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Event detection efficiency for single-top events in CDF II

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Abstract

We present event detection efficiencies for the two electroweak single-top processes relevant at the Tevatron, i.e. t-channel (Wg-fusion) and s-channel (W^*) production. Our evaluation is based on MadEvent Monte Carlo events. In addition, we include detection efficiencies of backgrounds, whose production cross sections are well predicted by theory: $t\bar{t}$, diboson (WW, WZ and ZZ) production and $Z \to \tau^+\tau^-$. We use Monte Carlo events simulated and recontructed with software release 5.3.3. The results of this note cover the run range from run no. 141544 to no. 203799.

1 Introduction

In Run II at the Tevatron, single-top quarks are expected to be produced electroweakly via *t-channel* or *s-channel* exchange of an off mass shell W boson. The two production modes are also referred to as $W-$gluon fusion or W^* process. Figure 1 depicts Feynman diagrams for the two production modes. The theoretical cross section at $\sqrt{s} = 1.96$ TeV for $M_{\text{top}} = 175$ GeV$/c^2$ is: (0.88 ± 0.11) pb for the s-channel and (1.98 ± 0.25) pb for the t-channel, respectively [1]. The cross sections change as a function of the top quark mass. The functional form of this change is in good approximation linear. For the t-channel the cross section changes by $^{-1.6}_{+1.75}\% \cdot \delta M_{\text{top}}(\text{GeV})$; for the s-channel by $^{-2.33}_{+2.71}\% \cdot \delta M_{\text{top}}(\text{GeV})$. The PDF uncertainty is $^{+11.3}_{-8.1}\%$ for the t-channel and $^{+4.7}_{-3.9}\%$ for the s-channel. The total

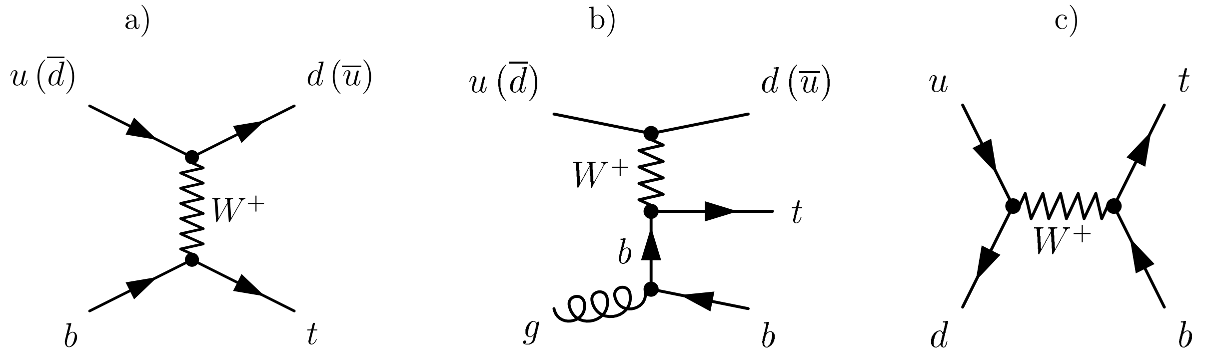

Figure 1: Feynman diagrams for single-top production. a) t-channel $2 \to 2$ process, assumes the introduction of a b quark PDF; b) t-channel $2 \to 3$ W-gluon-fusion diagram, which is an NLO contribution if a b quark PDF is used; c) LO s-channel (W^*) diagram.

uncertainty on both cross sections is about 13%. We note that the combined single-top cross section of about 2.9 pb is roughly twice smaller than the $t\bar{t}$ cross section [3, 4, 5, 6].

In Run I at the Tevatron, both CDF and DØ have searched for single-top production [9, 10, 7, 8]. The published 95% C.L. upper limits set by CDF are 13 pb on t-channel production, 18 pb on s-channel production, and 14 pb for the combined channels [7]. The limits reported by the DØ Collaboration are comparable: 22 pb on t-channel and 17 pb on s-channel production [9, 10].

The CDF collaboration published first Run II search results in February 2005. This analysis uses data corresponding to $162\,\mathrm{pb}^{-1}$ and sets upper limits on the t-channel and s-channel cross sections: $\sigma_{\mathrm{t-channel}} < 10.1\,\mathrm{pb}$ and $\sigma_{\mathrm{s-channel}} < 13.6\,\mathrm{pb}$ [11]. DØ analyzed $230\,\mathrm{pb}^{-1}$ of data and obtains upper limits of $\sigma_{\mathrm{t-channel}} < 5.0\,\mathrm{pb}$ and $\sigma_{\mathrm{s-channel}} < 6.4\,\mathrm{pb}$ [12].

Preliminary studies show that a $3\,\sigma$ excess could be observed by CDF with roughly $2.0\,\mathrm{fb}^{-1}$ of data. This projection takes systematic uncertainties into account. The estimate is based on the first results published by CDF in Run II and adds improvements that can be obtained with a neural network. The aim of this document is to present the event detection efficiency ϵ_{evt} for single-top events.

2 Monte Carlo Samples and Selection Requirements

The single-top Monte Carlo samples used for this analysis are generated by the matrix element generator MadEvent [13]. Simulation and production were performed using the 5.3.3 release of the CDF offline software. The reconstructed events were passed through TopFind, linked against CDF software release 5.3.3_nt, to produce TopNtuples [14]. Table 1 gives an overview on the Monte Carlo samples we use. All these Monte Carlo samples were simulated with run dependent settings covering the run range from run no. 141544 to no. 203799.

MadEvent implements the correct polarization of the top quark. The theory of electroweak interactions predicts that single-top quarks are 100% polarized along the d quark direction in the top quark rest frame [15, 16, 17]. The modelling of the single-top

Sample	Process	Generator	Description	N events
ttop1oNew+ ttop2oNew_match	t-ch.	MadEvent	matched sample	600060
ttop0oNewCat	s-ch.	MadEvent	LO	577276
ttopvl+ttopkl+ttopyl+ ttoptl	$t\bar{t}$	Pythia	inclusive, $M_{\mathrm{top}} = 175\,\mathrm{GeV}$	2965060
wtop1w+wtop2w	WW	Pythia	$W_1 \to e,\, \mu,\, \tau + \nu$	606877
wtop1z+wtop2z	WZ	Pythia	inclusive	594502
ztopcz	ZZ	Pythia	inclusive	412866
ztop1i	$Z \to \tau\tau$	Pythia	inclusive	925632

Table 1: Signal Monte Carlo samples used in the single-top analysis and background Monte Carlo samples for Monte Carlo based background estimates. All single-top samples decay the W from the top quark decay to leptons, $W \to e, \mu, \tau + \nu$.

t-channel has a particular intricacy. If only the leading order diagram, Figure 1a, is used, the $\bar{b}$ (also called the second b) is obtained by backward evolution with the shower Monte Carlo program Pythia [18]. The kinematic distributions of the $\bar{b}$ are not well modelled by this procedure. In particular, the p_{T} distribution of the second b is too soft, and the η distribution to much forward (shifted to high values of $|\eta|$). The problem can be obviated by generating two t-channel samples with MadEvent, one $2 \to 2$ ($qb \to q't$) and one $2 \to 3$ ($qg \to q'tb$) sample, see Figure 1b. Both samples are mixed to better reproduce the theoretically predicted distributions of the second b quark. The exact mixing prescription is documented in detail in references [19, 20].

2.1 Baseline Cuts

The selection requirements used are the standard cuts of the CDF top physics group for lepton+jets analyses [21]. For Monte Carlo events we first require the OBSV vertex to be in the fiducial volume of the detector: $|z_0| < 60$ cm (`fabs(TN->obsp_Vz[0])<60.0`). The tight lepton selections along with the corresponding TopNtuple implementation are given in Table 2 (central electrons), Table 3 (plug electrons) and Table 4 (central muons).

Jet Counting: We count jets using the corrected transverse energy E_{T}. Corrections are applied to all jets reclustered with *TopEventModule* (jet collection 3; JetClu algorithm, cone size 0.4). We use corrections for relative energy, time-dependence, energy scale and multiple-interactions, i.e. level 4 corrections [22]. We count jets with $E_{\mathrm{T}}^{\mathrm{corr}} \geq 15\,\mathrm{GeV}$ and $|\eta_{\mathrm{Detector}}| < 2.8$. We extend the standard tight jet definition by enlarging the η range from $|\eta_{\mathrm{Detector}}| < 2.0$ to $|\eta_{\mathrm{Detector}}| < 2.8$. The reason for that is that we can significantly improve our signal-to-background ratio by this measure. We expect our acceptance for t-channel single-top events to increase by about 30%. The background and the s-channel acceptances on the other hand do not increase significantly: s-channel $\approx +2\%$, $Wb\bar{b}$ +4%, $Wc\bar{c}$ +7%, Wc +15%. Overall we gain in S/B. Table 5 shows the jet multiplicity

<table>
<tr><td>Selection Cut</td><td>TopNtuple Implementation</td></tr>
<tr><td>CEM electron
Fiducial
$E_{\mathrm{T}} \geq 20.0$ GeV</td><td><code>ele->Region == 0</code>
<code>ele->Fiducial == 1</code>
<code>ele->Et >= 20.0</code></td></tr>
<tr><td>$p_{\mathrm{T}}^{\mathrm{trk}} \geq 10.0$ GeV
$E_{\mathrm{had}}/E_{\mathrm{em}} \leq 0.055 + 0.00045E$
$L_{\mathrm{shr}} \leq 0.2$
$E/P \leq 2.0$ if $E_{\mathrm{T}} < 100.0$ OR
$p_{\mathrm{T}}^{\mathrm{trk}} > 50$ GeV if $E_{\mathrm{T}} \geq 100.0$
$|z_0| \leq 60.0$ cm
$\Delta z| \leq 3.0$ cm
$-3.0 \leq Q \cdot \Delta x \leq 1.5$ (cm)

$\chi^2_{\mathrm{strip}} \leq 10.0$
Good COT Axial Segments≥ 3
Good COT Stereo Segments≥ 2
Conversion Veto</td><td><code>ele->TrkPt >= 10.0</code>
<code>ele->Hadem <= (0.055+0.00045*ele->En)</code>
<code>ele->LshrTrk <= 0.2</code>
<code>((ele->EP<2.0)&&(ele->Et<100.0))||</code>
<code>((ele->TrkPt>50.0)&&(ele->Et>=100.0))</code>
<code>fabs(ele->TrkZ0) <= 60.0</code>
<code>fabs(ele->DeltaZ) <= 3.0</code>
<code>qdx=((float)ele->Charge)*ele->DeltaX;</code>
<code>(qdx >= -3.0)&&(qdx <= 1.5)</code>
<code>ele->StripChi2 <= 10.0</code>
<code>ele->TrkAxSeg >= 3</code>
<code>ele->TrkStSeg >= 2</code>
<code>ele->Conversion != 1</code></td></tr>
<tr><td>Isolation ≤ 0.1</td><td><code>ele->Isol < 0.1</code></td></tr>
</table>

Table 2: The selection cuts for central (CEM) electrons. The TopNtuple implementation is given (`ele` is a pointer to an `electron` object).

<table>
<tr><td>Selection Cut</td><td>TopNtuple Implementation</td></tr>
<tr><td>Plug electron
$E_{\mathrm{T}} \geq 20.0$ GeV</td><td><code>ele->Region == 1</code>
<code>ele->Et >= 20.0</code></td></tr>
<tr><td>$1.2 < \eta_{\mathrm{PES}} < 2.0$

Tower fit
$E_{\mathrm{had}}/E_{\mathrm{em}} < 0.05$
$\chi^2_{PEM} < 10.0$
Shower profile

PHX match
$|z_0| \leq 60.0$ cm
$N_{\mathrm{Hits}}^{\mathrm{Si}} \geq 3$
$\Delta R(\mathrm{centr_{PES}}, \mathrm{centr_{PEM}}) \leq 3.0$

Shower Max</td><td><code>(fabs(ele->Pes2dEta) > 1.2)&&</code>
<code>(fabs(ele->Pes2dEta) < 2.0)</code>
<code>ele->Pem3x3FitTow!=0</code>
<code>ele->Hadem < 0.05</code>
<code>ele->Pem3x3Chisq < 10.0</code>
<code>(ele->Et > 100.0)||((ele->Pes2d5by9U>0.65)</code>
<code>&&(ele->Pes2d5by9V>0.65))</code>
<code>ele->PhxMatch == true</code>
<code>fabs(ele->TrkZ0) <= 60.0</code>
<code>ele->TrkSiHits >= 3</code>
<code>float dR =</code>
<code>sqrt((ele->Pes2dX-pemX)*(ele->Pes2dX-pemX)+</code>
<code>(ele->Pes2dY-pemY)*(ele->Pes2dY-pemY));</code>
<code>dR <= 3.0</code>
<code>ele->NumPes2d != 0</code></td></tr>
<tr><td>Isolation ≤ 0.1</td><td><code>ele->Isol < 0.1</code></td></tr>
</table>

Table 3: The selection cuts for plug (PHX) electrons. The TopNtuple implementation is given (`ele` is a pointer to an `electron` object).

Selection Cut	TopNtuple Implementation
CMUP muon	`(muo->muontype&3) == 3`
CMX muon	`(muo->muontype&4) == 4`
$p_{\mathrm{T}}^{\mathrm{corr}} \geq 20.0$ GeV/c	`muo->PtCorr >= 20.0`
$E_{\mathrm{had}} \leq \max\left(6,\ 6 + 0.028\left(p^{\mathrm{corr}} - 100\right)\right)$	`(muo->HadEnergy <= 6.0) ||`
	`(muo->HadEnergy <= 6.0+0.028`
	`*(muo->Pcorr - 100.0))`
$E_{\mathrm{em}} \leq \max\left(2,\ 2 + 0.0115(p^{\mathrm{corr}} - 100)\right)$	`(muo->EmEnergy <= 2.0) ||`
	`(muo->EmEnergy <= 2.0+0.0115`
	`*(muo->Pcorr-100.0))`
$\|z_0\| \leq 60.0$ cm	`fabs(muo->Z0) <= 60.0`
for CMUP muons only:	
CMU$\|\Delta x\| \leq 3.0$ cm	`fabs(muo->CmuDx) <= 3.0`
CMP$\|\Delta x\| \leq 5.0$ cm	`fabs(muo->CmpDx) <= 5.0`
CMU fiducial	`(mu->CmuFidX < 0.0)&&`
	`(mu->CmuFidZ < 0.0)`
CMP fiducial	`(mu->CmpFidX < 0.0)&&`
	`(mu->CmpFidZ < -3.0)`
for CMX muons only:	
CMX$\|\Delta x\| \leq 6.0$ cm (for CMX muons only)	`fabs(muo->CmxDx) <= 6.0`
CMX fiducial	`(mu->CmxFidX < 0.0)&&`
	`(mu->CmxFidZ < -3.0)`
CMX exit radius > 140.0	`Rho(mu->Eta, mu->Z0) > 140.0`
Good COT Axial Segments ≥ 3	`muo->TrkAxSeg >= 3`
Good COT Stereo Segments ≥ 2	`muo->TrkStSeg >= 2`
$\|d_0\| \leq 0.2$ cm if no Si hits	`(muo->TrkSiHits == 0) &&`
	`fabs(muo->D0) <= 0.2`
$\|d_0\| \leq 0.02$ cm if Si hits	`(muo->TrkSiHits != 0) &&`
	`fabs(muo->D0) <= 0.02`
Isolation ≤ 0.1	`muo->Isol <= 0.1`
Cosmic Veto (for data only)	`(su->fTopEventClass & 0x20) == 0`

Table 4: The baseline cuts for CMUP and CMX muons. The TopNtuple implementation is given. `muo` is a pointer to a `muon` object. `su` is a pointer to the top `summary` object. The cosmic veto is only applied to data, not Monte Carlo events.

n jets	1	2	3	4	≥ 5
t-channel	25.2%	57.9%	14.2%	2.5%	0.3%
s-channel	19.3%	64.7%	13.6%	2.1%	0.3%

Table 5: Jet multiplicity distribution after b tag for t-channel and s-channel events.

distribution for t-channel and s-channel single-top events passing the pre-selection, which includes the b tag requirement. The bulk of the events is concentrated in the 2-jet bin.

Cut on $\not\!\!E_\mathbf{T}$: To select leptonic W boson events we require a missing transverse energy of $\not\!\!E_T \geq 20$ GeV. Since we use corrected jet energies, we also need to use corrected $\not\!\!E_T$ to be consistent. The following corrections are performed: (1) Since muons pass the calorimeter without showering, we have to correct for that. For muons identified as *tight muons* this is already done by *TopEventModule* and the corrected quantitiy is available in the *TopNtuples* we use for our analysis, variable `su->fmuoMet`, where `su` is a pointer to the `summary` object. (2) The second correction to $\not\!\!E_T$ arises from jet energy corrections. We calculate the difference between the corrected and raw jet energy: $\Delta E_\mathrm{T} = E_T(\mathrm{raw}) - E_T(\mathrm{corr.})$. Jet energy corrections are applied as described above. The $\not\!\!E_T$ is corrected by adding the energy differences ΔE_T vectorially. We then demand $\not\!\!E_T$ (corr.) ≥ 20 GeV.

Cosmic rejection: On muon data only, we use the cosmic tagger flag to reject cosmic ray events, `(su->fTopEventClass & 0x20) != 0)`. Certain quantities used for cosmic rejection are not well modelled by the Monte Carlo detector simulation. Therefore, we do not include the cosmic rejection in the Monte Carlo acceptance calculation. The signal loss for W+2 jet events was estimated from data and is 1.23%. [23]. This has to be included as an additional factor in the event detection efficiency.

Dilepton rejection: We require one and only one tight lepton. We also veto events where an additional loose lepton is found. The following loose lepton categories are used: CMU (muons with stubs only reconstructed in the CMU detector, not seen in the CMP), CMP (muons only reconstructed in the CMP detector, not seen in the CMU), BMU, and non-isolated muons in CEM, PHX, CMUP, or CMX.

Z boson rejection: We veto events, if we find a second, loosely identified lepton candidate, that forms an invariant mass with the primary lepton between $76 < M_{\ell\ell} < 106$ GeV/c^2. In TopNtuple this is implemented as
`(su->fTopEventClass & 0x8) == 0`.

b tag requirement: At least one jet must be identified as likely to contain a b quark (`jet->secvTag == 1`). The b tagging relies on the reconstruction of displaced secondary vertices with the silicon microstrip detector. Secondary vertices with a transverse decay length significance ($\Delta L_{xy}/\sigma_{xy}$) above 3 are accepted as a b tag for jets. For consistency we require that the charged lepton z_0 is within a window of 5 cm around the primary vertex used for b tagging.

The cut flow of our event selection is illustrated in Table 6 for the single-top t-channel sample.

After the di-lepton veto we subdivide the events in four categories according to the subsystem where the tight lepton was detected: `CEM`, `PHX`, `CMUP` and `CMX`.

3 Single-Top Event Detection Efficiency

The final aim of our analysis is to calculate the single-top quark production cross section σ_{st}. The calculation is based on the following formula:

$$\sigma_{\mathrm{st}} = \frac{N_{\mathrm{signal}}}{\epsilon_{\mathrm{evt}} \cdot \int \mathcal{L}\, dt} \tag{1}$$

Here N_{signal} is the number of observed signal events, which we obtain for example from a maximum likelohood fit. ϵ_{evt} is the event detection efficiency which is the average probability of a single-top event to be detected, i.e. to be found in the sample of selected candidates. $\int \mathcal{L}\, dt$ is the integrated luminosity, which we will abbreviate as $\mathcal{L}_{\mathrm{int}}$ in the paragraphs below.

At the current stage the integrated luminosity of CDF is not high enough to make a measurement of σ_{st} which is significantly different from 0. Therefore, we will set an upper limit on the cross section. For this (1) is not directly used. However, we will use (1) to calculate the number of expected signal events. For this purpose it takes the form:

$$N_{\mathrm{signal}}^{\mathrm{predict}} = \sigma_{\mathrm{st}}^{\mathrm{theo}} \cdot \epsilon_{\mathrm{evt}} \cdot \mathcal{L}_{\mathrm{int}} \tag{2}$$

The purpose of this note is to document the calculation of ϵ_{evt}, the event detection efficiency. This is done using the Monte Carlo samples listed in Table 1. ϵ_{evt} can be decomposed into 4 factors:

$$\epsilon_{\mathrm{evt}} = \epsilon_{\mathrm{evt}}^{\mathrm{MC}} \cdot \epsilon_{\mathrm{BR}} \cdot \epsilon_{\mathrm{corr}} \cdot \epsilon_{\mathrm{trig}} \tag{3}$$

Here $\epsilon_{\mathrm{evt}}^{\mathrm{MC}}$ is the event detection efficiency as we obtain it from our samples of simulated events. In some of these samples the W boson was only allowed to decay into leptons: $W \to e/\mu/\tau + \nu$. This has to be taken into account by applying the factor $\epsilon_{\mathrm{BR}} = 0.324$ [24]. ϵ_{corr} is a correction factor which takes into account the difference between simulated and data events and thereby gives a measure of how well the Monte Carlo simulation models the detector. ϵ_{trig} is the trigger efficiency. The correction factor is again composed out of several parts:

$$\epsilon_{\mathrm{corr}} = \frac{\epsilon_{\mathrm{z0}}^{\mathrm{data}}}{\epsilon_{\mathrm{z0}}^{\mathrm{MC}}} \cdot \frac{\epsilon_{\mathrm{leptonid}}^{\mathrm{data}}}{\epsilon_{\mathrm{leptonid}}^{\mathrm{MC}}} \cdot \frac{\epsilon_{\mathrm{reco}}^{\mathrm{data}}}{\epsilon_{\mathrm{reco}}^{\mathrm{MC}}} \cdot \frac{\epsilon_{\mathrm{tag}}^{\mathrm{data}}}{\epsilon_{\mathrm{tag}}^{\mathrm{MC}}} \tag{4}$$

Since trigger and id efficiencies vary for different subdetectors (we use CEM, PHX, CMUP and CMX), we have different ϵ_{evt} in the four cases: $\epsilon_{\mathrm{evt}}^{\mathrm{CEM}}$, $\epsilon_{\mathrm{evt}}^{\mathrm{PHX}}$, $\epsilon_{\mathrm{evt}}^{\mathrm{CMUP}}$ and $\epsilon_{\mathrm{evt}}^{\mathrm{CMX}}$. The

Cut	0 jet	1 jet	2 jet	3 jet	4 jet	$\geq$ 5 jets	all
Total	11514	135394	287304	136399	25299	4150	600060
Good Run	10270	120666	256023	121352	22473	3689	534473
OBSV < 60.0	10043	117878	249895	117374	21735	3567	520492
CMX Good Total	9948	117253	248886	118075	21893	3600	519655
$\geq$ 1 Tight Std. lepton	3606	40244	71810	14471	2259	295	132685
LooseLepton cut	3604	40227	71797	14471	2259	295	132653
CEM electrons							
Tight Di-Lepton Veto	1566	18507	34122	6852	1075	133	62255
Z Vertex Cut	1566	18504	34114	6846	1074	132	62236
Z veto	1555	18302	33533	6740	1056	129	61315
Missing Et	1466	16376	30279	6056	955	118	55250
taggable (Info)	0	12019	27055	5739	933	116	45862
b tag $\geq$ 1	0	5781	13777	3349	564	88	23559
PHX electrons							
Tight Di-Lepton Veto	699	6451	9725	1871	279	39	19064
Z Vertex Cut	699	6451	9725	1871	279	39	19064
Z veto	692	6400	9599	1833	277	39	18840
Missing Et	647	5588	8367	1591	244	30	16467
taggable (Info)	0	4216	7721	1542	241	29	13749
b tag $\geq$ 1	0	1991	3862	902	165	14	6934
CMUP muons							
Tight Di-Lepton Veto	870	10383	19368	3967	620	74	35282
Z Vertex Cut	870	10383	19366	3966	620	74	35279
Z veto	869	10345	19217	3930	615	73	35049
Missing Et	813	9230	17130	3494	546	65	31278
taggable (Info)	0	6797	15271	3309	536	65	25978
b tag $\geq$ 1	0	3219	7646	1905	337	42	13149
CMX muons							
Tight Di-Lepton Veto	441	4692	8292	1715	267	48	15455
Z Vertex Cut	441	4692	8292	1715	267	48	15455
Z veto	440	4666	8248	1708	264	48	15374
Missing Et	422	4140	7323	1520	230	44	13679
taggable (Info)	0	3040	6569	1466	227	44	11346
b tag $\geq$ 1	0	1465	3340	856	146	19	5826
All							
Tight Di-Lepton Veto	3576	40033	71507	14405	2241	294	132056
Z Vertex Cut	3576	40030	71497	14398	2240	293	132034
Z veto	3556	39713	70597	14211	2212	289	130578
Missing Et	3348	35334	63099	12661	1975	257	116674
taggable (Info)	0	26072	56616	12056	1937	254	96935
b tag $\geq$ 1	0	12456	28625	7012	1212	163	49468

Table 6: Cut flow table of single top event selection for single-top t-channel events (ttop1oNew+ttop1oNew_match).

determination of $\epsilon_{\mathrm{evt}}^{\mathrm{MC}}$ from Monte Carlo simulations will be discussed in the next section. We use the following values for the trigger efficiencies and reconstruction and identification scale factors which were derived from data:

- The electron and muon trigger and identification efficiencies are listed in Table 7,

Effciencies	CEM	PHX	CMUP	CMX
Trigger	0.979±0.003	0.86±0.04	0.915± 0.005	0.962± 0.005
ID/Reco.	0.981± 0.005	0.942 ± 0.013	0.921± 0.011	0.99 ± 0.0060

Table 7: Electron and muon trigger efficiencies and ID efficiency scale (correction) factors.

see references [25, 26, 27]. We apply numbers averaged oevr the entire run range.

- $\epsilon_{z0}^{\rm data} = 0.955 \pm 0.003$ is the z vertex cut efficiency in data [28]. In Monte Carlo this efficiency can be extracted from the values listed in the acceptance tables.

- The b tagging efficiency differs between data and Monte Carlo. Therefore, we need to correct our acceptance calculation which is based on Monte Carlo events. $SF_{tag} = \epsilon_{\rm tag-jet}^{\rm data}/\epsilon_{\rm tag-jet}^{\rm MC} = 0.89 \pm 0.07$ is the correction factor for the b tagging efficiency [29]. This correction factor is valid per tagged b jet. If a Monte Carlo sample contained only events with one and only one b jet per event, the factor would be applicable globally. However, since there are also double-tagged or even triple-tagged events, a global correction factor has to be determined. It is also possible to bin the distribution of the number of b tags in the Monte Carlo samples and then use the per b tag jet scale factor given above to calculate the correction factor given per jet bin. If the fractions of 1-tag, 2-tag, and 3-tag events in a given jet bin are f_1, f_2, and f_3 respectively, then for that jet bin:

$$K_1 = SF_{tag} + 2 \cdot \frac{f_2}{f_1} SF_{tag}(1 - SF_{tag}) + 3 \cdot \frac{f_3}{f_1} SF_{tag}(1 - SF_{tag})^2 \quad (5)$$

$$K_2 = SF_{tag}^2 + 3 \cdot \frac{f_3}{f_2} SF_{tag}^2(1 - SF_{tag}) \quad (6)$$

$$K_{12} = f_1 SF_{tag} + f_2(2SF_{tag} - SF_{tag}^2) + f_3(3SF_{tag} - 3SF_{tag}^2 + SF_{tag}^3) \quad (7)$$

The results on the correction factor $K = \epsilon_{\rm tag}^{\rm data}/\epsilon_{\rm tag}^{\rm MC}$ obtained with this method are given in Table 8 for 3 cases: (1) 1 or 2 b tags (K_{12}), (2) exactly 1 b tag (K_1), (3) exactly 2 b tags (K_2).

B-tag Efficiencies				
Process	Sample	K_{12}	K_1	K_2
t-chan 1 Jet bin	ttop1oNew+ttop2oNew_match	0.89±0.07	0.89±0.07	–
t-chan 2 Jet bin	ttop1oNew+ttop2oNew_match	0.89±0.07	0.89±0.07	0.79±0.12
t-chan 3 Jet bin	ttop1oNew+ttop2oNew_match	0.91±0.06	0.93±0.05	0.79±0.13
s-chan 1 Jet bin	ttop0oNewCat	0.89±0.07	0.89±0.07	–
s-chan 2 Jet bin	ttop0oNewCat	0.92±0.06	0.96±0.03	0.79±0.12
s-chan 3 Jet bin	ttop0oNewCat	0.92±0.05	0.96±0.03	0.79±0.13

Table 8: Correction factor for the b tagging efficiency of the various single-top samples.

	t-channel		
Cut	1 jet	2 jet	3 jet
Total	135394	287304	136399
Good Run	120666	256023	121352
OBSV< 60.0	117878	249895	117374
K_1	0.89 ± 0.07	0.89 ± 0.07	0.93 ± 0.05
K_2	–	0.79 ± 0.12	0.79 ± 0.13
K_{12}	0.89 ± 0.07	0.89 ± 0.07	0.91 ± 0.06
CEM electrons			
b tag ≥ 1	5781	13777	3349
$\epsilon_{\rm MC}$ [%]	1.082	2.578	0.627
$\epsilon_{\rm event}$ $[10^{-4}]$	28.4 ± 2.7	67.1 ± 6.4	16.6 ± 1.4
PHX electrons			
b tag ≥ 1	1991	3862	902
$\epsilon_{\rm MC}$ [%]	0.373	0.723	0.169
$\epsilon_{\rm event}$ $[10^{-4}]$	8.3 ± 1.1	15.9 ± 2.1	3.8 ± 4.5
CMUP Muons			
b tag ≥ 1	3219	7646	1905
$\epsilon_{\rm MC}$ [%]	0.602	1.431	0.356
$\epsilon_{\rm event}$ $[10^{-4}]$	13.9 ± 1.5	32.7 ± 3.6	8.3 ± 0.8
CMX Muons			
b tag ≥ 1	1465	3340	856
$\epsilon_{\rm MC}$ [%]	0.274	0.625	0.160
$\epsilon_{\rm event}$ $[10^{-4}]$	7.1 ± 0.7	16.1 ± 1.6	4.2 ± 0.3
Number of expected events			
$N(695.50{\rm pb}^{-1})$	7.92 ± 0.84	18.10 ± 1.87	4.50 ± 0.40
$N(1000.00{\rm pb}^{-1})$	11.40 ± 1.20	26.05 ± 2.70	6.48 ± 0.58

Table 9: t-channel event yield estimate for the single-top event selection.

We determine the event detection efficiency based on Monte Carlo events. We apply all selection and identification cuts to the simulated data. Tables 9 and 10 summarize the calculation for t- and s-channel. The number of remaining events in the 1-jet, 2-jet and 3-jet bin after the pre-selection are given in the line named `b tag` $\geq$ `1`. We use the number of events passing the good run criterium as denominator (line `Good Run`). We apply the version 10a of the good run list. The bit combination is 1141. The Monte Carlo event detection efficiency $\epsilon_{\rm evt}^{\rm MC}$ is calculated separately for the subdetectors where the primary lepton is reconstructed: CEM, PHX, CMUP, and CMX.

	s-channel		
Cut	1 jet	2 jet	3 jet
Total	111169	283109	142314
Good Run	99418	252979	127156
OBSV< 60.0	97294	246538	122719
K_1	0.89 ± 0.07	0.96 ± 0.03	0.96 ± 0.03
K_2	–	0.79 ± 0.12	0.79 ± 0.13
K_{12}	0.89 ± 0.07	0.92 ± 0.06	0.92 ± 0.05
CEM electrons			
b tag ≥ 1	5975	20326	4220
ϵ_{MC} [%]	1.158	3.940	0.818
$\epsilon_{\mathrm{event}}$ [10^{-4}]	30.4 ± 2.9	105.3 ± 7.6	21.9 ± 1.6
PHX electrons			
b tag ≥ 1	1664	5120	1037
ϵ_{MC} [%]	0.323	0.992	0.201
$\epsilon_{\mathrm{event}}$ [10^{-4}]	7.1 ± 1.0	22.4 ± 2.5	4.5 ± 0.5
CMUP Muons			
b tag ≥ 1	3347	11469	2502
ϵ_{MC} [%]	0.649	2.223	0.485
$\epsilon_{\mathrm{event}}$ [10^{-4}]	14.9 ± 1.7	52.2 ± 4.4	11.4 ± 1.0
CMX Muons			
b tag ≥ 1	1510	4841	1019
ϵ_{MC} [%]	0.293	0.938	0.198
$\epsilon_{\mathrm{event}}$ [10^{-4}]	7.6 ± 0.7	24.9 ± 1.8	5.2 ± 0.4
Number of expected events			
$N(695.50\mathrm{pb}^{-1})$	3.67 ± 0.38	12.50 ± 1.00	2.63 ± 0.21
$N(1000.00\mathrm{pb}^{-1})$	5.28 ± 0.55	17.99 ± 1.43	3.78 ± 0.30

Table 10: s-channel event yield estimate for the single-top event selection.

To convert $\epsilon_{\mathsf{evt}}^{\mathsf{MC}} \cdot \epsilon_{\mathsf{BR}}$ into ϵ_{evt} we need to calculate ϵ_{corr} first. We have to do that for each sample separately, since the b tagging efficiency per event depends on the sample. We calculate the errors on ϵ_{corr} by adding the relative errors on $\epsilon_{\mathsf{z0}}^{\mathsf{data}}/\epsilon_{\mathsf{z0}}^{\mathsf{MC}}$, $\epsilon_{\mathsf{leptonid}}^{\mathsf{data}}/\epsilon_{\mathsf{leptonid}}^{\mathsf{MC}}$, $\epsilon_{\mathsf{reco}}^{\mathsf{data}}/\epsilon_{\mathsf{reco}}^{\mathsf{MC}}$ and $\epsilon_{\mathsf{tag}}^{\mathsf{data}}/\epsilon_{\mathsf{tag}}^{\mathsf{MC}}$. Having calculated ϵ_{corr} we compute ϵ_{evt} based on (3). The result is also presented in Tables 9 and 10. Using the values for ϵ_{evt} we calculate the number of expected events according to (2).

4 $\mathrm{t\bar{t}}$ background

$\mathrm{t\bar{t}}$ cross-section In $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV top quark production is dominated by $t\bar{t}$-pair production via the strong interaction. Quark-antiquark annihilation is the dominating sub-process, contributing about 85% of the cross section. NLO corrections to the cross section are available since the late 1980's [30, 31]. More recent calculations try to improve the predictions by resumming leading and next-to-leading logarithmic terms in the cross section. Table 11 shows the predictions of three different groups for $m_{\mathrm{top}} = 175$ GeV. The results of Berger and Contopanagos (BECO) were scaled down

	m_{top}	$\sigma_{t\bar{t}}$	Ref.
Berger and Conto.	175 GeV	$7.15^{+0.09}_{-0.55}$ pb	[3]
Bonciani et al.	175 GeV	$6.70^{+0.71}_{-0.88}$ pb	[4, 5]
Kidonakis	175 GeV	6.77 ± 0.42 pb	[6]
Bonciani et al.	170 GeV	$7.83^{+0.86}_{-1.04}$ pb	[4, 5]
Bonciani et al.	180 GeV	$5.75^{+0.59}_{-0.75}$ pb	[4, 5]

Table 11: Cross section predictions by three different groups of theorists for $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.

from their predictions for $\sqrt{s} = 2.00$ TeV. In our analysis we use the prediction by Bonciani et al. (BCMN) [4, 5] to calculate the number of expected $t\bar{t}$ events. Two reasons motivate that decision:

1. BCMN work with the most recent set of PDFs.
2. The error assigned by BCMN includes systematic uncertainties due to the choice of the PDF.

To take into account different predictions by BECO and Kidonakis we assign half the difference between BCMN and BECO as additional systematic uncertainty $\Delta_2 = 0.23$ pb and add it in quadrature to the error assigned by BCMN. Since we use a Gaussian constraint on the background in our analysis we also need to symmetrize the errors. We do that by taking the average between the negative and positive errors. Additionally, we need to add the uncertainty in $\sigma_{t\bar{t}}$ due to the top mass uncertainty $\Delta m_{\mathrm{top}} = 5$ GeV. We take the average difference between the cross section for 170/175 GeV and 180/175 GeV, which is $\Delta_3 = 1.04$ GeV. Adding all three uncertainties in quadrature we get:

$$\Delta\sigma_{t\bar{t}} = \sqrt{0.795^2 + 0.23^2 + 1.04^2}\ \mathrm{pb} = 1.32\ \mathrm{pb} \tag{8}$$

Thus, we use $\sigma_{t\bar{t}} = (6.70 \pm 1.32)$ pb. Including the scaled uncertainty due to the other theoretical predictions (also for $m_{\mathrm{top}} = 170, 180$ GeV) we get the numbers given in Table 12.

170 GeV	(7.83 ± 1.54) pb
175 GeV	(6.70 ± 1.32) pb
180 GeV	(5.75 ± 1.13) pb

Table 12: Cross section predictions used in our analysis to predict the number of $t\bar{t}$ background events.

$\epsilon_{\mathbf{evt}}$: We calculate ϵ_{evt} for $t\bar{t}$ events using the Pythia Carlo program. We use the 2965060 events of the samples *ttopvl, ttopkl, ttopyl, ttoptl*. Table 13 lists the number of Monte Carlo events in the three jet bins under consideration. Furthermore, the Monte Carlo event detection efficiency, the event detection efficiency ϵ_{evt}, and the number of expected events are given.

	$t\bar{t}$		
Cut	1 jet	2 jet	3 jet
Total	33894	208893	528711
Good Run	29831	184225	465734
OBSV< 60.0	29243	180158	453156
K_1	0.89±0.07	0.94±0.04	0.96±0.03
K_2	0.89±0.07	0.79±0.12	0.80±0.13
K_{12}	0.89±0.07	0.91±0.06	0.92±0.06
CEM electrons			
b tag ≥ 1	1792	14482	33199
ϵ_{MC} [%]	0.069	0.554	1.270
$\epsilon_{\mathrm{event}}$ [10^{-6}]	561.80±54.16	4589.46±361.41	10583.63±781.38
PHX electrons			
b tag ≥ 1	425	3828	8510
ϵ_{MC} [%]	0.016	0.146	0.326
$\epsilon_{\mathrm{event}}$ [10^{-6}]	112.39±15.04	1023.30±118.74	2288.43±254.35
CMUP Muons			
b tag ≥ 1	1071	9094	20949
ϵ_{MC} [%]	0.041	0.348	0.801
$\epsilon_{\mathrm{event}}$ [10^{-6}]	294.62±32.72	2528.81±230.57	5860.06±501.91
CMX Muons			
b tag ≥ 1	421	3614	8194
ϵ_{MC} [%]	0.016	0.138	0.313
$\epsilon_{\mathrm{event}}$ [10^{-6}]	130.88±12.75	1135.74±90.49	2590.38±193.58
Number of expected events			
$N(695.50\mathrm{pb}^{-1})$	5.11±0.53	43.13±3.73	99.13±8.05
$N(1000.00\mathrm{pb}^{-1})$	7.36±0.77	62.06±5.36	142.63±11.58

Table 13: $t\bar{t}$ event yield estimate for the single-top event selection.

5 Di-Boson Acceptance

To predict the number of di-boson events in our selected data sample we use the theoretical cross sections predicted by Campbell and Ellis [32]:

$\sqrt{s}$	WW	WZ	ZZ
2.00 TeV	13.5 pb	4.02 pb	1.60 pb
1.96 TeV	13.30 pb	3.96 pb	1.57 pb

Campbell and Ellis give a relative error on the cross sections of 3%. Their numbers are given for $\sqrt{s} = 2.00$ TeV. We rescale those numbers to 1.96 TeV. We take the mean of a linear and a quadratic interpolation. We calculate the number of expected di-boson events in the same way as for single-top and $t\bar{t}$ production. We also calculate the number of expected events for the process $Z \rightarrow \tau\tau$. For this process we determine the cross section using the Z peak mass region for the invariant mass region of the lepton pair and and a K-factor of 1.4. This leads to $\sigma_Z \cdot \mathrm{BR}(Z \rightarrow \ell^+\ell^-) = (336.0 \pm 8.0)\,\mathrm{pb}$. The uncertainty due to the luminosity is not included, since it will be considered when calculating the number of expected events. The results are shown in Tables 14, 15, 16, and 17. The Monte Carlo event detection is given separately for the different subdetectors. $\epsilon_{\mathrm{event}}$ refers to the total event detection efficiency including the corresponding scale factors. The last section of these tables summarizes the number of expected events for each process. The numbers given refer to an integrated luminosity of $695.5\,\mathrm{pb}^{-1}$ and $1\,\mathrm{fb}^{-1}$.

	WW		
Cut	1 jet	2 jet	3 jet
Total	99105	181061	166408
Good Run	84777	154614	141867
OBSV< 60.0	82307	149692	136970
K_1	0.89±0.07	0.89±0.07	0.89±0.07
K_2	0.89±0.07	0.79±0.12	0.79±0.12
K_{12}	0.89±0.07	0.89±0.07	0.89±0.07
CEM electrons			
b tag ≥ 1	178	434	114
$\epsilon_{\rm MC}$ [%]	0.034	0.084	0.022
$\epsilon_{\rm event}$ [10^{-6}]	90.19±8.69	217.59±21.10	57.21±5.50
PHX electrons			
b tag ≥ 1	74	190	49
$\epsilon_{\rm MC}$ [%]	0.014	0.037	0.009
$\epsilon_{\rm event}$ [10^{-6}]	31.63±4.23	80.35±10.83	20.74±2.78
CMUP Muons			
b tag ≥ 1	116	229	76
$\epsilon_{\rm MC}$ [%]	0.022	0.044	0.015
$\epsilon_{\rm event}$ [10^{-6}]	51.57±5.73	100.74±11.26	33.47±3.71
CMX Muons			
b tag ≥ 1	58	107	34
$\epsilon_{\rm MC}$ [%]	0.011	0.021	0.007
$\epsilon_{\rm event}$ [10^{-6}]	29.14±2.84	53.20±5.21	16.92±1.64
Number of expected events			
$N(695.50\text{pb}^{-1})$	1.87±0.20	4.17±0.45	1.18±0.13
$N(1000.00\text{pb}^{-1})$	2.69±0.29	6.00±0.64	1.70±0.18

Table 14: WW event yield estimate for the single-top event selection.

	WZ		
Cut	1 jet	2 jet	3 jet
Total	95291	174110	154370
Good Run	81708	149009	131902
OBSV< 60.0	79181	144471	127542
K_1	0.89±0.07	0.93±0.05	0.93±0.05
K_2	0.89±0.07	0.79±0.12	0.80±0.13
K_{12}	0.89±0.07	0.91±0.06	0.91±0.06
CEM electrons			
b tag ≥ 1	306	678	168
$\epsilon_{\rm MC}$ [%]	0.060	0.133	0.033
$\epsilon_{\rm event}$ [10^{-6}]	492.92±47.52	1099.10±90.62	272.88±22.04
PHX electrons			
b tag ≥ 1	174	396	101
$\epsilon_{\rm MC}$ [%]	0.034	0.078	0.020
$\epsilon_{\rm event}$ [10^{-6}]	236.43±31.64	541.50±64.86	138.38±16.34
CMUP Muons			
b tag ≥ 1	153	360	92
$\epsilon_{\rm MC}$ [%]	0.030	0.071	0.018
$\epsilon_{\rm event}$ [10^{-6}]	216.26±24.02	512.08±48.83	131.12±12.25
CMX Muons			
b tag ≥ 1	97	172	54
$\epsilon_{\rm MC}$ [%]	0.019	0.034	0.011
$\epsilon_{\rm event}$ [10^{-6}]	154.95±15.10	276.50±23.06	86.98±7.11
Number of expected events			
$N(695.50{\rm pb}^{-1})$	3.02±0.32	6.68±0.63	1.73±0.16
$N(1000.00{\rm pb}^{-1})$	4.35±0.47	9.60±0.90	2.49±0.23

Table 15: WZ event yield estimate for the single-top event selection.

	ZZ		
Cut	1 jet	2 jet	3 jet
Total	49203	89107	51898
Good Run	44683	80913	47139
OBSV< 60.0	43154	77783	45296
K_1	0.89±0.07	0.95±0.04	0.94±0.04
K_2	0.89±0.07	0.79±0.12	0.79±0.12
K_{12}	0.89±0.07	0.91±0.06	0.91±0.06
CEM electrons			
b tag ≥ 1	8	31	25
ϵ_{MC} [%]	0.002	0.008	0.007
ϵ_{event} [10^{-6}]	17.48±1.68	68.63±5.26	55.14±4.40
PHX electrons			
b tag ≥ 1	5	18	11
ϵ_{MC} [%]	0.001	0.005	0.003
ϵ_{event} [10^{-6}]	9.21±1.23	33.62±3.83	20.46±2.40
CMUP Muons			
b tag ≥ 1	16	50	14
ϵ_{MC} [%]	0.004	0.013	0.004
ϵ_{event} [10^{-6}]	30.67±3.41	97.14±8.63	27.09±2.50
CMX Muons			
b tag ≥ 1	4	25	8
ϵ_{MC} [%]	0.001	0.007	0.002
ϵ_{event} [10^{-6}]	8.67±0.84	54.89±4.26	17.50±1.41
Number of expected events			
$N(695.50\text{pb}^{-1})$	0.07±0.01	0.28±0.02	0.13±0.01
$N(1000.00\text{pb}^{-1})$	0.10±0.01	0.40±0.03	0.19±0.02

Table 16: ZZ event yield estimate for the single-top event selection.

	$Z\to \tau\tau$		
Cut	1 jet	2 jet	3 jet
Total	323686	178660	22618
Good Run	286003	157797	19992
OBSV< 60.0	275290	151450	19221
K_1	0.89±0.07	0.89±0.07	0.89±0.07
K_2	0.89±0.07	0.00±0.00	0.84±0.17
K_{12}	0.89±0.07	0.89±0.07	0.89±0.07

CEM electrons

b tag ≥ 1	19	12	5
ϵ_{MC} [%]	0.002	0.001	0.001
ϵ_{event} $[10^{-6}]$	19.03±1.83	11.89±1.16	4.95±0.48

PHX electrons

b tag ≥ 1	9	2	3
ϵ_{MC} [%]	0.001	0.000	0.000
ϵ_{event} $[10^{-6}]$	7.60±1.02	1.67±0.23	2.51±0.34

CMUP Muons

b tag ≥ 1	7	6	3
ϵ_{MC} [%]	0.001	0.001	0.000
ϵ_{event} $[10^{-6}]$	6.15±0.68	5.21±0.59	2.61±0.29

CMX Muons

b tag ≥ 1	3	5	1
ϵ_{MC} [%]	0.000	0.001	0.000
ϵ_{event} $[10^{-6}]$	2.98±0.29	4.91±0.48	0.98±0.10

Number of expected events

$N(695.50\text{pb}^{-1})$	8.37±0.90	5.53±0.57	2.58±0.28
$N(1000.00\text{pb}^{-1})$	12.04±1.29	7.96±0.82	3.72±0.41

Table 17: $Z\to \tau\tau$ event yield estimate for the single top event selection.

6 Conclusions

We present the number of expected events for single-top, $t\bar{t}$, di-boson and $Z \to \tau\tau$ events in the CDF II detector for $695.5\,\mathrm{pb}^{-1}$ and $1\,\mathrm{fb}^{-1}$ of data. Table 18 summarizes our results for the 1-jet, 2-jets and 3-jets bin after requiring at least one b tagged jet. The single top signal estimate is based on simulated events generated with MadEvent. $t\bar{t}$ and di-boson Monte Carlo events were generated with Pythia.

Process	1 jet	2 jets	3 jets
	for $1\,\mathrm{fb}^{-1}$ of data		
t-channel	11.4 ± 1.2	26.1 ± 2.7	6.5 ± 0.6
s-channel	5.3 ± 0.6	18.0 ± 1.5	3.8 ± 0.3
$t\bar{t}$	7.4 ± 0.6	62.1 ± 5.4	142.6 ± 11.6
WW	2.7 ± 0.3	6.0 ± 0.6	1.7 ± 0.2
WZ	4.4 ± 0.5	9.6 ± 0.9	2.5 ± 0.2
ZZ	0.10 ± 0.01	0.40 ± 0.03	0.19 ± 0.02
$Z \to \tau\tau$	12.1 ± 1.3	8.0 ± 0.8	3.7 ± 0.4
Total MC bkg.	26.7 ± 1.5	86.1 ± 5.6	150.7 ± 11.6
	for $695.5\,\mathrm{pb}^{-1}$ of data		
t-channel	7.92 ± 0.84	18.10 ± 1.87	4.50 ± 0.40
s-channel	3.67 ± 0.38	12.50 ± 1.00	2.63 ± 0.21
$t\bar{t}$	5.11 ± 0.53	43.13 ± 3.73	99.13 ± 8.05
WW	1.87 ± 0.20	4.17 ± 0.45	1.18 ± 0.13
WZ	3.02 ± 0.32	6.68 ± 0.63	1.73 ± 0.16
ZZ	0.07 ± 0.01	0.28 ± 0.02	0.13 ± 0.01
$Z \to \tau\tau$	8.4 ± 0.9	5.5 ± 0.6	2.6 ± 0.3
Total MC bkg.	18.5 ± 1.1	58.9 ± 3.9	104.8 ± 8.1

Table 18: Summary of number of expected events for t-channel and s-channel single-top, $t\bar{t}$ and di-boson production.

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