

# Measurement of the underlying event activity in inclusive Z boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV

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## The CMS collaboration

*E-mail:* [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch)

**ABSTRACT:** This paper presents a measurement of the underlying event activity in proton-proton collisions at a center-of-mass energy of 13 TeV, performed using inclusive Z boson production events collected with the CMS experiment at the LHC. The analyzed data correspond to an integrated luminosity of  $2.1 \text{ fb}^{-1}$ . The underlying event activity is quantified in terms of the charged particle multiplicity, as well as of the scalar sum of the charged particles' transverse momenta in different topological regions defined with respect to the Z boson direction. The distributions are unfolded to the stable particle level and compared with predictions from various Monte Carlo event generators, as well as with similar CDF and CMS measurements at center-of-mass energies of 1.96 and 7 TeV respectively.

**KEYWORDS:** Hadron-Hadron scattering (experiments), Minimum bias, Event-by-event fluctuation

ARXIV EPRINT: [1711.04299](https://arxiv.org/abs/1711.04299)

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**1 Introduction**

The production of particles in a hadron-hadron collision includes contributions from parton-parton scatterings, initial-state radiation (ISR), final-state radiation (FSR), and beam-beam remnant (BBR) interactions. The large parton densities accessible in proton-proton (pp) collisions at the CERN LHC result in a significant probability of more than one parton-parton scattering in the same pp collision, a phenomenon known as multiple parton interactions (MPI). The combination of particle production from MPI (excluding the parton-parton scattering with the highest momentum transfer) and BBR interactions is commonly called the underlying event (UE). The UE usually produces particles at low transverse momentum ( $p_T$ ) that cannot be experimentally distinguished from the particles produced from ISR and FSR. These processes cannot be completely described by perturbative quantum chromodynamics (QCD) calculations, and require phenomenological models, whose parameters are tuned by means of fits to data.

The experimental measurement of the UE is often based on a process that defines the scale of the hardest parton-parton scattering, along with a phase space region with enhanced sensitivity to particle production associated with the UE activity. A number of measurements [1–9] have been performed by the Tevatron and LHC experiments at various center-of-mass energies, ranging from 0.3 TeV to 13 TeV, and using a variety of hard processes including events with high- $p_T$  charged particles or jets, Z+jets, and  $t\bar{t}$ +jets. Measurements of the UE associated with different hard processes are useful to test the level

of universality of the underlying MPI dynamics. Events with a harder scale are expected to correspond, on average, to proton-proton interactions with a smaller impact parameter and therefore with more MPI [10]. Such increased UE activity is observed to plateau at high energy scales, which indicates that the smallest impact parameters have been reached and hence maximum matter overlap in the pp collision [11].

This paper presents a measurement of the UE activity based on events with inclusive  $Z \rightarrow \mu^+\mu^-$  production at  $\sqrt{s} = 13$  TeV. Underlying event measurements based on Z boson production have been carried out previously at  $\sqrt{s} = 1.96$  TeV [9] and 7 TeV [3, 8] by Tevatron and LHC experiments. Z boson production is a process with a clean experimental signature and well understood theoretically, allowing clear identification of the UE activity. Measurements with Z bosons also make it possible to partially distinguish the MPI and ISR/FSR contributions [3, 12]. In this paper, the properties of the UE are measured as a function of conventional observables related to the impact parameter of the pp collision, such as the number of charged particles and the scalar sum of their  $p_T$ . The data are corrected for detector effects and compared to Monte Carlo (MC) event generators, as well as with earlier results at  $\sqrt{s} = 1.96$  TeV [9] and 7 TeV [3].

The outline of the paper is as follows. Section 2 describes the data and simulated samples used for the validation and unfolding studies. Section 3 gives a brief description of the CMS detector, whereas section 4 describes the event and track selection criteria, and the observables used for quantification of the UE. The unfolding procedure and systematic effects are discussed in section 5, and the final results are presented in section 6. Finally, the analysis is summarized in section 7.

## 2 Data and simulated samples

The analysis is performed on a sample of pp collisions at  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of  $2.1 \text{ fb}^{-1}$ . Data were collected with the CMS detector in 2015 when the average number of inelastic collisions per bunch crossing (pileup) was about 20.

For the evaluation of the event and track selection efficiencies, signal and background processes are simulated at next-to-leading order (NLO) accuracy with MC@NLO 2.2.2 [13] and, for single top production, with POWHEG 2.0 [14, 15]. To study the model dependence, the Z+jets events are also simulated at leading order (LO) with MADGRAPH5 2.2.2 [16, 17] combined with PYTHIA8 [18] using the CUET8PM1 [19] tune. Diboson (WW, WZ and ZZ) as well as multiple-jet production, via strong interaction processes, are generated at LO with PYTHIA8 standalone. The NNPDF3.0 [20] set is used as the default set of parton distribution functions (PDFs) for all generated LO and NLO samples.

These simulated samples are processed and reconstructed in the same manner as the collision data. The detector response is simulated in detail by using the GEANT4 package [21]. The samples include additional pileup pp interactions, with a multiplicity distribution matching that observed in data.

The measured UE distributions are unfolded to correct for detector effects and selection efficiencies, and compared to various MC simulation predictions:

- **MADGRAPH + PYTHIA8:** Z+jets events are generated with MADGRAPH, followed by parton showering and hadronization with PYTHIA8 (CUET8PM1 tune). The MADGRAPH generator includes up to 4 partons in the matrix element calculations, while additional jets can be generated by PYTHIA8 during parton showering.
- **POWHEG + PYTHIA8:** Z+jets events are produced up to NLO accuracy with the POWHEG ‘Multiscale-improved NLO’ method [15]. The PYTHIA8 generator assumes  $p_T$ -ordered parton showers, and the latter are interleaved with MPI. Tune CUET8PM1 is used for hadronization and parton showering. To quantify the effect of MPI, events are also simulated without MPI. To study the impact of color-reconnection (CR) between final state partons, PYTHIA8 events are also simulated without CR.
- **POWHEG + HERWIG++:** to further investigate the model dependence, POWHEG events are also hadronized using HERWIG++ [22] with tune EE5C [19]. HERWIG++, unlike PYTHIA8, generates angular-ordered parton showers. It simulates MPI according to a model similar to that of PYTHIA8, with tunable parameters for the regularization of the parton-parton cross section at very low momentum transfers, but without the interleaving with parton showers. In most models, the number of MPI follows a Poission distribution with a mean that depends on the overlap of the matter distributions of the hadrons.

Monte Carlo events are generated at  $\sqrt{s} = 7$  and 13 TeV, as well as for proton-antiproton collisions at  $\sqrt{s} = 1.96$  TeV.

### 3 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid, covering the pseudorapidity range  $|\eta| < 2.4$ , with detection planes based on three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers.

The silicon tracker measures charged particles within the range  $|\eta| < 2.5$ . It consists of 1440 silicon pixel and 15 148 silicon strip detector modules and is located in the 3.8 T field of the superconducting solenoid. For nonisolated particles of  $1 < p_T < 10$  GeV and  $|\eta| < 1.4$ , the track resolutions are typically 1.5% in  $p_T$  and 25–90 (45–150)  $\mu\text{m}$  in the transverse (longitudinal) impact parameter [23]. Matching muons to tracks measured in the silicon tracker results in a relative  $p_T$  resolution for muons with  $20 < p_T < 100$  GeV of 1.3–2.0% in the barrel and better than 6% in the endcaps. The  $p_T$  resolution in the barrel is better than 10% for muons with  $p_T$  up to 1 TeV [24].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [25].

## 4 Experimental methods

### 4.1 Event selection

Events are selected online by requiring the presence of at least two isolated muon candidates with  $p_T > 17$  (8) GeV for the leading (subleading) muon. Offline, events are required to have at least one well-reconstructed vertex [23] within  $\pm 24$  cm of the nominal interaction point along the  $z$ -direction. At least five tracks are required to be associated with the vertex, which should be at most 2 cm from the beam axis in the transverse plane. Muons are reconstructed with the particle-flow algorithm [26] and are required to satisfy identification criteria based on the number of hits in the muon detectors and tracker, the transverse impact parameter with respect to the beam axis, and the normalized  $\chi^2$  of the global muon track fit. The backgrounds from jets misidentified as muons and from semileptonic decays of heavy quarks are suppressed by applying an isolation condition on the muon candidates. The relative isolation variable,  $I_{\text{rel}}$ , for muons is defined as:

$$I_{\text{rel}} = \frac{[\sum p_T^{\text{charged}} + \max(0, \sum E_T^{\text{neutral}} + \sum E_T^\gamma - 0.5 \sum p_T^{\text{PU}})]}{p_T^\mu}. \quad (4.1)$$

Here  $\sum E_T^{\text{neutral}}$  and  $\sum E_T^\gamma$  are the sums of the transverse energies of neutral hadrons and photons, respectively, in a pseudorapidity-azimuth cone of size  $\Delta R \equiv \sqrt{(\eta^\mu - \eta^{\text{neutral},\gamma})^2 + (\phi^\mu - \phi^{\text{neutral},\gamma})^2} < 0.4$  around the muon direction. The quantity  $\sum p_T^{\text{charged}}$  represents the  $p_T$  sum of the charged hadrons, in the same cone around the muon, associated with the selected vertex. Finally,  $\sum p_T^{\text{PU}}$  is the  $p_T$  sum of the charged hadrons, in the same cone around the muon, not associated with the selected vertex. A muon is considered isolated if  $I_{\text{rel}} < 0.15$ . Misalignment in the detector geometry affects the measurement of muons in a different manner for data and simulation. To account for this effect, different muon momentum corrections [27] are applied to data and simulated events.

Offline, the leading and subleading muons are required to have a  $p_T$  larger than 20 and 10 GeV, respectively, so as to be in the region where the trigger efficiency is highest and  $p_T$ -independent [28]. These muons are required to be associated to the vertex with the largest value of the  $p_T^2$  sum of the tracks belonging to it. Events with two oppositely charged muons are further required to have an invariant mass ( $M_{\mu\mu}$ ) in the window 81–101 GeV. After all the selections, a high-purity sample of  $Z$  candidates is extracted with estimated background contributions, mainly from top quark and diboson processes, below 1%. About 1.3 million  $Z$  candidate events are left in the data, which is in agreement within 5% with the NLO simulation predictions.

### 4.2 Track selection

All charged particles, except the selected muons, with  $p_T > 0.5$  GeV and  $|\eta| < 2$  are considered for the UE study. To reduce the number of incorrectly reconstructed tracks, a high-purity reconstruction algorithm [29] is used.

The distance of closest approach between the track and the selected vertex in the transverse plane and in the longitudinal direction are required to be less than three times

the respective uncertainties. These requirements help reduce contamination of secondary tracks from decays of long-lived particles, photon conversions, and pileup. Tracks with poorly measured momenta are removed by requiring  $\sigma(p_T)/p_T < 5\%$ , where  $\sigma(p_T)$  is the uncertainty in the  $p_T$  measurement. The track selection efficiencies in the data and simulated samples agree within 4–5%.

These selected charged particle tracks are used to construct the relevant UE observables, namely the particle density and  $\Sigma p_T$  density, which are defined as follows:

- Particle density: the average number of charged particles in an event per unit  $\Delta\eta\Delta\phi$  area.
- $\Sigma p_T$  density: the average of the scalar  $p_T$  sum of all selected charged particles in an event per unit  $\Delta\eta\Delta\phi$  area.

Here,  $\Delta\eta = |\eta^Z - \eta^{\text{ch}}|$  and  $\Delta\phi = |\phi^Z - \phi^{\text{ch}}|$  are the pseudorapidity and azimuthal separation between each charged particle and the Z boson. In order to enhance the sensitivity to the UE, observables are calculated in different phase-space regions defined with respect to the  $\phi$  direction of the Z boson. These regions are classified as:

- *towards* region:  $\Delta\phi < 60^\circ$ ,
- *transverse* region:  $60^\circ < \Delta\phi < 120^\circ$ ,
- *away* region:  $\Delta\phi > 120^\circ$ .

The UE observables are studied as a function of the transverse momentum of the dimuon system ( $p_T^{\mu\mu}$ ).

## 5 Unfolding and systematic uncertainties

In order to compare data and predictions, the UE distributions are corrected to the stable particle level (lifetime  $c\tau > 10$  mm) with the iterative D’Agostini method [30], which also accounts for bin-to-bin migrations. In the present analysis, two-dimensional distributions are unfolded with a response matrix constructed from events simulated with MADGRAPH + PYTHIA8.

The unfolded measured distributions may be distorted by a variety of systematic effects, as discussed below.

- Model dependence: the events simulated with MADGRAPH + PYTHIA8 reproduce the measured  $p_T^{\mu\mu}$  distribution within 10–20%. The effect of this discrepancy on the final UE distributions is evaluated by reweighting the simulated sample so that it describes the measured  $p_T^{\mu\mu}$  distribution. These weights are applied to the response matrix used for the unfolding. The difference between the unfolded distributions with and without these weight factors is 2–5%. An additional cross-check is performed by using response matrices constructed with events simulated with the MADGRAPH + PYTHIA8 and the MC@NLO + PYTHIA8 event generators. The difference between the unfolded distributions obtained with the response matrices constructed with these two generators is found to be less than 0.5%.

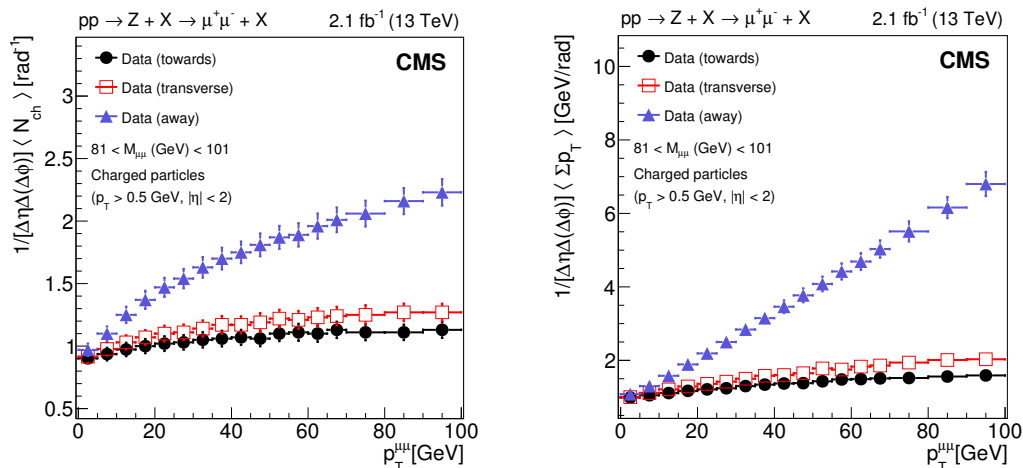
Observable	Uncertainty (%)
Model dependence	2–5
Tracking efficiency	4–6
Pileup	0.5
Trigger	0.1
Physics background	0.5–1
Muon momentum correction	0.4–0.7
Total Uncertainty	4.8–7.8

**Table 1.** Summary of the systematic uncertainties in the particle and  $\Sigma p_T$  densities.

- **Tracking efficiency:** the tracking efficiency is known with an uncertainty of 4% [23, 31]. To estimate the effect of this uncertainty on the UE distribution, 4% of the tracks are randomly removed in the simulated events while constructing the response matrix. The effect on the unfolded distributions is approximately 4–6%.
- **Pileup:** pileup events produce low- $p_T$  particles that can contribute to the UE activity. However, the effect of pileup is expected to be small in the present analysis because all tracks are required to originate from the same primary vertex. The effect of pileup is further reduced by the unfolding procedure because the simulated samples also include pileup. Any possible residual effect is evaluated by varying the pp inelastic cross section used in the simulation by 5%. The bias on the unfolded distributions is less than 0.5%.
- **Trigger:** the triggers used in the analysis require that the muons be isolated, which may bias the UE distributions. The effect of this requirement is evaluated by comparing UE distributions obtained with and without the trigger requirement in the simulation. This affects the results by up to 0.1%.
- **Physics background:** the Z boson production events are required to be in the mass window 81–101 GeV. In this region, there is a small (about 0.3%) contribution of dimuons from diboson and top quark decays. These background processes may bias the UE distributions because of the different event topologies and parton radiation patterns as compared to the Z boson events. The effect of these background processes is evaluated, using simulations, by comparing the UE distributions for the Z-boson events and for the Z-boson events combined with background processes. The UE distributions change by 0.5–1%.
- **Muon momentum correction:** the effect of the muon momentum corrections [27] is studied by comparing the corrected data distributions with the ones without corrections. The resulting effect on the particle density is up to 0.4%, and up to 0.7% for the  $\Sigma p_T$  density distribution.

Table 1 summarizes the dominant systematic uncertainties in the particle and  $\Sigma p_T$  densities. Adding all aforementioned sources in quadrature results in a total systematic uncertainty of 4.8–7.8%, depending on the UE observable and particular bin.





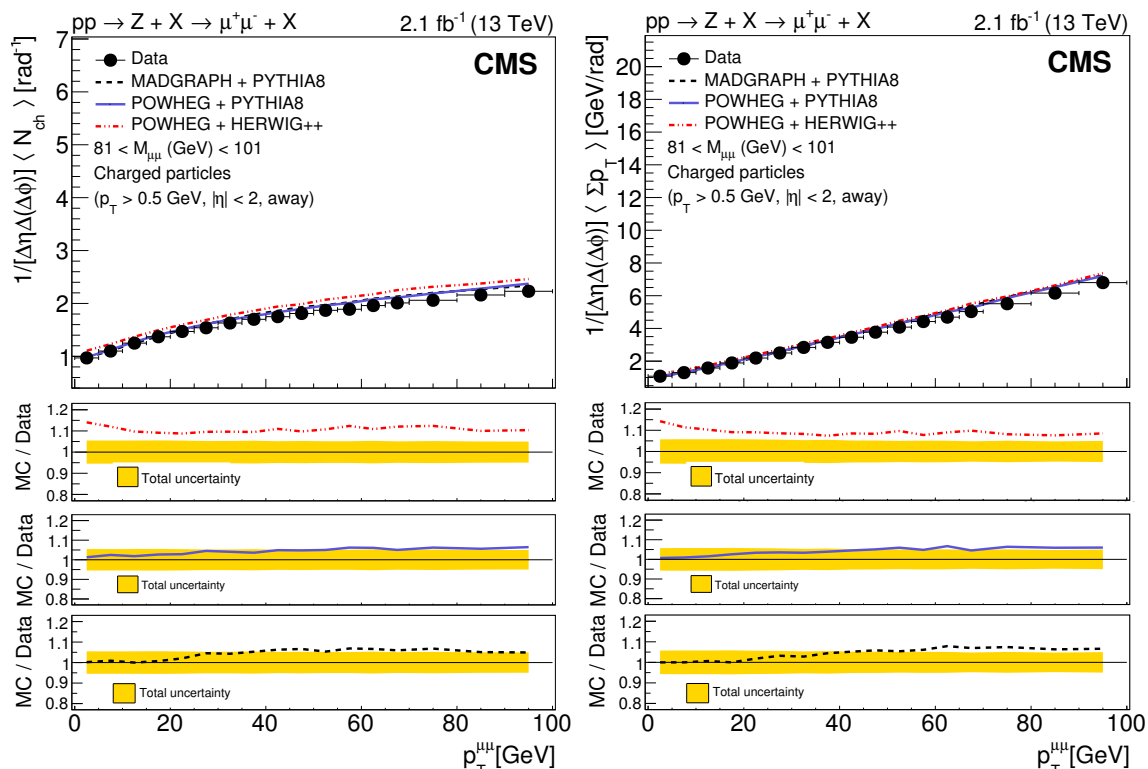
**Figure 1.** Unfolded distributions of particle density (left) and  $\Sigma p_T$  density (right) in Z events, as a function of  $p_T^{\mu\mu}$  in the *towards* ( $\Delta\phi < 60^\circ$ ), *transverse* ( $60^\circ < \Delta\phi < 120^\circ$ ), and *away* ( $\Delta\phi > 120^\circ$ ) regions. Error bars represent the statistical and systematic uncertainties added in quadrature.

## 6 Results and discussion

Figure 1 shows the comparison of the measured UE activity in the *towards*, *transverse*, and *away* regions. The activity in the *away* region increases sharply with  $p_T^{\mu\mu}$ , but more slowly in the *towards* and *transverse* regions. This is expected as particle production in the *away* region is mostly dominated by the hadronic recoil system, which is highly correlated with  $p_T^{\mu\mu}$ . Because of the large spatial separation, the contribution of the hadronic recoil is small in the *transverse* region, and becomes even smaller in the *towards* region. The activity in the three regions becomes similar as  $p_T^{\mu\mu}$  approaches zero; this observation again corroborates the hypothesis that differences in the UE activity for the three regions are due to varying parton radiation contributions. Unlike the UE measurement with leading jet/track [3, 6], in the present analysis the UE activity is not zero when  $p_T^{\mu\mu}$  approaches zero. This behavior reflects the fact that the initial scale in the Z boson events, given by the lepton pair invariant mass in the range 81–101 GeV, is already large enough to determine a significant overlap between the transverse parton densities of the colliding protons, and hence a large number of MPI. From the UE measurements using the leading charged particle (jet) approach [3, 6], it is observed that the MPI contribution reaches its maximal value at an energy scale of 5 (12–15) GeV. Above this energy, there is a slow rise in the number of particles produced, which is mainly attributed to the increase in the parton radiation contributions. In the present measurement, the minimum scale is set by the dimuon mass (81–101 GeV), which is larger than the energy where the MPI contribution saturates. Therefore, the increase in UE activity with  $p_T^{\mu\mu}$  should be mainly ascribed to the rise in the recoil hadronic contribution and associated ISR/FSR [3].

Figures 2–4 present data-model comparisons of the UE distributions as a function of the Z boson  $p_T$  in the *away*, *transverse*, and *towards* regions, respectively. The bottom panel of each plot presents the ratio of the simulated to the measured distributions. The POWHEG

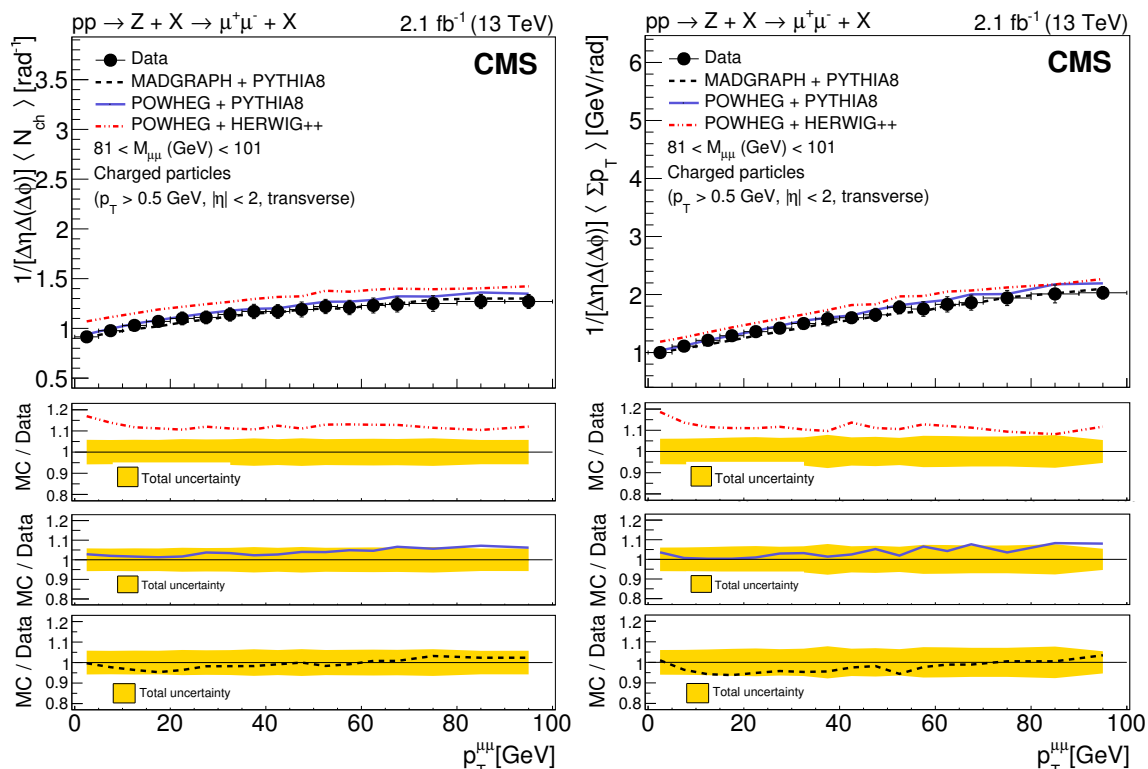




**Figure 2.** Unfolded distributions of particle density (left) and  $\Sigma p_T$  density (right) in  $Z$  events in the *away* region as a function of  $p_T^{\mu\mu}$ , compared to various model predictions: MADGRAPH + PYTHIA8 (dashed line), POWHEG + PYTHIA8 (solid line), and POWHEG + HERWIG++ (dashed-dotted line). The bottom panels of each plot show the ratios of the simulations to the measured distributions. The bands in the bottom panels represent the statistical and systematic uncertainties added in quadrature.

sample, which uses HERWIG++ for parton showering and hadronization, overestimates the UE activity by 10–15% in all topological regions, whereas when PYTHIA8 is used the measured distributions are reproduced within 5%. The MADGRAPH sample in combination with PYTHIA8 also reproduces the measurement within 5%. The MC@NLO predictions (not shown in the figures) have the same level of agreement with the data as MADGRAPH. Color reconnection between the produced partons influences the multiplicity and  $p_T$  of final-state particles. Its global impact in the measured UE observables is evaluated by comparing the PYTHIA8 predictions with and without CR, and is found to be negligible.

To understand the evolution of the UE activity with  $\sqrt{s}$ , the present measurement is compared with results obtained at  $\sqrt{s} = 1.96$  TeV at the Tevatron and at 7 TeV at the LHC. As the *away* region is dominated by the jet balancing the  $Z$  boson, the particle activity in this region is not considered for this specific study. Figures 5–8 show the UE activity as a function of  $p_T^{\mu\mu}$  at  $\sqrt{s} = 1.96, 7,$  and 13 TeV. The predictions of POWHEG with PYTHIA8 as well as with HERWIG++ are also shown. The ratios of the simulations to the measurements are plotted in the bottom panel of each plot. The POWHEG + PYTHIA8 predictions reproduce the measurements within 10% at  $\sqrt{s}$  of 1.96 TeV and 7 TeV, and within

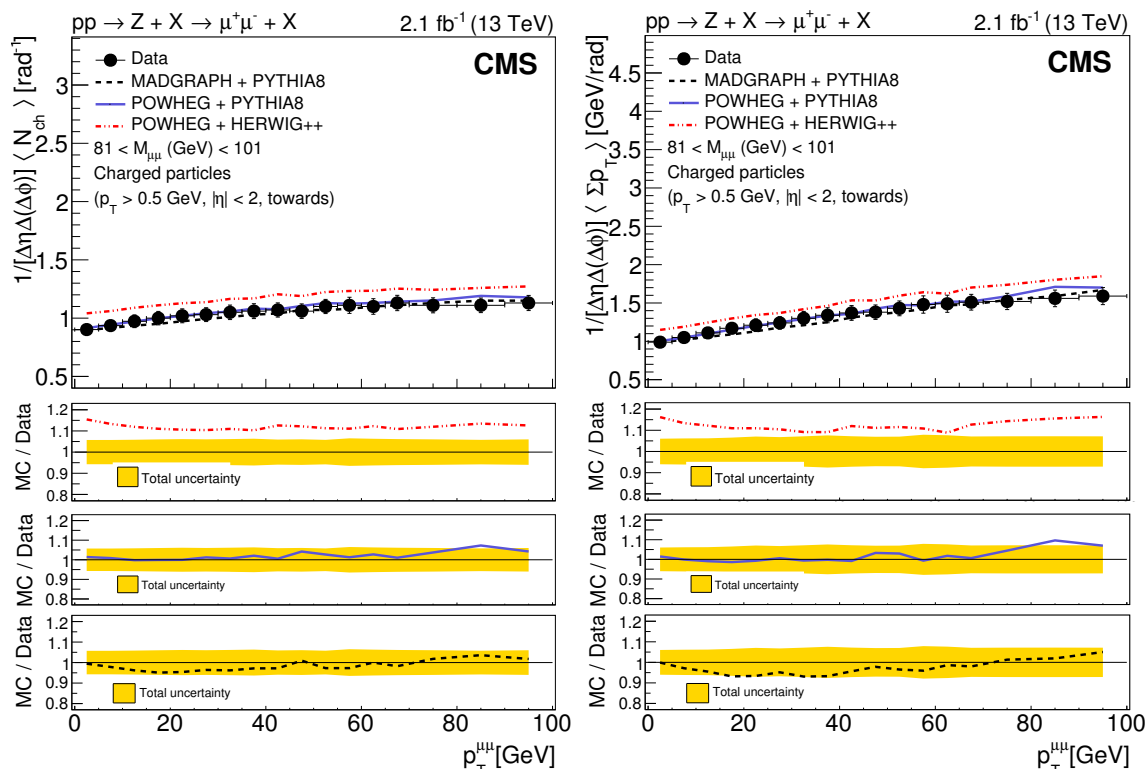


**Figure 3.** Unfolded distributions of particle density (left) and  $\Sigma p_T$  density (right) in  $Z$  events in the *transverse* region as a function of  $p_T^{\mu\mu}$ , compared to various model predictions: MADGRAPH + PYTHIA8 (dashed line), POWHEG + PYTHIA8 (solid line), and POWHEG + HERWIG++ (dashed-dotted line). The bottom panels of each plot show the ratios of the simulations to the measured distributions. The bands in the bottom panels represent the statistical and systematic uncertainties added in quadrature.

5% at 13 TeV. The combination of POWHEG and HERWIG++ describes the measurements within 10–15, 10–20, and 20–40% at  $\sqrt{s}$  of 1.96, 7, and 13 TeV, respectively.

The data show a significant increase in the UE activity with  $\sqrt{s}$ , which is qualitatively described by the model predictions. The collision energy evolution is quantified in figure 9, which shows the ratio of the UE activities at 13 and 7 TeV, and at 1.96 and 7 TeV, for the data and the simulations. An increase of 25–30% in particle and  $\Sigma p_T$  densities is observed as the collision energy increases from 7 to 13 TeV. This behavior is quantitatively well described by POWHEG + PYTHIA8 and POWHEG + HERWIG++. As the collision energy increases from 1.96 to 7 TeV, the UE activity increases by 60–80% for both the particle and  $\Sigma p_T$  densities. Event generators predict a slower rise, but the agreement improves at higher values of  $p_T^{\mu\mu}$ . The increase in particle and  $\Sigma p_T$  densities from 7 to 13 TeV is consistent with that observed in the leading jet/track analyses [3, 6].

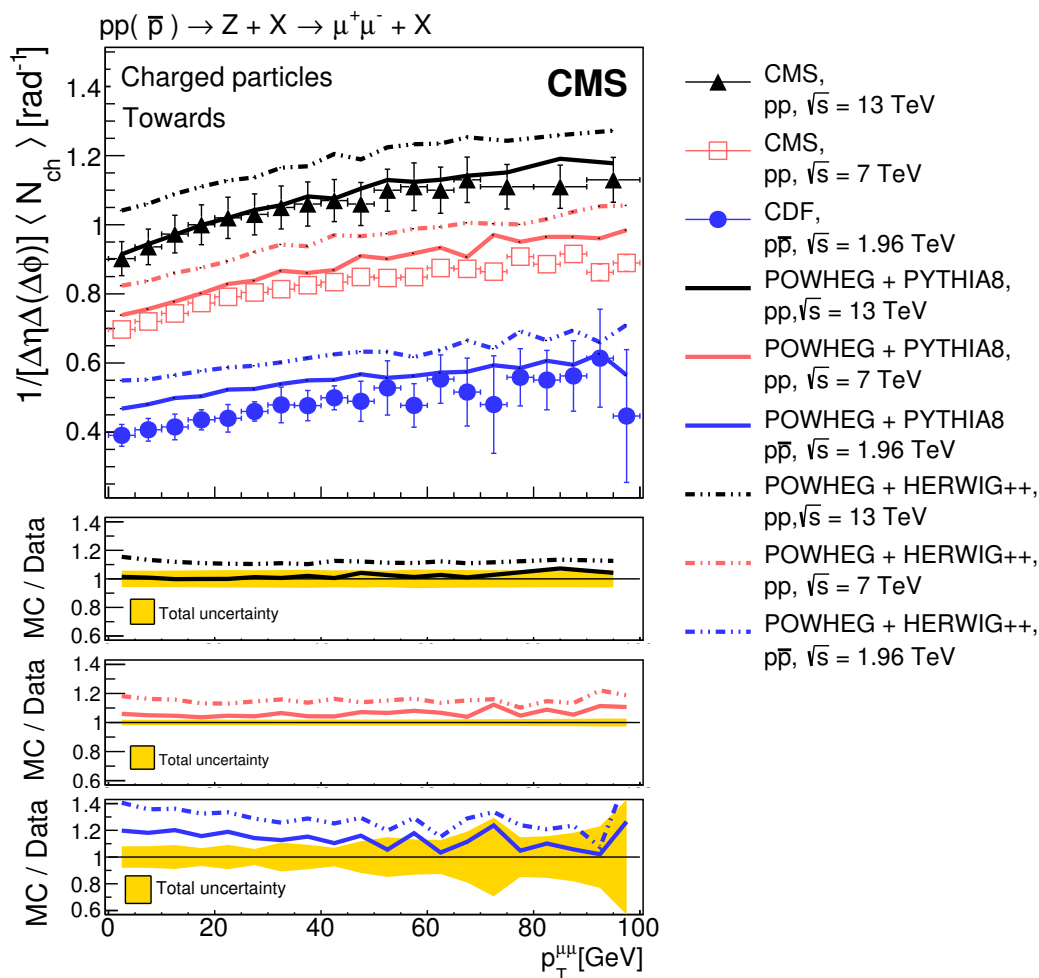
To further quantify the energy dependence of the UE activity, events with a  $p_T^{\mu\mu}$  smaller than 5 GeV are studied. Setting an upper limit on  $p_T^{\mu\mu}$  reduces the ISR and FSR contributions and the remaining UE activity stems mainly from MPI. With the requirement  $p_T^{\mu\mu} < 5$  GeV, the UE activity is similar in the *towards* and *transverse* regions. Therefore,



**Figure 4.** Unfolded distributions of particle density (left) and  $\Sigma p_T$  density (right) in  $Z$  events in the *towards* region as a function of  $p_T^{\mu\mu}$ , compared to various model predictions: MADGRAPH + PYTHIA8 (dashed line), POWHEG + PYTHIA8 (solid line), and POWHEG + HERWIG++ (dashed-dotted line). The bottom panels of each plot show the ratios of the simulations to the measured distributions. The bands in the bottom panels represent the statistical and systematic uncertainties added in quadrature.

the UE activity is combined in these two regions. Figure 10 shows the UE activity, with the  $p_T^{\mu\mu} < 5$  GeV requirement, as a function of  $\sqrt{s}$  for data compared to model predictions. There is a significant increase, by a factor 2–2.5, as the collision energy rises from 1.96 to 13 TeV, which is qualitatively reproduced by POWHEG. The energy evolution is better described by POWHEG with PYTHIA8, whereas hadronization with HERWIG++ overestimates the UE activity at all collision energies. The comparison of the distributions with and without MPI indicates that the ISR and FSR contributions, which increase slowly with center-of-mass energy, are small.

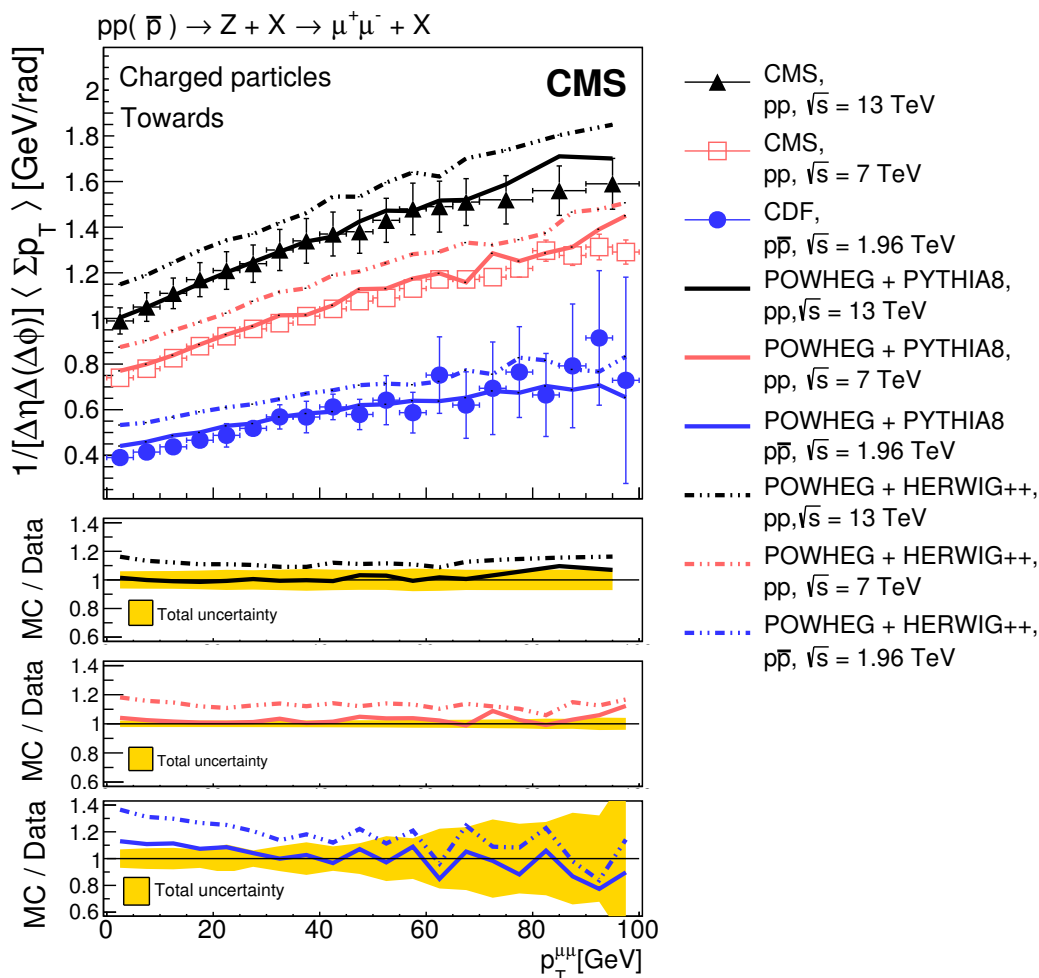
The CUETP8M1 and EE5C tunes employed here are mostly obtained from fits to minimum-bias measurements and UE measurements with leading jets or leading tracks. The fact that these tunes reproduce globally well the present data supports the hypothesis that the UE activity is independent of the hard process. The present study also confirms that the collision energy dependence of the UE activity is similar for different hard processes. Unlike UE studies with a leading track/jet, the present measurements provide new handles to better understand the evolution of ISR, FSR, and MPI contributions separately, as functions of the event energy scale and the collision energy.



**Figure 5.** Comparison of the particle density measured in Z events at  $\sqrt{s} = 13$  TeV with that at 7 (CMS) [3] and 1.96 TeV (CDF) [9] in the *towards* region as a function of  $p_T^{\mu\mu}$ . The data are also compared with the model predictions of POWHEG + PYTHIA8 (solid line) and POWHEG + HERWIG++ (dashed-dotted line). The bottom panels of each plot show the ratios of the model predictions to the measurements. The bands in the bottom panels represent the statistical and systematic uncertainties added in quadrature.

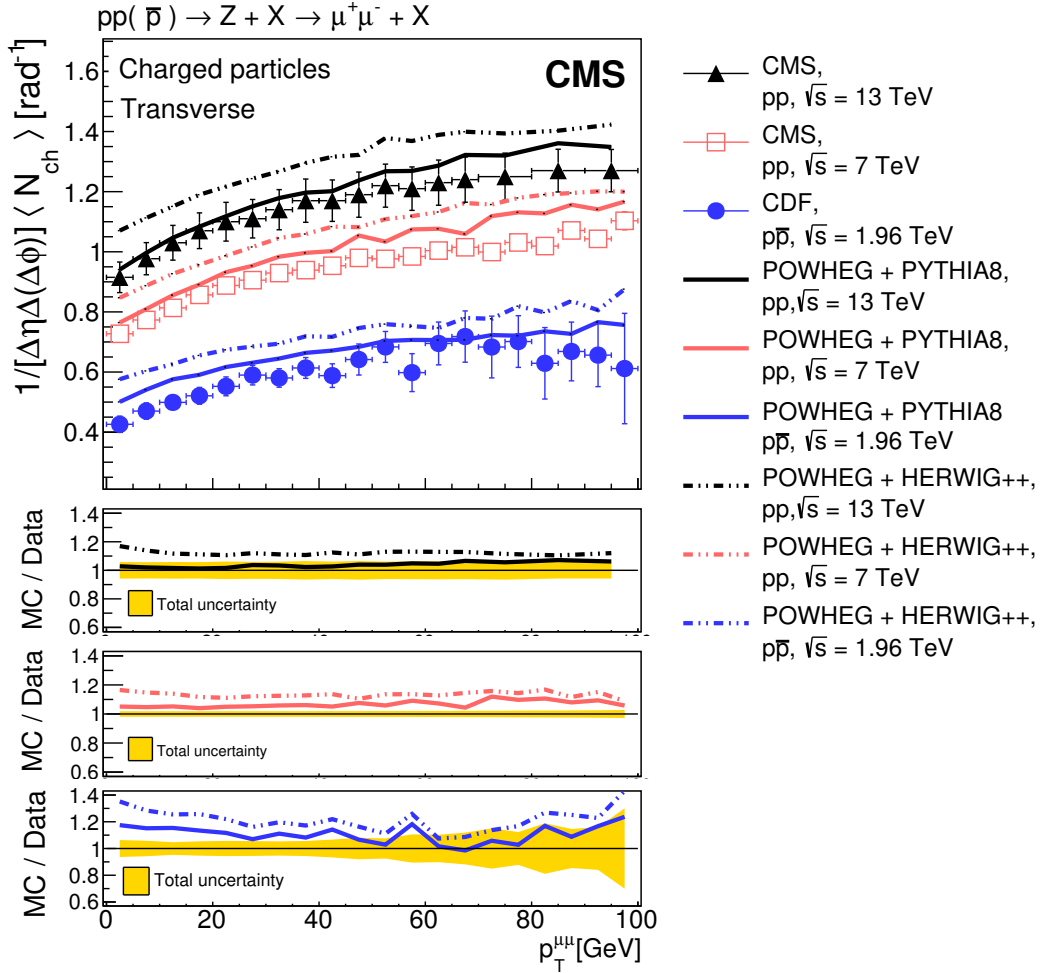
## 7 Summary

This paper presents a measurement of the underlying event (UE) activity using inclusive Z boson production events in proton-proton collisions at a center-of-mass energy of 13 TeV. The data correspond to an integrated luminosity of  $2.1 \text{ fb}^{-1}$ . The UE activity, quantified in terms of charged particle and  $\Sigma p_T$  densities, is measured as a function of the  $p_T$  of the muon pair from the Z boson decay. The distributions are corrected for detector effects and compared to various model predictions. The MADGRAPH and POWHEG generators, with parton showering and hadronization modeled with PYTHIA8 using the CUET8PM1 tune, reproduce the measurements within 5%. The combination of POWHEG and HERWIG++ (tune EE5C) overestimates the measurements by 10–15%. The present results are also

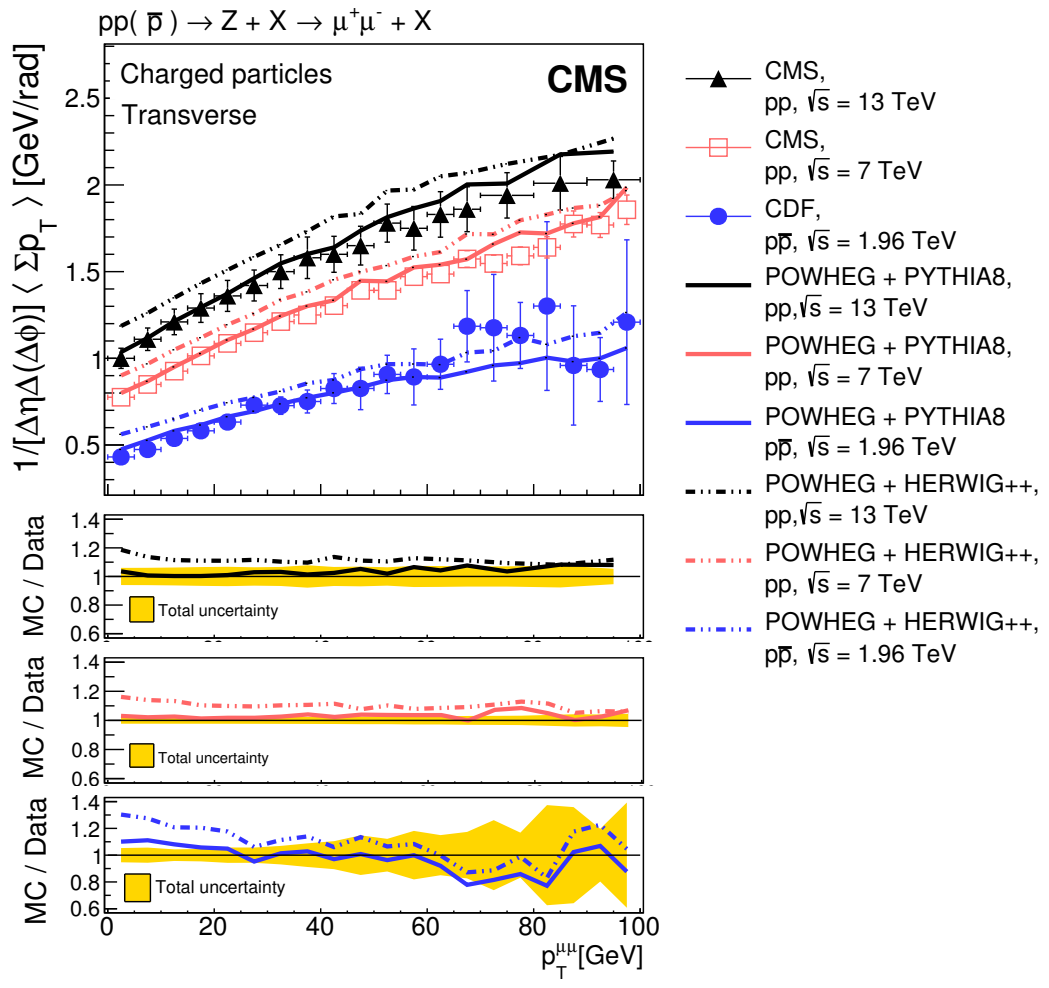


**Figure 6.** Comparison of the  $\Sigma p_T$  density measured in Z events at  $\sqrt{s} = 13$  TeV with that at 7 TeV (CMS) [3] and 1.96 TeV (CDF) [9] in the *towards* region as a function of  $p_T^{\mu\mu}$ . The data are also compared with the model predictions of POWHEG + PYTHIA8 (solid line) and POWHEG + HERWIG++ (dashed-dotted line). The bottom panels of each plot show the ratios of the model predictions to the measurements. The bands in the bottom panels represent the statistical and systematic uncertainties added in quadrature.

compared with previous measurements at 1.96 and 7 TeV. The UE activity almost doubles as the collision energy increases from 1.96 to 13 TeV. Monte Carlo event generators provide a reasonable description of the evolution of the UE activity as the collision energy rises from 1.96 to 13 TeV, although they tend to underestimate its increase in the 1.96–7 TeV range. The overall good description of the UE activity in Z boson events by Monte Carlo generators previously tuned to minimum-bias and leading track/jet UE measurements confirms the universality of the physical processes producing the underlying event in pp collisions at high energies.

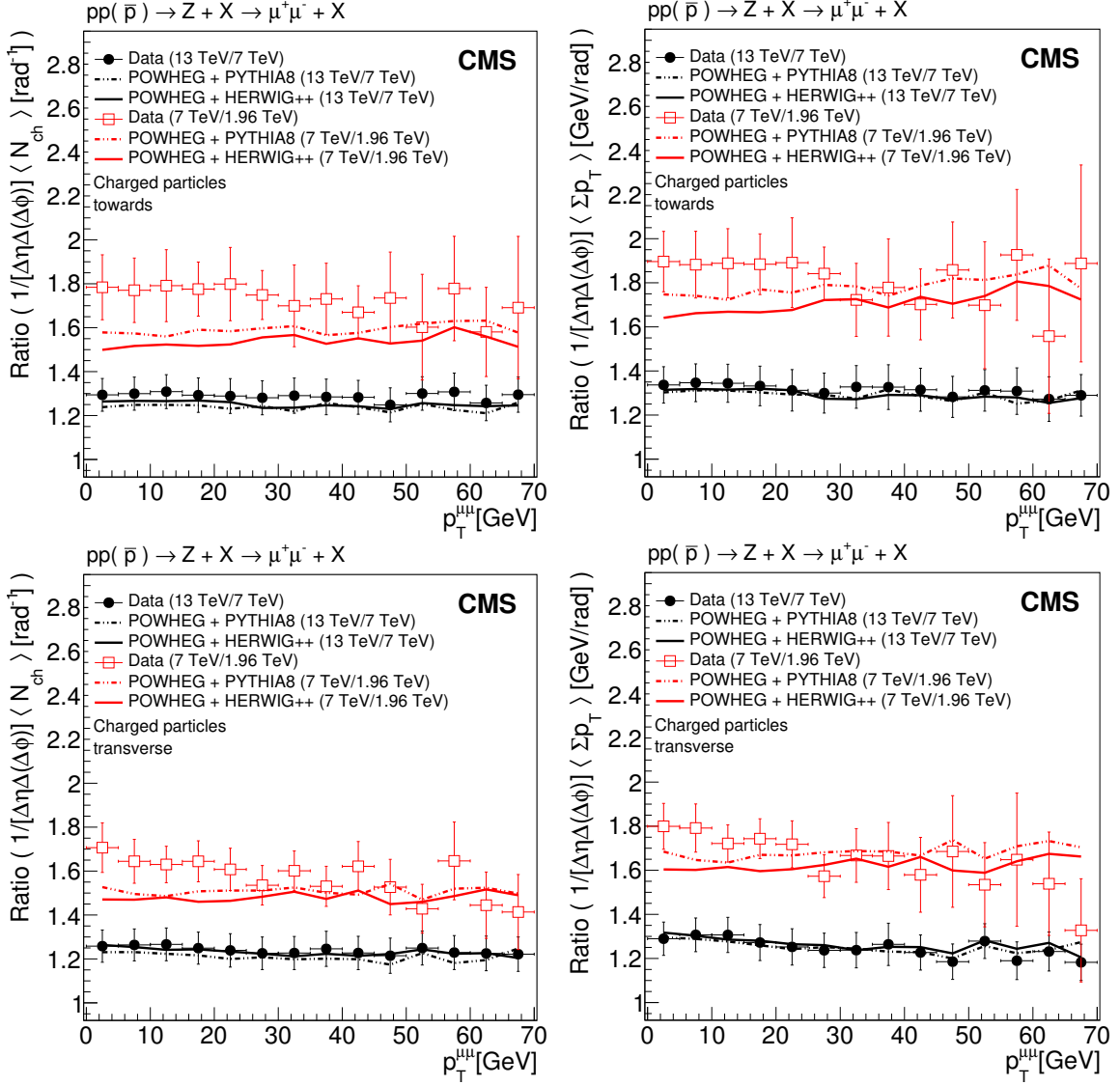


**Figure 7.** Comparison of the particle density measured in Z events at  $\sqrt{s} = 13 \text{ TeV}$  with that at 7 (CMS) [3] and 1.96 TeV (CDF) [9] in the *transverse* region as a function of  $p_T^{\mu\mu}$ . The data are also compared with the model predictions of POWHEG + PYTHIA8 (solid line) and POWHEG + HERWIG++ (dashed-dotted line). The bottom panels of each plot show the ratios of model predictions to the measurements. The bands in the bottom panels represent the statistical and systematic uncertainties added in quadrature.

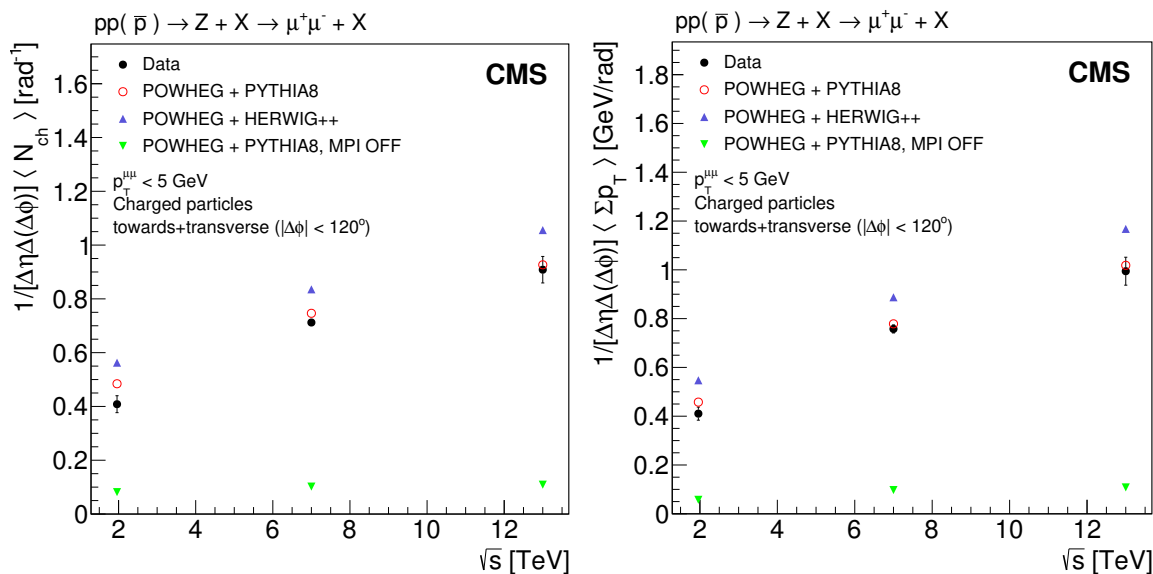


**Figure 8.** Comparison of the  $\Sigma p_T$  density measured in Z events at  $\sqrt{s} = 13$  TeV with that at 7 (CMS) [3] and 1.96 TeV (CDF) [9] in the *transverse* region as a function of  $p_T^{\mu\mu}$ . The data are also compared with the predictions of POWHEG + PYTHIA8 (solid line) and POWHEG + HERWIG++ (dashed-dotted line). The bottom panels of each plot show the ratios of the model predictions to the measurements. The bands in the bottom panels represent the statistical and systematic uncertainties added in quadrature.





**Figure 9.** Comparison of the increase in UE activity in Z events, from  $\sqrt{s} = 1.96$  TeV (CDF) [9] to 7 TeV (CMS) [3], with that from  $\sqrt{s} = 7$  TeV (CMS) to 13 TeV (CMS) in the *towards* (top) and *transverse* (bottom) regions. Panels on the left show the particle density, whereas panels on the right show the  $\Sigma p_T$  density as a function of  $p_T^{\mu\mu}$ . The data distributions are also compared with predictions of POWHEG + PYTHIA8 (dashed-dotted line) and POWHEG + HERWIG++ (solid line). The error bars represent the statistical and systematic uncertainties added in quadrature.



**Figure 10.** Average particle density (left) and average  $\Sigma p_T$  density (right) for Z events with  $p_T^{\mu\mu} < 5$  GeV as a function of the center-of-mass energy, measured by CMS and CDF [9] in the combined *towards + transverse* regions, compared to predictions from POWHEG + PYTHIA8, POWHEG + HERWIG++, and POWHEG + PYTHIA8 without MPI. The error bars represent the statistical and systematic uncertainties added in quadrature.

## 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 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 and the CMS detector provided by the following funding agencies: the Austrian Federal Ministry of Science, Research and Economy and the Austrian Science Fund; the Belgian Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport, and the Croatian Science Foundation; the Research Promotion Foundation, Cyprus; the Secretariat for Higher Education, Science, Technology and Innovation, Ecuador; the Ministry of Education and Research, Estonian Research Council via IUT23-4 and IUT23-6 and European Regional Development Fund, Estonia; the Academy of Finland, Finnish Ministry of Education and Culture, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules / CNRS, and Commissariat à l'Énergie Atomique et aux Énergies Alternatives / CEA, France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz-Gemeinschaft Deutscher

Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Scientific Research Foundation, and National Innovation Office, Hungary; the Department of Atomic Energy and the Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Ministry of Science, ICT and Future Planning, and National Research Foundation (NRF), Republic of Korea; the Lithuanian Academy of Sciences; the Ministry of Education, and University of Malaya (Malaysia); the Mexican Funding Agencies (BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI); the Ministry of Business, Innovation and Employment, New Zealand; the Pakistan Atomic Energy Commission; the Ministry of Science and Higher Education and the National Science Centre, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR, Dubna; the Ministry of Education and Science of the Russian Federation, the Federal Agency of Atomic Energy of the Russian Federation, Russian Academy of Sciences, the Russian Foundation for Basic Research and the Russian Competitiveness Program of NRNU “MEPhI”; the Ministry of Education, Science and Technological Development of Serbia; the Secretaría de Estado de Investigación, Desarrollo e Innovación, Programa Consolider-Ingenio 2010, Plan de Ciencia, Tecnología e Innovación 2013-2017 del Principado de Asturias and Fondo Europeo de Desarrollo Regional, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, UniZH, Canton Zurich, and SER); the Ministry of Science and Technology, Taipei; the Thailand Center of Excellence in Physics, the Institute for the Promotion of Teaching Science and Technology of Thailand, Special Task Force for Activating Research and the National Science and Technology Development Agency of Thailand; the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the National Academy of Sciences of Ukraine, and State Fund for Fundamental Researches, Ukraine; the Science and Technology Facilities Council, U.K.; the US Department of Energy, and the US National Science Foundation.

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Scientific and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

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## The CMS collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

### Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler<sup>1</sup>, A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, D. Rabady, N. Rad, H. Rohringer, J. Schieck<sup>1</sup>, R. Schöfbeck, M. Spanring, D. Spitzbart, J. Strauss, W. Waltenberger, J. Wittmann, C.-E. Wulz<sup>1</sup>, M. Zarucki

### Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

### Universiteit Antwerpen, Antwerpen, Belgium

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

### Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskiy, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

### Université Libre de Bruxelles, Bruxelles, Belgium

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang<sup>2</sup>

### Ghent University, Ghent, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

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

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, M. Vidal Marono, S. Wertz

### Université de Mons, Mons, Belgium

N. Beliy

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

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>3</sup>, A. Custódio, E.M. Da Costa, G.G. Da Silveira<sup>4</sup>, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>3</sup>, F. Torres Da Silva De Araujo, A. Vilela Pereira

**Universidade Estadual Paulista <sup>a</sup>, Universidade Federal do ABC <sup>b</sup>, São Paulo, Brazil**

S. Ahuja<sup>a</sup>, C.A. Bernardes<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>, D. Romero Abad<sup>b</sup>, J.C. Ruiz Vargas<sup>a</sup>

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

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, S. Stoykova, G. Sultanov

**University of Sofia, Sofia, Bulgaria**

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

**Beihang University, Beijing, China**

W. Fang<sup>5</sup>, X. Gao<sup>5</sup>

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

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

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

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez

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

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

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

Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov<sup>6</sup>, T. Susa

**University of Cyprus, Nicosia, Cyprus**

M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski



**Charles University, Prague, Czech Republic**

M. Finger<sup>7</sup>, M. Finger Jr.<sup>7</sup>

**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**

Y. Assran<sup>8,9</sup>, M.A. Mahmoud<sup>10,9</sup>, A. Mahrous<sup>11</sup>

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

R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

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

P. Eerola, J. Pekkanen, M. Voutilainen

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

J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini,  
S. Lehti, T. Lindén, P. Luukka, E. Tuominen, J. Tuominiemi, E. Tuovinen

**Lappeenranta University of Technology, Lappeenranta, Finland**

J. Talvitie, T. Tuuva

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

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour,  
S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci,  
M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

**Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université  
Paris-Saclay, Palaiseau, France**

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot,  
R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen,  
C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan,  
Y. Sirois, A.G. Stahl Leitner, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

**Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg,  
France**

J.-L. Agram<sup>12</sup>, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon,  
C. Collard, E. Conte<sup>12</sup>, X. Coubez, J.-C. Fontaine<sup>12</sup>, D. Gelé, U. Goerlach, M. Jansová,  
A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut  
de Physique Nucléaire de Lyon, Villeurbanne, France**

S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni,  
J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh,

M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov<sup>13</sup>, V. Sordini, M. Vander Donckt, S. Viret

**Georgian Technical University, Tbilisi, Georgia**

A. Khvedelidze<sup>7</sup>

**Tbilisi State University, Tbilisi, Georgia**

D. Lomidze

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

C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

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

A. Albert, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teysier, S. Thüer

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

G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl<sup>14</sup>

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

M. Aldaya Martin, T. Arndt, C. Asawatrangkuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras<sup>15</sup>, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo<sup>16</sup>, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, A. Harb, J. Hauk, M. Hempel<sup>17</sup>, H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann<sup>17</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

**University of Hamburg, Hamburg, Germany**

S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo<sup>14</sup>, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderden, A. Vanhoefer, B. Vormwald

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

M. Akbiyik, C. Barth, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann<sup>14</sup>,

S.M. Heindl, U. Husemann, F. Kassel<sup>14</sup>, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

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

S. Kesisoglou, A. Panagiotou, N. Saoulidou

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou, C. Foudas, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradass, J. Strologas, F.A. Triantis

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

M. Csanad, N. Filipovic, G. Pasztor

**Wigner Research Centre for Physics, Budapest, Hungary**

G. Bencze, C. Hajdu, D. Horvath<sup>18</sup>, Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>19</sup>, A.J. Zsigmond

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

N. Beni, S. Czellar, J. Karancsi<sup>20</sup>, A. Makovec, J. Molnar, Z. Szillasi

**Institute of Physics, University of Debrecen, Debrecen, Hungary**

M. Bartók<sup>19</sup>, P. Raics, Z.L. Trocsanyi, B. Ujvari

**Indian Institute of Science (IISc), Bangalore, India**

S. Choudhury, J.R. Komaragiri

**National Institute of Science Education and Research, Bhubaneswar, India**

S. Bahinipati<sup>21</sup>, S. Bhowmik, P. Mal, K. Mandal, A. Nayak<sup>22</sup>, D.K. Sahoo<sup>21</sup>, N. Sahoo, S.K. Swain

**Panjab University, Chandigarh, India**

S. Bansal, S.B. Beri, V. Bhatnagar, U. Bhawandeep, R. Chawla, N. Dhingra, R. Gupta, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, J.B. Singh, G. Walia

**University of Delhi, Delhi, India**

A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, Ashok Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, Aashaq Shah, R. Sharma, V. Sharma

**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**

R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

**Indian Institute of Technology Madras, Madras, India**

P.K. Behera

**Bhabha Atomic Research Centre, Mumbai, India**R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>14</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar**Tata Institute of Fundamental Research-A, Mumbai, India**

T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

**Tata Institute of Fundamental Research-B, Mumbai, India**S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity<sup>23</sup>, G. Majumder, K. Mazumdar, T. Sarkar<sup>23</sup>, N. Wickramage<sup>24</sup>**Indian Institute of Science Education and Research (IISER), Pune, India**

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**S. Chenarani<sup>25</sup>, E. Eskandari Tadavani, S.M. Etesami<sup>25</sup>, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi<sup>26</sup>, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>27</sup>, M. Zeinali**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, C. Caputo<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, F. Errico<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a,b</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a,14</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>**INFN Sezione di Bologna <sup>a</sup>, Università di Bologna <sup>b</sup>, Bologna, Italy**G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, S.S. Chhibra<sup>a</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a</sup>**INFN Sezione di Catania <sup>a</sup>, Università di Catania <sup>b</sup>, Catania, Italy**S. Albergo<sup>a,b</sup>, S. Costa<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, F. Giordano<sup>a,b</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>**INFN Sezione di Firenze <sup>a</sup>, Università di Firenze <sup>b</sup>, Firenze, Italy**G. Barbagli<sup>a</sup>, K. Chatterjee<sup>a,b</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, L. Russo<sup>a,28</sup>, G. Sguazzoni<sup>a</sup>, D. Strom<sup>a</sup>, L. Viliani<sup>a,b,14</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera<sup>14</sup>**INFN Sezione di Genova <sup>a</sup>, Università di Genova <sup>b</sup>, Genova, Italy**V. Calvelli<sup>a,b</sup>, F. Ferro<sup>a</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>**INFN Sezione di Milano-Bicocca <sup>a</sup>, Università di Milano-Bicocca <sup>b</sup>, Milano, Italy**L. Brianza<sup>a,b</sup>, F. Brivio<sup>a,b</sup>, V. Ciriolo<sup>a,b</sup>, M.E. Dinardo<sup>a,b</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, M. Malberti<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, K. Pauwels<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Pigazzini<sup>a,b,29</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>**INFN Sezione di Napoli <sup>a</sup>, Università di Napoli ‘Federico II’ <sup>b</sup>, Napoli, Italy, Università della Basilicata <sup>c</sup>, Potenza, Italy, Università G. Marconi <sup>d</sup>, Roma, Italy**S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, S. Di Guida<sup>a,d,14</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a,b</sup>, A.O.M. Iorio<sup>a,b</sup>, W.A. Khan<sup>a</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,14</sup>, P. Paolucci<sup>a,14</sup>, C. Sciacca<sup>a,b</sup>, F. Thyssen<sup>a</sup>**INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Padova, Italy, Università di Trento <sup>c</sup>, Trento, Italy**P. Azzi<sup>a,14</sup>, N. Bacchetta<sup>a</sup>, L. Benato<sup>a,b</sup>, D. Bisello<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, A. Carvalho Antunes De Oliveira<sup>a,b</sup>, P. Checchia<sup>a</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, S. Lacaprara<sup>a</sup>, P. Lujan, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, S. Ventura<sup>a</sup>, P. Zotto<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>**INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy**A. Braghieri<sup>a</sup>, F. Fallavollita<sup>a,b</sup>, A. Magnani<sup>a,b</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>**INFN Sezione di Perugia <sup>a</sup>, Università di Perugia <sup>b</sup>, Perugia, Italy**L. Alunni Solestizi<sup>a,b</sup>, M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, C. Cecchi<sup>a,b</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, R. Leonardi<sup>a,b</sup>, E. Manoni<sup>a</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Rossi<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, D. Spiga<sup>a</sup>**INFN Sezione di Pisa <sup>a</sup>, Università di Pisa <sup>b</sup>, Scuola Normale Superiore di Pisa <sup>c</sup>, Pisa, Italy**K. Androsov<sup>a</sup>, P. Azzurri<sup>a,14</sup>, G. Bagliesi<sup>a</sup>, J. Bernardini<sup>a</sup>, T. Boccali<sup>a</sup>, L. Borrello, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,b</sup>, R. Dell’Orso<sup>a</sup>, G. Fedi<sup>a</sup>, L. Giannini<sup>a,c</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a,28</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, E. Manca<sup>a,c</sup>, G. Mandorli<sup>a,c</sup>, L. Martini<sup>a,b</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, A. Savoy-Navarro<sup>a,30</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

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

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, M. Cipriani<sup>a,b</sup>, N. Daci<sup>a</sup>, D. Del Re<sup>a,b,14</sup>, M. Diemoz<sup>a</sup>, S. Gelli<sup>a,b</sup>, E. Longo<sup>a,b</sup>, F. Margaroli<sup>a,b</sup>, B. Marzocchi<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, R. Paramatti<sup>a,b</sup>, F. Preiato<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>

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

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>a,b</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</sup>, F. Cenna<sup>a,b</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, A. Degano<sup>a,b</sup>, N. Demaria<sup>a</sup>, B. Kiani<sup>a,b</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Monteno<sup>a</sup>, M.M. Obertino<sup>a,b</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, F. Ravera<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, K. Shchelina<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>, P. Traczyk<sup>a,b</sup>

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

S. Belforte<sup>a</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, A. Zanetti<sup>a</sup>

**Kyungpook National University, Daegu, Korea**

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

**Chonbuk National University, Jeonju, Korea**

A. Lee

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

H. Kim, D.H. Moon, G. Oh

**Hanyang University, Seoul, Korea**

J.A. Brochero Cifuentes, J. Goh, T.J. Kim

**Korea University, Seoul, Korea**

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

**Seoul National University, Seoul, Korea**

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

**University of Seoul, Seoul, Korea**

M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu

**Sungkyunkwan University, Suwon, Korea**

Y. Choi, C. Hwang, J. Lee, I. Yu

**Vilnius University, Vilnius, Lithuania**

V. Dudenas, A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali<sup>31</sup>, F. Mohamad Idris<sup>32</sup>, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**

Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz<sup>33</sup>, R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadán-Trejo, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

**Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico**

A. Morelos Pineda

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

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

P.H. Butler

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

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

**National Centre for Nuclear Research, Swierk, Poland**

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

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

K. Bunkowski, A. Byszuk<sup>34</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, B. Calpas, A. Di Francesco, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela

**Joint Institute for Nuclear Research, Dubna, Russia**

I. Golutvin, V. Karjavin, I. Kashunin, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev<sup>35,36</sup>, V.V. Mitsyn, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, V. Trofimov, B.S. Yuldashev<sup>37</sup>, A. Zarubin, V. Zhiltsov



**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**

Y. Ivanov, V. Kim<sup>38</sup>, E. Kuznetsova<sup>39</sup>, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

**Institute for Theoretical and Experimental Physics, Moscow, Russia**

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

**Moscow Institute of Physics and Technology, Moscow, Russia**

T. Aushev, A. Bylinkin<sup>36</sup>

**National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia**

M. Chadeeva<sup>40</sup>, P. Parygin, D. Philippov, S. Polikarpov, E. Popova, V. Rusinov

**P.N. Lebedev Physical Institute, Moscow, Russia**

V. Andreev, M. Azarkin<sup>36</sup>, I. Dremin<sup>36</sup>, M. Kirakosyan<sup>36</sup>, A. Terkulov

**Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia**

A. Baskakov, A. Belyaev, E. Boos, A. Ershov, A. Gribushin, L. Khein, V. Klyukhin, O. Kodolova, I. Lokhtin, O. Lukina, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

**Novosibirsk State University (NSU), Novosibirsk, Russia**

V. Blinov<sup>41</sup>, D. Shtol<sup>41</sup>, Y. Skovpen<sup>41</sup>

**State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia**

I. Azhgirey, I. Bayshev, S. Bitiukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

**University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia**

P. Adzic<sup>42</sup>, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**

J. Alcaraz Maestre, A. Álvarez Fernández, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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

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**Universidad de Oviedo, Oviedo, Spain**

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

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**Paul Scherrer Institut, Villigen, Switzerland**

W. Bertl<sup>†</sup>, L. Caminada<sup>48</sup>, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

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**Universität Zürich, Zurich, Switzerland**

T.K. Aarrestad, C. Amsler<sup>49</sup>, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Takahashi, A. Zucchetta

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**Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand**

B. Asavapibhop, K. Kovitangoon, G. Singh, N. Srimanobhas

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

A. Adiguzel<sup>50</sup>, F. Boran, S. Cerci<sup>51</sup>, S. Damarseekin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos<sup>52</sup>, E.E. Kangal<sup>53</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut<sup>54</sup>, K. Ozdemir<sup>55</sup>, D. Sunar Cerci<sup>51</sup>, B. Tali<sup>51</sup>, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Bilin, G. Karapinar<sup>56</sup>, K. Ocalan<sup>57</sup>, M. Yalvac, M. Zeyrek

**Bogazici University, Istanbul, Turkey**

E. Gülmez, M. Kaya<sup>58</sup>, O. Kaya<sup>59</sup>, S. Tekten, E.A. Yetkin<sup>60</sup>

**Istanbul Technical University, Istanbul, Turkey**

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak

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

B. Grynyov

**National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine**

L. Levchuk, P. Sorokin

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

K.W. Bell, A. Belyaev<sup>62</sup>, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

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**University of California, Santa Barbara - Department of Physics, Santa Barbara, U.S.A.**

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

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**Florida Institute of Technology, Melbourne, U.S.A.**

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**University of Illinois at Chicago (UIC), Chicago, U.S.A.**

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**The University of Iowa, Iowa City, U.S.A.**

B. Bilki<sup>65</sup>, W. Clarida, K. Dilsiz<sup>66</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>67</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul<sup>68</sup>, Y. Onel, F. Ozok<sup>69</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

**Johns Hopkins University, Baltimore, U.S.A.**

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

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**Kansas State University, Manhattan, U.S.A.**

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

**Lawrence Livermore National Laboratory, Livermore, U.S.A.**

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**University of Maryland, College Park, U.S.A.**

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

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**Northeastern University, Boston, U.S.A.**

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Ori-moto, R. Teixeira De Lima, D. Trocino, D. Wood

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S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

**University of Notre Dame, Notre Dame, U.S.A.**

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J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

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**University of Puerto Rico, Mayaguez, U.S.A.**

S. Malik, S. Norberg

**Purdue University, West Lafayette, U.S.A.**

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, J.F. Schulte, J. Sun, F. Wang, W. Xie

**Purdue University Northwest, Hammond, U.S.A.**

T. Cheng, N. Parashar, J. Stupak



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**University of Rochester, Rochester, U.S.A.**

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

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R. Ciesielski, K. Goulianos, C. Mesropian

**Rutgers, The State University of New Jersey, Piscataway, U.S.A.**

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

**University of Tennessee, Knoxville, U.S.A.**

A.G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

**Texas A&M University, College Station, U.S.A.**

O. Bouhali<sup>70</sup>, A. Castaneda Hernandez<sup>70</sup>, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>71</sup>, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

**Texas Tech University, Lubbock, U.S.A.**

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**Vanderbilt University, Nashville, U.S.A.**

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

**University of Virginia, Charlottesville, U.S.A.**

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

**Wayne State University, Detroit, U.S.A.**

R. Harr, P.E. Karchin, J. Sturdy, S. Zaleski

**University of Wisconsin - Madison, Madison, WI, U.S.A.**

M. Brodski, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

- †: Deceased
- 1: Also at Vienna University of Technology, Vienna, Austria
  - 2: Also at State Key Laboratory of Nuclear Physics and Technology; Peking University, Beijing, China
  - 3: Also at Universidade Estadual de Campinas, Campinas, Brazil
  - 4: Also at Universidade Federal de Pelotas, Pelotas, Brazil
  - 5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
  - 6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
  - 7: Also at Joint Institute for Nuclear Research, Dubna, Russia
  - 8: Also at Suez University, Suez, Egypt
  - 9: Now at British University in Egypt, Cairo, Egypt
  - 10: Also at Fayoum University, El-Fayoum, Egypt
  - 11: Now at Helwan University, Cairo, Egypt
  - 12: Also at Université de Haute Alsace, Mulhouse, France
  - 13: Also at Skobeltsyn Institute of Nuclear Physics; Lomonosov Moscow State University, Moscow, Russia
  - 14: Also at CERN; European Organization for Nuclear Research, Geneva, Switzerland
  - 15: Also at RWTH Aachen University; III. Physikalisches Institut A, Aachen, Germany
  - 16: Also at University of Hamburg, Hamburg, Germany
  - 17: Also at Brandenburg University of Technology, Cottbus, Germany
  - 18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
  - 19: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group; Eötvös Loránd University, Budapest, Hungary
  - 20: Also at Institute of Physics; University of Debrecen, Debrecen, Hungary
  - 21: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
  - 22: Also at Institute of Physics, Bhubaneswar, India
  - 23: Also at University of Visva-Bharati, Santiniketan, India
  - 24: Also at University of Ruhuna, Matara, Sri Lanka
  - 25: Also at Isfahan University of Technology, Isfahan, Iran
  - 26: Also at Yazd University, Yazd, Iran
  - 27: Also at Plasma Physics Research Center; Science and Research Branch; Islamic Azad University, Tehran, Iran
  - 28: Also at Università degli Studi di Siena, Siena, Italy
  - 29: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy
  - 30: Also at Purdue University, West Lafayette, U.S.A.
  - 31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
  - 32: Also at Malaysian Nuclear Agency; MOSTI, Kajang, Malaysia
  - 33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
  - 34: Also at Warsaw University of Technology; Institute of Electronic Systems, Warsaw, Poland
  - 35: Also at Institute for Nuclear Research, Moscow, Russia
  - 36: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
  - 37: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
  - 38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
  - 39: Also at University of Florida, Gainesville, U.S.A.
  - 40: Also at P.N. Lebedev Physical Institute, Moscow, Russia
  - 41: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia

- 42: Also at Faculty of Physics; University of Belgrade, Belgrade, Serbia
- 43: Also at INFN Sezione di Roma; Sapienza Università di Roma, Rome, Italy
- 44: Also at University of Belgrade; Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 45: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 46: Also at National and Kapodistrian University of Athens, Athens, Greece
- 47: Also at Riga Technical University, Riga, Latvia
- 48: Also at Universität Zürich, Zurich, Switzerland
- 49: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 50: Also at Istanbul University; Faculty of Science, Istanbul, Turkey
- 51: Also at Adiyaman University, Adiyaman, Turkey
- 52: Also at Istanbul Aydin University, Istanbul, Turkey
- 53: Also at Mersin University, Mersin, Turkey
- 54: Also at Cag University, Mersin, Turkey
- 55: Also at Piri Reis University, Istanbul, Turkey
- 56: Also at Izmir Institute of Technology, Izmir, Turkey
- 57: Also at Necmettin Erbakan University, Konya, Turkey
- 58: Also at Marmara University, Istanbul, Turkey
- 59: Also at Kafkas University, Kars, Turkey
- 60: Also at Istanbul Bilgi University, Istanbul, Turkey
- 61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 62: Also at School of Physics and Astronomy; University of Southampton, Southampton, United Kingdom
- 63: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 64: Also at Utah Valley University, Orem, U.S.A.
- 65: Also at Beykent University, Istanbul, Turkey
- 66: Also at Bingol University, Bingol, Turkey
- 67: Also at Erzincan University, Erzincan, Turkey
- 68: Also at Sinop University, Sinop, Turkey
- 69: Also at Mimar Sinan University; Istanbul, Istanbul, Turkey
- 70: Also at Texas A&M University at Qatar, Doha, Qatar
- 71: Also at Kyungpook National University, Daegu, Korea