

# Jet peak shapes based on two-particle angular correlations in lead-lead collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

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## Abstract

The longitudinal invariance of jet-induced peaks in two-particle correlation functions from relativistic lead-lead collisions is experimentally explored. The data were collected at a center-of-mass energy per nucleon pair of 5.02 TeV in 2018 using the CMS detector. The dataset corresponds to an integrated luminosity of  $0.607 \text{ nb}^{-1}$ . Long- and short-range correlations are studied through two-dimensional distributions of the separations in pseudorapidity and azimuth between particles in an event. Jets manifest as a well-defined peak at small angular separations, and the shape of this peak provides insight into jet medium interactions. This Letter examines the evolution of the jet peak shape, focusing on the dependence of its width and longitudinal asymmetry on the transverse momentum, collision centrality, and pseudorapidity of the associated charged particles. The jet-peak distributions of lower transverse momentum particles broaden in both pseudorapidity and azimuth with increasing collision overlap, with the broadening in pseudorapidity being more pronounced. The longitudinal asymmetry of the peaks is also found to increase as the average pseudorapidity increases. These results are compared to proton-proton collision data that were obtained at the same nucleon-nucleon collision center-of-mass energy with an integrated luminosity of  $252 \text{ nb}^{-1}$ .

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## 1 Introduction

In ultrarelativistic heavy ion collisions, a deconfined state of quarks and gluons, known as the quark-gluon plasma (QGP), forms as the system reaches equilibrium [1, 2]. In the early stage of such collisions, high-momentum transfer (hard) processes result in high-energy partons. These lead to collimated streams of particles (jets) that interact with the QGP through “jet quenching” phenomena [3]. Experimental evidence for jet quenching has been observed at both the BNL RHIC [4, 5] and the CERN LHC [6–9].

While many previous studies of jet quenching have focused on reconstructing the final-state particle distributions associated with jets at high transverse momentum ( $p_T$ ) [10], two-particle correlations in pseudorapidity ( $\eta$ ) and azimuth ( $\phi$ ) offer a complementary method for studying jet properties in heavy ion collisions. These correlations measure the relative separations in pseudorapidity ( $\Delta\eta$ ) and azimuth ( $\Delta\phi$ ) of a high- $p_T$  “trigger” particle and lower- $p_T$  associated particles. Jets appear as a well-defined “near-side” peak at ( $\Delta\eta = 0, \Delta\phi = 0$ ). In these correlations, an elongated “away-side” structure in  $\Delta\eta$  at  $\Delta\phi = \pi$  is also typically present, corresponding to the recoil parton in a dijet event. For specific kinematic selections of trigger and associated particle transverse momenta, heavy ion collisions reveal a suppression of the away-side and a moderate enhancement for the near-side correlation yields in collisions where there is a large overlap of the nuclei, indicating medium-induced modifications [11–14]. The shape of the jet peak arising from particle correlations within a given jet cone is also sensitive to medium-induced modifications. Two-particle correlation measurements of jet peak shapes allow for simple background corrections and cover a broader range of jet energies and early stage dynamics than typically explored in studies with fully reconstructed jets [15].

In high-energy heavy ion collisions, an approximate invariance is expected of jet yields under longitudinal boosts near midrapidity [16]. However, at forward rapidities, this invariance may break down as a result of the longitudinal expansion of the created medium and the evolving parton densities. Particle densities within given jets can also be affected by the longitudinal expansion. In this study, the shapes of near-side jet peaks in two-particle angular correlations are used to characterize the particle densities within high- $p_T$  jets. By measuring this observable over a wide  $\eta$  range, we investigate the extent to which longitudinal invariance holds and how longitudinal dynamics modify the jet-associated yields. These measurements also provide sensitivity to kinematic regions where initial-state effects, such as parton saturation [17], may become increasingly relevant.

Using PbPb collision data, this Letter examines the angular distribution of associated charged particles relative to a charged hadron trigger across the full  $\phi$  and wide  $\eta$  coverage ( $|\eta| < 2.4$ ) of the CMS detector at the LHC. The data are collected at a center-of-mass energy per nucleon pair of  $\sqrt{s_{NN}} = 5.02$  TeV. Results are also reported for proton-proton (pp) collisions at the same nucleon-nucleon collision center-of-mass energy to provide a reference. Using two-particle correlations, the longitudinal ( $\Delta\eta$ ) and transverse ( $\Delta\phi$ ) widths of the near-side jet peak are determined. In addition, the longitudinal invariance of this peak shape is studied for higher-momentum trigger particles at forward rapidities.

Tabulated results are provided in the HEPData record for this analysis [18].

## 2 Experimental setup and data sample

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume, there is a silicon pixel and

strip tracker that measures the trajectories of charged particles in the range  $|\eta| < 2.5$ , a lead-tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. For charged particles of  $1 < p_T < 10$  GeV and  $|\eta| < 1.4$ , the typical track resolution is 1.5% in  $p_T$  and 25–90 (45–150)  $\mu\text{m}$  in the transverse (longitudinal) impact parameter [19–21]. Steel and quartz-fiber Cherenkov hadron forward (HF) calorimeters cover the range  $2.9 < |\eta| < 5.2$  on either side of the interaction region and are azimuthally divided into  $20^\circ$  modular wedges, which are further segmented to form  $0.175 \times 0.175$  radians ( $\Delta\eta \times \Delta\phi$ ) towers. For heavy ion collisions, centrality is defined as the fraction of the total inelastic hadronic cross section, with 0% corresponding to the full overlap of the two colliding nuclei. A detailed description of the CMS experiment can be found in Ref. [22, 23].

The analysis is based on PbPb (pp) collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV data, which were collected by the CMS experiment in 2018 (2017) with a two-tiered trigger system. The first level trigger consists of custom hardware processors and uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz [24]. The second level or high-level trigger consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing. The PbPb and pp data sets correspond to integrated luminosities of  $0.607 \text{ nb}^{-1}$  [25] and  $252 \text{ nb}^{-1}$  [26–28], respectively, with approximately 4.3 billion PbPb minimum-bias (MB) events and 15 billion pp MB events. The MB events are selected by requiring energy deposition above thresholds in the range of approximately 6–12 GeV in both of the HF calorimeters located on either side of the interaction region [29]. Further selections are applied offline to reject events from background processes (beam-gas interactions and non-hadronic collisions), as discussed in Ref. [30]. In the offline analysis, events are required to have at least one interaction vertex, based on two or more reconstructed tracks, with a distance of less than 15 cm from the center of the nominal interaction point along the beam axis,  $v_z$ . The primary vertex (PV) is defined as the vertex with the highest sum of the squares of the  $p_T$  values of its associated tracks in the event, as described in Section 9.4.1 of Ref. [31]. In the final analysis, the PbPb collision events are required to have at least two calorimeter towers in the HF detectors on both sides of the interaction region with energy deposits of more than 4 GeV per tower. These criteria remove approximately 99% of ultraperipheral (non-hadronic) collision events.

The selected tracks are corrected for tracking efficiency and acceptance using simulated Monte Carlo samples produced by PYTHIA 8.212 [32] with the CP5 tune [33] for pp collisions, and HYDJET 1.9 [34] for PbPb collisions. The HYDJET generator simulates both soft and hard components in heavy ion collisions by combining a parametrized hydrodynamic expansion with multiple PYTHIA/PYQUEN events. While the soft component (track  $p_T \lesssim 5$  GeV) in these simulations shows approximate boost invariance, including at forward rapidity, the hard component (track  $p_T \gtrsim 5$  GeV) does not. This difference between the approximately boost-invariant soft component and the non-invariant hard component reflects HYDJET’s internal modeling assumptions rather than robust physical predictions. The response of the CMS detector to these simulated events is modeled using GEANT4 [35].

### 3 Analysis procedure

High-purity [19] tracks resulting from the passage of charged particles through the detector are selected in the range  $|\eta| < 2.4$ , requiring that the significances of the reconstructed longitudinal distance ( $d_z$ ) and the transverse distance ( $d_{xy}$ ) from the beam axis satisfy  $|d_z|/\sigma_z < 3$  and  $|d_{xy}|/\sigma_{xy} < 3$ , respectively, where  $\sigma_z$  and  $\sigma_{xy}$  denote the associated uncertainties in the measurements of  $d_z$  and  $d_{xy}$ . Additionally, the  $p_T$  resolution for each track, expressed as  $\sigma_{p_T}/p_T$ ,

must be less than 10%. The number of layers hit in the silicon tracker must be greater than ten, and the  $\chi^2$  of the track fit per degree of freedom per layers hit in the silicon tracker is required to be less than 0.18. These conditions define the nominal track selection criteria.

### 3.1 Longitudinal and transverse widths of the near-side jet peak

The correlation between two charged particles is calculated as a function of  $\Delta\eta = \eta_{\text{asso}} - \eta_{\text{trig}}$  and  $\Delta\phi = \phi_{\text{asso}} - \phi_{\text{trig}}$  (defined between  $-\pi/2$  and  $3\pi/2$  to visualize the back-to-back jet peaks). The correlation is expressed in terms of the associated yield per trigger particle in a given interval of trigger and associated particle  $p_T$ . The number of trigger particles for each interval of an event is denoted by  $N_{\text{trig}}$ , which is corrected for the tracking efficiency and the rate of misreconstructed tracks.

The signal distribution,  $S(\Delta\eta, \Delta\phi)$ , is constructed using pairs of particles from the same event, and is normalized by the number of trigger particles. It is defined as

$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{same}}}{d\Delta\eta d\Delta\phi} \quad (1)$$

where  $N^{\text{same}}$  is the number of particle pairs in the  $(\Delta\eta, \Delta\phi)$  bin for the event [36–38].

The mixed events distribution  $B(\Delta\eta, \Delta\phi)$  is constructed by pairing the trigger particles in each interval of an event with the particles from ten different events [36–38]. The mixed-events are selected such that they are within the same centrality (in PbPb collisions) or track multiplicity (in pp collisions) range as the primary event, and such that the relative difference of the PV along the z-axis is less than 2 cm. The mixed-event distribution,  $B(\Delta\eta, \Delta\phi)$ , is given by

$$B(\Delta\eta, \Delta\phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{mix}}}{d\Delta\eta d\Delta\phi} \quad (2)$$

where  $N^{\text{mix}}$  is the number of mixed-event pairs in a given  $(\Delta\eta, \Delta\phi)$  bin [11, 36–40]. The signal and mixed-event distributions are first calculated for each event, and then averaged over all events within the same centrality or track multiplicity class. The correlation function, also referred to as the per-trigger associated yield, is defined as

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\phi} = C_2(\Delta\eta, \Delta\phi) = B(0, 0) \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)} \quad (3)$$

where  $N^{\text{pair}}$  is the pair-acceptance corrected same-event pairs in a given  $(\Delta\eta, \Delta\phi)$  bin.

Figure 1 (left) shows a typical signal distribution, which has the physical correlations in the form of a peak on the top of a triangular-shaped continuum. The mixed-event distribution, shown in Fig. 1 (middle), reflects this continuum, which results from detector-related artifacts, such as the pair-acceptance effect that is also present in the signal distribution. The ratio  $\frac{B(0,0)}{B(\Delta\eta, \Delta\phi)}$  corrects for the pair-acceptance effects present in the signal distribution. After applying this correction, a residual  $\Delta\eta$ -dependent modulation can remain in the mixed-event corrected correlation function. Possible imperfections in the event mixing are examined by studying the  $\Delta\eta$  distribution in the  $\Delta\phi$  sideband region  $1.2 < \Delta\phi < \pi - 1.2$ . Any residual non-uniformity observed in this region is corrected by flattening the corresponding  $\Delta\eta$  dependence. The final pair-acceptance corrected per-trigger associated yield distribution, after all corrections, is shown in Fig. 1 (right) [11, 36–40].

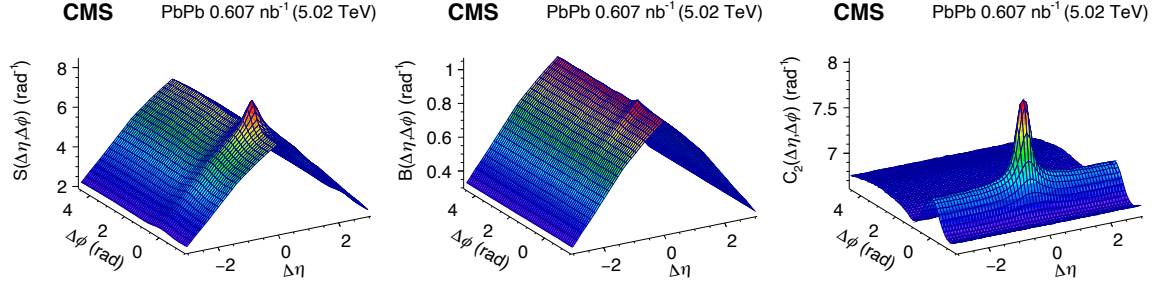


Figure 1: Average signal (left), mixed-event (middle), and pair-acceptance corrected per-trigger associated yield (right) distributions for 0–10% centrality events, with  $4 < p_{T,\text{trig}} < 8$  GeV and  $2 < p_{T,\text{asso}} < 3$  GeV, in PbPb collision data at 5.02 TeV.

A long-range background contribution remains in the distribution. This background is determined using the distribution with  $|\Delta\eta| > 2$  and is subtracted to isolate the near-side, short-range jet correlations.

To determine the longitudinal and transverse widths of the near-side jet peak, the projections of the two-dimensional (2D) correlations onto the  $\Delta\eta$  and  $\Delta\phi$  axes are fitted separately using a double-Gaussian function. The effective width ( $\sigma$ ) of each projected distribution is defined as the amplitude-weighted quadratic mean of the two Gaussian widths of the respective distribution. Figure 2 shows the one-dimensional (1D)  $\Delta\eta$  and  $\Delta\phi$  projections along with the associated fits for the respective ranges of  $|\Delta\eta| < 2$  and  $|\Delta\phi| < 1.5$ .

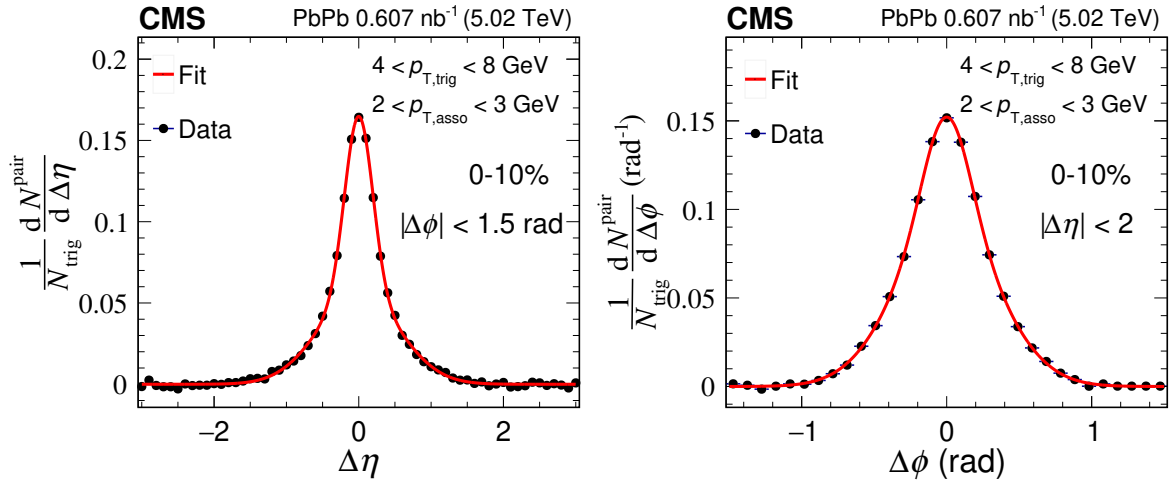


Figure 2: (Left) One-dimensional  $\Delta\eta$  projection and (right) One-dimensional  $\Delta\phi$  projection.

### 3.2 Longitudinal asymmetry of the near-side peak from mid to forward rapidity

The Longitudinal invariance of the near-side peak is investigated by studying the asymmetry of the associated yield around  $\Delta\eta = 0$  as a function of  $\eta_{\text{trig}}$  using two-particle correlations. The analysis is performed for eight trigger particle  $\eta$  ranges, with range boundaries  $[-2, -1.5, -1, -0.5, 0, 0.5, 1, 1.5, 2]$ . For symmetric systems there should be mirror symmetry, with the distribution for  $\eta_{\text{trig}} > 0$  being the mirror image of the distribution for  $\eta_{\text{trig}} < 0$ .

Figure 3 shows the average of the  $C_2(\Delta\eta, \Delta\phi)$  distributions for  $1.5 < \eta_{\text{trig}} < 2$  and the mirror image of  $C_2$  for  $-2 < \eta_{\text{trig}} < -1.5$ , with  $|\eta_{\text{asso}}| < 2.4$ , in PbPb (left) and pp (right) collisions. The  $p_T$  ranges for the trigger and associated particles are  $12 < p_{T,\text{trig}} < 16$  GeV and  $2 < p_{T,\text{asso}} <$

3 GeV, respectively.

Fig. 4 shows the 1D projections in  $\Delta\eta$  with  $|\Delta\phi| < 1.5$  after subtracting a long-range background contribution. This long-range contribution is obtained using the projected values with  $|\Delta\eta| > 2$ . The asymmetry of the jet peak shape is characterized by taking the ratio of associated yields ( $Y$ ) within an  $\eta_{\text{asso}}$  range of 0.7 units on either side of the peak,  $Y_{\Delta\eta>0}/Y_{\Delta\eta<0}$ . The range boundaries are chosen to avoid edge effects influencing the results in any of the measured  $\eta_{\text{trig}}$  ranges.

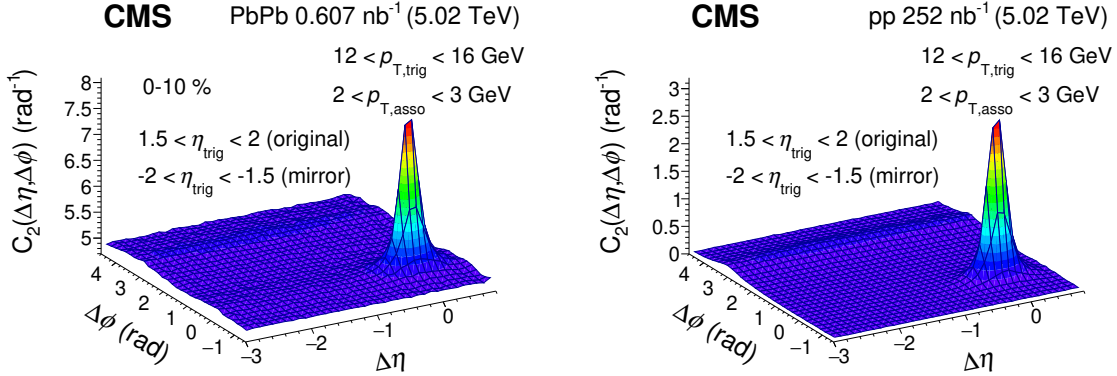


Figure 3: Two-dimensional correlation distributions in the 0–10% centrality interval for PbPb (left) and pp (right) collisions are shown, with  $1.5 < |\eta_{\text{trig}}| < 2$ ,  $12 < p_{T,\text{trig}} < 16$  GeV, and  $2 < p_{T,\text{asso}} < 3$  GeV.

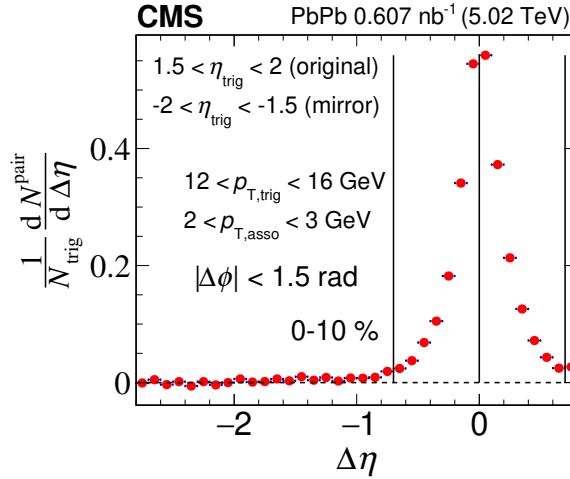


Figure 4: One-dimensional  $\Delta\eta$  projection from the long-range background-subtracted averaged 2D correlation, combining  $1.5 < \eta_{\text{trig}} < 2$  (original) and  $-2 < \eta_{\text{trig}} < -1.5$  (mirror). Three vertical lines correspond to a  $\Delta\eta$  value of  $-0.7$ ,  $0$  and  $0.7$  from left to right. The dashed line indicates the zero level on the y-axis.

## 4 Systematic uncertainties

Systematic uncertainties arising from the selected vertex range, the track selection, the centrality calibration, tracking efficiency, pileup, pair-acceptance corrections, and the long-range background subtractions are studied. The near-side jet peak widths and yields are calculated for three PV  $v_z$  ranges to determine any vertex acceptance effects, with  $|v_z| < 3$  cm,  $-15 < v_z < -3$  cm, and  $3 < v_z < 15$  cm, where the nominal vertex-z range is  $|v_z| < 15$  cm.

High-quality tracks are selected according to the criteria discussed in Section 3. These criteria are varied to investigate their influence on the final results. The maximum allowed values for  $|d_z|/\sigma_z$  and  $|d_{xy}|/\sigma_{xy}$  are varied from 2 to 5, respectively. The maximum allowed value for  $\sigma_{p_T}/p_T$  is varied from 0.05 to 0.15, and the maximum allowed normalized  $\chi^2$  for tracks is varied from 0.15 to 0.18. The centrality calibration is varied to estimate the related systematic uncertainty in the width of the near-side peak for PbPb collisions. The tracking efficiency is varied by its associated uncertainty of 5%. Pileup is negligible in PbPb and its influence is studied in pp collisions by determining how the number of associated tracks for reconstructed vertices varied with the distance between vertices. For the pair-acceptance correction, any residual non-uniformity observed in the  $\Delta\eta$  distribution within the  $\Delta\phi$  sideband region ( $1.2 < \Delta\phi < \pi - 1.2$ ) is fitted with a smooth function, and the correlation function is flattened using this fitted shape. The effect of this correction on the near-side peak widths and yields is taken as the systematic uncertainty associated with the pair-acceptance correction. For the long-range background subtraction, two  $\Delta\eta$  regions are considered to estimate the uncertainty:  $2 < |\Delta\eta| < 2.5$  and  $|\Delta\eta| > 2.5$ . The near-side peak width is obtained from a double-Gaussian fit in each case, and the larger deviation between the two results is assigned as the systematic uncertainty associated with the long-range background subtraction. Individual effects for positive and negative  $\eta_{\text{trig}}$  are considered as one of the systematic sources for longitudinal asymmetry studies. The nominal  $\Delta\eta$  ranges are over 0.7 units for both  $\Delta\eta > 0$  and  $\Delta\eta < 0$ . For the systematic variations, these ranges are changed to extend over 0.6 and 0.8 units, respectively.

Systematic uncertainties from different sources are determined after accounting for statistical fluctuations in systematic error calculations. The maximum systematic uncertainty on  $\sigma_{\Delta\eta}$ ,  $\sigma_{\Delta\phi}$  and yield ratio is within 2%. Table 1 for PbPb and Table 2 for pp summarizes the systematic uncertainties from different sources, with the total uncertainty for each observable calculated as the quadratic sum of the respective individual uncertainties.

Table 1: Summary of the absolute systematic uncertainties for  $\sigma_{\Delta\eta}$ ,  $\sigma_{\Delta\phi}$ , and the associated yield ratio. The leftmost column lists all systematic sources, while the other columns show the range of systematic uncertainties across all  $p_T$ ,  $\eta$  and centrality ranges in minimum-bias PbPb collisions. All values are scaled by a factor of  $10^3$ .

Systematic sources	$\sigma_{\Delta\eta}$	$\sigma_{\Delta\phi}$	$Y_{\Delta\eta>0}/Y_{\Delta\eta<0}$
Vertex $z$	0.016 – 2.5	0.027 – 1.3	4 – 5
Track requirements	0.12 – 4.9	0.15 – 4.9	4 – 5
Centrality	0.03 – 1.4	0.02 – 0.49	4 – 5
Tracking efficiency	0 – 0.02	0 – 0.01	0.33 – 3.5
Pair acceptance correction	0.08 – 2.4	0 – 0.85	—
Background subtraction	0.53 – 5.3	0.49 – 3	—
Yield $\Delta\eta$ range	—	—	0.98 – 2.7
Total uncertainty	0.85 – 7.9	0.7 – 3.1	8.6 – 9.3

## 5 Results

Figure 5 shows the centrality dependence of the longitudinal  $\sigma_{\Delta\eta}$  and transverse  $\sigma_{\Delta\phi}$  values in different  $p_T$  ranges of the triggered and the associated particles. It is observed that the near-side jet peak shape has similar widths in  $\Delta\eta$  and  $\Delta\phi$  for pp collisions and peripheral PbPb collisions with 50–80% centrality. Both  $\sigma_{\Delta\eta}$  and  $\sigma_{\Delta\phi}$  increase toward central PbPb collisions, with the

Table 2: Summary of the absolute systematic uncertainties for  $\sigma_{\Delta\eta}$ ,  $\sigma_{\Delta\phi}$ , and the associated yield ratio. The leftmost column lists all systematic sources, while the other columns show the range of systematic uncertainties across all  $p_T$  and  $\eta$  ranges in minimum-bias pp collisions. All values are scaled by a factor of  $10^3$ .

Systematic sources	$\sigma_{\Delta\eta}$	$\sigma_{\Delta\phi}$	$Y_{\Delta\eta>0}/Y_{\Delta\eta<0}$
Vertex z	0.036 – 2.4	0 – 1.2	4 – 5
Track requirements	0.87 – 2.2	0.35 – 3.5	4 – 5
Pileup	0.04 – 0.25	0 – 0.21	—
Tracking efficiency	—	—	0.14 – 3.5
Pair acceptance correction	0.2 – 1	0.014 – 0.71	—
Background subtraction	0.31 – 1.3	0.17 – 1.5	—
Yield $\Delta\eta$ range	—	—	1.7 – 2.6
Total uncertainty	1.6 – 2.4	1 – 3.8	7 – 7.9

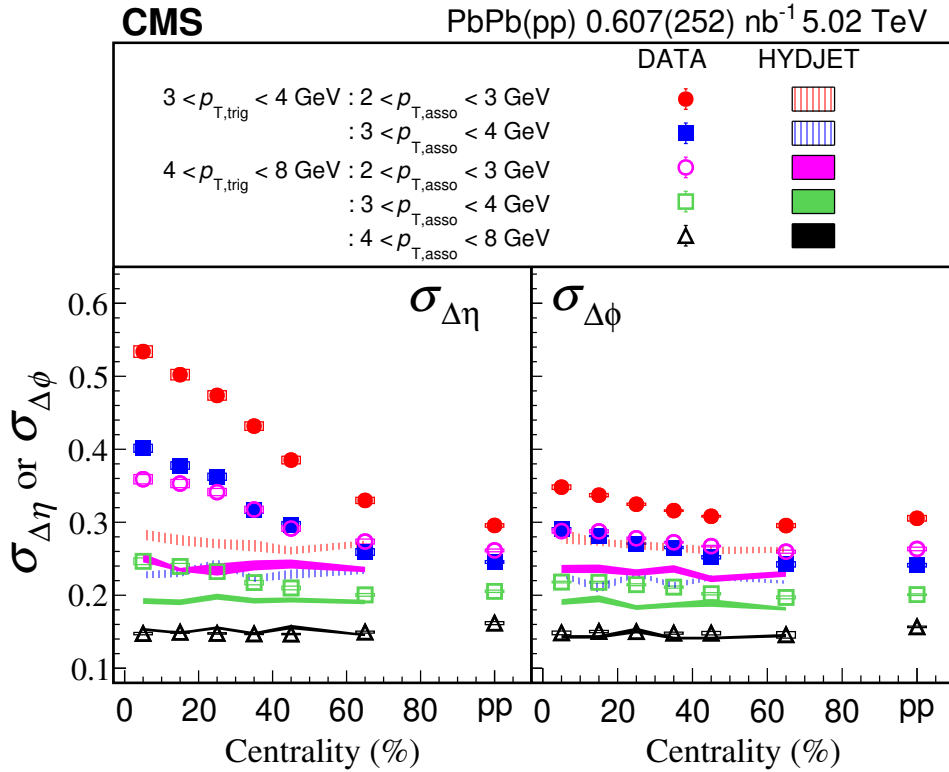


Figure 5: Centrality dependence of the longitudinal  $\sigma_{\Delta\eta}$  (left panel) and transverse  $\sigma_{\Delta\phi}$  (right panel) values are presented in different  $p_T$  ranges for PbPb collisions and pp collisions (right-most points in each panel). The same symbols are used for the same  $p_{T,asso}$  selections, with open markers representing high  $p_{T,trig}$  and closed markers for low  $p_{T,trig}$ . The statistical uncertainties of the data points are smaller than the marker size, and rectangular boxes indicate the systematic uncertainties. Expected values from HYDJET 1.9 are represented by bands: hatched for low  $p_{T,trig}$  and solid-filled for high  $p_{T,trig}$ .

longitudinal broadening in  $\Delta\eta$  being significantly larger than that in  $\Delta\phi$ . This longitudinal broadening is most pronounced for the low- $p_T$  trigger and associated particle ranges, while the

centrality dependence of both widths becomes weaker with increasing  $p_T$ .

A possible explanation for these results is that longitudinal collective flow deforms the jet shape as the soft fragments of a jet (low-momentum hadrons that carry only a small fraction of the jet energy) interacts with the longitudinal flow of the QGP medium [41]. Alternatively, the observed behavior could result from energy loss of the progenitor parton of the trigger hadron in passing through the QGP medium [42]. In contrast, HYDJET 1.9 does not predict the centrality-dependent broadening of the longitudinal jet peak width, reflecting limitations in its modeling assumptions.

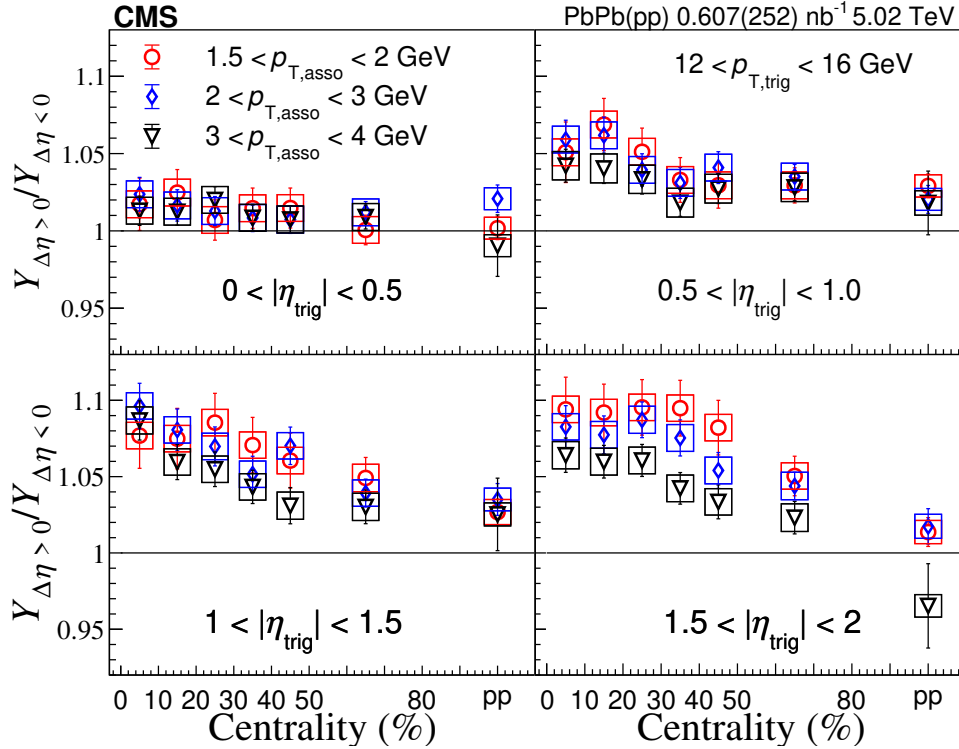


Figure 6: Associated yield ratios between  $\Delta\eta > 0$  and  $\Delta\eta < 0$  within the range of  $0 < |\Delta\eta| < 0.7$  as a function of centrality in different  $p_{T,asso}$  and  $\eta_{trig}$  ranges for PbPb and pp collisions (rightmost bin) are presented in the above panel. The above panel consists of four plots, each corresponding to a different value of  $\eta_{trig}$ . Each plot consists of three colored markers representing different  $p_{T,asso}$  values ( $1.5 < p_{T,asso} < 2$  GeV,  $2 < p_{T,asso} < 3$  GeV,  $3 < p_{T,asso} < 4$  GeV), while  $p_{T,trig}$  is fixed ( $12 < p_{T,trig} < 16$  GeV). The vertical bars indicate statistical uncertainties, while the rectangular open boxes represent systematic uncertainties.

Figure 6 shows the associated yield ratio  $Y_{\Delta\eta>0}/Y_{\Delta\eta<0}$  as a function of centrality for different  $p_T$  ranges of associated particles. The measurement is also presented in different  $\eta$  ranges of the triggered particles, arranged from top left to bottom right. The pp results are shown in the last bin of each plot.

A significant increase in the associated yield ratio is observed as the selection moves toward forward pseudorapidity (high  $\eta_{trig}$ ). At midrapidity (low  $\eta_{trig}$ ), the associated yield ratio remains close to unity and shows minimal dependence on  $p_{T,asso}$ , indicating a nearly symmetric near-side peak structure. However, at larger  $\eta_{trig}$ , the ratio exhibits a significant increase, particularly for central PbPb collisions, along with a pronounced dependence on  $p_{T,asso}$ .

This asymmetry trend suggests a systematic shift in the jet-like correlation structure toward positive  $\Delta\eta$  as the  $\eta$  of the trigger particle increases. One possible interpretation of this  $\eta$

dependence of the near-side jet peak asymmetry, manifested as a higher associated yield for  $\Delta\eta > 0$  (where  $\eta_{\text{trig}}$  is always positive by construction), is that the soft fragments of a high- $p_T$  jet experience a forward-directed push resulting from interactions with the longitudinally expanding medium [41]. The increasing asymmetry with collision centrality further supports the idea that medium effects play a significant role. This asymmetric behavior suggests a potential breaking of the longitudinal invariance of the near-side peak across the  $\Delta\eta$  range.

## 6 Summary

The centrality and pseudorapidity ( $\eta$ ) dependencies of jet peak shapes have been explored using two-particle correlations. Lead-lead (PbPb) collision data at a center-of-mass energy per nucleon pair of 5.02 TeV were recorded using the CMS detector at the CERN LHC. These minimum-bias data correspond to an integrated luminosity of  $0.607 \text{ nb}^{-1}$ . Proton-proton (pp) collision data at the same nucleon-nucleon collision energy and with an integrated luminosity of  $252 \text{ nb}^{-1}$  are also analyzed to provide a reference. The separations in pseudorapidity ( $\Delta\eta$ ) and azimuth ( $\Delta\phi$ ) of all particles within specific transverse momentum ( $p_T$ ) ranges are used to form two-dimensional correlation distributions that are averaged over all events. Jets result in a peak shaped structure corresponding to particle pairs with small angular separation. Jet peak shapes, characterized by associated widths in  $\Delta\eta$  and  $\Delta\phi$ , are presented as functions of centrality. The jet peak asymmetry as a function of  $\eta$  is also studied.

For PbPb collisions, both the longitudinal ( $\sigma_{\Delta\eta}$ ) and transverse ( $\sigma_{\Delta\phi}$ ) widths of the near-side jet peak exhibit a centrality-dependent broadening compared to the pp reference. The effect is more pronounced in  $\Delta\eta$ , indicating a stronger modification of the correlation structure along the longitudinal direction. At higher particle transverse momenta, the centrality dependence of both widths becomes weaker, approaching the pp baseline within uncertainties. Overall, the stronger longitudinal than transverse broadening may reflect the influence of longitudinal expansion or partonic energy loss mechanisms in the medium.

The asymmetry of the jet peak distribution in  $\Delta\eta$  is studied through the ratio of yields on the positive and negative sides of the jet peak. This ratio is evaluated in distinct  $|\eta_{\text{trig}}|$  ranges and for various energy thresholds of the higher- $p_T$  particle in each pair. The ratio is found to increase with the average  $|\eta_{\text{trig}}|$  value. For a given  $|\eta_{\text{trig}}|$  range, the ratio measured in peripheral events is found similar to that in pp collisions, but increases significantly towards more central collisions. These results suggest that the jet properties are modified through in medium interactions in a longitudinally expanding QGP medium.

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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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


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









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



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











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

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











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









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






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K. Osterberg , M. Voutilainen 





















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



















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








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






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







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













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
























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

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








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











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






### Indian Institute of Technology Madras, Madras, India

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### Tata Institute of Fundamental Research-A, Mumbai, India

L. Bhatt, S. Dugad , G.B. Mohanty , M. Shelake , P. Suryadevara










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

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S. Bahinipati<sup>42</sup> , D. Maity<sup>43</sup> , P. Mal , K. Naskar<sup>43</sup> , A. Nayak<sup>43</sup> , S. Nayak , K. Pal , R. Raturi, P. Sadangi, S.K. Swain , S. Varghese<sup>43</sup> , D. Vats<sup>43</sup> 








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### Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi<sup>45</sup> , A. Jafari<sup>46</sup> , M. Zeinali<sup>47</sup> 














### Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Bashiri , S. Chenarani<sup>48</sup> , S.M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie , M. Mohammadi Najafabadi , S. Tizchang<sup>49</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> , B. D'Anzi<sup>a,b</sup> , N. De Filippis<sup>a,c</sup> , M. De Palma<sup>a,b</sup> , W. Elmetenawee<sup>a,b,50</sup> , N. Ferrara<sup>a,b</sup> , L. Fiore<sup>a</sup> , G. Iaselli<sup>a,c</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> , 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

G. Abbiendi<sup>a</sup> , C. Battilana<sup>a,b</sup> , D. Bonacorsi<sup>a,b</sup> , P. Capiluppi<sup>a,b</sup> , A. Castro<sup>+a,b</sup> , F.R. Cavallo<sup>a</sup> , M. Cuffiani<sup>a,b</sup> , G.M. Dallavalle<sup>a</sup> , T. Diotallevi<sup>a,b</sup> , F. Fabbri<sup>a</sup> , A. Fanfani<sup>a,b</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,51</sup> , M. Lorusso<sup>a,b</sup> , L. Lunerti<sup>a</sup> , S. Marcellini<sup>a</sup> , G. Masetti<sup>a</sup> , F.L. Navarria<sup>a,b</sup> , G. Paggi<sup>a,b</sup> , A. Perrotta<sup>a</sup> , F. Primavera<sup>a,b</sup> , A.M. Rossi<sup>a,b</sup> , S. Rossi Tisbeni<sup>a,b</sup> , T. Rovelli<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,52</sup> , A. Di Mattia<sup>a</sup> , A. Lapertosa<sup>a</sup> , R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,52</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. Bianco , S. Meola<sup>53</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> , 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> , 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> ,  
B.S. Pinolini<sup>a</sup>, G. Pizzati<sup>a,b</sup> , S. Ragazzi<sup>a,b</sup> , T. Tabarelli de Fatis<sup>a,b</sup> 











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S. Buontempo<sup>a</sup> , A. Cagnotta<sup>a,b</sup> , F. Carnevali<sup>a,b</sup> , N. Cavallo<sup>a,c</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,54</sup> , P. Paolucci<sup>a,31</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**

R. Ardino<sup>a</sup> , P. Azzi<sup>a</sup> , N. Bacchetta<sup>a,55</sup> , D. Bisello<sup>a,b</sup> , P. Bortignon<sup>a</sup> ,  
G. Bortolato<sup>a,b</sup> , A.C.M. Bulla<sup>a</sup> , T. Dorigo<sup>a,56</sup> , S. Fantinel<sup>a</sup> , F. Fanzago<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> ,  
A.T. Meneguzzo<sup>a,b</sup> , J. Pazzini<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> , M. Zanetti<sup>a,b</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</sup> , D. Fiorina<sup>a</sup> , P. Montagna<sup>a,b</sup> , M. Pelliccioni<sup>a</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. Ascoti<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</sup>, L. Fanò<sup>a,b</sup> , V. Mariani<sup>a,b</sup> , M. Menichelli<sup>a</sup> , F. Moscatelli<sup>a,57</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> ,  
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







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
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
















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







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
























































































































V. Avati, A. Bellora<sup>61</sup> , L. Forthomme , L. Grzanka , M. Malawski , K. Piotrkowski 
















































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






















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G. Karathanasis , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , M. Magherini , L. Malgeri , M. Mannelli , M. Matthewman, A. Mehta , F. Meijers , S. Mersi , E. Meschi , M. Migliorini , V. Milosevic , F. Monti , F. Moortgat , M. Mulders , I. Neutelings , S. Orfanelli, F. Pantaleo , G. Petrucciani , A. Pfeiffer , M. Pierini , M. Pitt , H. Qu , D. Rabadý , B. Ribeiro Lopes , F. Riti , M. Rovere , H. Sakulin , R. Salvatico , S. Sanchez Cruz , S. Scarfi , M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas<sup>64</sup> , A.G. Stahl Leiton , A. Steen , S. Summers , D. Treille , P. Tropea , E. Vernazza , J. Wanczyk<sup>65</sup> , J. Wang, S. Wuchterl , P. Zehetner , P. Zejdl 





















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

T. Bevilacqua<sup>66</sup> , L. Caminada<sup>66</sup> , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli<sup>66</sup> , L. Noehte<sup>66</sup> , T. Rohe , A. Samalan 





#### **ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland**

T.K. Aarrestad , M. Backhaus , G. Bonomelli , C. Cazzaniga , K. Datta , P. De Bryas Dexmiers D'archiac<sup>65</sup> , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , C. Grab , N. Härringer , T.G. Harte , W. Lustermann , A.-M. Lyon , M. Malucchi , R.A. Manzoni , M. Marchegiani , L. Marchese , A. Mascellani<sup>65</sup> , F. Nessi-Tedaldi , F. Pauss , V. Perovic , S. Pigazzini , B. Ristic , R. Seidita , J. Steggemann<sup>65</sup> , A. Tarabini , D. Valsecchi , R. Wallny 













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C. Amsler<sup>67</sup> , P. Bäertschi , M.F. Canelli , G. Celotto , K. Cormier , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechti , A. Macchiolo , P. Meiring , F. Meng , J. Motta , A. Reimers , P. Robmann, M. Senger , E. Shokr , F. Stäger , R. Tramontano 




#### **National Central University, Chung-Li, Taiwan**

C. Adloff<sup>68</sup>, D. Bhowmik, C.M. Kuo, W. Lin , P.K. Rout , S. Taj , P.C. Tiwari<sup>39</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. Asawatrangkuldee , N. Srimanobhas , V. Wachirapusanand 


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Y. Maghrbi 

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D. Agyel , F. Boran , F. Dolek , I. Dumanoglu<sup>69</sup> , E. Eskut , Y. Guler<sup>70</sup> , E. Gurpinar Guler<sup>70</sup> , C. Isik , O. Kara , A. Kayis Topaksu , Y. Komurcu , G. Onengut , K. Ozdemir<sup>71</sup> , A. Polatoz , B. Tali<sup>72</sup> , U.G. Tok , E. Uslan , I.S. Zorbakir 

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

M. Yalvac<sup>73</sup> 

#### **Bogazici University, Istanbul, Turkey**










B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya<sup>74</sup> , O. Kaya<sup>75</sup> , M.A. Sarkisla<sup>76</sup>,

S. Tekten<sup>77</sup> 





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A. Cakir , K. Cankocak<sup>69,78</sup> , S. Sen<sup>79</sup> 

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O. Aydilek<sup>80</sup> , B. Hacisahinoglu , I. Hos<sup>81</sup> , B. Kaynak , S. Ozkorucuklu , O. Potok ,  
H. Sert , C. Simsek , C. Zorbilmez 


**Yildiz Technical University, Istanbul, Turkey**

S. Cerci , B. Isildak<sup>82</sup> , D. Sunar Cerci , T. Yetkin<sup>22</sup> 















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

A. Boyaryntsev , B. Grynyov 























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L. Levchuk 









































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

D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans ,  
H. Flacher , J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Parames-  
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


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A.H. Ball, K.W. Bell , A. Belyaev<sup>83</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill ,  
C. Cooke , A. Elliot , K.V. Ellis, J. Gajownik , K. Harder , S. Harper , J. Linacre ,  
K. Manolopoulos, M. Moallemi , D.M. Newbold , E. Olaiya , D. Petyt , T. Reis ,  
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











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I. Andreou , R. Bainbridge , P. Bloch , O. Buchmuller, C.A. Carrillo Montoya ,  
D. Colling , J.S. Dancu, I. Das , P. Dauncey , G. Davies , M. Della Negra ,  
S. Fayer, G. Fedi , G. Hall , H.R. Hoorani , A. Howard, G. Iles , C.R. Knight ,  
P. Krueper , J. Langford , K.H. Law , J. León Holgado , L. Lyons , A.-M. Magnan ,  
B. Maier , S. Mallios , A. Mastronikolis , M. Mieskolainen , J. Nash<sup>84</sup> , M. Pesaresi ,  
P.B. Pradeep , B.C. Radburn-Smith , A. Richards, A. Rose , L. Russell , K. Savva ,  
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


**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 

**Catholic University of America, Washington, DC, USA**

















R. Bartek , A. Dominguez , S. Raj , A.E. Simsek , S.S. Yu 

**The University of Alabama, Tuscaloosa, Alabama, USA**

B. Bam , A. Buchot Perraguin , R. Chudasama , S.I. Cooper , C. Crovella ,  
G. Fidalgo , S.V. Gleyzer , A. Khukhunaishvili , K. Matchev , E. Pearson, C.U. Perez 

P. Rumerio<sup>85</sup> , E. Usai , R. Yi 



















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

G. De Castro, Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , E. Fontanesi , D. Gastler , F. Golf , S. Jeon , J. O'cain, I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , A.G. Zecchinelli 














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G. Barone , G. Benelli , D. Cutts , S. Ellis , L. Gouskos , M. Hadley , U. Heintz , K.W. Ho , J.M. Hogan<sup>86</sup> , T. Kwon , G. Landsberg , K.T. Lau , J. Luo , S. Mondal , T. Russell , S. Sagir<sup>87</sup> , X. Shen , M. Stamenkovic , N. Venkatasubramanian 



**University of California, Davis, Davis, California, USA**

S. Abbott , B. Barton , C. Brainerd , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , M. Chertok , M. Citron , J. Conway , P.T. Cox , R. Erbacher , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , S. Ostrom , W. Wei , S. Yoo 

























**University of California, Los Angeles, California, USA**

K. Adamidis, M. Bachtis , D. Campos, R. Cousins , A. Datta , 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 , D. Diaz , J. Duarte , L. Giannini , Y. Gu, J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , D. Primosch, M. Quinnan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil 


















**University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA**

A. Barzdukas , L. Brennan , C. Campagnari , K. Downham , C. Grieco , M.M. Hussain, J. Incandela , J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , S.N. Santpur , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , D. Stuart , T.Á. Vámi , X. Yan , D. Zhang 

**California Institute of Technology, Pasadena, California, USA**

A. Albert , S. Bhattacharya , A. Bornheim , O. Cerri, J. Mao , H.B. Newman , G. Reales Gutiérrez, T. Sievert, M. Spiropulu , J.R. Vlimant , R.A. Wynne , S. Xie , R.Y. Zhu 





**Carnegie Mellon University, Pittsburgh, Pennsylvania, USA**

J. Alison , S. An , P. Bryant , M. Cremonesi, V. Dutta , E.Y. Ertorer , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, M. Kanemura, C. Liu , T. Mudholkar , 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 , A. Hassani , J. Parkes , 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 , D.J. Cranshaw , J. Dickinson , J. Fan , X. Fan , J. Grassi , S. Hogan , P. Kotamnives , J. Monroy , G. Niendorf , M. Oshiro , J.R. Patterson , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 










**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 , T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , 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>88</sup> , F. Ravera , A. Reinsvold Hall<sup>89</sup> , L. Ristori , M. Safdari , E. Sexton-Kennedy , 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 

**University of Florida, Gainesville, Florida, USA**

C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field, C. Huh , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , N. Menendez , 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. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez , H. Prosper , P.R. Prova, M. Wulansatiti , R. Yohay , J. Zhang










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

B. Alsufyani , S. Butalla , S. Das , T. Elkafrawy<sup>19</sup> , 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 , J.h. Lee , D. S. Lemos , C. Mills , S. Nanda , B. Ozek , T. Phan, D. Pilipovic , R. Pradhan , E. Prifti, P. Roy, T. Roy , N. Singh, M.B. Tonjes , N. Varelas , M.A. Wadud , Z. Ye , J. Yoo 










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

M. Alhousseini , D. Blend , K. Dilsiz<sup>90</sup> , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili<sup>91</sup> , O. Neogi, H. Ogul<sup>92</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>93</sup> 

**Johns Hopkins University, Baltimore, Maryland, USA**


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

**The University of Kansas, Lawrence, Kansas, USA**


















A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , S. Popescu<sup>94</sup> , C. Rogan 

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






















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

B. Allmond , R. Gujju Gurunadha , N. Islam, A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , 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 , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranjpe, E. Popova<sup>95</sup> , A. Shevelev , L. Wang , L. Zhang 













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

C. Baldenegro Barrera , J. Bendavid , S. Bright-Thonney , I.A. Cali , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, G. Grosso , P. Harris, D. Hoang , 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 , G.S.F. Stephans , D. Walter , Z. Wang , B. Wyslouch , T. J. Yang 













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

B. Crossman , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , M. Revering , 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 , A. Rohilla , J.E. Siado , W. Tabb , A. Vagnerini , A. Wightman , F. Yan , D. Yu 












#### **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 , P. Young 




























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

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










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

S. Dittmer , K.A. Hahn , D. Li , Y. Liu , 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 , 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, I. Mcalister, T. McCauley , C. Mcgrady , C. Moore , Y. Musienko<sup>24</sup> , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti , A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygala 

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

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



















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

H. Bouchamaoui , K. Coldham, P. Das , G. Dezoort , P. Elmer , P. Fackeldey , A. Frankenthal , B. Greenberg , N. Haubrich , K. Kennedy, G. Kopp , S. Kwan , Y. Lai , D. Lange , A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen , F. Simpson , D. Stickland , C. Tully , L.H. Vage 




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

S. Malik , R. Sharma 

















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

A.S. Bakshi , S. Chandra , R. Chawla , A. Gu , L. Gutay, M. Jones , A.W. Jung , M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , J.F. Schulte , A. K. Virdi , F. Wang , A. Wildridge , W. Xie , Y. Yao , Y. Zhong 

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

J. Dolen , N. Parashar , A. Pathak 





















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

D. Acosta , A. Agrawal , T. Carnahan , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner, F.J.M. Geurts , T. Huang , I. Krommydas , N. Lewis, W. Li , J. Lin , O. Miguel Colin , B.P. Padley , R. Redjimi , J. Rotter , E. Yigitbasi , Y. Zhang 

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

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , A. Garcia-Bellido , H.S. Hare , O. Hindrichs , N. Parmar , P. Parygin<sup>95</sup> , R. Taus 













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

B. Chiarito, J.P. Chou , S.V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton , D. Jaroslowski , S. Konstantinou , I. Laflotte , A. Lath , J. Martins , R. Montalvo, K. Nash, 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, S. Higginbotham , T. Holmes , A.R. Kanuganti , N. Karunarathna , J. Lawless, L. Lee , E. Nibigira , S. Spanier 













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






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







































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


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