CDF Note 7702

Search for anomalous semileptonic decays in jets produced in association with a W boson

The CDF Collaboration
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Abstract

We present a search for anomalous semileptonic decays in jets produced in association with a W boson, in proton-antiproton collisions at $\sqrt{s}$=1.96 TeV. The dataset of 162$\pm$10 pb^{-1} was collected with the CDF II detector at the Fermilab Tevatron Collider. We select events with one W boson and at least one jet consistent with the fragmentation of a heavy quark (b, c) undergoing a semileptonic decay to muon. We compare the observed events and their kinematic properties with the expectation based on standard model production and decay of W plus heavy flavor jets. No discrepancy is seen between the observed events and the expectation.

Preliminary Results for Summer 2005 Conferences

I. INTRODUCTION

The observation of anomalous semileptonic decay is predicted by some theories of physics beyond the standard model (SM) [1, 2]. A light scalar bottom quark could, for instance, enhance the semileptonic branching ratio of observed B decays. In this scenario, the decay of supersymmetric $\tilde{B}$ mesons, characterized by leptons and charmed mesons $\tilde{B} \to \ell^- \ \tilde{\nu} \ D \ X$ or $\tilde{B} \to \ell^- \ D \ X$ (where $\tilde{\nu}$ indicates a scalar neutrino and X labels possible additional conventional hadrons), would have much in common with conventional B decays. An excess of semileptonic decays in the exclusive W boson plus jets spectrum was observed at CDF during Run I of the Tevatron Collider [3], but the excess was not statistically significant enough to establish a signal. The CLEO Collaboration has searched for such an excess in B decays just below the $e^+e^- \to B\bar{B}$ threshold, finding no indication of a supersymmetric $\tilde{B}$ meson in the mass range $3.5-4.5$ GeV/c^2 [4]. The DØ Collaboration has also recently reported on a search for excess of $Wb\bar{b}$ production using semileptonic decays [5], setting an upper limit of 26 pb on the production of a non-SM $Wb\bar{b}$-like process and 14 pb on the production of a non-SM Top-like process.

We present a study of the W boson plus jets data set, produced in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV during Run II of the Fermilab Tevatron, and collected by the CDF II detector. We search for B meson decay in jets selected by a lifetime algorithm (SecVtx) [6], which identifies b-jets from their displaced secondary vertexes. Semileptonic B meson decay to muon is identified using the SLT algorithm [7], which searches for muons with transverse momentum $p_T > 3$ GeV/c within jets of particles. At the Tevatron, the primary SM contributions to W plus a heavy flavor quark in the final state arise from the production of W$b\bar{b}$, $Wc\bar{c}$, Wc and $t\bar{t}$, with small contributions also from WZ (with $Z \to b\bar{b}, c\bar{c}$) and single top quark production. We identify the W boson by its decay to an electron or muon, both of which are relatively isolated and carry large transverse momentum, plus a neutrino. We refer to these high p_T electrons or muons as "primary leptons". The neutrino escapes the detector and results in an imbalance of total transverse energy, referred to as "missing E_T "($\not\!\!E_T$). Quarks produced in association with the W hadronize and are observed as jets of charged and neutral particles. The dominant background is due to QCD production of multijets, where one of the jets is identified as the primary lepton, and there is large $\not\!\!E_T$ in the event which emulates the presence of a neutrino. Moreover, one of the jets must contain a heavy flavor quark or be misidentified as containing one. Other background sources arise from $Zb\bar{b}$, $Zc\bar{c}$, WW, ZZ and $Z \to \tau\tau$ events. Starting from the composition of the W+jets sample with at least one jet tagged by the SecVtx algorithm, we determine the efficiency of additionally tagging the same jet with the SLT algorithm. The efficiencies are measured from a combination of data and Monte Carlo simulation of the SM processes. We then compare the number of events observed with a SecVtx-SLT double tag in at least one jet, with the expectation in each exclusive W plus jet multiplicity count. Because the number of events *observed* after SecVtx tagging is used to calculate the expectation, we effectively compare the semileptonic branching ratio of the SM processes with the observation, without explicitly introducing the theory cross section of the SM contributions themselves, some of which, like $Wb\bar{b}$, may have large theoretical uncertainties.

II. THE CDF II DETECTOR

The CDF II detector is described in detail elsewhere [8]. The components used in this analysis include the silicon vertex detector (SVX), the central outer tracker (COT), the central electromagnetic and hadronic calorimeter and the central muon detectors. The SVX is a five layer double-sided silicon microstrip detector, providing charged particle tracking information in the pseudorapidity [9] range $|\eta| \leq 2.0$. The COT is an open cell drift chamber providing track measurements for $|\eta| \leq 1.0$ and is contained, together with the SVX, in a 1.4 T magnetic field aligned coaxially with the $p\bar{p}$ beams. The electromagnetic calorimeter is a lead-scintillator sandwich and the hadronic calorimeter is an iron-scintillator sandwich. The central muon detector comprises a four layers drift chambers covering $|\eta| < 0.6$ (CMU), followed by additional 60 cm of steel and four more layers of muon drift chambers (CMP). The central muon extension (CMX) system provides muon detection in the region $0.6 < |\eta| < 1.0$ with four to eight layers of drift chambers.

III. DATA SAMPLE AND EVENT SELECTION

This analysis is based on an integrated luminosity of 162$\pm$10 pb^{-1} (150$\pm$9 pb^{-1} with the CMX detector operational) collected with the CDF II detector between March 2002 and August 2003. The triggers for events with a candidate W boson are based on selecting high transverse momentum electrons and muons. CDF employs a three-level trigger that uses progressively refined particle momentum and energy information. At the third level, muons (electrons) are required to have a minimum p_T (E_T) of 18 GeV/c. Monte Carlo simulations are performed using PYTHIA v6.2 [10] and HERWIG v6.4 [11, 12], coupled with CTEQ5L parton distribution functions [13]. Proper modeling of b and c hadron decay is provided by QQ v9.1 [14]. Diboson and W plus heavy flavor production is modeled with ALPGEN [15].

A detailed description of the event selection is given in [6]. Differences specific to this analysis are due mainly to the reprocessing of the muon track-segment reconstruction and matching using the latest available offline software, and the introduction of muon fiducial requirements for the primary muon, as done in [7]. Candidate electrons from W decay must have a EM cluster with $E_T > 20$ GeV associated to a track with $p_T > 10$ GeV/c. The cluster is required to have the electromagnetic to hadronic fraction and shower shape compatible with an electron deposit. Candidate muons must pass a minimum $p_T > 20$ GeV/c selection requirement, have a track segment in the muon chambers that matches the extrapolated COT track, and leave in the calorimeter an energy consistent with the deposition expected from a minimum ionizing particle. Since leptons from W decay are expected to be relatively isolated from other energy deposits, the calorimeter transverse energy in a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ around the lepton (not including the lepton energy itself) divided by the E_T (p_T) of the lepton is required to be less than 0.1. The event must also pass a minimum $\not\!\!E_T > 20$ GeV, consistent with the presence of a neutrino from the W boson decay. Finally, the W+jets dataset is categorized according to the number of jets in the event with $E_T > 15$ GeV and $|\eta| < 2.0$. Jets are identified using a fixed-cone algorithm with a cone opening of 0.4 and are constrained to originate from the $p\bar{p}$ collision vertex. The jet energies are corrected to account for variations of the detector response in η, calorimeter gain instability and event multiple interactions.

A. The SecVtx Algorithm

We use the SecVtx algorithm to identify jets originating from heavy-quark (b, c) fragmentation. The SecVtx algorithm relies on the displacement of secondary vertexes relative to the primary vertex. The algorithm selects an event-by-event primary vertex nearest to the identified primary electron or muon from the W decay. The search for a secondary vertex is performed on a per-jet basis and leads to the calculation of the two dimensional decay length L_{2D} [16]. Secondary vertexes corresponding to the decay of heavy flavor hadrons are expected to have large positive L_{2D} (positive tag). The average efficiency for tagging b-jets is a function of the jet E_T and ranges from about 20% for softer jets ($E_T \simeq 20$ GeV) to around 40% for jets with E_T above 40 GeV. The efficiency and geometrical acceptance of the algorithm is estimated with Monte Carlo simulation, with the overall normalization determined from the data. A sample of dijets events enhanced in heavy flavor b decay is compared to a simulation of $2 \rightarrow 2$ parton events, and yields the data to Monte Carlo absolute normalization scale factor of 0.82$\pm$0.06.

B. W+jets events with a SecVtx tagged jet

Table I shows the number of events that pass all our selection requirements with at least one jet tagged by the SecVtx. In the three or more jets multiplicity case, events are listed with and without requiring high total transverse energy (H_T). H_T is defined as the scalar sum of the electron E_T or

Table I: Total number of W+jets events with at least one positive SecVtx tagged jet observed in the dataset, and the estimated sample composition according to the SM contributions.

Jet multiplicity:	W+1 jet	W+2 jets	$W+\geq 3$ jets ($H_T > 0$ GeV)	$W+\geq 3$ jets ($H_T > 200$ GeV)
Data observation	157	70	59	50
Estimated sample composition				
Wbb	37.0±11.2	19.6±5.7	6.02±1.64	3.29±0.90
$Wc\bar{c}$	13.7±3.4	7.0±1.9	2.01±0.60	1.10±0.33
Wc	34.5±9.0	6.7±1.7	1.55±0.40	0.78±0.23
$Zb\bar{b}$	0.7±0.2	0.3±0.1	0.09±0.09	0.04±0.04
$Zc\bar{c}$	0.4±0.1	0.3±0.1	0.09±0.09	0.04±0.04
WW	0.6±0.1	1.0±0.2	0.41±0.06	0.13±0.02
WZ	0.5±0.1	1.0±0.2	0.31±0.03	0.13±0.01
ZZ	0.0±0.0	0.1±0.0	0.00±0.00	0.10±0.01
$Z \rightarrow \tau\tau$	1.1±0.2	0.1±0.1	0.00±0.00	0.00±0.00
QCD	24.3±3.5	9.1±1.7	4.97±1.14	3.02±0.73
Mistags	40.8±6.1	14.8±2.1	7.11±0.85	4.39±0.53
Single t (s channel)	0.6±0.1	1.8±0.2	0.72±0.10	0.52±0.10
Single t (t channel)	2.0±0.2	2.2±0.3	0.62±0.10	0.52±0.10
$t\bar{t}$	0.9±0.1	6.1±0.5	35.09±3.11	35.94±1.88
Total	157.0	70.0	59.00	50.00

muon p_T, the event $\not\!\!E_T$ and jet E_T for jets with $E_T > 8$ GeV and $|\eta| < 2.4$. Large H_T is often used to enhance the $t\bar{t}$ contribution in samples with high jet multiplicity, since the large mass of the top quark causes H_T to be higher, on average, than in W+jets events.

With respect to the observed SecVtx-tagged events of Table I, we determine the sample composition as follows. We start from the sample composition already accurately estimated in [6], which uses the techniques broadly outlined below for convenience. SecVtx mistags, i.e. jets that have a SecVtx secondary vertex and yet do not result from the fragmentation of a heavy quark, are estimated from the data using the negative L_{2D} tags as a model. W+heavy flavor events are estimated using the heavy flavor fractions, defined as the ratio of the observed W+heavy flavor and W+jets cross sections, multiplied by the number of W+jets events in the data before tagging and by the efficiency of the SecVtx algorithm. The fraction of W+heavy flavor production is calculated with a matrix elements Monte Carlo simulation, since the relative contribution of the important diagrams is well defined. Notice that being the absolute normalization linked to the W+jets data, any non-SM contribution would be at least partially hidden in the expected number of tagged events, but could be highlighted from the measurement of the semileptonic branching fraction. The QCD background is determined from data using selection requirements that reject the W+jets signal, and then extrapolating the observed distribution of QCD events into the signal kinematic region. The remaining SM contributions are estimated using Monte Carlo simulations, and the $t\bar{t}$ production cross section is measured in $W+\geq 3$ jets by subtracting all the SM backgrounds to the total observed events. Likewise, the $t\bar{t}$ contribution to our sample is the difference between the observed number of events in $W+\geq 3$ jets and the total SM expectation, excluding $t\bar{t}$ itself. The corresponding measured $t\bar{t}$ cross section is 5.3±1.4 pb for $H_T > 0$ GeV (5.6±1.4 pb for $H_T > 200$ GeV). The small component from $t\bar{t}$ in the W+1,2 jets multiplicity is calculated using the expected ratio of reconstructed $t\bar{t}$ events in $W+\geq 3$ jets, to W+1 and W+2 jets. The ratio is $R_{3\rightarrow 1} = 0.027$ and $R_{3\rightarrow 2} = 0.207$ respectively and is estimated with a $t\bar{t}$ Monte Carlo simulation. Finally, we scale the overall composition of [6], expressed in terms of expected tagged events, proportionally to the observed number of tagged events in this analysis. The scaling between expected and observed events is less than a few percent across different jet multiplicity. The breakdown of the sample composition of the W+jets events, with at least one SecVtx tagged jet, is summarized in Table I. The sum of the components is equal to the observed events by construction.

C. The SLT Algorithm

The SLT is used to search for muons from semileptonic heavy flavor decay within SecVtx tagged jets. The SLT algorithm constructs a single χ^2 variable (L) from the three muon detectors (CMU, CMUP, CMX) based on matching between the track position, extrapolated from the COT to the muon chambers, and the track segments measured by the muon systems. Matching at the muon chambers depends upon muon multiple scattering and, at high p_T, intrinsic resolution of the drift chambers. The quantity L is constructed using parametrization of the matching resolutions directly measured from data. Muons with $p_T > 3$ GeV/c are detected with average efficiency of $\sim$85% and are required to be within $\Delta R < 0.6$ of a jet axis. Moreover, the z-coordinate of the track at the origin must be within 5 cm of the reconstructed event vertex. Background is preferentially rejected because on average the match between the extrapolated track and the muon-chamber track segment is worse. Candidate tracks are identified as muons if $|L| < 3.5$ (SLT tag). The "fake"probability, i.e. the probability that the algorithm misidentifies a hadron as a muon, is measured from data using a sample of photon plus jets events. The number of fakes is counted on a per-track basis for jets with $E_T > 15$ GeV, and a probability matrix is constructed as a function of the track p_T, η and ϕ. The number of tags predicted with such technique agrees to within 10% of the observation in a variety of samples, including generic jets and Z+jets. A contribution of $F_{HF} = 21.0 \pm 1.4\%$ of the tags in γ+jets is seen coming from genuine heavy flavor fragmentation, hence subtracted from all fake predictions based on the probability matrix.

D. W+jets events with a SecVtx-SLT double tagged jet

We estimate the expected number of events with double tagged jets by multiplying the contributions in Table I for the efficiency of tagging with the SLT algorithm a heavy flavor jet already tagged by the SecVtx. The efficiency depends primarily on the semileptonic branching ratio, $B \to \ell\ \nu\ X$, and the muon minimum p_T of 3 GeV/c, but it is also affected by the SLT algorithm overall efficiency and correlations with the selected jets. An example of correlation is between the minimum energy requirement on the jets ($E_T > 15$ GeV), and the presence of a minimum ionizing particle such as a muon. Muon energy is largely not collected by the calorimeters, and consequently the energy of the jets is measured low. The effect is properly modeled in the simulation. Since the efficiency depends on kinematic properties of the jets and muons, it is therefore specific to jets from different physics processes.

1. Efficiency of the SLT algorithm on SecVtx tagged jets

For $Wb\bar{b}$, $Wc\bar{c}$, $t\bar{t}$, single t, diboson events and $Z \to \tau\tau$ the efficiencies are determined from Monte Carlo simulation and shown in Table II, for different jet multiplicity. In simulating the SLT algorithm, we use both the efficiency of tagging a muon, measured from data and applied to muons in the jets, and the probability of tagging a jet with a mistag, using the mistag probability matrix. As a cross check of the prediction of SLT-SecVtx double tags in W+jets events, we apply the same procedure to a sample of events triggered on 8 GeV electrons or muons. The events are selected by requiring two back-to-back jets, one of which contains the trigger lepton, and both with a positive SecVtx tag. The selection yields a highly pure ($\sim$ 95%) $b\bar{b}$ sample, plus $\sim$ 5% $c\bar{c}$ events. We simulate the sample with dijets, using the HERWIG generator, and measure the SLT efficiency in the jet opposite the trigger lepton. The efficiency is applied to the data to estimate the number of SLT-SecVtx double tagged jets and a comparison is made with the number of observed double tagged jets. The

Table II: Efficiencies (in %) of tagging with the SLT algorithm a jet already tagged by the SecVtx algorithm.

Jet multiplicity:	W+1 jet	W+2 jets	$W+\geq 3$ jets ($H_T > 0$ GeV)	$W+\geq 3$ jets ($H_T > 200$ GeV)
Wbb, Zbb	7.1±0.6	8.0±0.7	7.8±1.0	8.2±1.1
$Wc\bar{c}$, Wc, $Zc\bar{c}$	4.4±0.5	3.9±0.4	4.1±0.7	4.4±0.8
WW	2.7±0.7	3.3±0.6	3.3±1.0	4.1±1.4
WZ	4.3±1.7	8.3±2.1	5.7±2.6	8.0±4.4
ZZ	16.4±7.3	8.3±3.6	5.9±3.5	8.3±5.7
$Z \to \tau\tau$	5.0±5.5	0.0±0.0	0.0±0.0	0.0±0.0
QCD	11.0±2.0	11.0±2.0	11.0±2.0	11.0±2.0
Mistags	1.7±0.2	1.4±0.2	1.2±0.1	1.0±0.1
Single t (s-channel)	7.8±1.2	9.8±1.1	9.3±1.3	9.1±1.3
Single t (t-channel)	7.2±1.0	7.2±0.9	6.8±1.3	6.5±1.4
$t\bar{t}$	12.3±1.4	11.2±1.1	10.1±0.9	10.0±1.0

observation agrees with the prediction to within 10%. The efficiency for the QCD component is estimated directly from data. We require anti isolation on the primary lepton, $I > 0.15$, in order to preferentially select QCD events. We maintain the high $\not\!\!E_T$ requirement, since this is correlated with the presence of muons and mistags. High $\not\!\!E_T$ can appear in generic jets events if a jet is pointing towards one of the non instrumented regions of the calorimeter. These typically correspond also to gaps in the absorber material where hadrons can escape through, reaching the muon chambers and being identified as muons. In the sample selected with anti isolation, jets separated from the primary lepton are tagged with the SecVtx and we measure the SLT tagging rate in those jets of 11±2%. The rate is independent of the jet multiplicity, the primary lepton's flavor (electron or muon) and isolation, for $I > 0.15$, while it increases with higher $\not\!\!E_T$. Finally, the probability of tagging with the SLT a light flavor jet that has been mistagged by the SecVtx algorithm (labeled "Mistags" in Table II) is determined using the track multiplicity of jets with negative L_{2D} in W+jets MC, weighted by the SLT mistag probability matrix.

To understand in more detail the efficiency of tagging with the SLT a SecVtx tagged jet it is useful to compare the four most important contributions of Tables I and II: $Wb\bar{b}$, $Wc\bar{c}$, QCD and $t\bar{t}$. The semileptonic branching ratio $B \to \ell\ \nu\ X$, including sequential decays, is $\simeq 20\%$ but only a smaller fraction of jets will pass the jet energy threshold of 15 GeV, depending on the boost of the heavy quark in the decay. In other words, the branching ratio as a function of the observed jet energy is skewed towards the lower end of the spectrum. The muon momentum requirement $p_T > 3$ GeV/c and the intrinsic efficiency of the SLT algorithm lead to an overall efficiency of $\simeq 7.5\%$ for jets in $Wb\bar{b}$ events. Semileptonic decay from $Wc\bar{c}$, Wc produce softer muons and softer jets, and we estimate an efficiency of $\simeq 4\%$. The efficiency in QCD events would be similar to $Wb\bar{b}$, except for the fact that the $\not\!\!E_T$ is not originated from the neutrino of the W decay, but from the largely uncollected muon energy and the neutrino from the decay chain $b \to \ell\ \nu\ X$ or $b \to c \to \ell\ \nu\ X$. This correlation leads to a higher efficiency, $\simeq 11\%$. Finally, in $t\bar{t}$ events there is a higher boost associated with the b fragmentation so the muon momentum and the jet energy spectra are harder than for $Wb\bar{b}$. The efficiency in these jets is $\simeq 11\%$.

IV. RESULTS AND CONCLUSIONS

The number of W+jets events with at least one SLT-SecVtx double tag is shown in Table III and Figure 1, together with the expectation from the SM. There is no excess of observed events with double tagged jets. The quoted uncertainty in the SM expectation is the total systematic uncertainty. Since we use the number of observed events with a SecVtx tagged jet and the efficiency of SLT tagging, the systematic uncertainties in the event selection, acceptance and reconstruction efficiency, cancel out. The systematic uncertainties considered here include the efficiency of the SLT algorithm to tag muons inside jets from heavy quark fragmentation ($+1/-8\%$), or from accidental mistags ($\pm10\%$). The uncertainties also include a contribution from particle tracking efficiency in dense environments ($\pm5\%$), due the Monte Carlo modeling of the detector, and a contribution from the modeling of the jet energy calibration in the Monte Carlo ($\pm2\%$), which enters as a correlation between the jet $E_T > 15$ GeV requirement and the presence of a muon in the jet. Uncertainty on the SM semileptonic decay B.R. of B mesons ($\pm4.4\%$) is also considered. Basic kinematic properties of the sample are studied and compared with the expectations. Figure 2 shows the distribution of the double tagged jets E_T (a), L_{2D} (b) and the SLT muons p_T (c), $p_T^{\rm rel}$ (d). The quantity $p_T^{\rm rel}$ is the component of the muon momentum orthogonal to the jet axis. Muons from heavy flavor decay receive a relatively large boost orthogonal to the jet axis. Figures 1(c) and 1(d) have one extra data entry because one jet has two identified SLT muons. Template distributions for the SM processes are obtained from Monte Carlo simulations with the exception of the QCD template, which is derived from data with the primary lepton isolation $I > 0.15$. The observed distributions agree well with the SM predictions. Kolmogorov-Smirnov (KS) tests of the shape of the distributions yield the probability of 90% and 19% for the jet E_T and L_{2D} spectra respectively. Probabilities of 69% and 60% are returned by the KS test on the distribution of the SLT muons p_T and $p_T^{\rm rel}$.

Table III: Number of events with at least one jet tagged by both the SLT and the SecVtx algorithm. The total expectation is based on the contributions from all SM processes.

Jet multiplicity:	W+1 jet	W+2 jets	$W+\geq 3$ jets ($H_T > 0$ GeV)	$W+\geq 3$ jets ($H_T > 200$ GeV)
Wbb	2.63±0.81	1.56±0.46	0.46±0.17	0.27±0.10
$Wc\bar{c}$	0.60±0.15	0.27±0.08	0.08±0.03	0.05±0.02
Wc	1.51±0.40	0.26±0.07	0.06±0.02	0.03±0.01
Diboson, $Z \to \tau\tau$	0.09±0.06	0.12±0.02	0.03±0.01	0.02±0.01
Z+heavy flavor	0.07±0.01	0.03±0.01	0.01±0.01	0.00±0.00
Mistags	0.70±0.13	0.20±0.04	0.08±0.01	0.04±0.01
QCD	2.70±0.62	1.00±0.26	0.55±0.16	0.33±0.10
Single top	0.19±0.02	0.33±0.03	0.11±0.02	0.08±0.02
$t\bar{t}$	0.11±0.01	0.69±0.08	3.56±0.06	3.60±0.49
SM expectation	8.6±1.2	4.5±0.9	4.9±0.5	4.4±0.4
Data observation	7	5	1	1

In summary, we have compared the observed number of W+jets events with at least one jet tagged by both the SecVtx and the SLT algorithm, with the expectation based on SM events and the semileptonic B.R. in heavy quark fragmentation. We observe no excess of events above expectation, and the kinematic properties of the sample agrees with SM processes. We are planning to set a 95% C.L. limit on the excess of events and set upper limits on the production cross section of a non-SM particle with high semileptonic B.R.

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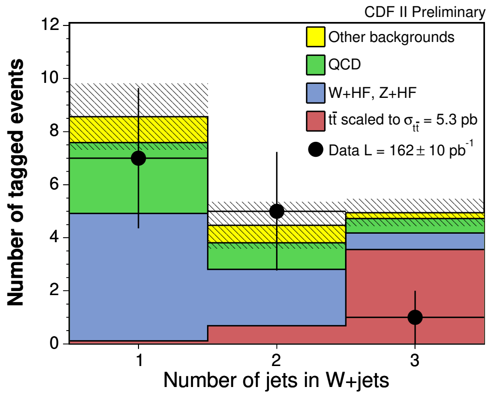

Figure 1: Number of W+jets events with at least on jet tagged by both the SLT and the SecVtx algorithm. W plus 3 jets includes any multiplicity above 3.

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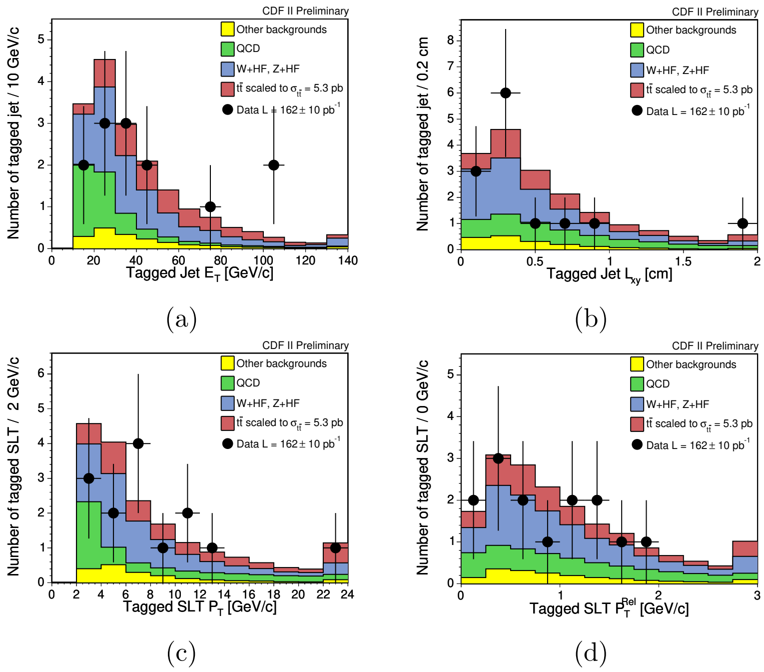

Figure 2: Kinematic distributions of double tagged jets.

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