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Search for Invisible Top Decays with 1.9 fb^{-1} of CDF-II Data

The CDF Collaboration

Abstract

We report on the method of doing an indirect search for invisible top decays. By comparing the yield of loose double b-tag lepton + jet candidate events to what is expected based on theoretical cross sections, upper limits on various decay modes are calculated. Assuming a top mass of 175 GeV/c^2, we find of 95% C.L. limits, ranging from $\mathcal{B}(t \rightarrow Zc) < 13\%$ to $\mathcal{B}(t \rightarrow \text{invisible}) < 9\%$.

Contents

1 Introduction

In the standard model (SM), top almost always decays to a W boson and a b quark. In this analysis, we will search for the possibility of alternative top decays. The general idea is to consider the yield of our standard lepton + jet selection with two b tags and look for a deviation from expected as defined by the theoretical $t\bar{t}$ production cross section.

In order for this analysis to be sensitive to a non $t \to Wb$ decay, the relative acceptance of $t\bar{t} \to Wb\ XY$ (where XY is the non-standard decay) must be significantly different than that of $t\bar{t} \to Wb\ Wb$. For this analysis, we are considering the non-SM decays of $t \to Zc$, $t \to \gamma c$, $t \to gc$, and $t \to$ invisible.

2 Theoretical $t\bar{t}$ Production Cross Section

Theoretical predictions for the inclusive $t\bar{t}$ production cross section are well known to next-to-leading order (NLO) in QCD with soft gluon threshold resummation up to next-to-leading logarithmic (NLL) accuracy. In April/May 2008, three groups published updated calculations of the $t\bar{t}$ production cross section [1, 2, 3]. All of them utilize recent versions of the most common parton distribution functions (PDFs), prominently CTEQ6.5M [4] and MSTW NNLO [5]. We are reporting the current results using the Reference [1].

For this analysis we will incorporate cross section uncertainties in the pseudo-experiments used to construct the Feldman-Cousins bands. We add the scale and the PDF uncertainties in quadrature, separately for the positive and the negative variation in case of asymmetric uncertainties. To be consistent with the PDF sets used in the Monte Carlo simulation, we use CTEQ PDFs for the final result.

Table 1: Theoretical predictions of $t\bar{t}$ production cross section at $\sqrt{s} = 1.96$ TeV. Uncertainties shown are the sum in quadrature of the scale and PDF systematic unceratinties.

Top Mass (GeV)	Theory Xsec (pb)
170.0	$7.85^{+0.63}_{-0.67}$
172.5	$7.26^{+0.57}_{-0.62}$
175.0	$6.73^{+0.52}_{-0.57}$

3 Event Selection and Backgrounds

Our signal sample is the double loose SECVTX b-tag lepton + jets sample (see Table 2 for full list of selection criteria). Note that this is the identical event selection and background table as used in our direct top FCNC search [6].

Table 2: Selection criteria for the $t\bar{t}$ cross section analysis requiring two or more loose SECVTX tags.

Selection Criterion	**Selection Cut**
Lepton type	Tight central electron and muon: (TCE, CMUP, CMX)
Number of tight leptons	exactly 1
Number of jets	≥ 3
Jet E_T (Level 5 corrected)	≥ 20 GeV
Missing E_T	≥ 30 GeV
Z veto	Yes
Dilepton veto	Yes
$\lvert z\rvert$ jet vertex	≤ 60 cm
Δz lepton-jet vertex	≤ 5 cm
H_T	≥ 200 GeV
Number of loose SECVTX tags	≥ 2

The algorithm for calculating non-$t\bar{t}$ background estimates [7] has an intrinsic weak dependence on the number of $t\bar{t}$ events in each jet bin. To treat this dependence, we choose an observed $t\bar{t}$ cross section so that the number of predicted events is equal to the number of observed events assuming $\mathcal{B}(t \to Wb) = 1$. It is important to note that if we no longer assumed that $\mathcal{B}(t \to Wb) = 1$, this would change the reported $t\bar{t}$ cross section (*i.e.,* 8.8 pb), but not the background estimate.

4 Acceptances, Efficiencies, and Backgrounds

The SM $t\bar{t} \to Wb\,Wb$ acceptance convoluted with efficiency and W branching fraction as well as background numbers are in Table 3. All acceptances are calculated using Pythia [8]. See Appendix A for breakup of background uncertainties. The relative acceptances of different decay modes are shown in Table 4.

Table 3: SM $t\bar{t} \to Wb\,Wb$ acceptance $\bigotimes$ efficiency and background numbers and their relative uncertainties.

Category	**Value**	**Relative uncertainty (%)**
Theory $\sigma_{t\bar{t}}$ (pb)	6.7	11.9
SM Acc. $\bigotimes$ eff. (%)	1.47	16.6
Background (events)	30.5	40.3

Table 4: The relative acceptance $\bigotimes$ efficiency and W branching fraction for different decay modes. $\mathcal{R}_{\mathrm{wx/ww}}$ is the relative acceptance when one top decays to the Wb while the other decays to the new decay. $\mathcal{R}_{\mathrm{xx/ww}}$ is when both top quarks decay to the new decay. The relative uncertainty on all of these numbers is 1%. Note that we do not currently have MC where both top quarks decay to $t \to gc$ or $t \to \gamma c$. We use the $t \to Zc$ for $\mathcal{R}_{\mathrm{xx/ww}}$ which is an over-estimate.

Decay	$\mathcal{R}_{\mathbf{wx/ww}}$ **(%)**	$\mathcal{R}_{\mathbf{xx/ww}}$ **(%)**
$t \to Zc$	31.8	2.0
$t \to gc$	27.2	2.0
$t \to \gamma c$	18.3	2.0
$t \to$ invisible	0.0	0.0

5 Limits

We employ a Feldman-Cousins (FC) construction which includes systematic uncertainties, as we have done for the direct $t \to Zc$ search. [6] In this FC construction, the acceptance bands relate the true branching fractions of the considered decay with the number of observed "lepton+jets" candidate events with at least three jets (as described in Section 3).

To create the FC acceptance bands for different true values, we generate pseudo-experiments (PEs) using the acceptance and background estimates in Section 4. For each PE, we Gaussian fluctuate each number within its uncertainties while making sure the resulting number is physical (*i.e.,* non-negative). We then Poisson fluctuate the total expected number of events. This is repeated 10 million times for each true value of the branching fraction (currently 0% to 20% in 1% stpes) for each of the decays ($t \to Zc$, $t \to gc$, $t \to \gamma c$, and $t \to$ invisible). See example distributions in Figure 1.

Using the distributions of PEs, we created and fit likelihood ratios for branching fraction. Using the fitted likelihood ratio (see Figure 2 for examples), we calculated 95% acceptance bands for the decays $t \to Zc$, $t \to \gamma c$, $t \to$ invisible as shown in Figure 3.

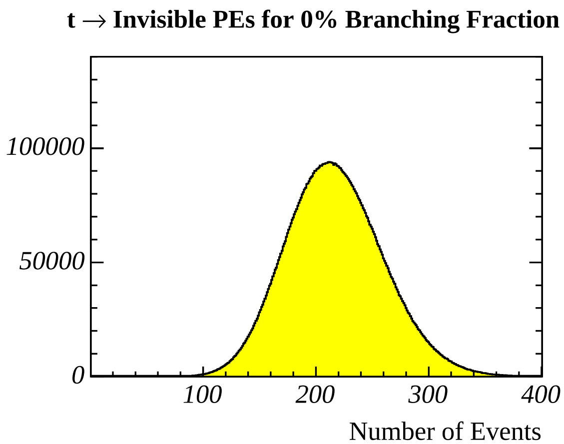
Using the FC bands for a particular decay and the PE distribution where $\mathcal{B}(t \to Wb) = 100\%$, we can calculate expected limits for our decay modes. For every value of observed number of events, we add the limit from the FC bands to a histogram, weighted by the probability to have observed this number of events (see Figure 4).

Using this method, we calculated expected limit distributions for our four decay modes. See Table 5 and Figure 5 for details.

6 Results

Assuming a top mass of 175 GeV/c^2 and observing 277 "lepton + jets" double loose b-tag candidate events, we find the upper limits as shown in table 6.

These results assume a theoretical top cross sections shown in Table 1.



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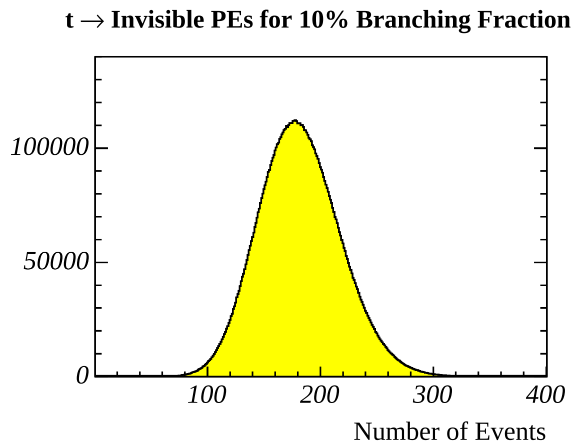

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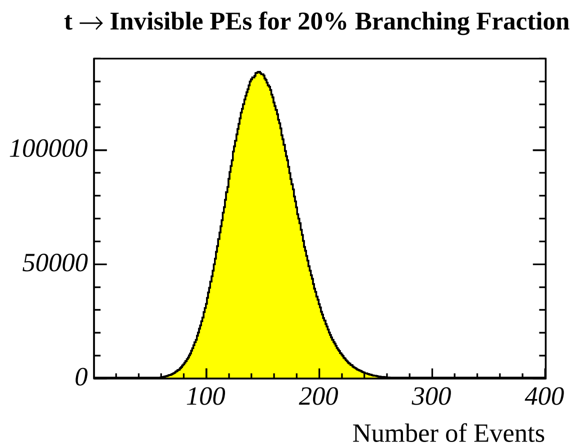

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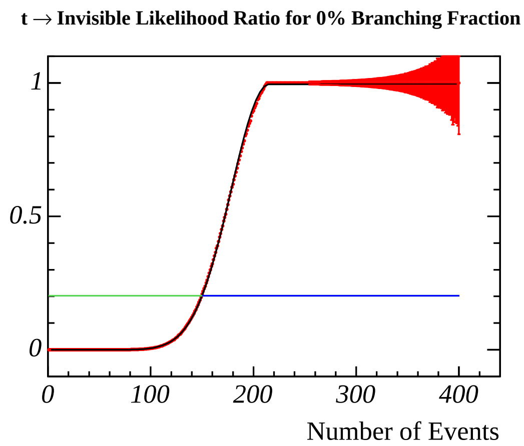
Figure 1: Distribution of observed number of events for PEs for a given branching fraction of (a) $\mathcal{B}(t \to \text{invisible}) = 0\%$, (b) $\mathcal{B}(t \to \text{invisible}) = 10\%$, and (c) $\mathcal{B}(t \to \text{invisible}) = 20\%$. Note that as the branching fraction of $t \to$ invisible grows, the number of observed events gets smaller.



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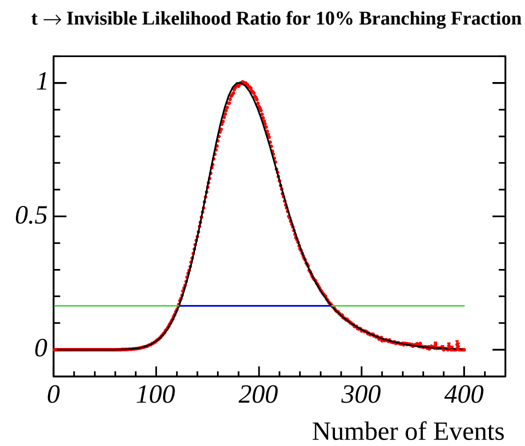

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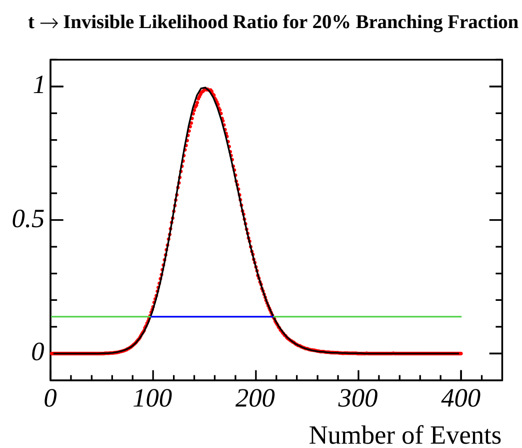

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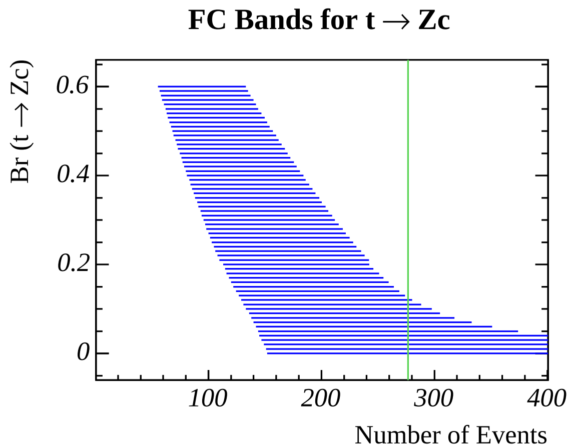
Figure 2: The likelihood ratio distributions (red points and error bars) and fits (black curves) for (a) $\mathcal{B}(t \to \text{invisible}) = 0\%$, (b) $\mathcal{B}(t \to \text{invisible}) = 10\%$, and (c) $\mathcal{B}(t \to \text{invisible}) = 20\%$. The heigt of the horizontal bar is chosen so 95% of all PEs have a likleihood ratio above this value. The blue line segments are the intervals of the acceptance band for the given true values.



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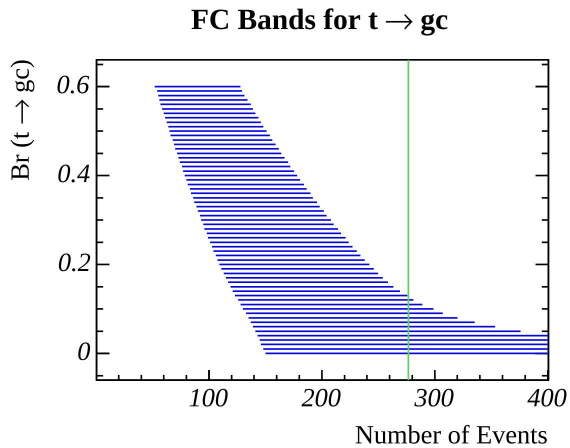

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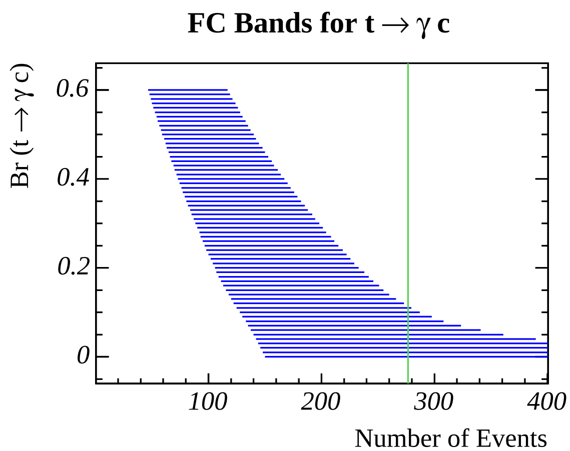

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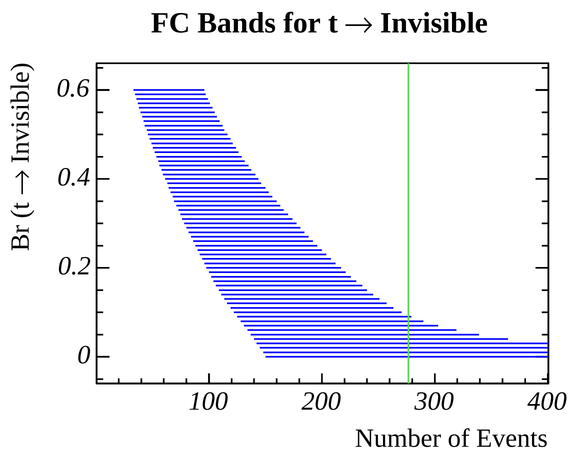


(d)

Figure 3: The FC acceptance bands for (a) $t \to Zc$, (b) $t \to gc$, (c)$t \to \gamma c$, and (d) $t \to$ invisible assuming a top mass of 175 GeV/c^2.

Table 5: The expected limit median and $\pm 1\sigma$ quantiles for (a) $t \to Zc$, (b) $t \to gc$, (c)$t \to \gamma c$, and (d) $t \to$ invisible for top masses of 175 GeV/c^2, 172.5 GeV/c^2, and 170 GeV/c^2.

Decay	$\mathcal{R}_{\mathbf{wx/ww}}$ (%)	175 GeV (%)	172.5 GeV (%)	170 GeV (%)
$t \to Zc$	32	28^{+14}_{-12}	28^{+14}_{-11}	27^{+14}_{-11}
$t \to gc$	27	26^{+14}_{-11}	26^{+13}_{-11}	26^{+13}_{-11}
$t \to \gamma c$	18	24^{+12}_{-10}	24^{+12}_{-10}	23^{+12}_{-10}
$t \to$ invisible	0	20^{+10}_{-8}	19^{+10}_{-8}	19^{+10}_{-8}

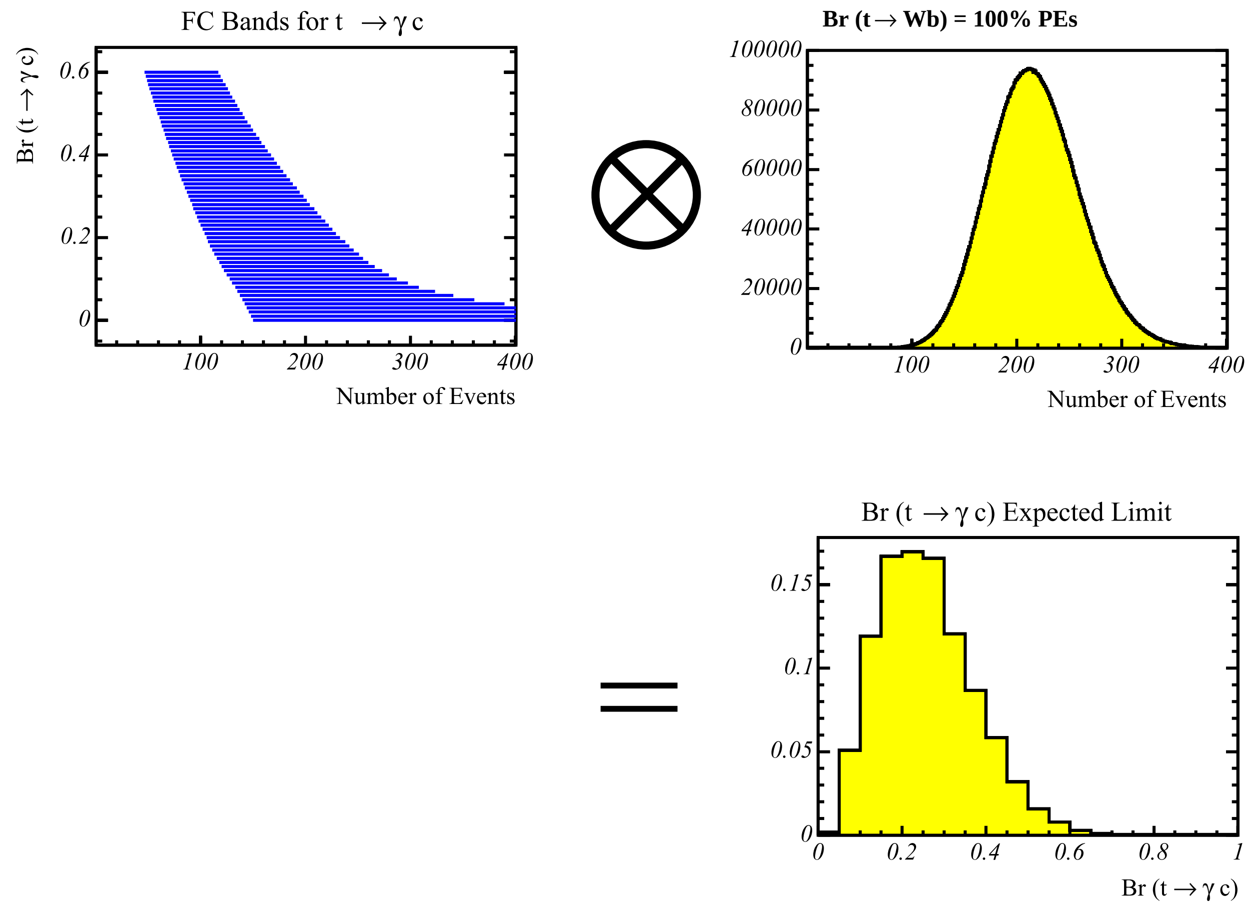
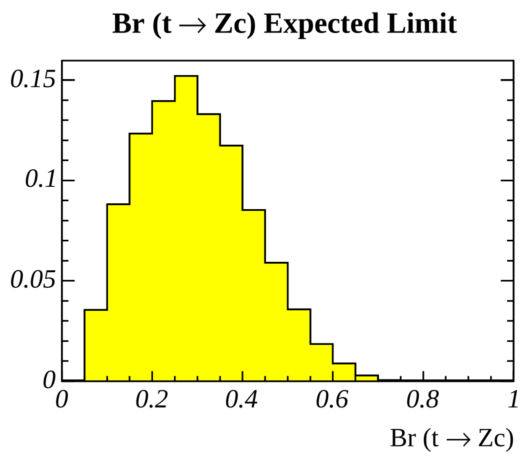


Figure 4: To calculated expected limits, we convolute the upper limits given an observed number of events plot with the PE distribution assuming $\mathcal{B}(t \to Wb) = 100\%$.

Table 6: The measured upper limits for (a) $t \to Zc$, (b) $t \to gc$, (c)$t \to \gamma c$, and (d) $t \to$ invisible for top masses of 175 GeV/c^2, 172.5 GeV/c^2, and 170 GeV/c^2.

Decay	$\mathcal{R}_{\mathbf{wx/ww}}$ (%)	**Upper Limit (%)** (175 GeV)	**Upper Limit (%)** (172.5 GeV)	**Upper Limit (%)** (170 GeV)
$\mathcal{B}(t \to Zc)$	32	13	15	18
$\mathcal{B}(t \to gc)$	27	12	14	17
$\mathcal{B}(t \to \gamma c)$	18	11	12	15
$\mathcal{B}(t \to \text{invisible})$	0	9	10	12



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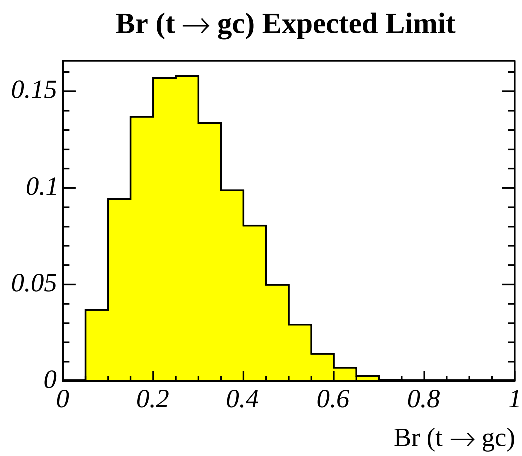

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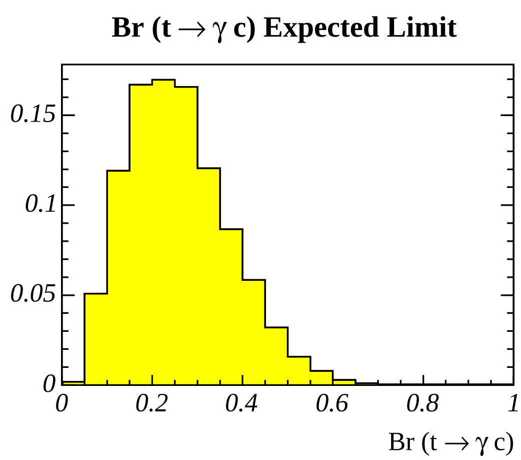

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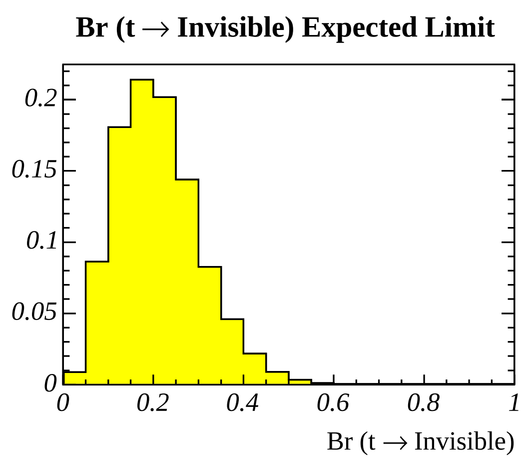

(d)

Figure 5: The expected limit distributions for (a) $t \rightarrow Zc$, (b) $t \rightarrow gc$, (c)$t \rightarrow \gamma c$, and (d) $t \rightarrow$ invisible assuming a top mass of 175 GeV/c^2. The expected limit median and $\pm 1\sigma$ quantiles are reported in Table 5.

A Background Table

Table 7: Background table for the Lepton+Jets selection with $\geq$ 2 loose SECVTX tags. A $t\bar{t}$ production cross section of $\sigma_{t\bar{t}} = 8.8$ pb is inferred.

Sample	**1 Jet**	**2 Jets**	**3 Jets**	**4 Jets**	**$\geq$ 5 Jets**
Tagged WW	0.0±0.0	0.5±0.1	0.5±0.1	0.2±0.0	0.1±0.0
Tagged WZ	0.0±0.0	2.6±0.3	0.8±0.1	0.2±0.0	0.0±0.0
Tagged ZZ	0.0±0.0	0.1±0.0	0.0±0.0	0.0±0.0	0.0±0.0
Tagged SM $t\bar{t}$ (8.8 pb)	0.0±0.0	32.9±5.2	90.2±14.1	113.7±17.6	41.1±6.3
Tagged Single Top (s)	0.0±0.0	8.4±1.2	2.8±0.4	0.7±0.1	0.1±0.0
Tagged Single Top (t)	0.0±0.0	2.0±0.3	1.8±0.2	0.5±0.1	0.1±0.0
Tagged Z+LF	0.0±0.0	1.1±0.2	0.7±0.1	0.2±0.0	0.1±0.0
Tagged $Wb\bar{b}$	0.0±0.0	33.9±13.3	10.6±4.3	2.0±0.9	0.5±0.2
Tagged $Wc\bar{c}/Wc$	0.0±0.0	6.1±2.5	2.7±1.1	0.7±0.3	0.2±0.1
Tagged Total HF	0.0±0.0	39.9±15.8	13.3±5.3	2.6±1.2	0.6±0.3
Tagged Total MC	0.0±0.0	47.5±6.8	96.9±14.9	115.6±17.8	41.5±6.4
Tagged Mistags	0.0±0.0	4.3±1.0	2.6±0.7	0.7±0.2	0.2±0.1
Tagged Non-W	0.0±0.0	2.7±1.9	0.8±1.5	0.5±1.5	0.2±1.5
Total Prediction	0.0±0.0	94.5±17.4	113.6±15.9	119.4±17.9	42.5±6.5
Observed	0.0±0.0	107.0±0.0	118.0±0.0	115.0±0.0	44.0±0.0

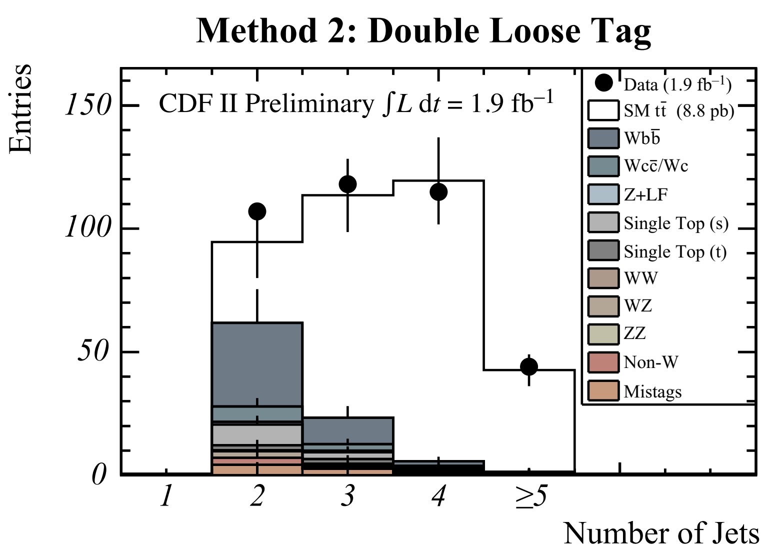

Figure 6: Graphical representation of Table 7. A $t\bar{t}$ production cross section of $\sigma_{t\bar{t}} = 8.8$ pb is assumed.

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