Next-to-leading order \( pp \to W' \to tb \) production at 14 TeV and 33 TeV

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I update the predicted leading order and next-to-leading order cross sections and total widths for \( W' \) bosons that decay to top and bottom quarks at 14 TeV and 33 TeV \( pp \) colliders \( (pp \to W' \to tb) \). Separate tables are included for right- and left-handed bosons. Theoretical uncertainties are completely dominated by parton distribution function uncertainties, and are computed for \( W_{\pm} \) production at a 14 TeV \( pp \) collider.

New charged vector currents, generically called \( W' \) bosons, appear in many models with extended gauge explanations of electroweak symmetry breaking. As long as these new bosons couple to fermions, a model-independent search can probe the parameter space of all such models by looking for the decay of the \( W' \) boson into a final state involving a top quark and bottom quark \cite{1}. While the general case of mixed right- and left-handed couplings can be probed, nearly all models assume a term enters the Lagrangian of the form

\[
\mathcal{L} = \frac{g'}{2\sqrt{2}} V'_{ij} W_{\mu} f_i f_j \gamma^\mu (1 \pm \gamma_5) f^j + \text{H.c.},
\]

where \( g' \) plays the role of \( g_{SM} \) from the Standard Model (SM), and \( V'_{ij} \) is a generalized Cabibbo-Kobayashi-Maskawa (CKM) matrix that also allows for lepton generation mixing.

Searches for \( W' \) bosons decaying to a top and bottom quark final state \cite{1} have been performed since Run I of the Fermilab Tevatron \cite{2}. The now standard analysis involves searching for a \( t\bar{b}j\) invariant mass peak, where each object is isolated, and applies loose \( W \) and top-mass constraints to reduce backgrounds \cite{1}. Last year we updated the standard analysis to optimize the search for the 7 TeV and 8 TeV runs of the Large Hadron Collider \cite{3}. The ATLAS \cite{4} and CMS \cite{5} Collaborations used the cross sections of Ref. \cite{3} to publish strong lower bounds on the mass of a \( W' \) boson. Current mass limits are \( \sim 2000 \) GeV if the \( W' \) boson has Standard Model-like (SM) couplings.

A previous full simulation study of the reach at a 14 TeV \( pp \) collider was performed in 2003 \cite{6}. The conclusions of that study showed the mass reach with SM-like couplings should be \( \sim 5-5.5 \) TeV, or about \( 1/3 \) of the collider energy. This limit is directly attributable to the loss of quark-antiquark luminosity in a \( pp \) collider at large-\( x \) proton momentum fraction. More important, Ref. \cite{6} presented the model-independent reach in the coupling ratio \( g'/g_{SM} \) versus \( W' \) mass, and compared it to a few classes of models. One of the key results of Ref. \cite{6} was that all models with narrow-width \( W' \) bosons fall somewhere in this space. Hence, all experimental measurements should produce limits, or a discovery, as a function of \( g'/g_{SM} \) versus \( M_{W'} \).

Just prior to the final meeting of the Community Summer Study, in Ref. \cite{7} we proposed a new analysis that expands the reach in the \( tb \) final state by searching for a “boosted-top” tag, where the \( Wj \) decay products of the top quark decay can not be isolated. In addition, we introduced a new “boosted-bottom” tag to identify bottom jets in the TeV range in order to overcome dijet backgrounds. This new search is optimized for TeV dijets with one boosted-top and one boosted-bottom tag. Using this search method it should be possible to extend the existing mass reach for \( W' \) bosons with SM-like couplings to about 2600 GeV, and the model-independent reach in coupling ratio \( g'/g_{SM} \) by nearly a factor of two if \( M_{W'} > 1500 \) GeV with existing 8 TeV LHC data. This analysis should be done for the upcoming 14 TeV run of the LHC as well.

This white paper summarizes the leading order (LO) and next-to-leading order (NLO) cross sections and widths for \( pp \to W' \to tb \) production for the upcoming 14 TeV run of the Large Hadron Collider, and the proposed 33 TeV run examined by the Community Summer Study (CSS). Detailed study of the kinematics has shown that in both the standard \cite{3} and boosted \cite{7} analyses, the NLO correction can be treated as a \( K \)-factor times LO. Hence, the tables below list both LO and NLO results for a wide range of possible \( W' \) masses.

All cross sections are calculated using the code from Ref. \cite{1}, updated for modern parton distribution function (PDF) sets and CKM matrix values. Leading order cross sections are calculated with CTEQ6L1 parton distribution functions (PDFs) \cite{8}, while NLO cross sections use CT10 \cite{8} PDFs. The top-quark mass is taken to be \( 173.2 \pm 1 \) GeV \cite{9}, and \( \alpha_s = 0.118 \pm 0.001 \). Uncertainties due to the top-quark mass and \( \alpha_s \) are negligible (< 1%) for the \( W' \) masses shown. Estimates of the NLO theoretical uncertainty due to choice of scale is also comparatively small (1–2%) in all cases. Hence, the central values of the predictions are shown to three decimal places. Using the standard CTEQ

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Modified Tolerance Method for error determination (first published for this cross section [1]) and CT10, the current PDF uncertainty ranges from 10–30% depending on the $W'$ mass, and whether it is right- or left-handed. These uncertainties should come down with improved fitting of large-$x$ PDFs using LHC data.

Cross sections are calculated for $\bar{t}b$ and $t\bar{b}$ separately, for both 14 TeV and 33 TeV $pp$ colliders. Cross sections at 14 TeV for right-handed $W'_R$ bosons are listed by mass at LO and NLO in femtobarns in Table I. Current PDF uncertainties are shown for the NLO cross sections. Cross sections for left-handed $W'_L$ bosons are listed by mass at LO and NLO in femtobarns in Table II. Note, the left-handed cross sections assume no interference with the standard model production process. See Sec. II of Ref. [2] for a description of how to use the left-handed normalizations. Cross sections at 33 TeV are listed for $W'_R$ and $W'_L$ in Tables III and IV respectively. LO and NLO total widths for the $W'$ bosons are also provided in all tables for use in simulation studies.

Many models that attempt to explain electroweak symmetry breaking predict the existence of $W'$ bosons. This white paper provides the LO and NLO cross sections and total widths necessary to determine the model-independent reach at 14 TeV and 33 TeV $pp$ colliders. Since resonant production is expected up to $\sim 1/3$ of the collider energy, a 33 TeV $pp$ collider should be able to observe or exclude most perturbative models with $W'$ bosons with masses below 10 TeV.

Acknowledgments

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TABLE I: LO and NLO total width in (GeV) and cross section with PDF errors in (fb) vs. \( M_{W_R} \) at \( \sqrt{s} = 14 \) TeV, where the decay to leptons is not allowed.

| Mass (GeV) | \( \Gamma_{LO} \) (GeV) | \( \sigma^0_{LO} \) (fb) | \( \sigma^0_{NLO} \) (fb) | \( \Gamma_{NLO} \) (GeV) | \( \sigma^0_{NLO} \) (fb) | \( \sigma^0_{NLO} \) (fb) |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 500 | 11.97 | 87300 | 48400 | 12.47 | 112000 | +7600 | -5200 |
| 750 | 18.58 | 22700 | 11300 | 19.24 | 29000 | +1400 | -1800 |
| 1000 | 25.07 | 7960 | 3580 | 25.88 | 9970 | +960 | -350 |
| 1250 | 31.51 | 3350 | 1380 | 32.46 | 4210 | +280 | -420 |
| 1500 | 37.93 | 1580 | 600 | 39.03 | 1950 | +120 | -180 |
| 1750 | 44.33 | 805 | 284 | 45.58 | 779 | +67 | -64 |
| 2000 | 50.72 | 432 | 142 | 52.11 | 369 | +33 | -40 |
| 2250 | 57.11 | 242 | 75.5 | 58.65 | 186 | +20 | -17 |
| 2500 | 63.49 | 139 | 41.4 | 65.17 | 98.7 | +11.0 | -11.1 |
| 2750 | 69.86 | 81.6 | 23.4 | 71.70 | 54.3 | +6.8 | -6.8 |
| 3000 | 76.24 | 48.8 | 13.6 | 78.22 | 30.9 | +4.2 | -4.4 |
| 3250 | 82.61 | 29.6 | 8.06 | 84.73 | 18.1 | +3.0 | -2.8 |
| 3500 | 88.99 | 18.1 | 4.88 | 91.23 | 10.8 | +1.8 | -1.9 |
| 3750 | 95.36 | 11.2 | 3.02 | 97.76 | 6.57 | +1.43 | -1.02 |
| 4000 | 101.7 | 7.05 | 1.90 | 104.3 | 4.13 | +0.84 | -0.82 |
| 4250 | 108.1 | 4.47 | 1.226 | 110.8 | 2.62 | +0.63 | -0.49 |
| 4500 | 114.5 | 2.87 | 0.806 | 117.3 | 1.71 | +0.41 | -0.34 |
| 4750 | 120.8 | 1.87 | 0.543 | 123.8 | 1.13 | +0.29 | -0.21 |
| 5000 | 127.2 | 1.24 | 0.375 | 130.3 | 0.765 | +0.205 | -0.137 |
| 5250 | 133.6 | 0.841 | 0.266 | 136.8 | 0.35 | +0.126 | -0.104 |
| 5500 | 139.9 | 0.586 | 0.194 | 143.3 | 0.380 | +0.091 | -0.065 |
| 5750 | 146.3 | 0.419 | 0.145 | 149.8 | 0.278 | +0.062 | -0.044 |
| 6000 | 152.7 | 0.309 | 0.112 | 156.3 | 0.209 | +0.042 | -0.030 |
| 6250 | 159.0 | 0.235 | 0.088 | 162.8 | 0.161 | +0.028 | -0.022 |
| 6500 | 165.4 | 0.184 | 0.071 | 169.3 | 0.102 | +0.014 | -0.010 |
| 6750 | 171.8 | 0.148 | 0.059 | 175.8 | 0.084 | +0.009 | -0.008 |
| 7000 | 178.1 | 0.121 | 0.049 | 182.3 | 0.070 | +0.008 | -0.006 |
| Mass (GeV) | $\Gamma_{\text{LO}}$ (GeV) | $\sigma_{\text{LO}}^6$ (fb) | $\sigma_{\text{LO}}^6$ (fb) | $\Gamma_{\text{NLO}}$ (GeV) | $\sigma_{\text{NLO}}^6$ (fb) | $\sigma_{\text{NLO}}^6$ (fb) |
|-----------|----------------|----------------|----------------|----------------|----------------|----------------|
| 500       | 16.21          | 64100          | 35600          | 16.71          | 84300          | 47200          |
| 750       | 24.95          | 16800          | 8370           | 25.60          | 21700          | 11000          |
| 1000      | 33.56          | 5950           | 2680           | 34.36          | 7610           | 3510           |
| 1250      | 42.12          | 2510           | 1040           | 43.07          | 3190           | 1350           |
| 1500      | 50.66          | 1190           | 452            | 51.76          | 1480           | 594            |
| 1750      | 59.18          | 606            | 215            | 60.43          | 742            | 282            |
| 2000      | 67.69          | 326            | 108            | 69.08          | 395            | 143            |
| 2250      | 76.20          | 183            | 57.5           | 77.74          | 219            | 76.1           |
| 2500      | 84.70          | 105            | 31.7           | 86.39          | 124            | 41.9           |
| 2750      | 93.20          | 62.2           | 18.1           | 95.03          | 72.7           | 24.0           |
| 3000      | 101.7          | 37.4           | 10.6           | 103.7          | 42.9           | 14.2           |
| 3250      | 110.2          | 22.8           | 6.33           | 112.3          | 25.9           | 8.52           |
| 3500      | 118.7          | 14.1           | 3.88           | 120.9          | 15.9           | 5.28           |
| 3750      | 127.2          | 8.82           | 2.43           | 129.6          | 9.86           | 3.32           |
| 4000      | 135.7          | 5.59           | 1.55           | 138.2          | 6.23           | 2.16           |
| 4250      | 144.2          | 3.59           | 1.02           | 146.8          | 3.98           | 1.42           |
| 4500      | 152.6          | 2.34           | 0.683          | 155.5          | 2.61           | 0.958          |
| 4750      | 161.1          | 1.55           | 0.469          | 164.1          | 1.74           | 0.662          |
| 5000      | 169.6          | 1.05           | 0.331          | 172.7          | 1.19           | 0.471          |
| 5250      | 178.1          | 0.731          | 0.240          | 181.4          | 0.842          | 0.343          |
| 5500      | 186.6          | 0.521          | 0.179          | 190.0          | 0.612          | 0.256          |
| 5750      | 195.1          | 0.382          | 0.136          | 198.6          | 0.459          | 0.195          |
| 6000      | 203.6          | 0.288          | 0.107          | 207.2          | 0.353          | 0.153          |
| 6250      | 212.1          | 0.223          | 0.085          | 215.9          | 0.277          | 0.122          |
| 6500      | 220.6          | 0.177          | 0.070          | 224.5          | 0.225          | 0.100          |
| 6750      | 229.0          | 0.144          | 0.058          | 233.1          | 0.185          | 0.082          |
| 7000      | 237.5          | 0.119          | 0.048          | 241.7          | 0.155          | 0.069          |
TABLE III: LO and NLO total width in (GeV) and cross section in (fb) vs. \(W_R\) mass for \(pp \rightarrow W'_R \rightarrow t\bar{b} (\bar{t}b)\) at \(\sqrt{S} = 33\) TeV, where the decay to leptons is not allowed.

| Mass (GeV) | \(\Gamma_{LO}\) (GeV) | \(\sigma_{LO}^{t\bar{b}}\) (fb) | \(\sigma_{LO}^{\bar{t}b}\) (fb) | \(\Gamma_{NLO}\) (GeV) | \(\sigma_{NLO}^{t\bar{b}}\) (fb) | \(\sigma_{NLO}^{\bar{t}b}\) (fb) |
|------------|------------------------|-------------------------------|-----------------------------|------------------------|-----------------------------|-----------------------------|
| 500        | 11.97                  | 281000                        | 183000                      | 12.47                  | 345000                      | 229000                      |
| 1000       | 25.07                  | 31100                        | 17900                      | 25.88                  | 38400                      | 22900                      |
| 1500       | 37.93                  | 7610                         | 3960                      | 39.03                  | 9560                      | 5030                       |
| 2000       | 50.72                  | 2660                         | 1270                      | 52.11                  | 3290                      | 1620                       |
| 2500       | 63.49                  | 1130                         | 496                      | 65.17                  | 1410                      | 638                        |
| 3000       | 76.24                  | 543                           | 221                      | 78.22                  | 665                      | 281                        |
| 4000       | 101.7                  | 157                          | 56.3                      | 104.3                  | 188                      | 72.1                       |
| 5000       | 127.2                  | 54.3                          | 17.5                      | 130.3                  | 63.7                      | 22.6                       |
| 6000       | 152.7                  | 20.8                          | 6.23                      | 156.3                  | 24.0                      | 8.09                       |
| 7000       | 178.1                  | 8.51                          | 2.43                      | 182.3                  | 9.53                      | 3.18                       |
| 8000       | 203.6                  | 3.64                          | 1.02                      | 208.4                  | 4.00                      | 1.35                       |
| 9000       | 229.1                  | 1.62                          | 0.457                      | 234.4                  | 1.76                      | 0.609                      |
| 10000      | 254.5                  | 0.750                          | 0.220                      | 260.4                  | 0.812                      | 0.297                      |
| 11000      | 280.0                  | 0.363                          | 0.114                      | 286.3                  | 0.395                      | 0.155                      |
| 12000      | 305.4                  | 0.187                          | 0.064                      | 312.3                  | 0.208                      | 0.087                      |
| 13000      | 330.9                  | 0.104                          | 0.039                      | 338.3                  | 0.119                      | 0.053                      |
| 14000      | 356.4                  | 0.063                          | 0.025                      | 364.3                  | 0.074                      | 0.035                      |
| 15000      | 381.8                  | 0.041                          | 0.018                      | 390.3                  | 0.051                      | 0.024                      |
TABLE IV: LO and NLO total width in (GeV) and cross section with PDF errors in (fb) vs. $W'_L$ mass for $pp \rightarrow W'_L \rightarrow t\bar{b}$ ($\bar{t}b$) at $\sqrt{S} = 33$ TeV, where the decay to leptons is allowed, but no interference is included.

| Mass (GeV) | $\Gamma_{LO}$ (GeV) | $\sigma^{LO}_{LO}$ (fb) | $\sigma^{LO}_{NLO}$ (fb) | $\Gamma_{NLO}$ (GeV) | $\sigma^{NLO}_{LO}$ (fb) | $\sigma^{NLO}_{NLO}$ (fb) |
|------------|---------------------|------------------------|-------------------------|---------------------|------------------------|-------------------------|
| 500        | 16.21               | 206000                 | 134000                  | 16.71               | 254000                 | 172000                  |
| 1000       | 33.56               | 23200                  | 13400                   | 34.36               | 29600                  | 17100                   |
| 1500       | 50.66               | 5700                   | 2970                    | 51.76               | 7210                   | 3850                    |
| 2000       | 67.69               | 1990                   | 952                     | 69.08               | 2490                   | 1220                    |
| 2500       | 84.70               | 848                    | 374                     | 86.39               | 1050                   | 488                     |
| 3000       | 101.7               | 408                    | 167                     | 103.7               | 504                    | 216                     |
| 4000       | 135.7               | 119                    | 42.8                    | 138.2               | 143                    | 55.7                    |
| 5000       | 169.6               | 41.2                   | 13.5                    | 172.7               | 48.5                   | 17.4                    |
| 6000       | 203.6               | 15.9                   | 4.83                    | 207.2               | 18.4                   | 6.32                    |
| 7000       | 237.5               | 6.56                   | 1.91                    | 241.7               | 7.43                   | 2.51                    |
| 8000       | 271.5               | 2.85                   | 0.818                   | 276.2               | 3.18                   | 1.09                    |
| 9000       | 305.4               | 1.29                   | 0.377                   | 310.7               | 1.43                   | 0.506                   |
| 10000      | 339.4               | 0.612                  | 0.187                   | 345.2               | 0.676                  | 0.253                   |
| 11000      | 373.3               | 0.306                  | 0.100                   | 379.7               | 0.340                  | 0.137                   |
| 12000      | 407.3               | 0.164                  | 0.058                   | 414.1               | 0.186                  | 0.079                   |
| 13000      | 441.2               | 0.095                  | 0.036                   | 448.6               | 0.111                  | 0.050                   |
| 14000      | 475.1               | 0.059                  | 0.024                   | 483.1               | 0.071                  | 0.033                   |
| 15000      | 509.1               | 0.040                  | 0.017                   | 517.5               | 0.049                  | 0.023                   |