CDF Note 10704

A Study of Quark Fragmentation using Kaons Produced in Association with Prompt $D_s^\pm/D^\pm$ Mesons

The CDF Collaboration
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Quark fragmentation is a non-perturbative process for which Monte Carlo event generators implement only phenomenological models that have been tuned to reproduce general properties of hadron production. We perform an analysis that probes the process of quark fragmentation more directly by studying kaons produced during the fragmentation of charm quarks to form $D_s^\pm$ or $D^\pm$ mesons. We apply particle identification techniques to measure the fraction of events in which a track produced in association with the prompt $D_s^\pm/D^\pm$ meson is a kaon and compare the observed kinematic properties with predictions of fragmentation models implemented in the PYTHIA and HERWIG Monte Carlo event generators. We find that the fragmentation models used in PYTHIA and HERWIG provide a better qualitative description of some kinematic properties of the leading kaon, which is produced early in the fragmentation process, compared with those produced later in the fragmentation process, for which these models underestimate the fraction of kaons.

Preliminary Results for Winter 2012 Conferences

I. INTRODUCTION

Quantum Chromodynamics is a well established model that describes the strong interaction, however there are some observables for which the theory only provides qualitative predictions at best. The QCD Lagrangian describes quarks and gluons, whereas experimentally only hadrons can be observed in a detector. Perturbative QCD calculations can be used to describe the properties of quarks and gluons at small distances or high momentum transfers. Since the running coupling constant becomes large at large distances, perturbation theory breaks down and fails to describe the interaction between quarks and gluons as they move apart. This leaves a gap in the theoretical description of the process by which partons produced in a high energy interaction are transformed into the final observable hadrons. The phenomenological picture of a typical high energy interaction consists of an initial phase involving parton production, which can be described using perturbative QCD. This is followed by a non-perturbative phase in which partons recede from each other and are combined via the strong force to form colorless hadrons. This phenomenon is known as *fragmentation* or *hadronization*.

The fragmentation process is governed by soft non-perturbative phenomena with energy scales of the order of a few GeV. Since perturbative QCD can not be applied at such low energy scales, there is no formal theory that describes the fragmentation process. Instead, a number of phenomenological models have been proposed to describe the quark fragmentation process. Two frequently used models are the *string fragmentation* [1] and the *cluster fragmentation* models [2]. The string fragmentation model is implemented in the PYTHIA [3] Monte Carlo event generator, whereas, the HERWIG [4] Monte Carlo event generator uses the cluster fragmentation model.

Since the description of the fragmentation process is provided using phenomenological models, studying aspects of the non-perturbative process in data is important for validation of the models. Although a number of fragmentation studies have been conducted at LEP, the non-perturbative process has not been extensively probed at hadron colliders. In this analysis we probe the non-perturbative aspects of quark fragmentation by measuring the quark flavor fractions of charged particles produced in association with $D_s^{\pm}$ and $D^{\pm}$ mesons. Since QCD locally conserves quark flavor, this probes new details of the process by which quark anti-quark pairs are produced and subsequently form bound states in the fragmentation of a heavy quark jet.

Previous studies of heavy quark fragmentation at CDF have studied the production of kaons and pions around bottom mesons [5]. These results showed that more fragmentation kaons are produced around B_s^0 mesons as compared to B^0 and B^+. Although this observation is in qualitative agreement with the predictions of the string fragmentation model used in PYTHIA, a detailed study of the charge-flavor correlations between the kaons and the decay flavor of B_s^0 mesons is not feasible because of the high B_s^0 oscillation frequency. Instead, we perform an analysis to study kaon production around charm mesons, namely $D_s^{\pm}$ and $D^{\pm}$. According to the naive fragmentation model, a kaon will be produced in the first fragmentation branch in association with a $D_s^{\pm}$, whereas, creation of a $D^{\pm}$ meson results in the production a pion in the first fragmentation branch as illustrated in Figure 1. Hence, more opposite sign kaons are likely to be produced around $D_s^{\pm}$ as compared to $D^{\pm}$. Another advantage is that there are no known strong decays that can produce charge correlations between $D_s^{\pm}/D^{\pm}$ mesons and kaons unlike $D^{**0} \rightarrow D^+\pi^-$ and $B_s^{**0} \rightarrow B^+K^-$ decays. Consequently, any charge correlation observed between the fragmentation kaon and $D_s^{\pm}$ will be due to flavor conservation in the first fragmentation branch.

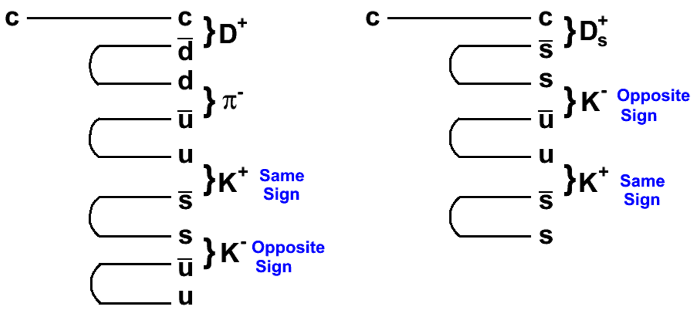

FIG. 1: Hadronization of a charm quark leading to the formation of charm mesons. Oppositely charged kaons are more likely to be produced in the first fragmentation branch around $D_s^{\pm}$ whereas pions are more likely to be produced around $D^{\pm}$ mesons.

In this study, we provide a comparison of various kinematical distributions of kaons produced around prompt $D_s^{\pm}$ and prompt $D^{\pm}$ that allows us to extract information about the properties of the kaon produced in the first fragmentation branch, which is generated only around prompt $D_s^{\pm}$. We compare the results in data with predictions of the PYTHIA event generator that uses the string fragmentation model and the HERWIG event generator that uses the cluster fragmentation model.

II. ANALYSIS OVERVIEW

Using a sample of events collected with CDF's all-hadronic heavy flavor trigger [6], we reconstruct $D_s^{\pm}/D^{\pm} \to \phi\pi^{\pm}$, $\phi \to K^+K^-$ decays and analyze events that have invariant mass in the range $1.75 < m(KK\pi) < 2.2$ GeV. The trigger path requires a pair of oppositely charged tracks that are identified as being displaced with respect to the primary vertex (collision point) based on the pattern of associated hits in the silicon detector. Both tracks are required to have transverse momentum $p_T > 2.0$ GeV and the sum of their transverse momentum has to be greater than 5.5 GeV. In addition, the trigger path includes requirements on the opening angle between the two tracks in the transverse plane and the decay length in the transverse plane. This event sample, obtained from 360 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV contains about $260,000$ $D_s^{\pm}$ and $140,000$ $D^{\pm}$ decays.

The $D_s^{\pm}/D^{\pm}$ mesons in the sample include the prompt D component that is produced due to hadronization of a charm quark and the secondary D component that is produced in decays of hadrons containing bottom quarks. In order to extract information pertaining to charm quark fragmentation, we are primarily interested in the prompt $D_s^{\pm}/D^{\pm}$ component. Hence, an important step in the analysis is the separation of the prompt and secondary components. We use the impact parameter distribution of the reconstructed $KK\pi$ candidates to statistically separate the prompt and secondary D components in data as discussed in Section III. The next step in the analysis it to apply particle identification techniques on a sample of tracks found in a cone of radius $\Delta R = 0.7$ around the reconstructed $KK\pi$ candidates in order to measure the kaon, pion and proton fractions around the various D components. The particle identification techniques used in the analysis are briefly described in Section IV.

The distribution of kaon fraction measured around the prompt $D_s^{\pm}/D^{\pm}$ component is obtained as a function of various kinematic quantities described in Section VIII. The final step in the analysis is to compare the distribution of the measured kaon fraction around prompt $D_s^{\pm}/D^{\pm}$ components with the distribution of kaon fraction around $D_s^{\pm}/D^{\pm}$ mesons produced in $c\bar{c}$ events generated using PYTHIA and HERWIG.

III. SEPARATING PROMPT AND SECONDARY $D_s^{\pm}/D^{\pm}$ COMPONENTS

A prompt $D_s^{\pm}/D^{\pm}$ meson that is created due to hadronization of a charm quark will be produced at the primary vertex and should ideally have zero impact parameter with respect to the primary vertex. However, due to finite resolution of the detector the impact parameter distribution of the prompt component will follow a Gaussian distribution with the width of the Gaussian being equal to the detector resolution. A secondary $D_s^{\pm}/D^{\pm}$ meson that is produced in B decays will be boosted and can have non zero impact parameter with respect to the primary vertex as illustrated in Figure 2. This difference in the inherent shape of the impact parameter distribution of the two components measured with respect to the primary vertex can be used for separating the prompt and secondary $D_s^{\pm}/D^{\pm}$ components.

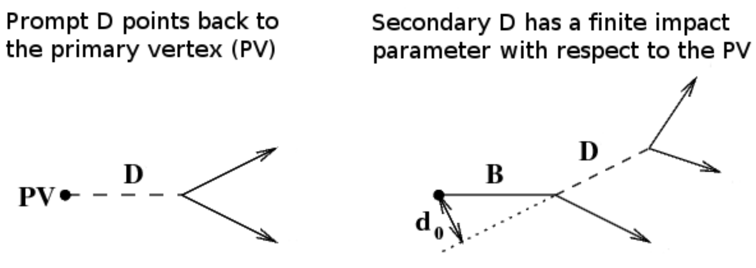

FIG. 2: A secondary D meson can have non zero impact parameter (d_0) with respect to the primary vertex, whereas, a prompt D meson will point back to the primary vertex and should ideally have zero impact parameter.

In the analysis, we statistically separate the prompt and secondary $D_s^{\pm}$ and $D^{\pm}$ components by using the invariant mass distribution and the impact parameter distributions of the reconstructed $KK\pi$ candidates in a likelihood fit. The invariant mass distribution is used to separate the $D_s^{\pm}$ and $D^{\pm}$ signal from the combinatorial background. The $D_s^{\pm}$ and $D^{\pm}$ signal peak is described using a double Gaussian function. The shape of the wide bump in the invariant mass distribution that occurs around 2.02 GeV is obtained using Monte Carlo samples of mis-reconstructed $D^+ \to K^-\pi^+\pi^+$ decays. A fourth order polynomial is used to describe the shape of the background component in the invariant mass distribution.

The impact parameter distribution is used to separate the prompt and secondary components in the $D_s^\pm$ and $D^\pm$ signal. The shape of the prompt D component in the impact parameter distribution is described using a double Gaussian function. In order to describe the shape of the secondary component, we extract the impact parameter distribution of secondary $D_s^\pm/D^\pm$ mesons using Monte Carlo samples of B decays, which is convoluted with the prompt resolution function. The shape of the background component in the impact parameter distribution is obtained by empirically. We compare the impact parameter distribution in the sideband regions in the invariant mass distribution and find that the background impact parameter is independent of mass. Hence, we use the same function to describe the shape of the background impact parameter in the sideband region and under the $D_s^\pm/D^\pm$ signal peaks.

A combined likelihood fit is performed in ranges of transverse momentum of the $KK\pi$ candidate. The invariant mass projections obtained from the fit in the lowest p_T range are shown in Figure 3. The impact parameter projections in the $D_s^\pm/D^\pm$ signal region defined within ±3 sigma from the $D_s^\pm/D^\pm$ signal peak are shown in Figure 4. We observe similar level of agreement between data and fit projections in the other transverse momentum ranges in which the likelihood fit is performed.

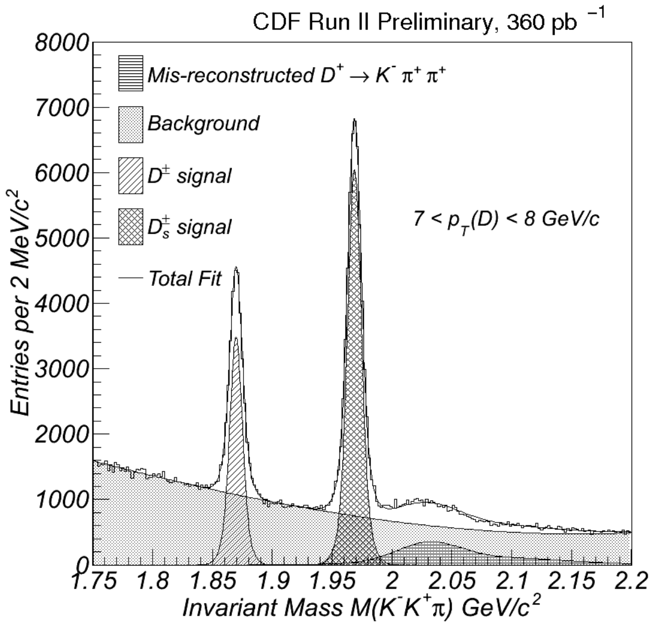

FIG. 3: The invariant mass projections obtained from the likelihood fit performed in the lowest $p_T(KK\pi)$ bin.

IV. PARTICLE IDENTIFICATION TECHNIQUES

We use two main particle identification techniques in the analysis, namely, the measurement of the specific ionization per unit track length (dE/dx) in the Central Outer Tracker (COT) and the time of flight of the particle measured in the Time-of-Flight (TOF) sub-detector. The parameterization of the TOF distribution is obtained by studying a sample of low momentum soft pions (π_s) from $D^* \to D^0\pi_s^\pm$ decays. The parameterization of the dE/dx distribution is obtained using a sample of generic tracks found in a cone around reconstructed $D^{*\pm} \to D^0\pi_s^\pm$ decays. Since the data sample used for the dE/dx study is not a pure sample of pions or kaons, we use the TOF distribution of the tracks in the cone around reconstructed D^* decays as additional information to identify the particles in the generic sample.

We test the combined TOF and dE/dx particle identification techniques on a sample of soft pions (π_s) from $D^{*\pm} \to D^0\pi_s^\pm$ decays and a sample of kaons from $\phi \to K^+K^-$ decays. The signal component in the soft pion sample is made of 100% pions, whereas the background component is considered to be a mixture of kaons, pions and protons. Using the combined particle identification techniques we measure the particle fractions in the signal and

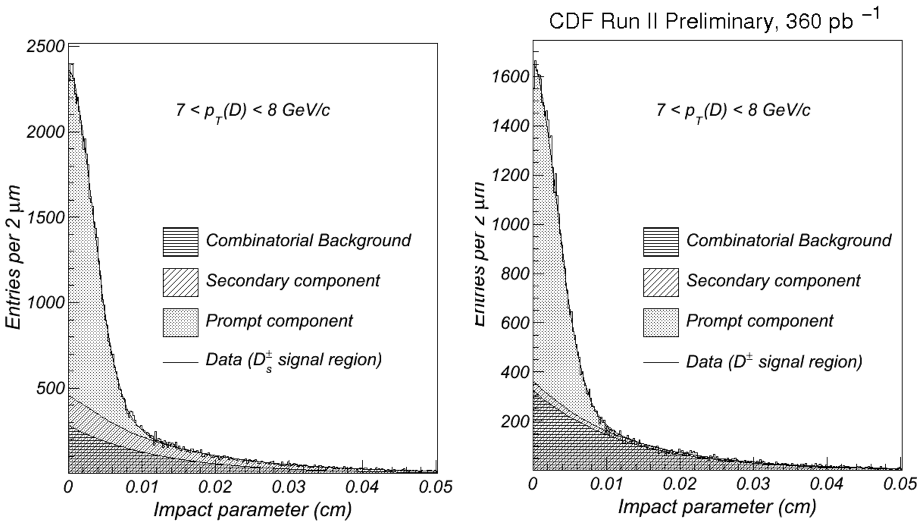

FIG. 4: The impact parameter projections obtained from the likelihood fit performed in the lowest $p_T(KK\pi)$ bin. The projections are made for the $D_s^\pm/D^\pm$ signal region defined within ± 3 sigma from the $D_s^\pm/D^\pm$ signal peak.

background regions. The measured value of the pion fraction in the signal region is found to be fairly consistent with the expected value of 100% for a pure pion sample. In the $\phi \to K^+K^-$ sample, the signal component is made of pure kaons and background is considered as a mixture of kaons, pions and protons. Similar to the studies using the soft pion sample, we measure the particle fractions in the signal and background regions using the combined particle identification techniques. The measured value of the kaon fraction in the signal region is found to be fairly consistent with the expected value of 100% in a pure kaon sample. The results of the studies using the two independent samples show that the combined particle identification techniques do not introduce a significant bias in identifying particles in the lower p_T regime, compared to higher p_T regime where the bias is slightly larger due to poorer separation power for $p_T > 2.0$ GeV/c.

V. MEASUREMENT OF THE KAON FRACTION AROUND PROMPT $D_s^\pm/D^\pm$ MESONS

We select the maximum-p_T track in a cone of radius $\Delta R = 0.7$ around a $KK\pi$ candidate based on the hypothesis that the maximum-p_T is more likely to be correlated with the production of a heavy meson in the fragmentation process. In about 77% of the data used in the analysis, we find only one track per cone and in only the remaining 23% of the data we pick the maximum-p_T out of two or three tracks in the cone. In addition, by studying PYTHIA samples, we find that the kinematic properties of the maximum-p_T track in the cone are not affected by the underlying event activity.

Using the sample of maximum-p_T tracks, we measure the kaon fraction around the prompt $D_s^\pm/D^\pm$ component by performing a multidimensional likelihood fit using the invariant mass and impact parameter distributions of the $KK\pi$ candidates; and the TOF and dE/dx distributions of the maximum-p_T track found in a cone around the reconstructed $KK\pi$ candidates.

The underlying principle of the multidimensional fitting procedure is as follows: Given the invariant mass and impact parameter of a $KK\pi$ candidate, we can use the probability density functions describing the shape of the various components in the $KK\pi$ invariant mass and impact parameter distributions to calculate the likelihood that the particular $KK\pi$ candidate is a prompt $D_s^\pm/D^\pm$ meson, a secondary $D_s^\pm/D^\pm$ meson or part of the background component. Using the probability density functions for the TOF and dE/dx distributions, we can calculate the likelihood that the maximum-p_T track found in the cone around a reconstructed $KK\pi$ candidate is a kaon, pion or proton. Although we measure particle fractions around the various D components (i.e. prompt, secondary and background) separately in the fitting procedure, we are mainly interested in the kaon fraction around the prompt $D_s^\pm/D^\pm$ component for a direct comparison with predictions of the Monte Carlo event generators.

VI. SOURCES OF SYSTEMATIC UNCERTAINTIES IN THE MEASURED KAON FRACTION

We study various sources that can result in a systematic uncertainty in the measured kaon fraction described below:

- The effect of kaons decaying in flight: Kaons produced in $p\bar{p}$ collisions can sometimes decay before traversing the CDF tracking system completely. Some of the kaons that decay in flight are either not reconstructed or mis-reconstructed. We account for this effect by studying the distribution of the fraction of generated kaons that are not reconstructed as a function of transverse momentum using Monte Carlo samples.
- Statistical error in the $KK\pi$ invariant mass and impact parameter PDFs: We use the $KK\pi$ invariant mass and impact parameter to statistically separate the prompt and secondary D components. The parameters in these probability distribution functions are obtained using a likelihood fitting procedure and have statistical errors. We estimate the systematic error that results by propagating the statistical uncertainty in the parameters of the mass and impact parameter PDFs.
- Statistical error in the calibration of particle identification variables: We use the TOF and dE/dx information for identifying kaons, pions and protons; and the parameterization of these distributions is obtained using calibration samples. We estimate the systematic error that results by propagating the statistical uncertainty in the calibration of the particle identification variables.
- Bias induced due to mis-identification of particle types: The kaon fraction can be biased due to mis-identification of the pion and proton components in the sample. We estimate the magnitude of the bias by studying pure kaon and pure pion samples; and find that the bias is smaller at lower momentum regime compared to higher momentum where we have poorer separation power between kaons and protons.

The results of the systematic studies indicate that the most significant source of error in the measured kaon fraction results from the bias induced due to mis-identification of particle types.

VII. MONTE CARLO EVENT GENERATORS USED FOR THE STUDY

Using PYTHIA version 8.1 [3], we generate $c\bar{c}$ events and require the $D_s^\pm/D^\pm$ mesons to be stable particles. For the HERWIG event generator, we use version 6.5 [4] to generate $q\bar{q}$ events requiring the $D_s^\pm/D^\pm$ mesons to be stable particles. Since using HERWIG we can only generate $q\bar{q}$ events, we require the bottom hadrons to be stable particles in order to exclude the secondary $D_s^\pm/D^\pm$ component from B decays.

VIII. RESULTS IN DATA AND COMPARISON WITH MONTE CARLO EVENT GENERATORS

We measure the kaon fraction around prompt $D_s^\pm/D^\pm$ mesons in the opposite sign and same sign charge combinations. In the opposite sign combination, the track in the cone and the D candidate are oppositely charged. In this case, we expect the kaon production to be enhanced around prompt $D_s^\pm$ compared to prompt $D^\pm$ since formation of a prompt $D_s^\pm$ meson requires conservation of strangeness in the first fragmentation branch. In the same sign combination, the track in the cone and the D candidate have the same sign charge. In this combination, we expect the kaon production be similar around both $D_s^\pm/D^\pm$ mesons since same sign kaons are likely to be produced in later branches of the fragmentation process.

In addition to the two charge combinations, we measure the kaon fraction around prompt $D_s^\pm/D^\pm$ mesons and compare the distribution in data with predictions of the PYTHIA and HERWIG Monte Carlo event generators in ranges of the following kinematic variables:

- Transverse momentum p_T of the maximum-p_T track found in a cone of radius $\Delta R = 0.7$ around the reconstructed $KK\pi$ candidates. The distribution of kaon fraction measured in ranges of p_T is shown in Figure 5.
- Invariant mass m_{DK} of the maximum-p_T track (using the kaon mass hypothesis) and the D candidate. The distribution of kaon fraction measured in ranges of m_{DK} is shown in Figure 6.
- Rapidity difference Δy of the maximum-p_T track and the D meson along the direction of the D momentum axis. The distribution of kaon fraction measured in ranges of Δy is shown in Figure 7.

IX. SUMMARY

We conducted an analysis to study some aspects of the non-perturbative quark fragmentation phenomenon by measuring the distribution of kaon fraction around prompt $D_s^{\pm}/D^{\pm}$ mesons. The results in data indicate that the in the opposite sign charge combination, kaon production around prompt $D_s^{\pm}$ is enhanced compared to production around prompt $D^{\pm}$. In the same sign charge combination, kaon production around prompt $D_s^{\pm}$ and prompt $D^{\pm}$ is similar. The enhanced production of oppositely charged kaons around prompt $D_s^{\pm}$ mesons is a feature of the phenomenological models used to describe the fragmentation process in Monte Carlo event generators.

We compared various kinematic distribution of the measured kaon fraction around prompt $D_s^{\pm}/D^{\pm}$ mesons with predictions of the string fragmentation model used in the PYTHIA event generator and the cluster fragmentation model used in the HERWIG event generator. The results of the comparative study indicate that the p_T distributions for early fragmentation kaons produced around prompt $D_s^{\pm}$ are in better qualitative agreement with predictions of fragmentation models compared to generic kaons that are produced in later fragmentation branches, for which the models underestimate the fraction of kaons. Conversely, the $D_s^{\pm}$-kaon invariant and rapidity-difference distributions indicate that the fragmentation models overestimate the fraction of kaons produced in early stages of the fragmentation process compared to the fraction of generic kaons that are produced in later branches, for which the predictions of the models are in better qualitative agreement with the distribution in data.

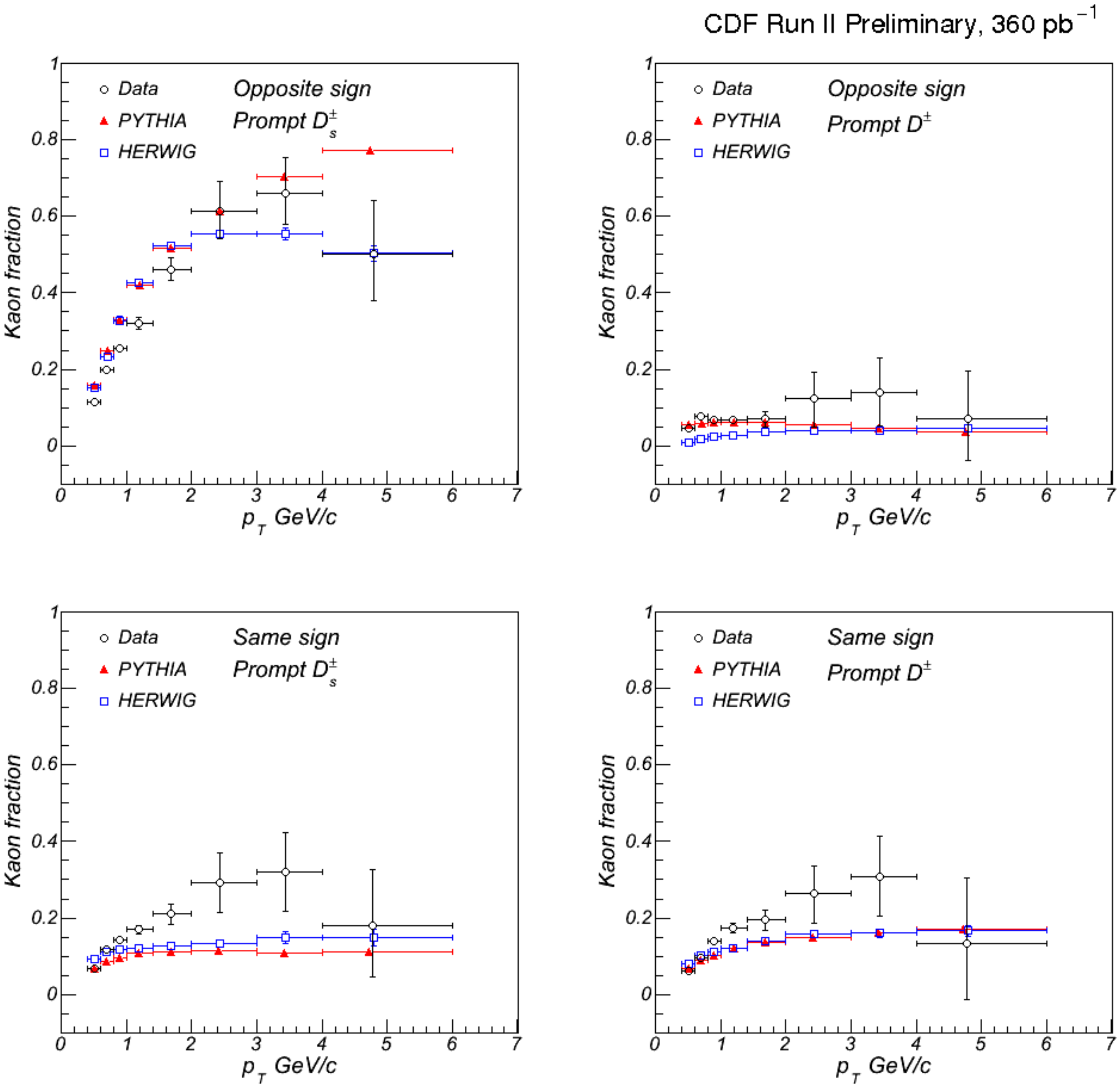

FIG. 5: Distribution of kaon fraction measured around prompt $D_s^{\pm}/D^{\pm}$ mesons in ranges of transverse momentum (p_T) of the maximum-p_T track found in the cone. Comparing the top left and top right plots we can see that kaon production around prompt $D_s^{\pm}$ is enhanced compared to prompt $D^{\pm}$, in the opposite sign combination. The bottom two plots indicate that kaon production in the same sign combination is similar around prompt $D_s^{\pm}$ and prompt $D^{\pm}$. The results indicate that the p_T distribution for early fragmentation kaons produced around prompt $D_s^{\pm}$ mesons is in better agreement with the predictions of the fragmentation models, compared to the distribution for generic kaons that are produced in the later fragmentation branches for which the models underestimate the kaon fraction.

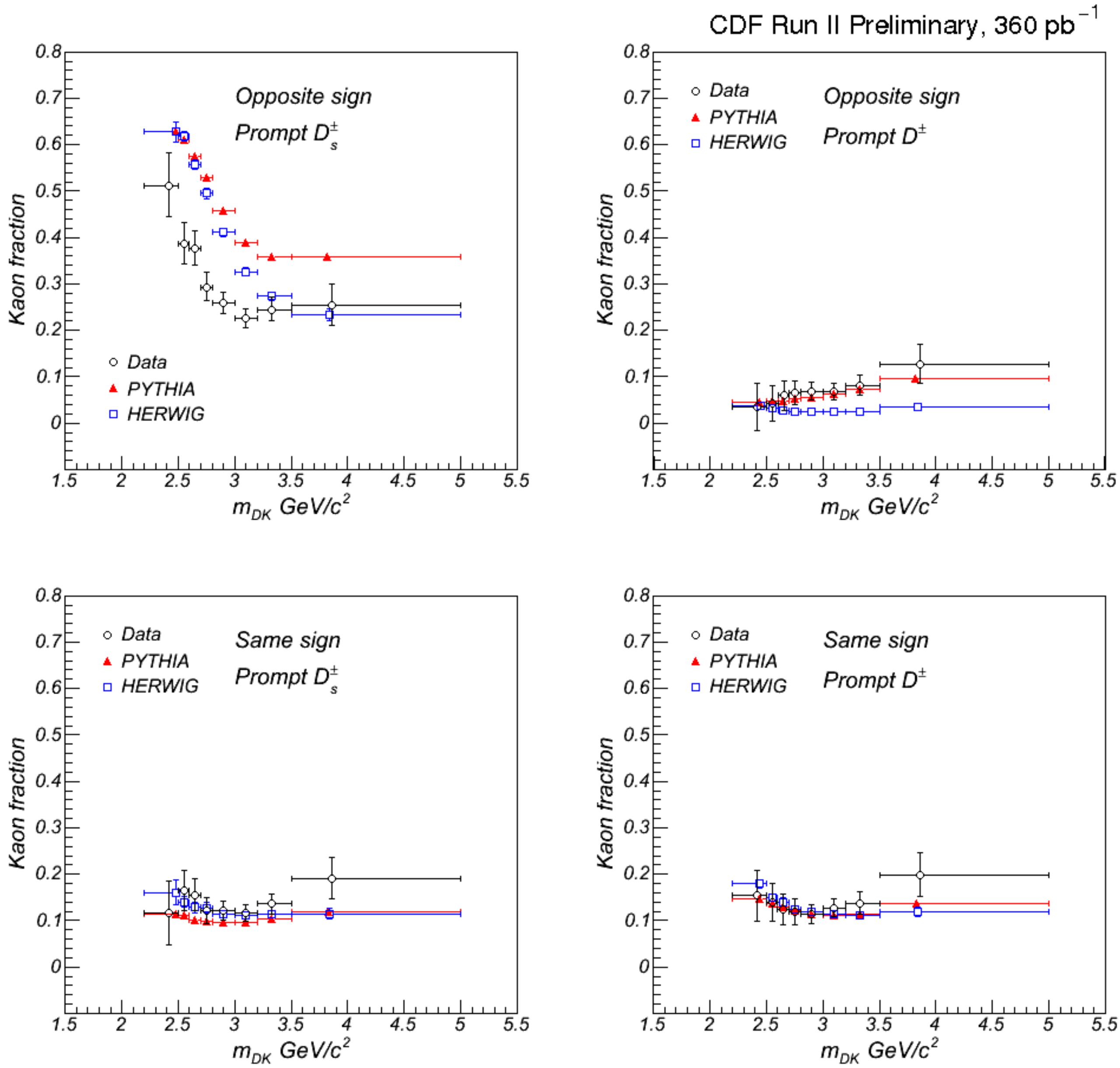

FIG. 6: Distribution of kaon fraction measured around prompt $D_s^\pm/D^\pm$ mesons in ranges of invariant mass of the the maximum-p_T track in the cone and the D candidate. Comparing the top left and top right plots we can see that kaon production around prompt $D_s^\pm$ is enhanced compared to prompt $D^\pm$ in the opposite sign combination. The bottom two plots indicate that kaon production in the same sign combination is similar around prompt $D_s^\pm$ and prompt $D^\pm$. The results indicate that the m_{DK} distribution for early fragmentation kaons produced around prompt $D_s^\pm$ mesons is overestimated by the fragmentation models, compared to the distribution for generic kaons that are produced later in the fragmentation process, for which the models are in better agreement with the data.

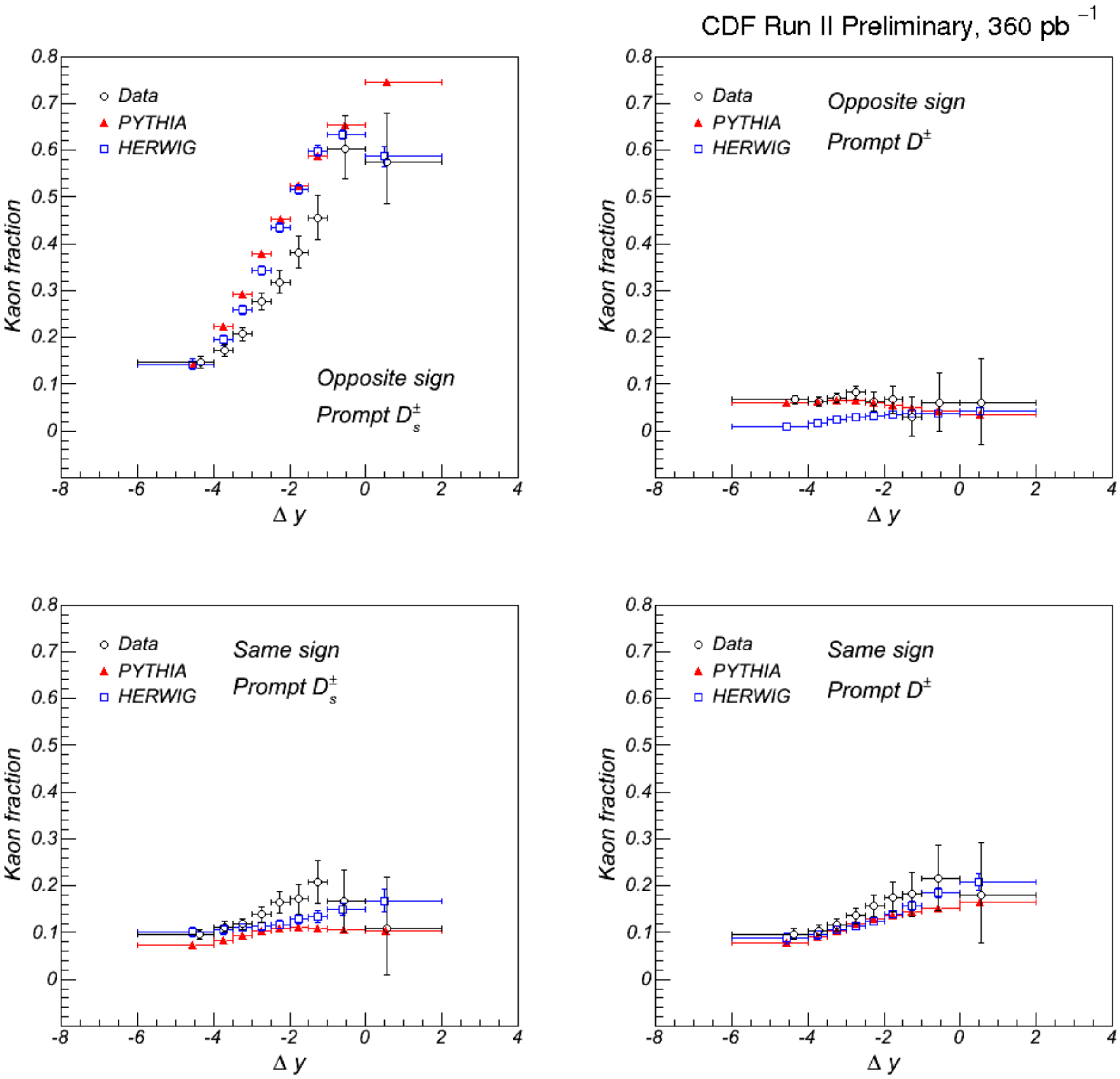

FIG. 7: Distribution of kaon fraction measured around prompt $D_s^\pm/D^\pm$ mesons in ranges of rapidity difference between the maximum-p_T track and the D candidate along the D momentum axis. Comparing the top left and top right plots we can see that kaon production around prompt $D_s^\pm$ is enhanced compared to prompt $D^\pm$ in the opposite sign combination. The bottom two plots indicate that kaon production in the same sign combination is similar around prompt $D_s^\pm$ and prompt $D_s^\pm$. The distribution in opposite sign combination peaks near $\Delta y = 0$, which indicates that early fragmentation kaons produced around prompt $D_s^\pm$ have similar rapidity in the direction of the $D_s^\pm$ momentum. The results indicate that the Δy distribution for early fragmentation kaons produced around prompt $D_s^\pm$ mesons is overestimated by the fragmentation models, whereas the predictions of the models are in better qualitative agreement with the distribution for generic kaons that are produced in later fragmentation branches.

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[1] B. Andersson et al, Phys. Rev. Lett. **97**, 31 (1983).
[2] D. Amati and G. Veneziano, Phys. Lett. B **83**, 87 (1979).
[3] T. Sjostrand, S. Mrenna, P. Skands, *A Brief Introduction to PYTHIA 8.1*, LU TP 07-28, October 2007.
[4] G. Corcella, I.G. Knowles, G. Marchesini, S. Moretti, K. Odagiri, P. Richardson, M.H. Seymour and B.R. Webber, *HERWIG 6.5 Release Note*, hep-ph/0210213.
[5] D. Usynin, M. Jones, J. Kroll, *Study of Charged Particle Species Produced in Association with B^0, B^- and B_s Mesons*, CDF Note 8137, April 13, 2006.
[6] B. Ashmanskas et al., Nucl. Instrum. Methods Phys. Res. A **518**, 532 (2004);