EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-216
2024/09/27

CMS-GEN-22-001

# Energy-scaling behavior of intrinsic transverse momentum parameters in Drell–Yan simulation

The CMS Collaboration*



## Abstract

We present an analysis based on models of the intrinsic transverse momentum of partons in nucleons by studying the dilepton transverse momentum in Drell–Yan events. Using parameter tuning in event generators and existing data from fixed-target experiments, from the Tevatron, and from the LHC, our investigation spans three orders of magnitude in center-of-mass energy and two orders of magnitude in dilepton invariant mass. The results show an energy-scaling behavior of the intrinsic transverse momentum parameters, independent of the dilepton invariant mass at a given center-of-mass energy.

*Submitted to Physical Review Letters*



*See Appendix C for the list of collaboration members

The description of high-energy hadron-hadron collisions relies on the modeling of the non-perturbative regime of quantum chromodynamics (QCD). In particular, the modeling of the intrinsic transverse momenta of partons inside the colliding protons (intrinsic $k_T$) represents a challenge both experimentally and theoretically. Several approaches exist to describe the intrinsic $k_T$, including those with transverse-momentum-dependent parton distribution functions (PDFs) [1–3], and those based on first-principle approaches such as lattice QCD [4–6]. The most widely used frameworks for the description of collision events at the LHC are general-purpose Monte Carlo (MC) event generators that include parton shower descriptions, such as PYTHIA 8 [7, 8], HERWIG 7 [9], and SHERPA [10]. They are based on collinear PDFs and usually model the intrinsic $k_T$ as a random variable with a Gaussian distribution, whose width is a tunable parameter. However, the extracted intrinsic $k_T$ parameter does not necessarily correspond to a simple model of nonperturbative physics, but also compensates for deficiencies in the parton shower model. These considerations motivate the study presented in this Letter.

The region of Drell–Yan (DY) production where the lepton-pair system is produced with low transverse momentum around a few GeV is especially suited for the study of the intrinsic $k_T$ models as it provides a clean, high-resolution final state, and has been studied widely in collider experiments [11–23]. Previous studies illustrate the sensitivity of this region to high-order QCD contributions [24] and include their own treatments of nonperturbative physics effects [25, 26].

For the results presented in this Letter, we use DY data measured from various types of hadron collisions at different center-of-mass energies and the corresponding simulations to extract nonperturbative-QCD information, and to study the interplay between the intrinsic $k_T$ parameter and the perturbative evolution including the initial-state radiation (ISR). The analysis is performed with the PYTHIA 8 and HERWIG 7 event generators, which provide different options of ordering variables and energy thresholds for partonic emissions, and the results are compared with those of the previous studies with CASCADE [2, 3, 27]. Their models of the underlying event (UE), which consist of multiple-parton interactions (MPI) and beam remnants (BR), as well as hadronization, ISR and final-state radiation (FSR), have been extensively studied [28–30]. The measurements of the differential cross section of DY processes as a function of the dilepton transverse momentum ($p_T(\ell^+\ell^-)$) are summarized in Table 1, in which the proton-lead (pPb) measurement data were converted for comparison with pp collisions by correcting for the number of nucleons, and corresponding simulations are used to tune the intrinsic $k_T$ parameter. Tabulated results are provided in the HEPData record for this analysis [31].

Predictions of the DY cross section are produced at next-to-leading order (NLO) using MADGRAPH5_aMC@NLO v3.4.1 [32] and the matrix-element computation is matched to the PYTHIA 8 or HERWIG 7 generator for parton shower and UE activity modeling. The intrinsic $k_T$ parameter is tuned without changing any other parameters. We observe that the UE parameters have a small impact on the DY $p_T(\ell^+\ell^-)$ distribution, and that the intrinsic $k_T$ parameter has little effect on the UE observables, as shown in Appendix A. The UE tunes used in this analysis are based on various PDFs, partonic emission orderings, and settings in MPI and BR modeling, as listed below:

- PYTHIA 8 tunes: The PYTHIA 8.243 generator is used for the $p_T$-ordered parton shower and hadronization, and the UE model is parameterized by the CP3, CP4, or CP5 tune [29]. The three tunes have the strong coupling $\alpha_S(m_Z)$ set to 0.118, use NLO strong-coupling evolution, and employ NLO or next-to-NLO (NNLO) PDFs in the hard scattering, parton showering, ISR, FSR, MPI, and BR modelings.
- HERWIG 7 tunes: The HERWIG 7.1.4 generator is used for the angular-ordered parton

Table 1: Measurements of the Drell–Yan differential cross section as a function of $p_T(\ell^+\ell^-)$ at various center-of-mass energies $\sqrt{s}$ from different hadron-collision processes used as inputs for the intrinsic $k_T$ tunes. The $\sqrt{s}$ in pPb collisions represents the nucleon-nucleon center-of-mass energy. The variable $Q$ represents the energy scale of the hard scattering, approximated by the dilepton invariant mass. The Z boson mass is denoted as $m(\mathrm{Z})$.

| Experiment | Collision type | $\sqrt{s}$ [GeV] | $Q$ [GeV] |
|---|---|---|---|
| E866/NuSea [11, 12] | pp/pd, fixed target | 38.8 | 4–12.85 |
| R209 [13] | pp | 62 | 5–8 |
| PHENIX [14] | pp | 200 | 4.8–8.2 |
| D0/CDF [15, 16] | $\mathrm{p\bar{p}}$ | 1800 | $m(\mathrm{Z})$ |
| D0/CDF [17, 18] | $\mathrm{p\bar{p}}$ | 1960 | $m(\mathrm{Z})$ |
| CMS [19] | pp | 2760 | $m(\mathrm{Z})$ |
| ATLAS [20] | pp | 8000 | 46–150 |
| CMS [21] | pPb | 8160 | 15–120 |
| CMS [22] | pp | 13000 | 50–1000 |
| LHCb [23] | pp | 13000 | $m(\mathrm{Z})$ |

shower and hadronization, and the CH2 and CH3 tunes [30] are used for the UE modeling. Both tunes use $\alpha_S(m_Z) = 0.118$ with NNLO strong-coupling evolution and the NNLO NNPDF3.1 PDFs for the parton shower, but different $\alpha_S$ and PDF sets in the MPI and BR modelings.

These UE tunes used measurements at $\sqrt{s}$ from 0.9 to 13 TeV by the CDF and CMS experiments, modelling the behavior of UE-sensitive variables across all these energies, as well as the kinematics of high $p_T$ jet, $\mathrm{t\bar{t}}$ and DY production at the CMS.

The intrinsic $k_T$ is modeled similarly in PYTHIA and HERWIG by a Gaussian distribution with tunable parameters. In PYTHIA, the width $q_s$ of the Gaussian distribution is related to the parameter BEAMREMNANTS:PRIMORDIALKTHARD $\simeq q_s/\sqrt{2}$, whereas in HERWIG, it is given by the parameter SHOWERHANDLER:INTRINSICPTGAUSSIAN $= q_s$. Either of these parameters is referred to as tunable intrinsic $k_T$ parameter $q$ in the following.

In each scenario of $\sqrt{s}$ given in Table 1, we assume that the DY differential cross section versus $p_T(\ell^+\ell^-)$ depends on $q$. Simulated samples of events are generated with different choices of the parameter $q$ sampled from the tuning range, resulting in varied predictions of the DY differential cross section. The dependence of the cross section on $q$ predicted for each bin in $p_T(\ell^+\ell^-)$ is extracted by interpolating the simulated values, as well as their uncertainty, with polynomial functions $f_i(q)$ and $u_{f_i(q)}$, respectively, in each bin $i$ of $p_T(\ell^+\ell^-)$. The PROFESSOR 2 software [34] is employed to perform the interpolation and compute a goodness of fit (GOF), based on the $\chi^2$ distribution, for quantifying the agreement between the interpolated simulated values and those measured in the data. The GOF is defined as

$$\chi^2(q) = \sum_i \frac{(f_i(q) - d_i)^2}{u_{d_i}^2 + u_{f_i(q)}^2}, \tag{1}$$

where $d_i$ and $u_{d_i}$ are the cross section and its uncertainty measured in data in bin $i$, respectively. For measurements performed at $\sqrt{s} > 1$ TeV, the value of $\chi^2$ is obtained by summing over the bins $i$ that correspond to the low-$p_T(\ell^+\ell^-)$ range 0–10 GeV because of its high sensitivity to the intrinsic $k_T$ model. For measurements at $\sqrt{s} < 1$ TeV, the whole range of $p_T(\ell^+\ell^-)$ available in the data, which is below 10 GeV, is considered for computing the value of $\chi^2$. For each measurement at a given $\sqrt{s}$, the final tuned parameter $q$ is taken to be the one that minimizes the respective GOF.

The uncertainties in the tuned parameter originate from the variations of the GOF. The uncertainty due to the choice of $p_{\mathrm{T}}(\ell^+\ell^-)$ range is estimated as the difference between the resulting tuned parameter when considering the $p_{\mathrm{T}}(\ell^+\ell^-)$ ranges [0, 10] and [0, 15] GeV for $\sqrt{s} > 1$ TeV, because the transition from the nonperturbative to perturbative contributions takes place approximately between 10–20 GeV. With regard to the $\sqrt{s} < 1$ TeV cases, this uncertainty is estimated as the difference between the parameter tuned using the range [0 GeV, max($p_{\mathrm{T}}$)] and [0, 2] GeV (for $\sqrt{s} = 38.8$ GeV) or [0, 4] GeV (for $\sqrt{s} = 62$ and 200 GeV). The uncertainty due to the choice of the functional form used for the interpolation is taken to be the difference between the parameter tuned using order-5 polynomials as the central value and that using order-3 polynomials as the systematic deviation. The uncertainty from the limited statistical precision in the simulation is estimated by substituting the denominator of Eq. (1) with $u^2_{f_i(q)}$ and determining the parameter values that result in a value of $\chi^2$ increased by 1 compared to the minimum. The contribution from the uncertainty of the measured data is estimated by repeating the tuning for varied values of the differential DY cross section. These varied values are obtained by sampling from Gaussian distributions centered at the nominal values of measured cross sections and with standard deviations equal to their uncertainties. The covariance between the uncertainties contributed by the measured data for different generator setups is estimated from the covariance between the corresponding tunes obtained from the varied measurements. The other uncertainty sources are approximately uncorrelated among the tunes. The uncertainty from the measurement is dominant in most of the tunes, ranging from 2 to 20%, depending on the measurement precision.

The impact of the center-of-mass energy on the intrinsic $k_{\mathrm{T}}$ parameter is investigated by tuning the generators to the $p_{\mathrm{T}}(\ell^+\ell^-)$ measurements for each experimental setup in Table 1. The results show an energy-scaling behavior of the intrinsic $k_{\mathrm{T}}$ parameter for both generators and all setups, as indicated in Fig. 1. The function $q(\sqrt{s}) = b\sqrt{s}^a$ is fitted to the points, with fit parameters $a$ and $\log_{10}(b)$ describing the slope and intercept of the function, respectively. The same slope $a$ is assumed for all generator setups based on observation, which is supported by the combined value of $\chi^2_{\text{lin.}}$ of all linear fits divided by the total number of degrees of freedom (NDF), $\chi^2_{\text{lin.}}/\text{NDF} = 1.27$, under this assumption and the corresponding $p$-value [35] of 0.11. The slope of the fitted function is $a = 0.162 \pm 0.005$. When fitted with free-floating slopes, the resulting slopes are $0.163 \pm 0.006$, $0.164 \pm 0.006$, $0.170 \pm 0.008$, $0.160 \pm 0.008$ and $0.155 \pm 0.007$ for the CP3, CP4, CP5, CH2 and CH3 tunes, respectively, which are compatible with each other. The generators can be improved by implementing the energy scaling of the intrinsic $k_{\mathrm{T}}$ parameters provided by this analysis.

Besides the intrinsic $k_{\mathrm{T}}$ model, the DY $p_{\mathrm{T}}(\ell^+\ell^-)$ distribution also receives contributions from ISR. Therefore, the intrinsic $k_{\mathrm{T}}$ parameters in the generators practically compensate the ISR contribution below the cutoff scale in the tunes to DY measured data. To investigate the effect of the ISR cutoff scale on the intrinsic $k_{\mathrm{T}}$ parameter, we perform an energy-dependent intrinsic $k_{\mathrm{T}}$ tune with a different ISR cutoff scale, controlled by the regularization parameter SPACESHOWER:PT0REF in PYTHIA and SUDAKOVCOMMON:PTMIN in HERWIG. The tuning process and determination of the uncertainty follows the same strategy used in the results shown in Fig. 1 in the PYTHIA CP5 or HERWIG CH3 setups. The SPACESHOWER:PT0REF parameter is changed to 1 GeV from the default value of 2 GeV for PYTHIA and the SUDAKOVCOMMON:PTMIN parameter is changed to 0.7 GeV from the default value of 1.22 GeV for HERWIG, such that the simulation can still reasonably describe the observed DY $p_{\mathrm{T}}(\ell^+\ell^-)$ distribution after the intrinsic $k_{\mathrm{T}}$ tunes. Lowering the cutoff scale induces more low-energy ISR contribu-

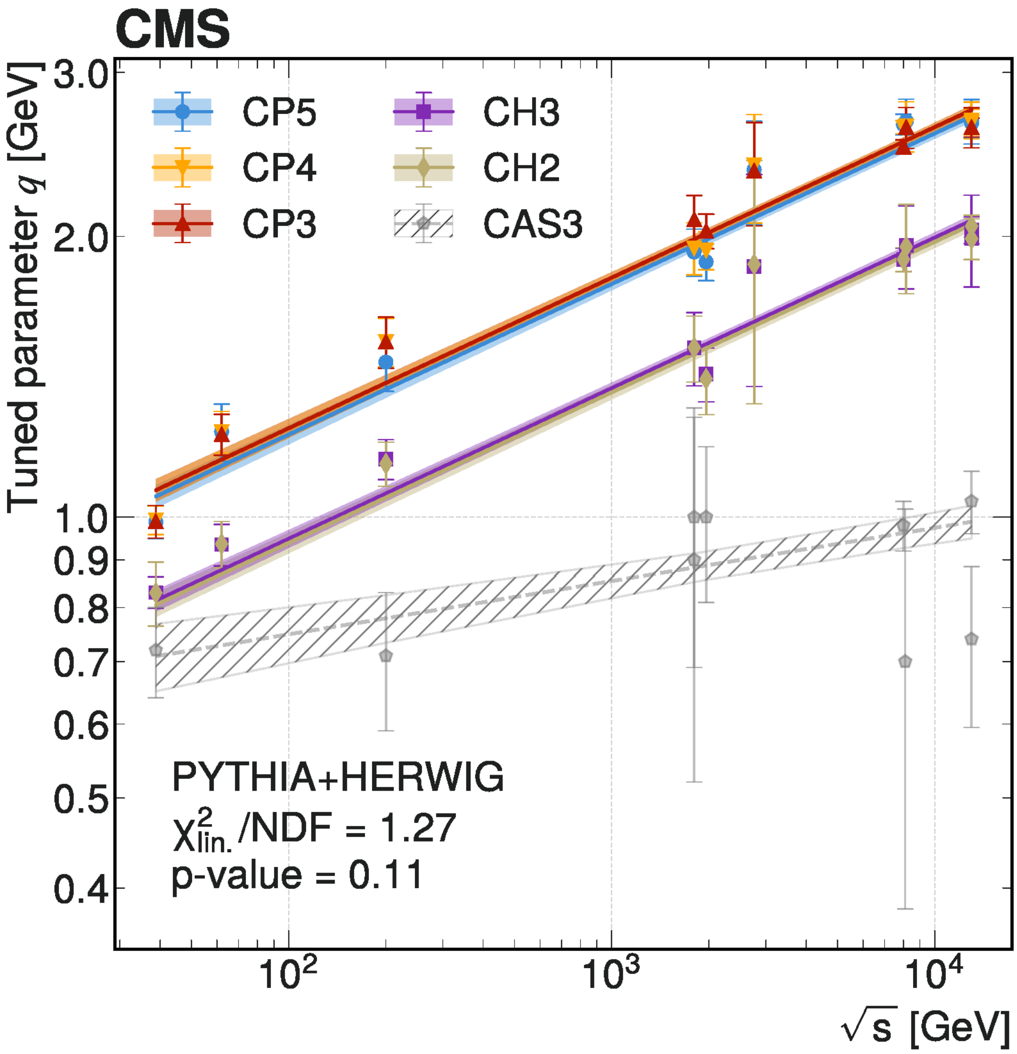


Figure 1: Tuned parameter $q$ values for DY measurements at different center-of-mass energies (points) for various PYTHIA and HERWIG setups (colors). The error bars on the points represent the tuning uncertainties. The tuned values are given in Appendix B. For each generator setup, the function $b\sqrt{s}^a$ is fitted to the points and shown as a line, assuming the same slope $a$ for all the settings. The $\chi^2_{\text{lin.}}$/NDF and $p$-value of the combined linear fit is given in the plot. The uncertainty in each fit is shown as a colored band and corresponds to the up and down variations of the fit parameters, propagated from the tune uncertainties. The CASCADE predictions (CAS3) [2, 3] are also fitted separately with the function $b\sqrt{s}^a$ for comparison with PYTHIA and HERWIG.

tions to the low-$p_T(\ell^+\ell^-)$ DY distribution.

Figure 2 shows the results of the combined fit for the tuned parameter in the PYTHIA CP5 setup with SPACESHOWER:PT0REF set to 1 GeV and the default case, and those for the tuned parameter in the HERWIG CH3 setup with SUDAKOVCOMMON:PTMIN set to 0.7 GeV and the default case. For each generator setting, the function $b\sqrt{s}^a$ is fitted to the points and shown as a line, allowing various slopes $a$ and offsets $\log_{10}(b)$. The $\chi^2_{\text{lin.}}$/NDF and $p$-value of the fit are 1.71 and 0.04 for PYTHIA (1.15 and 0.30 for HERWIG), respectively. The reported $p$-values are the significance of the $\chi^2$ test with 16 degrees of freedom from 20 tuned results and four parameters to fit, including two slope parameters and two offset parameters. The slope parameters for the PYTHIA setups are $0.172 \pm 0.009$ (default) and $0.170 \pm 0.009$ (lower ISR cutoff), and the slopes for the HERWIG setups are $0.153 \pm 0.007$ (default) and $0.130 \pm 0.009$ (lower ISR cutoff). This result shows that the variation of the ISR threshold in the simulation does not change the energy-scaling behavior of intrinsic $k_T$ tunes, and causes a mild change of the slope only for very low values of the threshold.

The energy-scaling behavior of the intrinsic $k_T$ tunes can lead to deeper insights about the nonperturbative-QCD contributions in the low-$p_T(\ell^+\ell^-)$ region of the DY process after extracting and comparing the effects of perturbative QCD in the tunes. On the one hand, the tunes are affected by perturbative-QCD models varying among the generator setups, because both ISR and intrinsic $k_T$ play a role in describing the $p_T(\ell^+\ell^-)$ in the DY process. These effects are demonstrated by the variations of the intercepts of the linear fit, as shown in the fits in Figs. 1 and 2. Additionally, the PYTHIA and HERWIG generators use different showering models, PYTHIA using $p_T$-ordered showering and HERWIG using angular-ordered showering, which leads to more low-energy ISR in the HERWIG generation of DY events and less compensation from the nonperturbative part to model $p_T(\ell^+\ell^-)$. Therefore, the intercepts in the HERWIG fit are smaller than those for the PYTHIA fit in Fig. 1. On the other hand, the slopes of the linear fits are similar for the various PYTHIA and HERWIG tunes in combination with the DY matrix element computed at NLO, despite their differences in the PDF, the order in the parton shower, and the cutoff scale of showering. Stable under variations of perturbative-QCD modeling and hard-scattering scales, this energy-scaling behavior potentially originates from nonperturbative-QCD effects, pointing to the need for further theoretical investigation. The adjustment of intrinsic $k_T$ under higher-order or resummed Drell–Yan matrix elements and their corresponding energy-scaling behaviors presents a compelling avenue for future research, as nonperturbative-QCD effects are increasingly incorporated into these matrix elements.

A different approach to modeling the intrinsic $k_T$ is implemented in the CASCADE generator [27] ("CAS3" in Fig. 1), which accounts for the effect of low-energy gluons with a nonperturbative Sudakov form-factor [26], using the parton branching method [1, 2]. The CASCADE generator predicts an intrinsic $k_T$ [2, 3] that, compared with PYTHIA and HERWIG, is less dependent on the collider energy as shown in Fig. 1. The energy scaling of the intrinsic $k_T$ parameters in the PYTHIA and HERWIG models may be necessary to account for nonperturbative and low-energy gluon emissions not included in the parton showers.

To explore the dependence of intrinsic $k_T$ parameters on the DY hard-scattering scale $Q$, tunings are performed using the DY differential cross section versus $p_T(\ell^+\ell^-)$ in exclusive ranges of dilepton invariant mass $m(\ell^+\ell^-)$ for $\sqrt{s} = 38.8$ GeV, and 8, 8.16, and 13 TeV, in which measurements in multiple $m(\ell^+\ell^-)$ ranges are available. As shown in Fig. 3, the intrinsic $k_T$ tunes of either PYTHIA (CP5) or HERWIG (CH2) are similar for various $m(\ell^+\ell^-)$ ranges at the same $\sqrt{s}$, which leads to the hypothesis that the intrinsic $k_T$ parameter is identical for all the $m(\ell^+\ell^-)$ ranges at a fixed $\sqrt{s}$. Figure 3 shows the results of a constant fit to the tuned parameter val-

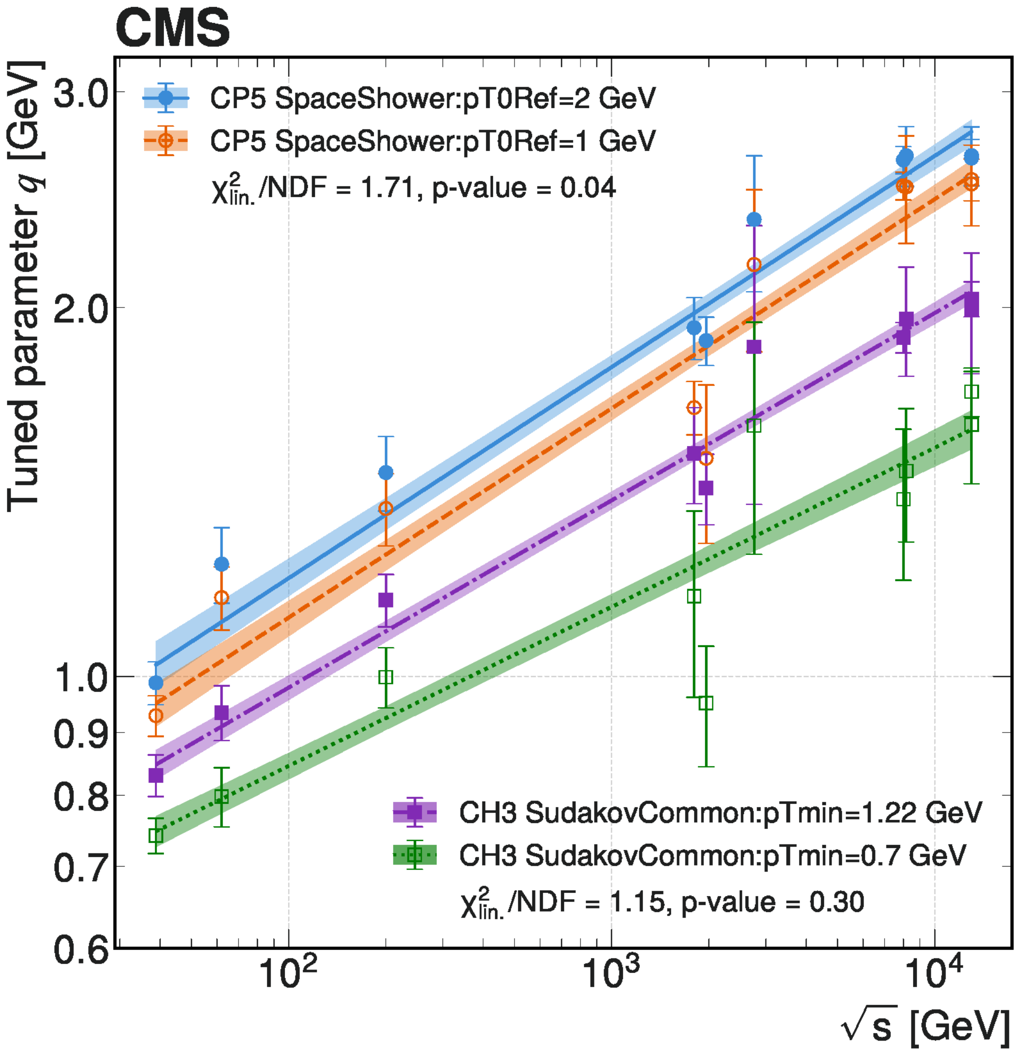


Figure 2: Tuned parameter $q$ values for DY measurements at different center-of-mass energies (points) for various generator settings (lines and bands). The error bars on the points represent the tuning uncertainties. The tuned values are given in Appendix B. For the PYTHIA CP5 setup, the parameter SPACESHOWER:PT0REF is set to 1 GeV (orange dashed) or its default value of 2 GeV (blue solid). For the HERWIG CH3 setup, the parameter SUDAKOVCOMMON:PTMIN is set to 0.7 GeV (green dotted) or its default value of 1.22 GeV (purple dash-dotted). The function $b\sqrt{s}^a$ is fitted to the points of each generator setting and shown as a line, allowing free-floating slopes $a$ and offsets $\log_{10}(b)$. The uncertainty in each fit is shown as a colored band and corresponds to the up and down variations of the fit parameters, propagated from the tune uncertainties.

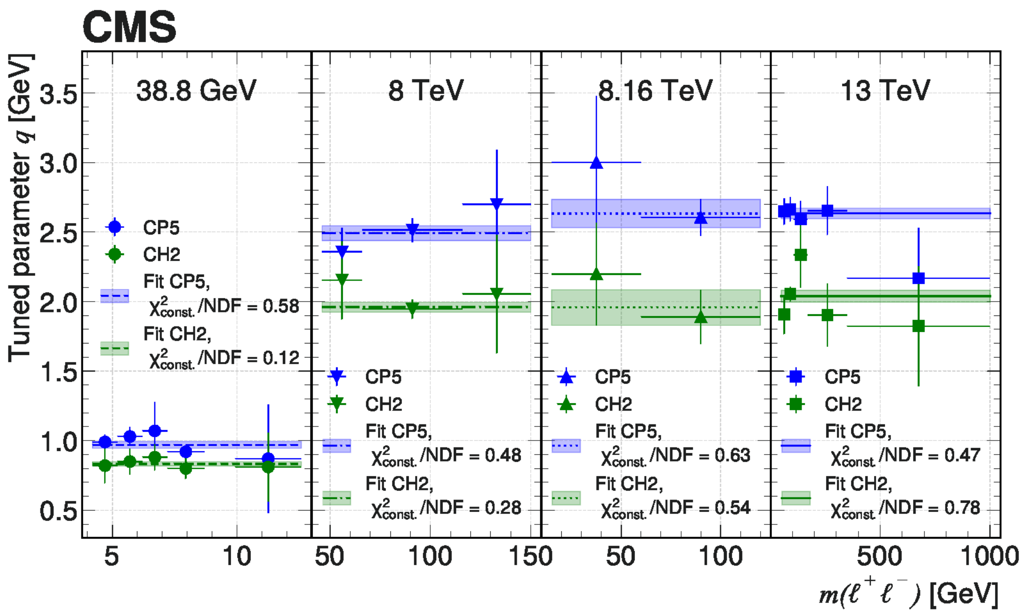


Figure 3: Tuned parameter values (points) for DY measurements at four different center-of-mass energies (panels) for the PYTHIA CP5 (blue) and HERWIG CH3 (green) setups. The error bars on the points represent the tuning uncertainties. The tuned values are given in Appendix B. For each generator setup, a constant is fitted to the points and shown as a line. The uncertainty in each fit, propagated from the tune uncertainties, is shown as a colored band.

ues based on this hypothesis, which is compatible with the tuned values as indicated by the value of $\chi^2_{\text{const.}}/\text{NDF}$ being close to 1. This investigation of the $Q$-dependence of the intrinsic $k_{\text{T}}$ tunes under fixed $\sqrt{s}$ complements previous studies on the $\sqrt{s}$-dependence of the resummed nonperturbative Sudakov factor under fixed $Q$, as summarized in Ref. [36].

Defining the fractions of the hadron momentum carried by the incoming pair of quarks in the DY process to be $x_1$ and $x_2$, $m(\ell^+\ell^-)$ is given by $m(\ell^+\ell^-) = x_1 x_2 \sqrt{s}$ at leading order. Since the tuned values are stable versus $x_1 x_2 \sqrt{s}$ for given values of $\sqrt{s}$, the intrinsic $k_{\text{T}}$ parameter is independent of $x_1 x_2$ within the present precision. Furthermore, the impact of $x_1/x_2$ on the intrinsic $k_{\text{T}}$ tunes is demonstrated by the tunes using the CMS and LHCb measurements at $\sqrt{s} = 13\,\text{TeV}$ because of the different rapidity regions used for the measurements by the two experiments. The tunes to the two measurements agree within the uncertainties (shown in Fig. 1), which indicates the intrinsic $k_{\text{T}}$ tune to be stable under $x_1/x_2$ variations and suggests its independence of the momentum fractions $x_1$ and $x_2$ individually.

In summary, generator tunes of the intrinsic transverse momentum $k_{\text{T}}$ were used to explore model-independent features of nonperturbative quantum chromodynamics (QCD). The tunes were performed for various underlying-event setups in the generators PYTHIA and HERWIG using the Drell–Yan cross section differential in the dilepton transverse momentum measured in multiple types of hadron collision experiments with $\sqrt{s}$ ranging from 38.8 GeV to 13 TeV. The results show a linear relation between the logarithm of the intrinsic $k_{\text{T}}$ parameter and $\log_{10}(\sqrt{s})$ for all generator setups, with the intercepts altered by generator-dependent perturbative-QCD models such as choices of parton distribution functions or parton shower parameters. The slope is $0.162 \pm 0.005$, independent of the generator setup, and related to nonperturbative-QCD effects such as nonresolvable low-energy gluon emissions in parton showers. The tunes were also performed using measurements in various regions of dilepton invariant mass and demonstrated the independence of the intrinsic $k_{\text{T}}$ parameter with respect to the dilepton mass at each $\sqrt{s}$. This indicates the independence of the intrinsic $k_T$ on the longitudinal momentum fractions of the quarks in colliding hadrons in Drell–Yan processes.

## Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

## References

[1] A. Bermudez Martinez et al., "The transverse momentum spectrum of low mass Drell–Yan production at next-to-leading order in the parton branching method", *Eur. Phys. J. C* **80** (2020) 598, doi:10.1140/epjc/s10052-020-8136-y, arXiv:2001.06488.

[2] I. Bubanja et al., "The small $k_T$ region in Drell–Yan production at next-to-leading order with the parton branching method", *Eur. Phys. J. C* **84** (2024) 154, doi:10.1140/epjc/s10052-024-12507-0, arXiv:2312.08655.

[3] M. Mendizabal, F. Guzman, H. Jung, and S. Taheri Monfared, "On the role of soft gluons in collinear parton densities and parton shower event generators", 2023. arXiv:2309.11802.

[4] P. Hägler, B. U. Musch, J. W. Negele, and A. Schäfer, "Intrinsic quark transverse momentum in the nucleon from lattice QCD", *Euro. Phys. Lett.* **88** (2009) 61001, doi:10.1209/0295-5075/88/61001, arXiv:0908.1283.

[5] B. U. Musch et al., "Transverse-momentum distribution of quarks in the nucleon from lattice QCD", in *Proceedings of LIGHT CONE 2008 Relativistic Nuclear and Particle Physics — PoS(LC2008)*, volume 061, p. 053. 2009. doi:10.22323/1.061.0053.

[6] B. U. Musch, P. Hägler, J. W. Negele, and A. Schäfer, “Exploring quark transverse momentum distributions with lattice QCD”, *Phys. Rev. D* **83** (2011) 094507, doi:10.1103/PhysRevD.83.094507, arXiv:1011.1213.

[7] C. Bierlich et al., “A comprehensive guide to the physics and usage of PYTHIA 8.3”, *SciPost Phys. Codeb.* **2022** (2022) 8, doi:10.21468/SciPostPhysCodeb.8, arXiv:2203.11601.

[8] T. Sjöstrand and P. Z. Skands, “Multiple interactions and the structure of beam remnants”, *JHEP* **03** (2004) 053, doi:10.1088/1126-6708/2004/03/053, arXiv:hep-ph/0402078.

[9] J. Bellm et al., “Herwig 7.0/Herwig++ 3.0 release note”, *Eur. Phys. J. C* **76** (2016) 196, doi:10.1140/epjc/s10052-016-4018-8, arXiv:1512.01178.

[10] Sherpa Collaboration, “Event generation with Sherpa 2.2”, *SciPost Phys.* **7** (2019) 034, doi:10.21468/SciPostPhys.7.3.034, arXiv:1905.09127.

[11] NuSea Collaboration, “Absolute Drell–Yan dimuon cross-sections in 800 GeV/$c$ pp and pd collisions”, 2003. arXiv:hep-ex/0302019.

[12] J. C. Webb, “Measurement of continuum dimuon production in 800-GeV/$c$ proton nucleon collisions”. PhD thesis, New Mexico State U., 2003. arXiv:hep-ex/0301031. doi:10.2172/1155678.

[13] D. Antreasyan et al., “Dimuon scaling comparison at 44 GeV and 62 GeV”, *Phys. Rev. Lett.* **48** (1982) 302, doi:10.1103/PhysRevLett.48.302.

[14] PHENIX Collaboration, “Measurements of $\mu\mu$ pairs from open heavy flavor and Drell–Yan in $\mathrm{p}+\mathrm{p}$ collisions at $\sqrt{s} = 200$ GeV”, *Phys. Rev. D* **99** (2019) 072003, doi:10.1103/PhysRevD.99.072003, arXiv:1805.02448.

[15] D0 Collaboration, “Measurement of the inclusive differential cross section for Z bosons as a function of transverse momentum in $\overline{\mathrm{p}}\mathrm{p}$ collisions at $\sqrt{s} = 1.8$ TeV”, *Phys. Rev. D* **61** (2000) 032004, doi:10.1103/PhysRevD.61.032004, arXiv:hep-ex/9907009.

[16] CDF Collaboration, “The transverse momentum and total cross section of $\mathrm{e}^{+}\mathrm{e}^{-}$ pairs in the Z boson region from $\mathrm{p}\overline{\mathrm{p}}$ collisions at $\sqrt{s} = 1.8$ TeV”, *Phys. Rev. Lett.* **84** (2000) 845, doi:10.1103/PhysRevLett.84.845, arXiv:hep-ex/0001021.

[17] D0 Collaboration, “Measurement of the normalized $\mathrm{Z}/\gamma^{*} \to \mu^{+}\mu^{-}$ transverse momentum distribution in $\mathrm{p}\overline{\mathrm{p}}$ collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Lett. B* **693** (2010) 522, doi:10.1016/j.physletb.2010.09.012, arXiv:1006.0618.

[18] CDF Collaboration, “Transverse momentum cross section of $\mathrm{e}^{+}\mathrm{e}^{-}$ pairs in the Z-boson region from $\mathrm{p}\overline{\mathrm{p}}$ collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. D* **86** (2012) 052010, doi:10.1103/PhysRevD.86.052010, arXiv:1207.7138.

[19] CMS Collaboration, “Study of Z production in PbPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV in the dimuon and dielectron decay channels”, *JHEP* **03** (2015) 022, doi:10.1007/JHEP03(2015)022, arXiv:1410.4825.

[20] ATLAS Collaboration, “Measurement of the transverse momentum and $\phi^{*}_{\eta}$ distributions of Drell–Yan lepton pairs in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **76** (2016) 291, doi:10.1140/epjc/s10052-016-4070-4, arXiv:1512.02192.

[21] CMS Collaboration, "Study of Drell–Yan dimuon production in proton-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV", *JHEP* **05** (2021) 182, doi:10.1007/JHEP05(2021)182, arXiv:2102.13648.

[22] CMS Collaboration, "Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell–Yan production in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **83** (2023) 628, doi:10.1140/epjc/s10052-023-11631-7, arXiv:2205.04897.

[23] LHCb Collaboration, "Precision measurement of forward Z boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV", *JHEP* **07** (2022) 026, doi:10.1007/JHEP07(2022)026, arXiv:2112.07458.

[24] C. T. H. Davies, B. R. Webber, and W. J. Stirling, "Drell–Yan cross-sections at small transverse momentum", *Nucl. Phys. B* **256** (1985) 413, doi:10.1016/0550-3213(85)90402-X.

[25] M. Guzzi, P. M. Nadolsky, and B. Wang, "Nonperturbative contributions to a resummed leptonic angular distribution in inclusive neutral vector boson production", *Phys. Rev. D* **90** (2014) 014030, doi:10.1103/PhysRevD.90.014030, arXiv:1309.1393.

[26] S.-Y. Wei, "Exploring the non-perturbative Sudakov factor via $Z^0$-boson production in pp collisions", *Phys. Lett. B* **817** (2021) 136356, doi:10.1016/j.physletb.2021.136356, arXiv:2009.06514.

[27] S. Baranov et al., "CASCADE3 a Monte Carlo event generator based on TMDs", *Eur. Phys. J. C* **81** (2021) 425, doi:10.1140/epjc/s10052-021-09203-8, arXiv:2101.10221.

[28] CMS Collaboration, "Underlying event measurements with leading particles and jets in pp collisions at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary CMS-PAS-FSQ-15-007, 2015.

[29] CMS Collaboration, "Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements", *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

[30] CMS Collaboration, "Development and validation of HERWIG 7 tunes from CMS underlying-event measurements", *Eur. Phys. J. C* **81** (2021) 312, doi:10.1140/epjc/s10052-021-08949-5, arXiv:2011.03422.

[31] HEPData record for this analysis, 2024. doi:10.17182/hepdata.154142.

[32] J. Alwall et al., "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

[33] Placeholder for journal reference to appendices, 2024.

[34] A. Buckley et al., "Systematic event generator tuning for the LHC", *Eur. Phys. J. C* **65** (2010) 331, doi:10.1140/epjc/s10052-009-1196-7, arXiv:0907.2973.

[35] E. Gross and O. Vitells, "Trial factors for the look elsewhere effect in high energy physics", *Eur. Phys. J. C* **70** (2010) 525, doi:10.1140/epjc/s10052-010-1470-8, arXiv:1005.1891.

[36] C. Balázs and C.-P. Yuan, "Soft gluon effects on lepton pairs at hadron colliders", *Phys. Rev. D* **56** (1997) 5558, `doi:10.1103/PhysRevD.56.5558`, `arXiv:hep-ph/9704258`.

# A Decoupling the underlying-event and Drell–Yan dilepton transverse momentum descriptions

The analysis in this chapter shows the mutual influence of the intrinsic $k_T$ tune on the underlying-event (UE) description, and vice versa. The results of approximate decoupling of the two parts rationalize the studies in the main text of tuning the intrinsic $k_T$ using fixed UE tunes. Our baseline is the PYTHIA CP5 UE tune [29], recently developed by the CMS Collaboration, for which five parameters controlling multiple-parton interactions and color reconnection were varied. This tune was obtained using UE data measured by CDF and CMS at center-of-mass energies of 1.96, 7 and 13 TeV.

To assess the impact of the UE parameterization on the Drell–Yan (DY) dilepton transverse momentum ($p_T(\ell^+\ell^-)$) spectrum, we generated DY samples and their $p_T(\ell^+\ell^-)$ distributions with the intrinsic $k_T$ parameter fixed to the tuned result and the UE parameters set to either the CP5 tune-up or tune-down variation. The difference between the two predictions reflects the effects of the UE-tune uncertainty on the DY $p_T(\ell^+\ell^-)$ spectrum, shown as red bands in Fig. A.1 (left), which are much smaller than the uncertainty from the intrinsic $k_T$ variations shown as violet bands.

Similarly, we studied the impact of the intrinsic $k_T$ variation on observables that are sensitive to the UE models and have been used to obtain the CP5 tune. With the UE parameters fixed to the CP5 tune, we generated minimum-bias events with the tuned intrinsic $k_T$ parameter, shown as violet markers in Fig. A.1 (right). The intrinsic $k_T$ tune uncertainty was estimated from the difference between the tune-up and -down variations, represented as the violet band in Fig. A.1 (right). Compared with the UE tune uncertainty represented by the red band, the impact of the intrinsic $k_T$ variations on UE-sensitive observables is small. The results shown in Fig. A.1 imply that the parameter space for UE and intrinsic $k_T$ can be factorized.

Besides the intrinsic $k_T$ model, also the lower cutoff scale of initial state radiation (ISR) (SPACESHOWER:PT0REF in PYTHIA) affects the DY $p_T(\ell^+\ell^-)$ distribution, as indicated in the main text and shown in Fig. 2. However, the UE observables are sensitive to the ISR cutoff scale. The combined tune of the intrinsic $k_T$ parameter and the cutoff scale of ISR to the DY $p_T(\ell^+\ell^-)$ distribution alters the UE observable, which is shown as the blue markers in Fig. A.1 (right). For the purpose of decoupling the intrinsic $k_T$ study from the UE modeling when investigating its scaling behavior with the collision energy and hard-scattering scale, the parameter for the ISR cutoff is fixed to its default value in the studies shown in Figs. 1 and 3.

In summary, the study assesses the mutual impacts of the variation of the intrinsic $k_T$ tune on the UE, and that of the UE tune on the DY transverse momentum, and concludes that the impacts are negligible, which supports our approach of tuning the intrinsic $k_T$ parameters with fixed UE parameters.

# B Tuning results

Table B.1 gives the tuning results shown in Fig. 1. Tables B.2 and B.3 give the tuning results corresponding to the entries "CP5 SpaceShower:pT0Ref = 1 GeV" and "CH3 SudakovCommon:pTmin = 0.7 GeV" in Fig. 2, respectively. Table B.4 gives the tuning results shown in Fig. 3.

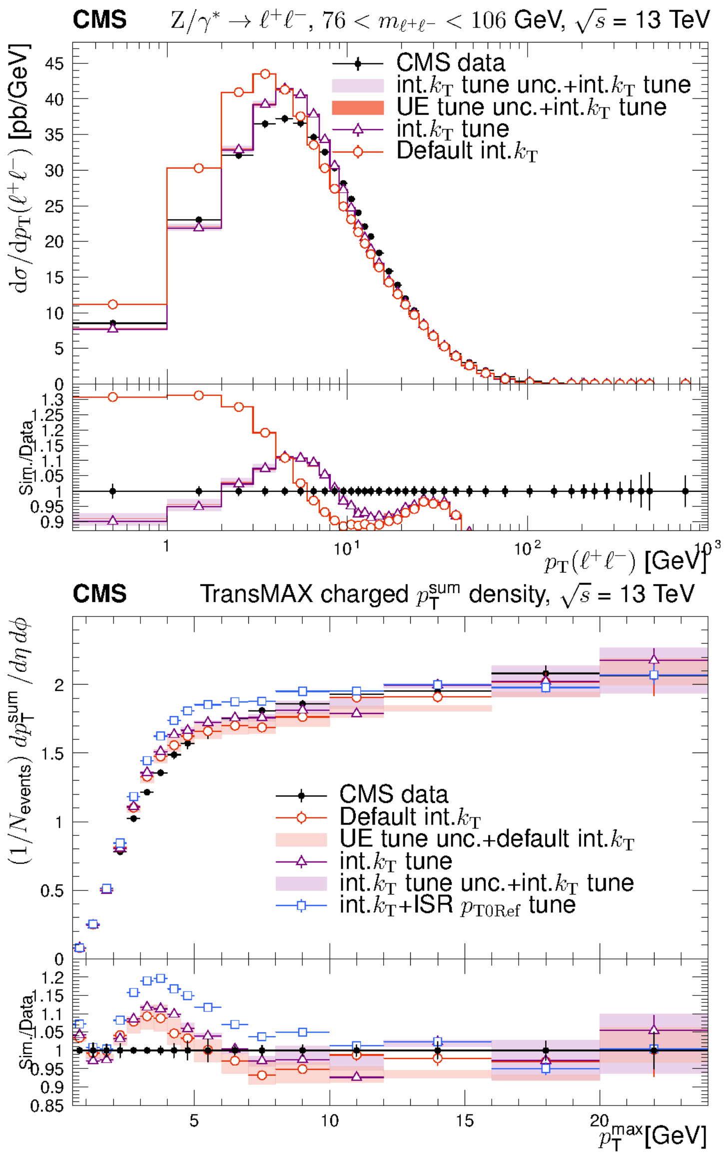


Figure A.1: Effects of the variation of the UE parameters on the DY $p_T(\ell^+\ell^-)$ spectrum (upper), and of the variation of the intrinsic $k_T$ parameter on the density of the scalar sum of the charged-particle transverse momenta ($p_T^{sum}$) on the rapidity ($\eta$) - azimuthal angle ($\phi$) space as a function of the transverse momentum of the leading charged particle ($p_T^{max}$) in the transMAX region averaged over $N_{events}$ generated events [28] in the minimum bias (MB) process (lower), which is one of the observables used for UE tuning. For each event, the transMAX region is defined by the direction of the leading charged particle in the space transverse to the proton beams. Assuming $\phi$ as the azimuthal angle of the leading charged particle, the ranges of $\phi_1$ satisfying $60^\circ < |\phi - \phi_1| < 120^\circ$ define the two transverse regions, in which transMAX is the one with a higher activity. The red and violet shaded areas represent the predictions from the up and down variations of the UE tune and the intrinsic $k_T$ tune, respectively. In the upper distribution, both shaded areas are based on the prediction of tuned intrinsic $k_T$ parameter on top of PYTHIA CP5 ("int.$k_T$ tune"). In the lower distribution, the red shaded area is based on the prediction of the intrinsic $k_T$ parameter set to the default 1.8 and the UE tune set to PYTHIA CP5 ("Default int.$k_T$"), while the violet shaded area is based on the "int.$k_T$ tune" prediction. The error bars represent the statistical uncertainty in the simulated events. The upper distribution also includes the UE prediction of the combined tune of the intrinsic $k_T$ and the ISR cutoff scale to the DY $p_T(\ell^+\ell^-)$ distribution ("int.$k_T$ +ISR $p_{T0Ref}$ tune").

Table B.1: Tune results for the BEAMREMNANTS:PRIMORDIALKTHARD parameter in PYTHIA 8 and the SHOWERHANDLER:INTRINSICPTGAUSSIAN parameter in HERWIG 7, taking into account the uncertainty from tune ranges (range) and the functions for interpolation (int.).

| $\sqrt{s}$ | Generator setup | Tune result ± MC stat. ± data unc. ± range ± int. |
|---|---|---|
| 38.8 GeV | PYTHIA 8 CP5 | $0.988 \pm 0.0008 \pm 0.029 \pm 0.022 \pm 0.015$ |
| | PYTHIA 8 CP4 | $0.993 \pm 0.0008 \pm 0.029 \pm 0.017 \pm 0.009$ |
| | PYTHIA 8 CP3 | $0.990 \pm 0.004 \pm 0.03 \pm 0.017 \pm 0.020$ |
| | HERWIG 7 CH2 | $0.829 \pm 0.0005 \pm 0.017 \pm 0.010 \pm 0.06$ |
| | HERWIG 7 CH3 | $0.830 \pm 0.0005 \pm 0.017 \pm 0.010 \pm 0.026$ |
| 62 GeV | PYTHIA 8 CP5 | $1.24 \pm 0.0008 \pm 0.07 \pm 0.0015 \pm 0.06$ |
| | PYTHIA 8 CP4 | $1.24 \pm 4 \times 10^{-8} \pm 0.06 \pm 0.0012 \pm 0.006$ |
| | PYTHIA 8 CP3 | $1.23 \pm 0.0009 \pm 0.06 \pm 0.0010 \pm 0.012$ |
| | HERWIG 7 CH2 | $0.94 \pm 0.0006 \pm 0.05 \pm 0.0012 \pm 0.024$ |
| | HERWIG 7 CH3 | $0.93 \pm 0.0006 \pm 0.04 \pm 0.0014 \pm 0.019$ |
| 200 GeV | PYTHIA 8 CP5 | $1.47 \pm 0.0022 \pm 0.08 \pm 0.005 \pm 0.06$ |
| | PYTHIA 8 CP4 | $1.54 \pm 0.0024 \pm 0.09 \pm 0.003 \pm 0.004$ |
| | PYTHIA 8 CP3 | $1.54 \pm 0.0024 \pm 0.09 \pm 0.003 \pm 0.022$ |
| | HERWIG 7 CH2 | $1.14 \pm 0.0014 \pm 0.06 \pm 0.003 \pm 0.018$ |
| | HERWIG 7 CH3 | $1.15 \pm 0.0015 \pm 0.06 \pm 0.005 \pm 0.004$ |
| 1.8 TeV | PYTHIA 8 CP5 | $1.93 \pm 0.012 \pm 0.11 \pm 0.02 \pm 0.015$ |
| | PYTHIA 8 CP4 | $1.94 \pm 0.013 \pm 0.12 \pm 0.04 \pm 0.0005$ |
| | PYTHIA 8 CP3 | $2.09 \pm 0.013 \pm 0.12 \pm 0.03 \pm 0.007$ |
| | HERWIG 7 CH2 | $1.52 \pm 0.014 \pm 0.12 \pm 0.03 \pm 0.0024$ |
| | HERWIG 7 CH3 | $1.52 \pm 0.014 \pm 0.13 \pm 0.03 \pm 0.010$ |
| 1.96 TeV | PYTHIA 8 CP5 | $1.88 \pm 0.017 \pm 0.08 \pm 0.10 \pm 0.009$ |
| | PYTHIA 8 CP4 | $1.93 \pm 0.018 \pm 0.08 \pm 0.03 \pm 0.009$ |
| | PYTHIA 8 CP3 | $2.03 \pm 0.019 \pm 0.08 \pm 0.03 \pm 0.008$ |
| | HERWIG 7 CH2 | $1.41 \pm 0.023 \pm 0.10 \pm 0.08 \pm 0.0019$ |
| | HERWIG 7 CH3 | $1.42 \pm 0.021 \pm 0.09 \pm 0.024 \pm 0.021$ |
| 2.76 TeV | PYTHIA 8 CP5 | $2.36 \pm 0.022 \pm 0.3 \pm 0.005 \pm 0.005$ |
| | PYTHIA 8 CP4 | $2.39 \pm 0.020 \pm 0.3 \pm 0.024 \pm 0.013$ |
| | PYTHIA 8 CP3 | $2.35 \pm 0.023 \pm 0.3 \pm 0.004 \pm 0.007$ |
| | HERWIG 7 CH2 | $1.87 \pm 0.03 \pm 0.5 \pm 0.06 \pm 0.003$ |
| | HERWIG 7 CH3 | $1.9 \pm 0.03 \pm 0.4 \pm 0.18 \pm 0.018$ |
| 8 TeV | PYTHIA 8 CP5 | $2.64 \pm 0.006 \pm 0.0251 \pm 0.06 \pm 0.0016$ |
| | PYTHIA 8 CP4 | $2.62 \pm 0.008 \pm 0.022 \pm 0.04 \pm 0.006$ |
| | PYTHIA 8 CP3 | $2.50 \pm 0.008 \pm 0.012 \pm 0.03 \pm 0.026$ |
| | HERWIG 7 CH2 | $1.89 \pm 0.008 \pm 0.015 \pm 0.05 \pm 0.007$ |
| | HERWIG 7 CH3 | $1.89 \pm 0.007 \pm 0.009 \pm 0.05 \pm 0.007$ |
| 8.16 TeV | PYTHIA 8 CP5 | $2.66 \pm 0.029 \pm 0.14 \pm 0.02 \pm 0.015$ |
| | PYTHIA 8 CP4 | $2.63 \pm 0.029 \pm 0.16 \pm 0.023 \pm 0.013$ |
| | PYTHIA 8 CP3 | $2.62 \pm 0.029 \pm 0.13 \pm 0.015 \pm 0.007$ |
| | HERWIG 7 CH2 | $1.96 \pm 0.03 \pm 0.19 \pm 0.06 \pm 0.027$ |
| | HERWIG 7 CH3 | $1.96 \pm 0.03 \pm 0.17 \pm 0.09 \pm 0.02$ |
| 13 TeV (CMS) | PYTHIA 8 CP5 | $2.648 \pm 0.006 \pm 0.027 \pm 0.028 \pm 0.04$ |
| | PYTHIA 8 CP4 | $2.654 \pm 0.006 \pm 0.027 \pm 0.08 \pm 0.004$ |
| | PYTHIA 8 CP3 | $2.619 \pm 0.006 \pm 0.028 \pm 0.05 \pm 0.009$ |
| | HERWIG 7 CH2 | $2.05 \pm 0.03 \pm 0.04 \pm 0.03 \pm 0.035$ |
| | HERWIG 7 CH3 | $2.03 \pm 0.03 \pm 0.04 \pm 0.021 \pm 0.010$ |
| 13 TeV (LHCb) | PYTHIA 8 CP5 | $2.66 \pm 0.009 \pm 0.06 \pm 0.13 \pm 0.0007$ |
| | PYTHIA 8 CP4 | $2.67 \pm 0.009 \pm 0.06 \pm 0.10 \pm 0.003$ |
| | PYTHIA 8 CP3 | $2.62 \pm 0.009 \pm 0.06 \pm 0.11 \pm 0.00007$ |
| | HERWIG 7 CH2 | $1.99 \pm 0.04 \pm 0.06 \pm 0.05 \pm 0.04$ |
| | HERWIG 7 CH3 | $1.99 \pm 0.06 \pm 0.14 \pm 0.16 \pm 0.06$ |

Table B.2: Tune results for the BEAMREMNANTS:PRIMORDIALKTHARD parameter in PYTHIA 8 with the CP5 tune setup. The parameter SPACESHOWER:PT0REF was set to 1 GeV.

| $\sqrt{s}$ | Tune result ± MC stat. ± data unc. ± range ± int. |
|---|---|
| 38.8 GeV | $0.929 \pm 0.001 \pm 0.03 \pm 0.015 \pm 0.0005$ |
| 62 GeV | $1.16 \pm 1.8 \times 10^{-10} \pm 0.07 \pm 0.0014 \pm 0.00018$ |
| 200 GeV | $1.37 \pm 0.003 \pm 0.09 \pm 0.006 \pm 0.003$ |
| 1.8 TeV | $1.66 \pm 0.013 \pm 0.08 \pm 0.007 \pm 0.016$ |
| 1.96 TeV | $1.51 \pm 0.016 \pm 0.11 \pm 0.18 \pm 0.08$ |
| 2.76 TeV | $2.2 \pm 0.026 \pm 0.3 \pm 0.006 \pm 0.025$ |
| 8 TeV | $2.51 \pm 0.04 \pm 0.03 \pm 0.008 \pm 0.04$ |
| 8.16 TeV | $2.51 \pm 0.05 \pm 0.20 \pm 0.021 \pm 0.14$ |
| 13 TeV (CMS) | $2.54 \pm 0.008 \pm 0.04 \pm 0.09 \pm 0.0024$ |
| 13 TeV (LHCb) | $2.52 \pm 0.014 \pm 0.09 \pm 0.17 \pm 0.0021$ |

Table B.3: Tune results for the SHOWERHANDLER:INTRINSICPTGAUSSIAN parameter in HERWIG 7 with the CH3 tune setup. The parameter SUDAKOVCOMMON:PTMIN was set to 0.7 GeV.

| $\sqrt{s}$ | Tune result ± MC stat. ± data unc. ± range ± int. |
|---|---|
| 38.8 GeV | $0.742 \pm 0.0010 \pm 0.024 \pm 0.0010 \pm 0.004$ |
| 62 GeV | $0.80 \pm 0.00021 \pm 0.04 \pm 0.0020 \pm 0.00024$ |
| 200 GeV | $1.00 \pm 0.0018 \pm 0.06 \pm 0.004 \pm 0.0023$ |
| 1.8 TeV | $1.16 \pm 0.024 \pm 0.18 \pm 0.06 \pm 0.07$ |
| 1.96 TeV | $0.95 \pm 0.025 \pm 0.10 \pm 0.012 \pm 0.005$ |
| 2.76 TeV | $1.60 \pm 0.018 \pm 0.23 \pm 0.10 \pm 0.24$ |
| 8 TeV | $1.395 \pm 0.07 \pm 0.17 \pm 0.14 \pm 0.08$ |
| 8.16 TeV | $1.47 \pm 0.028 \pm 0.17 \pm 0.03 \pm 0.04$ |
| 13 TeV (CMS) | $1.71 \pm 0.025 \pm 0.016 \pm 0.00017 \pm 0.07$ |
| 13 TeV (LHCb) | $1.60 \pm 0.06 \pm 0.08 \pm 0.13 \pm 0.05$ |

Table B.4: Results of the tune to various ranges of the $m(\ell^+\ell^-)$ for values of $\sqrt{s}$ of 38.8 GeV and 8, 8.16, and 13 TeV.

| $\sqrt{s}$ | $m(\ell^+\ell^-)$ range | Tune result ± MC stat. and data unc. ± range ± int. | |
|---|---|---|---|
| | | PYTHIA CP5 | HERWIG CH2 |
| 38.8 GeV | 4.2 – 5.2 GeV | $0.99 \pm 0.05 \pm 0.020 \pm 0.010$ | $0.82 \pm 0.03 \pm 0.011 \pm 0.05$ |
| | 5.2 – 6.2 GeV | $1.03 \pm 0.06 \pm 0.020 \pm 0.025$ | $0.85 \pm 0.03 \pm 0.010 \pm 0.09$ |
| | 6.2 – 7.2 GeV | $1.07 \pm 0.08 \pm 0.010 \pm 0.20$ | $0.88 \pm 0.05 \pm 0.010 \pm 0.11$ |
| | 7.2 – 8.7 GeV | $0.92 \pm 0.04 \pm 0.025 \pm 0.005$ | $0.80 \pm 0.03 \pm 0.016 \pm 0.05$ |
| | 10.2 – 12.85 GeV | $0.87 \pm 0.31 \pm 0.18 \pm 0.16$ | $0.81 \pm 0.23 \pm 0.09 \pm 0.06$ |
| 8 TeV | 46 – 66 GeV | $2.36 \pm 0.17 \pm 0.0016 \pm 0.05$ | $2.15 \pm 0.27 \pm 0.03 \pm 0.07$ |
| | 66 – 116 GeV | $2.51 \pm 0.07 \pm 0.017 \pm 0.05$ | $1.95 \pm 0.05 \pm 0.04 \pm 0.011$ |
| | 116 – 150 GeV | $2.70 \pm 0.33 \pm 0.13 \pm 0.17$ | $2.1 \pm 0.4 \pm 0.0005 \pm 0.006$ |
| 8.16 TeV | 15 – 60 GeV | $3.0 \pm 0.4 \pm 0.19 \pm 0.10$ | $2.2 \pm 0.3 \pm 0.10 \pm 0.11$ |
| | 60 – 120 GeV | $2.61 \pm 0.13 \pm 0.033 \pm 0.009$ | $1.89 \pm 0.18 \pm 0.08 \pm 0.003$ |
| 13 TeV | 50 – 76 GeV | $2.65 \pm 0.07 \pm 0.06 \pm 0.017$ | $1.91 \pm 0.14 \pm 0.02 \pm 0.007$ |
| | 76 – 106 GeV | $2.66 \pm 0.03 \pm 0.08 \pm 0.003$ | $2.05 \pm 0.05 \pm 0.02 \pm 0.01$ |
| | 106 – 170 GeV | $2.59 \pm 0.07 \pm 0.11 \pm 0.03$ | $2.34 \pm 0.23 \pm 0.07 \pm 0.16$ |
| | 170 – 350 GeV | $2.65 \pm 0.16 \pm 0.07 \pm 0.007$ | $1.90 \pm 0.16 \pm 0.16 \pm 0.02$ |
| | 350 – 1000 GeV | $2.17 \pm 0.4 \pm 0.018 \pm 0.017$ | $1.8 \pm 0.4 \pm 0.13 \pm 0.03$ |

## C The CMS Collaboration

**Yerevan Physics Institute, Yerevan, Armenia**
A. Hayrapetyan, A. Tumasyan[1]

**Institut für Hochenergiephysik, Vienna, Austria**
W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, I. Mikulec, J. Schieck[2], R. Schöfbeck, D. Schwarz, M. Sonawane, W. Waltenberger, C.-E. Wulz[2]

**Universiteit Antwerpen, Antwerpen, Belgium**
T. Janssen, T. Van Laer, P. Van Mechelen

**Vrije Universiteit Brussel, Brussel, Belgium**
N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat[3], G.P. Van Onsem, S. Van Putte, D. Vannerom

**Université Libre de Bruxelles, Bruxelles, Belgium**
B. Bilin, B. Clerbaux, A.K. Das, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, J. Jaramillo, A. Khalilzadeh, F.A. Khan, K. Lee, M. Mahdavikhorrami, A. Malara, S. Paredes, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

**Ghent University, Ghent, Belgium**
M. De Coen, D. Dobur, G. Gokbulut, Y. Hong, J. Knolle, L. Lambrecht, D. Marckx, K. Mota Amarilo, K. Skovpen, N. Van Den Bossche, J. van der Linden, L. Wezenbeek

**Université Catholique de Louvain, Louvain-la-Neuve, Belgium**
A. Benecke, A. Bethani, G. Bruno, C. Caputo, J. De Favereau De Jeneret, C. Delaere, I.S. Donertas, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, T.T. Tran, S. Wertz

**Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil**
G.A. Alves, M. Alves Gallo Pereira, E. Coelho, G. Correia Silva, C. Hensel, T. Menezes De Oliveira, C. Mora Herrera[4], A. Moraes, P. Rebello Teles, M. Soeiro, A. Vilela Pereira[4]

**Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil**
W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, T. Laux Kuhn, M. Macedo, J. Martins[7], L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

**Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil**
C.A. Bernardes[6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

**Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria**
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Shopova, G. Sultanov

**University of Sofia, Sofia, Bulgaria**
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

**Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile**
S. Keshri, D. Laroze, S. Thakur

**Beihang University, Beijing, China**
T. Cheng, T. Javaid, L. Yuan

**Department of Physics, Tsinghua University, Beijing, China**
Z. Hu, Z. Liang, J. Liu

**Institute of High Energy Physics, Beijing, China**
G.M. Chen[8], H.S. Chen[8], M. Chen[8], F. Iemmi, C.H. Jiang, A. Kapoor[9], H. Liao, Z.-A. Liu[10], R. Sharma[11], J.N. Song[10], J. Tao, C. Wang[8], J. Wang, Z. Wang[8], H. Zhang, J. Zhao

**State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**
A. Agapitos, Y. Ban, S. Deng, B. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, X. Sun, D. Wang, H. Yang, L. Zhang, Y. Zhao, C. Zhou

**Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory 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[12], B. Li, K. Yi[13,14], J. Zhang

**Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China**
X. Gao[15], Y. Li

**Zhejiang University, Hangzhou, Zhejiang, China**
Z. Lin, C. Lu, M. Xiao

**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**
F. Ramirez, 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**
D. Giljanovic, 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[16], T. Susa

**University of Cyprus, Nicosia, Cyprus**
A. Attikis, K. Christoforou, A. Hadjiagapiou, C. Leonidou, J. Mousa, C. Nicolaou, L. Paizanos, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

**Charles University, Prague, Czech Republic**
M. Finger, M. Finger Jr., A. Kveton

**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**
B. El-mahdy, S. Khalil[17], E. Salama[18,19]

**Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**
M.A. Mahmoud, Y. Mohammed

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**
K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

**Department of Physics, University of Helsinki, Helsinki, Finland**
H. Kirschenmann, K. Osterberg, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**
S. Bharthuar, N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Myllymäki, M.m. Rantanen, H. Siikonen, J. Tuominiemi

**Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**
P. Luukka, H. Petrow

**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[20], P. Simkina, M. Titov, M. Tornago

**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**
F. Beaudette, G. Boldrini, P. Busson, A. Cappati, C. Charlot, M. Chiusi, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, M. Nguyen, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, L. Urda Gómez, E. Vernazza, A. Zabi, A. Zghiche

**Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**
J.-L. Agram[21], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Van Hove, 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, C. Dozen[22], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

**Georgian Technical University, Tbilisi, Georgia**
D. Chokheli, I. Lomidze, Z. Tsamalaidze[16]

**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**
V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, D. Pérez Adán, N. Röwert, M. Teroerde

**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J.L. Spah, A. Stein, F. Torres Da Silva De Araujo[23], S. Wiedenbeck, S. Zaleski

**RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**
C. Dziwok, G. Flügge, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**
H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[24], K. Borras[25], A. Campbell, A. Cardini, C. Cheng, F. Colombina, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[24], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, B. Kaech, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[26], W. Lohmann[27], F. Lorkowski, 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, Y. Otarid, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, J. Rübenach, L. Rygaard, A. Saggio, M. Scham[28,25], S. Schnake[25], P. Schütze, C. Schwanenberger[24], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, S. Taheri Monfared, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[25], C. Wissing, Y. Yang, A. Zimermmane Castro Santos

**University of Hamburg, Hamburg, Germany**
A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, S. Bollweg, M. Bonanomi, P. Connor, K. El Morabit, Y. Fischer, E. Garutti, A. Grohsjean, J. Haller, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

**Karlsruher Institut fuer Technologie, Karlsruhe, Germany**
S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[29], R. Hofsaess,

M. Horzela, U. Husemann, J. Kieseler, M. Klute, R. Koppenhöfer, J.M. Lawhorn, M. Link, A. Lintuluoto, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, N. Trevisani, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, X. Zuo

**Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece**
G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[29], A. Stakia

**National and Kapodistrian University of Athens, Athens, Greece**
P. Kontaxakis, G. Melachroinos, Z. Painesis, I. Papavergou, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

**National Technical University of Athens, Athens, Greece**
G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

**University of Ioánnina, Ioánnina, Greece**
K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, C. Kamtsikis, 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[30,31], K. Márton, A.J. Rádl[32], F. Sikler, V. Veszpremi

**MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary**
M. Csanád, K. Farkas, A. Fehérkuti[33], M.M.A. Gadallah[34], Á. Kadlecsik, P. Major, 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[33], F. Nemes[33], T. Novak

**Panjab University, Chandigarh, India**
S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[35], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, T. Sheokand, J.B. Singh, A. Singla

**University of Delhi, Delhi, India**
A. Ahmed, A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, A. Kumar, M. Naimuddin, K. Ranjan, M.K. Saini, S. Saumya

**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**
S. Baradia, S. Barman[36], 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.C. Behera, S. Chatterjee, G. Dash, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[37], D. Kumar[37], T. Mishra, B. Parida, P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

**Tata Institute of Fundamental Research-A, Mumbai, India**
S. Dugad, G.B. Mohanty, M. Shelake, P. Suryadevara

**Tata Institute of Fundamental Research-B, Mumbai, India**
A. Bala, S. Banerjee, R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, S. Kumar, G. Majumder, K. Mazumdar, S. Parolia, A. Thachayath

**National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India**
S. Bahinipati[38], C. Kar, D. Maity[39], P. Mal, V.K. Muraleedharan Nair Bindhu[39], K. Naskar[39], A. Nayak[39], S. Nayak, K. Pal, P. Sadangi, S.K. Swain, S. Varghese[39], D. Vats[39]

**Indian Institute of Science Education and Research (IISER), Pune, India**
S. Acharya[40], A. Alpana, S. Dube, B. Gomber[40], P. Hazarika, B. Kansal, A. Laha, B. Sahu[40], S. Sharma, K.Y. Vaish

**Isfahan University of Technology, Isfahan, Iran**
H. Bakhshiansohi[41], A. Jafari[42], M. Zeinali[43]

**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**
S. Bashiri, S. Chenarani[44], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, S. Tizchang[45]

**University College Dublin, Dublin, Ireland**
M. Felcini, M. Grunewald

**INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy**
M. Abbrescia[a,b], A. Colaleo[a,b], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,46], L. Fiore[a], G. Iaselli[a,c], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

**INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy**
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], P. Capiluppi[a,b], A. Castro[†a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,47], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], G. Paggi[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], S. Rossi Tisbeni[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

**INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy**
S. Costa[a,b,48], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,48], C. Tuve[a,b]

**INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy**
P. Assiouras[a], G. Barbagli[a], G. Bardelli[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], T. Kello[a], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a], M. Meschini[a], S. Paoletti[a], A. Papanastassiou[a,b], G. Sguazzoni[a], L. Viliani[a]

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**
L. Benussi, S. Bianco, S. Meola[49], D. Piccolo

**INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy**
P. Chatagnon[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

**INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy**
A. Benaglia[a], F. Brivio[a], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], B.S. Pinolini[a], G. Pizzati[a,b], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

**INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy**
S. Buontempo[a], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,50], P. Paolucci[a,29], B. Rossi[a]

**INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy**
R. Ardino[a], P. Azzi[a], N. Bacchetta[a,51], D. Bisello[a,b], P. Bortignon[a], G. Bortolato[a,b], A. Bragagnolo[a,b], A.C.M. Bulla[a], R. Carlin[a,b], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], S. Giorgetti[a], E. Lusiani[a], M. Margoni[a,b], G. Maron[a,52], A.T. Meneguzzo[a,b], M. Migliorini[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

**INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy**
A. Braghieri[a], S. Calzaferri[a], D. Fiorina[a], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

**INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy**
S. Ajmal[a,b], M.E. Ascioti[a,b], G.M. Bilei[a], C. Carrivale[a,b], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,53], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

**INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy**
C. Aimè[a], C.A. Alexe[a,c], P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b], M. Cipriani[a,b], V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a], D. Matos Figueiredo[a], A. Messineo[a,b], S. Mishra[a], M. Musich[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a], T. Sarkar[a], A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P.G. Verdini[a]

**INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy**
C. Baldenegro Barrera[a,b], P. Barria[a], C. Basile[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], F. Errico[a,b], E. Longo[a,b], L. Martikainen[a,b], J. Mijuskovic[a,b], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a]

**INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy**
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a],

R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], L. Markovic[a,b], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], R. Mulargia[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], C. Tarricone[a,b], D. Trocino[a], G. Umoret[a,b], R. White[a,b]

**INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy**
J. Babbar[a,b], S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b]

**Kyungpook National University, Daegu, Korea**
S. Dogra, J. Hong, B. Kim, J. Kim, D. Lee, H. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, 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

**Hanyang University, Seoul, Korea**
E. Asilar, J. Choi, D. Kim, T.J. Kim, J.A. Merlin, Y. Ryou

**Korea University, Seoul, Korea**
S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, S. Lee, J. Yoo

**Kyung Hee University, Department of Physics, Seoul, Korea**
J. Goh, S. Yang

**Sejong University, Seoul, Korea**
H. S. Kim, Y. Kim, S. Lee

**Seoul National University, Seoul, Korea**
J. Almond, J.H. Bhyun, J. Choi, J. Choi, W. Jun, J. Kim, Y.W. Kim, S. Ko, H. Kwon, H. Lee, J. Lee, J. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

**University of Seoul, Seoul, Korea**
W. Jang, D.Y. Kang, Y. Kang, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, I.J. Watson

**Yonsei University, Department of Physics, Seoul, Korea**
S. Ha, H.D. Yoo

**Sungkyunkwan University, Suwon, Korea**
M. Choi, M.R. Kim, H. Lee, 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, A. Gaile, C. Munoz Diaz, D. Osite, G. Pikurs, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

**University of Latvia (LU), Riga, Latvia**
N.R. Strautnieks

**Vilnius University, Vilnius, Lithuania**
M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

**National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**
I. Yusuff[54], Z. Zolkapli

**Universidad de Sonora (UNISON), Hermosillo, Mexico**
J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz[55], R. Lopez-Fernandez, J. Mejia Guisao, C.A. Mondragon Herrera, A. Sánchez Hernández

**Universidad Iberoamericana, Mexico City, Mexico**
C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**
I. Bautista, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

**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, H.R. Hoorani, W.A. Khan

**AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland**
V. Avati, L. Grzanka, M. Malawski

**National Centre for Nuclear Research, Swierk, Poland**
H. Bialkowska, M. Bluj, M. Górski, M. Kazana, M. Szleper, P. Zalewski

**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**
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, T. Camporesi, G. Da Molin, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, T. Niknejad, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

**Faculty of Physics, University of Belgrade, Belgrade, Serbia**
P. Adzic, P. Milenovic

**VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**
D. Devetak, M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic

**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**
J. Alcaraz Maestre, Cristina F. Bedoya, J.A. Brochero Cifuentes, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. Llorente Merino, E. Martin Viscasillas, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, S. Sánchez Navas, J. Sastre, J. Vazquez Escobar

**Universidad Autónoma de Madrid, Madrid, Spain**
J.F. de Trocóniz

**Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain**
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, P. Leguina, E. Palencia Cortezon, J. Prado Pico, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

**Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain**
S. Bhowmik, S. Blanco Fernández, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

**University of Colombo, Colombo, Sri Lanka**
B. Kailasapathy[56], D.D.C. Wickramarathna

**University of Ruhuna, Department of Physics, Matara, Sri Lanka**
W.G.D. Dharmaratna[57], K. Liyanage, N. Perera

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**
D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, A.A. Bin Anuar, A. Bocci, L. Borgonovi, C. Botta, E. Brondolin, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[27], S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, L. Malgeri, M. Mannelli, M. Matthewman, A. Mehta, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, H. Qu, D. Rabady, B. Ribeiro Lopes, M. Rovere, H. Sakulin, S. Sanchez Cruz, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[58], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, D. Walter, J. Wanczyk[59], J. Wang, K.A. Wozniak[60], S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**
T. Bevilacqua[61], L. Caminada[61], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[61], L. Noehte[61],

T. Rohe, A. Samalan

**ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland**
T.K. Aarrestad, M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[59], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, C. Martin Perez, A. Mascellani[59], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, B. Ristic, F. Riti, R. Seidita, J. Steggemann[59], A. Tarabini, D. Valsecchi, R. Wallny

**Universität Zürich, Zurich, Switzerland**
C. Amsler[62], P. Bärtschi, M.F. Canelli, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, F. Meng, U. Molinatti, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

**National Central University, Chung-Li, Taiwan**
C. Adloff[63], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[37], S.S. Yu

**National Taiwan University (NTU), Taipei, Taiwan**
L. Ceard, K.F. Chen, P.s. 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. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

**Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey**
D. Agyel, F. Boran, F. Dolek, I. Dumanoglu[64], E. Eskut, Y. Guler[65], E. Gurpinar Guler[65], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, Y. Komurcu, G. Onengut, K. Ozdemir[66], A. Polatoz, B. Tali[67], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

**Middle East Technical University, Physics Department, Ankara, Turkey**
G. Sokmen, M. Yalvac[68]

**Bogazici University, Istanbul, Turkey**
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[69], O. Kaya[70], S. Tekten[71]

**Istanbul Technical University, Istanbul, Turkey**
A. Cakir, K. Cankocak[64,72], G.G. Dincer[64], S. Sen[73]

**Istanbul University, Istanbul, Turkey**
O. Aydilek[74], B. Hacisahinoglu, I. Hos[75], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

**Yildiz Technical University, Istanbul, Turkey**
S. Cerci, B. Isildak[76], D. Sunar Cerci, T. Yetkin

**Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine**
A. Boyaryntsev, B. Grynyov

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

L. Levchuk

**University of Bristol, Bristol, United Kingdom**
D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[77], K. Walkingshaw Pass

**Rutherford Appleton Laboratory, Didcot, United Kingdom**
A.H. Ball, K.W. Bell, A. Belyaev[78], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, A. Elliot, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

**Imperial College, London, United Kingdom**
I. Andreou, R. Bainbridge, P. Bloch, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, G.S. Chahal[79], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, C.R. Knight, J. Langford, J. León Holgado, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, M. Mieskolainen, J. Nash[80], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[29], 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, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

**Catholic University of America, Washington, DC, USA**
R. Bartek, A. Dominguez, A.E. Simsek

**The University of Alabama, Tuscaloosa, Alabama, USA**
B. Bam, A. Buchot Perraguin, R. Chudasama, S.I. Cooper, C. Crovella, S.V. Gleyzer, E. Pearson, C.U. Perez, P. Rumerio[81], E. Usai, R. Yi

**Boston University, Boston, Massachusetts, USA**
A. Akpinar, C. Cosby, 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

**Brown University, Providence, Rhode Island, USA**
G. Benelli, D. Cutts, L. Gouskos, M. Hadley, U. Heintz, J.M. Hogan[82], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, S. Mondal, N. Pervan, T. Russell, S. Sagir[83], X. Shen, F. Simpson, M. Stamenkovic, N. Venkatasubramanian, X. Yan

**University of California, Davis, Davis, California, USA**
S. Abbott, 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, F. Zhang

**University of California, Los Angeles, California, USA**
M. Bachtis, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

**University of California, Riverside, Riverside, California, USA**
R. Clare, J.W. Gary, M. Gordon, G. Hanson, W. Si

**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, M. Quinnan, B.V. Sathia Narayanan, 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, 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, S. Wang, D. Zhang

**California Institute of Technology, Pasadena, California, USA**
S. Bhattacharya, A. Bornheim, O. Cerri, A. Latorre, J. Mao, H.B. Newman, G. Reales Gutiérrez, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

**Carnegie Mellon University, Pittsburgh, Pennsylvania, USA**
J. Alison, S. An, P. Bryant, M. Cremonesi, V. Dutta, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, 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, G. Karathanasis, N. Manganelli, 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, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, S. Hogan, P. Kotamnives, J. Monroy, 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, G. Cummings, J. Dickinson, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, 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, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[84], F. Ravera, A. Reinsvold Hall[85], 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, 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, K. Matchev, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, Y. Takahashi, J. Wang

**Florida State University, Tallahassee, Florida, USA**
T. Adams, A. Al Kadhim, A. Askew, S. Bower, V. Hagopian, 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, M.M. Baarmand, S. Butalla, S. Das, T. Elkafrawy[19], M. Hohlmann, E. Yanes

**University of Illinois Chicago, Chicago, Illinois, USA**
M.R. Adams, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, D. S. Lemos, A.H. Merrit, C. Mills, S. Nanda, G. Oh, B. Ozek, D. Pilipovic, R. Pradhan, E. Prifti, T. Roy, S. Rudrabhatla, N. Singh, M.B. Tonjes, N. Varelas, M.A. Wadud, Z. Ye, J. Yoo

**The University of Iowa, Iowa City, Iowa, USA**
M. Alhusseini, D. Blend, K. Dilsiz[86], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[87], O. Neogi, H. Ogul[88], Y. Onel, A. Penzo, C. Snyder, E. Tiras[89]

**Johns Hopkins University, Baltimore, Maryland, USA**
B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, 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, M. Pitt, S. Popescu[90], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, G. Wilson

**Kansas State University, Manhattan, Kansas, USA**
B. Allmond, R. Gujju Gurunadha, 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, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[91], A. Shevelev, L. Wang

**Massachusetts Institute of Technology, Cambridge, Massachusetts, USA**
J. Bendavid, 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. Kovalskyi, 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, Z. Wang, B. Wyslouch, T. J. Yang

**University of Minnesota, Minneapolis, Minnesota, USA**
B. Crossman, B.M. Joshi, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, M. Revering, R. Rusack, R. Saradhy, N. Strobbe

**University of Nebraska-Lincoln, Lincoln, Nebraska, USA**
K. Bloom, D.R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, 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, M. Morris, D. Nguyen, J. Pekkanen, 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, J. Li, M. Lu, G. Madigan, R. Mccarthy, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, D. Wood

**Northwestern University, Evanston, Illinois, USA**
J. Bueghly, S. Dittmer, K.A. Hahn, Y. Liu, M. Mcginnis, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco

**University of Notre Dame, Notre Dame, Indiana, USA**
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K.W. Ho, K. Hurtado Anampa, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[16], 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, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, K. Wei, B.L. Winer, B. R. Yates

**Princeton University, Princeton, New Jersey, USA**
H. Bouchamaoui, K. Coldham, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, S. Kwan, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

**University of Puerto Rico, Mayaguez, Puerto Rico, USA**
S. Malik

**Purdue University, West Lafayette, Indiana, USA**
A.S. Bakshi, S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, V. Scheurer, J.F. Schulte, M. Stojanovic, J. Thieman, A. K. Virdi, F. Wang, A. Wildridge, W. Xie, Y. Yao

**Purdue University Northwest, Hammond, Indiana, USA**
J. Dolen, N. Parashar, A. Pathak

**Rice University, Houston, Texas, USA**
D. Acosta, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, I. Krommydas, 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, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[91], 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. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, J. Reichert, H. Routray, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

**University of Tennessee, Knoxville, Tennessee, USA**
D. Ally, A.G. Delannoy, S. Fiorendi, S. Higginbotham, T. Holmes, A.R. Kanuganti, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

**Texas A&M University, College Station, Texas, USA**
D. Aebi, M. Ahmad, T. Akhter, K. Androsov[59], O. Bouhali[92], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[93], H. Kim, S. Luo, R. Mueller, D. Overton, D. Rathjens, A. Safonov

**Texas Tech University, Lubbock, Texas, USA**
N. Akchurin, J. Damgov, N. Gogate, V. Hegde, A. Hussain, Y. Kazhykarim, K. Lamichhane, S.W. Lee, 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, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

**University of Virginia, Charlottesville, Virginia, USA**
B. Cardwell, H. Chung, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, C. Neu

**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, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, 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 institute or an international laboratory covered by a cooperation agreement with CERN**
S. Afanasiev, V. Alexakhin, D. Budkouski, I. Golutvin†, I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[94], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[95], A. Zarubin, I. Zhizhin, G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[94], P. Levchenko[96], V. Murzin, V. Oreshkin, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev†, Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, I. Tlisova, A. Toropin, T. Aushev, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[97,98], V. Popov, A. Zhokin, R. Chistov[94], M. Danilov[94], S. Polikarpov[94], V. Andreev, M. Azarkin, M. Kirakosyan, A. Terkulov, E. Boos, V. Bunichev, M. Dubinin[84], L. Dudko, V. Klyukhin, O. Kodolova[98], O. Lukina, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin, A. Snigirev, V. Blinov[94],

T. Dimova[94], A. Kozyrev[94], O. Radchenko[94], Y. Skovpen[94], V. Kachanov, D. Konstantinov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, D. Druzhkin[99]

**Authors affiliated with an institute formerly covered by a cooperation agreement with CERN**
V. Chekhovsky, V. Makarenko

†: Deceased
[1]Also at Yerevan State University, Yerevan, Armenia
[2]Also at TU Wien, Vienna, Austria
[3]Also at Ghent University, Ghent, Belgium
[4]Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[5]Also at Universidade Estadual de Campinas, Campinas, Brazil
[6]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
[7]Also at UFMS, Nova Andradina, Brazil
[8]Also at University of Chinese Academy of Sciences, Beijing, China
[9]Also at China Center of Advanced Science and Technology, Beijing, China
[10]Also at University of Chinese Academy of Sciences, Beijing, China
[11]Also at China Spallation Neutron Source, Guangdong, China
[12]Now at Henan Normal University, Xinxiang, China
[13]Also at Nanjing Normal University, Nanjing, China
[14]Now at The University of Iowa, Iowa City, Iowa, USA
[15]Also at Université Libre de Bruxelles, Bruxelles, Belgium
[16]Also at an institute or an international laboratory covered by a cooperation agreement with CERN
[17]Also at Zewail City of Science and Technology, Zewail, Egypt
[18]Also at British University in Egypt, Cairo, Egypt
[19]Now at Ain Shams University, Cairo, Egypt
[20]Also at Purdue University, West Lafayette, Indiana, USA
[21]Also at Université de Haute Alsace, Mulhouse, France
[22]Also at Istinye University, Istanbul, Turkey
[23]Also at The University of the State of Amazonas, Manaus, Brazil
[24]Also at University of Hamburg, Hamburg, Germany
[25]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[26]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[27]Also at Brandenburg University of Technology, Cottbus, Germany
[28]Also at Forschungszentrum Jülich, Juelich, Germany
[29]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[30]Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
[31]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[32]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[33]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[34]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[35]Also at Punjab Agricultural University, Ludhiana, India
[36]Also at University of Visva-Bharati, Santiniketan, India
[37]Also at Indian Institute of Science (IISc), Bangalore, India
[38]Also at IIT Bhubaneswar, Bhubaneswar, India
[39]Also at Institute of Physics, Bhubaneswar, India
[40]Also at University of Hyderabad, Hyderabad, India
[41]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany

[42]Also at Isfahan University of Technology, Isfahan, Iran
[43]Also at Sharif University of Technology, Tehran, Iran
[44]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[45]Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
[46]Also at Helwan University, Cairo, Egypt
[47]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[48]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[49]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[50]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[51]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[52]Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
[53]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[54]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[55]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[56]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[57]Also at Saegis Campus, Nugegoda, Sri Lanka
[58]Also at National and Kapodistrian University of Athens, Athens, Greece
[59]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[60]Also at University of Vienna, Vienna, Austria
[61]Also at Universität Zürich, Zurich, Switzerland
[62]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[63]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[64]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[65]Also at Konya Technical University, Konya, Turkey
[66]Also at Izmir Bakircay University, Izmir, Turkey
[67]Also at Adiyaman University, Adiyaman, Turkey
[68]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[69]Also at Marmara University, Istanbul, Turkey
[70]Also at Milli Savunma University, Istanbul, Turkey
[71]Also at Kafkas University, Kars, Turkey
[72]Now at Istanbul Okan University, Istanbul, Turkey
[73]Also at Hacettepe University, Ankara, Turkey
[74]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[75]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[76]Also at Yildiz Technical University, Istanbul, Turkey
[77]Also at Vrije Universiteit Brussel, Brussel, Belgium
[78]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[79]Also at IPPP Durham University, Durham, United Kingdom
[80]Also at Monash University, Faculty of Science, Clayton, Australia
[81]Also at Università di Torino, Torino, Italy
[82]Also at Bethel University, St. Paul, Minnesota, USA
[83]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[84]Also at California Institute of Technology, Pasadena, California, USA

[85]Also at United States Naval Academy, Annapolis, Maryland, USA
[86]Also at Bingol University, Bingol, Turkey
[87]Also at Georgian Technical University, Tbilisi, Georgia
[88]Also at Sinop University, Sinop, Turkey
[89]Also at Erciyes University, Kayseri, Turkey
[90]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[91]Now at another institute or international laboratory covered by a cooperation agreement with CERN
[92]Also at Texas A&M University at Qatar, Doha, Qatar
[93]Also at Kyungpook National University, Daegu, Korea
[94]Also at another institute or international laboratory covered by a cooperation agreement with CERN
[95]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
[96]Also at Northeastern University, Boston, Massachusetts, USA
[97]Also at Imperial College, London, United Kingdom
[98]Now at Yerevan Physics Institute, Yerevan, Armenia
[99]Also at Universiteit Antwerpen, Antwerpen, Belgium