Disentangling the soft and hard components of the pp collisions using the spher(o)city approach

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A new method to extract information from the pp data is proposed. The approach is based on the use of the event structure variables: sphericity and sphericity, to split the data into enhanced soft and hard processes samples corresponding to events with large and low numbers of multi-parton interactions, respectively. The present study was developed in the framework of Pythia 8.180 for inelastic pp collisions at $\sqrt{s} = 7$ TeV. As an application of the method, a study of the identified particle transverse momentum spectra and their ratios; is presented for soft (isotropic) and hard (jetty-like) events. The flow-like effect on these observables due to multi-parton interactions and color reconnection is relevant for soft events suggesting that partons inside the jet do not feel color reconnection and its flow-like consequences.

Due to the composite nature of hadrons, it is possible to have events in which two or more distinct hard parton-parton interactions occur simultaneously in a single hadron-hadron collision. The phenomenon, named multi-parton interactions (MPI) [1], has been supported by data [2-4] and is a key ingredient in the Monte Carlo approach leaves out many of the details of the pp interactions, respectively. The present study was developed in the framework of Pythia 8.180 for inelastic pp collisions at $\sqrt{s} = 7$ TeV. As an application of the method, a study of the identified particle transverse momentum spectra and their ratios; is presented for soft (isotropic) and hard (jetty-like) events. The flow-like effect on these observables due to multi-parton interactions and color reconnection is relevant for soft events suggesting that partons inside the jet do not feel color reconnection and its flow-like consequences.

In this letter observables which usually are not considered in the analysis of minimum bias data are shown to bring a new insight into the fine structure of the events. In an earlier letter [13] it was demonstrated that the color reconnection (CR) mechanism implemented in Pythia 8.180 [14] creates flow-like patterns in pp collisions which increases with the number of MPI (nMPI). The average nMPI rises almost proportionally with the event multiplicity and their correlations. However, this approach leaves out many of the details of the pp interactions making hard to describe observables like the jet production rate as a function of the event multiplicity [9-11] and the approximately linear increase of the $J/\psi$ yield with the event multiplicity [12]. New observables are needed to understand which component of the hadronic interactions, hard (pQCD) and/or soft (phenomenological models), is worst described by theory causing the overall disagreements.

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Variables transverse sphericity ($S_T$) and sphericity ($S_0$) are used in this work, by definition both are collinear safe. $S_T$ is defined in terms of the eigen-values $\lambda_1$, $\lambda_2$ ($\lambda_1 > \lambda_2$):  

$$S_T = \frac{2\lambda_2}{\lambda_2 + \lambda_1},$$

resulting from the diagonalization of the transverse momentum matrix:

$$S_{xy} = \frac{1}{\sum_j p_{Tj}} \sum_i \frac{1}{p_{Ti}} \left( p_{x_i}^2 p_{y_i}^2 + p_{x_i} p_{y_i} + p_{x_i}^2 p_{y_i}^2 \right).$$

FIG. 1. (Color online) Correlation between the number of multi-partonic interactions, nMPI, and spher(o)city. The solid and dotted lines indicate the the average nMPI as a function of sphericity and sphericity, respectively. The horizontal line shows the value for inelastic pp collisions. Also results for low and high multiplicity, $z$, are shown.
FIG. 2. (Color online) Transverse momentum distributions of jetty-like and soft events selected either with sphericity (empty markers) or spherocity (full markers). A comparison with the inclusive distribution (line) is also shown. Distributions were calculated for primary charged particles in $|\eta| < 1$.

Transverse spherocity is defined for a unit transverse vector $\hat{n}$ which minimizes the ratio below:

$$S_0 = \frac{\pi^2}{4} \left( \frac{\sum p_{T_i}^2 \times \hat{n}}{\sum p_{T_i}} \right)^2.$$  

(2)

By construction, the limits of the variables are related to specific configurations in the transverse plane

$$S_T(S_0) = \begin{cases} 0 & \text{“pencil-like” limit (hard events)} \\ 1 & \text{“isotropic” limit (soft events)} \end{cases}.$$  

The event shape variables were studied for inelastic pp collisions generated with Pythia 8.180 tune 4C [18], about $2.5 \times 10^9$ events were produced for each set of simulations. More than two primary charged particles having $p_T$ above 500 MeV/c in $|\eta| < 0.8$ were requested for each event to ensure that experiments at the LHC be able to perform this kind of analysis. Only $\approx 49\%$ of the events satisfy these requirements. The jetty-like events discussed here are those having $S_0$ ($S_T$) below 0.1 and represent 3.51% (1.84%) of the inelastic cross section, while the soft ones have event shape values above 0.9 and correspond to 0.06% (1.72%) of the inelastic cross section.

The correlation between event shapes and quantities at the partonic stage was studied. Figure 1 shows several curves corresponding to the average nMPI as a function of $S_T$ and $S_0$. Results are shown for the entire sample (inclusive) and for two extreme values of multiplicity given in terms of the variable $z = (dN/d\eta)/(dN/d\eta)$. The main features of the correlation plots are the following: i) nMPI increases proportionally with the value of $S_0$ or $S_T$. For the inclusive sample, $S_0$ nMPI increases sharply at high $S_0$ values. ii) The dependence for high $z$ saturates around 17 in the high $S_0$ and $S_T$ ranges. iii) The distributions for $S_T$ and $S_0$ at high $z$ are more similar than for the inclusive ones.

Spherocity is more effective in discriminating multi-jet topologies than sphericity [17]. The effect of this feature can be seen in Fig. 2 where the transverse momentum distributions of primary charged particles are shown for soft and jetty-like events selected either with $S_0$ or $S_T$. The production of low $p_T$ particles ($p_T < 3$ GeV/c) for soft events is significantly larger than in the inclusive sample, while, the production of particle with larger $p_T$ is reduced. For jetty-like events, the particle production for $p_T < 2$ GeV/c is similar to that of the inclusive sample, for larger $p_T$ the power law tail is more prominent than that observed in inelastic events. Finally, for soft events a small power law tail is visible; stronger for $S_T$ than for $S_0$ in line with the existence of multijet events at large $S_T$.

In the following, only results using sphericity are presented since with this observable the largest nMPls events can be selected. The top panel of Fig. 3 shows the invariant yields, $dN/dy$, of primary $\pi^+ + \pi^-$, $K^+ + K^-$, $p + \bar{p}$, $\phi$-meson and $\Lambda$-baryon for low and high $S_0$ events computed for $|y| < 0.5$. Results for two sets of simulations are shown, the first one including color reconnection using the value for the reconnection range, RR= 1.5, as in tune 4C. The second simulation uses RR = 0 (without CR). This comparison is motivated by the fact that CR produces flow-like effects which are augmented in events with high nMPI. Color reconnection makes the spectra harder in a $p_T$ region around 2 GeV/c, the hardening increases with the hadron mass. This effect is not observed neither in high $S_0$ events when RR= 0 nor in jetty-like events (with and without CR). Soft events are more affected by CR than jetty-like ones due to the different average nMPI. To quantify the effects on both sub-samples the yields obtained with CR are normalized to those where RR= 0, the ratios are plotted in the bottom panel of Fig. 3. The ratios for $\pi/K$/p are close to one (within 10%) for jetty like events, while, for high $S_0$ events they are significantly higher. Indeed, this ratio shows up a maximum which is reached at higher $p_T$ when RR is not zero. It is worth to note that the mass effect is small for jetty-like events, e.g., the functional forms of the ratios as a function of $p_T$ for pions and protons are almost equal, but for high $S_0$ events this is not the case.

Figure 4 shows the particle ratios, i.e., the yields, $dN/dy$, of $K^+ + K^-$, $p + \bar{p}$, $\phi$-meson normalized to that for pions. The results are presented for jetty-like and soft events, the simulations included CR. For $p_T$ below 2 GeV/c the ratios exhibit a depletion going from low to high $S_0$, for larger $p_T$ the ratios are higher in high $S_0$ events. For $p_T$ above 5-6 GeV/c the proton-to-pion ratio in high $S_0$ events returns to the value obtained for low $S_0$. The other two ratios which involve strange hadrons deviate from each other when the transverse momentum exceeds 2 GeV/c. These results are compared to those
where the inelastic pp interactions have a partonic transverse momentum, $p_T$, of 6 or 30 GeV/$c$, being this the most energetic pQCD process. The sample with 6 GeV/$c$ jets is in a qualitatively good agreement with results for spherical events, this is due to the fact that the particles inside jets with $p_T = 6$ GeV/$c$ result in jet of very small energy likely to be in the realm of soft processes. As the energy of the jet increases the corresponding particle ratios decrease. This feature is also seen when the results for soft events are compared to those for the hard ones using the spherocity approach. In Table I the $p_T$ integrated particle ratios are reported in spherocity intervals. Within $\approx 10\%$ they are found to be the same in the soft and hard interactions. This suggests that the important differences in the ratios as a function of $p_T$ between jetty and soft events (see Fig.4) are due to a deformation of the respective spectra and not due to a genuine change in the yields.

In summary, we have demonstrated the possibilities of the event structure analysis to separate events with very different amount of MPI and hardness. Low number of MPI will refer to enhanced hard processes samples and will be distinguished by an event structure which will be pencil-like, while the other extreme represented by $S_T$ or $S_0$ close to one will represent soft events where the maximum number of MPI is reached. We have shown that

![Graph showing transverse momentum spectra of various particles](image)

**FIG. 3.** (Color online) Transverse momentum spectra of $\pi^\pm$, $K^\pm$, $p(\bar{p})$, $\phi$ and $\Lambda$ obtained for pp collisions at $\sqrt{s} = 7$ TeV simulated with Pythia 8.180 tune 4C are shown in the top panel. Results for jetty-like (squares) and soft (circles) events are compared. To illustrate the flow-like effect on the spectra [13], two event classes simulated with (full markers) and without (empty markers) color reconnection are presented. Spectra were measured for primary charged particles in $|y| < 0.5$. The ratio with to without color reconnection is shown in the bottom panel.

| $S_0$ interval | $K^+K^-$ | $p+\bar{p}$ | $2\phi$ |
|----------------|----------|-------------|---------|
| 0.0-0.1        | 0.11267 (2) | 0.07038 (1) | 0.01035 (1) |
| 0.1-0.2        | 0.11064 (1) | 0.06836 (1) | 0.00956 (1) |
| 0.2-0.3        | 0.10967 (1) | 0.06708 (1) | 0.00930 (1) |
| 0.3-0.4        | 0.10938 (1) | 0.06628 (1) | 0.00918 (0) |
| 0.4-0.5        | 0.10938 (1) | 0.06570 (1) | 0.00913 (0) |
| 0.5-0.6        | 0.10945 (1) | 0.06528 (1) | 0.00910 (0) |
| 0.6-0.7        | 0.10962 (1) | 0.06495 (1) | 0.00908 (0) |
| 0.7-0.8        | 0.10993 (1) | 0.06472 (1) | 0.00908 (1) |
| 0.8-0.9        | 0.11043 (1) | 0.06447 (1) | 0.00907 (1) |
| 0.9-1.0        | 0.11114 (6) | 0.06408 (4) | 0.00907 (3) |
we can very easily have access to the nMPI by choosing the appropriate interval of $S_0$ or $S_T$. It has to be noted that the range between the extremes is not of immediate interest since there we find the average behavior normally used to tune the models. It is clear that disentangling the building blocks of the collision should enhance our understanding and facilitate the theoretical calculations where so far the soft and hard processes are represented but their relative importance is often a free parameter. The method has been applied to the case of particle ratios showing the feasibility and bringing an interesting result, namely the completely different behavior for the hard (low $S_0$) and soft (high $S_0$) parts. The results suggest that a similar approach would be of interest in many other analyses where accounting for the jets is sometimes cumbersome: momentum correlations (HBT); radial flow; azimuthal flow; mean $p_T$ vs multiplicity, etc.

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