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Study of ϕ and η correlations in minimum bias events with the D0 detector at the Fermilab Tevatron Collider

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We study a new way to describe minimum bias events based on angular distributions in ≈5 million minimum bias $p\bar{p}$ collisions collected between April 2002 and February 2006 with the D0 detector at the Fermilab Tevatron Collider. We demonstrate that the distribution of $\Delta\phi$ in the detector transverse plane between the leading track and all other tracks is a robust observable that can be used for tuning of multiple color interaction models. Pseudorapidity correlations of the $\Delta\phi$ distributions are also studied.

Preliminary Results for DIS 2010 Conference

I. MOTIVATION AND ANALYSIS OVERVIEW

The non-perturbative nature of low energy QCD makes it necessary to develop heuristic descriptions of processes that cannot be approximated otherwise. Models that describe these soft processes are implemented in Monte Carlo event generators. They contain many parameters that need to be tuned using experimental input. Among the input most commonly used are charged particle multiplicities as a function of pseudorapidity ($\eta = -\ln[\tan(\theta/2)]$, where θ is the angle to the z-axis) and mean transverse momentum (p_T) of tracks as a function of track multiplicity.However, these variables cannot be considered to be an exhaustive description of the soft QCD processes. Identifying new variables can provide further insights into the non-perturbative processes themselves and allow us to probe areas where the behavior of the tunes differ.

Studies of soft QCD processes are often done in so-called minimum bias events. The definition of a minimum bias event is not universal because it depends on experimental and detector characteristics. Details of the construction of the minimum bias sample used in this analysis are given in section III. Since one of the major features of minimum bias events is their abundance, the statistical uncertainty of minimum bias measurements can be very small. In order to not spoil this advantage by having to apply much larger systematic uncertainties, we choose to define our measured variables so that they are as independent as possible to the track fake rate and the tracking efficiency. Differences in the azimuthal angle ϕ defined in the plane transverse to the beam line (z-axis) are often used in this context, since all physical processes should be symmetric in ϕ. This makes $\Delta\phi$, the angle between the highest p_T track and each other tracks in the same event, very robust. The general shape of the distribution consists of peaks at 0 and π on top of a pedestal of a certain height. In order to study this shape while minimizing the effect of the presence of fake tracks and the imperfect tracking of the detector, we choose to subtract the fitted minimum from each histogram bin in the distribution and then normalize to unit area.

II. THE D0 DETECTOR

For this analysis, we use data collected with the D0 detector at the Fermilab Tevatron Collider between April 2002 and February 2006. This measurement was done using charged particle tracks in the central tracker of the detector, which consists of a silicon microstrip tracker inside a central fiber tracker, itself surrounded by a solenoidal magnet. The silicon microstrip tracker geometry consists of six central barrel sections with four readout layers and twelve disks. The central fiber tracker geometry consists of eight concentric cylinders of scintillating fibers. Each cylinder supports two doublet layers of fibers, one along the beam direction(axial) and one at a $\pm 3^\circ$ stereo angle. Using both detectors allows for a primary vertex position resolution of 35μm along the beam line direction and excellent transverse momentum resolution for charged particle tracks. This measurement relies also on the identification of muons in the D0 muon system which is constituted of central proportional drift tubes, a toroidal magnet system and a forward system of mini drift tubes. Scintillation counters are used to trigger on the muons. Detailed information about the D0 detector can be found in [1].

III. MINIMUM BIAS SAMPLE SELECTION

To construct a sample of minimum bias events we require interactions that are not biased by the trigger decision. To achieve this, we look at bunch crossings with more than one proton antiproton interaction and identify the single collision that fired the trigger; all other collisions in that bunch crossing are then regarded as minimum bias events. The triggers used are dimuon triggers, which rely exclusively on the muon sub-detector system, making them as independent as possible of the tracking system. We use tracks of all pseudorapidities and transverse momenta to find primary vertices (PVs) using the method described in [2]. We require that these PVs are reconstructed from at least 5 tracks. To identify the triggered PV we match the trigger requirement that the event has two muon candidates with $p_T > 2$ GeV, each with at least one reconstructed segment in the muon system. We then require that both muons are associated to the same PV, and that the dimuon object formed from the identified pair is also associated to this PV. This triggered PV is unsuitable for a minimum bias study, so it is discarded as well as all tracks that are associated to it. All other PVs are added to the minimum bias primary vertex (MBPV) sample, if they are at least 0.5 cm away from the triggered PV (minimizing ambiguities in the track association) and are within 20 cm in z around the center of the detector, ensuring full tracking coverage. A track selection is then applied to ensure track quality and good association of tracks to the MBPVs. First, all tracks are associated to the PV relative to which they have the lowest χ^2_{vrt}, defined as $\chi^2_{vrt} = [(\text{ip}/\sigma)_{axial}]^2 + [(\text{ip}/\sigma)_{stereo}]^2$, where (ip/$\sigma$) is the impact parameter significance in the given direction. This variable is a good discriminant against fake tracks and tracks arising from decays of long lived particles such as pions from K_S. We select a track only if it is associated to a MBPV, has $\chi^2_{vrt} < 25$ relative to the

PV to which it is associated, has $p_T > 0.5$ GeV and has $|\eta| < 2$. We find approximately 5 million MBPVs that satisfy all our requirements in the data set. The total number of selected tracks in the selected vertices is ≈25 million.

To compare results from data with minimum bias Monte Carlo simulations, the construction of PVs and the MBPV and track selections must be mimicked on Monte Carlo collisions. A simple yet sufficient model for PV construction would be to only use Monte Carlo collisions with at least 5 prompt tracks with $p_T > 200$ MeV and $|\eta| < 2.5$. Then, the same track selection as in data must be applied.

IV. ANGULAR CORRELATIONS IN MINIMUM BIAS PRIMARY VERTICES

To construct the $\Delta\phi$ variable, we first identify, for each MBPV, the selected associated track with the largest p_T. The variable we will study is the angle $\Delta\phi$ between this track and all other selected tracks associated to the same MBPV. The number of tracks in a bin of width $\pi/50$ in the $\Delta\phi$ histogram is labeled N^T. Uncorrelated fake tracks and real tracks wrongly associated to an MBPV are distributed uniformly in $\Delta\phi$ and thus constitute a flat background to the overall $\Delta\phi$ distribution. To avoid having to measure their contribution, we do a polynomial fit to the minimum of the distribution and subtract the value of the minimum ($N^T_{\rm min}$) from all the $\Delta\phi$ bins. This removes more than the background from fake tracks, but the shape of the distribution above the level of $N^T_{\rm min}$ is preserved. The absolute level of the shape remaining after subtraction is affected by the tracking efficiency, but we can minimize this dependency by normalizing the distribution and only studying the shape. This way, we suppress the two greatest sources of systematic uncertainty of such a study. The observable can then be expressed as $(N^T - N^T_{\rm min})/\sum(N^T - N^T_{\rm min})$ versus $\Delta\phi$ to the leading track of the same MBPV. The $\Delta\phi$ distributions obtained from Monte Carlo events at the particle and reconstructed levels with this method are identical within statistical uncertainties. From this starting point, we investigated experimental effects and effects of the event reconstruction in data. We did not find any effects that spoiled this match. We concluded that it is not necessary to unfold the experimental result back to particle level explicitly before comparing it to theoretical models.

The general structure of the $\Delta\phi$ distribution, as shown in Fig. 1 (a), is easily understandable. The leading track on average forms the center of a very soft jet creating the peak at 0. This leading track has to be balanced causing a peak to form also at π. By construction, the tracks contributing to this peak have a softer p_T spectrum (with larger fluctuations in $\Delta\phi$) so more tracks are needed for the p_T balance, making the peak wider. Furthermore, the recoil does not align with the leading track but rather with the sum of tracks close to the leading track, broadening the recoil peak. The relative height of the two peaks varies greatly depending on the $|\eta|$ range of tracks considered in the measurement. Since the peak at 0 consists of tracks mostly within a very soft jet they also have a correlation with the leading track in $|\eta|$. Therefore, most of them lie inside the $|\eta|$ range studied. The recoil however does not need to be correlated with the leading track in $|\eta|$. Thus only a fraction of the recoil tracks are in this $|\eta|$ range. When the range is extended, more tracks from the recoil side are included in the measurement, enhancing the peak at π. The relative height of the two peaks, combined with their widths, fixes the position of $N^T_{\rm min}$.

We have compared the distribution obtained from data with some tunes and models implemented in PYTHIA version 6.421[3] in two $|\eta|$ ranges: $|\eta| <1$, historically the region for which tuning data is provided [4, 5], and $|\eta| <2$, the region accessible with the D0 detector. The comparison of the data $\Delta\phi$ distribution, subtracted and normalized, to three PYTHIA tune and model implementations (Rick Field's Tune A[6], the Perugia 0 tune (P0)[7] and the Generalized Area Law model of color reconnections (GAL)[8]) in those two $|\eta|$ ranges are shown in Fig. 1 (a) and (b). These tunes and models were chosen because they have a range of interesting features. Tune A is historically significant and uses Q^2-ordered parton showers while tune P0 is a more recent tune which is an update of the First Sandhoff-Skands tune (S0)[9] and uses p_T-ordered showers. They both use the color-annealing model for color reconnections. GAL is based on tune S0 but uses the Generalized Area Law color reconnection model. In comparing the distributions in Fig. 1 (a) and (b), it is clear that the extended reach of the D0 detector allows us to access a region that affects the shape significantly and where the Monte Carlo tunes and models present large differences, increasing the tuning power.

We define a second observable by assigning the tracks to two η regions based on the rapidity of the leading track. We define tracks to belong to the "same" region if their η values have the same sign as the leading track, and "opposite" otherwise. This track assignment to η regions is illustrated in Fig. 2. We define our observable to be the distribution resulting from the subtraction of the "opposite" region distribution from the "same" region one, and then normalized, again minimizing the effect of fakes and tracking efficiency. This can be expressed as $(N^T_{\rm same} - N^T_{\rm opp})/\sum(N^T_{\rm same} - N^T_{\rm opp})$ versus $\Delta\phi$ to the leading track of the same MBPV where $N^T_{\rm same}$ and $N^T_{\rm opp}$ are the the number of tracks in a bin of width $\pi/50$ in the "same" and the "opposite" η regions respectively. The distributions measured in data are shown in Fig. 1 (c) and (d) for the two $|\eta|$ regions also considered in the previous variable, as well as the prediction from the same three PYTHIA tunes and models as before. Its structure has a rather broad and high same side peak, and a flatter tail. Again in this case, the extended reach of the D0 detector allows us to access a region that affects the shape significantly and where the Monte Carlo tunes and models present large differences.

The systematic uncertainties on these distributions are presented in Table I. We evaluated the systematic uncertainties on the minimum number of tracks required in PV construction and the one associated to p_T resolution by varying those cuts in data and Monte Carlo and measuring the effect on the $\Delta\phi$ distribution. We varied the minimum number of tracks required in PV construction from 3 to 7 and the p_T cut value between 0.4875 and 5.125 GeV. We evaluated the systematic uncertainty associated to the p_T dependence of the tracking efficiency by measuring the effect of applying a large extra inefficiency to data and a range of efficiency models to Monte Carlo events. In the case of the η dependence of the tracking efficiency, we studied the effect of Monte Carlo and data-driven tracking efficiencies as measured on electrons from Z decays on the shape of the $\Delta\phi$ distributions. For the ϕ dependence of the tracking efficiency we used the ϕ distribution of tracks in the data set as an efficiency measurement and applied it to Monte Carlo data. We measured the tracking efficiency as a function of ϕ in data separately for leading tracks and non-leading tracks since their p_T spectra are different. We then evaluated the effect of the introduced inefficiencies on the $\Delta\phi$ distribution in order to assign a systematic uncertainty. We evaluated the systematic uncertainty associated to the contamination of the data sample with tracks from long-lived resonances by varying the χ^2_{vrt} cut on data as well as measuring the contribution of decay products of K^0_s to the $\Delta\phi$ distribution. We measured the systematic uncertainty from the association of tracks to the wrong MBPV by constructing, in data events with more than one MBPV, the $\Delta\phi$ distribution of tracks, subtracted and normalized, to the leading track of another MBPV in the same event and measuring deviations from flatness. We also studied the systematic uncertainty associated to the presence of fakes by investigating the $\Delta\phi$ distribution coming only from tracks with a large z distance to the MBPV, which enriches the fake content. By measuring deviations from flatness of the $\Delta\phi$ distribution for these tracks we evaluated the systematic uncertainty associated with fakes. Finally, we evaluated the systematic effect of the difference in tracking efficiency between the forward and backward halves of the detector on the "same minus opposite" measurement directly from the distributions of tracks in data. The combined systematic uncertainties on both observables is 2.8%.

TABLE I: Preliminary systematic uncertainties

Source	Uncertainty	Source	Uncertainty
η dependence of the tracking efficiency	<2%	p_T dependence of the tracking efficiency	0.5%
Minimum number of tracks in PV construction	1%	Uncorrelated fakes	<0.3%
ϕ dependence of the tracking efficiency	<1%	Contamination by long-lived particles	<0.3%
Track-vertex misassociation	<1%	η asymmetry of tracking efficiency[a]	<0.2%
Track p_T resolution	0.5%	**Combined systematic uncertainty**	**2.8%**

[a] "same minus opposite" only

V. SUMMARY

We have presented new variables, the distributions of which can be used to tune the simulation of minimum bias events. Both are constructed to minimize systematic uncertainties through fake rates or efficiencies, making them ideal candidates for tuning. We see that by extending coverage to the region $|\eta| < 2$, the variables' power is increased.

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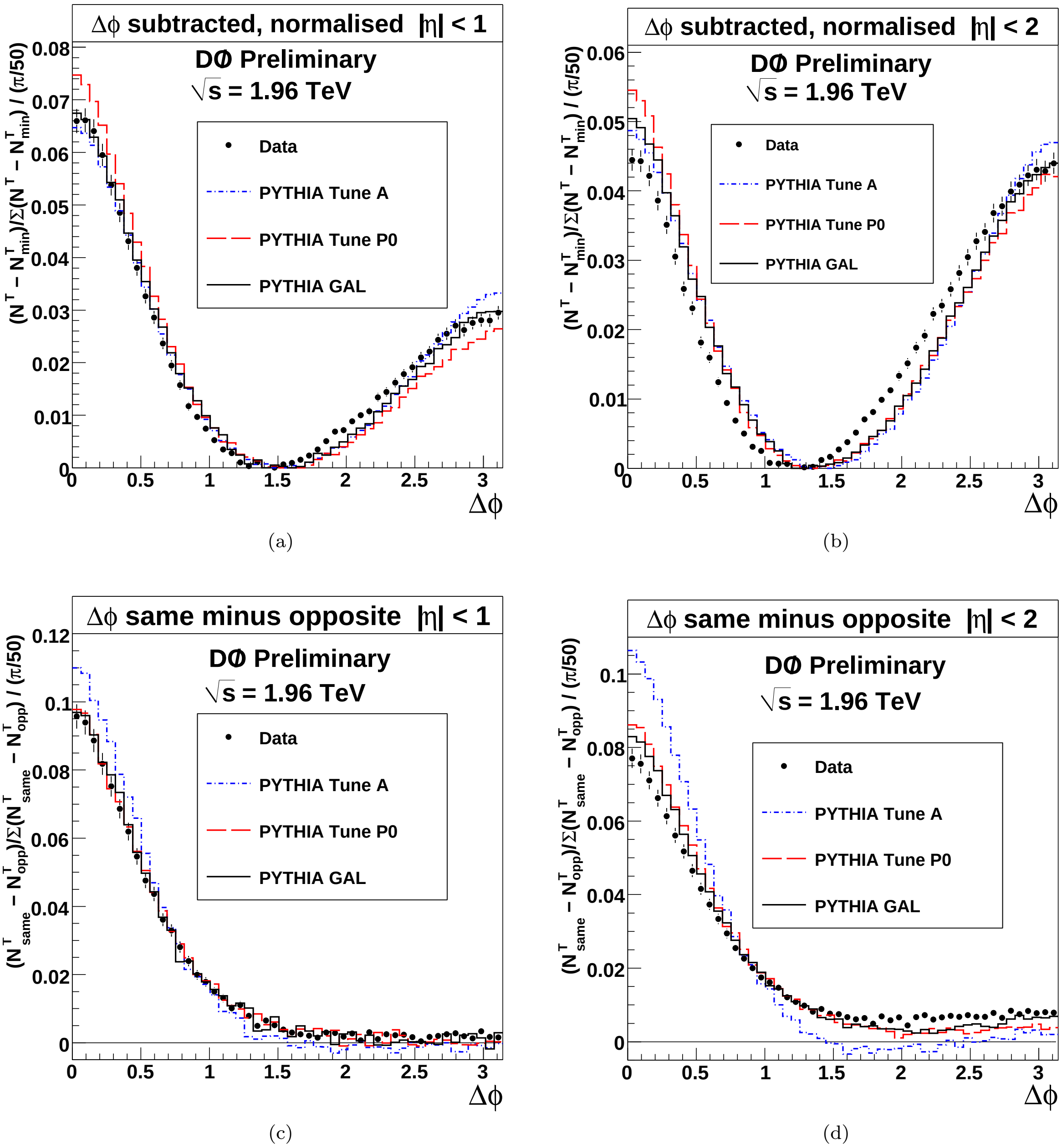

FIG. 1: $\frac{N^T - N^T_{\rm min}}{\sum(N^T - N^T_{\rm min})}$ versus $\Delta\phi$ to the leading track of the same MBPV, where N^T is the number of tracks in a bin of width $\pi/50$ and $N^T_{\rm min}$ is the fitted minimum of the N^T versus $\Delta\phi$ distribution, in data tracks with (a) $|\eta| < 1$ and (b) $|\eta| < 2$. $\frac{N^T_{\rm same} - N^T_{\rm opp}}{\sum(N^T_{\rm same} - N^T_{\rm opp})}$ versus $\Delta\phi$ to the leading track of the same MBPV where $N^T_{\rm same}$ and $N^T_{\rm opp}$ are the the number of tracks in a bin of width $\pi/50$ in the "same" and the "opposite" η regions respectively, for tracks with (c) $|\eta| < 1$ and (d) $|\eta| < 2$. Error bars include systematic uncertainties.

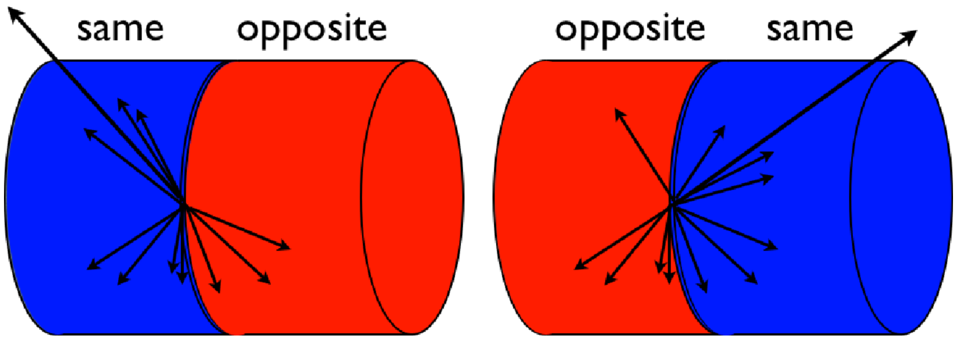

FIG. 2: Illustration of the assignment of tracks associated to an MBPV to the "same" or the "opposite" η region as a function of the position of the leading track. The longest arrow corresponds to the track with leading p_T.