

MIT Open Access Articles

Probing color coherence effects in pp collisions at $\sqrt{s}=7$ TeV

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

Citation: Chatrchyan, S., V. Khachatryan, A. M. Sirunyan, A. Tumasyan, W. Adam, T. Bergauer, M. Dragicevic, et al. "Probing color coherence effects in pp collisions at $\sqrt{s}=7$ TeV." Eur. Phys. J. C 74, no. 6 (June 2014).

As Published: <http://dx.doi.org/10.1140/epjc/s10052-014-2901-8>

Publisher: Springer-Verlag

Persistent URL: <http://hdl.handle.net/1721.1/89417>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Terms of use: Creative Commons Attribution



Probing color coherence effects in pp collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

CERN, Geneva, Switzerland

Received: 22 November 2013 / Accepted: 14 May 2014 / Published online: 11 June 2014
© CERN for the benefit of the CMS collaboration 2014. This article is published with open access at Springerlink.com

Abstract A study of color coherence effects in pp collisions at a center-of-mass energy of 7 TeV is presented. The data used in the analysis were collected in 2010 with the CMS detector at the LHC and correspond to an integrated luminosity of 36 pb^{-1} . Events are selected that contain at least three jets and where the two jets with the largest transverse momentum exhibit a back-to-back topology. The measured angular correlation between the second- and third-leading jet is shown to be sensitive to color coherence effects, and is compared to the predictions of Monte Carlo models with various implementations of color coherence. None of the models describe the data satisfactorily.

1 Introduction

An important feature of the color interaction in quantum chromodynamics (QCD) is that the outgoing partons produced in the hard interaction continue to interfere with each other during their fragmentation phase. This phenomenon, called *color coherence*, manifests itself by the relative abundance of soft radiation in the region between the color connected final-state partons and the suppression of soft radiation elsewhere.

Color coherence phenomena were initially observed in e^+e^- collisions by several experiments at PETRA, PEP and LEP [1–8]. These experiments showed the coherence effect in $e^+e^- \rightarrow q\bar{q}g$ three-jet events through the suppression of particle production in the region between the quark and antiquark jets.

In hadron collisions, in addition to the color connection between the final-state partons, the color connection between the outgoing partons and the incoming partons must be considered. The Tevatron experiments CDF and D0 have both reported evidence for color coherence effects in measurements of the spatial correlations between neighboring jets [9, 10]. These correlations were not well reproduced by Monte Carlo (MC) simulations that use incoherent par-

ton shower models. However, the data were successfully described by simulations that include color coherence effects through the ordering of the parton emission angles [11].

The technique originally developed by the Tevatron experiments is used to study color coherence effects in pp collisions at $\sqrt{s} = 7$ TeV with the Compact Muon Solenoid (CMS) detector. Events with at least three jets (called three-jet events) are selected, and these jets are ordered by their transverse momenta $p_{T1} > p_{T2} > p_{T3}$ with respect to the beam direction. We measure the angular correlation between the second and third jet to probe the effects of color coherence.

The CMS detector has a right-handed coordinate system with its origin at the center of the detector. The z axis points along the direction of the counterclockwise beam, ϕ is the azimuthal angle in the transverse plane perpendicular to the beam, and θ is the polar angle relative to the z axis. The pseudorapidity of the i th jet is denoted by $\eta_i = -\ln[\tan(\theta_i/2)]$ and its azimuthal angle by ϕ_i .

The measured observable β [10] is defined as the azimuthal angle of the third jet with respect to the second jet in (η, ϕ) space as shown in Fig. 1. Implicitly, this can be expressed by

$$\tan \beta = \frac{|\Delta\phi_{23}|}{\Delta\eta_{23}}, \quad (1)$$

where $\Delta\phi_{23} = \phi_3 - \phi_2$ (defined so that $-\pi \leq \Delta\phi_{23} \leq \pi$), $\Delta\eta_{23} = \text{sign}(\eta_2) \cdot (\eta_3 - \eta_2)$, and $0 \leq \beta \leq \pi$. The absolute value of $\Delta\phi_{23}$ in Eq. 1 and the sign of the pseudorapidity of the second jet, $\text{sign}(\eta_2)$, in the definition of $\Delta\eta_{23}$ are introduced to map symmetric configurations around $\Delta\phi_{23} = 0$ or $\eta = 0$ onto the same β value. For $\Delta\phi_{23} = 0$, β is defined to be zero or π depending on the sign of $\Delta\eta_{23}$ being positive or negative. In the case of $\Delta\eta_{23} = 0$, which cannot happen simultaneously with $\Delta\phi_{23} = 0$, β is defined to equal $\pi/2$.

In a naive leading-order model the two partons are produced back-to-back in the transverse plane. One of the two partons may radiate a third parton. In the absence of color coherence effects there is no preferred direction of

*e-mail: cms-publication-committee-chair@cern.ch

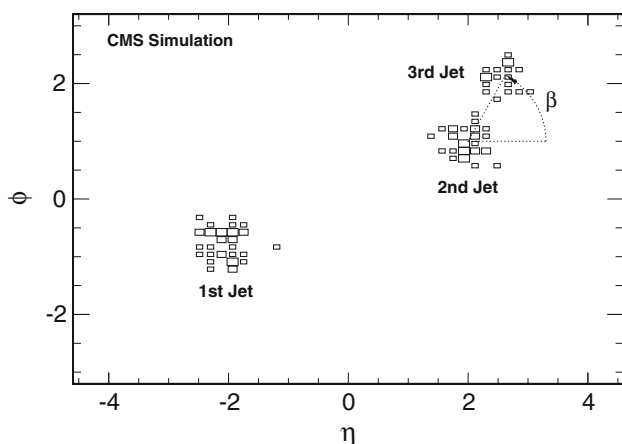


Fig. 1 Visualization of the observable β in (η, ϕ) space using a simulated three-jet event. The sizes of the *rectangular boxes* are proportional to the particle energies

emission of this third parton around the radiating parton. In contrast, when color coherence effects are present, the third parton will tend to lie in the event plane defined by the emitting parton and the beam axis. Therefore, in the presence of color coherence, the third jet population along the event plane (in particular near $\beta \approx 0$) will be enhanced and out of the plane ($\beta \approx \pi/2$) will be suppressed. The color coherence effects are expected to become stronger in the region between the second jet and the remnant when the angle between them becomes smaller. Therefore the study of the β variable is performed in two situations: when the second jet is rather central ($|\eta_2| \leq 0.8$) and when the second jet is more forward ($0.8 < |\eta_2| \leq 2.5$).

The aims of this paper are

- To measure the β distributions, normalized to the total number of events in each region, as a function of β separately in the central ($|\eta_2| \leq 0.8$) and forward region ($0.8 < |\eta_2| \leq 2.5$):

$$F_{\eta_2,i}(\beta) = \frac{N_{\eta_2,i}}{N_{\eta_2}}, \quad (2)$$

where N_{η_2} is the total number of events in the η_2 region, $N_{\eta_2,i}$ the number of events in the given i th β bin of the η_2 region. The choice of this normalization significantly reduces the impact of experimental systematic uncertainties such as the uncertainty in the luminosity.

- To gauge the sensitivity of the variable β to color coherence effects.
- To compare our measurements to the predictions of MC event generators with various implementations of color coherence.

2 The CMS detector

A detailed description of the CMS experiment can be found elsewhere [12]; so here we describe the detector systems most relevant to the present analysis. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume, a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter and a brass/scintillator hadron calorimeter (HCAL) are installed. The central tracking system provides coverage up to $|\eta| = 2.5$ in pseudorapidity and the calorimeters up to $|\eta| = 3.0$. An iron and quartz-fiber Cherenkov forward hadron calorimeter (HF) covers the pseudorapidity range $3.0 < |\eta| < 5.0$.

3 Event selection

The CMS detector records events using a two-level trigger system consisting of a hardware-based level-1 (L1) trigger and a software-based high-level trigger (HLT). For this study, single jet triggers that reconstruct jets from calorimeter energy deposits at L1 and HLT are used to select events based on different p_T jet thresholds. Five different triggers with p_T thresholds of 30, 50, 70, 100, and 140 GeV are used to select the events. The triggers were prescaled during the 2010 run when the associated rate exceeded the allocated band width except the highest-threshold one. Therefore, the events are split into five different bins in p_{T1} with each bin containing the events collected during a period when the appropriate trigger was not prescaled. Each bin starts at $p_{T\min}$ defined in such a way that the associated trigger efficiency exceeds 99 %. Table 2 lists the binning in p_{T1} , and, for each bin, it gives the associated trigger, the number of selected events, and the integrated luminosity for the period during which the given trigger was not prescaled.

Jets are reconstructed with the anti- k_T algorithm [13], which is implemented in the FASTJET package [14] using a distance parameter $R = 0.5$, from a list of particle candidates reconstructed using the particle-flow (PF) algorithm. This PF algorithm [15] reconstructs all particle candidates in each event using an optimized combination of information from all CMS subdetector systems: muons, electrons (with associated bremsstrahlung photons), photons (unconverted and converted), and charged/neutral hadrons. The four-vectors of the neutral particles are computed by assuming that they come from the primary vertex, which is defined as the vertex with the highest sum of transverse momenta of all reconstructed tracks pointing to it. The reconstructed jet energy E is defined as the scalar sum of the energies of the constituents, and the jet momentum \mathbf{p} is the vector sum of the momenta of the constituents. The jet transverse momentum p_T is the component of \mathbf{p} perpendicular to the beam. The E and \mathbf{p} values

of a reconstructed jet are further corrected for the response of the detector, which is obtained from MC simulations, test beam results, and pp collision data [16, 17]. The corrections account for the presence of multiple pp collisions in the same or adjacent bunch crossings (pileup interactions) using the jet area method [18].

Events are required to have a primary vertex reconstructed within 24 cm of the detector center along the beam line [19]. Additional selection criteria are applied to each event to remove any spurious jet-like features originating from isolated noise patterns in certain HCAL regions [20]. Events having at least three jets with $p_T > 30$ GeV are selected. The pseudorapidity of the two leading jets must be within $|\eta_1|, |\eta_2| \leq 2.5$, while for the third jet no constraints are applied in order to avoid a bias in the β measurement.

To further reduce the background from misidentified jets, i.e., jets resulting from noise in the electromagnetic, hadron and/or hadron forward calorimeters, a set of tight identification criteria are applied: each jet should contain at least two particles, one of which is a charged hadron, and the jet energy fraction carried by neutral hadrons, photons, muons, and electrons should be less than 90 %. With these criteria the contamination of the sample with misidentified jets is suppressed to a level less than 1 % [15].

The dijet invariant mass of the two leading jets, M_{12} , is required to exceed 220 GeV to ensure a back-to-back configuration. With this requirement more than 98 % of the events have $|\Delta\phi_{12} - \pi| < 1$. Finally the distance in the (η, ϕ) space between the second and third jets is constrained to be $0.5 < \Delta R_{23} = \sqrt{(\Delta\eta_{23})^2 + (\Delta\phi_{23})^2} < 1.5$ in order to ensure a three-jet topology where the third jet is closer to the second jet.

Table 1 Summary of the event selection

| Selection criteria |
|---------------------------------------|
| $p_{T1} > 100$ GeV, $p_{T3} > 30$ GeV |
| $ \eta_1 , \eta_2 \leq 2.5$ |
| $M_{12} > 220$ GeV |
| $0.5 < \Delta R_{23} < 1.5$ |

Table 2 The binning in p_{T1} and, for each bin, the associated trigger, the integrated luminosity for the period during which the given trigger was not prescaled, and the number of selected events. The selection criteria are described in Table 1

| p_{T1} bin edges (GeV) | Trigger online threshold (GeV) | \mathcal{L}_{int} (pb^{-1}) | Number of events | | |
|--------------------------|--------------------------------|---|------------------|---------------------|---------------------------|
| | | | Total | $ \eta_2 \leq 0.8$ | $0.8 < \eta_2 \leq 2.5$ |
| 100–120 | 30 | 0.35 | 4511 | 1671 | 2840 |
| 120–160 | 50 | 4.5 | 67 086 | 27 069 | 40 017 |
| 160–200 | 70 | 9.2 | 50 071 | 23 055 | 27 016 |
| 200–250 | 100 | 20 | 39 464 | 18 987 | 20 477 |
| >250 | 140 | 36 | 31 999 | 16 728 | 15 271 |
| All | | | 193 131 | 87 510 | 105 621 |

The selections used in the analysis are summarized in Table 1. The numbers of events passing the selection criteria in each p_{T1} bin are summarized in Table 2. The measured $\Delta\eta_{23}$ and $\Delta\phi_{23}$ distributions are compared to various MC models in Figs. 2 and 3. In general a reasonable agreement is observed with the different models. A study of the amount of energy collected by the HF detector indicated that there is no diffractive component in the data sample.

4 Monte Carlo models

The reconstructed jets are compared to the predictions of four different Monte Carlo generators that simulate jet production in pp collisions at $\sqrt{s} = 7$ TeV. The numbers of events for all generator samples is much higher than the number of collected data events so the statistical uncertainties in the MC predictions are not visible in the figures.

The PYTHIA [21] (version 6.422) event generator uses leading-order (LO) matrix elements to generate the $2 \rightarrow 2$ hard process in perturbative QCD (pQCD) and the parton shower (PS) model to simulate higher-order processes [22–24]. The PS model gives a good description of parton emission when the emitted partons are close in phase space. Events are generated with the Z2 tune for the underlying event. This Z2 tune is identical to the Z1 tune described in Ref. [25], except that Z2 uses the CTEQ6L1 [26] parton distribution functions (PDFs) of the proton in which the parton showers are ordered in p_T . The hadronization is simulated using the Lund string model [27, 28]. The older D6T tune [29–31], where parton showers are ordered in Q^2 , is considered for comparison. The D6T tune was designed to describe the lower-energy results of UA5 and CDF. The color coherence effects are implemented in PYTHIA 6 by means of an angular ordering algorithm where the effects can be switched on and off via the steering parameters MSTP(67) and MSTJ(50), which control the initial-state and the final-state showers, respectively.

The PYTHIA 8 [32] (version 8.145) event generator, used with tune 4C [33], orders the parton showers in p_T and models the underlying event using the multiple-parton interaction

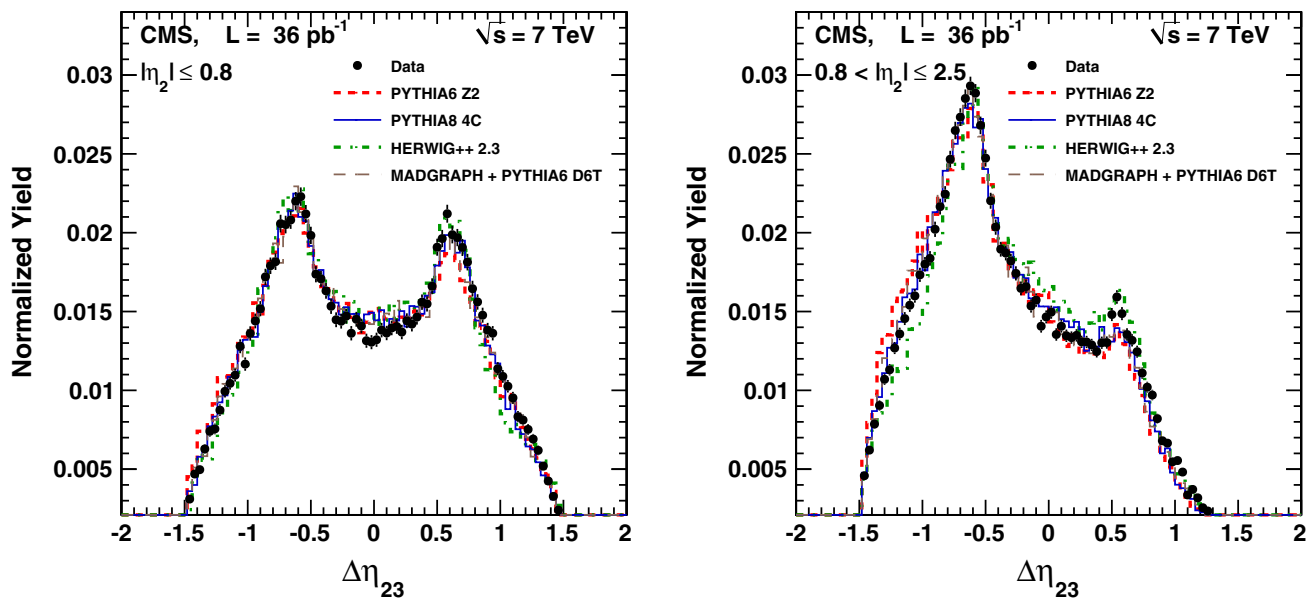


Fig. 2 Observed $\Delta\eta_{23}$ distributions, corrected for detector effects, compared to MC predictions by PYTHIA 6, PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 6. The MC samples are normalized to the total number of events in data

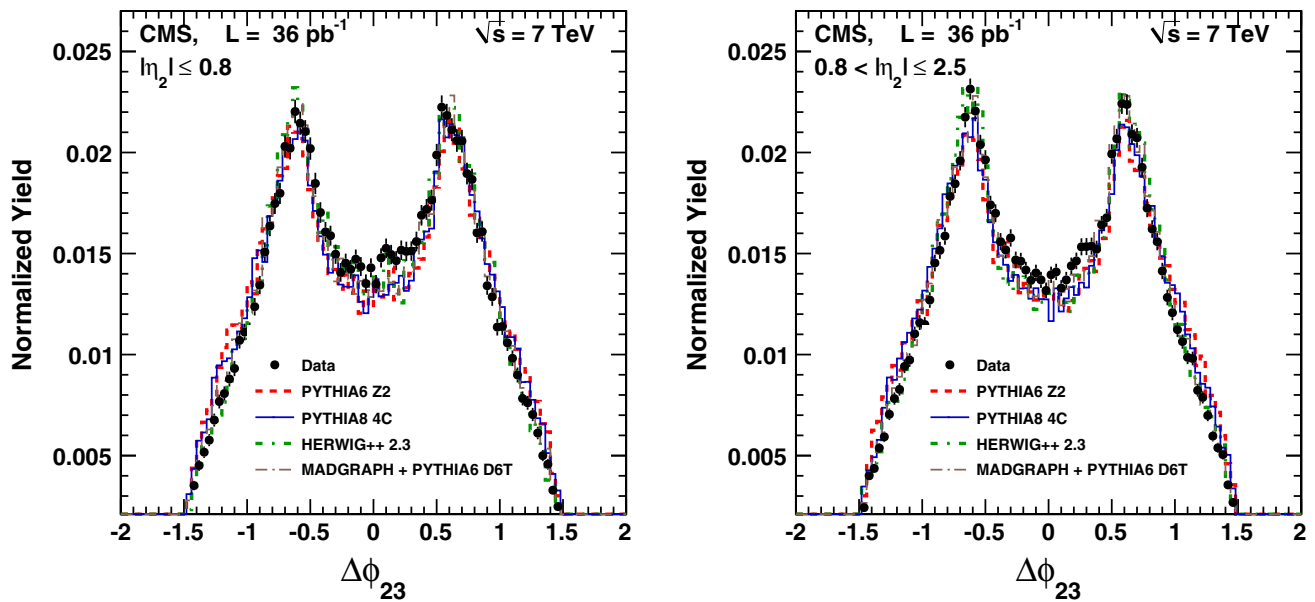


Fig. 3 Observed $\Delta\phi_{23}$ distributions, corrected for detector effects, compared to MC predictions by PYTHIA 6, PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 6. The MC samples are normalized to the total number of events in data

model from PYTHIA 6 including initial- and final-state QCD radiation. The color coherence effects are implemented in a similar manner as for the p_T -ordered showers in PYTHIA 6.

The HERWIG++ [11,34] (version 2.4.2) event generator takes LO matrix elements and simulates parton showers using the coherent branching algorithm with angular ordering of showers. The cluster hadronization model [35] is used in the formation of hadrons from the quarks and gluons produced in the parton shower. The underlying event is simulated using

the eikonal multiple partonic scattering model [36]. The color coherence effects are implemented by the angular ordering of emissions in the parton shower using the coherent branching algorithm [37].

The MADGRAPH 4 [38] (version 2.24) event generator is interfaced with PYTHIA 6 for the parton showering and the hadronization using the D6T tune and uses fixed-order matrix element calculations for the multiparton topologies. From two to four partons are considered in the final state. The

Table 3 Typical systematic and statistical uncertainties in the normalized β spectrum and the statistical errors

| Uncertainty sources | $ \eta_2 \leq 0.8$ | $0.8 < \eta_2 \leq 2.5$ |
|--------------------------------------|---------------------|---------------------------|
| Jet energy scale (JES) | 1.0 % | 1.0 % |
| Jet energy resolution (JER) | 0.4 % | 0.5 % |
| Jet angular resolution (JAR) | 0.5 % | 0.6 % |
| Physics model (PM) used in unfolding | 0.6 % | 0.7 % |
| Statistical uncertainty | 4.0 % | 3.7 % |

color coherence for the hard jets at leading order comes from the exact QCD color amplitudes in the model. The k_T MLM matching scheme [39] applied with a matching parameter of 60 GeV avoids double-counting between the partons from MADGRAPH and the PS.

5 Measurement of the normalized β distribution and systematic uncertainties

The measurement of the β distribution is performed in two regions defined by the pseudorapidity of the second jet: the central region $|\eta_2| \leq 0.8$ and the forward region $0.8 < |\eta_2| \leq 2.5$. The angular correlation effects considered in this analysis appear to have a reduced sensitivity to the transverse momentum of the leading jet p_{T1} . Consequently different p_{T1} bins are merged into one single bin.

The β distribution in a given η_2 region is obtained as a sum of the events weighted by the luminosity collected by the trigger used in the associated p_{T1} bin. In case of MC samples the β distribution is obtained by summing together the events weighted by their generation level weight in a given η_2 region. The normalized β distribution is then obtained by dividing the weighted number of events in a given bin of β by the total weighted number of events in the given η_2 region.

Table 4 The unfolded β distributions and their uncertainties for the central region $|\eta_2| \leq 0.8$. All uncertainties are symmetric and given in percent (%)

| β (degree) | $F_{\eta_2}(\beta)$ | σ_{Stat} | σ_{JES} | σ_{JER} | σ_{JAR} | σ_{PM} | σ_{Syst} |
|------------------|---------------------|-----------------|----------------|----------------|----------------|---------------|-----------------|
| 0–10 | 0.0549 | 3.5 | 1.0 | 0.3 | 0.4 | 0.6 | 1.3 |
| 10–20 | 0.0535 | 3.9 | 1.1 | 0.4 | 0.6 | 0.6 | 1.4 |
| 20–30 | 0.0544 | 4.2 | 0.5 | 0.5 | 0.3 | 0.6 | 1.0 |
| 30–40 | 0.0538 | 4.0 | 1.1 | 0.2 | 0.3 | 0.6 | 1.3 |
| 40–50 | 0.0525 | 3.8 | 0.5 | 0.5 | 0.5 | 0.6 | 1.1 |
| 50–60 | 0.0515 | 4.4 | 0.6 | 0.6 | 0.7 | 0.6 | 1.3 |
| 60–70 | 0.0515 | 4.3 | 0.6 | 0.4 | 0.6 | 0.6 | 1.1 |
| 70–80 | 0.0519 | 4.1 | 0.5 | 0.3 | 0.4 | 0.6 | 0.9 |
| 80–90 | 0.0511 | 4.2 | 0.4 | 0.4 | 0.5 | 0.6 | 1.0 |
| 90–100 | 0.0515 | 4.3 | 0.5 | 0.3 | 0.2 | 0.6 | 0.9 |
| 100–110 | 0.0528 | 4.3 | 0.5 | 0.4 | 0.5 | 0.6 | 1.0 |
| 110–120 | 0.0543 | 4.3 | 0.6 | 0.6 | 0.3 | 0.6 | 1.1 |
| 120–130 | 0.0580 | 4.1 | 1.2 | 0.5 | 0.4 | 0.6 | 1.5 |
| 130–140 | 0.0583 | 3.7 | 0.5 | 0.6 | 0.3 | 0.6 | 1.0 |
| 140–150 | 0.0616 | 4.2 | 0.6 | 0.5 | 0.5 | 0.6 | 1.1 |
| 150–160 | 0.0622 | 3.9 | 0.9 | 0.6 | 0.5 | 0.6 | 1.3 |
| 160–170 | 0.0626 | 3.6 | 0.7 | 0.5 | 0.6 | 0.6 | 1.2 |
| 170–180 | 0.0638 | 3.2 | 0.5 | 0.7 | 0.6 | 0.6 | 1.2 |

In order to correct for the smearing effects induced by the detector resolution, an unfolding procedure is performed using the response matrices obtained from MC event generators. For this purpose the events generated with the MC programs (PYTHIA 6, PYTHIA 8, MADGRAPH + PYTHIA 6, and HERWIG++) are processed through a full CMS detector simulation package based on GEANT 4 [40].

Particle-level jets are built from the four-vectors of the MC generated particles with hadronization, but without detector effects. These jets are obtained using the same jet algorithm as for the reconstructed events. The resolutions in $\Delta\eta_{23}$ and

Fig. 4 Observed β distributions for the data, corrected for detector effects, and for the MC generators (PYTHIA 6, PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 6) in the central ($|\eta_2| \leq 0.8$) and forward ($0.8 < |\eta_2| \leq 2.5$) regions. The error bars show the statistical uncertainties, while the yellow shaded bands correspond to the combined systematic uncertainty

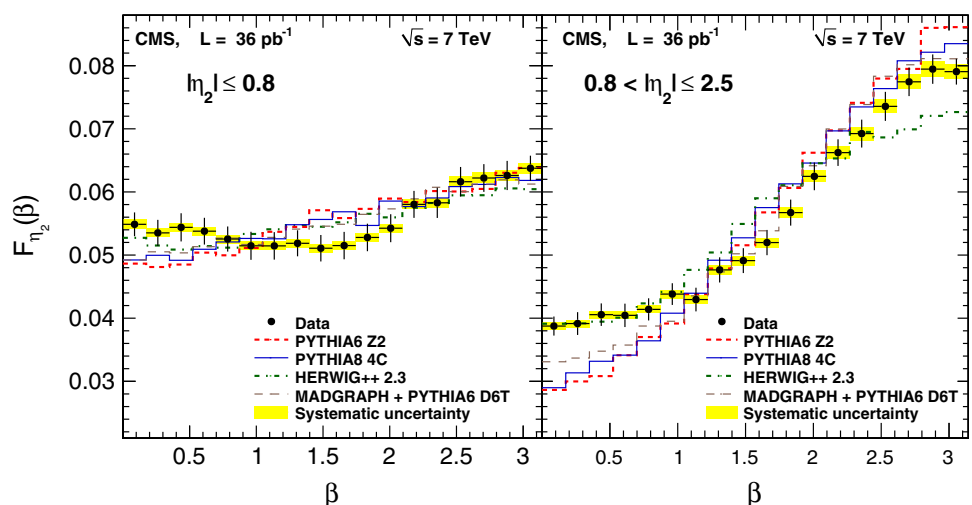


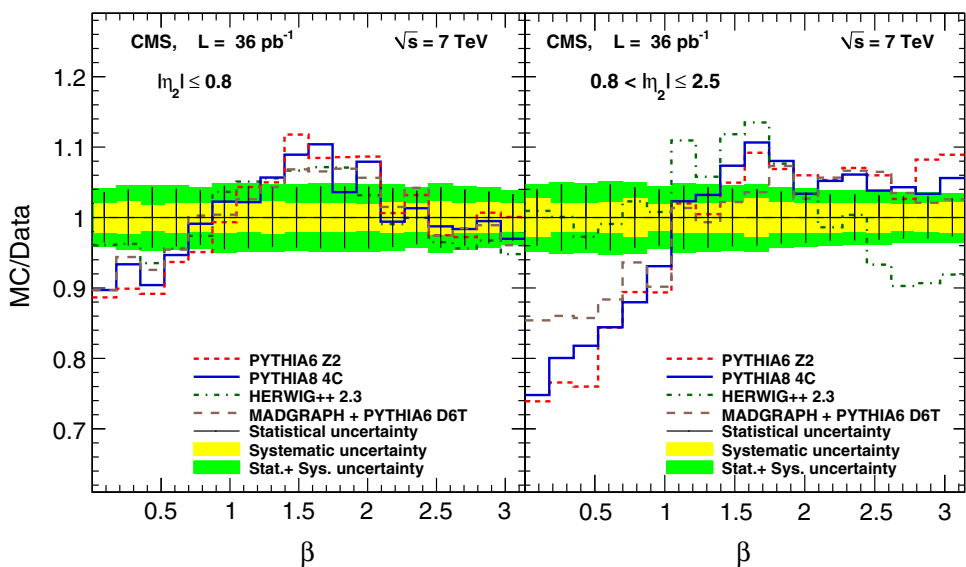
Table 5 The unfolded β distributions and their uncertainties for the forward region $0.8 < |\eta_2| \leq 2.5$. All uncertainties are symmetric and given in percent (%)

| β (degree) | $F_{\eta_2}(\beta)$ | σ_{Stat} | σ_{JES} | σ_{JER} | σ_{JAR} | σ_{PM} | σ_{Syst} |
|------------------|---------------------|------------------------|-----------------------|-----------------------|-----------------------|----------------------|------------------------|
| 0–10 | 0.0388 | 3.9 | 1.6 | 0.5 | 0.5 | 0.7 | 1.9 |
| 10–20 | 0.0391 | 4.6 | 0.6 | 0.5 | 0.6 | 0.7 | 1.2 |
| 20–30 | 0.0406 | 4.4 | 0.7 | 0.4 | 0.5 | 0.7 | 1.2 |
| 30–40 | 0.0404 | 4.6 | 0.5 | 0.4 | 0.5 | 0.7 | 1.1 |
| 40–50 | 0.0414 | 4.2 | 0.6 | 0.5 | 0.5 | 0.7 | 1.2 |
| 50–60 | 0.0438 | 3.9 | 0.7 | 0.4 | 0.4 | 0.7 | 1.1 |
| 60–70 | 0.0430 | 4.4 | 0.8 | 0.5 | 0.6 | 0.7 | 1.3 |
| 70–80 | 0.0476 | 4.2 | 0.5 | 0.5 | 0.6 | 0.7 | 1.2 |
| 80–90 | 0.0491 | 4.0 | 1.2 | 0.4 | 0.5 | 0.7 | 1.5 |
| 90–100 | 0.0520 | 3.9 | 0.8 | 0.5 | 0.4 | 0.7 | 1.2 |
| 100–110 | 0.0567 | 3.6 | 0.8 | 0.5 | 0.5 | 0.7 | 1.3 |
| 110–120 | 0.0625 | 3.5 | 0.7 | 0.5 | 0.5 | 0.7 | 1.2 |
| 120–130 | 0.0662 | 3.2 | 0.8 | 0.5 | 0.6 | 0.7 | 1.3 |
| 130–140 | 0.0692 | 3.2 | 0.7 | 0.4 | 0.6 | 0.7 | 1.2 |
| 140–150 | 0.0736 | 3.1 | 0.6 | 0.6 | 0.5 | 0.7 | 1.2 |
| 150–160 | 0.0774 | 2.9 | 0.7 | 0.4 | 0.6 | 0.7 | 1.2 |
| 160–170 | 0.0795 | 2.9 | 0.8 | 0.5 | 0.5 | 0.7 | 1.3 |
| 170–180 | 0.0791 | 2.6 | 0.8 | 0.6 | 0.5 | 0.7 | 1.3 |

$\Delta\phi_{23}$ are found to be of the order of 0.005 to 0.01, depending on the transverse momentum and pseudorapidity of the jets.

An iterative Bayesian unfolding technique [41] implemented in the RooUnfold package [42] is used to derive the unfolding corrections to the measured β distributions from the detector effects. The response matrix used to unfold the data is built using HERWIG++. The impact of the unfolding on the normalized distributions is typically of the order of 1 %.

Fig. 5 The ratio of the various MC predictions to the measured β distribution. The error bars show the statistical uncertainty of the data. The yellow band represents the systematic uncertainty, while the green band represents the total uncertainty



Most of the systematic effects cancel out in the normalized β distribution, but the residual influence of several sources of systematic uncertainty has been considered:

- The jet energy scale uncertainty is evaluated varying the jet response by 2.5–5 %, depending on the η and p_T of the jets [43]. The impact of this source of systematic uncertainties is below 1 %.
- The jet energy and angular resolutions are accounted for by varying them by ± 10 % [44] and rebuilding the response matrices for the unfolding accordingly. The observed impact from both sources is in the range of 0.4–0.6 %.
- The uncertainty due to the unfolding procedure is estimated by the dependence of the response matrix on the choice of MC generator, Alternative response matrices are built using alternative generators: PYTHIA 6, PYTHIA 8 and MADGRAPH + PYTHIA 6. The observed effect is of the order of 0.5 %.

The measurement is found to be insensitive to the number of pileup interactions within statistical fluctuations. In the data corresponding to this analysis the average number of pileup events per bunch crossing was around two. The total systematic uncertainties for each bin are about 2 %, and a list of the major uncertainties is summarized in Table 3. Each systematic source was found to be fully correlated between β and η_2 bins [43, 44]. However, the various systematic sources are uncorrelated among themselves.

6 Results

The unfolded β distributions are shown in Fig. 4 together with the predictions from the various MC models for the central ($|\eta_2| \leq 0.8$) and forward ($0.8 < |\eta_2| \leq 2.5$) regions.

The values of the unfolded β distributions and their uncertainties are presented in Tables 4 and 5.

The ratios of the various MC predictions to the measured β distributions are shown in Fig. 5. The data exhibit a clear enhancement of events compared to the PYTHIA and MADGRAPH generators near the event plane ($\beta = 0$) and a suppression in the transverse plane ($\beta = \pi/2$). The χ^2 comparisons of data with MC simulation, taking into account the statistical and systematic correlations between different data points, are shown separately for the central and forward regions in Table 6. The number of degrees of freedom (NDF)

Table 6 Values of χ^2 for comparisons of the β distribution for the data with the predictions of various MC generators. The number of degrees of freedom for both regions is 17

| MC event generator | χ^2/NDF | |
|---------------------|---------------------|---------------------------|
| | $ \eta_2 \leq 0.8$ | $0.8 < \eta_2 \leq 2.5$ |
| PYTHIA 6 Z2 | 2.5 | 8.1 |
| PYTHIA 8 4C | 1.7 | 6.4 |
| HERWIG++ 2.3 | 1.2 | 3.5 |
| MADGRAPH + PYTHIA 6 | 1.6 | 3.3 |

is 17, which is the number of bins minus one to account for the constraint imposed by the normalization.

None of the models used in the analysis describes the data satisfactorily. Even though PYTHIA 6 was adjusted with the Tevatron data, it fails to describe the LHC data since the χ^2/NDF is large. No significant difference is observed between the tunes D6T and Z2. The PYTHIA 8 tune 4C generator describes the data better than PYTHIA 6 over the entire phase space, but the disagreement in the forward region is not negligible. The HERWIG++ event generator describes the data better than the other MC generators in the central region, but the agreement is poor in the forward region. Finally, when MADGRAPH is used with the exact $2 \rightarrow 3$ matrix element calculations at LO, the global description of the data is improved with respect to PYTHIA 6 alone.

The impact of the color coherence effects is studied by switching them on and off for the first emission in the initial- and final-state showers in PYTHIA 6. One can observe in Fig. 6 that the agreement between the data and the simulation deteriorates when the color coherence effects in the MC events are suppressed. More quantitatively, the χ^2 divided by the number of degrees of freedom increases up to 7.7 in the central region and 11.5 in the forward region. The first emission in the initial- and final-state showers contributes roughly the

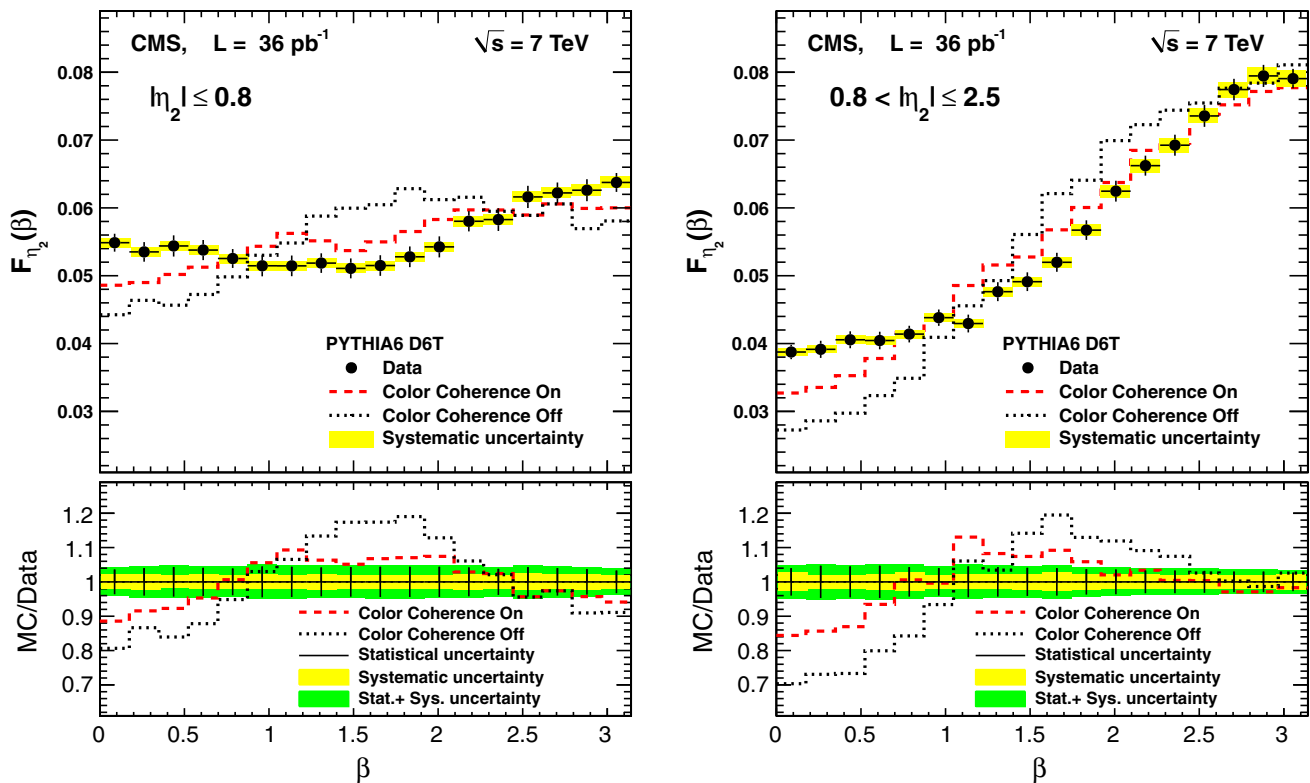


Fig. 6 The MC predictions for the β distribution from PYTHIA 6, with and without color coherence effects in the first branching of the initial- and final-state showers, compared to the measurement. The error bars

show the uncorrelated statistical uncertainty of the data. The yellow band represents the systematic uncertainty, while the green band represents the total uncertainty

same order. Using PYTHIA, it has been verified that the impact of the non-perturbative component of the QCD calculation (hadronization and underlying event) is negligible for this analysis. One conclusion from this PYTHIA study, as shown Fig. 6, is that the data clearly support larger color coherence effects than in present MC implementations.

7 Summary

Color coherence effects in multijet events have been studied in a sample of pp collisions corresponding to an integrated luminosity of 36 pb^{-1} , collected with the CMS detector at $\sqrt{s} = 7 \text{ TeV}$. Distributions of the variable β , which was previously used in similar analyses at the Tevatron, are used to measure the angular correlation between the second and third jets in transverse-momentum order, in the pseudorapidity and azimuthal angle space. The measurements, unfolded for detector effects, are compared to the predictions of the MC event generators PYTHIA 6, PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 6 in the central and forward rapidity regions. We have shown that the variable β is sensitive to color coherence effects, and insensitive to the hadronization and underlying event. It is necessary to implement the color coherence effects in MC simulations to better describe the data. Although the MC models in the analysis include this effect by default, none of them describes the data satisfactorily for all β values. The PYTHIA 6 expectations predict weaker color coherence effects than those observed, while PYTHIA 8 exhibits a better agreement with the data. The MADGRAPH MC generator, which uses the exact $2 \rightarrow 3$ matrix element calculations at LO matched to PYTHIA 6 for parton showering, improves the agreement with data with respect to PYTHIA 6 alone, while HERWIG++ describes the data in the central region better than the other MC generators but shows discrepancies in the forward region.

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: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-

FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThePCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Open Access This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

Funded by SCOAP³ / License Version CC BY 4.0.

References

- JADE Collaboration, Test of fragmentation models by comparison with three-jet events produced in $e^+e^- \rightarrow \text{hadrons}$. Phys. Lett. B **134**, 275 (1984). doi:[10.1016/0370-2693\(84\)90687-7](https://doi.org/10.1016/0370-2693(84)90687-7)
- TASSO Collaboration, A study of 3-jet events in e^+e^- annihilation into hadrons at 34.6 GeV c.m. energy. Zeit. Phys. C **29**, 29 (1985). doi:[10.1007/BF01571375](https://doi.org/10.1007/BF01571375)
- TPC/2 γ Collaboration, Tests of models for quark and gluon fragmentation in e^+e^- annihilation $\sqrt{s} = 29 \text{ GeV}$. Z. Phys. C **28**, 31 (1985). doi:[10.1007/BF01550246](https://doi.org/10.1007/BF01550246)
- TPC/2 γ Collaboration, Tests of models for parton fragmentation using three jet events in e^+e^- annihilation at $\sqrt{s} = 29 \text{ GeV}$. Phys. Rev. Lett. **54**, 270 (1985). doi:[10.1103/PhysRevLett.54.270](https://doi.org/10.1103/PhysRevLett.54.270)
- TPC/2 γ Collaboration, Comparison of the particle flow in $q\bar{q}g$ and $q\bar{q}\gamma$ events in e^+e^- annihilation. Phys. Rev. Lett. **57**, 945 (1986). doi:[10.1103/PhysRevLett.57.945](https://doi.org/10.1103/PhysRevLett.57.945)
- MARK2 Collaboration, Comparison of the particle flow in three-jet and radiative two-jet events from e^+e^- annihilation at $E_{\text{c.m.}} = 29 \text{ GeV}$. Phys. Rev. Lett. **57**, 1398 (1986). doi:[10.1103/PhysRevLett.57.1398](https://doi.org/10.1103/PhysRevLett.57.1398)
- OPAL Collaboration, A study of coherence of soft gluons in hadron jets. Phys. Lett. B **247**, 617 (1990). doi:[10.1016/0370-2693\(90\)91911-T](https://doi.org/10.1016/0370-2693(90)91911-T)
- L3 Collaboration, Evidence for gluon interference in hadronic Z decays. Phys. Lett. B **353**, 145 (1995). doi:[10.1016/0370-2693\(95\)00552-V](https://doi.org/10.1016/0370-2693(95)00552-V)
- CDF Collaboration, Evidence for color coherence in $p\bar{p}$ collisions at $\sqrt{s} = 1.8 \text{ TeV}$. Phys. Rev. D **50**, 5562 (1994). doi:[10.1103/PhysRevD.50.5562](https://doi.org/10.1103/PhysRevD.50.5562)
- D0 Collaboration, Color coherent radiation in multijet events from $p\bar{p}$ collisions at $\sqrt{s} = 1.8 \text{ TeV}$. Phys. Lett. B **414**, 419 (1997). doi:[10.1016/S0370-2693\(97\)01190-8](https://doi.org/10.1016/S0370-2693(97)01190-8)
- G. Marchesini, B. Webber, Monte Carlo simulation of general hard processes with coherent QCD radiation. Nucl. Phys. B **310**, 461 (1988). doi:[10.1016/0550-3213\(88\)90089-2](https://doi.org/10.1016/0550-3213(88)90089-2)
- CMS Collaboration, The CMS experiment at the CERN LHC. JINST **3**, S08004 (2008). doi:[10.1088/1748-0221/3/08/S08004](https://doi.org/10.1088/1748-0221/3/08/S08004)
- M. Cacciari, G.P. Salam, G. Soyez, The anti- k_r jet clustering algorithm. JHEP **04**, 063 (2008). doi:[10.1088/1126-6708/2008/04/063](https://doi.org/10.1088/1126-6708/2008/04/063)
- M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual. Eur. Phys. J. C **72**, 1896 (2012). doi:[10.1140/epjc/s10052-012-1896-2](https://doi.org/10.1140/epjc/s10052-012-1896-2). arXiv:1111.6097
- CMS Collaboration, Particle-flow event reconstruction in CMS and performance for jets, taus, and $E_{\text{T}}^{\text{miss}}$. CMS Physics Analysis Summary CMS-PAS-PFT-09-001 (2009)
- CMS Collaboration, Determination of the jet energy scale in CMS with pp collisions at $\sqrt{s} = 7 \text{ TeV}$. CMS Physics Analysis Summary CMS-PAS-JME-10-010 (2010)
- CMS Collaboration, Jet energy resolution in CMS at $\sqrt{s} = 7 \text{ TeV}$. CMS Physics Analysis Summary CMS-PAS-JME-10-014 (2010)

18. M. Cacciari, G.P. Salam, Pileup subtraction using jet areas. *Phys. Lett. B* **659**, 119 (2008). doi:[10.1016/j.physletb.2007.09.077](https://doi.org/10.1016/j.physletb.2007.09.077)
19. CMS Collaboration, Tracking and primary vertex results in first 7 TeV collisions. CMS Physics Analysis Summary CMS-PAS-TRK-10-005 (2010)
20. CMS Collaboration, Calorimeter jet quality criteria for the first CMS collision data. CMS Physics Analysis Summary CMS-PAS-JME-09-008 (2010)
21. T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual. *JHEP* **05**, 026 (2006). doi:[10.1088/1126-6708/2006/05/026](https://doi.org/10.1088/1126-6708/2006/05/026)
22. M. Bengtsson, T. Sjöstrand, A comparative study of coherent and non-coherent parton shower evolution. *Nucl. Phys. B* **289**, 810 (1987). doi:[10.1016/0550-3213\(87\)90407-X](https://doi.org/10.1016/0550-3213(87)90407-X)
23. M. Bengtsson, T. Sjöstrand, Coherent parton showers versus matrix elements—implications of PETRA/PEP data. *Phys. Lett. B* **185**, 435 (1987). doi:[10.1016/0370-2693\(87\)91031-8](https://doi.org/10.1016/0370-2693(87)91031-8)
24. T. Sjöstrand, P.Z. Skands, Transverse-momentum-ordered showers and interleaved multiple interactions. *Eur. Phys. J. C* **39**(2), 129 (2005). doi:[10.1140/epjc/s2004-02084-y](https://doi.org/10.1140/epjc/s2004-02084-y)
25. R. Field, Early LHC underlying event data-findings and surprises (2010). [arXiv:1010.3558](https://arxiv.org/abs/1010.3558)
26. J. Pumplin et al., New generation of parton distributions with uncertainties from global QCD analysis. *JHEP* **07**, 012 (2002). doi:[10.1088/1126-6708/2002/07/012](https://doi.org/10.1088/1126-6708/2002/07/012)
27. B. Anderson, G. Gustafson, G. Ingelman, T. Sjöstrand, Parton fragmentation and string dynamics. *Phys. Rep.* **97**, 31 (1983). doi:[10.1016/0370-1573\(83\)90080-7](https://doi.org/10.1016/0370-1573(83)90080-7)
28. T. Sjöstrand, The merging of jets. *Phys. Lett. B* **142**, 420 (1984). doi:[10.1016/0370-2693\(84\)91354-6](https://doi.org/10.1016/0370-2693(84)91354-6)
29. R. Field, Physics at the Tevatron. *Acta Phys. Polon. B* **39**, 2611 (2008)
30. R. Field, in *Proceedings of the First International Workshop on Multiple Partonic Interactions at the LHC MPI'08, Perugia, Italy, Oct 2009*, ed. by P. Bartalini, L. Fanó. Studying the Underlying Event at CDF and the LHC (2009), p. 12 [arXiv:1003.4220](https://arxiv.org/abs/1003.4220)
31. T. Sjöstrand, M.V. Zijl, A multiple interaction model for the event structure in hadron collisions. *Phys. Rev. D* **36**, 2019 (1987). doi:[10.1103/PhysRevD.36.2019](https://doi.org/10.1103/PhysRevD.36.2019)
32. T. Sjöstrand, S. Mrenna, P. Skands, A brief introduction to PYTHIA 8.1. *Comput. Phys. Commun.* **178**, 852 (2008). doi:[10.1016/j.cpc.2008.01.036](https://doi.org/10.1016/j.cpc.2008.01.036)
33. R. Corke, T. Sjöstrand, Interleaved parton showers and tuning prospects. *JHEP* **03**, 032 (2011). doi:[10.1007/JHEP03\(2011\)032](https://doi.org/10.1007/JHEP03(2011)032)
34. M. Bähr et al., HERWIG++ physics and manual. *Eur. Phys. J. C* **58**, 639 (2008). doi:[10.1140/epjc/s10052-008-0798-9](https://doi.org/10.1140/epjc/s10052-008-0798-9)
35. B.R. Webber, A QCD model for jet fragmentation including soft gluon interference. *Nucl. Phys. B* **238**, 492 (1984). doi:[10.1016/0550-3213\(84\)90333-X](https://doi.org/10.1016/0550-3213(84)90333-X)
36. M. Bähr, S. Gieseke, M.H. Seymour, Simulation of multiple partonic interactions in Herwig++. *JHEP* **07**, 076 (2006). doi:[10.1088/1126-6708/2008/07/076](https://doi.org/10.1088/1126-6708/2008/07/076)
37. S. Gieseke, P. Stephens, B. Webber, New formalism for QCD parton showers. *JHEP* **12**, 045 (2003). doi:[10.1088/1126-6708/2003/12/045](https://doi.org/10.1088/1126-6708/2003/12/045)
38. J. Alwall et al., MadGraph/MadEvent v4: the new web generation. *JHEP* **09**, 028 (2007). doi:[10.1088/1126-6708/2007/09/028](https://doi.org/10.1088/1126-6708/2007/09/028)
39. S. Mrenna, P. Richardson, Matching matrix elements and parton showers with HERWIG and PYTHIA. *JHEP* **05**, 040 (2004). doi:[10.1088/1126-6708/2004/05/040](https://doi.org/10.1088/1126-6708/2004/05/040). [arXiv:hep-ph/0312274](https://arxiv.org/abs/hep-ph/0312274)
40. S. Agostinelli et al., GEANT4—a simulation toolkit. *Nucl. Instr. Methods A* **506**, 250 (2003). doi:[10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)
41. G. D'Agostini, A multidimensional unfolding method based on Bayes' theorem. *Nucl. Instrum. Methods A* **362**, 487 (1995). doi:[10.1016/0168-9002\(95\)00274-X](https://doi.org/10.1016/0168-9002(95)00274-X)
42. T. Auye, in *Proceedings of the PHYSTAT 2011 Workshop on Statistical Issues Related to Discovery Claims in Search Experiments and Unfolding*. CERN, Geneva, Switzerland, 17–20 Jan 2011, ed. by H.B. Prosper, L. Lyons. Unfolding Algorithms and Tests Using RooUnfold (2011), p. 313. [arXiv:1105.1160](https://arxiv.org/abs/1105.1160)
43. CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS. *JINST* **6**, P11002 (2011). doi:[10.1088/1748-0221/6/11/P11002](https://doi.org/10.1088/1748-0221/6/11/P11002)
44. CMS Collaboration, Jet performance in pp collisions at $\sqrt{s} = 7$ TeV. CMS Physics Analysis Summary CMS-PAS-JME-10-003 (2010)

The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

S. Chatrchyan, V. Khachatryan, A. M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V. M. Ghete, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady², B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerp, Belgium

S. Alderweireldt, M. Bansal, S. Bansal, T. Cornelis, E. A. De Wolf, X. Janssen, A. Knutsson, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussels, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, A. Kalogeropoulos, J. Keaveney, S. Lowette, M. Maes, A. Olbrechts, S. Tavernier, W. Van Doninck, P. Van Mulders, G. P. Van Onsem, I. Villella

Université Libre de Bruxelles, Brussels, Belgium

C. Caillol, B. Clerbaux, G. De Lentdecker, L. Favart, A. P. R. Gay, T. Hreus, A. Léonard, P. E. Marage, A. Mohammadi, L. Perniè, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, Belgium

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Dildick, G. Garcia, B. Klein, J. Lellouch, A. Marinov, J. McCartin, A. A. Ocampo Rios, D. Ryckbosch, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, S. Walsh, E. Yazgan, N. Zaganidis

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

S. Basegmez, C. Beluffi³, G. Bruno, R. Castello, A. Caudron, L. Ceard, G. G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco⁴, J. Hollar, P. Jez, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrkowski, A. Popov⁵, M. Selvaggi, M. Vidal Marono, J. M. Vizan Garcia

Université de Mons, Mons, Belgium

N. Bely, T. Caeberts, E. Daubie, G. H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G. A. Alves, M. Correa Martins Junior, T. Martins, M. E. Pol, M. H. G. Souza

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

W. L. Aldá Júnior, W. Carvalho, J. Chinellato⁶, A. Custódio, E. M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, M. Malek, D. Matos Figueiredo, L. Mundim, H. Nogima, W. L. Prado Da Silva, A. Santoro, A. Sznajder, E. J. Tonelli Manganote⁶, A. Vilela Pereira

Universidade Estadual Paulista, São Paulo, Brazil

F. A. Dias⁷, T. R. Fernandez Perez Tomei, C. Lagana, S. F. Novaes, Sandra S. Padula

Universidade Federal do ABC, São Paulo, Brazil

C. A. Bernardes, E. M. Gregores, P. G. Mercadante

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

V. Genchev², P. Iaydjiev², S. Piperov, M. Rodozov, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, V. Kozuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

J. G. Bian, G. M. Chen, H. S. Chen, C. H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, X. Wang, Z. Wang

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

C. Asawatangtrakuldee, Y. Ban, Y. Guo, Q. Li, W. Li, S. Liu, Y. Mao, S. J. Qian, D. Wang, L. Zhang, W. Zou

Universidad de Los Andes, Bogotá, Colombia

C. Avila, C. A. Carrillo Montoya, L. F. Chaparro Sierra, J. P. Gomez, B. Gomez Moreno, J. C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, R. Plestina⁸, D. Polic, I. Puljak

University of Split, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, S. Morovic, L. Tikvica

University of Cyprus, Nicosia, Cyprus

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P. A. Razis

Charles University, Prague, Czech Republic

M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, EgyptA. A. Abdelalim⁹, Y. Assran¹⁰, S. Elgammal⁹, A. Ellithi Kamel¹¹, M. A. Mahmoud¹², A. Radi^{13,14}**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

M. Kadastik, M. Müntel, M. Murumaa, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, M. J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J. L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, FranceS. Baffioni, F. Beaudette, L. Benhabib, M. Bluj¹⁵, P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, A. Florent, R. Granier de Cassagnac, M. Haguenaue, P. Miné, C. Mironov, I. N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi**Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France**J.-L. Agram¹⁶, J. Andrea, D. Bloch, J.-M. Brom, E. C. Chabert, C. Collard, E. Conte¹⁶, F. Drouhin¹⁶, J.-C. Fontaine¹⁶, D. Gelé, U. Goerlach, C. Goetzmann, P. Juillot, A.-C. Le Bihan, P. Van Hove**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

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

S. Beauceron, N. Beaupere, G. Boudoul, S. Brochet, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, GeorgiaZ. Tsamalaidze¹⁷**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**C. Autermann, S. Beranek, M. Bontenackels, B. Calpas, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, K. Klein, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov⁵**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, M. Olschewski, K. Padeken, P. Papacz, H. Pieta, H. Reithler, S. A. Schmitz, L. Sonnenschein, J. Stegmann, D. Teysier, S. Thüer, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, GermanyV. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann², A. Nowack, I. M. Nugent, L. Perchalla, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany

I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, A. J. Bell, M. Bergholz¹⁸, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, A. Grebenyuk, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, D. Horton, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, J. Leonard, K. Lipka, W. Lohmann¹⁸, B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A. B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, F. Nowak, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, R. Placakyte, A. Raspereza, P. M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Ö. Sahin, J. Salfeld-Nebgen, R. Schmidt¹⁸, T. Schoerner-Sadenius, N. Sen, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

M. Aldaya Martin, V. Blobel, H. Enderle, J. Erfle, E. Garutti, U. Gebbert, M. Görner, M. Gosselink, J. Haller, K. Heine, R. S. Höing, G. Kaussen, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, I. Marchesini, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille¹⁹, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, D. Troendle, E. Usai, L. Vanelderen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff², F. Hartmann², T. Hauth², H. Held, K. H. Hoffmann, U. Husemann, I. Katkov⁵, J. R. Komaragiri, A. Kornmayer², P. Lobelle Pardo, D. Martschei, M. U. Mozer, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, S. Röcker, F.-P. Schilling, G. Schott, H. J. Simonis, F. M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

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

G. Anagnostou, G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, E. Ntomari, I. Topsis-giotis

University of Athens, Athens, Greece

L. Gouskos, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Ioánnina, Ioannina, Greece

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath²⁰, F. Sikler, V. Veszpremi, G. Vesztergombi²¹, A. J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary

J. Karancsi, P. Raics, Z. L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India

S. K. Swain²²

Panjab University, Chandigarh, India

S. B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M. Z. Mehta, M. Mittal, N. Nishu, A. Sharma, J. B. Singh

University of Delhi, Delhi, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B. C. Choudhary, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, P. Saxena, V. Sharma, R. K. Shivpuri

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan, A. P. Singh

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A. K. Mohanty², L. M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-EHEP, Mumbai, India

T. Aziz, R. M. Chatterjee, S. Ganguly, S. Ghosh, M. Guchait²³, A. Gurtu²⁴, G. Kole, S. Kumar, M. Maity²⁵, G. Majumder, K. Mazumdar, G. B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage²⁶

Tata Institute of Fundamental Research-HECR, Mumbai, India

S. Banerjee, S. Dugad

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

H. Arfaei, H. Bakhshiansohi, S. M. Etesami²⁷, A. Fahim²⁸, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh²⁹, M. Zeinali

University College Dublin, Dublin, Ireland

M. Grunewald

INFN Sezione di Bari, Bari, Italy

M. Abbrescia, L. Barbone, C. Calabria, S. S. Chhibra, A. Colaleo, D. Creanza, N. De Filippis, M. De Palma, L. Fiore, G. Iaselli, G. Maggi, M. Maggi, B. Marangelli, S. My, S. Nuzzo, N. Pacifico, A. Pompili, G. Pugliese, G. Selvaggi, L. Silvestris, G. Singh, R. Venditti, P. Verwilligen, G. Zito

Università di Bari, Bari, Italy

M. Abbrescia, L. Barbone, C. Calabria, S. S. Chhibra, M. De Palma, B. Marangelli, S. Nuzzo, A. Pompili, G. Selvaggi, G. Singh, R. Venditti

Politecnico di Bari, Bari, Italy

D. Creanza, N. De Filippis, G. Iaselli, G. Maggi, S. My, G. Pugliese

INFN Sezione di Bologna, Bologna, Italy

G. Abbiendi, A. C. Benvenuti, D. Bonacorsi, S. Braibant-Giacomelli, L. Brigliadori, R. Campanini, P. Capiluppi, A. Castro, F. R. Cavallo, G. Codispoti, M. Cuffiani, G. M. Dallavalle, F. Fabbri, A. Fanfani, D. Fasanella, P. Giacomelli, C. Grandi, L. Guiducci, S. Marcellini, G. Masetti, M. Meneghelli, A. Montanari, F. L. Navarria, F. Odorici, A. Perrotta, F. Primavera, A. M. Rossi, T. Rovelli, G. P. Siroli, N. Tosi, R. Travaglini

Università di Bologna, Bologna, Italy

D. Bonacorsi, S. Braibant-Giacomelli, L. Brigliadori, R. Campanini, P. Capiluppi, A. Castro, G. Codispoti, M. Cuffiani, A. Fanfani, D. Fasanella, L. Guiducci, M. Meneghelli, F. L. Navarria, F. Primavera, A. M. Rossi, T. Rovelli, G. P. Siroli, N. Tosi, R. Travaglini

INFN Sezione di Catania, Catania, Italy

S. Albergo, G. Cappello, M. Chiorboli, S. Costa, F. Giordano², R. Potenza, A. Tricomi, C. Tuve

Università di Catania, Catania, Italy

S. Albergo, G. Cappello, M. Chiorboli, S. Costa, R. Potenza, A. Tricomi, C. Tuve

INFN Sezione di Firenze, Florence, Italy

G. Barbagli, V. Ciulli, C. Civinini, R. D'Alessandro, E. Focardi, S. Frosali, E. Gallo, S. Gonzi, V. Gori, P. Lenzi, M. Meschini, S. Paoletti, G. Sguazzoni, A. Tropiano

Università di Firenze, Florence, Italy

V. Ciulli, R. D'Alessandro, E. Focardi, S. Frosali, S. Gonzi, V. Gori, P. Lenzi, A. Tropiano

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genoa, Italy

P. Fabbriatore, R. Ferretti, F. Ferro, M. Lo Vetere, R. Musenich, E. Robutti, S. Tosi

Università di Genova, Genoa, Italy

R. Ferretti, M. Lo Vetere, S. Tosi

INFN Sezione di Milano-Bicocca, Milan, Italy

A. Benaglia, M. E. Dinardo, S. Fiorendi, S. Gennai, A. Ghezzi, P. Govoni, M. T. Lucchini², S. Malvezzi, R. A. Manzoni², A. Martelli², D. Menasce, L. Moroni, M. Paganoni, D. Pedrini, S. Ragazzi, N. Redaelli, T. Tabarelli de Fatis

Università di Milano-Bicocca, Milan, Italy

M. E. Dinardo, S. Fiorendi, A. Ghezzi, P. Govoni, M. T. Lucchini², R. A. Manzoni², A. Martelli², M. Paganoni, S. Ragazzi, T. Tabarelli de Fatis

INFN Sezione di Napoli, Naples, Italy

S. Buontempo, N. Cavallo, A. De Cosa, F. Fabozzi, A. O. M. Iorio, L. Lista, S. Meola², M. Merola, P. Paolucci²

Università di Napoli ‘Federico II’, Naples, Italy

A. De Cosa, A. O. M. Iorio

Università della Basilicata, Potenza, Italy

N. Cavallo, F. Fabozzi

Università G. Marconi, Rome, Italy

S. Meola²

INFN Sezione di Padova, Padua, Italy

P. Azzi, N. Bacchetta, M. Bellato, D. Bisello, A. Branca, R. Carlin, P. Checchia, T. Dorigo, U. Dosselli, M. Galanti², F. Gasparini, U. Gasparini, P. Giubilato, A. Gozzelino, K. Kanishchev, S. Lacaprara, I. Lazzizzera, M. Margoni, A. T. Meneguzzo, J. Pazzini, N. Pozzobon, P. Ronchese, M. Sgaravatto, F. Simonetto, E. Torassa, M. Tosi, A. Triossi, P. Zotto, A. Zucchetta, G. Zumerle

Università di Padova, Padua, Italy

D. Bisello, A. Branca, R. Carlin, M. Galanti, F. Gasparini, U. Gasparini, P. Giubilato, M. Margoni, A. T. Meneguzzo, J. Pazzini, N. Pozzobon, P. Ronchese, F. Simonetto, M. Tosi, P. Zotto, A. Zucchetta, G. Zumerle

Università di Trento, Trento, Italy

K. Kanishchev, I. Lazzizzera

INFN Sezione di Pavia, Pavia, Italy

M. Gabusi, S. P. Ratti, C. Riccardi, P. Vitulo

Università di Pavia, Pavia, Italy

M. Gabusi, S. P. Ratti, C. Riccardi, P. Vitulo

INFN Sezione di Perugia, Perugia, Italy

M. Biasini, G. M. Bilei, L. Fanò, P. Lariccia, G. Mantovani, M. Menichelli, A. Nappi[†], F. Romeo, A. Saha, A. Santocchia, A. Spiezia

Università di Perugia, Perugia, Italy

M. Biasini, L. Fanò, P. Lariccia, G. Mantovani, A. Nappi[†], F. Romeo, A. Santocchia, A. Spiezia

INFN Sezione di Pisa, Pisa, Italy

K. Androsov³⁰, P. Azzurri, G. Bagliesi, J. Bernardini, T. Boccali, G. Broccolo, R. Castaldi, M. A. Ciocci, R. T. D’Agnolo², R. Dell’Orso, F. Fiori, L. Foà, A. Giassi, M. T. Grippo³⁰, A. Kraan, F. Ligabue, T. Lomtadze, L. Martini³⁰, A. Messineo, C. S. Moon³¹, F. Palla, A. Rizzi, A. Savoy-Navarro³², A. T. Serban, P. Spagnolo, P. Squillacioti, R. Tenchini, G. Tonelli, A. Venturi, P. G. Verdini, C. Vernieri

Università di Pisa, Pisa, Italy

A. Messineo, A. Rizzi, G. Tonelli

Scuola Normale Superiore di Pisa, Pisa, Italy

G. Broccolo, R. T. D’Agnolo², F. Fiori, L. Foà, F. Ligabue, C. Vernieri

INFN Sezione di Roma, Rome, Italy

L. Barone, F. Cavallari, D. Del Re, M. Diemoz, M. Grassi, E. Longo, F. Margaroli, P. Meridiani, F. Micheli, S. Nourbakhsh, G. Organtini, R. Paramatti, S. Rahatlou, C. Rovelli, L. Soffi

Università di Roma, Rome, Italy

L. Barone, D. Del Re, M. Grassi, E. Longo, F. Margaroli, F. Micheli, S. Nourbakhsh, G. Organtini, S. Rahatlou, L. Soffi

INFN Sezione di Torino, Turin, Italy

N. Amapane, R. Arcidiacono, S. Argiro, M. Arneodo, R. Bellan, C. Biino, N. Cartiglia, S. Casasso, M. Costa, A. Degano, N. Demaria, C. Mariotti, S. Maselli, E. Migliore, V. Monaco, M. Musich, M. M. Obertino, N. Pastrone, M. Pelliccioni², A. Potenza, A. Romero, M. Ruspa, R. Sacchi, A. Solano, A. Staiano, U. Tamponi

Università di Torino, Turin, Italy

N. Amapane, S. Argiro, R. Bellan, S. Casasso, M. Costa, A. Degano, E. Migliore, V. Monaco, A. Potenza, A. Romero, R. Sacchi, A. Solano

Università del Piemonte Orientale, Novara, Italy

R. Arcidiacono, M. Arneodo, M. M. Obertino, M. Ruspa

INFN Sezione di Trieste, Trieste, Italy

S. Belforte, V. Candelise, M. Casarsa, F. Cossutti², G. Della Ricca, B. Gobbo, C. La Licata, M. Marone, D. Montanino, A. Penzo, A. Schizzi, A. Zanetti

Università di Trieste, Trieste, Italy

V. Candelise, G. Della Ricca, C. La Licata, M. Marone, D. Montanino, A. Schizzi

Kangwon National University, Chunchon, Korea

S. Chang, T. Y. Kim, S. K. Nam

Kyungpook National University, Taegu, Korea

D. H. Kim, G. N. Kim, J. E. Kim, D. J. Kong, S. Lee, Y. D. Oh, H. Park, D. C. Son

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

J. Y. Kim, Zero J. Kim, S. Song

Korea University, Seoul, Korea

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T. J. Kim, K. S. Lee, S. K. Park, Y. Roh

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

Y. Choi, Y. K. Choi, J. Goh, M. S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

I. Grigelionis, A. Juodagalvis

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz³³, R. Lopez-Fernandez, J. Martínez-Ortega, A. Sanchez-Hernandez, L. M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H. A. Salazar Ibarquen

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

E. Casimiro Linares, A. Morelos Pineda, M. A. Reyes-Santos

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P. H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

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

M. Ahmad, M. I. Asghar, J. Butt, H. R. Hoorani, S. Khalid, W. A. Khan, T. Khurshid, S. Qazi, M. A. Shah, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szeleper, G. Wrochna, P. Zalewski

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

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, W. Wolszczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal

N. Almeida, P. Bargassa, C. Beirão Da Cruz E. Silva, P. Faccioli, P. G. Ferreira Parracho, M. Gallinaro, F. Nguyen, J. Rodrigues Antunes, J. Seixas², J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg, Russia

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S. V. Rusakov, A. Vinogradov

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

A. Belyaev, E. Boos, M. Dubinin⁷, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

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

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

P. Adzic³⁴, M. Djordjevic, M. Ekmedzic, D. Krpic³⁴, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas², N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J. P. Fernández Ramos, A. Ferrando, J. Flix, M. C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J. M. Hernandez, M. I. Josa, G. Merino, E. Navarro De Martino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M. S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J. F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

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

J. A. Brochero Cifuentes, I. J. Cabrillo, A. Calderon, S. H. Chuang, J. Duarte Campderros, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F. J. Munoz Sanchez, T. Rodrigo, A. Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A. H. Ball, D. Barney, J. Bendavid, J. F. Benitez, C. Bernet⁸, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J. A. Coarasa Perez, S. Colafranceschi³⁵, M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, S. Gowdy, R. Guida, J. Hammer, M. Hansen, P. Harris, C. Hartl, A. Hinzmann, V. Innocente, P. Janot, E. Karavakis, K. Kousouris, K. Krajczar, P. Lecoq, Y.-J. Lee, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M. Mulders, P. Musella, E. Nesvold, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzì, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimià, D. Piparo, M. Plagge, L. Quertenmont, A. Racz, W. Reece, G. Rolandi³⁶, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁷, D. Spiga, B. Stieger, M. Stoye, A. Tsiros, G. I. Veres²¹, J. R. Vlimant, H. K. Wöhri, S. D. Worm³⁸, W. D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H. C. Kaestli, S. König, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, P. Bortignon, M. A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Luster, B. Mangano, A. C. Marini, P. Martinez Ruiz del Arbol, D. Meister, N. Mohr, F. Moortgat, C. Nägeli³⁹, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, M. Quittnat, F. J. Ronga, M. Rossini, L. Sala, A. K. Sanchez, A. Starodumov⁴⁰, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H. A. Weber

Universität Zürich, Zurich, Switzerland

C. AMSLER⁴¹, V. Chiochia, C. Favaro, M. Ivova Rikova, B. Kilminster, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Taroni, M. Verzetti, Y. Yang

National Central University, Chung-Li, Taiwan

M. Cardaci, K. H. Chen, C. Ferro, C. M. Kuo, S. W. Li, W. Lin, Y. J. Lu, R. Volpe, S. S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y. H. Chang, Y. W. Chang, Y. Chao, K. F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K. Y. Kao, Y. J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J. G. Shiu, Y. M. Tzeng, M. Wang

Chulalongkorn University, Bangkok, Thailand

B. Asavapibhop, N. Suwonjandee

Cukurova University, Adana, Turkey

A. Adiguzel, M. N. Bakirci⁴², S. Cerci⁴³, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E. E. Kangal, A. Kayis Topaksu, G. Onengut⁴⁴, K. Ozdemir, S. Ozturk⁴², A. Polatoz, K. Sogut⁴⁵, D. Sunar Cerci⁴³, B. Tali⁴³, H. Topakli⁴², M. Vergili

Physics Department, Middle East Technical University, Ankara, Turkey

I. V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A. M. Guler, G. Karapinar⁴⁶, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U. E. Surat, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, B. Isildak⁴⁷, M. Kaya⁴⁸, O. Kaya⁴⁸, S. Ozkorucuklu⁴⁹, N. Sonmez⁵⁰

Istanbul Technical University, Istanbul, Turkey

H. Bahtiyar⁵¹, E. Barlas, K. Cankocak, Y. O. Günaydin⁵², F. I. Vardarli, M. Yücel

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

L. Levchuk, P. Sorokin

University of Bristol, Bristol, UK

J. J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G. P. Heath, H. F. Heath, L. Kreczko, C. Lucas, Z. Meng, S. Metson, D. M. Newbold³⁸, K. Nirunpong, S. Paramesvaran, A. Poll, S. Senkin, V. J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, UK

K. W. Bell, A. Belyaev⁵³, C. Brew, R. M. Brown, D. J. A. Cockerill, J. A. Coughlan, K. Harder, S. Harper, J. Ilic, E. Olaiya, D. Petyt, B. C. Radburn-Smith, C. H. Shepherd-Themistocleous, I. R. Tomalin, W. J. Womersley

Imperial College, London, UK

R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas³⁸, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko⁴⁰, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi⁵⁴, D. M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp[†], A. Sparrow, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle

Brunel University, Uxbridge, UK

M. Chadwick, J. E. Cole, P. R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I. D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA

J. Dittmann, K. Hatakeyama, A. Kasmir, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA

O. Charaf, S. I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA

A. Avetisyan, T. Bose, C. Fantasia, A. Heister, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, J. St. John, L. Sulak

Brown University, Providence, USA

J. Alimena, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer

University of California, Davis, Davis, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P. T. Cox, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett, J. Pilot, F. Ricci-Tam, B. Rutherford, M. Searle, S. Shalhout, J. Smith, M. Squires, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA

V. Andreev, D. Cline, R. Cousins, S. Erhan, P. Everaerts, C. Farrell, M. Felcini, J. Hauser, M. Ignatenko, C. Jarvis, G. Rakness, P. Schlein[†], E. Takasugi, P. Traczyk, V. Valuev, M. Weber

University of California, Riverside, USA

J. Babb, R. Clare, J. Ellison, J. W. Gary, G. Hanson, J. Heilman, P. Jandir, H. Liu, O. R. Long, A. Luthra, M. Malberti, H. Nguyen, A. Shrinivas, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA

W. Andrews, J. G. Branson, G. B. Cerati, S. Cittolin, D. Evans, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵⁵, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, C. Campagnari, T. Danielson, K. Flowers, P. Geffert, C. George, F. Golf, J. Incandela, C. Justus, D. Kovalskyi, V. Krutelyov, R. Magaña Villalba, N. Mccoll, V. Pavlunin, J. Richman, R. Rossin, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, USA

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, E. Di Marco, J. Duarte, D. Kcira, Y. Ma, A. Mott, H. B. Newman, C. Pena, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, R. Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D. W. Jang, Y. F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

J. P. Cumalat, B. R. Drell, W. T. Ford, A. Gaz, E. Luiggi Lopez, U. Nauenberg, J. G. Smith, K. Stenson, K. A. Ulmer, S. R. Wagner

Cornell University, Ithaca, USA

J. Alexander, A. Chatterjee, N. Eggert, L. K. Gibbons, W. Hopkins, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J. R. Patterson, A. Ryd, E. Salvati, W. Sun, W. D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA

D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L. A. T. Bauerdick, A. Beretvas, J. Berryhill, P. C. Bhat, K. Burkett, J. N. Butler, V. Chetluru, H. W. K. Cheung, F. Chlebana, S. Cihangir, V. D. Elvira, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, L. Gray, D. Green, O. Gutsche, D. Hare, R. M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, K. Kaadze, B. Klima, S. Kunori, S. Kwan, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J. M. Marraffino, V. I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko⁵⁶, C. Newman-Holmes, V. O'Dell, O. Prokofyev, N. Ratnikova, E. Sexton-Kennedy, S. Sharma, W. J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, J. C. Yun

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G. P. Di Giovanni, D. Dobur, A. Drozdetskiy, R. D. Field, M. Fisher, Y. Fu, I. K. Furic, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J. F. Low, K. Matchev, P. Milenovic⁵⁷, G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA

V. Gaultney, S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J. L. Rodriguez

Florida State University, Tallahassee, USA

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K. F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA

M. M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA

M. R. Adams, L. Apanasevich, V. E. Bazterra, R. R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C. E. Gerber, D. J. Hofman, S. Khalatyan, P. Kurt, F. Lacroix, D. H. Moon, C. O'Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

The University of Iowa, Iowa City, USA

U. Akgun, E. A. Albayrak⁵¹, B. Bilki⁵⁸, W. Clarida, K. Dilsiz, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya⁵⁹, A. Mestvirishvili, A. Moeller, J. Nachtman, C. R. Newsom, H. Ogul, Y. Onel, F. Ozok⁵¹, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin⁶⁰, K. Yi

Johns Hopkins University, Baltimore, USA

B. A. Barnett, B. Blumenfeld, S. Bolognesi, G. Giurgiu, A. V. Gritsan, G. Hu, P. Maksimovic, C. Martin, M. Swartz, A. Whitbeck

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, R. P. Kenny III, M. Murray, D. Noonan, S. Sanders, R. Stringer, J. S. Wood

Kansas State University, Manhattan, USA

A. F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, L. K. Saini, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA

A. Baden, B. Calvert, S. C. Eno, J. A. Gomez, N. J. Hadley, R. G. Kellogg, T. Kolberg, Y. Lu, M. Marionneau, A. C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M. B. Tonjes, S. C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA

A. Apyan, G. Bauer, W. Busza, I. A. Cali, M. Chan, L. Di Matteo, V. Dutta, G. Gomez Ceballos, M. Goncharov, D. Gulhan, Y. Kim, M. Klute, Y. S. Lai, A. Levin, P. D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, G. S. F. Stephans, F. Stöckli, K. Sumorok, D. Velicanu, R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A. S. Yoon, M. Zanetti, V. Zhukova

University of Minnesota, Minneapolis, USA

B. Dahmes, A. De Benedetti, A. Gude, J. Haupt, S. C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA

J. G. Acosta, L. M. Cremaldi, R. Kroeger, S. Oliveros, L. Perera, R. Rahmat, D. A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, S. Bose, D. R. Claes, A. Dominguez, M. Eads, R. Gonzalez Suarez, J. Keller, I. Kravchenko, J. Lazo-Flores, S. Malik, F. Meier, G. R. Snow

State University of New York at Buffalo, Buffalo, USA

J. Dolen, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S. Rappoccio, Z. Wan

Northeastern University, Boston, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, A. Massironi, D. Nash, T. Orimoto, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA

A. Anastassov, K. A. Hahn, A. Kubik, L. Lusito, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA

D. Berry, A. Brinkerhoff, K. M. Chan, M. Hildreth, C. Jessop, D. J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D. M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

The Ohio State University, Columbus, USA

L. Antonelli, B. Bylsma, L. S. Durkin, C. Hill, R. Hughes, K. Kotov, T. Y. Ling, D. Puigh, M. Rodenburg, G. Smith, C. Vuosalo, B. L. Winer, H. Wolfe

Princeton University, Princeton, USA

E. Berry, P. Elmer, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, S. A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, H. Saka, D. Stickland, C. Tully, J. S. Werner, S. C. Zenz, A. Zuranski

University of Puerto Rico, Mayaguez, USA

E. Brownson, A. Lopez, H. Mendez, J. E. Ramirez Vargas

Purdue University, West Lafayette, USA

E. Alagoz, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, K. Jung, O. Koybasi, M. Kress, N. Leonardo, D. Lopes Pegna, V. Maroussov, P. Merkel, D. H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, H. D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA

N. Parashar

Rice University, Houston, USA

A. Adair, B. Akgun, K. M. Ecklund, F. J. M. Geurts, W. Li, B. Michlin, B. P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D. C. Miner, G. Petrillo, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulios, G. Lungu, S. Malik, C. Mesropian

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

S. Arora, A. Barker, J. P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

G. Cerizza, M. Hollingsworth, K. Rose, S. Spanier, Z. C. Yang, A. York

Texas A&M University, College Station, USA

O. Bouhali⁶¹, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁶², V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P. R. Duerdo, K. Kovitangoon, S. W. Lee, T. Libeiro, I. Volobouev

Vanderbilt University, Nashville, USA

E. Appelt, A. G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA

M. W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood

Wayne State University, Detroit, USA

S. Gollapinni, R. Harr, P. E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, USA

D. A. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, S. Duric, E. Friis, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klappers, J. Klukas, A. Lanaro, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G. A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W. H. Smith, J. Swanson

† Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
- 4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
- 5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 6: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 7: Also at California Institute of Technology, Pasadena, USA
- 8: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 9: Also at Zewail City of Science and Technology, Zewail, Egypt
- 10: Also at Suez Canal University, Suez, Egypt
- 11: Also at Cairo University, Cairo, Egypt
- 12: Also at Fayoum University, El-Fayoum, Egypt
- 13: Also at British University in Egypt, Cairo, Egypt
- 14: Now at Ain Shams University, Cairo, Egypt
- 15: Also at National Centre for Nuclear Research, Swierk, Poland
- 16: Also at Université de Haute Alsace, Mulhouse, France
- 17: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 18: Also at Brandenburg University of Technology, Cottbus, Germany
- 19: Also at The University of Kansas, Lawrence, USA

- 20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 21: Also at Eötvös Loránd University, Budapest, Hungary
- 22: Also at Tata Institute of Fundamental Research-EHEP, Mumbai, India
- 23: Also at Tata Institute of Fundamental Research-HECR, Mumbai, India
- 24: Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 25: Also at University of Visva-Bharati, Santiniketan, India
- 26: Also at University of Ruhuna, Matara, Sri Lanka
- 27: Also at Isfahan University of Technology, Isfahan, Iran
- 28: Also at Sharif University of Technology, Tehran, Iran
- 29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 30: Also at Università degli Studi di Siena, Siena, Italy
- 31: Also at Centre National de la Recherche Scientifique (CNRS)-IN2P3, Paris, France
- 32: Also at Purdue University, West Lafayette, USA
- 33: Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico
- 34: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 35: Also at Facoltà Ingegneria, Università di Roma, Rome, Italy
- 36: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 37: Also at University of Athens, Athens, Greece
- 38: Also at Rutherford Appleton Laboratory, Didcot, UK
- 39: Also at Paul Scherrer Institut, Villigen, Switzerland
- 40: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 41: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 42: Also at Gaziosmanpasa University, Tokat, Turkey
- 43: Also at Adiyaman University, Adiyaman, Turkey
- 44: Also at Cag University, Mersin, Turkey
- 45: Also at Mersin University, Mersin, Turkey
- 46: Also at Izmir Institute of Technology, Izmir, Turkey
- 47: Also at Ozyegin University, Istanbul, Turkey
- 48: Also at Kafkas University, Kars, Turkey
- 49: Also at Suleyman Demirel University, Isparta, Turkey
- 50: Also at Ege University, Izmir, Turkey
- 51: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 52: Also at Kahramanmaras Sütcü Imam University, Kahramanmaras, Turkey
- 53: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
- 54: Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
- 55: Also at Utah Valley University, Orem, USA
- 56: Also at Institute for Nuclear Research, Moscow, Russia
- 57: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 58: Also at Argonne National Laboratory, Argonne, USA
- 59: Also at Erzincan University, Erzincan, Turkey
- 60: Also at Yildiz Technical University, Istanbul, Turkey
- 61: Also at Texas A&M University at Qatar, Doha, Qatar
- 62: Also at Kyungpook National University, Daegu, Korea