

# Particle transformers for identifying Lorentz-boosted Higgs bosons decaying to a pair of W bosons

The CMS Collaboration\*

## Abstract

A novel deep neural network classifier, a “particle transformer” (PART), is introduced for the identification of highly Lorentz-boosted resonances reconstructed as single, multipronged jets in measurements and searches performed by the CMS Collaboration at the CERN LHC. Based on a self-attention mechanism that allows the model to weigh the importance of different particles, PART is trained on a wide variety of topologies, notably demonstrating strong performance for the first time on jets originating from boosted Higgs boson decays to W bosons. The PART algorithm achieves a tagging efficiency of more than 50% for such jets at a background efficiency of 1%, while maintaining decorrelation from the jet mass. A calibration is performed in proton-proton collision data collected by CMS at a center-of-mass energy of 13 TeV, with a data set corresponding to a total luminosity of  $138 \text{ fb}^{-1}$ . Data-to-simulation selection efficiency scale factors are measured to be in the 0.9–1.0 range, with relative uncertainties between 7 and 23%. The tagging capability of PART enhances the sensitivity of standard model measurements and searches for beyond-the-standard-model resonances decaying to hadronic diboson systems.

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# 1 Introduction

Since discovering the Higgs boson (H) [1–3], the CMS and ATLAS Collaborations at CERN have been focused on precisely measuring its properties and interactions. Identifying its hadronic final states is an important avenue for doing so, as well as for searching for new physics processes. Traditionally, however, they have been considered challenging at a hadron collider because of the large background from standard model (SM) events composed uniquely of jets produced through the strong interaction, referred to as quantum chromodynamics (QCD) multi-jet events, as well as resonant processes such as top quark pair ( $t\bar{t}$ ) production.

Over the past few years, the advent of progressively more advanced deep-learning (DL) techniques for jet identification, combined with the exploration of the highly Lorentz-boosted regime, has allowed the CMS experiment to steadily address this challenge. By exploiting the detailed features of jets, including particle content, kinematic properties, and the presence and character of secondary vertices, algorithms, such as DEEPAK8 [4], DEEPDOUBLEX [5], interaction networks [6, 7], and PARTICLENET [8–10], which collectively use convolutional, recurrent, and graph neural networks (GNNs), have significantly improved our performance in tagging jets originating from decays of boosted resonances. At a typical working point with a signal efficiency of about 50%, these advanced algorithms have improved background rejection by nearly an order of magnitude compared with simpler algorithms based on high-level jet features. They have been successfully employed to set some of the most stringent constraints on SM H to bottom quark ( $H \rightarrow b\bar{b}$ ) decays in the gluon fusion (ggF) and vector boson fusion (VBF) production modes [11], the charm Yukawa coupling [12], H pair (HH) production, and the quartic coupling of two Higgs bosons and two weak (V) vector bosons HHVV [13], as well as many beyond the SM (BSM) theories [14–18].

These previous DL models have primarily focused on identifying *two-pronged* [19] large-radius jets, originating from the hadronization of two b or two c quarks produced in  $H \rightarrow b\bar{b}$  and  $H \rightarrow c\bar{c}$  decays. In this paper, we introduce a new model based on the particle transformer (PART) architecture [20], and generalize it to identify large-radius jets with three or more prongs as well. These include the hadronic decay of  $t \rightarrow Wb \rightarrow qqb$ , and of the H to a W boson pair and then to four quarks,  $H \rightarrow WW^* \rightarrow 4q$ . The latter, in particular, has seldom been explored at the LHC and only in the context of BSM searches [21]. This presents an opportunity to significantly constrain SM parameters, such as the quartic coupling between the Higgs and V boson, HHVV. It may also facilitate searches for a variety of new physics signatures, such as heavy Higgs bosons and two-Higgs-doublet models [22–24], where a large fraction of the signal exhibits a signature of a boosted W boson pair decaying hadronically, as well as BSM resonances decaying to boosted multiple vector boson systems [25–28].

Significant challenges to  $H \rightarrow WW^*$  tagging include the asymmetric kinematic properties of the intermediate vector bosons and the lack of a similar and abundant SM proxy for its calibration. We address these with a novel data generation and training scheme, and the use of a new calibration technique based on the primary Lund jet plane (LJP) [29, 30]. The calibration is performed in data collected in 2016–2018 with the CMS detector at the LHC in proton-proton (pp) collisions at a center-of-mass energy of 13 TeV, with a data set corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ . Finally, we discuss an application of these techniques to the first search for SM HH production in the all-hadronic  $b\bar{b}WW$  decay mode [31].

The rest of this paper is organized as follows. Section 2 describes the CMS detector, Section 3 explains the relevant event reconstruction algorithms, and Section 4 details the event simulations used in this work. Section 5 then introduces the PART model architecture, input features, and training, and Section 6 presents its performance and calibration for  $H \rightarrow WW^* \rightarrow 4q$  tag-

ging compared with a previous state-of-the-art algorithm. Section 7 discusses its impact on the all-hadronic  $HH \rightarrow b\bar{b}WW$  search. Finally, a summary is presented in Section 8.

## 2 The CMS detector

The CMS apparatus [32, 33] is a multipurpose, nearly hermetic detector, designed to trigger on [34–36] and identify electrons, muons, photons, and (charged and neutral) hadrons [37–39]. Its central feature 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. Forward calorimeters extend the pseudorapidity ( $\eta$ ) coverage provided by the barrel and endcap detectors. Muons are reconstructed using gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [32, 33].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4  $\mu$ s [34]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to a few kHz before data storage [35].

The silicon tracker used in 2016 measured charged particles within the range  $|\eta| < 2.5$ . For nonisolated particles of  $1 < p_T < 10$  GeV and  $|\eta| < 1.4$ , the track resolutions were typically 1.5% in  $p_T$  and 25–90 (45–150)  $\mu$ m in the transverse (longitudinal) impact parameter [39]. At the start of 2017, a new pixel detector was installed [40]; the upgraded tracker measured particles up to  $|\eta| = 3.0$  with typical resolutions of 1.5% in  $p_T$  and 20–75  $\mu$ m in the transverse impact parameter [41] for nonisolated particles of  $1 < p_T < 10$  GeV. According to simulation studies [42], similar improvement is expected in the longitudinal direction.

## 3 Event reconstruction

A particle-flow (PF) algorithm [43] aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. In this process, particles are identified exclusively as charged or neutral hadrons, photons, electrons, or muons, and are collectively referred to as PF candidates. The energy of photons is obtained from the ECAL measurement. 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 spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [44]. Secondary vertices (SVs), such as those found in b hadron decays, are reconstructed using the inclusive vertex finder algorithm, which identifies tracks with large impact parameters [45].

For each event, hadronic jets are clustered from these reconstructed particles using the infrared- and collinear-safe anti- $k_T$  algorithm [46, 47] with a distance parameter of 0.4 (AK4 jets) or 0.8 (AK8 jets). Jet momentum is determined as the vector sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the true momentum over the whole  $p_T$  spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions to the jet momentum. The charged-hadron subtraction [48] and pileup-per-particle identification (PUPPI) [49, 50] algorithms are used to mitigate the effect of pileup on AK4 and AK8 jets, respectively. In the PUPPI algorithm, charged particles identified as originating from pileup vertices are removed, while each neutral particle is assigned a probability weight indicating its likelihood of originating from the primary vertex. The AK8 jets are then clustered using the output PF candidate list, where the four-momenta of each particle are reweighted accordingly. For both jet types, jet energy corrections derived from simulation ensure that the average measured jet energies are aligned with those of particle-level jets. To account for residual differences between data and simulation in the jet energy scale, in situ momentum balance measurements are performed in dijet, photon+jet, Z+jet, and multijet events, with appropriate corrections applied based on these results [51].

To identify subjets within AK8 jets for the LJP calibration procedure described in Section 6, the reconstructed jet constituents are reclustered using the exclusive- $k_T$  algorithm [52, 53], which uses a target number of subjets as its stopping criterion rather than a distance parameter. The exclusive- $k_T$  algorithm was found in Ref. [30] to be more effective at identifying subjets than the Cambridge–Aachen [54, 55] and anti- $k_T$  algorithms widely used in similar analyses. Following Ref. [30], the reclustered subjets have their energies corrected using the same factors applied to the respective AK8 jets, and their  $k_T$  clustering history is used to measure their LJP.

Two algorithms are used in this paper to calculate the mass of AK8 jets. The first is the soft-drop (SD) algorithm [56], with parameters  $z = 0.1$  and  $\beta = 0$ , which prunes soft and collinear radiation from the jet. The algorithm outputs two subjets, whose invariant mass is taken to be the SD mass ( $m_{SD}$ ). The second is a mass regression algorithm using the PARTICLENET architecture, which leverages PF candidate and SV information in a GNN to predict the jet mass ( $m_{reg}$ ), and has demonstrated improved mass resolution of two-pronged jets compared with the SD mass with the aforementioned parameters [10]. The DEEPJET recurrent neural network algorithm [57] is used to identify AK4 jets originating from b quarks, as discussed in Section 6.

The missing transverse momentum vector  $\vec{p}_T^{\text{miss}}$  is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, and its magnitude is denoted as  $p_T^{\text{miss}}$  [58]. The  $\vec{p}_T^{\text{miss}}$  is modified to account for corrections to the energy scale of the reconstructed jets in the event.

## 4 Event simulation

The PART algorithm is trained on simulated signal events containing jets from boosted Higgs boson-like decays and background events with top quark-like or QCD jets. During training, it is essential that a wide range of jet masses and momenta are included, as described in Section 5.2, to ensure PART does not learn to identify specific resonance masses or  $p_T$  ranges, thereby decorrelating the tagger output from jet mass and  $p_T$ . For this reason, the simulated samples are generated with a broad range of resonance masses. Higgs boson-like and top quark-like topologies are simulated using, respectively, a spin-2 G resonance decaying to HH and a  $Z'$  resonance decaying to  $t\bar{t}$ , with the masses of the G, H,  $Z'$ , and t resonances varied as

described below. We exclusively consider AK8 jets in model training and evaluation. All events are simulated under the 2017 data-taking conditions; however, the algorithm can be applied to and is calibrated for all years of data taking in Run 2. The performance of PART trained using samples simulated under 2017 data-taking conditions for data collected in 2016 and 2018 has been found to be consistent with that of 2017.

The H jet topology is simulated via G decaying to HH, generated with MADGRAPH5\_aMC@NLO 2.6.5 [59] at leading order (LO). The jet  $p_T$  and mass ranges are controlled by varying the G mass ( $m_G$ ), ranging from 600 to 6000 GeV in 100 GeV increments, and  $m_H$ , ranging from 15 to 250 GeV in 5 GeV increments for  $m_H < 50$  GeV and 10 GeV increments for  $m_H > 50$  GeV. The G boson width is set to 1 MeV, while the narrow width approximation (NWA) is applied to the Higgs boson. The H decays are simulated with JHUGEN 7.1.4 [60] for  $H \rightarrow WW^* \rightarrow 4q$  or  $\ell\nu qq$  decay processes, and with PYTHIA 8.205 for  $H \rightarrow b\bar{b}$ ,  $H \rightarrow c\bar{c}$ ,  $H \rightarrow s\bar{s}$ ,  $H \rightarrow q\bar{q}$ , and  $H \rightarrow \tau^+\tau^-$  decays. To improve mass decorrelation and performance on the SM  $H \rightarrow WW^*$  topology, the ratio of the W boson mass ( $m_W$ ) to the Higgs boson mass ( $m_H$ ) is kept fixed to the SM value of 0.64 [61] for each  $m_H$  point. While  $m_W$  in principle affects the relative branching fractions of the  $H \rightarrow WW^* \rightarrow 4q$  and  $\ell\nu qq$  decay modes, the two processes are generated separately in equal proportion.

The t jet topology is simulated using a spin-0 resonance  $Z'$  decaying to  $t\bar{t}$ , generated with MADGRAPH5\_aMC@NLO 2.6.5 at LO. The masses of the  $Z'$  boson ( $m_{Z'}$ ) and the top quark ( $m_t$ ) are varied identically to the H jet setup, with the widths set to 1% of  $m_{Z'}$  for the  $Z'$  boson and the NWA for the top quark. The W boson decays are simulated at the matrix element level, with the  $m_W$  again configured such that  $m_W/m_t = 0.47$ , i.e., at the SM value [61]. This setup improves the decorrelation of t tagging performance from the jet mass, while maintaining sensitivity to the top quark jet background characteristic of the SM configuration. Additionally, the width of the W boson is set equal to  $m_W$ , i.e., significantly larger than its SM value, resulting in the  $m_W$  being more varied across events. This further improves the sensitivity to BSM top quark-like decays where the ratio  $m_W/m_t$  may be different from the SM value. The G and  $Z'$  particles are used purely as convenient means to produce and control the kinematic properties of H and t jets and do not otherwise influence PART training. The masses of the particles considered in H and t jet simulations are summarized in Table 1.

The QCD multijet events are simulated at LO using PYTHIA 8.205 [62] with the jet  $p_T$  sampled from different ranges to ensure broad coverage in jet mass and  $p_T$ . The ‘‘ghost association’’ method [63] is employed to determine the flavor of the partons that produce the jets, wherein reconstructed jets are reclustered with the final generated b or c hadrons in their decay chains. Their four-momenta are adjusted to preserve only directional information without affecting the jet momentum. The jet origin is determined by counting the number of ghost-associated b or c hadrons. Jets originating from resonant boosted Higgs bosons and top quarks are categorized according to the number and flavor of daughter quarks falling within the reconstructed AK8 jet.

Additional test samples are generated for performance evaluation alone, with more events in particular with SM  $H \rightarrow WW^*$  and  $t\bar{t}$  jet topologies, to evaluate the performance of PART for SM searches. The Higgs boson topology for testing is produced through a similar process to that for the training sample, but with  $m_G$  fixed at 1000 GeV and SM values for  $m_H$  and  $m_W$ . The SM top quark-like jets are simulated using the same resonant  $t\bar{t}$  process, with  $m_{Z'}$  ranging from 1200 to 4500 GeV. The parameters  $m_W$ ,  $m_t$ , and the W boson width are all fixed to their SM values. Finally, the performance is evaluated for BSM signals of scalar bosons (Y) decaying to SM W bosons as well, for searches for new Higgs boson-like resonances away from the SM

$m_H$ . These are simulated similarly to the H jet training samples, with G decaying to HY and  $m_G$  and the Y mass ( $m_Y$ ) varying, but the Y decaying to the SM W bosons.

Table 1: Summary of particle masses in the PART training samples.

	H jets ( $G \rightarrow HH$ )		t jets ( $Z' \rightarrow t\bar{t}$ )
$m_G$	600–6000 GeV	$m_{Z'}$	600–6000 GeV
$m_H$	15–250 GeV	$m_t$	15–250 GeV
$m_W$	Fixed to SM ratio: $0.64m_H$	$m_W$	Fixed to SM ratio: $0.47m_t$
All other particles: SM values			

The calibration of PART is demonstrated on simulated HH events in Section 7. Production via the ggF channel is simulated at next-to-LO (NLO) accuracy in perturbative QCD using POWHEG 2.0 [64–67], whereas the VBF channel is simulated at LO using MADGRAPH5\_aMC@NLO 2.6.5 [59]. A basis of samples is simulated with different  $\kappa_{2V}$ ,  $\kappa_\lambda$ , and  $\kappa_V$  coupling modifiers and linear combinations of these are used to model all possible variations. The parameter  $\kappa_\lambda$  is the coupling modifier of the Higgs boson trilinear self-interaction,  $\kappa_{2V}$  the interaction between two vector bosons and two Higgs bosons, and  $\kappa_V$  the interaction between a Higgs boson and two vector bosons.

The production cross sections of the ggF samples are normalized to the next-to-NLO (NNLO) predictions for each coupling value [68–74], whereas the SM VBF production cross section is normalized to the prediction at next-to-NNLO (N<sup>3</sup>LO) in QCD with the same N<sup>3</sup>LO/LO correction applied to all other couplings.

For all processes in this paper, the parton showering, hadronization, and underlying event interactions are simulated using PYTHIA 8.205 [62] with the CP5 [75] tune. The parton distribution functions used correspond to those from NNPDF 3.0 [76] and 3.1 [77]. The response of the CMS detector is modeled with the GEANT4 package [78], with pileup included by overlaying simulated minimum bias interactions on the hard scattering process.

## 5 The PART algorithm

The PART algorithm is an AK8 jet tagger that incorporates a dedicated  $H \rightarrow WW$  classification node while achieving decorrelation with the jet mass. It is a self-attention-based model that is trained to distinguish between QCD jets and a variety of hadronically and leptonically decaying H and t jets for general use beyond  $H \rightarrow WW$  identification as well. This section describes the PART model, including training samples, input features, model architecture, training procedures, and performance benchmarks.

### 5.1 Model architecture and inputs

We employ a particle transformer architecture, which has been shown to achieve state-of-the-art performance on large-scale data sets [20], outperforming convolutional and graph neural networks, such as PARTICLENET, with similar computational efficiencies. The PART algorithm processes input particles and vertices as a permutation-invariant set of tokens, updating each particle’s features through a series of modified multi-head self-attention blocks, referred to as “particle attention blocks” (PABs). Beyond the standard self-attention mechanism [79], which allows the model to weigh the importance of different inputs when updating their collective representations, PABs incorporate pairwise features between the input particles and vertices that are embedded and used as attention biases in each block. After eight PABs, two more class

attention blocks (CABs) [80] use the learned features to update a randomly initialized class token, which aggregates these features into a global representation of the jet. This class token is then passed through a final multi-layer perceptron (MLP) that outputs the class probabilities, which are normalized by a softmax function [81], and the jet mass as an auxiliary training objective (as discussed in Section 5.2). A diagram of the architecture is shown in Fig. 1.

Transformers are additionally more computationally efficient than GNNs and, hence, we find that PART has a 6% faster inference time than the PARTICLENET model of Refs. [9, 10] despite a significantly larger model capacity, with 2.3 million parameters compared with the 500,000 of PARTICLENET. The PART model has also been shown to require fewer floating point operations per inference than comparable PARTICLENET models [20].

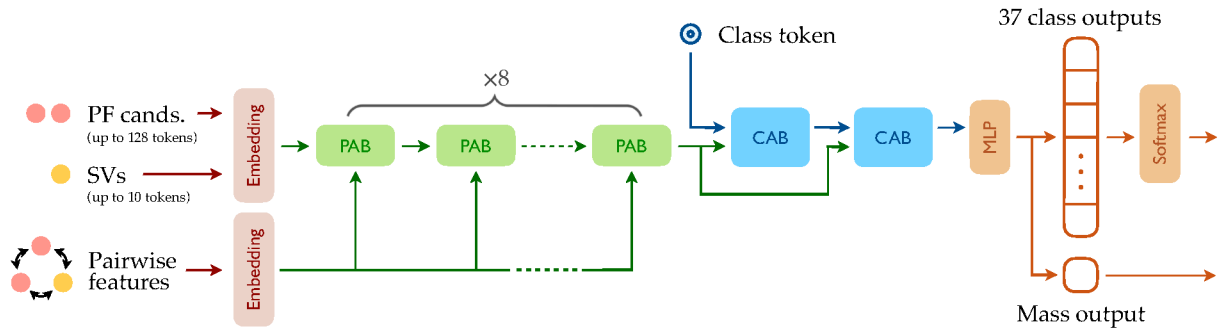


Figure 1: Diagram of the PART model architecture. The model processes two different sets of input features per jet, from PF candidates and SVs. These features are embedded using separate MLPs into 128-dimensional representations before being concatenated and passed through eight PABs. Pairwise features are also calculated between each input element, which are embedded using a single one-dimensional convolutional layer and used as attention biases for each PAB. Two CABs then use the learned features to update a randomly initialized class token, which aggregates these features into a global representation of the jet. Their output is then finally passed through an MLP that outputs the class probabilities, which are normalized by a softmax function, as well as the jet mass.

A unique feature of our algorithm with respect to Ref. [20] is the use of two different sets of input features: PF candidates and SVs within the jet. Based on the distributions of their multiplicities, we select up to 128 PF candidates and 10 SVs per jet, covering nearly all jets. For jets exceeding these limits, only the highest- $p_T$  objects are retained as inputs. The PF candidates, including both charged and neutral particles, are taken as constituents of the AK8 jet. Their input features include kinematic information, particle charge and type, as well as track-related properties in the case of charged particles. Properties of SVs whose momentum direction lies within the jet, such as kinematic information and impact parameters, are also included as input features. The full set of features is listed in Table 2. The features of all two data groups are embedded using separate MLPs into 128-dimensional representations before being concatenated and passed through the PABs. All input features are preprocessed such that their means and standard deviations across the training distributions are approximately 0 and 1, respectively.

Pairwise features  $\ln \Delta$ ,  $\ln(k_T/\text{GeV})$ ,  $\ln z$ , and  $\ln(m^2/\text{GeV}^2)$  are calculated between all input ele-

ments from their four-momenta [82], where

$$\Delta = \sqrt{(\Delta y)^2 + (\Delta\phi)^2}, \quad (1)$$

$$k_T = \min(p_{T,a}, p_{T,b})\Delta, \quad (2)$$

$$z = \min(p_{T,a}, p_{T,b}) / (p_{T,a} + p_{T,b}), \quad (3)$$

$$m^2 = (E_a + E_b)^2 - \|\mathbf{p}_a + \mathbf{p}_b\|^2, \quad (4)$$

$\Delta y$  and  $\Delta\phi$  are the pairwise differences in rapidity and the azimuthal angle, respectively;  $p_{T,i} = (p_{x,i}^2 + p_{y,i}^2)^{1/2}$  is the transverse momentum; and  $\mathbf{p}_i = (p_{x,i}, p_{y,i}, p_{z,i})$  is the momentum 3-vector and  $\|\cdot\|$  is the norm, for  $i = a, b$ . These features are embedded into a 64-dimensional representation using one-dimensional convolutional layers and then used as attention biases for each PAB. These architectural hyperparameters are based on those in Ref. [20].

## 5.2 Model training

The final states for each topology are categorized by the number of quarks and leptons per jet, and then further separated by flavor. Notably, jets from fully hadronic  $H \rightarrow WW^*$  decays are separated into 4- and 3-pronged jets (4q and 3q), to account for jets that may not capture all four  $WW^*$  daughter quarks. Other Higgs boson decay modes, including  $H \rightarrow qq$  and  $H \rightarrow \tau\tau$ , are also targeted for applications to other CMS searches, which will be the subject of future work. The full set of training classes is shown in Fig. 2.

The primary goal of PART is jet classification among these 37 classes, along with an auxiliary task of regressing the jet mass. The classification task uses a cross-entropy loss function, while the mass regression task uses the “log-cosh” loss:

$$\mathcal{L}_{\log\text{-cosh}}(m_{\text{true}}, m_{\text{pred}}) = \ln(\cosh((m_{\text{pred}} - m_{\text{true}})/\text{GeV})), \quad (5)$$

where  $m_{\text{true}}$  is chosen to be the resonance mass,  $m_H$  or  $m_t$ , for H and t jets, and the generator-level  $m_{\text{SD}}$  for QCD jets, as described in Ref. [10], expressed in units of GeV. The log-cosh function has been shown to be more performant for jet mass regression than common alternatives such as the mean-squared-error loss [9]. The overall training objective is to minimize the sum of the cross-entropy and log-cosh losses simultaneously, with the log-cosh loss weighted by a hyperparameter  $\lambda$  to balance the two objectives. The value of  $\lambda$  has been tuned empirically to 0.05.

The PART algorithm is trained to be decorrelated with the jet mass firstly by varying  $m_H$  and  $m_t$  in the training samples, as described in Section 4. For H decays into light SM particles, i.e., quarks and  $\tau$  leptons, varying  $m_H$  alone is sufficient to achieve mass decorrelation, while maintaining strong tagging performance, as illustrated by studies of the PARTICLENET algorithm [9, 10]. However, the high mass of the W boson poses a challenge for the  $H \rightarrow WW$  topologies. Namely, if  $m_W$  were to remain fixed to its SM value, three distinct kinematic phases would be present in the training samples for the  $H \rightarrow WW$  topology as a function of  $m_H$ : 1) two off-shell W bosons for  $m_H \lesssim m_W$ ; 2) one off-shell and one on-shell W boson for  $m_W \lesssim m_H \lesssim 2m_W$ ; and 3) two on-shell W bosons for  $m_H \gtrsim 2m_W$ . This variation in the jet kinematics was found to harm the model performance on the SM  $H \rightarrow WW$  topology, as well as to introduce biases in the performance with respect to the jet mass. To address this, training samples are generated with varying  $m_W$  as well, as described in Section 4, ensuring PART is optimized for the SM  $H \rightarrow WW^*$  on-shell plus off-shell topology and improving its mass decorrelation.

Table 2: The complete set of input features per AK8 jet used for the PART model training. Two types of inputs are considered: PF candidates and secondary vertices (SVs). The PF candidate features marked with a star (\*) apply only to charged PF candidates and a null value is used for neutral candidates.

Variable	Definition
PF candidates	
$\ln(p_T/\text{GeV})$	Logarithm of the particle $p_T$
$\ln(E/\text{GeV})$	Logarithm of the particle energy
$\Delta\eta(\text{jet})$	Difference in pseudorapidity between the particle and the jet axis
$\Delta\phi(\text{jet})$	Difference in azimuthal angle between the particle and the jet axis
$ \eta $	Absolute value of the particle pseudorapidity
$q$	Electric charge of the particle
isMuon	True if the particle is identified as a muon
isElectron	True if the particle is identified as an electron
isChargedHadron	True if the particle is identified as a charged hadron
isPhoton	True if the particle is identified as a photon
isNeutralHadron	True if the particle is identified as a neutral hadron
pvAssociationQuality	Quality of the association of the track to the primary vertices (*)
lostInnerHits	Quality of the track related to missing hits on the pixel layers (*)
$\chi^2/\text{ndof}$	The $\chi^2$ value of the trajectory fit normalized to the number of degrees of freedom (*)
qualityMask	Quality of the track (*)
$d_z$	Longitudinal impact parameter of the track (*)
$d_z/\sigma_{d_z}$	Significance of the longitudinal impact parameter (*)
$d_{xy}$	Transverse impact parameter of the track (*)
$d_{xy}/\sigma_{d_{xy}}$	Significance of the transverse impact parameter (*)
$\eta_{\text{rel}}$	Pseudorapidity of the track relative to the jet axis (*)
$p_{T,\text{rel}} \text{ ratio}$	Relative track momentum perpendicular to the jet axis (*)
$p_{\text{par,rel}} \text{ ratio}$	Relative track momentum parallel to the jet axis (*)
$d_{3D}$	Signed three-dimensional (3D) impact parameter of the track [83] (*)
$d_{3D}/\sigma_{3D}$	Signed 3D impact parameter significance of the track (*)
trackDistance	Distance between the track and jet axis at the point of closest approach (*)
Secondary vertices within the jet	
$\ln(p_T/\text{GeV})$	Logarithm of the SV $p_T$ , defined as the $p_T$ of the vector sum of the tracks associated with the SV
$m_{\text{SV}}$	Invariant mass of the tracks associated with the SV
$\Delta\eta(\text{jet})$	Difference in pseudorapidity between the SV and the jet axis
$\Delta\phi(\text{jet})$	Difference in azimuthal angle between the SV and the jet axis
$ \eta $	Absolute value of the SV pseudorapidity
$N_{\text{tracks}}$	Number of tracks associated with the SV
$\chi^2/\text{ndof}$	The $\chi^2$ value of the SV fit normalized to the number of degrees of freedom
$d_{2D}$	Signed two-dimensional (2D) impact parameter of the SV
$d_{2D}/\sigma_{2D}$	Signed 2D impact parameter significance of the SV
$d_{3D}$	Signed 3D impact parameter of the SV
$d_{3D}/\sigma_{3D}$	Signed 3D impact parameter significance of the SV

Process	Final state	Flavor	Classes
H→WW (all-hadronic)	qq̄q̄q̄	⊗ 0c / 1c / 2c	3
	qq̄q		3
H→WW (semileptonic)	eνq̄q̄	⊗ 0c / 1c	2
	μνq̄q̄		2
	τ <sub>e</sub> νq̄q̄		2
	τ <sub>μ</sub> νq̄q̄		2
	τ <sub>h</sub> νq̄q̄		2
H→qq̄		b <b>̄</b> b̄	1
		c <b>̄</b> c̄	1
		s <b>̄</b> s̄	1
		qq̄ (q=u/d)	1
H→ττ	τ <sub>e</sub> τ <sub>h</sub>		1
	τ <sub>μ</sub> τ <sub>h</sub>		1
	τ <sub>h</sub> τ <sub>h</sub>		1
t→bW (hadronic)	bq̄q̄	⊗ 1b + 0c / 1c	2
	bq		2
t→bW (leptonic)	bēν	⊗ 1b	1
	bμν		1
	bτ <sub>e</sub> ν		1
	bτ <sub>μ</sub> ν		1
	bτ <sub>h</sub> ν		1
QCD		b	1
		b <b>̄</b> b̄	1
		c	1
		c <b>̄</b> c̄	1
		others (udsg)	1

Figure 2: Full suite of AK8 jet topologies considered for the PART multiclass classification task. Jet types are first categorized by the number of quarks and leptons in the final state, and then further separated by flavor, as shown in the table on the left. The symbols  $\tau_e$ ,  $\tau_\mu$ , and  $\tau_h$  refer to  $\tau$  lepton decays to electrons, muons, and hadrons, respectively. The total number of subclasses for each process, therefore, is given by the tensor product ( $\otimes$ ) between the different final states and flavors. Diagrams illustrating the corresponding jet topologies, which are not exhaustive, are shown on the right.

To further improve decorrelation, we ensure training classes share similar mass distributions by sampling uniformly in the two-dimensional (2D)  $m_{SD}$  and  $\ln(p_T/\text{GeV})$  per class, as in Ref. [9]. The 2D sampling weights are derived in 10 GeV bins of  $m_{SD}$  between 20 and 260 GeV and 11 bins in  $p_T$  uniformly distributed in logarithmic scale between 200 and 2500 GeV, ensuring a uniform distribution in  $m_{SD}$  and  $\ln(p_T/\text{GeV})$ .

Additionally, jets from each class are sampled during the training according to the relative weights in Table 3 to balance the class distributions. Each of the four major processes:  $H \rightarrow WW$ ,  $H \rightarrow 2$ -pronged,  $t$ , and QCD jets are weighted equally; i.e., the weights in each row in Table 3 sum to unity. Within each process, the classes are weighted according to the SM branching fractions, except for  $H \rightarrow 2$ -pronged jets, where the  $b\bar{b}$ ,  $c\bar{c}$ ,  $s\bar{s}$ , and  $q\bar{q}$  classes are all weighted equally to avoid the  $b\bar{b}$  final state dominating because of its significantly higher branching fraction. We find that variations in the weighting scheme do not significantly affect performance; in particular, networks trained with different weight configurations can be made equivalent by rescaling the output probability scores. The choice of weights is therefore mainly

driven by technical considerations for class balance.

Table 3: Relative weights of each of the classes used for training the PART model. Each of the four major processes:  $H \rightarrow WW$ ,  $H \rightarrow 2$ -pronged,  $t \rightarrow bW$ , and QCD jets, are weighted equally and have one row dedicated to them each.

Process	H $\rightarrow$ WW						
Final state	qqqq	qqq	$e\nu qq$	$\mu\nu qq$	$\tau_e\nu qq$	$\tau_\mu\nu qq$	$\tau_h\nu qq$
Weight	0.32	0.08	0.2	0.2	0.03	0.03	0.14
Process	H $\rightarrow$ 2-pronged						
Final state	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$q\bar{q}$	$\tau_e\tau_h$	$\tau_\mu\tau_h$	$\tau_h\tau_h$
Weight	0.16	0.16	0.16	0.16	0.08	0.08	0.2
Process	t $\rightarrow$ bW						
Final state	$bq\bar{q}$	bq	$be\nu$	$b\mu\nu$	$b\tau_e\nu$	$b\tau_\mu\nu$	$b\tau_h\nu$
Weight	0.32	0.08	0.2	0.2	0.03	0.03	0.14
Process	QCD						
Final state	All						
Weight	1						

The training is performed using the WEAVER framework [84], a DL toolkit based on the PYTORCH [85] Python library, on three Nvidia GTX 3090 GPUs in parallel. The total data set comprises 52.4 million jets, with 80% reserved for training and 20% for validation, and we use a batch size of 512 jets. Rather than one pass of the entire data set defining an epoch, we define one epoch as processing 15,000 batches or 7.68 million jets (sampled from 80% of the data set) for training and 1000 batches or 0.512 million jets (sampled from the remaining 20%) for validation, continuously iterating through the data set. The model is trained over 50 epochs. A model snapshot is saved at the end of each epoch, and the model with the lowest hybrid loss on the evaluation set is selected as the final model. The LOOKAHEAD optimizer [86], paired with RADAM [87] as the inner optimizer, is used for training. The initial learning rate is set to  $5 \times 10^{-3}$ , remaining constant for the first 70% of iterations before decaying exponentially at the start of each subsequent epoch, and reaching 1% of the initial value by the final epoch. Figure 3 presents the loss curves during the training for the training and validation data sets, separated into the classification (cross-entropy) and regression (log-cosh) terms. No evidence of overfitting is observed.

### 5.3 Performance of jet mass reconstruction

The performance of the PART algorithm in reconstructing the jet mass is shown in Fig. 4 for jets originating from four different processes:  $H \rightarrow b\bar{b}$ ,  $H \rightarrow WW^* \rightarrow 4q$ ,  $t \rightarrow bq\bar{q}$ , and QCD, for the SM values of  $m_H = 125$  GeV,  $m_t = 172.5$  GeV, and  $m_W = 80.4$  GeV. The reconstructed jet mass distributions using the SD and PARTICLENET algorithms are also shown for comparison. The mass of the resonance peaks  $m_{\text{peak}}$  is extracted by locating the maximum of a Gaussian kernel-smoothed mass distribution obtained from each histogram, with the mass resolution quantified by the full width at half maximum (FWHM) of the peak. Both quantities are shown in the legend of Fig. 4 for each algorithm and resonant process.

We observe improved mass resolution from both PARTICLENET and PART with respect to  $m_{\text{SD}}$

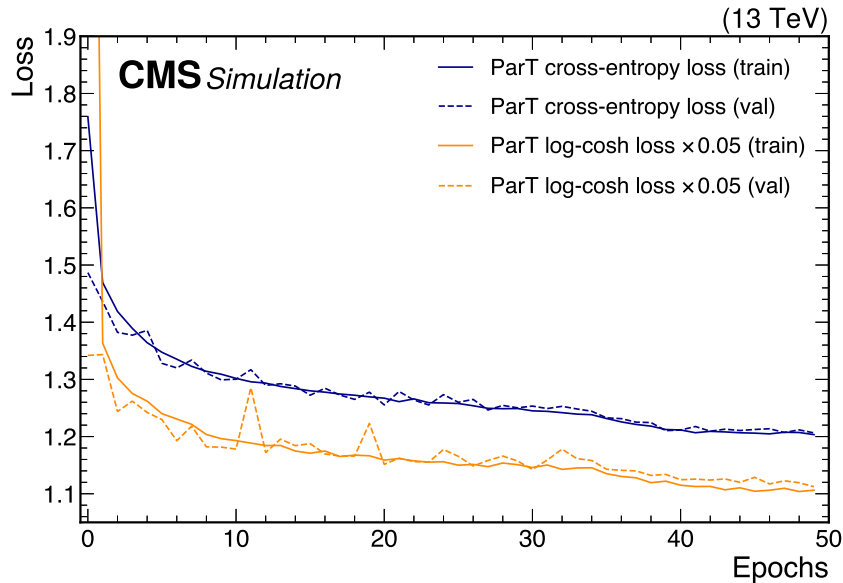


Figure 3: Evolution of the loss function values for the PART model on the training and validation data sets over training epochs, shown separately for the classification (cross-entropy) and regression (log-cosh) terms.

for the two-pronged  $H \rightarrow b\bar{b}$  decay, while PART in particular is the most performant for the higher-pronged  $H \rightarrow WW^* \rightarrow 4q$  and  $t \rightarrow bq\bar{q}$  decays. One feature of the SD algorithm shown in Fig. 4, using the CMS parameters described in Section 3, is a relatively strong removal of PF candidates from the jet. This yields an  $m_{SD}$  value close to 0 GeV for a significant fraction of H and t jets, and a large tail in the  $m_{SD}$  distribution below the true mass. We note, however, that no specific optimization of the SD algorithm for these topologies was attempted. We observe a slight bias towards a higher predicted reconstructed mass for H and t jets than the true values from both PARTICLENET and PART, which we attribute to the presence of high-mass jets in the training sample. Finally, we observe smoothly falling distributions for QCD jets for all three algorithms.

## 6 Performance and calibration of $H \rightarrow WW$ tagging

### 6.1 Performance

To evaluate the performance of the  $H \rightarrow WW$  tagging, we use a single discriminant focusing on distinguishing hadronic  $H \rightarrow WW$  jets from t and QCD multijet jets, defined as

$$T_{HWW} = \frac{P_{HWW4q} + P_{HWW3q}}{P_{QCD} + P_{top} + P_{HWW4q} + P_{HWW3q}}, \quad (6)$$

where  $P_{HWW4q}$ ,  $P_{HWW3q}$ ,  $P_{top}$ , and  $P_{QCD}$  are the sum of the predicted probabilities of their respective subcategories.

The performance of the tagger using this discriminant in differentiating between SM  $H \rightarrow WW$  “signal” and QCD and t background jets is shown in the receiver operating characteristic curves in Fig. 5, where signal and background efficiencies are defined as the fraction of signal and background jets passing a given discriminant threshold. The curves are provided for several ranges of jet  $p_T$ . For the H and t jets, we use only the AK8 jets that lie within  $\Delta R < 0.8$  of the generator-level H or t, respectively, while for QCD we select the jet with the highest  $p_T$

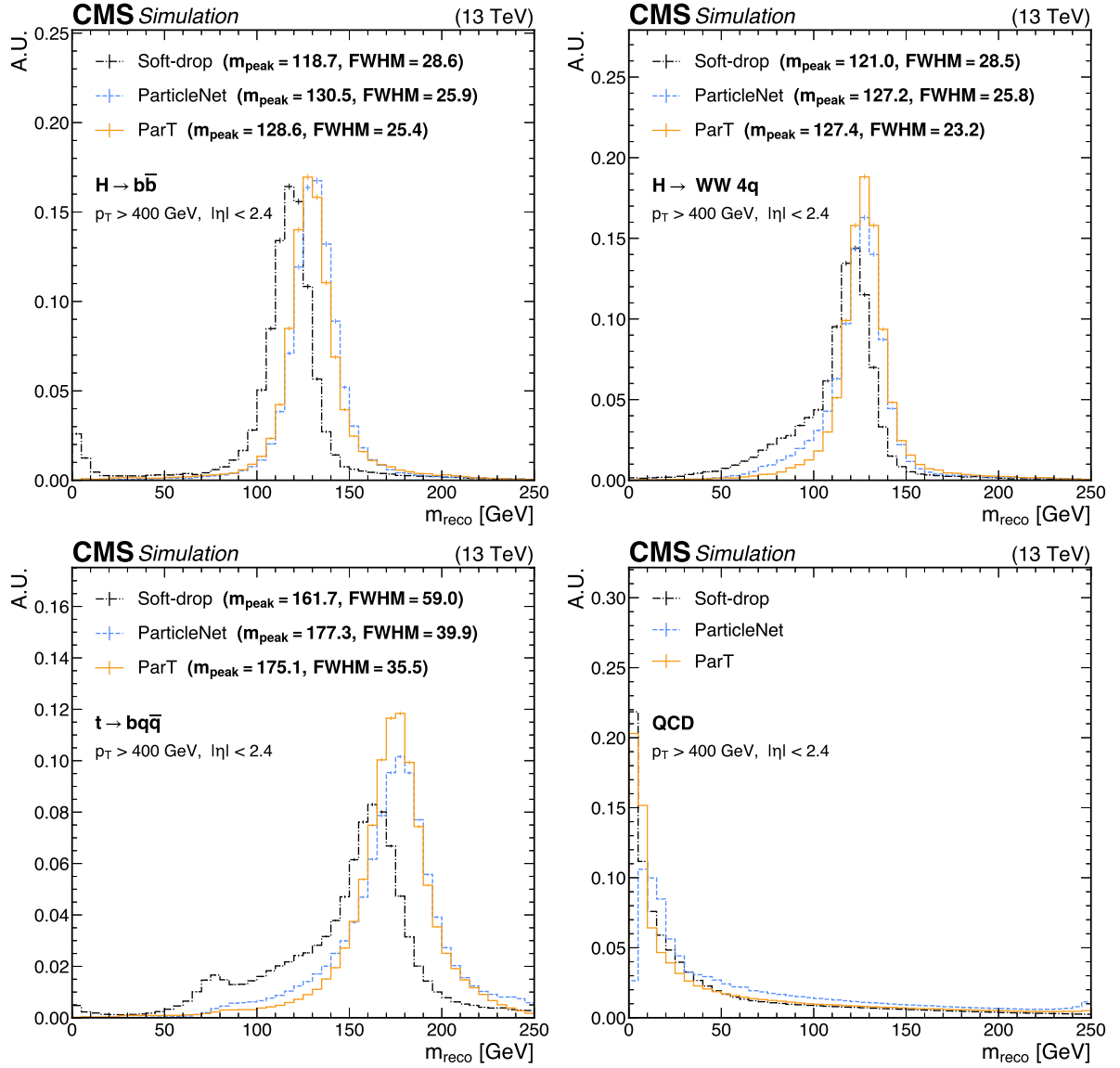


Figure 4: Comparison of jet mass reconstruction ( $m_{\text{reco}}$ ) using the SD, PARTICLENET, and PART algorithms, for  $H \rightarrow b\bar{b}$  (upper left),  $H \rightarrow WW$  (upper right),  $t \rightarrow bq\bar{q}$  (lower left), and QCD (lower right) jets with the SM values of  $m_H$  and  $m_t$ . An offline selection is applied to the AK8 jets of  $p_T > 400$  GeV and  $|\eta| < 2.4$ . Statistical uncertainties in the bin yields originating from the limited number of simulated events are represented by vertical error bars. The mass at the peak ( $m_{\text{peak}}$ ) for each algorithm, calculated using Gaussian kernel density estimation, and the mass resolution, quantified by the FWHM of the resonance peak, are shown as well for H and t jets.

in the event. An offline selection for  $p_T > 200$  GeV,  $m_{SD} > 30$  GeV, and  $|\eta| < 2.4$  is applied to all jets.

We compare our model with the mass-decorrelated DEEPAK8-MD algorithm [4], which was previously state-of-the-art in CMS for  $H \rightarrow WW$  jet identification. Unlike the PART algorithm, which respects inductive biases of jets such as permutation invariance and heterogeneity of the jet constituents, the DEEPAK8-MD algorithm represents jets as 2D images and uses a convolutional neural network architecture for classification.

The DEEPAK8-MD algorithm was trained to distinguish among jets originating from  $H \rightarrow 4q$  (output  $P_{H4q}$ ),  $W \rightarrow q\bar{q}$  ( $P_{Wqq}$ ),  $t \rightarrow bq\bar{q}$  ( $P_{top}$ ) decays, and others. A discriminant targeting  $H \rightarrow 4q$  and  $W \rightarrow q\bar{q}$  jets, while vetoing QCD jets, can be constructed from its outputs, as in Refs. [17, 18]. To further improve the suppression of the  $t\bar{t}$  background, the DEEPAK8-MD discriminant can be extended to veto both QCD and  $t \rightarrow bq\bar{q}$  jets. The resulting discriminant, referred to as the DEEPAK8-MD score, is defined as

$$\text{DEEPAK8-MD score} = \frac{P_{Wqq} + P_{H4q}}{P_{QCD} + P_{top} + P_{Wqq} + P_{H4q}}. \quad (7)$$

The performance of this discriminant is shown in Fig. 5 as well. We observe up to ten times stronger QCD jet rejection for the same signal efficiencies using PART with respect to the DEEPAK8-MD score, and up to eight times stronger  $t$  jet rejection. Thus, through the architectural and training advancements described in this paper, PART significantly outperforms DEEPAK8-MD.

We additionally evaluate the performance of PART in identifying BSM scalar resonances  $Y$  decaying to SM  $W$  bosons, shown in Fig. 6. We observe that despite being optimized exclusively for the SM  $H \rightarrow WW$  topology, PART performs similarly for a small range of  $m_Y$  away from the SM  $m_H$ ; however, there is some performance degradation for  $m_Y = 250$  GeV, at the boundary of the training mass range. This suggests that PART can be used to search for general BSM  $Y \rightarrow WW \rightarrow 4q$  signatures for  $m_Y < 250$  GeV [88]. Finally, Fig. 7 shows the confusion matrix, with each row indicating the fraction of jets per category classified as the column category by PART. We observe generally strong agreement between the true and predicted classes, with higher misclassification rates within subcategories with similar final states, such as  $H \rightarrow WW \rightarrow \tau_e \nu qq$  and  $H \rightarrow WW \rightarrow e \nu qq$ , as expected.

## 6.2 Mass decorrelation

In many analyses, it is desirable for the tagger to be decorrelated with the jet mass, as this allows for the use of sideband regions in the jet mass distribution to constrain backgrounds and reduce systematic uncertainties [89]. The decorrelation of PART's outputs with the jet mass is examined in Fig. 8 for jets in simulated QCD multijet events. Figure 8 also presents the performance of the DEEPAK8-MD discriminant for comparison, which uses an adversarial training strategy for mass decorrelation. To quantify the degree of mass decorrelation, we consider the Jensen–Shannon distance (JSD) [90] using base 2, a symmetrized variant of the Kullback–Leibler divergence [91], between the  $m_{SD}$  distributions with and without PART and DEEPAK8-MD selections. The JSD quantifies the difference between the two distributions and is bounded between 0 and 1, with a lower value indicating better agreement and, hence, better decorrelation. It is reported in Fig. 9 for a range of different tagger selection efficiencies and jet  $p_T$  bins.

We observe that the  $m_{SD}$  distributions remain generally consistent within statistical uncertainties across increasingly tighter selections on the PART  $T_{HWW}$  discriminant; however, there is

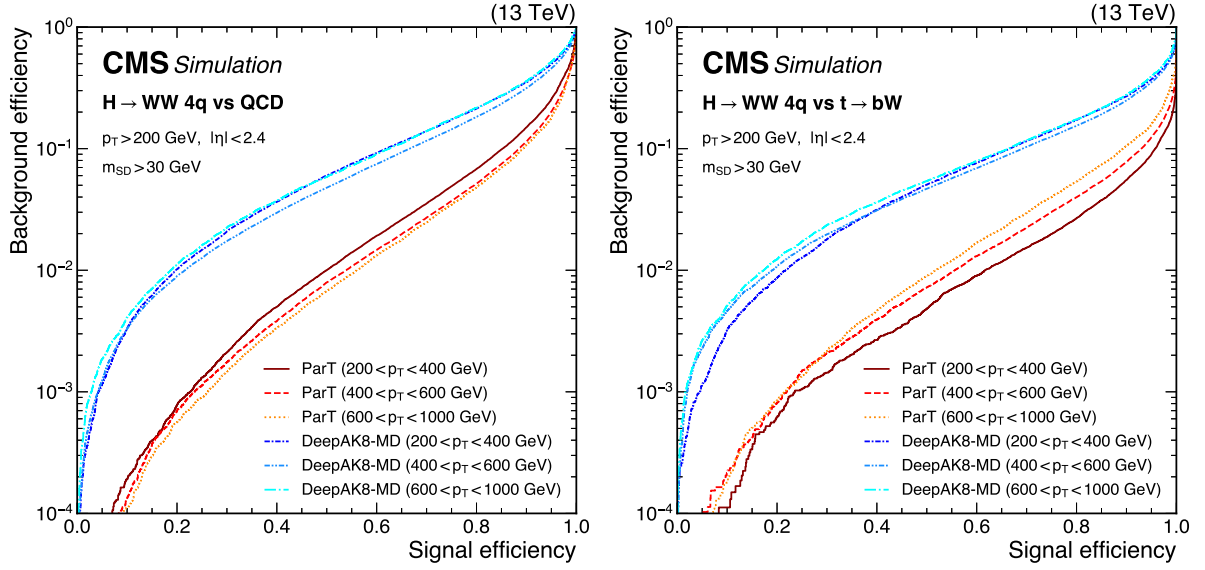


Figure 5: Receiver operating characteristic curves for  $H \rightarrow WW$  signal jets, with the SM values of  $m_H$  and  $m_t$ , versus background jets from simulated QCD multijet (left) and  $t\bar{t}$  events (right), for the PART  $T_{HWW}$  and the DEEPAK8-MD scores in the  $p_T$  ranges 200–400, 400–600, and 600–1000 GeV. An offline selection is applied to the AK8 jets of  $p_T > 200$  GeV and  $|\eta| < 2.4$ . Signal jets are required to contain all four generator-level quarks from the  $W$  boson decays within  $\Delta R(\text{jet}, q) < 0.8$ .

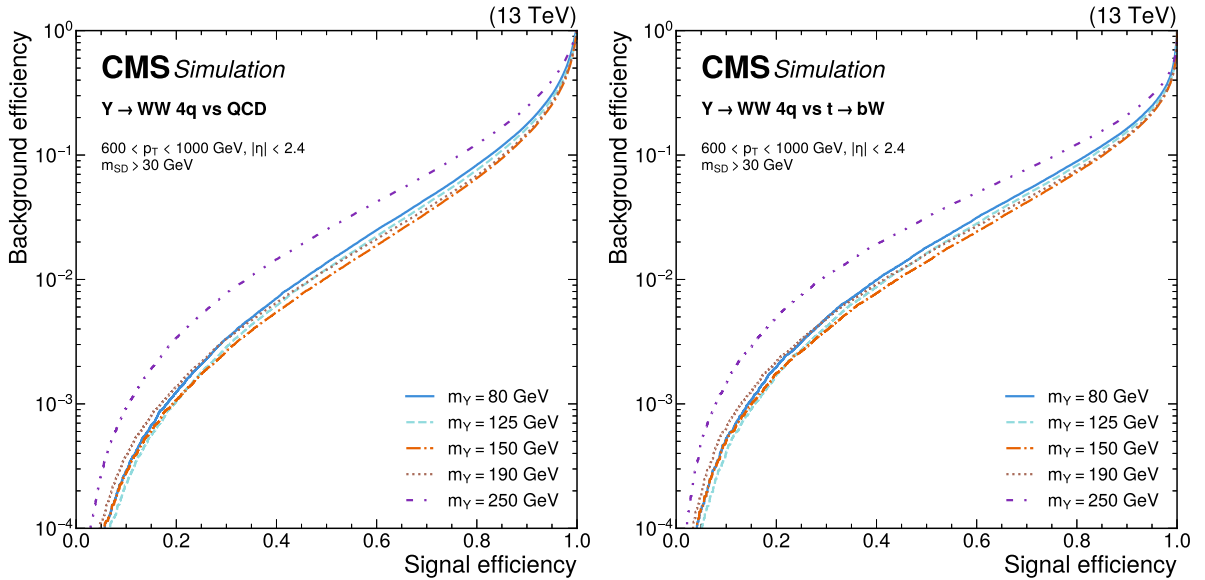


Figure 6: Receiver operating characteristic curves for  $Y \rightarrow WW^*$  signal jets, with varying  $m_Y$  and SM  $m_W$ , versus background jets from simulated QCD multijet (left) and  $t\bar{t}$  events (right), for the PART  $T_{HWW}$  score. An offline selection is applied to the AK8 jets of  $600 < p_T < 1000$  GeV,  $|\eta| < 2.4$ , and  $m_{SD} > 30$  GeV.

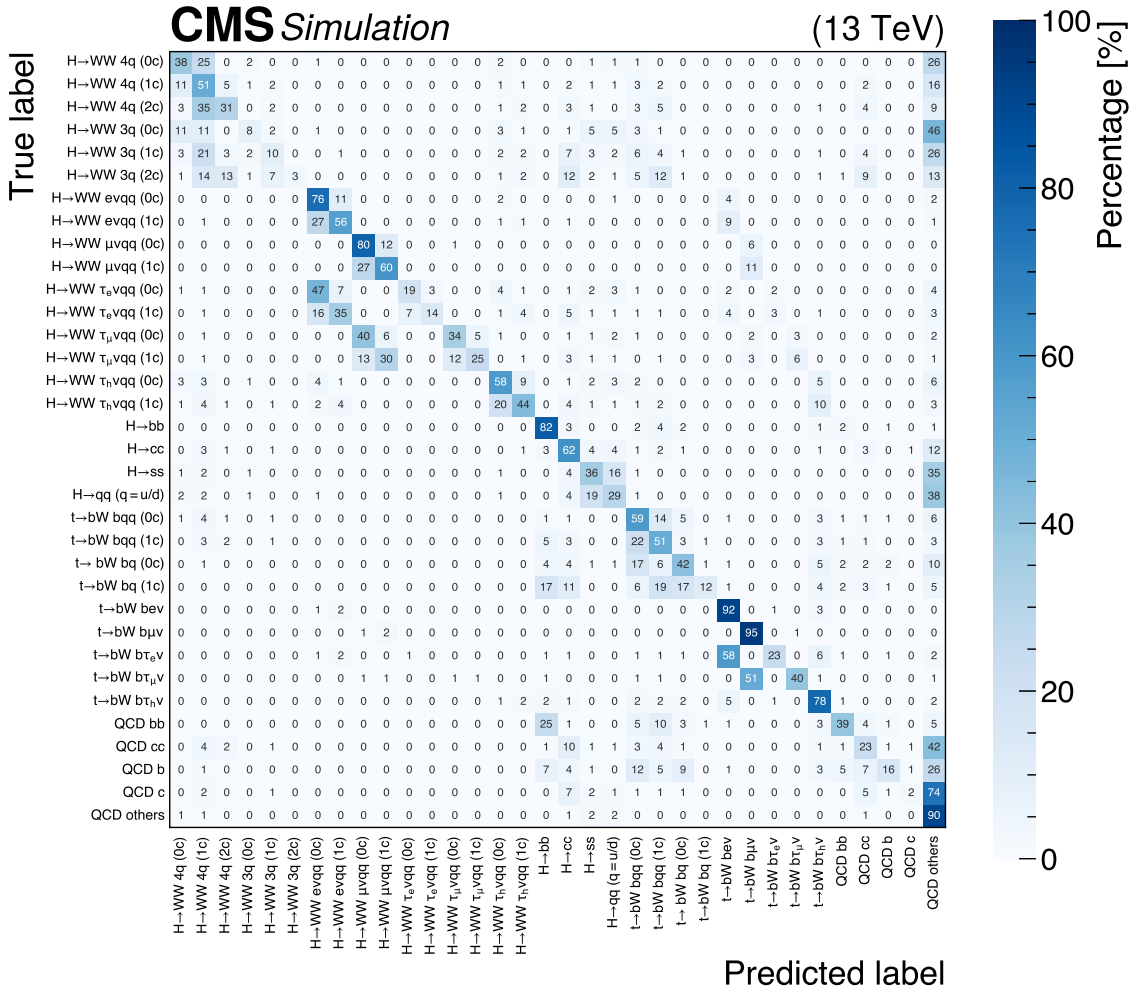


Figure 7: Confusion matrix with each row indicating the fraction of jets per category classified as the column category by PART. An offline selection is applied to the AK8 jets of  $p_T > 200$  GeV and  $|\eta| < 2.4$ .

some evidence of discrepancies in the tails, motivating an increase of the training mass range. This will be the subject of future work. Furthermore, by using samples of varying resonance masses for PART rather than the adversarial approach of DEEPAK8-MD, we are able to employ a simpler loss function and obviate the challenge of training a model with competing objectives; thus, we observe consistently lower JSD values for PART across a range of selection efficiencies and jet  $p_T$ .

### 6.3 Calibration using the Lund jet plane

Jet identification algorithms are typically calibrated using a similar but more abundant SM process as a proxy for the signal process. For example, for boosted  $H \rightarrow b\bar{b}$  calibration, the CMS experiment has used jets produced through Z boson decays to  $b\bar{b}$  and through gluon splitting to  $b\bar{b}$  to measure data versus signal simulation disagreement in the tagger score modeling [92]. However, for  $H \rightarrow WW^* \rightarrow 4q$  jets, it is difficult to define such a high-purity data sample of four-pronged jets. Instead, we use a novel method that measures data versus simulation differences in the per-subjet radiation pattern based on densities of their primary LJPs [29], as introduced in Ref. [30].

The primary LJP of a jet represents each successive hardest splitting in the 2D  $(\ln(1/\Delta), \ln(k_T/\text{GeV}))$  plane, where  $\Delta$  is the angular separation between the emitting and emitted particles and  $k_T$  is the product of  $\Delta$  and the  $p_T$  of the emitted particle. As discussed in Ref. [29], the primary LJP captures important information about the substructure of the jet. The ratio of the densities of primary LJPs of jets from data and simulation are measured in Ref. [30] per subjet in merged two-pronged jets originating from W bosons, clustered with the  $k_T$  algorithm to two exclusive jets, and binned in subjet  $p_T$ .

To measure a correction for the signal efficiency, first, a data-to-simulation relative weight per event is derived for the signal using the primary LJP splittings for each subjet in the  $H \rightarrow WW$  jet, following the procedure described in Ref. [30]. Each  $H \rightarrow WW$  jet is categorized as either two-, three-, or four-pronged based on the number of quarks within the jet radius, using information from the event generator, and is then reclustered into the corresponding number of subjets. The relative event weight is defined as the product, taken over all subjets in each splitting, of the data-to-simulation density ratios of primary LJPs, parameterized by  $k_T$ ,  $\Delta$ , and the subjet  $p_T$ . Systematic uncertainties related to the validity of this procedure and the quark-subjet correspondence are discussed below. The final event weights are then either applied to the simulated signal events, as in the top quark validation study shown in Fig. 11 below, or used to derive a single data-to-simulation scale factor (SF), defined as the ratio of the signal yield with and without the event weights, as in the HH search in Section 7. A schematic of the overall calibration procedure is shown in Fig. 10.

Uncertainties from the correction procedure are propagated as systematic uncertainties in the SF. The following sources are considered, as described in detail in Ref. [30]: 1) statistical uncertainties in the derived LJP ratio from the limited number of data events in the W boson enriched sample (“ratio stat.”); 2) systematic uncertainties in the ratio because of possible simulation mismodeling (“ratio syst.”), estimated using “tag and probe” measurements; 3) uncertainties in the extrapolation of the SF to high  $p_T$  subjets (“ $p_T$  extrap.”); 4) uncertainties in the true number of prongs inside the  $H \rightarrow WW$  jet (“# prongs”); 5) whether there exists a correct, one-to-one correspondence between the reclustered subjets and  $H \rightarrow WW$  daughter quarks (“unclust. prongs”); and 6) differences between the LJP densities of the W boson jets used for the correction and the  $H \rightarrow WW$  signal jets (“distortion”). The impacts of these uncertainties for different HH signals are quantified in Table 4. Generally, the uncertainty in the unclustered

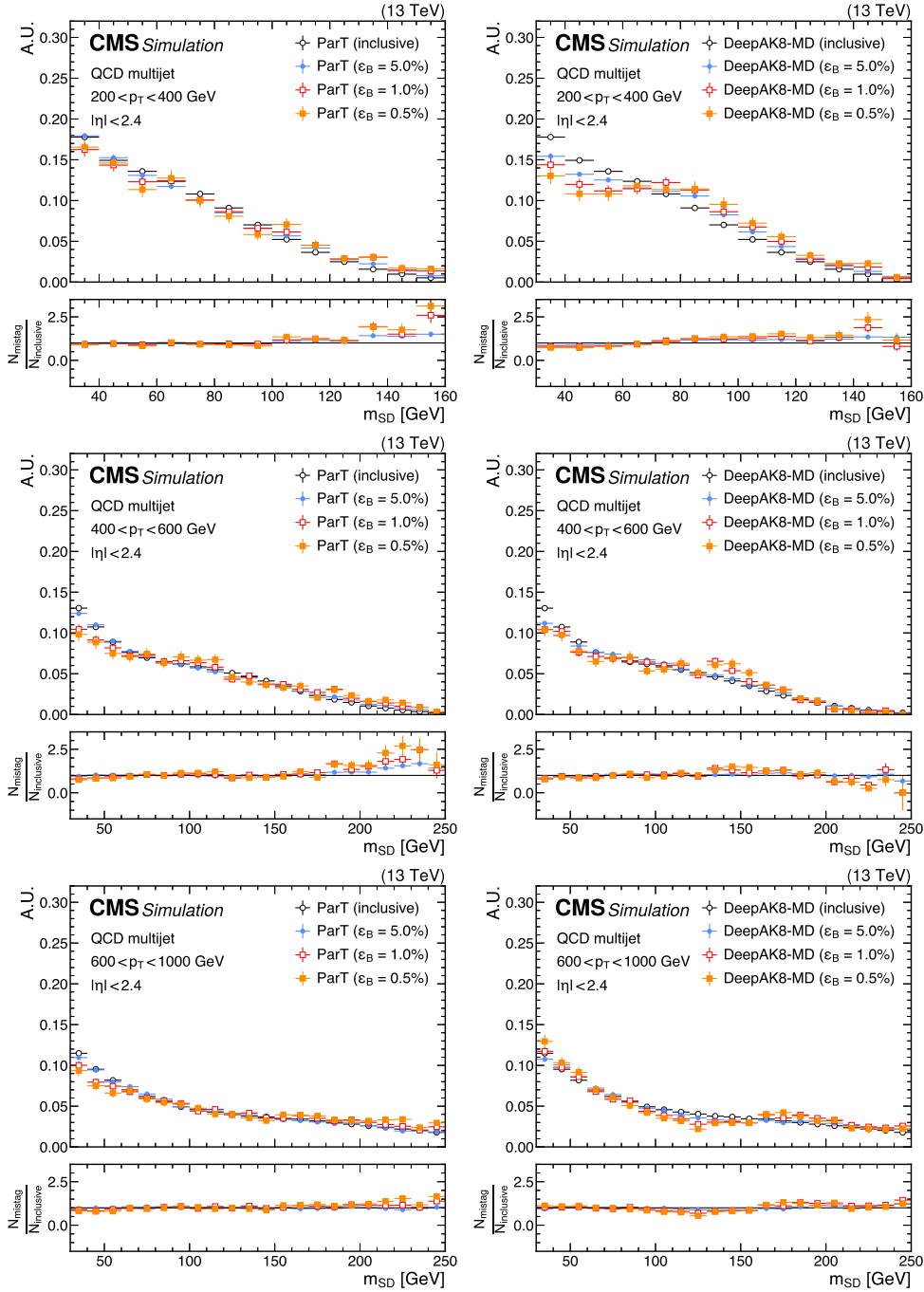


Figure 8: Distributions of  $m_{SD}$  for jets from QCD multijet events, in the  $p_T$  ranges 200–400 GeV (upper), 400–600 GeV (middle) and 600–1000 GeV (lower), after no selections (“inclusive”) on the PART  $T_{HWW}$  score (left) and the DEEPAK8-MD score (right) as well as selections corresponding to QCD jet selection efficiencies ( $\epsilon_B$ ) of 5.0%, 1.0%, and 0.5%. The error bars represent the statistical uncertainties originating from the limited number of simulated events. The lower panels display the ratio of the normalized  $m_{SD}$  distributions for the different selection efficiencies ( $N_{mistag}$ ) to the normalized inclusive  $m_{SD}$  distribution ( $N_{inclusive}$ ). An offline selection is applied to the AK8 jets of  $p_T > 400$  GeV,  $|\eta| < 2.4$ , and  $m_{SD} > 30$  GeV.

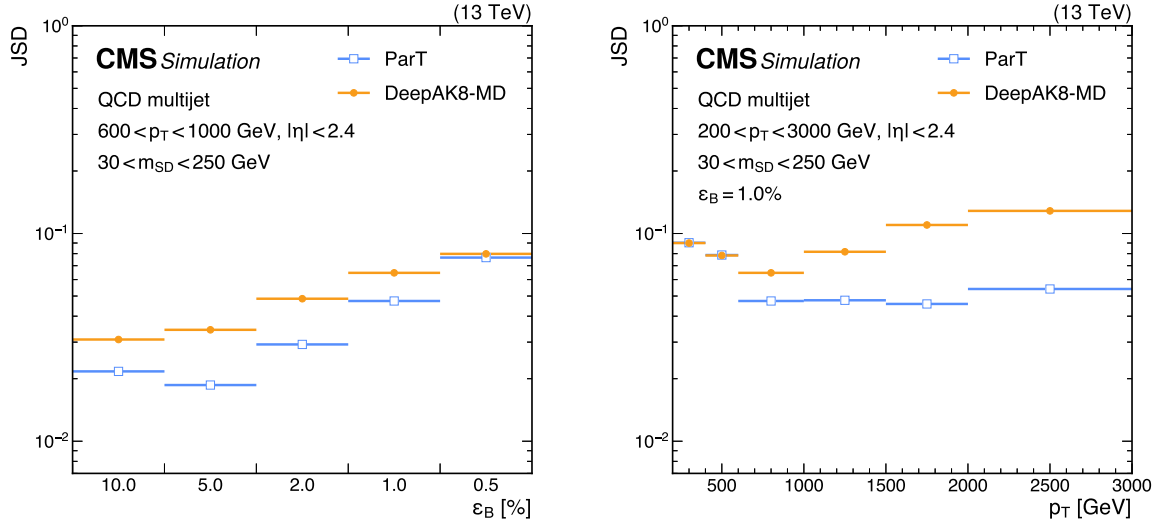


Figure 9: The Jensen–Shannon distance (JSD) using base 2 between the  $m_{SD}$  distribution of jets from QCD multijet events with and without a selection on the PART and DEEPAK8-MD tagger scores. On the left, the JSD is plotted for tagger selections corresponding to different QCD jet selection efficiencies ( $\epsilon_B$ ), with an offline selection of  $600 < p_T < 1000$  GeV,  $|\eta| < 2.4$ , and  $30 < m_{SD} < 250$  GeV applied to the jets. On the right, the JSD is plotted for different jet  $p_T$  bins, at a fixed  $\epsilon_B$  of 1%.

prongs is dominant, followed by systematic uncertainties in the LJP ratios and the distortion uncertainties.

Table 4: Signal efficiency SFs and uncertainties for the BDT selections on the PART  $H \rightarrow WW$  tagging outputs in the  $HH \rightarrow b\bar{b}WW$  search, measured using the LJP calibration method for different HH signals and analysis regions. Both the total combined uncertainty and the components defined in the text are shown.

Region	Process	SF	Ratio stat.	Uncertainty components (fractional)				
				Ratio syst.	$p_T$ extrap.	# prongs	Unclust. prongs	Dist.
ggF	SM ggF HH	$0.91^{+0.19}_{-0.13}$	0.02	0.08	0.00	0.03	$+0.17$ $-0.08$	$+0.09$ $-0.08$
	SM VBF HH	$0.94^{+0.22}_{-0.18}$	0.02	0.15	0.00	0.01	$+0.16$ $-0.07$	$+0.07$ $-0.08$
	VBF HH ( $\kappa_{2V} = 0$ )	$0.99^{+0.17}_{-0.08}$	0.02	0.02	0.01	0.02	$+0.17$ $-0.07$	$+0.02$ $-0.00$
	VBF HH ( $\kappa_{2V} = 2$ )	$1.00^{+0.18}_{-0.07}$	0.02	0.01	0.01	0.02	$+0.17$ $-0.07$	$+0.02$ $-0.00$
VBF	SM ggF HH	$0.83^{+0.22}_{-0.15}$	0.03	0.13	0.01	0.04	$+0.20$ $-0.09$	$+0.09$ $-0.07$
	SM VBF HH	$0.91^{+0.21}_{-0.19}$	0.02	0.18	0.00	0.02	$+0.12$ $-0.05$	$+0.07$ $-0.07$
	VBF HH ( $\kappa_{2V} = 0$ )	$0.88^{+0.14}_{-0.09}$	0.02	0.07	0.01	0.02	$+0.14$ $-0.06$	$+0.03$ $-0.01$
	VBF HH ( $\kappa_{2V} = 2$ )	$0.89^{+0.14}_{-0.08}$	0.02	0.06	0.01	0.02	$+0.13$ $-0.06$	$+0.03$ $-0.01$

#### 6.4 Validation on jets from boosted top quark decays

The LJP calibration method is validated for PART on jets from decays of boosted top quark candidates. We define a semileptonic boosted  $t\bar{t}$  enriched data sample, tagging a leptonically decaying top quark ( $t \rightarrow bW \rightarrow b\mu\nu$ ), and probing an opposite-side high- $p_T$  AK8 jet representing

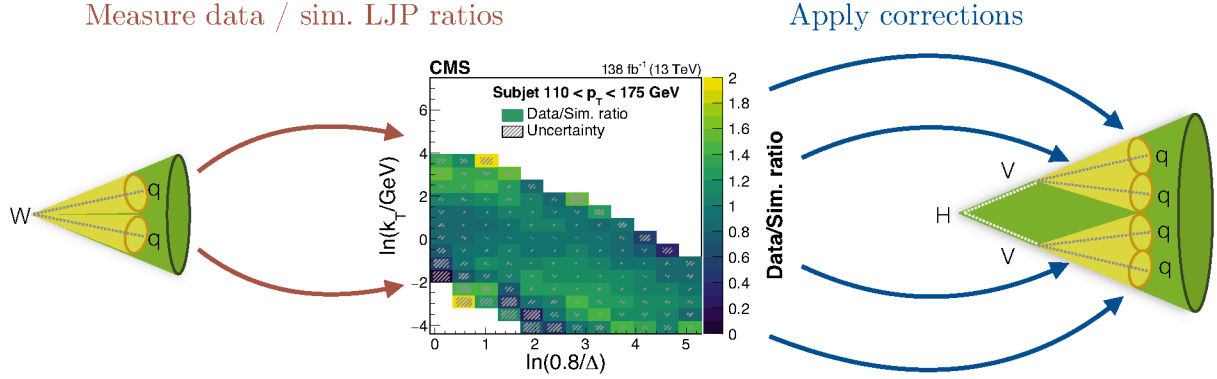


Figure 10: Schematic of the LJP calibration method for  $H \rightarrow WW$  tagging. Ratios of primary LJP densities in data and simulation are first measured per subjet in merged two-pronged  $W$  jets, with an example of such a ratio reproduced from Ref. [30]. These are then used to derive correction factors for  $H \rightarrow WW$  signal jets per prong.

the hadronically decaying top quark. The event selection follows that of the control region in Ref. [30], comprising muon triggers and offline selections for a  $b$ -tagged AK4 jet, a leptonically decaying  $W$  boson—based on the presence of a muon and  $p_T^{\text{miss}}$ —and a high- $p_T$  AK8 jet with a mass close to  $m_t$ . Jets from simulated  $t\bar{t}$  samples are categorized using generator-level particles as either: “ $t$ -matched”—with all three daughter quarks lying within the jet; “ $W$ -matched”—with only the  $W$  daughter quarks inside the jet; or “ $t$ - and  $W$ -unmatched”—neither of these two cases. Only the  $t$ -matched jets are reweighted with the LJP ratios, as they are expected to be the most similar to the  $H \rightarrow WW$  signal jets and, indeed, dominate the high-scoring bins in Fig. 11.

We consider the  $T_{\text{HWW}}$  discriminant from Eq. (6), excluding  $P_{\text{top}}$  from the denominator to retain top quark events in the high tagger score bins:

$$T_{\text{HWW}}^{\text{No top}} = \frac{P_{\text{HWW}4q} + P_{\text{HWW}3q}}{P_{\text{QCD}} + P_{\text{HWW}4q} + P_{\text{HWW}3q}}. \quad (8)$$

The  $T_{\text{HWW}}^{\text{No top}}$  distributions from the 2017 data sets before and after LJP-reweighting of the events with matched top quark jets are shown in Fig. 11 (left). The combined uncertainties per bin are also shown in the distributions and data versus simulation ratios. We observe an overall improvement in the agreement between data and simulation, with the  $\chi^2$  test statistic value improving from 20.7 to 16.6. Importantly, the data and simulation yields are all consistent within statistical and systematic uncertainties in these bins. We also show the effect of LJP calibration of the DEEPAK8-MD discriminant in Fig. 11 (right), defined similarly as in Eq. (7), excluding  $P_{\text{top}}$  from the denominator:

$$\text{DEEPAK8-MD score (No top)} = \frac{P_{Wqq} + P_{H4q}}{P_{\text{QCD}} + P_{Wqq} + P_{H4q}}. \quad (9)$$

We observe a similar improvement in the agreement between data and simulation; however, overall, the agreement is worse than that of PART.

## 7 Impact on measuring $HH \rightarrow b\bar{b}WW$ production properties

One property of the Higgs boson that is particularly challenging to measure is its quartic HHVV coupling. Deviations to this coupling can significantly enhance VBF HH, particularly

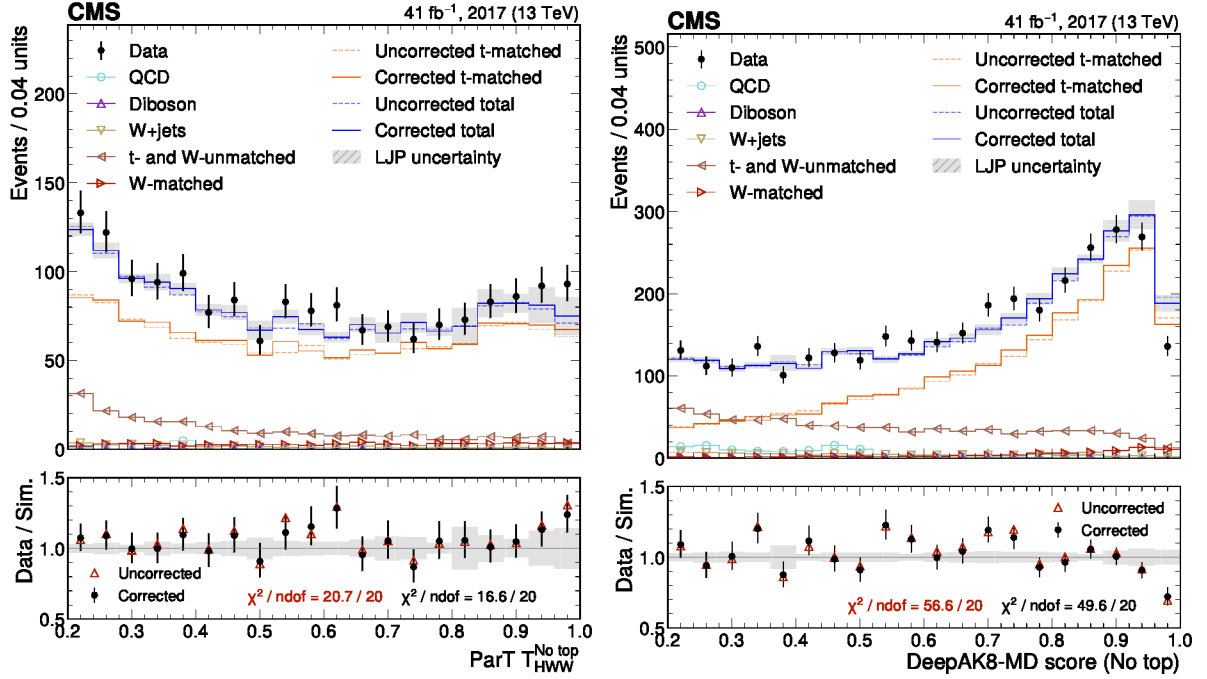


Figure 11: Distributions of the  $\text{PART } T_{\text{HWW}}^{\text{No top}}$  (left) and DEEPAK8-MD (No top) (right) discriminants with and without the LJP corrections for t-matched jets for data and individual simulated processes in the upper panels, and data versus simulation ratios in the lower panels. The combined uncertainties from LJP-based SFs per bin are shown in shaded gray, and the statistical uncertainty in the number of data events per bin is represented by vertical error bars in the upper and lower panels. The  $\chi^2$  test statistic values between data and simulation, normalized to the number of degrees of freedom (ndof), are also shown for both discriminants with and without LJP corrections.

at high HH invariant mass, which is why recent searches for boosted  $\text{HH} \rightarrow \text{b}\bar{\text{b}}\text{b}\bar{\text{b}}$  have been successful in constraining this coupling [13, 93]. This motivates further exploration of boosted HH production, particularly for the first time in the all-hadronic  $\text{b}\bar{\text{b}}\text{W}\text{W}$  channel [31], which represents the largest branching fraction of HH decays after  $\text{b}\bar{\text{b}}\text{b}\bar{\text{b}}$ . However, such a search necessitates powerful classification algorithms for both  $\text{H} \rightarrow \text{b}\bar{\text{b}}$  and  $\text{W}\text{W}^*$  to discriminate against the dominant QCD multijet background.

The primary physics objects considered in the search are two large-radius (AK8) jets, each representing one of the two Higgs bosons, which are tagged as  $\text{H} \rightarrow \text{b}\bar{\text{b}}$  candidates and  $\text{H} \rightarrow \text{W}\text{W}$  candidates using DL algorithms. Offline selections are defined using a selection on the  $\text{H} \rightarrow \text{b}\bar{\text{b}}$  tagging score of the  $\text{b}\bar{\text{b}}$  candidate jet, and multivariate selections using a boosted decision tree (BDT) on the PART scores of the  $\text{W}\text{W}^*$  candidate, along with kinematic variables, targeting the ggF and VBF production modes. Working points for the BDT are optimized for expected limits for ggF and VBF HH cross sections, with signal (background) efficiencies of 7% ( $\approx 0.01\%$ ) and 20% ( $\approx 0.003\%$ ), respectively. As shown in Fig. 5, the PART algorithm is critical to achieving this level of signal-to-background discrimination, and the sensitivity would be significantly negatively impacted using, e.g., DEEPAK8-MD, which has an  $\approx 78\%$  lower  $\text{H} \rightarrow \text{W}\text{W}^* \rightarrow 4\text{q}$  jet tagging efficiency than PART at a 0.1% QCD jet background efficiency.

Several sources of theoretical and experimental systematic uncertainties are considered in the signal and background modeling in the signal regions. Overall, the dominant uncertainty in the HH signal strength is the statistical uncertainty in the QCD multijet background estimation,

driven by the limited data sample size in the signal region, with an impact on the best fit signal strength of 50% relative to the overall uncertainty. The next largest source of uncertainty is in the signal efficiency of the BDT selections on the PART  $H \rightarrow WW$  tagging outputs, measured using the LJP method. A summary of the calculated SFs and uncertainties for different HH signals and signal regions is provided in Table 4, where the overall uncertainty ranges between 15 and 25%, and has a relative impact of 23% on the best fit signal strength. A more detailed description of the all-hadronic  $HH \rightarrow b\bar{b}WW$  search can be found in Section 4.4.2 of Ref. [31].

## 8 Summary

The particle transformer (PART) deep neural network for classifying a wide variety of jets from decays of Lorentz-boosted resonances has been presented. In particular, PART enables effective identification of all-hadronic Higgs boson to W boson ( $H \rightarrow WW^* \rightarrow 4q$ ) decays by the CMS experiment for the first time. A novel training strategy is used to address challenges pertaining to  $H \rightarrow WW$  classification, through which PART achieves  $>50\%$   $H \rightarrow WW^* \rightarrow 4q$  selection efficiency with a multijet background efficiency of 1%, while maintaining decorrelation with the jet mass. The performance is calibrated on data using the primary Lund jet planes of individual subjets, with data-to-simulation scale factors measured in the 0.9–1.0 range, and relative uncertainties between 7 and 23%. The PART algorithm represents a significant advancement in the identification capabilities of multiprong jets from highly boosted resonances in CMS, illustrated by the first search for boosted Higgs boson pair production in the all-hadronic  $b\bar{b}WW$  channel.

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## Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

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






## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, V. Makarenko , A. Tumasyan<sup>1</sup> 

















### Institut für Hochenergiephysik, Vienna, Austria

W. Adam , L. Benato , T. Bergauer , M. Dragicevic , C. Giordano , P.S. Hussain , M. Jeitler<sup>2</sup> , N. Krammer , A. Li , D. Liko , M. Matthewman, J. Schieck<sup>2</sup> , R. Schöfbeck<sup>2</sup> , M. Shooshtari , M. Sonawane , W. Waltenberger , C.-E. Wulz<sup>2</sup> 
















### Universiteit Antwerpen, Antwerpen, Belgium

T. Janssen , H. Kwon , D. Ocampo Henao , T. Van Laer , P. Van Mechelen 

### Vrije Universiteit Brussel, Brussel, Belgium

J. Bierkens , N. Breugelmans, J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , F. Heyen, Y. Hong , P. Kashko , S. Lowette , I. Makarenko , D. Müller , J. Song , S. Tavernier , M. Tytgat<sup>3</sup> , G.P. Van Onsem , S. Van Putte , D. Vannerom 
















### Université Libre de Bruxelles, Bruxelles, Belgium

B. Bilin , B. Clerbaux , A.K. Das, I. De Bruyn , G. De Lentdecker , H. Evard , L. Favart , P. Gianneios , A. Khalilzadeh, F.A. Khan , A. Malara , M.A. Shahzad, A. Sharma , L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer , F. Zhang 












### Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , G. Gokbulut , D. Marckx , K. Skovpen , A.M. Tomaru, N. Van Den Bossche , J. van der Linden , J. Vandenbroeck , L. Wezenbeek 






















### Université Catholique de Louvain, Louvain-la-Neuve, Belgium

H. Aarup Petersen , S. Bein , A. Benecke , A. Bethani , G. Bruno , A. Cappati , J. De Favereau De Jeneret , C. Delaere , F. Gameiro Casalinho , A. Giammanco , A.O. Guzel , V. Lemaitre, J. Lidrych , P. Malek , P. Mastrapasqua , S. Turcpar 












### Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves , M. Barroso Ferreira Filho , E. Coelho , C. Hensel , D. Matos Figueiredo , T. Menezes De Oliveira , C. Mora Herrera , P. Rebello Teles , M. Soeiro , E.J. Tonelli Manganote<sup>4</sup> , A. Vilela Pereira 







### Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W.L. Aldá Júnior , H. Brandao Malbouisson , W. Carvalho , J. Chinellato<sup>5</sup> , M. Costa Reis , E.M. Da Costa , G.G. Da Silveira<sup>6</sup> , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza , S. S. Jesus , T. Laux Kuhn<sup>6</sup> , M. Macedo , K. Mota Amarilo , L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel , F. Torres Da Silva De Araujo<sup>7</sup> 






### Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes<sup>6</sup> , L. Calligaris , F. Damas , T.R. Fernandez Perez Tomei , E.M. Gregores , B. Lopes Da Costa , I. Maitto Silverio , P.G. Mercadante , S.F. Novaes , B. Orzari , Sandra S. Padula , V. Scheurer


### Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov , G. Antchev , P. Danev, R. Hadjiiska , P. Iaydjiev , M. Shopova , G. Sultanov 

**University of Sofia, Sofia, Bulgaria**

A. Dimitrov , L. Litov , B. Pavlov , P. Petkov , A. Petrov 

**Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile**

S. Keshri , D. Laroze , S. Thakur 


**Universidad Tecnica Federico Santa Maria, Valparaiso, Chile**

W. Brooks 















**Beihang University, Beijing, China**

T. Cheng , T. Javaid , L. Wang , L. Yuan 















**Department of Physics, Tsinghua University, Beijing, China**

Z. Hu , Z. Liang, J. Liu, X. Wang , H. Yang


**Institute of High Energy Physics, Beijing, China**

G.M. Chen<sup>8</sup> , H.S. Chen<sup>8</sup> , M. Chen<sup>8</sup> , Y. Chen , Q. Hou , X. Hou, F. Iemmi , C.H. Jiang, H. Liao , G. Liu , Z.-A. Liu<sup>9</sup> , J.N. Song<sup>9</sup>, S. Song , J. Tao , C. Wang<sup>8</sup>, J. Wang , H. Zhang , J. Zhao 


**State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**

A. Agapitos , Y. Ban , A. Carvalho Antunes De Oliveira , S. Deng , D. Fu , B. Guo, Q. Guo, C. Jiang , A. Levin , C. Li , Q. Li , Y. Mao, S. Qian, S.J. Qian , X. Qin, C. Quaranta , X. Sun , D. Wang , J. Wang, M. Zhang, Y. Zhao, C. Zhou 

**State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou, China**

S. Yang 

**Sun Yat-Sen University, Guangzhou, China**

Z. You 

**University of Science and Technology of China, Hefei, China**

K. Jaffel , N. Lu 

**Nanjing Normal University, Nanjing, China**

G. Bauer<sup>10,11</sup>, Z. Cui<sup>11</sup>, B. Li<sup>12</sup>, H. Wang , K. Yi<sup>13</sup> , J. Zhang 


**Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China**

Y. Li, Y. Zhou<sup>14</sup>





**Zhejiang University, Hangzhou, Zhejiang, China**

Z. Lin , C. Lu , M. Xiao<sup>15</sup> 




**Universidad de Los Andes, Bogota, Colombia**

C. Avila , D.A. Barbosa Trujillo , A. Cabrera , C. Florez , J. Fraga , J.A. Reyes Vega


**Universidad de Antioquia, Medellin, Colombia**

C. Rendón , M. Rodriguez , A.A. Ruales Barbosa , J.D. Ruiz Alvarez 

**University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**

N. Godinovic , D. Lelas , A. Sculac 










**University of Split, Faculty of Science, Split, Croatia**

M. Kovac , A. Petkovic , T. Sculac 

**Institute Rudjer Boskovic, Zagreb, Croatia**

P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , K. Jakovcic, A. Starodumov , T. Susa 

**University of Cyprus, Nicosia, Cyprus**

A. Attikis , K. Christoforou , S. Konstantinou , C. Leonidou , L. Paizanos , F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 

**Charles University, Prague, Czech Republic**

M. Finger<sup>†</sup> , M. Finger Jr. 

**Escuela Politecnica Nacional, Quito, Ecuador**

E. Ayala 



**Universidad San Francisco de Quito, Quito, Ecuador**

E. Carrera Jarrin 







**Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**

S. Elgammal<sup>16</sup>, A. Ellithi Kamel<sup>17</sup> 

**Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**

A. Hussein , H. Mohammed 











**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

M. Kadastik, T. Lange , C. Nielsen , J. Pata , M. Raidal , N. Seeba , L. Tani 

**Department of Physics, University of Helsinki, Helsinki, Finland**

E. Brücken , A. Milieva , K. Osterberg , M. Voutilainen 



**Helsinki Institute of Physics, Helsinki, Finland**

F. Garcia , P. Inkaew , K.T.S. Kallonen , R. Kumar Verma , T. Lampén , K. Lassila-Perini , B. Lehtela , S. Lehti , T. Lindén , N.R. Mancilla Xinto , M. Myllymäki , M.m. Rantanen , S. Saariokari , N.T. Toikka , J. Tuominiemi 


























**Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**

N. Bin Norjoharuddeen , H. Kirschenmann , P. Luukka , H. Petrow 















**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**

M. Besancon , F. Couderc , M. Dejardin , D. Denegri, P. Devouge, J.L. Faure , F. Ferri , P. Gaigne, S. Ganjour , P. Gras , G. Hamel de Monchenault , M. Kumar , V. Lohezic , Y. Maidannyk , J. Malcles , F. Orlandi , L. Portales , S. Ronchi , M.Ö. Sahin , A. Savoy-Navarro<sup>18</sup> , P. Simkina , M. Titov , M. Tornago 

**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**

R. Amella Ranz , F. Beaudette , G. Boldrini , P. Busson , C. Charlot , M. Chiusi , T.D. Cuisset , O. Davignon , A. De Wit , T. Debnath , I.T. Ehle , S. Ghosh , A. Gilbert , R. Granier de Cassagnac , L. Kalipoliti , M. Manoni , M. Nguyen , S. Obraztsov , C. Ochando , R. Salerno , J.B. Sauvan , Y. Sirois , G. Sokmen, L. Urda Gómez , A. Zabi , A. Zghiche 


















**Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**

J.-L. Agram<sup>19</sup> , J. Andrea , D. Bloch , J.-M. Brom , E.C. Chabert , C. Collard , G. Coulon, S. Falke , U. Goerlach , R. Haeberle , A.-C. Le Bihan , M. Meena , O. Poncet , G. Saha , P. Vaucelle 

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**

A. Di Florio 

**Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France**

D. Amram, S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , D. Contardo , P. Depasse , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg , G. Grenier , B. Ille , E. Jourd'Huy, M. Lethuillier , B. Massoteau , L. Mirabito, A. Purohit , M. Vander Donckt , J. Xiao 
























**Georgian Technical University, Tbilisi, Georgia**

I. Bagaturia<sup>20</sup> , I. Lomidze , Z. Tsamalaidze<sup>21</sup> 






**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**

V. Botta , S. Consuegra Rodríguez , L. Feld , K. Klein , M. Lipinski , P. Nattland , V. Oppenländer, A. Pauls , D. Pérez Adán , N. Röwert 





































**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

C. Daumann, S. Diekmann , N. Eich , D. Eliseev , F. Engelke , J. Erdmann , M. Erdmann , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , A. Jung , N. Kumar , M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , A. Pozdnyakov , W. Redjeb , H. Reithler , U. Sarkar , V. Sarkisovi , A. Schmidt , C. Seth, A. Sharma , J.L. Spah , V. Vaulin, S. Zaleski

































**RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**

M.R. Beckers , C. Dziwok , G. Flügge , N. Hoeflich , T. Kress , A. Nowack , O. Pooth , A. Stahl , A. Zotz 




















































**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

A. Abel, M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , I. Andreev , J. Bach , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , F. Blekman<sup>22</sup> , K. Borras<sup>23</sup> , A. Campbell , S. Chatterjee , L.X. Coll Saravia , G. Eckerlin, D. Eckstein , E. Gallo<sup>22</sup> , A. Geiser , M. Guthoff , A. Hinzmann , L. Jeppe , M. Kase-  
mann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Per-  
nia , K.-Y. Lin , K. Lipka<sup>24</sup> , W. Lohmann<sup>25</sup> , J. Malvaso , R. Mankel , I.-A. Melzer-  
Pellmann , M. Mendizabal Morentin , A.B. Meyer , G. Milella , K. Moral Figueroa ,  
A. Mussgiller , L.P. Nair , J. Niedziela , A. Nürnberg , J. Park , E. Ranken ,  
A. Raspereza , D. Rastorguev , L. Rygaard , M. Scham<sup>26,23</sup> , S. Schnake<sup>23</sup> ,  
P. Schütze , C. Schwanenberger<sup>22</sup> , D. Schwarz , D. Selivanova , K. Sharko ,  
M. Shchedrolosiev , D. Stafford , M. Torkian, A. Ventura Barroso , R. Walsh ,  
D. Wang , Q. Wang , K. Wichmann, L. Wiens<sup>23</sup> , C. Wissing , Y. Yang , S. Zakharov ,  
A. Zimmermann Castro Santos 

**University of Hamburg, Hamburg, Germany**

A.R. Alves Andrade , M. Antonello , S. Bollweg, M. Bonanomi , L. Ebeling, K. El Morabit , Y. Fischer , M. Frahm , E. Garutti , A. Grohsjean , A.A. Guvenli , J. Haller , D. Hundhausen, G. Kasieczka , P. Keicher , R. Klanner , W. Korcari , T. Kramer , C.c. Kuo, F. Labe , J. Lange , A. Lobanov , J. Matthiesen, L. Moureaux , K. Nikolopoulos , A. Paasch , K.J. Pena Rodriguez , N. Prouvost, B. Raciti , M. Rieger , D. Savoii , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , R. Ward , B. Wiederspan, M. Wolf , C. Yede 










**Karlsruher Institut fuer Technologie, Karlsruhe, Germany**

S. Brommer , A. Brusamolino , E. Butz , Y.M. Chen , T. Chwalek , A. Dierlamm , G.G. Dincer , D. Druzhkin , U. Elicabuk , N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann<sup>27</sup> , M. Horzela , F. Hummer , U. Husemann , J. Kieseler , M. Klute , J. Knolle , R. Kunnilan Muhammed Rafeek , O. Lavoryk , J.M. Lawhorn , A. Lintuluoto , S. Maier , A.A. Monsch , M. Mormile , Th. Müller , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , R. Schmieder , N. Shadskiy , I. Shvetsov , H.J. Simonis , L. Sowa , L. Stockmeier , K. Tauqeer , M. Toms , B. Topko , N. Trevisani , C. Verstege , T. Voigtländer , R.F. Von Cube , J. Von Den Driesch , M. Wassmer , C. Winter , R. Wolf , W.D. Zeuner , X. Zuo 






**Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece**

G. Anagnostou , G. Daskalakis , A. Kyriakis 










**National and Kapodistrian University of Athens, Athens, Greece**

G. Melachroinos , Z. Painesis , I. Paraskevas , N. Saoulidou , K. Theofilatos , E. Tziaferi , E. Tzovara , K. Vellidis , I. Zisopoulos 







**National Technical University of Athens, Athens, Greece**

T. Chatzistavrou , G. Karapostoli , K. Kousouris , E. Siamarkou , G. Tsipolitis 

**University of Ioánnina, Ioánnina, Greece**

I. Bestintzanos , I. Evangelou , C. Foudas , P. Katsoulis , P. Kokkas , P.G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strologas 

**HUN-REN Wigner Research Centre for Physics, Budapest, Hungary**

C. Hajdu , D. Horvath<sup>28,29</sup> , K. Márton , A.J. Rádl<sup>30</sup> , F. Sikler , V. Veszpremi 





**MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary**

M. Csanád , K. Farkas , A. Fehérkuti<sup>31</sup> , M.M.A. Gadallah<sup>32</sup> , Á. Kadlecik , M. León Coello , G. Pásztor , G.I. Veres 

**Faculty of Informatics, University of Debrecen, Debrecen, Hungary**

B. Ujvari , G. Zilizi 




**HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary**

G. Bencze , S. Czellar , J. Molnar , Z. Szillasi 




**Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary**

T. Csorgo<sup>31</sup> , F. Nemes<sup>31</sup> , T. Novak , I. Szanyi<sup>33</sup> 

**IIT Bhubaneswar, Bhubaneswar, India**

S. Bahinipati , S. Nayak , R. Raturi 

**Panjab University, Chandigarh, India**




S. Bansal , S.B. Beri , V. Bhatnagar , S. Chauhan , N. Dhingra<sup>34</sup> , A. Kaur , H. Kaur , M. Kaur , S. Kumar , T. Sheokand , J.B. Singh , A. Singla 

**University of Delhi, Delhi, India**




























































A. Bhardwaj , A. Chhetri , B.C. Choudhary , A. Kumar , A. Kumar , M. Naimuddin , S. Phor , K. Ranjan , M.K. Saini 


























**Indian Institute of Technology Mandi (IIT-Mandi), Himachal Pradesh, India**

P. Palni 





**University of Hyderabad, Hyderabad, India**S. Acharya<sup>35</sup> , B. Gomber **Indian Institute of Technology Kanpur, Kanpur, India**S. Mukherjee **Saha Institute of Nuclear Physics, HBNI, Kolkata, India**S. Bhattacharya , S. Das Gupta, S. Dutta , S. Dutta, S. Sarkar**Indian Institute of Technology Madras, Madras, India**M.M. Ameen , P.K. Behera , S. Chatterjee , G. Dash , A. Dattamunsi, P. Jana , P. Kalbhor , S. Kamble , J.R. Komaragiri<sup>36</sup> , T. Mishra , P.R. Pujahari , A.K. Sikdar , R.K. Singh , P. Verma , S. Verma , A. Vijay **IISER Mohali, India, Mohali, India**

B.K. Sirasva






















**Tata Institute of Fundamental Research-A, Mumbai, India**L. Bhatt, S. Dugad , G.B. Mohanty , M. Shelake , P. Suryadevara**Tata Institute of Fundamental Research-B, Mumbai, India**A. Bala , S. Banerjee , S. Barman<sup>37</sup> , R.M. Chatterjee, M. Guchait , Sh. Jain , A. Jaiswal, S. Kumar , M. Maity<sup>37</sup>, G. Majumder , K. Mazumdar , S. Parolia , R. Saxena , A. Thachayath **National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India**D. Maity<sup>38</sup> , P. Mal , K. Naskar<sup>38</sup> , A. Nayak<sup>38</sup> , K. Pal , P. Sadangi, S.K. Swain , S. Varghese<sup>38</sup> , D. Vats<sup>38</sup> **Indian Institute of Science Education and Research (IISER), Pune, India**S. Dube , P. Hazarika , B. Kansal , A. Laha , R. Sharma , S. Sharma , K.Y. Vaish **Indian Institute of Technology Hyderabad, Telangana, India**S. Ghosh **Isfahan University of Technology, Isfahan, Iran**H. Bakhshiansohi<sup>39</sup> , A. Jafari<sup>40</sup> , V. Sedighzadeh Dalavi , M. Zeinali<sup>41</sup> **Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**S. Bashiri , S. Chenarani<sup>42</sup> , S.M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie , M. Mohammadi Najafabadi , S. Tizchang<sup>43</sup> **University College Dublin, Dublin, Ireland**M. Felcini , M. Grunewald **INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy**M. Abbrescia<sup>a,b</sup> , M. Barbieri<sup>a,b</sup>, M. Buonsante<sup>a,b</sup> , A. Colaleo<sup>a,b</sup> , D. Creanza<sup>a,c</sup> , N. De Filippis<sup>a,c</sup> , M. De Palma<sup>a,b</sup> , W. Elmetenawee<sup>a,b,44</sup> , N. Ferrara<sup>a,c</sup> , L. Fiore<sup>a</sup> , L. Generoso<sup>a,b</sup>, L. Longo<sup>a</sup> , M. Louka<sup>a,b</sup> , G. Maggi<sup>a,c</sup> , M. Maggi<sup>a</sup> , I. Margjeka<sup>a</sup> , V. Mastrapasqua<sup>a,b</sup> , S. My<sup>a,b</sup> , F. Nenna<sup>a,b</sup> , S. Nuzzo<sup>a,b</sup> , A. Pellecchia<sup>a,b</sup> , A. Pompili<sup>a,b</sup> , G. Pugliese<sup>a,c</sup> , R. Radogna<sup>a,b</sup> , D. Ramos<sup>a</sup> , A. Ranieri<sup>a</sup> , L. Silvestris<sup>a</sup> , F.M. Simone<sup>a,c</sup> , Ü. Sözbilir<sup>a</sup> , A. Stamerra<sup>a,b</sup> , D. Troiano<sup>a,b</sup> , R. Venditti<sup>a,b</sup> , P. Verwilligen<sup>a</sup> , A. Zaza<sup>a,b</sup> **INFN Sezione di Bologna<sup>a</sup>, Università di Bologna<sup>b</sup>, Bologna, Italy**

C. Battilana<sup>a,b</sup> , D. Bonacorsi<sup>a,b</sup> , P. Capiluppi<sup>a,b</sup> , F.R. Cavallo<sup>a</sup> , M. Cuffiani<sup>a,b</sup> , G.M. Dallavalle<sup>a</sup> , T. Diotalevi<sup>a,b</sup> , F. Fabbri<sup>a</sup> , R. Farinelli<sup>a</sup> , D. Fasanella<sup>a</sup> , P. Giacomelli<sup>a</sup> , L. Giommi<sup>a,b</sup> , C. Grandi<sup>a</sup> , L. Guiducci<sup>a,b</sup> , S. Lo Meo<sup>a,45</sup> , M. Lorusso<sup>a,b</sup> , L. Lunerti<sup>a</sup> , S. Marcellini<sup>a</sup> , G. Masetti<sup>a</sup> , F.L. Navarra<sup>a,b</sup> , G. Paggi<sup>a,b</sup> , A. Perrotta<sup>a</sup> , A.M. Rossi<sup>a,b</sup> , S. Rossi Tisbeni<sup>a,b</sup> , G.P. Siroli<sup>a,b</sup> 





#### INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, Catania, Italy

S. Costa<sup>a,b,46</sup> , A. Di Mattia<sup>a</sup> , A. Lapertosa<sup>a</sup> , R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,46</sup> 





#### INFN Sezione di Firenze<sup>a</sup>, Università di Firenze<sup>b</sup>, Firenze, Italy

J. Altork<sup>a,b</sup> , P. Assiouras<sup>a</sup> , G. Barbagli<sup>a</sup> , G. Bardelli<sup>a</sup> , M. Bartolini<sup>a,b</sup> , A. Calandri<sup>a,b</sup> , B. Camaiani<sup>a,b</sup> , A. Cassese<sup>a</sup> , R. Ceccarelli<sup>a</sup> , V. Ciulli<sup>a,b</sup> , C. Civinini<sup>a</sup> , R. D'Alessandro<sup>a,b</sup> , L. Damenti<sup>a,b</sup>, E. Focardi<sup>a,b</sup> , T. Kello<sup>a</sup> , G. Latino<sup>a,b</sup> , P. Lenzi<sup>a,b</sup> , M. Lizzo<sup>a</sup> , M. Meschini<sup>a</sup> , S. Paoletti<sup>a</sup> , A. Papanastassiou<sup>a,b</sup>, G. Sguazzoni<sup>a</sup> , L. Viliani<sup>a</sup> 


























#### INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Colafranceschi<sup>47</sup> , S. Meola<sup>48</sup> , D. Piccolo 









#### INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genova, Italy

M. Alves Gallo Pereira<sup>a</sup> , F. Ferro<sup>a</sup> , E. Robutti<sup>a</sup> , S. Tosi<sup>a,b</sup> 



























#### INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy

A. Benaglia<sup>a</sup> , F. Brivio<sup>a</sup> , V. Camagni<sup>a,b</sup> , F. Cetorelli<sup>a,b</sup> , F. De Guio<sup>a,b</sup> , M.E. Dinardo<sup>a,b</sup> , P. Dini<sup>a</sup> , S. Gennai<sup>a</sup> , R. Gerosa<sup>a,b</sup> , A. Ghezzi<sup>a,b</sup> , P. Govoni<sup>a,b</sup> , L. Guzzi<sup>a</sup> , M.R. Kim<sup>a</sup> , G. Lavizzari<sup>a,b</sup>, M.T. Lucchini<sup>a,b</sup> , M. Malberti<sup>a</sup> , S. Malvezzi<sup>a</sup> , A. Massironi<sup>a</sup> , D. Menasce<sup>a</sup> , L. Moroni<sup>a</sup> , M. Paganoni<sup>a,b</sup> , S. Palluotto<sup>a,b</sup> , D. Pedrini<sup>a</sup> , A. Perego<sup>a,b</sup> , G. Pizzati<sup>a,b</sup> , T. Tabarelli de Fatis<sup>a,b</sup> 










#### INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy; Università della Basilicata<sup>c</sup>, Potenza, Italy; Scuola Superiore Meridionale (SSM)<sup>d</sup>, Napoli, Italy

S. Buontempo<sup>a</sup> , C. Di Fraia<sup>a,b</sup> , F. Fabozzi<sup>a,c</sup> , L. Favilla<sup>a,d</sup> , A.O.M. Iorio<sup>a,b</sup> , L. Lista<sup>a,b,49</sup> , P. Paolucci<sup>a,27</sup> , B. Rossi<sup>a</sup> 












#### INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università degli Studi di Cagliari<sup>c</sup>, Cagliari, Italy

P. Azzi<sup>a</sup> , N. Bacchetta<sup>a,50</sup> , D. Bisello<sup>a,b</sup> , P. Bortignon<sup>a,c</sup> , G. Bortolato<sup>a,b</sup> , A.C.M. Bulla<sup>a,c</sup> , R. Carlin<sup>a,b</sup> , P. Checchia<sup>a</sup> , T. Dorigo<sup>a,51</sup> , S. Fantinel<sup>a</sup> , F. Gasparini<sup>a,b</sup> , U. Gasparini<sup>a,b</sup> , S. Giorgetti<sup>a</sup> , E. Lusiani<sup>a</sup> , M. Margoni<sup>a,b</sup> , J. Pazzini<sup>a,b</sup> , F. Primavera<sup>a,b</sup> , P. Ronchese<sup>a,b</sup> , R. Rossin<sup>a,b</sup> , F. Simonetto<sup>a,b</sup> , M. Tosi<sup>a,b</sup> , A. Triossi<sup>a,b</sup> , S. Ventura<sup>a</sup> , P. Zotto<sup>a,b</sup> , A. Zucchetta<sup>a,b</sup> , G. Zumerle<sup>a,b</sup> 

#### INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy


































A. Braghieri<sup>a</sup> , S. Calzaferri<sup>a,b</sup> , P. Montagna<sup>a,b</sup> , M. Pelliccioni<sup>a,b</sup> , V. Re<sup>a</sup> , C. Riccardi<sup>a,b</sup> , P. Salvini<sup>a</sup> , I. Vai<sup>a,b</sup> , P. Vitulo<sup>a,b</sup> 

#### INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy

























S. Ajmal<sup>a,b</sup> , M.E. Ascioti<sup>a,b</sup>, G.M. Bilei<sup>a</sup> , C. Carrivale<sup>a,b</sup>, D. Ciangottini<sup>a,b</sup> , L. Della Penna<sup>a,b</sup>, L. Fanò<sup>a,b</sup> , V. Mariani<sup>a,b</sup> , M. Menichelli<sup>a</sup> , F. Moscatelli<sup>a,52</sup> , A. Rossi<sup>a,b</sup> , A. Santocchia<sup>a,b</sup> , D. Spiga<sup>a</sup> , T. Tedeschi<sup>a,b</sup> 

#### INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy; Università di Siena<sup>d</sup>, Siena, Italy









































C. Aimè<sup>a,b</sup> , C.A. Alexe<sup>a,c</sup> , P. Asenov<sup>a,b</sup> , P. Azzurri<sup>a</sup> , G. Bagliesi<sup>a</sup> , L. Bianchini<sup>a,b</sup> 

T. Boccali<sup>a</sup> , E. Bossini<sup>a</sup> , D. Bruschini<sup>a,c</sup> , R. Castaldi<sup>a</sup> , F. Cattafesta<sup>a,c</sup> , M.A. Ciocci<sup>a,d</sup> , M. Cipriani<sup>a,b</sup> , R. Dell'Orso<sup>a</sup> , S. Donato<sup>a,b</sup> , R. Forti<sup>a,b</sup> , A. Giassi<sup>a</sup> , F. Ligabue<sup>a,c</sup> , A.C. Marini<sup>a,b</sup> , A. Messineo<sup>a,b</sup> , S. Mishra<sup>a</sup> , V.K. Muraleedharan Nair Bindhu<sup>a,b</sup> , S. Nandan<sup>a</sup> , F. Palla<sup>a</sup> , M. Riggirello<sup>a,c</sup> , A. Rizzi<sup>a,b</sup> , G. Rolandi<sup>a,c</sup> , S. Roy Chowdhury<sup>a,53</sup> , T. Sarkar<sup>a</sup> , A. Scribano<sup>a</sup> , P. Solanki<sup>a,b</sup> , P. Spagnolo<sup>a</sup> , F. Tenchini<sup>a,b</sup> , R. Tenchini<sup>a</sup> , G. Tonelli<sup>a,b</sup> , N. Turini<sup>a,d</sup> , F. Vaselli<sup>a,c</sup> , A. Venturi<sup>a</sup> , P.G. Verdini<sup>a</sup> 







#### INFN Sezione di Roma<sup>a</sup>, Sapienza Università di Roma<sup>b</sup>, Roma, Italy

P. Akrap<sup>a,b</sup> , C. Basile<sup>a,b</sup> , S.C. Behera<sup>a</sup> , F. Cavallari<sup>a</sup> , L. Cunqueiro Mendez<sup>a,b</sup> , F. De Ruggi<sup>a,b</sup> , D. Del Re<sup>a,b</sup> , E. Di Marco<sup>a</sup> , M. Diemoz<sup>a</sup> , F. Errico<sup>a</sup> , L. Frosina<sup>a,b</sup> , R. Gargiulo<sup>a,b</sup> , B. Harikrishnan<sup>a,b</sup> , F. Lombardi<sup>a,b</sup> , E. Longo<sup>a,b</sup> , L. Martikainen<sup>a,b</sup> , J. Mijuskovic<sup>a,b</sup> , G. Organtini<sup>a,b</sup> , N. Palmeri<sup>a,b</sup> , R. Paramatti<sup>a,b</sup> , S. Rahatlou<sup>a,b</sup> , C. Rovelli<sup>a</sup> , F. Santanastasio<sup>a,b</sup> , L. Soffi<sup>a</sup> , V. Vladimirov<sup>a,b</sup>

#### INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Torino, Italy; Università del Piemonte Orientale<sup>c</sup>, Novara, Italy

N. Amapane<sup>a,b</sup> , R. Arcidiacono<sup>a,c</sup> , S. Argiro<sup>a,b</sup> , M. Arneodo<sup>a,c</sup> , N. Bartosik<sup>a,c</sup> , R. Bellan<sup>a,b</sup> , A. Bellora<sup>a,b</sup> , C. Biino<sup>a</sup> , C. Borca<sup>a,b</sup> , N. Cartiglia<sup>a</sup> , M. Costa<sup>a,b</sup> , R. Covarelli<sup>a,b</sup> , N. Demaria<sup>a</sup> , L. Finco<sup>a</sup> , M. Grippo<sup>a,b</sup> , B. Kiani<sup>a,b</sup> , L. Lanteri<sup>a,b</sup> , F. Legger<sup>a</sup> , F. Luongo<sup>a,b</sup> , C. Mariotti<sup>a</sup> , S. Maselli<sup>a</sup> , A. Mecca<sup>a,b</sup> , L. Menzio<sup>a,b</sup> , P. Meridiani<sup>a</sup> , E. Migliore<sup>a,b</sup> , M. Monteno<sup>a</sup> , M.M. Obertino<sup>a,b</sup> , G. Ortona<sup>a</sup> , L. Pacher<sup>a,b</sup> , N. Pastrone<sup>a</sup> , M. Ruspa<sup>a,c</sup> , F. Siviero<sup>a,b</sup> , V. Sola<sup>a,b</sup> , A. Solano<sup>a,b</sup> , A. Staiano<sup>a</sup> , C. Tarricone<sup>a,b</sup> , D. Trocino<sup>a</sup> , G. Umoret<sup>a,b</sup> , E. Vlasov<sup>a,b</sup> , R. White<sup>a,b</sup> 

#### INFN Sezione di Trieste<sup>a</sup>, Università di Trieste<sup>b</sup>, Trieste, Italy

J. Babbar<sup>a,b,53</sup> , S. Belforte<sup>a</sup> , V. Candelise<sup>a,b</sup> , M. Casarsa<sup>a</sup> , F. Cossutti<sup>a</sup> , K. De Leo<sup>a</sup> , G. Della Ricca<sup>a,b</sup> , R. Delli Gatti<sup>a,b</sup> 

#### Kyungpook National University, Daegu, Korea

S. Dogra , J. Hong , J. Kim, T. Kim , D. Lee , H. Lee , J. Lee, S.W. Lee , C.S. Moon , Y.D. Oh , S. Sekmen , B. Tae, Y.C. Yang 





#### Department of Mathematics and Physics - GWNU, Gangneung, Korea

M.S. Kim 

#### Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

G. Bak , P. Gwak , H. Kim , D.H. Moon , J. Seo 

#### Hanyang University, Seoul, Korea

E. Asilar , F. Carnevali , J. Choi<sup>54</sup> , T.J. Kim , Y. Ryou 

#### Korea University, Seoul, Korea

S. Ha , S. Han, B. Hong , J. Kim , K. Lee, K.S. Lee , S. Lee , J. Yoo 






#### Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh , J. Shin , S. Yang 

#### Sejong University, Seoul, Korea

Y. Kang , H. S. Kim , Y. Kim , B. Ko, S. Lee 

#### Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi , J. Choi, W. Jun , H. Kim , J. Kim , T. Kim, Y. Kim , Y.W. Kim , S. Ko , H. Lee , J. Lee , J. Lee , B.H. Oh , J. Shin , U.K. Yang, I. Yoon 

**University of Seoul, Seoul, Korea**

W. Jang , D.Y. Kang, D. Kim , S. Kim , J.S.H. Lee , Y. Lee , I.C. Park , Y. Roh, I.J. Watson 

**Yonsei University, Department of Physics, Seoul, Korea**

G. Cho, K. Hwang , B. Kim , S. Kim, K. Lee , H.D. Yoo 


**Sungkyunkwan University, Suwon, Korea**

Y. Lee , I. Yu 

**College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait**

T. Beyrouthy , Y. Gharbia 


**Kuwait University - College of Science - Department of Physics, Safat, Kuwait**

F. Alazemi 

**Riga Technical University, Riga, Latvia**

K. Dreimanis , O.M. Eberlins , A. Gaile , C. Munoz Diaz , D. Osite , G. Pikurs , R. Plese , A. Potrebko , M. Seidel , D. Sidiropoulos Kontos 

**University of Latvia (LU), Riga, Latvia**

N.R. Strautnieks 

**Vilnius University, Vilnius, Lithuania**

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**National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**

I. Yusuff<sup>55</sup> , Z. Zolkapli



**Universidad de Sonora (UNISON), Hermosillo, Mexico**

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**University of Montenegro, Podgorica, Montenegro**

I. Bubanja , N. Raicevic 

**University of Canterbury, Christchurch, New Zealand**

P.H. Butler 





**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**

A. Ahmad , M.I. Asghar , A. Awais , M.I.M. Awan, W.A. Khan 







**AGH University of Krakow, Krakow, Poland**

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

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














**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**

K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski ,  
A. Muhammad 





**Warsaw University of Technology, Warsaw, Poland**

P. Fokow , K. Pozniak , W. Zabolotny 

**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**

M. Araujo , D. Bastos , C. Beirão Da Cruz E Silva , A. Boletti , M. Bozzo ,  
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

























**Faculty of Physics, University of Belgrade, Belgrade, Serbia**

P. Adzic , L. Markovic , P. Milenovic , V. Milosevic 

**VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**

D. Devetak , M. Dordevic , J. Milosevic , L. Nadderd , V. Rekovic, M. Stojanovic 
















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














**Universidad Autónoma de Madrid, Madrid, Spain**

J.F. de Trocóniz 



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**Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain**

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

**University of Colombo, Colombo, Sri Lanka**

B. Kailasapathy<sup>56</sup> , D.D.C. Wickramarathna 

**University of Ruhuna, Department of Physics, Matara, Sri Lanka**














W.G.D. Dharmaratna<sup>57</sup> , K. Liyanage , N. Perera 

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
























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C.E. Brown , C. Caillol , G. Cerminara , P. Connor , K. Cormier , D. d'Enterria 

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
















#### **PSI Center for Neutron and Muon Sciences, Villigen, Switzerland**

T. Bevilacqua<sup>60</sup> , L. Caminada<sup>60</sup> , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , U. Langenegger , A. Nigamova , L. Noehte<sup>60</sup> , T. Rohe , A. Samalan 

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






#### **Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>61</sup> , P. Bärtschi , F. Bilandzija , M.F. Canelli , G. Celotto , V. Guglielmi , A. Jofrehei , B. Kilminster , T.H. Kwok , S. Leontsinis , V. Lukashenko , A. Macchiolo , F. Meng , M. Missiroli , J. Motta , P. Robmann, E. Shokr , F. Stäger , R. Tramontano , P. Viscone 

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D. Bhowmik, C.M. Kuo, P.K. Rout , S. Taj , P.C. Tiwari<sup>36</sup> 


#### **National Taiwan University (NTU), Taipei, Taiwan**

L. Ceard, K.F. Chen , Z.g. Chen, A. De Iorio , W.-S. Hou , T.h. Hsu, Y.w. Kao, S. Karmakar , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , X.f. Su , J. Thomas-Wilsker , L.s. Tsai, D. Tsionou, H.y. Wu , E. Yazgan 
















#### **High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand**

C. Asawatangkuldee , N. Srimanobhas 

#### **Tunis El Manar University, Tunis, Tunisia**

Y. Maghrbi 

#### **Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey**

D. Agyel , F. Dolek , I. Dumanoglu<sup>62</sup> , Y. Guler<sup>63</sup> , E. Gurpinar Guler<sup>63</sup> , C. Isik , O. Kara<sup>64</sup> , A. Kayis Topaksu , Y. Komurcu , G. Onengut , K. Ozdemir<sup>65</sup> , B. Tali<sup>66</sup> , U.G. Tok , E. Uslan , I.S. Zorbakir 

#### **Hacettepe University, Ankara, Turkey**

S. Sen 




**Middle East Technical University, Physics Department, Ankara, Turkey**

M. Yalvac<sup>67</sup> 







**Bogazici University, Istanbul, Turkey**

B. Akgun , I.O. Atakisi<sup>68</sup> , E. Gülmez , M. Kaya<sup>69</sup> , O. Kaya<sup>70</sup> , M.A. Sarkisla<sup>71</sup>,  
S. Tekten<sup>72</sup> 







**Istanbul Technical University, Istanbul, Turkey**

D. Boncukcu , A. Cakir , K. Cankocak<sup>62,73</sup> 

**Istanbul University, Istanbul, Turkey**

B. Hacisahinoglu , I. Hos<sup>74</sup> , B. Kaynak , S. Ozkorucuklu , O. Potok , H. Sert ,  
C. Simsek , C. Zorbilmez 


**Yildiz Technical University, Istanbul, Turkey**

S. Cerci , C. Dozen<sup>75</sup> , B. Isildak , E. Simsek , D. Sunar Cerci , T. Yetkin<sup>75</sup> 














**Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine**

A. Boyaryntsev , O. Dadazhanova, B. Grynyov 






















**National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine**

L. Levchuk 









































**University of Bristol, Bristol, United Kingdom**

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varan , L. Robertshaw , M.S. Sanjrani<sup>39</sup>, J. Segal, V.J. Smith 




**Rutherford Appleton Laboratory, Didcot, United Kingdom**

A.H. Ball, K.W. Bell , A. Belyaev<sup>76</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill ,  
A. Elliot , K.V. Ellis, J. Gajownik , K. Harder , S. Harper , J. Linacre , K. Manolopoulos,  
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








**Imperial College, London, United Kingdom**








































































































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K.H. Law , J. León Holgado , L. Lyons , A.-M. Magnan , B. Maier , S. Mallios ,  
A. Mastronikolis , M. Mieskolainen , J. Nash<sup>77</sup> , M. Pesaresi , P.B. Pradeep ,  
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R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , T. Virdee<sup>27</sup> , M. Vojinovic ,  
N. Wardle , D. Winterbottom 

**Brunel University, Uxbridge, United Kingdom**

J.E. Cole , A. Khan, P. Kyberd , I.D. Reid 

**Baylor University, Waco, Texas, USA**

S. Abdullin , A. Brinkerhoff , E. Collins , M.R. Darwish , J. Dittmann ,  
K. Hatakeyama , V. Hegde , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant ,  
C. Sutantawibul , J. Wilson 

**Bethel University, St. Paul, Minnesota, USA**J.M. Hogan **Catholic University of America, Washington, DC, USA**R. Bartek , A. Dominguez , S. Raj , B. Sahu<sup>35</sup> , A.E. Simsek , S.S. Yu **The University of Alabama, Tuscaloosa, Alabama, USA**B. Bam , A. Buchot Perraguin , S. Campbell, R. Chudasama , S.I. Cooper , C. Crovella , G. Fidalgo , S.V. Gleyzer , A. Khukhunaishvili , K. Matchev , E. Pearson, P. Rumerio<sup>78</sup> , E. Usai , R. Yi **Boston University, Boston, Massachusetts, USA**S. Cholak , G. De Castro, Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , J. Fulcher , F. Golf , S. Jeon , J. O'Cain, I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , E. Wurtz, A.G. Zecchinelli **Brown University, Providence, Rhode Island, USA**G. Barone , G. Benelli , D. Cutts , S. Ellis , L. Gouskos , M. Hadley , U. Heintz , K.W. Ho , T. Kwon , L. Lambrecht , G. Landsberg , K.T. Lau , J. Luo , S. Mondal , J. Roloff , T. Russell , S. Sagir<sup>79</sup> , X. Shen , M. Stamenkovic , N. Venkatasubramanian **University of California, Davis, Davis, California, USA**S. Abbott , S. Baradia , B. Barton , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , E. Cannart, M. Chertok , M. Citron , J. Conway , P.T. Cox , F. Eble , R. Erbacher , O. Kukral , G. Mocellin , S. Ostrom , I. Salazar Segovia, J.S. Tafoya Vargas , W. Wei , S. Yoo **University of California, Los Angeles, California, USA**K. Adamidis, M. Bachtis , D. Campos, R. Cousins , S. Crossley , G. Flores Avila , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , Y.f. Lo , E. Manca , A. Nunez Del Prado , D. Saltzberg , V. Valuev **University of California, Riverside, Riverside, California, USA**R. Clare , J.W. Gary , G. Hanson **University of California, San Diego, La Jolla, California, USA**A. Aportela , A. Arora , J.G. Branson , S. Cittolin , S. Cooperstein , B. D'Anzi , D. Diaz , J. Duarte , L. Giannini , Y. Gu, J. Guiang , V. Krutelyov , R. Lee , J. Letts , H. Li, M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , D. Primosch, M. Quinnan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , A. Yagil , Z. Zhao **University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA**A. Barzdukas , L. Brennan , C. Campagnari , S. Carron Montero<sup>80</sup> , K. Downham , C. Grieco , M.M. Hussain, J. Incandela , M.W.K. Lai, A.J. Li , P. Masterson , J. Richman , S.N. Santpur , R. Schmitz , D. Stuart , T.Á. Vami , X. Yan , D. Zhang **California Institute of Technology, Pasadena, California, USA**A. Albert , S. Bhattacharya , A. Bornheim , O. Cerri, R. Kansal , J. Mao , H.B. Newman , G. Reales Gutiérrez, T. Sievert, M. Spiropulu , J.R. Vlimant , R.A. Wynne , S. Xie **Carnegie Mellon University, Pittsburgh, Pennsylvania, USA**J. Alison , S. An , M. Cremonesi, V. Dutta , E.Y. Ertorer , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, M. Kanemura, C. Liu , M. Marchegiani 

P. Meiring , S. Murthy , P. Palit , K. Park , M. Paulini , A. Roberts , A. Sanchez , W. Terrill 
































































#### **University of Colorado Boulder, Boulder, Colorado, USA**

J.P. Cumalat , W.T. Ford , A. Hart , S. Kwan , J. Pearkes , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 



















#### **Cornell University, Ithaca, New York, USA**

J. Alexander , X. Chen , J. Dickinson , A. Duquette, J. Fan , X. Fan , J. Grassi , S. Hogan , P. Kotamnives , J. Monroy , G. Niendorf , M. Oshiro , J.R. Patterson , A. Ryd , J. Thom , P. Wittich , R. Zou , L. Zygala 













#### **Fermi National Accelerator Laboratory, Batavia, Illinois, USA**

M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , C. Cosby , G. Cummings , I. Dutta , V.D. Elvira , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , J. Hirschauer , V. Innocente , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , B. Klima , S. Lammel , C. Lee , D. Lincoln , R. Lipton , T. Liu , K. Maeshima , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena<sup>81</sup> , C.E. Perez Lara , V. Perovic , F. Ravera , A. Reinsvold Hall<sup>82</sup> , L. Ristori , M. Safdari , E. Sexton-Kennedy , E. Smith , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , C. Wang , I. Zoi 

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C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field, C. Huh , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , V. Sulimov , Y. Takahashi , J. Wang 
























#### **Florida State University, Tallahassee, Florida, USA**

T. Adams , A. Al Kadhim , A. Askew , S. Bower , R. Goff, R. Hashmi , A. Hassani , R.S. Kim , T. Kolberg , G. Martinez , M. Mazza , H. Prosper , P.R. Prova, R. Yohay 










#### **Florida Institute of Technology, Melbourne, Florida, USA**

B. Alsufyani , S. Butalla , S. Das , M. Hohlmann , M. Lavinsky, E. Yanes











#### **University of Illinois Chicago, Chicago, Illinois, USA**

M.R. Adams , N. Barnett, A. Baty , C. Bennett , R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , H. Gupta , M. Hawksworth , A. Hingrajiya, D.J. Hofman , Z. Huang , J.h. Lee , C. Mills , S. Nanda , G. Nigmatkulov , B. Ozek , T. Phan, D. Pilipovic , R. Pradhan , E. Prifti, P. Roy, T. Roy , D. Shekar, N. Singh, A. Thielen, M.B. Tonjes , N. Varelas , M.A. Wadud , J. Yoo 
























#### **The University of Iowa, Iowa City, Iowa, USA**

M. Alhusseini , D. Blend , K. Dilsiz<sup>83</sup> , O.K. Köseyan , A. Mestvirishvili<sup>84</sup> , O. Neogi, H. Ogul<sup>85</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>86</sup> 










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B. Blumenfeld , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , S. Sekhar , M.V. Srivastav , M. Swartz 



















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A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , R. Bhattacharya , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , S. Popescu<sup>87</sup> , C. Rogan , C. Royon , S. Rudrabhatla , S. Sanders , C. Smith , G. Wilson 





































**Kansas State University, Manhattan, Kansas, USA**

B. Allmond , N. Islam , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , G.G. Reddy , D. Roy , G. Sorrentino 













**University of Maryland, College Park, Maryland, USA**

A. Baden , A. Belloni , J. Bistany-riebman , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim , S. Lascio , P. Major , A.C. Mignerey , C. Palmer , C. Papageorgakis , M.M. Paranjpe , E. Popova<sup>88</sup> , A. Shevelev , L. Zhang 














**Massachusetts Institute of Technology, Cambridge, Massachusetts, USA**

C. Baldenegro Barrera , H. Bossi , S. Bright-Thonney , I.A. Cali , Y.c. Chen , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov , G. Grosso , P. Harris , D. Hoang , G.M. Innocenti , K. Ivanov , D. Kovalskiy , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , C. Mcginn , A. Novak , M.I. Park , C. Paus , C. Reissel , C. Roland , G. Roland , S. Rothman , T.a. Sheng , G.S.F. Stephans , D. Walter , J. Wang , Z. Wang , B. Wyslouch , T. J. Yang 














**University of Minnesota, Minneapolis, Minnesota, USA**

A. Alpana , B. Crossman , W.J. Jackson , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , R. Rusack , O. Sancar , R. Saradhy , N. Strobbe 





















**University of Nebraska-Lincoln, Lincoln, Nebraska, USA**

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , K.H.M. Kwok , A. Rohilla , J.E. Siado , W. Tabb , A. Vagnerini , A. Wightman , F. Yan 










**State University of New York at Buffalo, Buffalo, New York, USA**

H. Bandyopadhyay , L. Hay , H.w. Hsia , I. Iashvili , A. Kalogeropoulos , A. Kharchilava , A. Mandal , M. Morris , D. Nguyen , S. Rappoccio , H. Rejeb Sfar , A. Williams , D. Yu 
































**Northeastern University, Boston, Massachusetts, USA**

A. Aarif , G. Alverson , E. Barberis , J. Bonilla , B. Bylsma , M. Campana , J. Dervan , Y. Haddad , Y. Han , I. Israr , A. Krishna , M. Lu , N. Manganelli , R. Mccarthy , D.M. Morse , T. Orimoto , L. Skinnari , C.S. Thoreson , E. Tsai , D. Wood 






**Northwestern University, Evanston, Illinois, USA**

S. Dittmer , K.A. Hahn , M. Mcginnis , Y. Miao , D.G. Monk , M.H. Schmitt , A. Taliercio , M. Velasco , J. Wang 


















**University of Notre Dame, Notre Dame, Indiana, USA**

G. Agarwal , R. Band , R. Bucci , S. Castells , A. Das , A. Datta , A. Ehnis , R. Goldouzian , M. Hildreth , K. Hurtado Anampa , T. Ivanov , C. Jessop , A. Karneyeu , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano , N. Marinelli , T. McCauley , C. Mcgrady , C. Moore , Y. Musienko<sup>21</sup> , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti , A. Townsend , Y. Wan , M. Wayne , H. Yockey 

**The Ohio State University, Columbus, Ohio, USA**

M. Carrigan , R. De Los Santos , L.S. Durkin , C. Hill , M. Joyce , D.A. Wenzl, B.L. Winer , B. R. Yates 















**Princeton University, Princeton, New Jersey, USA**

H. Bouchamaoui , G. Dezoort , P. Elmer , A. Frankenthal , M. Galli , B. Greenberg , N. Haubrich , K. Kennedy, G. Kopp , Y. Lai , D. Lange , A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen , F. Simpson , D. Stickland , C. Tully 




**University of Puerto Rico, Mayaguez, Puerto Rico, USA**

S. Malik , R. Sharma 




















**Purdue University, West Lafayette, Indiana, USA**

S. Chandra , A. Gu , L. Gutay, M. Huwiler , M. Jones , A.W. Jung , D. Kondratyev , J. Li , M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , N.R. Saha , J.F. Schulte , F. Wang , A. Wildridge , W. Xie , Y. Yao , Y. Zhong 











**Purdue University Northwest, Hammond, Indiana, USA**

N. Parashar , A. Pathak , E. Shumka 





















**Rice University, Houston, Texas, USA**

D. Acosta , A. Agrawal , C. Arbour , T. Carnahan , P. Das , K.M. Ecklund , F.J.M. Geurts , T. Huang , I. Krommydas , N. Lewis, W. Li , J. Lin , O. Miguel Colin , B.P. Padley , R. Redjimi , J. Rotter , C. Vico Villalba , M. Wulansatiti , E. Yigitbasi , Y. Zhang 

**University of Rochester, Rochester, New York, USA**

O. Bessidskaia Bylund, A. Bodek , P. de Barbaro<sup>†</sup> , R. Demina , A. Garcia-Bellido , H.S. Hare , O. Hindrichs , N. Parmar , P. Parygin<sup>88</sup> , H. Seo , R. Taus 
















**Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA**

B. Chiarito, J.P. Chou , S.V. Clark , S. Donnelly, D. Gadkari , Y. Gershtein , E. Halkiadakis , C. Houghton , D. Jaroslawski , A. Kobert , I. Laflotte , A. Lath , J. Martins , M. Perez Prada , B. Rand , J. Reichert , P. Saha , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora 

**University of Tennessee, Knoxville, Tennessee, USA**

D. Ally , A.G. Delannoy , S. Fiorendi , J. Harris, T. Holmes , A.R. Kanuganti , N. Karunarathna , J. Lawless, L. Lee , E. Nibigira , B. Skipworth, S. Spanier 













**Texas A&M University, College Station, Texas, USA**

D. Aebi , M. Ahmad , T. Akhter , K. Androsov , A. Basnet , A. Bolshov, O. Bouhali<sup>89</sup> , A. Cagnotta , V. D'Amante , R. Eusebi , P. Flanagan , J. Gilmore , Y. Guo, T. Kamon , S. Luo , R. Mueller , A. Safonov 

**Texas Tech University, Lubbock, Texas, USA**

N. Akchurin , J. Damgov , Y. Feng , N. Gogate , W. Jin , Y. Kazhykarim, K. Lamichhane , S.W. Lee , C. Madrid , A. Mankel , T. Peltola , I. Volobouev 

**Vanderbilt University, Nashville, Tennessee, USA**

E. Appelt , Y. Chen , S. Greene, A. Gurrola , W. Johns , R. Kunnawalkam Elayavalli , A. Melo , D. Rathjens , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen , J. Zhang

**University of Virginia, Charlottesville, Virginia, USA**

























B. Cardwell , H. Chung , B. Cox , J. Hakala , G. Hamilton Ilha Machado, R. Hirosky 

M. Jose, A. Ledovskoy , C. Mantilla , C. Neu , C. Ramón Álvarez , Z. Wu

**Wayne State University, Detroit, Michigan, USA**

S. Bhattacharya , P.E. Karchin 











**University of Wisconsin - Madison, Madison, Wisconsin, USA**

A. Aravind , S. Banerjee , K. Black , T. Bose , E. Chavez , S. Dasu , P. Everaerts , C. Galloni, H. He , M. Herndon , A. Herve , C.K. Koraka , S. Lomte , R. Loveless , A. Mallampalli , A. Mohammadi , S. Mondal, T. Nelson, G. Parida , L. Pétré , D. Pinna , A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi , W. Vetens , A. Warden 

**Authors affiliated with an international laboratory covered by a cooperation agreement with CERN**

S. Afanasiev , V. Alexakhin , Yu. Andreev , T. Aushev , D. Budkouski , R. Chistov , M. Danilov , T. Dimova , A. Ershov , S. Gninenko , I. Gorbunov , A. Gribushin , A. Kamenev , V. Karjavine , M. Kirsanov , V. Klyukhin , O. Kodolova<sup>90</sup> , V. Koronkov , I. Korsakov, A. Kozyrev , N. Krasnikov , A. Lanev , A. Malakhov , V. Matveev , A. Nikitenko<sup>91,90</sup> , V. Palichik , V. Perelygin , S. Petrushanko , O. Radchenko , M. Savina , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen , K. Slizhevskiy, V. Smirnov , O. Teryaev , I. Tlisova , A. Toropin , N. Voytishin , A. Zarubin , I. Zhizhin 

**Authors affiliated with an institute formerly covered by a cooperation agreement with CERN**

L. Dudko , V. Kim<sup>21</sup> , V. Murzin , V. Oreshkin , D. Sosnov , E. Boos , V. Bunichev , M. Dubinin<sup>81</sup> , V. Savrin , A. Snigirev 

†: Deceased

<sup>1</sup>Also at Yerevan State University, Yerevan, Armenia

<sup>2</sup>Also at TU Wien, Vienna, Austria

<sup>3</sup>Also at Ghent University, Ghent, Belgium

<sup>4</sup>Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil

<sup>5</sup>Also at Universidade Estadual de Campinas, Campinas, Brazil

<sup>6</sup>Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

<sup>7</sup>Also at The University of the State of Amazonas, Manaus, Brazil

<sup>8</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>9</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>10</sup>Also at School of Physics, Zhengzhou University, Zhengzhou, China

<sup>11</sup>Now at Henan Normal University, Xinxiang, China

<sup>12</sup>Also at University of Shanghai for Science and Technology, Shanghai, China

<sup>13</sup>Also at The University of Iowa, Iowa City, Iowa, USA

<sup>14</sup>Also at Nanjing Normal University, Nanjing, China

<sup>15</sup>Also at Center for High Energy Physics, Peking University, Beijing, China

<sup>16</sup>Now at British University in Egypt, Cairo, Egypt

<sup>17</sup>Now at Cairo University, Cairo, Egypt

<sup>18</sup>Also at Purdue University, West Lafayette, Indiana, USA

<sup>19</sup>Also at Université de Haute Alsace, Mulhouse, France

<sup>20</sup>Also at Ilia State University, Tbilisi, Georgia

<sup>21</sup>Also at an institute formerly covered by a cooperation agreement with CERN

<sup>22</sup>Also at University of Hamburg, Hamburg, Germany

<sup>23</sup>Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

<sup>24</sup>Also at Bergische University Wuppertal (BUW), Wuppertal, Germany

- <sup>25</sup>Also at Brandenburg University of Technology, Cottbus, Germany
- <sup>26</sup>Also at Forschungszentrum Jülich, Juelich, Germany
- <sup>27</sup>Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- <sup>28</sup>Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
- <sup>29</sup>Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- <sup>30</sup>Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- <sup>31</sup>Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
- <sup>32</sup>Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- <sup>33</sup>Also at The University of Kansas, Lawrence, Kansas, USA
- <sup>34</sup>Also at Punjab Agricultural University, Ludhiana, India
- <sup>35</sup>Also at University of Hyderabad, Hyderabad, India
- <sup>36</sup>Also at Indian Institute of Science (IISc), Bangalore, India
- <sup>37</sup>Also at University of Visva-Bharati, Santiniketan, India
- <sup>38</sup>Also at Institute of Physics, Bhubaneswar, India
- <sup>39</sup>Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- <sup>40</sup>Also at Isfahan University of Technology, Isfahan, Iran
- <sup>41</sup>Also at Sharif University of Technology, Tehran, Iran
- <sup>42</sup>Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- <sup>43</sup>Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
- <sup>44</sup>Also at Helwan University, Cairo, Egypt
- <sup>45</sup>Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- <sup>46</sup>Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- <sup>47</sup>Also at James Madison University, Harrisonburg, Maryland, USA
- <sup>48</sup>Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- <sup>49</sup>Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- <sup>50</sup>Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- <sup>51</sup>Also at Lulea University of Technology, Lulea, Sweden
- <sup>52</sup>Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- <sup>53</sup>Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- <sup>54</sup>Also at Institut de Physique des 2 Infinis de Lyon (IP2I ), Villeurbanne, France
- <sup>55</sup>Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- <sup>56</sup>Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- <sup>57</sup>Also at Saegis Campus, Nugegoda, Sri Lanka
- <sup>58</sup>Also at National and Kapodistrian University of Athens, Athens, Greece
- <sup>59</sup>Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- <sup>60</sup>Also at Universität Zürich, Zurich, Switzerland
- <sup>61</sup>Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- <sup>62</sup>Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- <sup>63</sup>Also at Konya Technical University, Konya, Turkey
- <sup>64</sup>Also at Istanbul Topkapi University, Istanbul, Turkey
- <sup>65</sup>Also at Izmir Bakircay University, Izmir, Turkey
- <sup>66</sup>Also at Adiyaman University, Adiyaman, Turkey
- <sup>67</sup>Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- <sup>68</sup>Also at Istanbul Sabahattin Zaim University, Istanbul, Turkey

- 
- <sup>69</sup>Also at Marmara University, Istanbul, Turkey
- <sup>70</sup>Also at Milli Savunma University, Istanbul, Turkey
- <sup>71</sup>Also at Informatics and Information Security Research Center, Gebze/Kocaeli, Turkey
- <sup>72</sup>Also at Kafkas University, Kars, Turkey
- <sup>73</sup>Now at Istanbul Okan University, Istanbul, Turkey
- <sup>74</sup>Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- <sup>75</sup>Also at Istinye University, Istanbul, Turkey
- <sup>76</sup>Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- <sup>77</sup>Also at Monash University, Faculty of Science, Clayton, Australia
- <sup>78</sup>Also at Università di Torino, Torino, Italy
- <sup>79</sup>Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- <sup>80</sup>Also at California Lutheran University, Thousand Oaks, California, USA
- <sup>81</sup>Also at California Institute of Technology, Pasadena, California, USA
- <sup>82</sup>Also at United States Naval Academy, Annapolis, Maryland, USA
- <sup>83</sup>Also at Bingol University, Bingol, Turkey
- <sup>84</sup>Also at Georgian Technical University, Tbilisi, Georgia
- <sup>85</sup>Also at Sinop University, Sinop, Turkey
- <sup>86</sup>Also at Erciyes University, Kayseri, Turkey
- <sup>87</sup>Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
- <sup>88</sup>Now at another institute formerly covered by a cooperation agreement with CERN
- <sup>89</sup>Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar
- <sup>90</sup>Also at Yerevan Physics Institute, Yerevan, Armenia
- <sup>91</sup>Also at Imperial College, London, United Kingdom