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

The CMS Collaboration*
CERN, Geneva, Switzerland

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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 parton 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, $\phi$ is the azimuthal angle in the transverse plane perpendicular to the beam, and $\theta$ 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 $\phi_i$.

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

$$\tan \beta = \frac{|\Delta \phi_{23}|}{\Delta \eta_{23}},$$

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, 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 $\beta$ value. For $\Delta \phi_{23} = 0$, $\beta$ is defined to be zero or $\pi$ 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 $\Delta \phi_{23} = 0$, $\beta$ 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
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 $\beta$ 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 $\beta$ distributions, normalized to the total number of events in each region, as a function of $\beta$ separately in the central ($|\eta_2| \leq 0.8$) and forward region ($0.8 < |\eta_2| \leq 2.5$):

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

where $N_\eta$ is the total number of events in the $\eta$ region, $N_{\eta,i}$ the number of events in the given $i$th $\beta$ bin of the $\eta_2$ 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 $\beta$ 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 bandwidth except the highest-threshold one. Therefore, the events are split into five different bins in $p_T$, each bin containing the events collected during a period when the appropriate trigger was not prescaled. Each bin starts at $p_T$ defined in such a way that the associated trigger efficiency exceeds 99 %. Table 2 lists the binning in $p_T$, 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 $p$ is the vector sum of the momenta of the constituents. The jet transverse momentum $p_T$ is the component of $p$ perpendicular to the beam. The $E$ and $p$ values

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Fig. 1 Visualization of the observable $\beta$ in ($\eta, \phi$) space using a simulated three-jet event. The sizes of the rectangular boxes are proportional to the particle energies.
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 $\beta$ 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 ($\eta, \phi$) 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.

The selections used in the analysis are summarized in Table 1. The numbers of events passing the selection criteria in each $p_T$ 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.

### Table 1 Summary of the event selection

<table>
<thead>
<tr>
<th>Selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T1 &gt; 100$ GeV, $p_T3 &gt; 30$ GeV</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>$M_{12} &gt; 220$ GeV</td>
</tr>
<tr>
<td>$0.5 &lt; \Delta R_{23} &lt; 1.5$</td>
</tr>
</tbody>
</table>

### 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

<table>
<thead>
<tr>
<th>$p_T1$ bin edges (GeV)</th>
<th>Trigger online threshold (GeV)</th>
<th>$L_{int}$ (fb$^{-1}$)</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>$</td>
<td>\eta_2</td>
<td>\leq 0.8$</td>
</tr>
<tr>
<td>100–120</td>
<td>30</td>
<td>0.35</td>
<td>4511</td>
</tr>
<tr>
<td>120–160</td>
<td>50</td>
<td>4.5</td>
<td>67 086</td>
</tr>
<tr>
<td>160–200</td>
<td>70</td>
<td>9.2</td>
<td>50 071</td>
</tr>
<tr>
<td>200–250</td>
<td>100</td>
<td>20</td>
<td>39 464</td>
</tr>
<tr>
<td>&gt;250</td>
<td>140</td>
<td>36</td>
<td>31 999</td>
</tr>
<tr>
<td>All</td>
<td></td>
<td></td>
<td>193 131</td>
</tr>
<tr>
<td>Total</td>
<td>$0.8 &lt;</td>
<td>\eta_2</td>
<td>\leq 2.5$</td>
</tr>
<tr>
<td>100–120</td>
<td>30</td>
<td>0.35</td>
<td>1671</td>
</tr>
<tr>
<td>120–160</td>
<td>50</td>
<td>4.5</td>
<td>27 069</td>
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<td>160–200</td>
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<td>9.2</td>
<td>23 055</td>
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<td>100</td>
<td>20</td>
<td>18 987</td>
</tr>
<tr>
<td>&gt;250</td>
<td>140</td>
<td>36</td>
<td>16 728</td>
</tr>
<tr>
<td>All</td>
<td></td>
<td></td>
<td>87 510</td>
</tr>
</tbody>
</table>

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.
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 $\beta$ 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 $p_T$ 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 $\beta$ distribution and systematic uncertainties

The measurement of the $\beta$ 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 $p_T^1$. Consequently different $p_T^1$ bins are merged into one single bin.

The $\beta$ distribution in a given $\eta_2$ region is obtained as a sum of the events weighted by the luminosity collected by the trigger used in the associated $p_T^1$ bin. In case of MC samples the $\beta$ distribution is obtained by summing together the events weighted by their generation level weight in a given $\eta_2$ region. The normalized $\beta$ distribution is then obtained by dividing the weighted number of events in a given bin of $\beta$ by the total weighted number of events in the given $\eta_2$ region.

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

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

<table>
<thead>
<tr>
<th>$\beta$ (degree)</th>
<th>$F_{\mathcal{T}_1}(\beta)$</th>
<th>$\sigma_{\text{Stat}}$</th>
<th>$\sigma_{\text{JES}}$</th>
<th>$\sigma_{\text{IER}}$</th>
<th>$\sigma_{\text{JAR}}$</th>
<th>$\sigma_{\text{PM}}$</th>
<th>$\sigma_{\text{Syst}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–10</td>
<td>0.0549</td>
<td>3.5</td>
<td>1.0</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
<td>1.3</td>
</tr>
<tr>
<td>10–20</td>
<td>0.0535</td>
<td>3.9</td>
<td>1.1</td>
<td>0.4</td>
<td>0.6</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>20–30</td>
<td>0.0544</td>
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<td>30–40</td>
<td>0.0538</td>
<td>4.0</td>
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<td>0.3</td>
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<td>40–50</td>
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<tr>
<td>60–70</td>
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<td>0.6</td>
<td>1.1</td>
</tr>
<tr>
<td>150–160</td>
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<td>0.5</td>
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</tr>
<tr>
<td>170–180</td>
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<td>0.7</td>
<td>0.6</td>
<td>0.6</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Fig. 4 Observed $\beta$ 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 $\beta$ distributions and their uncertainties for the forward region $0.8 < |\eta_2| \leq 2.5$. All uncertainties are symmetric and given in percent (%).

<table>
<thead>
<tr>
<th>$\beta$ (degree)</th>
<th>$F_{\beta_2}(\beta)$</th>
<th>$\sigma_{\text{Stat}}$</th>
<th>$\sigma_{\text{JES}}$</th>
<th>$\sigma_{\text{JER}}$</th>
<th>$\sigma_{\text{JAR}}$</th>
<th>$\sigma_{\text{PM}}$</th>
<th>$\sigma_{\text{Syst}}$</th>
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<td>0.5</td>
<td>0.7</td>
<td>1.9</td>
</tr>
<tr>
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<td>0.7</td>
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<td>20–30</td>
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<td>0.4</td>
<td>0.5</td>
<td>0.7</td>
<td>1.2</td>
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<td>0.5</td>
<td>0.7</td>
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<td>0.5</td>
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<td>0.7</td>
<td>1.2</td>
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<tr>
<td>50–60</td>
<td>0.0438</td>
<td>3.9</td>
<td>0.7</td>
<td>0.4</td>
<td>0.4</td>
<td>0.7</td>
<td>1.1</td>
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<tr>
<td>90–100</td>
<td>0.0520</td>
<td>3.9</td>
<td>0.8</td>
<td>0.5</td>
<td>0.4</td>
<td>0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>100–110</td>
<td>0.0567</td>
<td>3.6</td>
<td>0.8</td>
<td>0.5</td>
<td>0.5</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>110–120</td>
<td>0.0625</td>
<td>3.5</td>
<td>0.7</td>
<td>0.5</td>
<td>0.5</td>
<td>0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>120–130</td>
<td>0.0662</td>
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<td>0.8</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
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</tr>
<tr>
<td>130–140</td>
<td>0.0692</td>
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<tr>
<td>140–150</td>
<td>0.0736</td>
<td>3.1</td>
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<td>0.7</td>
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<tr>
<td>150–160</td>
<td>0.0774</td>
<td>2.9</td>
<td>0.7</td>
<td>0.4</td>
<td>0.6</td>
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<tr>
<td>160–170</td>
<td>0.0795</td>
<td>2.9</td>
<td>0.8</td>
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<tr>
<td>170–180</td>
<td>0.0791</td>
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<td>0.6</td>
<td>0.5</td>
<td>0.7</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Most of the systematic effects cancel out in the normalized $\beta$ 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 $\eta$ 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 $\pm 10$ % [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 $\beta$ and $\eta_2$ bins [43,44]. However, the various systematic sources are uncorrelated among themselves.

6 Results

The unfolded $\beta$ 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 $\beta$ distributions and their uncertainties are presented in Tables 4 and 5.

The ratios of the various MC predictions to the measured $\beta$ 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 $\chi^2$ 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) 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 $\chi^2$/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 $\chi^2$ 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

### Table 6

| MC event generator | $\chi^2$/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                           |

Fig. 6 The MC predictions for the $\beta$ 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 $\sqrt{s} = 7$ TeV. Distributions of the variable $\beta$, 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 $\beta$ 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 $\beta$ 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.

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The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
S. Chatrchyan, V. Khachatryan, A. M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerp, Belgium

Vrije Universiteit Brussel, Brussels, Belgium

Université Libre de Bruxelles, Brussels, Belgium

Ghent University, Ghent, Belgium

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

Université de Mons, Mons, Belgium
N. Beliy, T. Caebergs, E. Daubie, G. H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

Universidade Estadual Paulista, São Paulo, Brazil
F. A. Dias, 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. Genchev, P. Iaydjiev, S. Piperov, M. Rodozov, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

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. Plestina, 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, Egypt
A. A. Abdelalim, Y. Assran, S. Elgammal, A. Ellithi Kamel, M. A. Mahmoud, A. Radi

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

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

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

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

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

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze

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

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

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
Deutsches Elektronen-Synchrotron, Hamburg, Germany

University of Hamburg, Hamburg, Germany

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

University of Athens, Athens, Greece
L. Gouskos, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Ioánnina, Ioánnina, 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. Horvath\textsuperscript{20}, F. Sikler, V. Veszpremi, G. Vesztergombi\textsuperscript{21}, 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. Swain\textsuperscript{22}

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
A. Abdulsalam, D. Dutta, S. Kaı̂las, V. Kumar, A. K. Mohanty\textsuperscript{2}, L. M. Pant, P. Shukla, A. Topkar

Saha Institute of Nuclear Physics, Kolkata, India

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, D. Dutta, S. Kaı̂las, V. Kumar, A. K. Mohanty\textsuperscript{2}, L. M. Pant, P. Shukla, A. Topkar
National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

National Centre for Nuclear Research, Swierk, Poland

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

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

Joint Institute for Nuclear Research, Dubna, Russia

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

Institute for Nuclear Research, Moscow, Russia

Institute for Theoretical and Experimental Physics, Moscow, Russia

P.N. Lebedev Physical Institute, Moscow, Russia

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. Petrushenko, V. Savrin, A. Snigirev

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

Faculty of Physics and Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
P. Adzic³⁴, M. Djordjevic, M. Ekmedzic, D. Kric³⁴, J. Milosevic

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

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J. F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

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

Springer
CERN, European Organization for Nuclear Research, Geneva, Switzerland

Paul Scherrer Institut, Villigen, Switzerland

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

Universität Zürich, Zurich, Switzerland
C. Amsler, V. Chiochia, C. Favaro, M. Ivoiva Rikova, B. Kilminster, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Taroni, M. Verzetti, Y. Yang

National Central University, Chung-Li, Taiwan

National Taiwan University (NTU), Taipei, Taiwan

Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, N. Suwonjandee

Cukurova University, Adana, Turkey

Physics Department, Middle East Technical University, Ankara, Turkey

Bogazici University, Istanbul, Turkey
E. Gülmez, B. Isildak, M. Kaya, S. Ozkorucuklu, N. Sonmez

Istanbul Technical University, Istanbul, Turkey
H. Bahtiyar, E. Barlas, K. Cankocak, Y. O. Günaydın, F. I. Vardarlı, M. Yücel

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk, P. Sorokin
University of Bristol, Bristol, UK

Rutherford Appleton Laboratory, Didcot, UK

Imperial College, London, UK

Brunel University, Uxbridge, UK

Baylor University, Waco, USA
J. Dittmann, K. Hatakeyama, A. Kasmi, 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. Lajic, J. Rohlf, D. Sperka, J. St. John, L. Sulak

Brown University, Providence, USA

University of California, Davis, Davis, USA

University of California, Los Angeles, USA

University of California, Riverside, USA

University of California, San Diego, La Jolla, USA

University of California, Santa Barbara, Santa Barbara, USA

California Institute of Technology, Pasadena, USA
Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA

Massachusetts Institute of Technology, Cambridge, USA

University of Minnesota, Minneapolis, USA

University of Mississippi, Oxford, USA

University of Nebraska-Lincoln, Lincoln, USA

State University of New York at Buffalo, Buffalo, USA

Northeastern University, Boston, USA

Northwestern University, Evanston, USA

University of Notre Dame, Notre Dame, USA

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

University of Puerto Rico, Mayaguez, USA
E. Brownson, A. Lopez, H. Mendez, J. E. Ramirez Vargas

Purdue University, West Lafayette, USA

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. Goulianos, G. Lungu, S. Malik, C. Mesropian

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

University of Tennessee, Knoxville, USA

Texas A&M University, College Station, USA

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P. R. Dudero, K. Kovitanggoon, 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. Luo, J. Velkovska

University of Virginia, Charlottesville, USA

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

† 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 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 Sütçü İmam 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 Yıldız Technical University, Istanbul, Turkey
61: Also at Texas A&M University at Qatar, Doha, Qatar
62: Also at Kyungpook National University, Daegu, Korea