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Measurement of the Top Quark Mass in the Lepton+Jets channel using the Decay Length Technique

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We present an updated measurement of the top quark mass using the transverse decay length of b-hadrons from top decays. This technique relies solely on tracking and thus avoids the jet energy scale uncertainty that is common to all other methods. We apply our novel method to the lepton+jets sample corresponding to 695 pb^{-1} and extract a measurement of $m_t = 183.9^{+15.7}_{-13.9}\,(stat.) \pm 5.6\,(syst.)$ GeV/c^2. While this is not a competitive measurement of the top quark mass by itself, since the decay length technique is uncorrelated with other methods, this result may help to reduce the overall uncertainty on the top mass in combination with other results.

Preliminary Results

I. INTRODUCTION

In the absence of a direct observation of a Higgs boson, one of the most important measurements that can be made with Run 2 data is a precise determination of the top quark mass. This is because the top quark mass is the dominant uncertainty in global Standard Model fits to the Higgs mass. A precision measurement of the top quark mass constrains the allowed Higgs mass values within the SM. It will tell us where to look before the Higgs is discovered and test whether it is SM or not after a signal has been established. Recently, much progress has been made in reducing the uncertainty in measurements of the top quarks mass. Unfortunately, all currently employed techniques are limited by the same systematic uncertainty, the calorimeter jet energy scale.

We have developed and studied a novel method to measure the top quark mass using the transverse decay length of b-hadrons from top decays [1]. The method exploits the fact that top quarks at the Tevatron are produced nearly at rest. In the rest frame of the top quark, the boost given to the bottom quark as a consequence of the top's decay can be written simply:

$$\gamma_b = \frac{m_t^2 + m_b^2 - m_W^2}{2m_t m_b} \approx 0.4\frac{m_t}{m_b} \tag{1}$$

where the approximation makes use of the fact that $m_t \gg m_b$. The top quark's mass therefore (to the extent that the threshold approximation holds) is strongly correlated with the boost given to the b-quark and the subsequent b-hadron after fragmentation. Thus, the average lifetime of the b-hadrons resultant from top decays can be used to statistically infer the mass of the top quark. In this analysis, rather than measuring the average lifetime, we simply measure the experimentally more accessible average transverse decay length of the b-hadrons, which we denote $\langle L_{xy}\rangle$.

This technique relies on tracking to precisely determine the decay length. It does not use any calorimeter information and thus avoids any jet energy scale uncertainty. We have previously used our novel method to measure the top quark mass using 318 pb^{-1} with the result $m_t = 207.8^{+27.6}_{-22.3}$ $(stat.)$ $\pm$ 6.5 $(syst.)$ GeV/c^2. In this note, we present an updated measurement applying the decay length technique to 695 pb^{-1} CDF data.

II. DATA SAMPLE & EVENT SELECTION

Run 2 of the Tevatron collides protons and anti-protons at a center-of-mass energy of 1.96 TeV. In such collisions, the Standard Model (SM) predicts that pairs of top and anti-top quarks be produced through quark/anti-quark annihilation (85%) and gluon fusion (15%). Top quarks are expected to decay almost exclusively to a W boson and a b quark. When one W decays leptonically, the $t\bar{t}$ event contains a high transverse momentum (p_T) lepton, missing transverse energy from the undetected neutrino and 4 high transverse energy jets, 2 of which originate from b quarks. We use this decay channel to measure the top quark mass using the decay length technique.

This analysis is based on data collected with the CDFII detector [2] between March 2002 and September 2005. The data are collected with an inclusive lepton trigger that requires an electron or muon with E_T >18 GeV (p_T >18 GeV/c for the muon). The total integrated luminosity of this data sample is 695 pb^{-1}. From this inclusive lepton dataset we select events offline with a reconstructed isolated electron E_T (muon p_T) greater than 20 GeV, missing E_T >20 GeV and at least 3 jets with E_T >15 GeV. Finally, we require at least one jet in the event to be "b-tagged" by the reconstruction of a secondary vertex within that jet. In the following, we refer to the dataset selected above as the "tagged lepton+jets" sample.

III. MEASUREMENT OF TRANSVERSE DECAY LENGTH

A. Secondary Vertex Tagging Algorithm

The secondary vertex algorithm (`SecVtx`) used is described in detail in Ref. [3]. This algorithm exploits the relatively long lifetime of b-hadrons in top decays to reconstruct a secondary vertex significantly displaced from the primary interaction. The primary event vertex is reconstructed with a precision of 10-20 μm for $t\bar{t}$ events. Secondary vertex tagging operates on a per-jet basis, where only tracks within the jet cone are considered for each jet in the event. A set of cuts involving the numbers of silicon hits attached to the tracks, the quality of those hits, and the $\chi^2/d.o.f.$ of the final track fit are applied to reject mis-reconstructed tracks. Displaced tracks in the jet are selected based on the significance of their impact parameter (d_0) with respect to the primary vertex and are used as input to the `SecVtx` algorithm. `SecVtx` uses a two pass approach to find secondary vertices. In the first pass it attempts to reconstruct a secondary vertex which includes at least three tracks. If the first pass is unsuccessful, a second pass is attempted which makes tighter track requirements and tries to reconstruct a two track vertex.

Once a secondary vertex is found, the two-dimensional decay length, L_{xy} is calculated as the projection onto the jet axis, in the plane transverse to the beam only, of the vector pointing from the primary vertex to the secondary vertex. The sign of L_{xy} is given by the ϕ difference between the jet axis and the secondary vertex vector (positive if less than 90 deg, negative is greater than 90 deg). The secondary vertices corresponding to the decay of b and c hadrons will have large positive L_{xy}, while the secondary vertices from a random set of mis-measured tracks will be peaked around $L_{xy} = 0$. A jet is said to be positively tagged if $L_{xy}/\sigma_{L_{xy}} > 3$ and negatively tagged if $L_{xy}/\sigma_{L_{xy}} < -3$. Positively tagged jets have a high purity of heavy flavor jets and are identified as such, while negatively tagged jets are mostly light quark jets.

B. Simulation of L_{xy}

This analysis requires an accurate simulation of L_{xy}. To check the accuracy of the CDF II simulation we examine heavy-flavor enriched data samples. We use dijet data samples recorded on an 8 GeV electron(muon) trigger path. We compare these to `Herwig` [4] dijet Monte Carlo samples. To increase the $b\bar{b}$ purity of these samples we require that the lepton that triggered the event be contained within a jet that is also positively tagged by `SecVtx`. We also require there to be another jet, at least 2.0 radians away in azimuth, that is also positively tagged. Finally, we we require the secondary vertex mass of the tagged jets to be greater than 1.5 GeV/c^2. With the essentially triple-tagged (two vertex plus one soft-lepton) selection, a purity of $\sim 99\%$ $b\bar{b}$ is obtained. For all events passing the selection criteria, we histogram the L_{xy} for all positive tags. These histograms are plotted, in linear and log scales, with data and MC overlaid in Figures 1 and 2. Visually, we can see the simulation seems to model L_{xy} very well. We quantify this agreement by comparing the mean L_{xy} for both data and MC. We find the following:

$$\langle L_{xy}^{data} \rangle = 0.378 \pm 002 \ cm \tag{2}$$

$$\langle L_{xy}^{MC} \rangle = 0.381 \pm 0.004 \ cm \tag{3}$$

From these, we compute a data/MC scale-factor to be applied to the mean L_{xy} obtained from the MC:

$$SF_{L_{xy}} = 0.992 \pm 0.012 \tag{4}$$

From this, we conclude that our simulation models the transverse decay length of b-hadrons with sufficient accuracy. We do, however, take the 1.2% uncertainty on the central value as a systematic uncertainty. Note that this ratio encompasses many different possible sources of discrepancy between our data and our MC simulation such as detector resolution effects, fragmentation effects, and b-hadron lifetime effects.

IV. BACKGROUNDS

The tagged lepton+jets sample selected as described above has an expected signal-to-background ratio of about 2.5:1. The dominant background is QCD production of W-boson plus multijet events. These events enter the signal sample when either one of the jets is a b-jet or c-jet, or a light quark jet that has been mis-tagged as containing a second vertex. The other substantial background in this analysis comes from events without W bosons. These events are typically QCD dijet events where one jet has faked a high-P$_T$ lepton and mismeasured energies produce apparent missing E$_T$. Additionally, other processes such as $WW, WZ, ZZ, Z \rightarrow \tau\tau$ and single-top contribute small amounts to the tagged lepton+jet sample. The estimated background contributions for each of the above sources are summarized as a function of jet multiplicity in Table I.

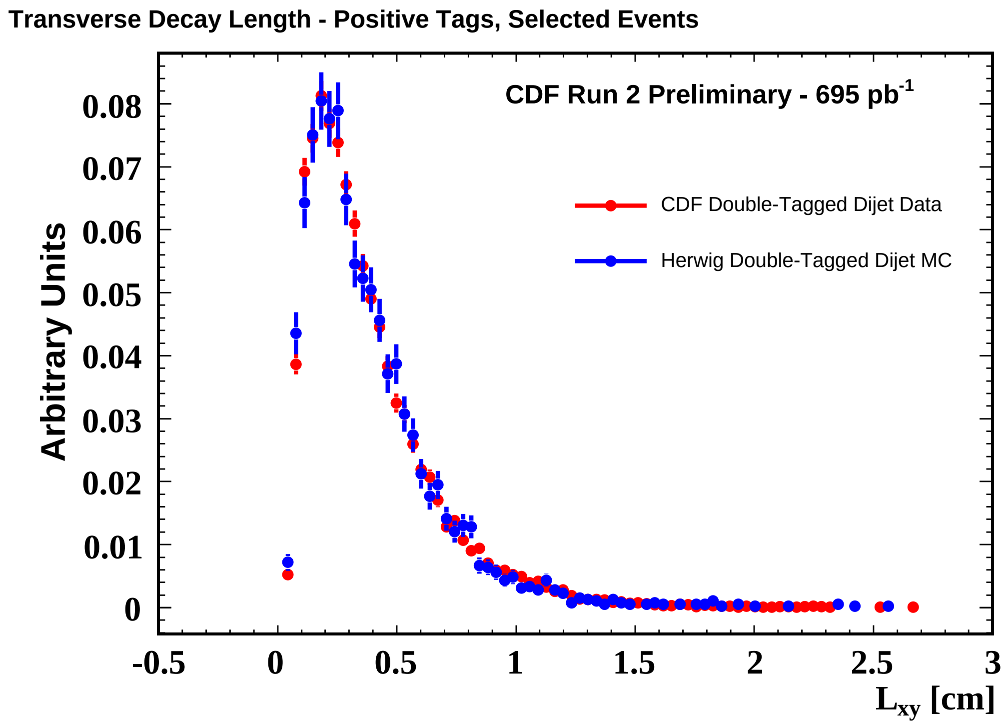

FIG. 1: Comparison of L_{xy} of positive tags in double-tagged events with an identified electron or muon in one of the two tagged jets. 8 Gev lepton data and dijet MC are compared. Both the lepton tag and the away tag are included.

Bkg. Source	Est. Num. Evts (3 jets)	Est. Num. Evts ($\geq$ 4 jets)
Wbb	23.4 ± 6.1	4.5 ± 1.3
$Wc\bar{c}$	10.1 ± 3.1	2.1 ± 0.7
Wc	6.5 ± 1.6	0.4 ± 0.1
QCD	7.8 ± 2.4	4.7 ± 1.0
Mistags	32.9 ± 3.7	8.0 ± 0.9
$WW, WZ, ZZ, Z \to \tau\tau$	4.6 ± 1.0	1.1 ± 0.3
Single top	4.5 ± 0.5	0.8 ± 0.1
Total	90.0 ± 10.7	21.6 ± 2.4

TABLE I: Backgrounds sources and their estimated contributions to the tagged lepton+jets sample with 3 and 4 or more jets.

V. EXPECTED L_{xy} DISTRIBUTIONS - SIGNAL AND BACKGROUND

We produce `Herwig` $t\bar{t}$ Monte Carlo samples with top quark masses ranging from 130-230 GeV in 5 GeV intervals. We subject these simulated events to the identical event selection as that required of the data. After selection, the transverse decay lengths of all positive tags are histogrammed in order to obtain L_{xy} distributions for each mass point. A similar process is performed for each of the backgrounds described above. We use `Alpgen + Herwig` $Wb\bar{b}$ + parton, $Wc\bar{c}$ + parton, and Wc + parton Monte Carlo to model the L_{xy} distributions for the W + heavy-flavor backgrounds. Similiarly, we use `Alpgen + Herwig` W + parton Monte Carlo to model the L_{xy} distribution from the W + mistag background. For the purpose of this analysis, diboson events are considered mistags and the mistag L_{xy} distribution obtained above is used to model their small contribution. The non-W (QCD) background L_{xy} distribution is obtained directly from CDF data. We select events with identical criteria as that for the signal sample, save the requirement that the lepton be calorimetrically isolated where instead we explicitly require the lepton be non-isolated. For many top analyses, single top is a background to the pair-produced signal. With the decay length technique, however, this is not the case. Although the correlation is not quite as strong as for pair-produced tops [?] the mean L_{xy} from b-hadrons from single top decays is also correlated with the top quarks mass. We use `Pythia` [5] Monte Carlo to model the single-top L_{xy} distribution.

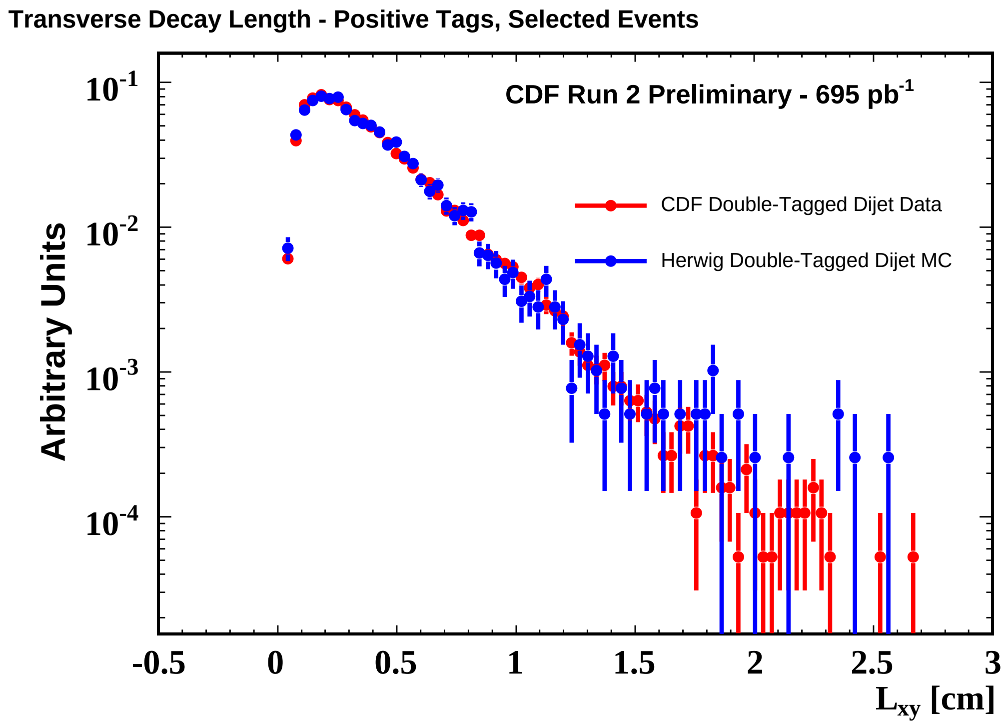

FIG. 2: Log-scale comparison of L_{xy} of positive tags in double-tagged events with an identified electron or muon in one of the two tagged jets. 8 Gev lepton data and dijet MC are compared. Both the lepton tag and the away tag are included.

A. Check Backgrounds Shapes with Data in W+1,2 jet events

As a cross-check on the modeling of L_{xy} distributions for the various background processes, we examine the data in the background dominated 1 and 2 jet events in the W+jet sample. The L_{xy} distribution of positive tags in selected events from the one and two jet bins is plotted together with expected contributions from background MC overlaid in Figure 3. Reasonable agreement between MC and data is observed - a K.S. probability of 32.1% is found. *N.B.* To facilitate the shape comparison, the MC is normalized to the observed data.

VI. MEASUREMENT METHOD

The signal and background L_{xy} distributions described in the previous section are treated as probability density functions from which ensembles of pseudo-experiments are formed. In forming each ensemble, the number of events are obtained by separately Poisson fluctuating the signal and each background about their expected contributions. The number of events for each process is converted to a number of tags by multiplying by the double-tag probability for that process. This procedure is repeated 1,000 times for each mass point over the full mass range 130-230 GeV. The mean L_{xy} that results from each pseudo-experiment is histogrammed from which the mean and $\pm 1\sigma$ variance are extracted as a function of mass. These points are fit to third degree polynomials. The fit to the mean establishes the most probable value for a true top mass given a measured mean L_{xy} and is the function that will be used to make the top mass measurement from the measured L_{xy} extracted from data. Similarly, the fits to the variance form $\pm 1\sigma$ Neyman confidence intervals which will be used to give the statistical uncertainty of the measurement.

VII. ESTIMATES OF SYSTEMATIC UNCERTAINTIES

Systematic uncertainties for this measurement can be classified according to three types of sources. The first arise from the accuracy of modelling of factors that affect the top (or subsequent bottom) quark's momentum such as radiation, fragmentation, and PDFs. These uncertainties are estimated by varying the relevant parameters in the

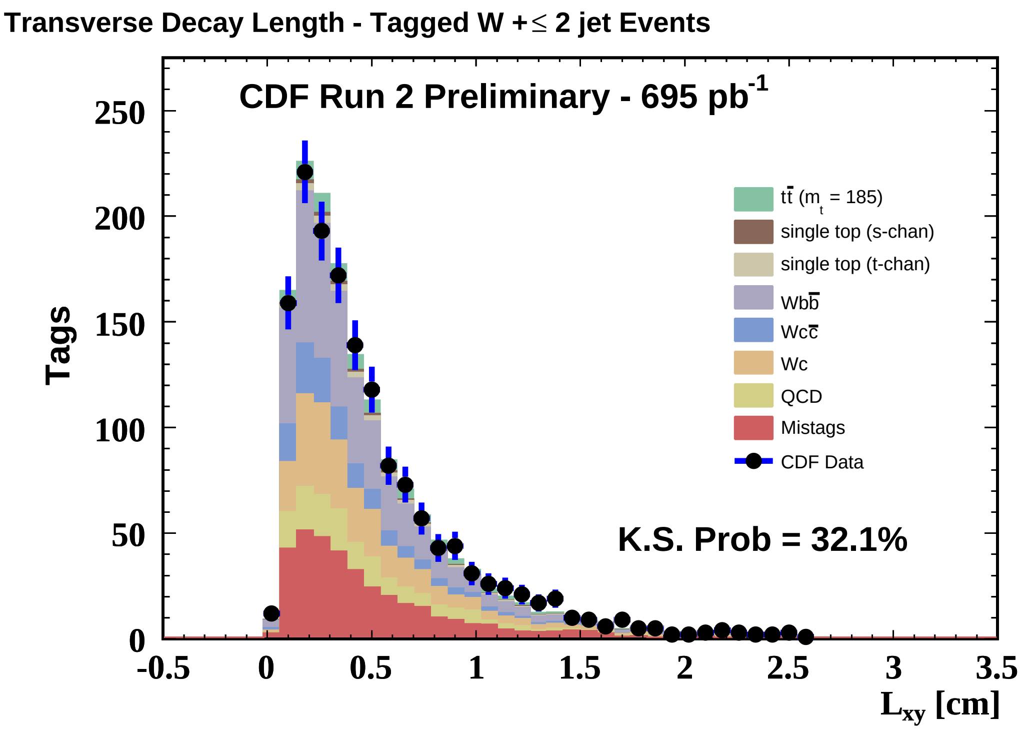

FIG. 3: Black points are the L_{xy} distribution of positive tags in selected events with 1 or 2 jets, for which little or no top contribution is expected. Expected contributions from background MC are overlaid in the solid stacked histogram. *N*.B. To facilitate the shape comparison, the MC is normalized to the observed data.

Monte Carlo and measuring the affect on the mean L_{xy}. The second type of systematic uncertainty comes potential inaccuracies in the size or shape of background L_{xy} distributions. We estimate these affects by varying the expected background contributions within their uncertainty and comparing the shapes to control samples from data. The final type of systematic uncertainty arises from imperfections of detector simulation of L_{xy} (or other experimentally indistinguishable disagreements between Monte Carlo and data such as could arise from, for example, imprecise knowledge of b-hadron lifetimes). This uncertainty is taken as the error on the mean L_{xy} data/MC ratio as discussed above. Table II lists each of the sources of systematic error and their corresponding uncertainties.

A total systematic uncertainty of 5.6 GeV is assigned to the current measurement. Note that this uncertainty is small when compared to the current statistical uncertainty of the measurement. Note also that one of the largest components of systematic error concerns the background shapes and normalization. These are as large as they in part due to the fact that sample purity has been sacrificed in an attempt to minimize the largest uncertainty associated with the measurement, i.e. that due to the limited statistics of the sample. As the data sample grows and statistical uncertainty is reduced to the level of the current systematics, one can add additional cuts to improve sample purity and proportionately decrease the significance of background related systematic uncertainties. Finally, note that the largest systematic arises from the limited Monte Carlo statistics used to derive the mean L_{xy} data/MC ratio.

VIII. RESULTS

From 456 positive `SECVTX` tags in 375 events in the lepton+jets sample corresponding to 695 pb^{-1} we measure:

$$\langle L_{xy} \rangle = 0.5808 \ \pm 0.0227 \ cm \tag{5}$$

With this value, we draw a vertical line on the most-probable value and confidence interval curves obtained above as illustrated in Figure 4 and extract a measurement of:

$$m_t = 183.9^{+15.7}_{-13.9} \ (stat.) \ \pm \ 5.6 \ (syst.) \ GeV/c^2. \tag{6}$$

The L_{xy} distribution of positive tags in selected events from which mean transverse decay length used to measure top mass is extracted is plotted together with expected contributions from signal and background MC overlaid in

Source of Systematic Error	Uncertainty (GeV)
Generator/Fragmentation	0.7
ISR	1.0
FSR	0.9
PDF	0.5
Jet Energy Scale	0.3
Background Shape	2.3
Background Normalization	2.3
Multiple Interactions	0.2
Data/MC $\langle L_{xy} \rangle$ SF	4.2
Total	5.6

TABLE II: Summary of sources of systematic error and their estimated uncertainties

Figure 5. *N*.B. To facilitate the shape comparison, the MC is normalized to the observed data. Reasonable agreement between data and MC is observed - a K.S. probability of 3.8% is found.

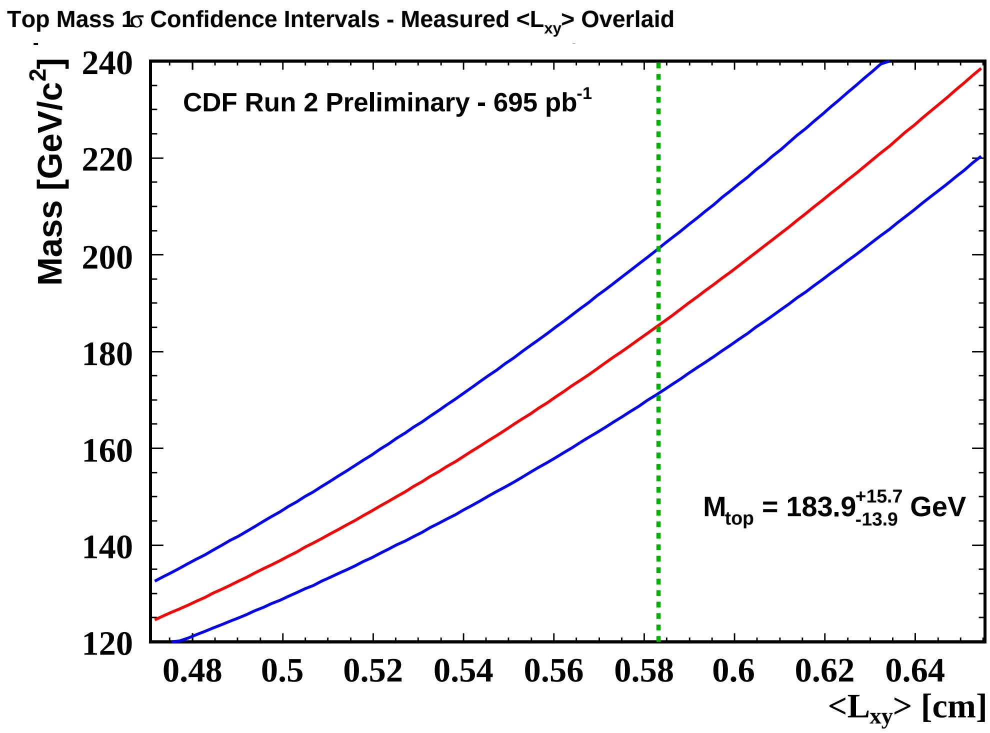

FIG. 4: Most-probable (red) and 1σ (blue) m_t curves as a function of mean transverse decay length. Measured mean transverse decay length is overlaid as green dashed line.

A. Comments on the Result

Here, we examine the likelihood of obtaining this result if the true top mass is, for example, 175 GeV. This question is addressed by looking at our 175 GeV pseudo-experiments, discussed previously. We plot the mean transverse decay length resultant from these pseudo-experiments and overlay the result measured in CDF data in Figure 6. The probability of obtaining a result with equal (or greater) discrepancy from the mean transverse decay length corresponding to that resultant from pseudo-experiments generated with a top mass of 175 GeV is found to be 34%.

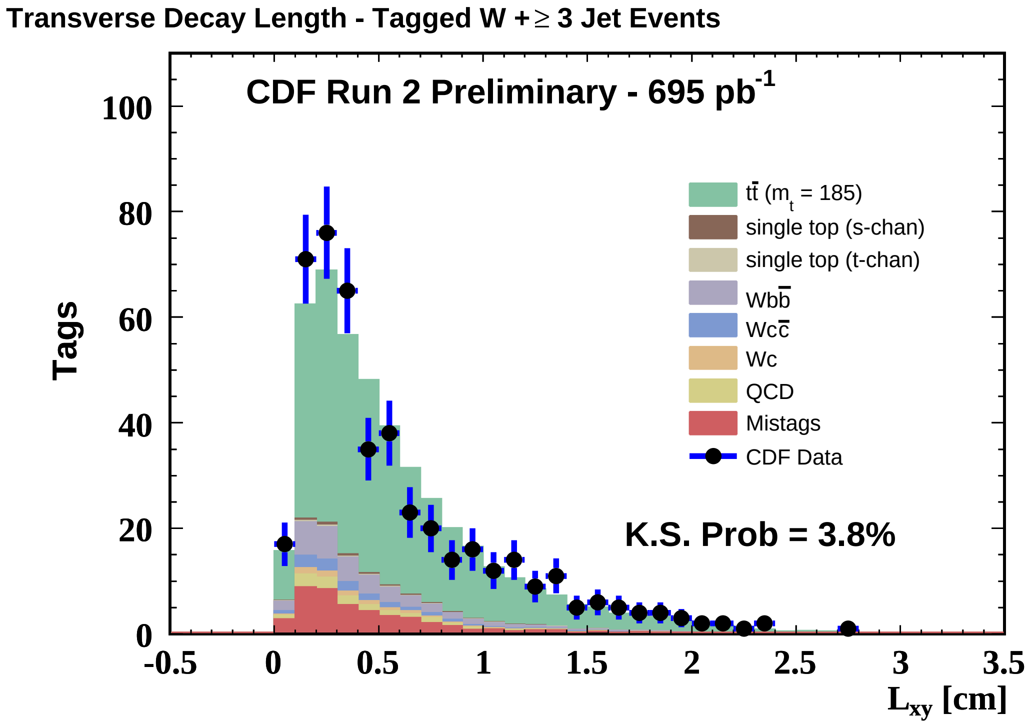

FIG. 5: Black points are the L_{xy} distribution of positive tags in selected events from which mean transverse decay length used to measure top mass is extracted. Expected contributions from signal and background MC are overlaid in the solid stacked histogram. *N*.B. To facilitate the shape comparison, the MC is normalized to the observed data.

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[5] T. Sjostrand et al., High-Energy-Physics Event Generation with PYTHIA 6.1, Comput. Phys. Commun. **135**, 238 (2001).
[] This difference comes from the t-channel production mechanism which is responsible for $\sim 2/3$ of the single-top yield.

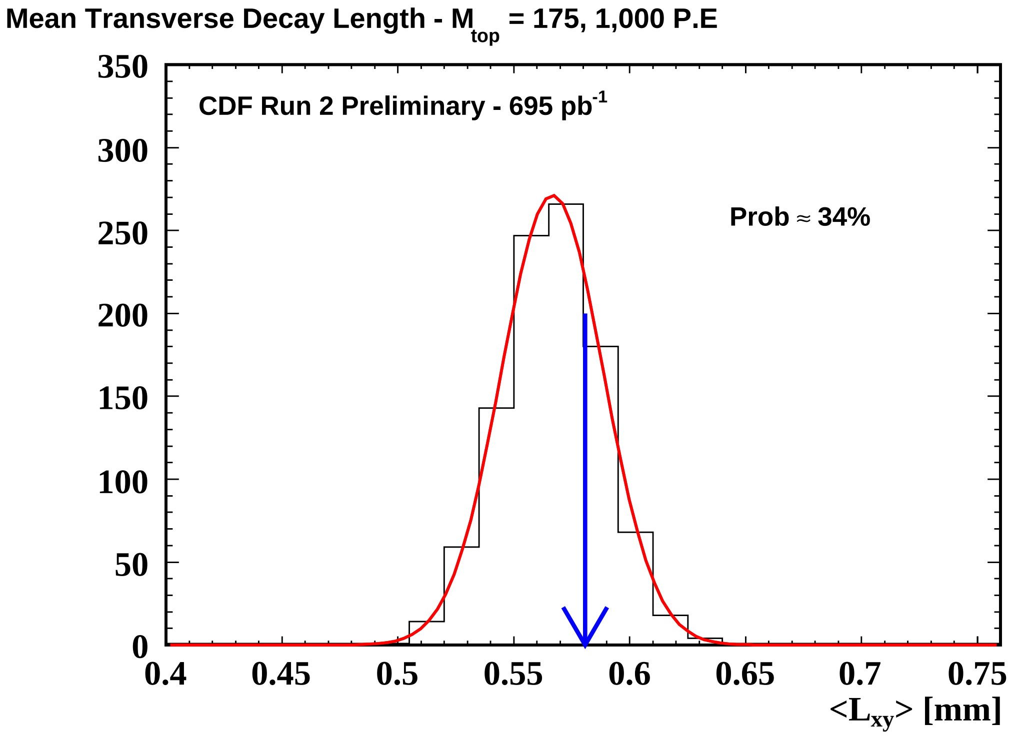

FIG. 6: The mean transverse decay length resultant from pseudo-experiments generated with a top mass of 175 GeV, with the value for the mean decay length observed in CDF indicated by the blue arrow. From this distribution, the probability of obtaining a result with equal (or greater) discrepancy from the mean transverse decay length corresponding to 175 GeV is found to be 34%.