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W+Jets at CDF: Evidence for Top Quarks

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Recently, an anomaly of W +jets events at large invariant masses has been reported by CDF. Many interpretations as physics beyond the Standard Model are being offered. We show how such an invariant mass peak can arise from a slight shift in the relative normalization of the top and WW backgrounds.

In recent years, the Tevatron experiments have run a successful search program studying weak gauge boson and top quarks as well as searching for a Higgs boson and for new physics. A specific search for V +jets production ($V = W, Z$) [1–3] follows a long list of motivations [4]: we can test QCD effects such as the so-called staircase scaling of n -jet production [5], we can search for triple gauge boson couplings in W^+W^- and $W^\pm Z$ production [1, 6], we can search for technicolor signals [7, 8], or in the case of two bottom jets we can look for WH associated production [9]. Some of these channels include a study of the invariant mass of the two leading jets recoiling against a leptonically decaying W boson

$$p\bar{p} \rightarrow (W \rightarrow \ell\nu) + 2 \text{ jets} + X \quad (\ell = \mu, e) \quad (1)$$

In their published study of WV production based on an integrated luminosity of 3.9 fb^{-1} and focused on an invariant mass regime $m_{jj} = 50 - 130 \text{ GeV}$ the CDF collaboration has started to observe a slight excess of events in the region of $m_{jj} = 150 - 180 \text{ GeV}$ [1]. A D0 search based on the lower luminosity of 1.1 fb^{-1} does not show any excess in this mass range [10].

More recently, the CDF collaboration has published a dedicated study of the same anomaly [2] with harder background rejection cuts and reports a 3.2σ anomaly in the m_{jj} spectrum. The excess is compatible with a resonance around 150 GeV . Many papers have since been published, explaining this observation, including technicolor [11], supersymmetric [12], lepto-phobic Z' boson [13], color octets [14], and other interpretations [15]. In this paper we suggest an explanation of the excess based on a slight relative shift of the weight of different background contributions on the WV pole and in the higher-mass region. While it is possible to relieve the tension of the measurement and the background prediction for example by a systematic shift in m_{jj} to our knowledge ours is the only way to explain the observed peak within the Standard Model. Obviously, the final answer will most likely be a combination of several such background effects.

The second peak from top decays

One of the backgrounds to W +jets production is the production of top quarks. Unlike to all other Standard Model channels, top quarks lead to a second peak in the m_{jj} distribution, in addition to the W mass peak. The angular correlation behind this second peak is between the bottom and the up-type quark q_\uparrow from the W -decay. In the W rest frame the distribution is given by

$$P(\cos\theta) = \frac{3}{8} (1 + \cos\theta)^2 F_R + \frac{3}{8} (1 - \cos\theta)^2 F_L + \frac{3}{4} \sin^2\theta F_0. \quad (2)$$

In the Standard Model the relative size of these contributions is $F_0 : F_L : F_R \simeq 0.7 : 0.3 : 0$ [16]. The corresponding invariant mass m_{bq_\uparrow} is

$$P(m_{bq_\uparrow}) = \frac{f_R(r)F_R + f_L(r)F_L + f_0(r)F_0}{m_{bj}^{\max}} \quad \text{with} \quad r = \frac{m_{bq_\uparrow}}{m_{bj}^{\max}} = \sqrt{\frac{1 - \cos\theta}{2}}, \quad (3)$$

$f_R(r) = 6r(1 - r^2)^2$, $f_L(r) = 6r^5$, and $f_0(r) = 12r^3(1 - r^2)$. Its upper endpoint is $m_{bj}^{\max} = \sqrt{m_t^2 - m_W^2} = 154.6 \text{ GeV}$, neglecting the bottom mass.

The theory prediction for the m_{bq_\uparrow} distribution we show in Figure 1. Because of the left-handed W interaction m_{bq_\uparrow} gets contributions from f_L and f_0 ; m_{bq_\downarrow} corresponds to exchanging f_L and f_R . Experimentally, we cannot distinguish between q_\uparrow and q_\downarrow , so instead we define the invariant mass m_{bj_1} with the harder of the two W decay jets. This distribution is harder than m_{bq_\uparrow} . Without b tagging the only observable distribution is $m_{j_1j_2}$, using the hardest

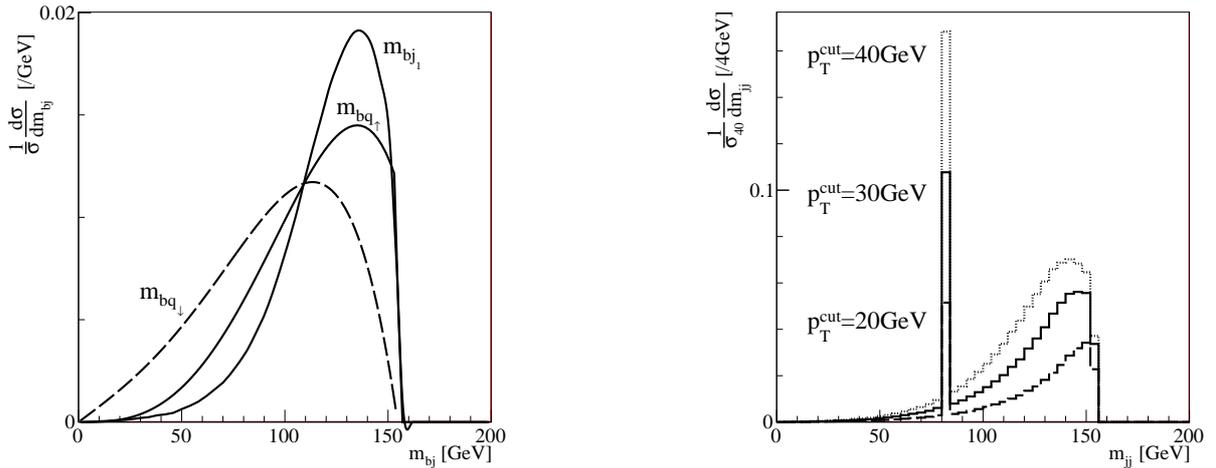


Figure 1: Left: theory predictions for the m_{bq_1} , m_{bq_2} and m_{bj_1} distributions at the parton level, simulated for top pair production. Right: $m_{j_1j_2}$ distribution with $p_{T,j_3} < 20$ GeV (dashed), 30 GeV (solid) and 40 GeV (dotted).

two jets from the top decay. It shows a double peak structure from the sum of the W peak and the m_{bj_1} distribution. In Figure 1 we also show how a stricter jet veto not only reduces the number of events but also produces a harder second peak in m_{jj} . For a W +jets analysis this implies that a resonance search really searches for a new peak on top of a not very well understood Standard Model peak.

Loose cuts

In this first part of our paper we look at the original WV analysis with the less significant but nevertheless clearly visible excess, shown in the left panel of Figure 2 [1, 17]. The basic acceptance and background rejection cuts are on one lepton and at least two jets plus missing transverse energy with

$$\begin{aligned}
 E_{T,\ell} &> 20 \text{ GeV} & \not{p}_T &< 25 \text{ GeV} & M_{T,W} &> 30 \text{ GeV} \\
 E_{T,j} &> 20 \text{ GeV} & |\eta_j| &< 2.4 & |\Delta\phi_{\not{p}_T, j_1}| &> 0.4 \\
 p_{T,jj} &> 40 \text{ GeV} & |\Delta\eta_{jj}| &< 2.5. & &
 \end{aligned} \tag{4}$$

The main background is W +jets production with a variable normalization which can be fixed from the shape of the m_{jj} distribution. This background shows essentially no structure. The second background is QCD jet production faking a lepton and missing transverse energy. For a W decaying to an electron this background is about four times the size of the muon decay signature [17]. Again, this background has no visible structure in m_{jj} .

Of roughly similar size is the top background, consisting of top pairs and of single top production. As discussed above, this background has a distinct shape, namely two peaks including a Jacobian peak around 140 GeV. We see this shape in the right panel of Figure 2. The peak arises if we combine the b jet with one of the two light-flavor jets from the W decay, which means it gets contributions from top pair production and from single top production with a W boson. In the analysis, this background is normalized to the theory predictions $\sigma_{t\bar{t}} = 7.5$ pb and $\sigma_{\text{single } t} = 2.9$ pb [20]. The signal in this analysis is WV production. It has a clear peak dominated by W^+W^- production at $m_{jj} = 80$ GeV, smeared by the experimental resolution. Its extracted rate, corrected to the total cross section without any detector effects or branching ratios is 13.5 ± 4.4 pb for electrons and 23.5 ± 4.9 pb for muons. In combination this gives $18.1 \pm 3.3(\text{stat}) \pm 2.5(\text{syst})$ pb. This combined number is compatible with the theory prediction.

However, the two significantly different results for the electron and the muon analyses with their different background compositions mostly in the Z +jets and QCD jets channels raise the question how well we actually know the total composition of all backgrounds. For backgrounds which do not have a distinct m_{jj} shape this question is not very relevant, but for the top background and the WV signal it matters. In the right panel of Figure 2 we first show the individual templates for the top background and for the WV channel. Our simulation is based on ALPGEN [18] + PYTHIA [19] at the particle level. To model the measured m_{jj} distribution we apply a Gaussian smearing. Our

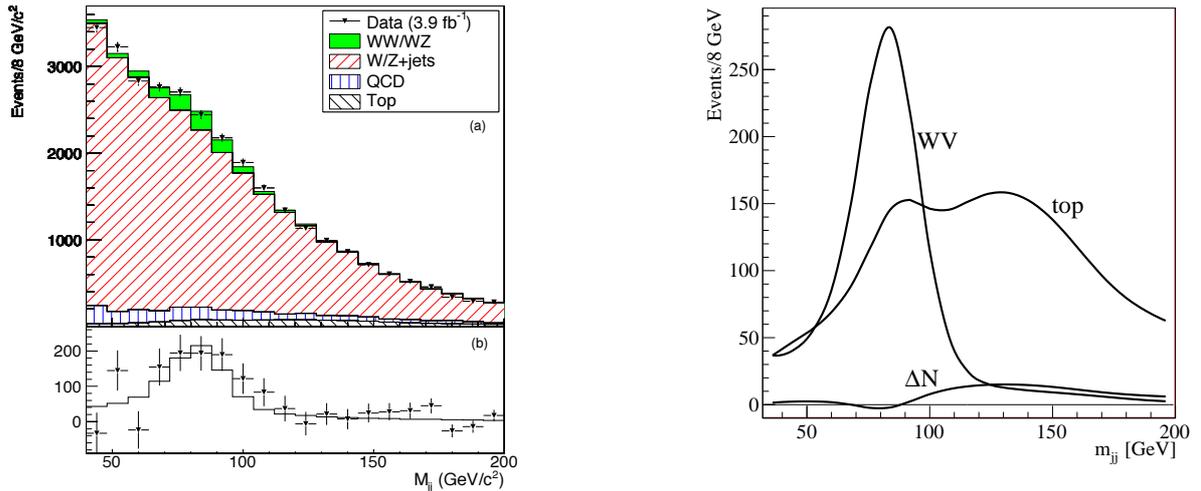


Figure 2: Left: excess in the m_{jj} distribution above the WV peak, as reported by CDF [1]. The electron and muon decay channels are added. Right: m_{jj} templates for the WV and top samples individually. The normalization is chosen to match the CDF data. We also show the difference between the two samples for a 10% change of σ_{top} and a corresponding shift in σ_{WV} , as described in the text.

template m_{jj} distributions reproduce the CDF results [17]. The normalization we fix to the 4.3 fb^{-1} of Ref. [17], to properly take into account detector effects and efficiencies. This means that whenever we discuss the normalization of different cross sections we refer to the total rate after efficiencies and detector effects.

The difference between the two templates becomes relevant if we change the relative contributions of the top and WV backgrounds. The difference clearly matches the slight observed excess. To quantify this effect we compute the change in event numbers associated with a shift of the integrated rate or efficiency. We independently consider the peak region and the high mass regime

$$\begin{aligned} \Delta N_{[64,96]} &= 926 \frac{\Delta\sigma_{WV}}{\sigma_{WV}} + 542 \frac{\Delta\sigma_{\text{top}}}{\sigma_{\text{top}}} \\ \Delta N_{[120,170]} &= 88 \frac{\Delta\sigma_{WV}}{\sigma_{WV}} + 915 \frac{\Delta\sigma_{\text{top}}}{\sigma_{\text{top}}} . \end{aligned} \quad (5)$$

These event numbers correspond to the CDF analysis [17]. Requiring that the sensitive normalization of the WV mass peak $m_{jj} = 64 - 96 \text{ GeV}$ be unchanged relates the two shifts as $(\Delta\sigma_{WV})/\sigma_{WV} = -0.59 (\Delta\sigma_{\text{top}})/\sigma_{\text{top}}$, assuming efficiencies do not vastly vary between the two mass windows. Using this relation we find a net shift in the high mass region

$$\Delta N_{[120,170]} = 863 \frac{\Delta\sigma_{\text{top}}}{\sigma_{\text{top}}} . \quad (6)$$

Throughout this paper σ really means the cross section after cuts and efficiencies, *i.e.* $\sigma \times \epsilon_{\text{cuts}} \times \epsilon_{\text{rec}}$. The shape of the difference we show in Figure 2 for $(\Delta\sigma_{\text{top}})/\sigma_{\text{top}} = 10\%$. The experimentally observed excess for the loose set of cuts has the same shape. In Figure 2 the mass window $m_{jj} = 120 - 170 \text{ GeV}$ includes roughly 100 events which usually are attributed to the WV contribution and any kind of new physics. If we conservatively neglect possible WV contributions, according to Eq.(6) this corresponds to an $\mathcal{O}(10\%)$ shift in the combined top rate.

For the sum of top pairs and single top production with its different hard processes this shift could arise from a combination of experimental efficiencies and distributions mostly of the many jets involved. For example, the number of events which we expect from the combined top sample is very sensitive to the $p_{T,j}$ requirements we apply. Moreover, from the CDF publications [1, 17] it is not clear how exactly the tW single top channel has been computed [

22]

. Its size before cuts ranges around 1% of the top pair cross section [21], but after the cuts Eq.(4) it could well account for a larger fraction of the shift in relative normalization.

The compensating shift in the WV rate is even smaller and clearly within the sizable uncertainties of up to $\mathcal{O}(30\%)$ for the individual decay channels. In short, a very slight shift of the top sample normalization after cuts and efficiencies

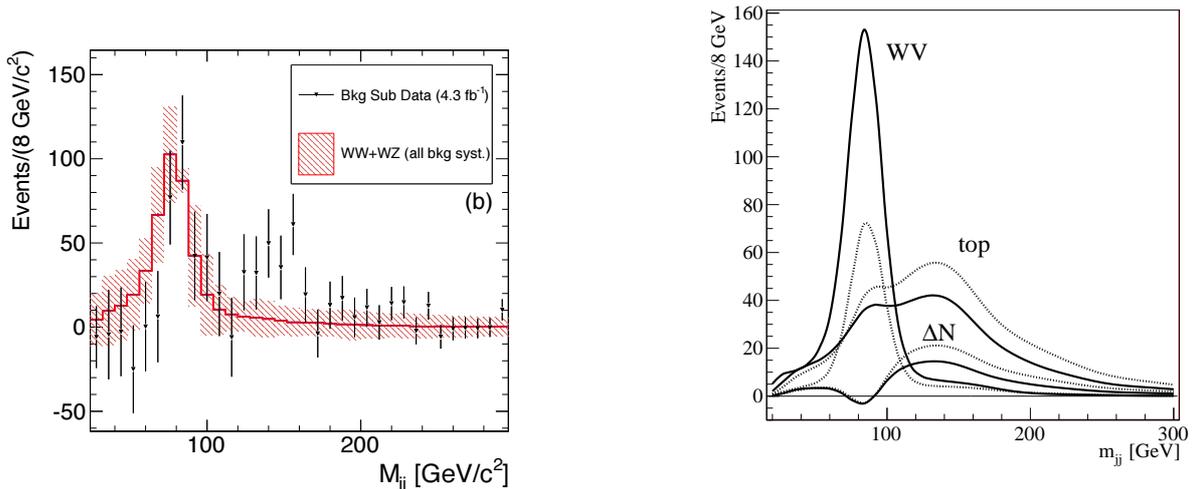


Figure 3: Left: excess in the m_{jj} distribution above the WV peak, as reported by CDF [2]. The electron and muon decay channels are added. Right: m_{jj} templates for the WV and top samples individually. The dark lines assume $E_{T,j} = 30$ GeV for the jet criteria, the lighter lines 40 GeV. We also show the difference between the two samples for a 40% change of σ_{top} and a corresponding shift in σ_{WV} , as described in the text.

compensated for by a shift of the WV rate completely explains the observed high- m_{jj} anomaly. We should, however, remark that this loose cuts analysis is not a serious challenge to Standard Model explanations. It only serves as a way to illustrate and check our approach before we apply it to the more challenging dedicated analysis [2].

Hard cuts

After observing the m_{jj} anomaly in their WV analysis CDF performed a dedicated analysis of this shape. To focus on the high-mass regime and to remove backgrounds they change some of the cuts shown in Eq.(4) to

- (1) exactly two jets with $E_{T,j} > 30$ GeV (2) additional dilepton veto . (7)

As we will see later, the veto on three or more jets makes a big difference, both in the extraction of the signal and in the uncertainties on the background estimates. Unlike for the loose cuts this experimental analysis show a distinct excess in Figure 3. The additional requirements affects the relative composition of all channels in the $m_{jj} = [28, 200]$ GeV window [17]. For example, WV production now contributes 6.4% of all events, compared to 3.4% for the loose cuts. The top contribution very slightly decreases from 6.0% to 5.8%. For the two mass windows we now find

$$\begin{aligned} \Delta N_{[64,96]} &= 475 \frac{\Delta\sigma_{WV}}{\sigma_{WV}} + 137 \frac{\Delta\sigma_{\text{top}}}{\sigma_{\text{top}}} \\ \Delta N_{[120,170]} &= 45 \frac{\Delta\sigma_{WV}}{\sigma_{WV}} + 244 \frac{\Delta\sigma_{\text{top}}}{\sigma_{\text{top}}}. \end{aligned} \quad (8)$$

Again, we use σ for the cross section after cuts and efficiencies, *i.e.* $\sigma \times \epsilon_{\text{cuts}} \times \epsilon_{\text{rec}}$. The number of events contributed by the different channels we show in some more detail in Table I. The relative normalization for Eq.(8) is fixed by the WV peak region, giving us $(\Delta\sigma_{WV})/\sigma_{WV} = -0.29 (\Delta\sigma_{\text{top}})/\sigma_{\text{top}}$ and

$$\Delta N_{[120,170]} = 231 \frac{\Delta\sigma_{\text{top}}}{\sigma_{\text{top}}}. \quad (9)$$

Naively, we see around 230 events in the high mass region $m_{jj} = 120 - 170$ GeV. From this number we have to subtract the number of events which are described by the WV channel, including systematic uncertainties. This leaves us with around 150 events which can for example be explained by a Gaussian new physics contribution.

However, this number of events changes after a more careful study of the m_{jj} distribution. First, in the $m_{jj} = 170 - 250$ GeV range we see a significant tail, consistently 10 to 20 events above the WV expectations. They might

	loose cuts							hard cuts						
	<i>tbW</i>	<i>tb</i>	<i>tj</i>	single <i>t</i>	<i>t</i> \bar{t}	top combined	<i>WV</i>	<i>tbW</i>	<i>tb</i>	<i>tj</i>	single <i>t</i>	<i>t</i> \bar{t}	top combined	<i>WV</i>
$N_{[28,200]}$	246	79.3	135	460 (19%)	2013 (81%)	2473 (100%)	1384	57.5	38.5	67.9	164 (26%)	476 (74%)	640 (100%)	704
$N_{[65,95]}$	54.8	18.1	29.8	103 (19%)	439 (81%)	542 (100%)	926	12.9	7.7	12.9	33.5 (24%)	103 (76%)	137 (100%)	475
$N_{[120,170]}$	90.2	23.1	42.8	156 (17%)	759 (83%)	915 (100%)	88	21.3	13.3	25.3	59.8 (25%)	184 (75%)	244 (100%)	45

Table I: Event numbers after normalization to the results shown in Ref. [17] for the relevant sub-processes and separated for the three interesting m_{jj} mass ranges. For the top sample we give the percentage contribution from top pairs and single top production.

be explained by some kind of continuous background which would also contribute to the $m_{jj} = 170 - 250$ GeV window. Secondly, under the WV peak of Figure 3 there are clearly events missing, of the order of 50. Our simple compensation of the WV and top channels cannot account for them because they are missing in the left side of the peak. Standard Model channels which rapidly drop towards larger m_{jj} values should help explaining them. This way we would slightly decrease the number of events missing in the higher mass regime.

Nevertheless, explaining an excess of more than 100 events in the $m_{jj} = 120 - 170$ GeV requires a sizable shift in the normalization of the top sample. The discussion around Eq.(9) implies $\Delta\sigma_{\text{top}} \gtrsim 0.43\sigma_{\text{top}}$ and a compensating shift in the WV rate of the order of $\mathcal{O}(10\%)$.

Of course, this does not mean a 43% shift in the theoretically predicted total cross section for top production. Almost a third of the the combined top sample is single top production. For the jet veto survival probability the CDF analysis includes neither a reliable experimental [23] nor a reliable theoretical estimate [21]. Thus, we expect a very large error bar on the single top rate after cuts and efficiencies the moment we try to understand the different channels or equivalently the QCD features of single top production. Top pair production might not be quite as critical because the parton shower approximation should describe jets properly [5, 24].

All efficiencies very strongly depend on the detailed simulation of the QCD jet activity and the p_T requirements. For example, if we increase the detection and veto threshold from 30 GeV to 40 GeV the over-all efficiency increases quite dramatically for the top sample, as shown in Figure 3 and expected from Figure 1. In addition, it changes the shape of the top template. A reduced efficiency for WV events means that instead of Eq.(9) we find $(\Delta\sigma_{WV}/\sigma_{WV}) = -0.68(\Delta\sigma_{\text{top}})/\sigma_{\text{top}}$ and makes it easier to explain the second peak. This indicates large theory and systematic uncertainties associated with the jet veto. The fact that it is challenging to describe the top sample after jet related cuts is illustrated by the poor separation of different single top channels in the corresponding CDF analysis [23]. We check that the corresponding uncertainty for loose cuts without a jet veto is very well under control.

Taking our 40 GeV templates at face value the required change in the combined top rate drops significantly, entirely due to a strong dependence on the poorly understood jet veto survival probability. In essence, subtracting combined top backgrounds after a jet veto combines too many caveats which have to be taken into account as correspondingly large systematic and theoretical uncertainties*.

Summary

We have shown that the apparent excess in W +jet events can be explained by Standard Model top backgrounds. Hadronically decaying top quarks generically produce two peaks in the m_{jj} distribution, one at the W mass and a second one in the 140 GeV range.

To explain the CDF measurements we have to enhance the normalization of the combined top pair and single top templates after cuts and detector efficiencies. Given the inherent difficulties in quantifying jet veto survival probabilities, such a shift in the 10% (for the WV analysis without a jet veto) or the 40% (for the high-mass analysis with a jet veto) range appears reasonable and expected from QCD considerations and the level of agreement of the CDF single top analysis with the Standard Model expectations [23]. To maintain the measured event numbers under the WV peak we compensate for this shift in the top template with another shift in the WV normalization. The latter does not exceed 10% and is well within the uncertainties indicated by the different CDF results for the individual electron and muon channels.

While our scenario might not point to the only experimental problem with the observed CDF anomaly, it clearly shows that the CDF analysis relies on a peak-on-peak background subtraction. Because the jet veto survival prob-

*Very similar bottom lines will apply to many LHC searches to come.

ability and hence the normalization of the peaked background is not well understood, such a subtraction is likely to produce a fake signal for new physics.

Note added: after this work was finished, another paper with somewhat similar conclusions appeared [25].

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