm{T}}/d\eta$ and for central collisions predicts a peak that is at significantly lower η than in the data.

Similarly to what has been seen in particle production at lower energy [57], the $dE_{\mathrm{T}}/d\eta$ per participating nucleon-nucleon pair increases with the number of nucleons that participate in the collisions (N_{part}) for η values on the lead side; it is rather independent of N_{part} near midrapidity, and it decreases with N_{part} for η values on the proton side. The η region used to define centrality has a strong impact on the nature of the events selected. There is a significant autocorrelation of the η range used to define centrality with $dE_{\mathrm{T}}/d\eta$ for data and the EPOS-LHC, QGSJET II, and HIJING event generators. None of the tested event generators are able to capture all aspects of the autocorrelations seen in data.

It is clear that cosmic ray event generators have difficulties modeling both the centrality and η dependence of proton-lead collisions. While the proton-lead system is significantly larger than the proton-nitrogen and proton-oxygen collisions occurring in air showers, these data illustrate the need for a better understanding of nuclear effects. Ultimately, protons colliding with light nuclei would be most valuable for this purpose.

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H. Malbouisson,[10] D. Matos Figueiredo,[10] M. Melo De Almeida,[10] C. Mora Herrera,[10] L. Mundim,[10] H. Nogima,[10]
W. L. Prado Da Silva,[10] L. J. Sanchez Rosas,[10] A. Santoro,[10] A. Sznajder,[10] M. Thiel,[10] E. J. Tonelli Manganote,[10,c]
F. Torres Da Silva De Araujo,[10] A. Vilela Pereira,[10] S. Ahuja,[11a] C. A. Bernardes,[11a] L. Calligaris,[11a]
T. R. Fernandez Perez Tomei,[11a] E. M. Gregores,[11b] P. G. Mercadante,[11b] S. F. Novaes,[11a] Sandra S. Padula,[11a]
D. Romero Abad,[11b] A. Aleksandrov,[12] R. Hadjiiska,[12] P. Iaydjiev,[12] A. Marinov,[12] M. Misheva,[12] M. Rodozov,[12]
M. Shopova,[12] G. Sultanov,[12] A. Dimitrov,[13] L. Litov,[13] B. Pavlov,[13] P. Petkov,[13] W. Fang,[14,e] X. Gao,[14,e] L. Yuan,[14]
M. Ahmad,[15] J. G. Bian,[15] G. M. Chen,[15] H. S. Chen,[15] M. Chen,[15] Y. Chen,[15] C. H. Jiang,[15] D. Leggat,[15] H. Liao,[15] Z. Liu,[15]
F. Romeo,[15] S. M. Shaheen,[15] A. Spiezia,[15] J. Tao,[15] C. Wang,[15] Z. Wang,[15] E. Yazgan,[15] H. Zhang,[15] J. Zhao,[15] Y. Ban,[16]
G. Chen,[16] A. Levin,[16] J. Li,[16] L. Li,[16] Q. Li,[16] Y. Mao,[16] S. J. Qian,[16] D. Wang,[16] Z. Xu,[16] Y. Wang,[17] C. Avila,[18] A. Cabrera,[18]
C. A. Carrillo Montoya,[18] L. F. Chaparro Sierra,[18] C. Florez,[18] C. F. González Hernández,[18] M. A. Segura Delgado,[18]
B. Courbon,[19] N. Godinovic,[19] D. Lelas,[19] I. Puljak,[19] T. Sculac,[19] Z. Antunovic,[20] M. Kovac,[20] V. Brigljevic,[21] D. Ferencek,[21]
K. Kadija,[21] B. Mesic,[21] A. Starodumov,[21,f] T. Susa,[21] M. W. Ather,[22] A. Attikis,[22] G. Mavromanolakis,[22] J. Mousa,[22]
C. Nicolaou,[22] F. Ptochos,[22] P. A. Razis,[22] H. Rykaczewski,[22] M. Finger,[23,g] M. Finger Jr.,[23,g] E. Ayala,[24] E. Carrera Jarrin,[25]
M. A. Mahmoud,[26,h,i] A. Mahrous,[26,j] Y. Mohammed,[26,h] S. Bhowmik,[27] A. Carvalho Antunes De Oliveira,[27]
R. K. Dewanjee,[27] K. Ehataht,[27] M. Kadastik,[27] M. Raidal,[27] C. Veelken,[27] P. Eerola,[28] H. Kirschenmann,[28] J. Pekkanen,[28]
M. Voutilainen,[28] J. Havukainen,[29] J. K. Heikkilä,[29] T. Järvinen,[29] V. Karimäki,[29] R. Kinnunen,[29] T. Lampén,[29]
K. Lassila-Perini,[29] S. Laurila,[29] S. Lehti,[29] T. Lindén,[29] P. Luukka,[29] T. Mäenpää,[29] H. Siikonen,[29] E. Tuominen,[29]
J. Tuominiemi,[29] T. Tuuva,[30] M. Besancon,[31] F. Couderc,[31] M. Dejardin,[31] D. Denegri,[31] J. L. Faure,[31] F. Ferri,[31] S. Ganjour,[31]
A. Givernaud,[31] P. Gras,[31] G. Hamel de Monchenault,[31] P. Jarry,[31] C. Leloup,[31] E. Locci,[31] J. Malcles,[31] G. Negro,[31]
J. Rander,[31] A. Rosowsky,[31] M. Ö. Sahin,[31] M. Titov,[31] A. Abdulsalam,[32,k] C. Amendola,[32] I. Antropov,[32] F. Beaudette,[32]
P. Busson,[32] C. Charlot,[32] R. Granier de Cassagnac,[32] I. Kucher,[32] S. Lisniak,[32] A. Lobanov,[32] J. Martin Blanco,[32]
M. Nguyen,[32] C. Ochando,[32] G. Ortona,[32] P. Paganini,[32] P. Pigard,[32] R. Salerno,[32] J. B. Sauvan,[32] Y. Sirois,[32]
A. G. Stahl Leiton,[32] A. Zabi,[32] A. Zghiche,[32] J.-L. Agram,[33,l] J. Andrea,[33] D. Bloch,[33] J.-M. Brom,[33] E. C. Chabert,[33]
V. Cherepanov,[33] C. Collard,[33] E. Conte,[33,l] J.-C. Fontaine,[33,l] D. Gelé,[33] U. Goerlach,[33] M. Jansová,[33] A.-C. Le Bihan,[33]
N. Tonon,[33] P. Van Hove,[33] S. Gadrat,[34] S. Beauceron,[35] C. Bernet,[35] G. Boudoul,[35] N. Chanon,[35] R. Chierici,[35] D. Contardo,[35]
P. Depasse,[35] H. El Mamouni,[35] J. Fay,[35] L. Finco,[35] S. Gascon,[35] M. Gouzevitch,[35] G. Grenier,[35] B. Ille,[35] F. Lagarde,[35]
I. B. Laktineh,[35] H. Lattaud,[35] M. Lethuillier,[35] L. Mirabito,[35] A. L. Pequegnot,[35] S. Perries,[35] A. Popov,[35,m] V. Sordini,[35]
M. Vander Donckt,[35] S. Viret,[35] S. Zhang,[35] T. Toriashvili,[36,n] D. Lomidze,[37] C. Autermann,[38] L. Feld,[38] M. K. Kiesel,[38]
K. Klein,[38] M. Lipinski,[38] M. Preuten,[38] M. P. Rauch,[38] C. Schomakers,[38] J. Schulz,[38] M. Teroerde,[38] B. Wittmer,[38]
V. Zhukov,[38,m] A. Albert,[39] D. Duchardt,[39] M. Endres,[39] M. Erdmann,[39] T. Esch,[39] R. Fischer,[39] S. Ghosh,[39] A. Güth,[39]
T. Hebbeker,[39] C. Heidemann,[39] K. Hoepfner,[39] H. Keller,[39] S. Knutzen,[39] L. Mastrolorenzo,[39] M. Merschmeyer,[39]
A. Meyer,[39] P. Millet,[39] S. Mukherjee,[39] T. Pook,[39] M. Radziej,[39] H. Reithler,[39] M. Rieger,[39] F. Scheuch,[39] A. Schmidt,[39]
D. Teyssier,[39] G. Flügge,[40] O. Hlushchenko,[40] B. Kargoll,[40] T. Kress,[40] A. Künsken,[40] T. Müller,[40] A. Nehrkorn,[40]
A. Nowack,[40] C. Pistone,[40] O. Pooth,[40] H. Sert,[40] A. Stahl,[40,o] M. Aldaya Martin,[41] T. Arndt,[41] C. Asawatangtrakuldee,[41]
I. Babounikau,[41] K. Beernaert,[41] O. Behnke,[41] U. Behrens,[41] A. Bermúdez Martínez,[41] D. Bertsche,[41] A. A. Bin Anuar,[41]
K. Borras,[41,p] V. Botta,[41] A. Campbell,[41] P. Connor,[41] C. Contreras-Campana,[41] F. Costanza,[41] V. Danilov,[41] A. De Wit,[41]
M. M. Defranchis,[41] C. Diez Pardos,[41] D. Domínguez Damiani,[41] G. Eckerlin,[41] T. Eichhorn,[41] A. Elwood,[41] E. Eren,[41]
E. Gallo,[41,q] A. Geiser,[41] J. M. Grados Luyando,[41] A. Grohsjean,[41] P. Gunnellini,[41] M. Guthoff,[41] M. Haranko,[41] A. Harb,[41]
J. Hauk,[41] H. Jung,[41] M. Kasemann,[41] J. Keaveney,[41] C. Kleinwort,[41] J. Knolle,[41] D. Krücker,[41] W. Lange,[41] A. Lelek,[41]
T. Lenz,[41] K. Lipka,[41] W. Lohmann,[41,r] R. Mankel,[41] I.-A. Melzer-Pellmann,[41] A. B. Meyer,[41] M. Meyer,[41] M. Missiroli,[41]
G. Mittag,[41] J. Mnich,[41] V. Myronenko,[41] S. K. Pflitsch,[41] D. Pitzl,[41] A. Raspereza,[41] M. Savitskyi,[41] P. Saxena,[41] P. Schütze,[41]
C. Schwanenberger,[41] R. Shevchenko,[41] A. Singh,[41] N. Stefaniuk,[41] H. Tholen,[41] A. Vagnerini,[41] G. P. Van Onsem,[41]
R. Walsh,[41] Y. Wen,[41] K. Wichmann,[41] C. Wissing,[41] O. Zenaiev,[41] R. Aggleton,[42] S. Bein,[42] L. Benato,[42] A. Benecke,[42]
V. Blobel,[42] M. Centis Vignali,[42] T. Dreyer,[42] E. Garutti,[42] D. Gonzalez,[42] J. Haller,[42] A. Hinzmann,[42] A. Karavdina,[42]
G. Kasieczka,[42] R. Klanner,[42] R. Kogler,[42] N. Kovalchuk,[42] S. Kurz,[42] V. Kutzner,[42] J. Lange,[42] D. Marconi,[42] J. Multhaup,[42]
M. Niedziela,[42] D. Nowatschin,[42] A. Perieanu,[42] A. Reimers,[42] O. Rieger,[42] C. Scharf,[42] P. Schleper,[42] S. Schumann,[42]
J. Schwandt,[42] J. Sonneveld,[42] H. Stadie,[42] G. Steinbrück,[42] F. M. Stober,[42] M. Stöver,[42] D. Troendle,[42] A. Vanhoefer,[42]
B. Vormwald,[42] M. Akbiyik,[43] C. Barth,[43] M. Baselga,[43] S. Baur,[43] E. Butz,[43] R. Caspart,[43] T. Chwalek,[43] F. Colombo,[43] W. De
Boer,[43] A. Dierlamm,[43] N. Faltermann,[43] B. Freund,[43] M. Giffels,[43] M. A. Harrendorf,[43] F. Hartmann,[43,o] S. M. Heindl,[43]
U. Husemann,[43] F. Kassel,[43,o] I. Katkov,[43,m] S. Kudella,[43] H. Mildner,[43] S. Mitra,[43] M. U. Mozer,[43] Th. Müller,[43] M. Plagge,[43]
G. Quast,[43] K. Rabbertz,[43] M. Schröder,[43] I. Shvetsov,[43] G. Sieber,[43] H. J. Simonis,[43] R. Ulrich,[43] S. Wayand,[43] M. Weber,[43]
T. Weiler,[43] S. Williamson,[43] C. Wöhrmann,[43] R. Wolf,[43] G. Anagnostou,[44] G. Daskalakis,[44] T. Geralis,[44] A. Kyriakis,[44]
D. Loukas,[44] G. Paspalaki,[44] I. Topsis-Giotis,[44] G. Karathanasis,[45] S. Kesisoglou,[45] P. Kontaxakis,[45] A. Panagiotou,[45]
N. Saoulidou,[45] E. Tziaferi,[45] K. Vellidis,[45] K. Kousouris,[46] I. Papakrivopoulos,[46] G. Tsipolitis,[46] I. Evangelou,[47] C. Foudas,[47]
P. Gianneios,[47] P. Katsoulis,[47] P. Kokkas,[47] S. Mallios,[47] N. Manthos,[47] I. Papadopoulos,[47] E. Paradas,[47] J. Strologas,[47]

F. A. Triantis,[47] D. Tsitsonis,[47] M. Bartók,[48,s] M. Csanad,[48] N. Filipovic,[48] P. Major,[48] M. I. Nagy,[48] G. Pasztor,[48] O. Surányi,[48] G. I. Veres,[48] G. Bencze,[49] C. Hajdu,[49] D. Horvath,[49,t] Á. Hunyadi,[49] F. Sikler,[49] T. Á. Vámi,[49] V. Veszpremi,[49] G. Vesztergombi,[49,u] N. Beni,[50] S. Czellar,[50] J. Karancsi,[50,v] A. Makovec,[50] J. Molnar,[50] Z. Szillasi,[50] P. Raics,[51] Z. L. Trocsanyi,[51] B. Ujvari,[51] S. Choudhury,[52] J. R. Komaragiri,[52] P. C. Tiwari,[52] S. Bahinipati,[53,w] C. Kar,[53] P. Mal,[53] K. Mandal,[53] A. Nayak,[53,x] D. K. Sahoo,[53,w] S. K. Swain,[53] S. Bansal,[54] S. B. Beri,[54] V. Bhatnagar,[54] S. Chauhan,[54] R. Chawla,[54] N. Dhingra,[54] R. Gupta,[54] A. Kaur,[54] A. Kaur,[54] M. Kaur,[54] S. Kaur,[54] R. Kumar,[54] P. Kumari,[54] M. Lohan,[54] A. Mehta,[54] K. Sandeep,[54] S. Sharma,[54] J. B. Singh,[54] G. Walia,[54] A. Bhardwaj,[55] B. C. Choudhary,[55] R. B. Garg,[55] M. Gola,[55] S. Keshri,[55] Ashok Kumar,[55] S. Malhotra,[55] M. Naimuddin,[55] P. Priyanka,[55] K. Ranjan,[55] Aashaq Shah,[55] R. Sharma,[55] R. Bhardwaj,[56,y] M. Bharti,[56] R. Bhattacharya,[56] S. Bhattacharya,[56] U. Bhawandeep,[56,y] D. Bhowmik,[56] S. Dey,[56] S. Dutt,[56,y] S. Dutta,[56] S. Ghosh,[56] K. Mondal,[56] S. Nandan,[56] A. Purohit,[56] P. K. Rout,[56] A. Roy,[56] S. Roy Chowdhury,[56] S. Sarkar,[56] M. Sharan,[56] B. Singh,[56] S. Thakur,[56,y] P. K. Behera,[57] R. Chudasama,[58] D. Dutta,[58] V. Jha,[58] V. Kumar,[58] P. K. Netrakanti,[58] L. M. Pant,[58] P. Shukla,[58] T. Aziz,[59] M. A. Bhat,[59] S. Dugad,[59] G. B. Mohanty,[59] N. Sur,[59] B. Sutar,[59] Ravindra Kumar Verma,[59] S. Banerjee,[60] S. Bhattacharya,[60] S. Chatterjee,[60] P. Das,[60] M. Guchait,[60] Sa. Jain,[60] S. Kumar,[60] M. Maity,[60,z] G. Majumder,[60] K. Mazumdar,[60] N. Sahoo,[60] T. Sarkar,[60,z] S. Chauhan,[61] S. Dube,[61] V. Hegde,[61] A. Kapoor,[61] K. Kothekar,[61] S. Pandey,[61] A. Rane,[61] S. Sharma,[61] S. Chenarani,[62,aa] E. Eskandari Tadavani,[62] S. M. Etesami,[62,aa] M. Khakzad,[62] M. Mohammadi Najafabadi,[62] M. Naseri,[62] F. Rezaei Hosseinabadi,[62] B. Safarzadeh,[62,ab] M. Zeinali,[62] M. Felcini,[63] M. Grunewald,[63] M. Abbrescia,[64a,64b] C. Calabria,[64a,64b] A. Colaleo,[64a] D. Creanza,[64a,64c] L. Cristella,[64a,64b] N. De Filippis,[64a,64c] M. De Palma,[64a,64b] A. Di Florio,[64a,64b] F. Errico,[64a,64b] L. Fiore,[64a] A. Gelmi,[64a,64b] G. Iaselli,[64a,64c] S. Lezki,[64a,64b] G. Maggi,[64a,64c] M. Maggi,[64a] G. Miniello,[64a,64b] S. My,[64a,64b] S. Nuzzo,[64a,64b] A. Pompili,[64a,64b] G. Pugliese,[64a,64c] R. Radogna,[64a] A. Ranieri,[64a] G. Selvaggi,[64a,64b] A. Sharma,[64a] L. Silvestris,[64a,o] R. Venditti,[64a] P. Verwilligen,[64a] G. Zito,[64a] G. Abbiendi,[65a] C. Battilana,[65a,65b] D. Bonacorsi,[65a,65b] L. Borgonovi,[65a,65b] S. Braibant-Giacomelli,[65a,65b] L. Brigliadori,[65a,65b] R. Campanini,[65a,65b] P. Capiluppi,[65a,65b] A. Castro,[65a,65b] F. R. Cavallo,[65a] S. S. Chhibra,[65a,65b] C. Ciocca,[65a] G. Codispoti,[65a,65b] M. Cuffiani,[65a,65b] G. M. Dallavalle,[65a] F. Fabbri,[65a] A. Fanfani,[65a,65b] P. Giacomelli,[65a] C. Grandi,[65a] L. Guiducci,[65a,65b] S. Marcellini,[65a] G. Masetti,[65a] A. Montanari,[65a] F. L. Navarria,[65a,65b] A. Perrotta,[65a] A. M. Rossi,[65a,65b] T. Rovelli,[65a,65b] G. P. Siroli,[65a,65b] N. Tosi,[65a] S. Albergo,[66a,66b] A. Di Mattia,[66a] R. Potenza,[66a,66b] A. Tricomi,[66a,66b] C. Tuve,[66a,66b] G. Barbagli,[67a] K. Chatterjee,[67a,67b] V. Ciulli,[67a,67b] C. Civinini,[67a] R. D'Alessandro,[67a,67b] E. Focardi,[67a,67b] G. Latino,[67a] P. Lenzi,[67a,67b] M. Meschini,[67a] S. Paoletti,[67a] L. Russo,[67a,ac] G. Sguazzoni,[67a] D. Strom,[67a] L. Viliani,[67a] L. Benussi,[68] S. Bianco,[68] F. Fabbri,[68] D. Piccolo,[68] F. Primavera,[68,o] F. Ferro,[69a] F. Ravera,[69a,69b] E. Robutti,[69a] S. Tosi,[69a,69b] A. Benaglia,[70a] A. Beschi,[70b] L. Brianza,[70a,70b] F. Brivio,[70a,70b] V. Ciriolo,[70a,70b,o] S. Di Guida,[70a,70b,o] M. E. Dinardo,[70a,70b] S. Fiorendi,[70a,70b] S. Gennai,[70a] A. Ghezzi,[70a,70b] P. Govoni,[70a,70b] M. Malberti,[70a,70b] S. Malvezzi,[70a] A. Massironi,[70a,70b] D. Menasce,[70a] L. Moroni,[70a] M. Paganoni,[70a,70b] D. Pedrini,[70a] S. Ragazzi,[70a,70b] T. Tabarelli de Fatis,[70a,70b] S. Buontempo,[71a] N. Cavallo,[71a,71c] A. Di Crescenzo,[71a,71b] F. Fabozzi,[71a,71c] F. Fienga,[71a] G. Galati,[71a] A. O. M. Iorio,[71a,71b] W. A. Khan,[71a] L. Lista,[71a] S. Meola,[71a,71d,o] P. Paolucci,[71a,o] C. Sciacca,[71a,71b] E. Voevodina,[71a,71b] P. Azzi,[72a] N. Bacchetta,[72a] D. Bisello,[72a,72b] A. Boletti,[72a,72b] A. Bragagnolo,[72c] R. Carlin,[72a,72b] P. Checchia,[72a] M. Dall'Osso,[72a,72b] P. De Castro Manzano,[72a] T. Dorigo,[72a] U. Dosselli,[72a] F. Gasparini,[72a,72b] U. Gasparini,[72a,72b] A. Gozzelino,[72a] S. Lacaprara,[72a] P. Lujan,[72a] M. Margoni,[72a,72b] A. T. Meneguzzo,[72a,72b] P. Ronchese,[72a,72b] R. Rossin,[72a,72b] F. Simonetto,[72a,72b] A. Tiko,[72a] E. Torassa,[72a] M. Zanetti,[72a,72b] P. Zotto,[72a,72b] G. Zumerle,[72a,72b] A. Braghieri,[73a] A. Magnani,[73a] P. Montagna,[73a,73b] S. P. Ratti,[73a,73b] V. Re,[73a] M. Ressegotti,[73a,73b] C. Riccardi,[73a,73b] P. Salvini,[73a] I. Vai,[73a,73b] P. Vitulo,[73a,73b] L. Alunni Solestizi,[74a,74b] M. Biasini,[74a,74b] G. M. Bilei,[74a] C. Cecchi,[74a,74b] D. Ciangottini,[74a,74b] L. Fanò,[74a,74b] P. Lariccia,[74a,74b] E. Manoni,[74a] G. Mantovani,[74a,74b] V. Mariani,[74a,74b] M. Menichelli,[74a] A. Rossi,[74a,74b] A. Santocchia,[74a,74b] D. Spiga,[74a] K. Androsov,[75a] P. Azzurri,[75a] G. Bagliesi,[75a] L. Bianchini,[75a] T. Boccali,[75a] L. Borrello,[75a] R. Castaldi,[75a] M. A. Ciocci,[75a,75b] R. Dell'Orso,[75a] G. Fedi,[75a] L. Giannini,[75a,75c] A. Giassi,[75a] M. T. Grippo,[75a] F. Ligabue,[75a,75c] E. Manca,[75a,75c] G. Mandorli,[75a,75c] A. Messineo,[75a,75b] F. Palla,[75a] A. Rizzi,[75a,75b] P. Spagnolo,[75a] R. Tenchini,[75a] G. Tonelli,[75a,75b] A. Venturi,[75a] P. G. Verdini,[75a] L. Barone,[76a,76b] F. Cavallari,[76a] M. Cipriani,[76a,76b] N. Daci,[76a] D. Del Re,[76a,76b] E. Di Marco,[76a,76b] M. Diemoz,[76a] S. Gelli,[76a,76b] E. Longo,[76a,76b] B. Marzocchi,[76a,76b] P. Meridiani,[76a] G. Organtini,[76a,76b] F. Pandolfi,[76a] R. Paramatti,[76a,76b] F. Preiato,[76a,76b] S. Rahatlou,[76a,76b] C. Rovelli,[76a] F. Santanastasio,[76a,76b] N. Amapane,[77a,77b] R. Arcidiacono,[77a,77c] S. Argiro,[77a,77b] M. Arneodo,[77a,77c] N. Bartosik,[77a] R. Bellan,[77a,77b] C. Biino,[77a] N. Cartiglia,[77a] F. Cenna,[77a,77b] S. Cometti,[77a] M. Costa,[77a,77b] R. Covarelli,[77a,77b] N. Demaria,[77a] B. Kiani,[77a,77b] C. Mariotti,[77a] S. Maselli,[77a] E. Migliore,[77a,77b] V. Monaco,[77a,77b] E. Monteil,[77a,77b] M. Monteno,[77a] M. M. Obertino,[77a,77b] L. Pacher,[77a,77b] N. Pastrone,[77a] M. Pelliccioni,[77a] G. L. Pinna Angioni,[77a,77b] A. Romero,[77a,77b] M. Ruspa,[77a,77c] R. Sacchi,[77a,77b] K. Shchelina,[77a,77b] V. Sola,[77a] A. Solano,[77a,77b] D. Soldi,[77a] A. Staiano,[77a] S. Belforte,[78a] V. Candelise,[78a,78b] M. Casarsa,[78a] F. Cossutti,[78a] G. Della Ricca,[78a,78b] F. Vazzoler,[78a,78b] A. Zanetti,[78a] D. H. Kim,[79] G. N. Kim,[79] M. S. Kim,[79] J. Lee,[79] S. Lee,[79] S. W. Lee,[79] C. S. Moon,[79] Y. D. Oh,[79] S. Sekmen,[79] D. C. Son,[79] Y. C. Yang,[79] H. Kim,[80] D. H. Moon,[80] G. Oh,[80] J. Goh,[81] T. J. Kim,[81] S. Cho,[82] S. Choi,[82] Y. Go,[82] D. Gyun,[82] S. Ha,[82] B. Hong,[82] Y. Jo,[82] K. Lee,[82] K. S. Lee,[82] S. Lee,[82] J. Lim,[82] S. K. Park,[82] Y. Roh,[82] H. S. Kim,[83] J. Almond,[84] J. Kim,[84] J. S. Kim,[84] H. Lee,[84] K. Lee,[84] K. Nam,[84] S. B. Oh,[84] B. C. Radburn-Smith,[84] S. h. Seo,[84] U. K. Yang,[84] H. D. Yoo,[84] G. B. Yu,[84] D. Jeon,[85] H. Kim,[85] J. H. Kim,[85] J. S. H. Lee,[85] I. C. Park,[85] Y. Choi,[86] C. Hwang,[86] J. Lee,[86] I. Yu,[86] V. Dudenas,[87] A. Juodagalvis,[87] J. Vaitkus,[87] I. Ahmed,[88] Z. A. Ibrahim,[88] M. A. B. Md Ali,[88,ad] F. Mohamad Idris,[88,ae] W. A. T. Wan Abdullah,[88] M. N. Yusli,[88] Z. Zolkapli,[88] H. Castilla-Valdez,[89]

E. De La Cruz-Burelo,[89] M. C. Duran-Osuna,[89] I. Heredia-De La Cruz,[89,af] R. Lopez-Fernandez,[89] J. Mejia Guisao,[89]
R. I. Rabadan-Trejo,[89] G. Ramirez-Sanchez,[89] R Reyes-Almanza,[89] A. Sanchez-Hernandez,[89] S. Carrillo Moreno,[90]
C. Oropeza Barrera,[90] F. Vazquez Valencia,[90] J. Eysermans,[91] I. Pedraza,[91] H. A. Salazar Ibarguen,[91] C. Uribe Estrada,[91]
A. Morelos Pineda,[92] D. Krofcheck,[93] S. Bheesette,[94] P. H. Butler,[94] A. Ahmad,[95] M. Ahmad,[95] M. I. Asghar,[95] Q. Hassan,[95]
H. R. Hoorani,[95] A. Saddique,[95] M. A. Shah,[95] M. Shoaib,[95] M. Waqas,[95] H. Bialkowska,[96] M. Bluj,[96] B. Boimska,[96]
T. Frueboes,[96] M. Górski,[96] M. Kazana,[96] K. Nawrocki,[96] M. Szleper,[96] P. Traczyk,[96] P. Zalewski,[96] K. Bunkowski,[97]
A. Byszuk,[97,ag] K. Doroba,[97] A. Kalinowski,[97] M. Konecki,[97] J. Krolikowski,[97] M. Misiura,[97] M. Olszewski,[97] A. Pyskir,[97]
M. Walczak,[97] P. Bargassa,[98] C. Beirão Da Cruz E Silva,[98] A. Di Francesco,[98] P. Faccioli,[98] B. Galinhas,[98] M. Gallinaro,[98]
J. Hollar,[98] N. Leonardo,[98] L. Lloret Iglesias,[98] M. V. Nemallapudi,[98] J. Seixas,[98] G. Strong,[98] O. Toldaiev,[98] D. Vadruccio,[98]
J. Varela,[98] A. Baginyan,[99] A. Golunov,[99] I. Golutvin,[99] V. Karjavin,[99] I. Kashunin,[99] V. Korenkov,[99] A. Lanev,[99]
A. Malakhov,[99] V. Matveev,[99,ah,ai] V. V. Mitsyn,[99] P. Moisenz,[99] V. Palichik,[99] V. Perelygin,[99] S. Shmatov,[99] N. Skatchkov,[99]
V. Smirnov,[99] V. Trofimov,[99] B. S. Yuldashev,[99,aj] A. Zarubin,[99] V. Golovtsov,[100] Y. Ivanov,[100] V. Kim,[100,ak]
E. Kuznetsova,[100,al] P. Levchenko,[100] V. Murzin,[100] V. Oreshkin,[100] I. Smirnov,[100] D. Sosnov,[100] V. Sulimov,[100] L. Uvarov,[100]
S. Vavilov,[100] A. Vorobyev,[100] Yu. Andreev,[101] A. Dermenev,[101] S. Gninenko,[101] N. Golubev,[101] A. Karneyeu,[101]
M. Kirsanov,[101] N. Krasnikov,[101] A. Pashenkov,[101] D. Tlisov,[101] A. Toropin,[101] V. Epshteyn,[102] V. Gavrilov,[102]
N. Lychkovskaya,[102] V. Popov,[102] I. Pozdnyakov,[102] G. Safronov,[102] A. Spiridonov,[102] A. Stepennov,[102] V. Stolin,[102]
M. Toms,[102] E. Vlasov,[102] A. Zhokin,[102] T. Aushev,[103] A. Bylinkin,[103] V. Andreev,[104] M. Azarkin,[104,ai] I. Dremin,[104,ai]
M. Kirakosyan,[104,ai] S. V. Rusakov,[104] A. Terkulov,[104] A. Baskakov,[105] A. Belyaev,[105] E. Boos,[105] A. Ershov,[105]
A. Gribushin,[105] L. Khein,[105] O. Kodolova,[105] V. Korotkikh,[105] I. Lokhtin,[105] O. Lukina,[105] I. Miagkov,[105] S. Obraztsov,[105]
S. Petrushanko,[105] V. Savrin,[105] A. Snigirev,[105] I. Vardanyan,[105] V. Blinov,[106,am] T. Dimova,[106,am] L. Kardapoltsev,[106,am]
D. Shtol,[106,am] Y. Skovpen,[106,am] I. Azhgirey,[107] I. Bayshev,[107] S. Bitioukov,[107] D. Elumakhov,[107] A. Godizov,[107]
V. Kachanov,[107] A. Kalinin,[107] D. Konstantinov,[107] P. Mandrik,[107] V. Petrov,[107] R. Ryutin,[107] S. Slabospitskii,[107] A. Sobol,[107]
S. Troshin,[107] N. Tyurin,[107] A. Uzunian,[107] A. Volkov,[107] A. Babaev,[108] S. Baidali,[108] P. Adzic,[109,an] P. Cirkovic,[109]
D. Devetak,[109] M. Dordevic,[109] J. Milosevic,[109] J. Alcaraz Maestre,[110] A. Álvarez Fernández,[110] I. Bachiller,[110]
M. Barrio Luna,[110] J. A. Brochero Cifuentes,[110] M. Cerrada,[110] N. Colino,[110] B. De La Cruz,[110] A. Delgado Peris,[110]
C. Fernandez Bedoya,[110] J. P. Fernández Ramos,[110] J. Flix,[110] M. C. Fouz,[110] O. Gonzalez Lopez,[110] S. Goy Lopez,[110]
J. M. Hernandez,[110] M. I. Josa,[110] D. Moran,[110] A. Pérez-Calero Yzquierdo,[110] J. Puerta Pelayo,[110] I. Redondo,[110]
L. Romero,[110] M. S. Soares,[110] A. Triossi,[110] C. Albajar,[111] J. F. de Trocóniz,[111] J. Cuevas,[112] C. Erice,[112]
J. Fernandez Menendez,[112] S. Folgueras,[112] I. Gonzalez Caballero,[112] J. R. González Fernández,[112] E. Palencia Cortezon,[112]
V. Rodríguez Bouza,[112] S. Sanchez Cruz,[112] P. Vischia,[112] J. M. Vizan Garcia,[112] I. J. Cabrillo,[113] A. Calderon,[113]
B. Chazin Quero,[113] J. Duarte Campderros,[113] M. Fernandez,[113] P. J. Fernández Manteca,[113] A. García Alonso,[113]
J. Garcia-Ferrero,[113] G. Gomez,[113] A. Lopez Virto,[113] J. Marco,[113] C. Martinez Rivero,[113] P. Martinez Ruiz del Arbol,[113]
F. Matorras,[113] J. Piedra Gomez,[113] C. Prieels,[113] T. Rodrigo,[113] A. Ruiz-Jimeno,[113] L. Scodellaro,[113] N. Trevisani,[113] I. Vila,[113]
R. Vilar Cortabitarte,[113] D. Abbaneo,[114] B. Akgun,[114] E. Auffray,[114] P. Baillon,[114] A. H. Ball,[114] D. Barney,[114] J. Bendavid,[114]
M. Bianco,[114] A. Bocci,[114] C. Botta,[114] T. Camporesi,[114] M. Cepeda,[114] G. Cerminara,[114] E. Chapon,[114] Y. Chen,[114]
G. Cucciati,[114] D. d'Enterria,[114] A. Dabrowski,[114] V. Daponte,[114] A. David,[114] A. De Roeck,[114] N. Deelen,[114] M. Dobson,[114]
T. du Pree,[114] M. Dünser,[114] N. Dupont,[114] A. Elliott-Peisert,[114] P. Everaerts,[114] F. Fallavollita,[114,ao] D. Fasanella,[114]
G. Franzoni,[114] J. Fulcher,[114] W. Funk,[114] D. Gigi,[114] A. Gilbert,[114] K. Gill,[114] F. Glege,[114] D. Gulhan,[114] J. Hegeman,[114]
V. Innocente,[114] A. Jafari,[114] P. Janot,[114] O. Karacheban,[114,r] J. Kieseler,[114] A. Kornmayer,[114] M. Krammer,[114,a] C. Lange,[114]
P. Lecoq,[114] C. Lourenço,[114] L. Malgeri,[114] M. Mannelli,[114] F. Meijers,[114] J. A. Merlin,[114] S. Mersi,[114] E. Meschi,[114]
P. Milenovic,[114,ap] F. Moortgat,[114] M. Mulders,[114] J. Ngadiuba,[114] S. Orfanelli,[114] L. Orsini,[114] F. Pantaleo,[114,o] L. Pape,[114]
E. Perez,[114] M. Peruzzi,[114] A. Petrilli,[114] G. Petrucciani,[114] A. Pfeiffer,[114] M. Pierini,[114] F. M. Pitters,[114] D. Rabady,[114]
A. Racz,[114] T. Reis,[114] G. Rolandi,[114,aq] M. Rovere,[114] H. Sakulin,[114] C. Schäfer,[114] C. Schwick,[114] M. Seidel,[114]
M. Selvaggi,[114] A. Sharma,[114] P. Silva,[114] P. Sphicas,[114,ar] A. Stakia,[114] J. Steggemann,[114] M. Tosi,[114] D. Treille,[114]
A. Tsirou,[114] V. Veckalns,[114,as] W. D. Zeuner,[114] L. Caminada,[115,at] K. Deiters,[115] W. Erdmann,[115] R. Horisberger,[115]
Q. Ingram,[115] H. C. Kaestli,[115] D. Kotlinski,[115] U. Langenegger,[115] T. Rohe,[115] S. A. Wiederkehr,[115] M. Backhaus,[116]
L. Bäni,[116] P. Berger,[116] N. Chernyavskaya,[116] G. Dissertori,[116] M. Dittmar,[116] M. Donegà,[116] C. Dorfer,[116] C. Grab,[116]
C. Heidegger,[116] D. Hits,[116] J. Hoss,[116] T. Klijnsma,[116] W. Lustermann,[116] R. A. Manzoni,[116] M. Marionneau,[116]
M. T. Meinhard,[116] F. Micheli,[116] P. Musella,[116] F. Nessi-Tedaldi,[116] J. Pata,[116] F. Pauss,[116] G. Perrin,[116] L. Perrozzi,[116]
S. Pigazzini,[116] M. Quittnat,[116] D. Ruini,[116] D. A. Sanz Becerra,[116] M. Schönenberger,[116] L. Shchutska,[116] V. R. Tavolaro,[116]
K. Theofilatos,[116] M. L. Vesterbacka Olsson,[116] R. Wallny,[116] D. H. Zhu,[116] T. K. Aarrestad,[117] C. Amsler,[117,au]
D. Brzhechko,[117] M. F. Canelli,[117] A. De Cosa,[117] R. Del Burgo,[117] S. Donato,[117] C. Galloni,[117] T. Hreus,[117] B. Kilminster,[117]
I. Neutelings,[117] D. Pinna,[117] G. Rauco,[117] P. Robmann,[117] D. Salerno,[117] K. Schweiger,[117] C. Seitz,[117] Y. Takahashi,[117]
A. Zucchetta,[117] Y. H. Chang,[118] K. y. Cheng,[118] T. H. Doan,[118] Sh. Jain,[118] R. Khurana,[118] C. M. Kuo,[118] W. Lin,[118]
A. Pozdnyakov,[118] S. S. Yu,[118] P. Chang,[119] Y. Chao,[119] K. F. Chen,[119] P. H. Chen,[119] W.-S. Hou,[119] Arun Kumar,[119] Y. y. Li,[119]
R.-S. Lu,[119] E. Paganis,[119] A. Psallidas,[119] A. Steen,[119] J. f. Tsai,[119] B. Asavapibhop,[120] N. Srimanobhas,[120]
N. Suwonjandee,[120] M. N. Bakirci,[121,av] A. Bat,[121] F. Boran,[121] S. Cerci,[121,aw] S. Damarseckin,[121] Z. S. Demiroglu,[121]
F. Dolek,[121] C. Dozen,[121] I. Dumanoglu,[121] E. Eskut,[121] S. Girgis,[121] G. Gokbulut,[121] Y. Guler,[121] E. Gurpinar,[121] I. Hos,[121,ax]

C. Isik,[121] E. E. Kangal,[121,ay] O. Kara,[121] U. Kiminsu,[121] M. Oglakci,[121] G. Onengut,[121] K. Ozdemir,[121,az] A. Polatoz,[121] D. Sunar Cerci,[121,aw] U. G. Tok,[121] S. Turkcapar,[121] I. S. Zorbakir,[121] C. Zorbilmez,[121] B. Isildak,[122,ba] G. Karapinar,[122,bb] M. Yalvac,[122] M. Zeyrek,[122] I. O. Atakisi,[123] E. Gülmez,[123] M. Kaya,[123,bc] O. Kaya,[123,bd] S. Ozkorucuklu,[123,be] S. Tekten,[123] E. A. Yetkin,[123,bf] M. N. Agaras,[124] S. Atay,[124] A. Cakir,[124] K. Cankocak,[124] Y. Komurcu,[124] S. Sen,[124,bg] B. Grynyov,[125] L. Levchuk,[126] F. Ball,[127] L. Beck,[127] J. J. Brooke,[127] D. Burns,[127] E. Clement,[127] D. Cussans,[127] O. Davignon,[127] H. Flacher,[127] J. Goldstein,[127] G. P. Heath,[127] H. F. Heath,[127] L. Kreczko,[127] D. M. Newbold,[127,bh] S. Paramesvaran,[127] B. Penning,[127] T. Sakuma,[127] D. Smith,[127] V. J. Smith,[127] J. Taylor,[127] A. Titterton,[127] A. Belyaev,[128,bi] C. Brew,[128] R. M. Brown,[128] D. Cieri,[128] D. J. A. Cockerill,[128] J. A. Coughlan,[128] K. Harder,[128] S. Harper,[128] J. Linacre,[128] E. Olaiya,[128] D. Petyt,[128] C. H. Shepherd-Themistocleous,[128] A. Thea,[128] I. R. Tomalin,[128] T. Williams,[128] W. J. Womersley,[128] G. Auzinger,[129] R. Bainbridge,[129] P. Bloch,[129] J. Borg,[129] S. Breeze,[129] O. Buchmuller,[129] A. Bundock,[129] S. Casasso,[129] D. Colling,[129] L. Corpe,[129] P. Dauncey,[129] G. Davies,[129] M. Della Negra,[129] R. Di Maria,[129] Y. Haddad,[129] G. Hall,[129] G. Iles,[129] T. James,[129] M. Komm,[129] C. Laner,[129] L. Lyons,[129] A.-M. Magnan,[129] S. Malik,[129] A. Martelli,[129] J. Nash,[129,bj] A. Nikitenko,[129,f] V. Palladino,[129] M. Pesaresi,[129] A. Richards,[129] A. Rose,[129] E. Scott,[129] C. Seez,[129] A. Shtipliyski,[129] G. Singh,[129] M. Stoye,[129] T. Strebler,[129] S. Summers,[129] A. Tapper,[129] K. Uchida,[129] T. Virdee,[129,o] N. Wardle,[129] D. Winterbottom,[129] J. Wright,[129] S. C. Zenz,[129] J. E. Cole,[130] P. R. Hobson,[130] A. Khan,[130] P. Kyberd,[130] C. K. Mackay,[130] A. Morton,[130] I. D. Reid,[130] L. Teodorescu,[130] S. Zahid,[130] K. Call,[131] J. Dittmann,[131] K. Hatakeyama,[131] H. Liu,[131] C. Madrid,[131] B. Mcmaster,[131] N. Pastika,[131] C. Smith,[131] R. Bartek,[132] A. Dominguez,[132] A. Buccilli,[133] S. I. Cooper,[133] C. Henderson,[133] P. Rumerio,[133] C. West,[133] D. Arcaro,[134] T. Bose,[134] D. Gastler,[134] D. Rankin,[134] C. Richardson,[134] J. Rohlf,[134] L. Sulak,[134] D. Zou,[134] G. Benelli,[135] X. Coubez,[135] D. Cutts,[135] M. Hadley,[135] J. Hakala,[135] U. Heintz,[135] J. M. Hogan,[135,bk] K. H. M. Kwok,[135] E. Laird,[135] G. Landsberg,[135] J. Lee,[135] Z. Mao,[135] M. Narain,[135] J. Pazzini,[135] S. Piperov,[135] S. Sagir,[135,bl] R. Syarif,[135] E. Usai,[135] D. Yu,[135] R. Band,[136] C. Brainerd,[136] R. Breedon,[136] D. Burns,[136] M. Calderon De La Barca Sanchez,[136] M. Chertok,[136] J. Conway,[136] R. Conway,[136] P. T. Cox,[136] R. Erbacher,[136] C. Flores,[136] G. Funk,[136] W. Ko,[136] O. Kukral,[136] R. Lander,[136] C. Mclean,[136] M. Mulhearn,[136] D. Pellett,[136] J. Pilot,[136] S. Shalhout,[136] M. Shi,[136] D. Stolp,[136] D. Taylor,[136] K. Tos,[136] M. Tripathi,[136] Z. Wang,[136] F. Zhang,[136] M. Bachtis,[137] C. Bravo,[137] R. Cousins,[137] A. Dasgupta,[137] A. Florent,[137] J. Hauser,[137] M. Ignatenko,[137] N. Mccoll,[137] S. Regnard,[137] D. Saltzberg,[137] C. Schnaible,[137] V. Valuev,[137] E. Bouvier,[138] K. Burt,[138] R. Clare,[138] J. W. Gary,[138] S. M. A. Ghiasi Shirazi,[138] G. Hanson,[138] G. Karapostoli,[138] E. Kennedy,[138] F. Lacroix,[138] O. R. Long,[138] M. Olmedo Negrete,[138] M. I. Paneva,[138] W. Si,[138] L. Wang,[138] H. Wei,[138] S. Wimpenny,[138] B. R. Yates,[138] J. G. Branson,[139] S. Cittolin,[139] M. Derdzinski,[139] R. Gerosa,[139] D. Gilbert,[139] B. Hashemi,[139] A. Holzner,[139] D. Klein,[139] G. Kole,[139] V. Krutelyov,[139] J. Letts,[139] M. Masciovecchio,[139] D. Olivito,[139] S. Padhi,[139] M. Pieri,[139] M. Sani,[139] V. Sharma,[139] S. Simon,[139] M. Tadel,[139] A. Vartak,[139] S. Wasserbaech,[139,bm] J. Wood,[139] F. Würthwein,[139] A. Yagil,[139] G. Zevi Della Porta,[139] N. Amin,[140] R. Bhandari,[140] J. Bradmiller-Feld,[140] C. Campagnari,[140] M. Citron,[140] A. Dishaw,[140] V. Dutta,[140] M. Franco Sevilla,[140] L. Gouskos,[140] R. Heller,[140] J. Incandela,[140] A. Ovcharova,[140] H. Qu,[140] J. Richman,[140] D. Stuart,[140] I. Suarez,[140] S. Wang,[140] J. Yoo,[140] D. Anderson,[141] A. Bornheim,[141] J. M. Lawhorn,[141] H. B. Newman,[141] T. Q. Nguyen,[141] M. Spiropulu,[141] J. R. Vlimant,[141] R. Wilkinson,[141] S. Xie,[141] Z. Zhang,[141] R. Y. Zhu,[141] M. B. Andrews,[142] T. Ferguson,[142] T. Mudholkar,[142] M. Paulini,[142] M. Sun,[142] I. Vorobiev,[142] M. Weinberg,[142] J. P. Cumalat,[143] W. T. Ford,[143] F. Jensen,[143] A. Johnson,[143] M. Krohn,[143] S. Leontsinis,[143] E. MacDonald,[143] T. Mulholland,[143] K. Stenson,[143] K. A. Ulmer,[143] S. R. Wagner,[143] J. Alexander,[144] J. Chaves,[144] Y. Cheng,[144] J. Chu,[144] A. Datta,[144] K. Mcdermott,[144] N. Mirman,[144] J. R. Patterson,[144] D. Quach,[144] A. Rinkevicius,[144] A. Ryd,[144] L. Skinnari,[144] L. Soffi,[144] S. M. Tan,[144] Z. Tao,[144] J. Thom,[144] J. Tucker,[144] P. Wittich,[144] M. Zientek,[144] S. Abdullin,[145] M. Albrow,[145] M. Alyari,[145] G. Apollinari,[145] A. Apresyan,[145] A. Apyan,[145] S. Banerjee,[145] L. A. T. Bauerdick,[145] A. Beretvas,[145] J. Berryhill,[145] P. C. Bhat,[145] G. Bolla,[145,u] K. Burkett,[145] J. N. Butler,[145] A. Canepa,[145] G. B. Cerati,[145] H. W. K. Cheung,[145] F. Chlebana,[145] M. Cremonesi,[145] J. Duarte,[145] V. D. Elvira,[145] J. Freeman,[145] Z. Gecse,[145] E. Gottschalk,[145] L. Gray,[145] D. Green,[145] S. Grünendahl,[145] O. Gutsche,[145] J. Hanlon,[145] R. M. Harris,[145] S. Hasegawa,[145] J. Hirschauer,[145] Z. Hu,[145] B. Jayatilaka,[145] S. Jindariani,[145] M. Johnson,[145] U. Joshi,[145] B. Klima,[145] M. J. Kortelainen,[145] B. Kreis,[145] S. Lammel,[145] D. Lincoln,[145] R. Lipton,[145] M. Liu,[145] T. Liu,[145] J. Lykken,[145] K. Maeshima,[145] J. M. Marraffino,[145] D. Mason,[145] P. McBride,[145] P. Merkel,[145] S. Mrenna,[145] S. Nahn,[145] V. O'Dell,[145] K. Pedro,[145] C. Pena,[145] O. Prokofyev,[145] G. Rakness,[145] L. Ristori,[145] A. Savoy-Navarro,[145,bn] B. Schneider,[145] E. Sexton-Kennedy,[145] A. Soha,[145] W. J. Spalding,[145] L. Spiegel,[145] S. Stoynev,[145] J. Strait,[145] N. Strobbe,[145] L. Taylor,[145] S. Tkaczyk,[145] N. V. Tran,[145] L. Uplegger,[145] E. W. Vaandering,[145] C. Vernieri,[145] M. Verzocchi,[145] R. Vidal,[145] M. Wang,[145] H. A. Weber,[145] A. Whitbeck,[145] D. Acosta,[146] P. Avery,[146] P. Bortignon,[146] D. Bourilkov,[146] A. Brinkerhoff,[146] L. Cadamuro,[146] A. Carnes,[146] M. Carver,[146] D. Curry,[146] R. D. Field,[146] S. V. Gleyzer,[146] B. M. Joshi,[146] J. Konigsberg,[146] A. Korytov,[146] P. Ma,[146] K. Matchev,[146] H. Mei,[146] G. Mitselmakher,[146] K. Shi,[146] D. Sperka,[146] J. Wang,[146] S. Wang,[146] Y. R. Joshi,[147] S. Linn,[147] A. Ackert,[148] T. Adams,[148] A. Askew,[148] S. Hagopian,[148] V. Hagopian,[148] K. F. Johnson,[148] T. Kolberg,[148] G. Martinez,[148] T. Perry,[148] H. Prosper,[148] A. Saha,[148] A. Santra,[148] V. Sharma,[148] R. Yohay,[148] M. M. Baarmand,[149] V. Bhopatkar,[149] S. Colafranceschi,[149] M. Hohlmann,[149] D. Noonan,[149] M. Rahmani,[149] T. Roy,[149] F. Yumiceva,[149] M. R. Adams,[150] L. Apanasevich,[150] D. Berry,[150] R. R. Betts,[150] R. Cavanaugh,[150] X. Chen,[150] S. Dittmer,[150] O. Evdokimov,[150] C. E. Gerber,[150] D. A. Hangal,[150] D. J. Hofman,[150] K. Jung,[150] J. Kamin,[150] C. Mills,[150] I. D. Sandoval Gonzalez,[150] M. B. Tonjes,[150] N. Varelas,[150] H. Wang,[150] X. Wang,[150] Z. Wu,[150] J. Zhang,[150] M. Alhusseini,[151] B. Bilki,[151,bo] W. Clarida,[151] K. Dilsiz,[151,bp] S. Durgut,[151] R. 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