CDF note 8235

B^0 Mixing and Tagger Performance in Semileptonic B Decays with $\sim$1 fb^{-1}

The CDF Collaboration
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We present a measurement of B^0 flavor oscillations using semileptonic $B \to \ell DX$ decays. Large statistics samples of ℓ^+D^- and ℓ^+D^{*-} enriched in B^0 decays, and ℓ^+D^0 enriched in B^+ decays, are reconstructed from a data sample of ~ 1 fb^{-1} collected with the CDF detector during Run II of the Fermilab Tevatron Collider. These data are also used to calibrate opposite-side lepton and jet charge tagging algorithms used to identify the production B flavor. These tagging methods, which have originally been developed using lepton plus displaced track trigger data, provide an event-by-event predicted dilution depending on event kinematic information. A dilution scale factor has been determined for each tagging method to account for differences between the original tagger calibration sample and the ℓD data. These dilution scale factors have been simultaneously determined with the Δm_d parameter, measured as $\Delta m_d = (0.509 \pm 0.010 \pm 0.016)$ ps^{-1}. The overall tagging power is determined to be $\epsilon\mathcal{D}^2 = 1.54 \pm 0.06$ %. This analysis constitutes a crucial test of the B mixing fitting framework. The obtained dilution scale factors serve as input to B_s^0 mixing analysis using the ℓD_s data sample.

Preliminary Results for FPCP2006

I. INTRODUCTION

This document is part of the effort of the CDF collaboration to develop and calibrate tools for the B_s oscillation analysis. The analysis described here determines the calibration factors of the dilution of opposite-side taggers using semileptonic B^0 and B^+ decays reconstructed in the two displaced track trigger and lepton + displaced track trigger data samples. Until we actually measure the B_s mixing frequency, those calibrations are a prerequisite to determine a lower limit on Δm_s using $B_s \to \ell D_s X$ candidates in the same data sample. At the same time, this analysis stands on its own as a measurement of the B^0 oscillation frequency.

A similar analysis has already been performed in the two displaced track trigger data sample with $\sim$355 pb^{-1} only [1]. Several improvements compared to the previous analysis have been introduced. The invariant mass of the lepton and the D meson is on average significantly lower for background events than for real B signal events. A cut on this variable was applied to greatly reduce the background. As further step we have included the lepton-D mass as a new variable on the unbinned likelihood framework. Second, we have used a finer binning on the k-factor distribution as a function of the lepton-D mass. In addition we have increased the data sample by using both two displaced track triggers and lepton + displaced track triggers and using $\sim$ 1 fb^{-1} of total integrated luminosity.

We have developed an unbinned likelihood fit based on D mass, lepton-D mass, proper decay length and tagging information of the reconstructed events. We apply opposite-side tagger algorithms to the data, using the expected dilution for each event, which originally has been calibrated on the inclusive lepton plus displaced track sample [2, 3]. Dilution scale factors are introduced in the likelihood to compensate for topological differences between the calibration sample and the sample used in this analysis. The $\ell D^0, \ell D^-, \ell D^*$ data samples are fitted simultaneously to determine the mixing frequency Δm_d and the dilution scale factors.

Throughout this document, the following abbreviations for the various tagger types are used. The soft muon and soft electron taggers are denoted SMT and SET, respectively. Here the prefix soft is used to indicates that the tagging lepton is not the trigger lepton, thus possessing a softer momentum spectrum. The three types of jet charge tagger, JQT, for tagging jets with a secondary vertex, highly displaced tracks content, and the rest (high p_T jets), are referred to as JVX, JJP and JPT. Charge conjugated are implicitly included as well.

II. DATA SAMPLE & EVENT SELECTION

This analysis is based on an integrated luminosity of $\sim$ 1 fb^{-1}, collected by the CDF II Detector [4] between March 2002 and January 2006. The data is gathered with the so-called "Two-Track Trigger" and "lepton+SVT Trigger". The first one selects events that contain track pairs with transverse momentum larger than 2 GeV/c and 120 μm $< d_0 <$ 1 mm, with d_0 the impact parameter of a track. These tracks are referred to as "SVT tracks". The second trigger requires one lepton with transverse momentum greater than 4 GeV/c plus and additional SVT track.

Three B meson final states are reconstructed in this analysis. These modes nominally correspond to the decays:

$$\begin{aligned}
B^0 &\to \ell^+ D^{*-} X, D^{*-} \to \bar{D^0}\pi_*^-, \bar{D^0} \to K^+\pi^-;\\
B^0 &\to \ell^+ D^- X, D^- \to K^+\pi^-\pi^-;\\
B^+ &\to \ell^+ \bar{D^0} X, \bar{D^0} \to K^+\pi^-.
\end{aligned}$$

Sample composition issues are discussed in the next section.

A common set of tools has been developed in order to reconstruct semileptonic B decays. The D meson candidates are selected in a loose mass window around the nominal PDG [5] value. B candidates, where the lepton is a displaced trigger track are in the following referred to as lepton SVT trigger events. The others, where at least two displaced trigger tracks are among the D decay tracks are referred to as lepton non-SVT trigger events. These two categories of events have been studied separately in this analysis as they have significant different ct distribution and backgrounds.

Additionally we split up our sample in eD and μD events, as the calorimeter and muon systems contribute differently to the background of this analysis. To identify the lepton tracks we use combined likelihoods of variables from various particle identification systems, that were originally developed for the opposite-side soft lepton taggers [3]. Different cuts where applied for muon candidates identified via different muon subsystems. The selection criteria applied on the candidates are listed in Tab. I; there, vertex probability and χ^2 are given by the three - and two dimensional vertex fits respectively, and L_{xy} stands for the decay length on the transverse plane. The overall number of signal events, $\frac{S}{\sqrt{S+B}}$ and $\frac{S}{B}$ for all channels are shown in Tab. II. The D and lepton-D mass distributions are shown in Figs. 2 and 3 respectively.

Cut	ℓD^0	ℓD^-	ℓD^*
ℓD vertex prob. $>$	10^{-6}	10^{-5}	10^{-6}
$\chi^2_{xy}(D) <$	20	20	20
$L_{xy}/\sigma_{L_{xy}}(D \to PV) >$	6	11	6
$L_{xy}/\sigma_{L_{xy}} >$	2	2	2
$p_T(K)$ [GeV/c] $>$	0.5	0.7	0.5
$\sigma_{ct}(\ell D)$ [cm] $<$	0.03	0.03	0.03
$m(\ell D)$ [GeV/c^2] $>$ to $<$	2.0 to 5.5	2.0 to 5.5	2.0 to 5.5
$ct(D)$ [cm] $>$ to $<$	-0.005 to 0.100	-0.005 to 0.200	-0.005 to 0.100
$p_T(\pi_\star)$ [GeV/c] $>$	—	—	0.4
$(m_{D^\star} - m_D)$ [GeV/c^2] $>$ to $<$	—	—	0.1435 to 0.1475

TABLE I: Selection criteria for the ℓD samples.

Decay	S/B	S
μD^0	3.8	409,600 $\pm$ 970
μD^+	1.3	218,500 $\pm$ 940
μD^*	$\geq$ 50	53,900 $\pm$ 230
eD^0	3.7	142,300 $\pm$ 540
eD^+	1.3	79,500 $\pm$ 630
eD^*	$\geq$ 50	21,000 $\pm$ 150

TABLE II: Number of signal events and S/B for the selected ℓD samples. Here background refers to combinatorial background only. A 3σ region around the D mass peak was chosen to determine those parameters.

III. SAMPLE COMPOSITION

This analysis uses three $\ell D^{(*)}$ samples, but there are actually multiple decay paths that contribute to a given observed final state. A necessary complication is the unraveling of the various types of cross-talk that contaminate a pure B^0 signal. The cross-talk between B^0 and B^+ decay channels that feed a common decay signature is the first concern. The various decay channels are mapped out in Figure 1. The path of a decay chain jumps up or down with the emission of a charged pion, and if it is un-detected, one will take a B^+ for a B^0, or the reverse. The combined effect of the relative branching ratios at each decay step will determine the relative sizes of the various decay signatures. The relative branching fractions for B decaying into D, D^* and D^{**} are respectively denoted by f, f^*, and f^{**} in Figure 1. The rate at which D^{**} mesons decay via D^* mesons versus D mesons is encoded in a parameter labeled P_V.

The remaining branching ratios are well known. Note that the decay $D^{*-} \to \bar{D}^0\pi^-$ takes place, but its isospin partner $\bar{D^{*0}} \to \bar{D^-}\pi^+$ does *not*, thereby creating a significant asymmetry in the sample composition at the level of raw physics. Even more important to the sample composition than the differences in raw branching ratios is the fact that our reconstruction is imperfect. In fact we do not even attempt to find π_{**} tracks from D^{**} decays, and when the π_{**} is charged we suffer from cross-talk. Slightly more subtle is the loss of π_* tracks from D^* decays. We do attempt to find charged pions from D^* decays, but this only occurs with some efficiency, $\epsilon(\pi_*)$. Lost charged pions from D^{**} and D^* decays are then the two sources of $B^0 \leftrightarrow B^+$ cross-talk.

Therefore, we must put all the sample composition parameters and the branching ratio inputs taken from the PDG [5] together to quantify the contributions of various decay channels for each decay final state. In addition we must apply a correction due to the different selection efficiencies for every decay chain. Furthermore the different lifetimes of B^0 and B^+ mesons have to be considered. The fractions of B^0 mesons in the ℓD^0, ℓD^+ and ℓD^* samples are ~26%, ~85% and ~90% respectively.

IV. DECAY LENGTH RECONSTRUCTION AND ct^* EFFICIENCY

The transverse decay length $L_{xy}(B)$ is defined as the displacement $\vec{X}$ in the transverse plane from the primary event vertex to the reconstructed B decay point, projected onto the ℓD transverse momentum

$$L_{xy}^B = \frac{\vec{X} \cdot \vec{p_T}(\ell D)}{|\vec{p_T}(\ell D)|}. \tag{1}$$

The B meson decay time is then given by

$$ct\,(B) = L_{xy}^B \, \frac{m(B)}{p_T(B)}, \tag{2}$$

where $m(B)$ is the B mass [5]. Since we do not fully reconstruct the B meson, we calculate the pseudo proper decay time t^* of the reconstructed B meson from the measured decay length L_{xy}^B as

$$ct^* = L_{xy}^B \, \frac{m(B)}{p_T(\ell D)} \tag{3}$$

and introduce a correction factor

$$K = \frac{p_T(\ell D)}{p_T(B)}. \tag{4}$$

This k-factor corrects between the reconstructed $p_T(\ell D)$ and the unknown p_T(B) in the data. The k-factor distribution $\mathcal{F}(K)$ is obtained from a MC simulation of the signal semileptonic decays taking into account the sample composition.

Due to the SVT track d_0 requirement in the trigger and some additional cuts, the reconstructed proper decay time distribution ct^* does not follow a pure exponential (modulo resolution and k-factor effects), but it is biased. This bias, expressed as an efficiency curve is obtained using Monte Carlo simulation. The ct^* bias curve is parameterized with a functional form that is allows analytical integration in the likelihood fit method. The overall ct^* distributions are shown in Fig. 4.

V. ANALYSIS OF B^0 OSCILLATION AND TAGGER CALIBRATION

Reconstruction of time-dependent B flavor asymmetry in the sample is necessary for any oscillation study. The probability density function describing the proper decay time of unmixed and mixed B^0 mesons is $(1 \pm \cos(\Delta m_d t)) \cdot e^{-ct/c\tau}$ where +(-) corresponds to the unmixed(mixed) meson. In order to determine whether a B meson has mixed or not, its flavor at production and at decay time have to be determined. While the flavor at decay time can be inferred directly from the decay products (e.g. the lepton charge) the production flavor has to be deduced from other information in the event via flavor tagging methods. As said above, the reliability of a tagging method is typically characterized by the dilution $\mathcal{D}$. Due to uncertainty in flavor tagging the observed probability density function description of the ct of the neutral B candidates tagged as "mixed" or "unmixed" becomes $(1 \pm \mathcal{D}\cos(\Delta m_d t)) \cdot e^{-ct/c\tau}$. The dilution $\mathcal{D}$ used in the probability density function is built on event-by-event basis. This means that instead of using an average dilution for each tagger the dilution of the tagger is determined separately for each event, as e.g. a function of the p_T^{rel} of the tagging lepton, the magnitude of the component of the opposite-side lepton momentum perpendicular to the axis of the jet which the lepton is associated to, or other quantities used for calibrating the tagger. As those dilutions have been calibrated on the inclusive lepton+SVT sample, the dilution for the ℓD sample might be different. A dilution scale factor $S_\mathcal{D}$ for each tagger is introduced, hence the form of the signal ct probability density function becomes $(1 \pm S_\mathcal{D}\mathcal{D}\cos(\Delta m_d t)) \cdot e^{-ct/c\tau}$. As we use event-by-event dilutions we add as well a term describing the probability density function of the predicted dilution for signal and background in the likelihood.

The evaluation of the systematic uncertainties was one of the main parts of the analysis. The largest systematic uncertainty comes from the fake lepton background description and from the sample composition of the signal sample. The resulting uncertainty contributions being listed in Tab. III.

Error Source	S_D^{SMT} [%]	S_D^{SET} [%]	S_D^{JVX} [%]	S_D^{JJP} [%]	S_D^{JPT} [%]	Δm_d [ps^{-1}]
SVT efficiency	0.02	0.03	0.03	0.12	0.10	0.0005
SVT $d0$ resolution	0.14	0.15	0.20	0.12	0.20	0.0011
σ_{ct}	0.01	0.03	0.01	0.02	0.02	0.0009
k factor binning	0.20	0.13	0.11	0.14	0.27	0.0008
Combinatorial background	0.18	0.14	0.13	0.19	0.29	0.0017
Physics Backgrounds	0.29	0.39	0.36	0.29	0.21	0.0035
$c\tau_{B_{d,u}}$ fixed	0.03	0.03	0.04	0.03	0.05	0.0001
Fraction of fake bckg	0.99	1.24	1.16	0.97	1.05	0.0011
Shape of fake bckg	0.09	0.09	0.09	0.12	0.10	0.0006
Dilution of fake bckg	2.32	2.15	2.30	2.61	2.12	0.0013
Sample composition	0.78	0.75	0.82	0.89	0.67	0.0153
lepton-D mass	0.04	0.09	0.06	0.20	0.26	0.0031
ct scale	—-	—-	—-	—-	—-	0.0020
Total Systematic	2.67	2.64	2.74	2.96	2.53	0.0164

TABLE III: Table of systematic uncertainties for the signal dilution scale factors and Δm_d.

The following results are obtained for the B^0 oscillation frequency

$$\Delta m_d = 0.509 \pm 0.010 \text{ (stat.) } \pm 0.016 \text{ (syst.) ps}^{-1},$$

and for the overall tagging performance

$$\epsilon\mathcal{D}^2 = 1.54 \pm 0.04 \text{ (stat.) } \pm 0.05 \text{ (syst.) } \%.$$

The results for the signal dilution scale factors and Δm_d for the three periods of the data taking, which the sample was divided, are listed in Tab. IV. For illustration purposes, the fit projections for the fitted asymmetries for each tagger in the combined ℓDX sample on 355 pb^{-1} are shown in Fig. 5.

VI. SUMMARY

The CDF Collaboration has performed a study of flavor oscillations in the B^0 system using semileptonic $B \to \ell DX$ decays in ~ 1 fb^{-1} data samples. This analysis provides the calibration of the opposite-side taggers for the ongoing B_s mixing analysis and an accurate measurement of the oscillation frequency Δm_d.

The following results were obtained for Δm_d

$$\Delta m_d = 0.509 \pm 0.010 \text{ (stat.) } \pm 0.016 \text{ (syst.) ps}^{-1}$$

Tagger	$\sqrt{<\mathcal{D}^2_{pred}>}$[%]	ϵ[%]	Scale factor [%]	$\epsilon\mathcal{D}^2$ [%]
	Period 1			
SMT	36.05	4.82 ± 0.04	92.52 ± 2.53 ± 2.67	0.535 ± 0.032 ± 0.034
SET	29.22	3.09 ± 0.03	103.39 ± 3.60 ± 2.64	0.292 ± 0.022 ± 0.017
JVX	18.08	7.74 ± 0.05	96.36 ± 4.11 ± 2.74	0.225 ± 0.020 ± 0.013
JJP	11.37	27.17 ± 0.08	96.41 ± 3.54 ± 2.96	0.346 ± 0.025 ± 0.021
JPT	4.54	51.86 ± 0.09	91.19 ± 6.45 ± 2.53	0.089 ± 0.013 ± 0.005
Total	–	94.68 ± 0.14	96.21 ± 2.07	1.487 ± 0.052 ± 0.046
	Period 2			
SMT	35.84	5.49 ± 0.05	98.45 ± 3.31 ± 2.67	0.684 ± 0.050 ± 0.041
JVX	19.63	8.84 ± 0.06	101.02 ± 4.92 ± 2.74	0.347 ± 0.036 ± 0.021
JJP	11.32	29.32 ± 0.09	92.64 ± 4.73 ± 2.96	0.323 ± 0.034 ± 0.022
JPT	4.51	51.67 ± 0.10	111.71 ± 9.02 ± 2.53	0.133 ± 0.022 ± 0.006
Total	–	95.32 ± 0.16	98.80 ± 2.77	1.487 ± 0.074 ± 0.052
	Period 3			
SMT	35.56	5.84 ± 0.06	107.79 ± 3.63 ± 2.67	0.815 ± 0.061 ± 0.047
JVX	19.47	9.16 ± 0.08	114.65 ± 5.67 ± 2.74	0.462 ± 0.049 ± 0.025
JJP	11.33	29.60 ± 0.12	98.64 ± 5.46 ± 2.96	0.362 ± 0.042 ± 0.023
JPT	4.53	50.65 ± 0.13	113.74 ± 10.58 ± 2.53	0.135 ± 0.026 ± 0.007
Total	–	95.25 ± 0.20	107.66 ± 3.03	1.775 ± 0.092 ± 0.058

TABLE IV: Opposite-side tagger performance the three periods of the data taking.

and for the overall tagging performance

$$\epsilon\mathcal{D}^2 = 1.54 \pm 0.04 \text{ (stat.)} \pm 0.05 \text{ (syst.)} \quad \%$$

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[1] See B^0 *Mixing and Tagger Performance in Semileptonic B Decays in the Two Track Trigger Data Sample*, available through the CDF B-Physics public results page: http://www-cdf.fnal.gov/physics/new/bottom/bottom.html
[2] See *Neural Network based Jet Charge Tagger in Semileptonic Sample* available through the CDF B Physics public results page: http://www-cdf.fnal.gov/physics/new/bottom/bottom.html
[3] See *Likelihood Based Soft Electron Tagging* and *Likelihood Based Soft Muon Tagging* available through the CDF B Physics public results page: http://www-cdf.fnal.gov/physics/new/bottom/bottom.html
[4] D. Acosta *et al.* [CDF Collaboration], Phys Rev D 71, 032001 (2005) and references therein.
[5] S. Eidelman *et al.* [Particle Data Group], "Review of particle physics", Phys. Lett. B 592, 1 (2004)

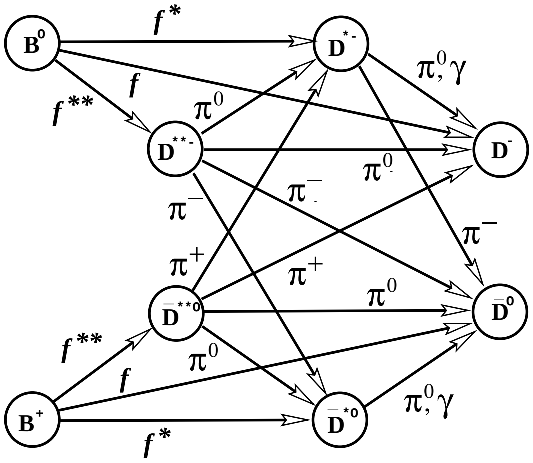

FIG. 1: The state diagram for possible $B \to \ell D^{(*)}$ transitions.

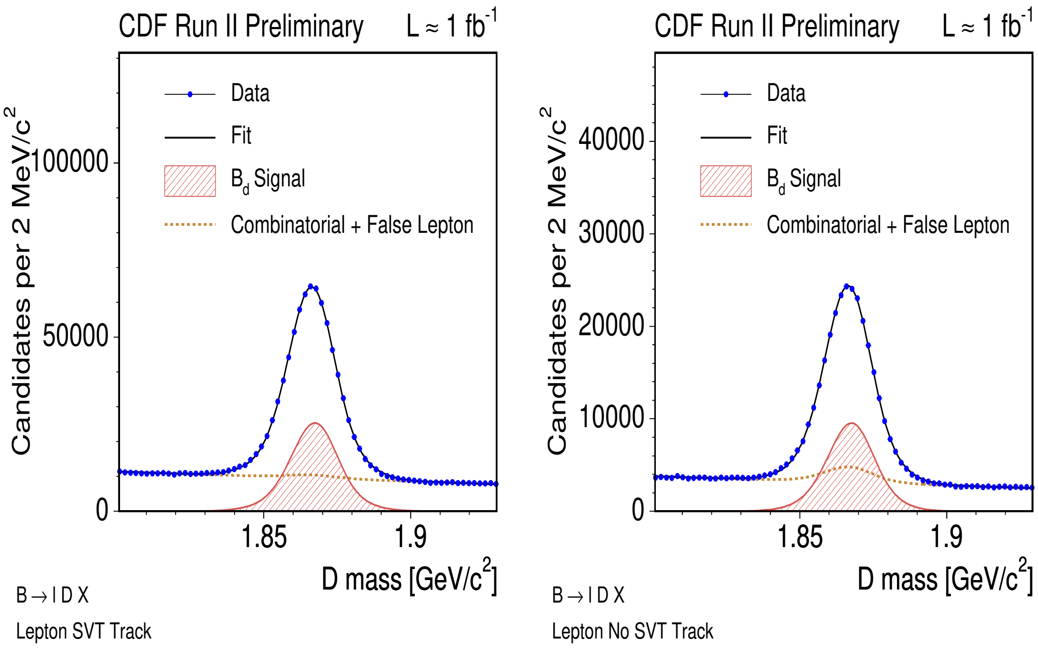

FIG. 2: Mass distributions and fit projections of all ℓDX modes. Left (right) distribution corresponds to the case where the lepton is (isnot) a SVT track

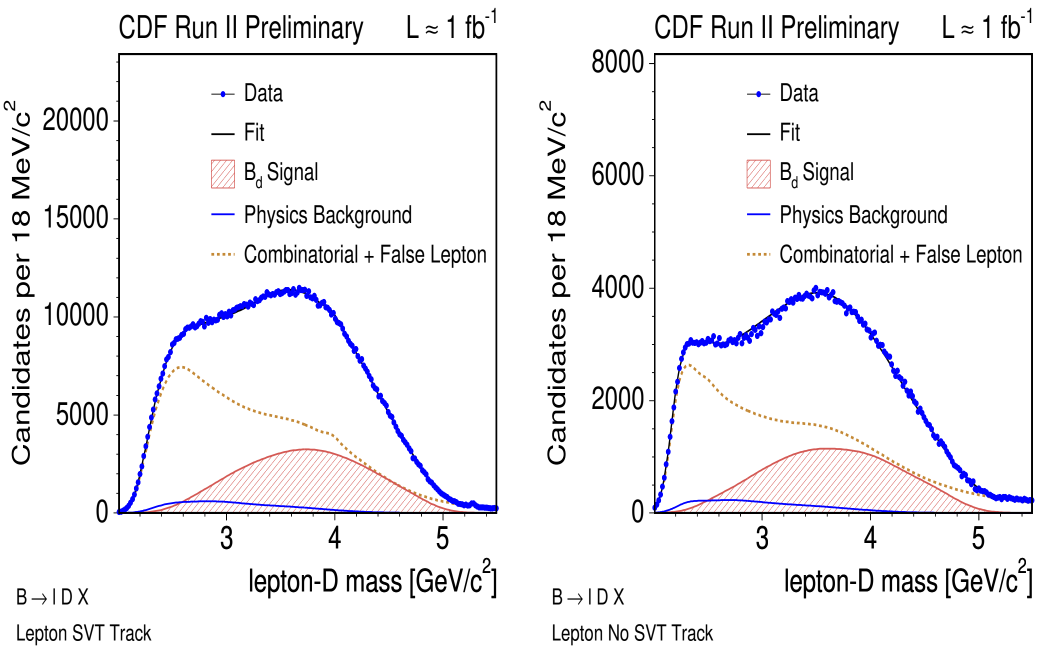

FIG. 3: $m(\ell D)$ distributions and fit projections of all ℓDX modes. Left (right) distribution corresponds to the case where the lepton is (isnot) a SVT track

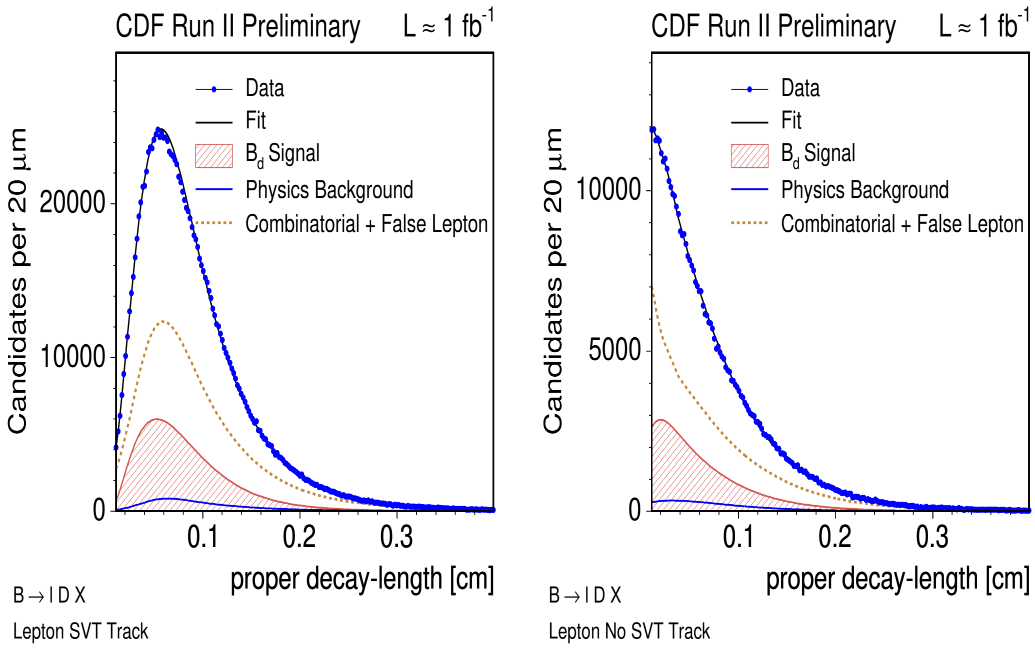

FIG. 4: Pseudo proper decay length distributions and fit projections of all ℓDX modes. Left (right) distribution corresponds to the case where the lepton is (isnot) a SVT track

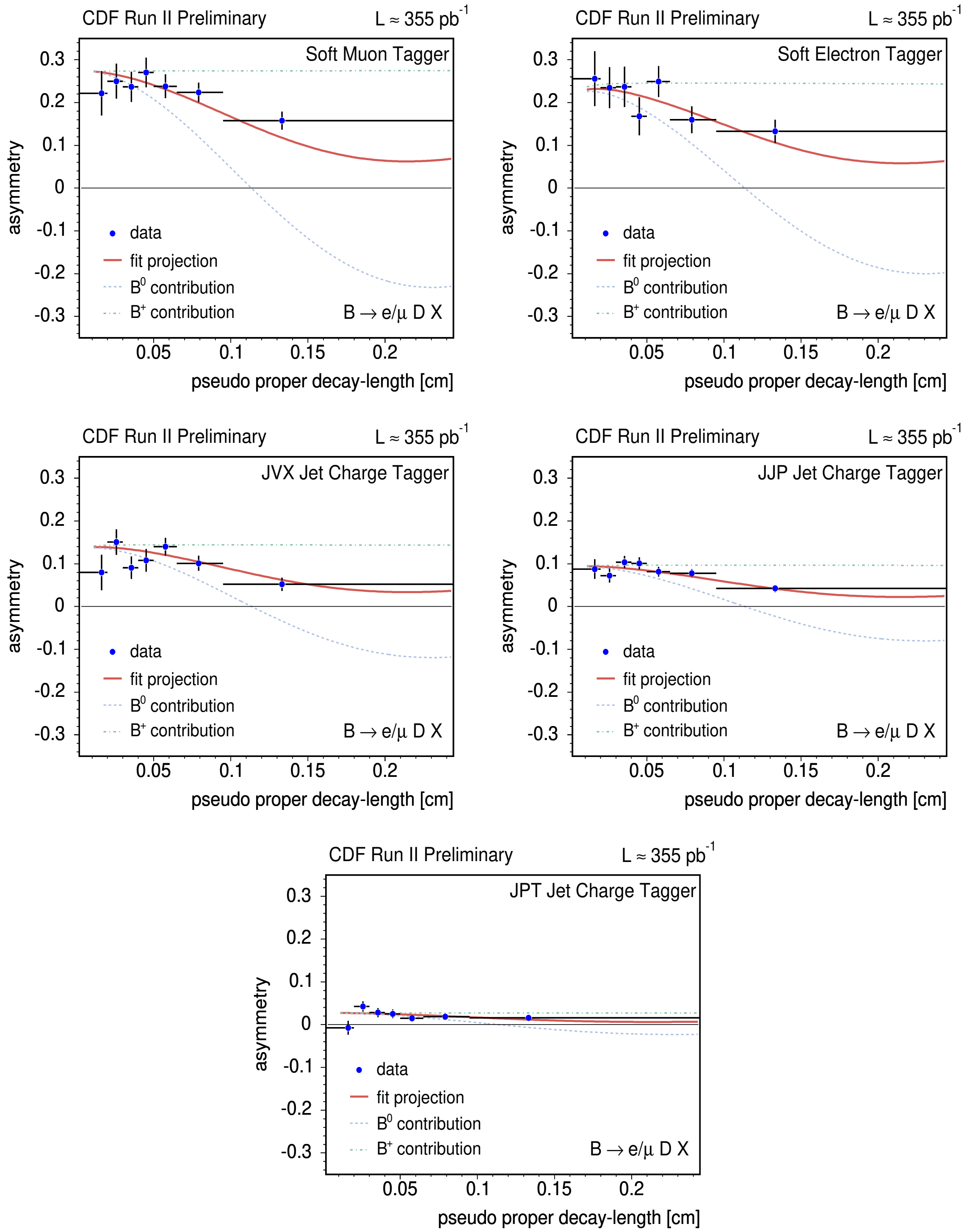

FIG. 5: Asymmetry in ℓDX events and fit projection. From top to bottom, left to right: SMT, SET, JVX, JJP and JPT tagged events.