Discovery potential for $T' \to tZ$ in the trilepton channel at the LHC

Lorenzo Basso
IPHC, Strasbourg

Based on LB, J. Andrea, arxiv:1411.7587

GDR 2014 Terascale@Heidelberg

Outline

- Simplified model for T' analyses
- Cut-based analysis
- Glimpses of MVA
- Results: Discovery potential
- Conclusions

Introduction

LHC run-I at $\sqrt{s} = 7/8$ TeV: found the Higgs boson

LHC run-II at $\sqrt{s} = 13(14)$ TeV: (among others) study Higgs boson properties, clarify if SM boson, search for New Physics

Which NP? To stay with the scalar sector, many BSM theories predicts new heavy fermions to stabilise the Higgs boson mass and to protect it from dangerous quadratic divergences

Generally, heavy partners of the third generation quarks with *vector-like* couplings: Extra Dimensions, Little Higgs Models, Composite Higgs Models

Here, **singlet top partner**: T'. Many models $\rightarrow$ simplified model

We also allow for generic mixing to 1^{st} generation quarks

Simplified model

M. Buchkremer et al. **Nucl.Phys. B876**, 376 (2013) [1305.4172]

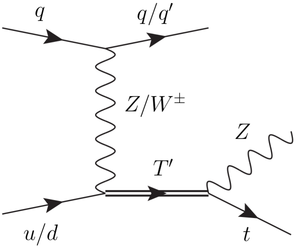
$$\mathcal{L}_{\mathrm{T}'} = g^* \left\{ \sqrt{\frac{R_L}{1+R_L}} \frac{g}{\sqrt{2}} [\overline{T'}_L W_\mu^+ \gamma^\mu d_L] + \sqrt{\frac{1}{1+R_L}} \frac{g}{\sqrt{2}} [\overline{T'}_L W_\mu^+ \gamma^\mu b_L] + \sqrt{\frac{R_L}{1+R_L}} \frac{g}{2\cos\theta_W} [\overline{T'}_L Z_\mu \gamma^\mu u_L] + \sqrt{\frac{1}{1+R_L}} \frac{g}{2\cos\theta_W} [\overline{T'}_L Z_\mu \gamma^\mu t_L] \right\} + h.c.$$

Only 3 parameters:

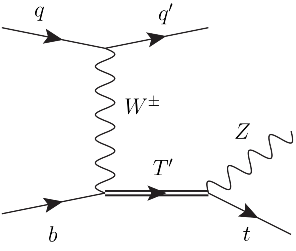
- $M_{T'}$, the vector-like mass of the top partner
- g^*, the coupling strength to SM quarks, only relevant in single production. $\sigma \propto (g^*)^2$
- R_L, the mixing coupling to first generation quarks. $R_L = 0$ corresponds to coupling to t/b only

This talk: single top partner production, trilepton decay mode via $T' \to tZ$, at the LHC at $\sqrt{s} = 13$ TeV and $\mathcal{L} = 100$ fb^{-1}

Single production and $T' \to tZ$



(a) $\mathcal{A}_1$



(b) $\mathcal{A}_3$

$$\sigma_{pp\to T'}(M_{T'}, R_L) = \mathcal{A}_1(M_{T'})\frac{R_L}{1+R_L} + \mathcal{A}_3(M_{T'})\frac{1}{1+R_L}$$

$$BR_{T'\to tZ}(M_{T'}, R_L) = \mathcal{B}(M_{T'})\frac{1}{1+R_L}$$

$M_{T'}$ (GeV)	$\mathcal{A}_1(M_{T'})$ (pb)	$\mathcal{A}_3(M_{T'})$ (pb)	$\mathcal{B}(M_{T'})$ (%)
800	1.2614	0.07242	22.4
1000	0.7752	0.03518	23.5
1200	0.5001	0.01826	24.0
1400	0.3331	0.00994	24.2
1600	0.2265	0.00561	24.4

Monte Carlo simulation details

LO samples simulation with

- parton level: `MG5_aMC@NLO` (`CTEQ6L1`)
- Hadronisiation/showering: `Pythia6` Tune Z2
- FastSim: `Delphes3` ma5Tune
- Analysis: `MadAnalysis5`

Signal:
5 benchmark points of T' mass in steps of 200 GeV: $M_{T'} \in [800; 1600]$ GeV, with $g^* = 0.1$ and $R_L = 0.5$. No k-factors

Backgrounds (plus up to 2 jets):

- 3 prompt leptons: $t\bar{t}W$, $t\bar{t}Z$, tZj, and WZ
- non-prompt leptons: $t\bar{t}$ and $Z/W + jets$

Samples normalised to NLO cross sections where available.

CMS detector emulation
Anti$-k_T$ algorithm with $R = 0.5$
b-tagging CVS medium working point: tag$= 70\%$, mistag$= 1\%$

Objects selection

Objects identification

$$p_T(\ell) > 20 \text{ GeV}, \qquad |\eta(e/\mu)| < 2.5/2.4\,, \tag{1}$$

$$p_T(j) > 40 \text{ GeV}, \qquad \Delta R(\ell, j) > 0.4\,, \tag{2}$$

$$|\eta(j)| < 5 \qquad |\eta(b)| < 2.4 \tag{3}$$

Background	no cuts	$1 \leq n_j \leq 3$	$n_\ell \equiv 3$	$n_b \equiv 1$
$t\bar{t}(+X)$	$7.5\,10^6$ (100%)	$6.1\,10^6$ (81.2%)	514.9 (**0.09%**)	243.8 (47.3%)
tZj	3521 (100%)	2953 (83.9%)	290.6 (9.8%)	170.0 (58.5%)
WZ	$1.4\,10^5$ (100%)	$5.7\,10^4$ (41.9%)	3883 (6.9%)	164.3 (**4.2%**)
Total	$7.6\,10^6$ (100%)	$6.1\,10^6$ (80.5%)	4689 (0.08%)	578.0 (12.3%)

$M_{T'}$ (GeV)	no cuts	$1 \leq n_j \leq 3$	$n_\ell \equiv 3$	$n_b \equiv 1$
800	119.7 (100%)	105.0 (87.8%)	39.3 (37.4%)	25.5 (64.8%)
1000	77.1 (100%)	67.8 (87.9%)	26.0 (38.4%)	16.4 (63.2%)
1200	52.0 (100%)	45.3 (87.2%)	16.1 (35.6%)	10.1 (62.4%)
1400	35.3 (100%)	30.5 (86.6%)	8.0 (26.1%)	4.8 (60.1%)
1600	24.5 (100%)	21.1 (86.0%)	3.8 (18.0%)	2.2 (58.3%)

Signal generated without taus

Cut-based analysis

Selections

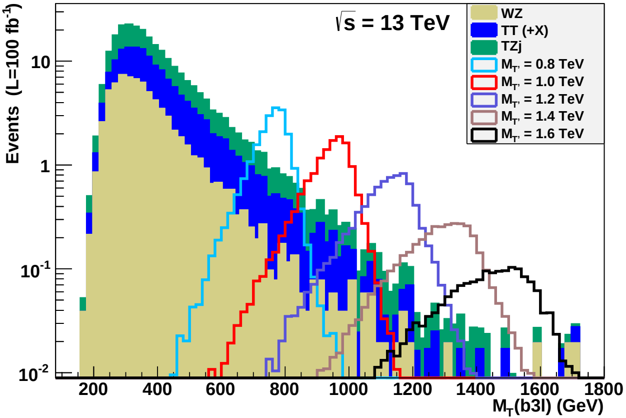
$$|M(\ell^+\ell^-)/\text{ GeV} - M_Z| < 15\,, \quad (4)$$
$$10 < M_T(\ell_W)/\text{GeV} < 150\,, \quad (5)$$
$$0 < M_T(\ell_W\, b)/\text{GeV} < 220\,. \quad (6)$$

Background	$n_b \equiv 1$	cut (4)	cut (5)	cut (6)
$t\bar{t}(+X)$	243.8 (47.3%)	154.8 (63.5%)	135.1 (87.3%)	83.0 (61.5%)
tZj	170.0 (58.5%)	155.6 (67.2%)	148.7 (95.6%)	139.8 (63.7%)
WZ	164.3 (4.2%)	146.9 (89.4%)	138.2 (94.1%)	71.5 $(\mathbf{51.7\%})$
Total	578.0 (12.3%)	457.2 (79.1%)	422.0 (92.3%)	294.3 (69.8%)

$M_{T'}$ (GeV)	$n_b \equiv 1$	cut (4)	cut (5)	cut (6)
800	25.5 (64.8%)	23.8 (93.6%)	22.2 (93.2%)	20.8 (93.6%)
1000	16.4 (63.2%)	15.4 (93.8%)	14.3 (92.4%)	13.4 (94.0%)
1200	10.1 (62.4%)	9.5 (94.2%)	8.7 (92.3%)	8.1 (92.3%)
1400	4.8 (60.1%)	4.5 (93.5%)	4.1 (92.1%)	3.8 (91.3%)
1600	2.2 (58.3%)	2.1 (93.3%)	1.9 (92.2%)	1.7 (90.0%)

Cuts optimised to retain $\geq \mathbf{90\%}$ of signal

$M_T(b\,3\ell)$



Signal clearly visible over background

Distribution in transverse mass, sharper peaks than invariant mass

Q: can we do better?

MultiVariate Analysis (MVA)

Cut-based strategy: suitable cuts on the most straightforward distributions
Is the best strategy?

Many additional variables to distinguish signal from background
Recall the kinematics: T' very heavy, $t - Z$ back-to-back and boosted

However, cutting on any of these variables unavoidably reduce also the signal

Solution:

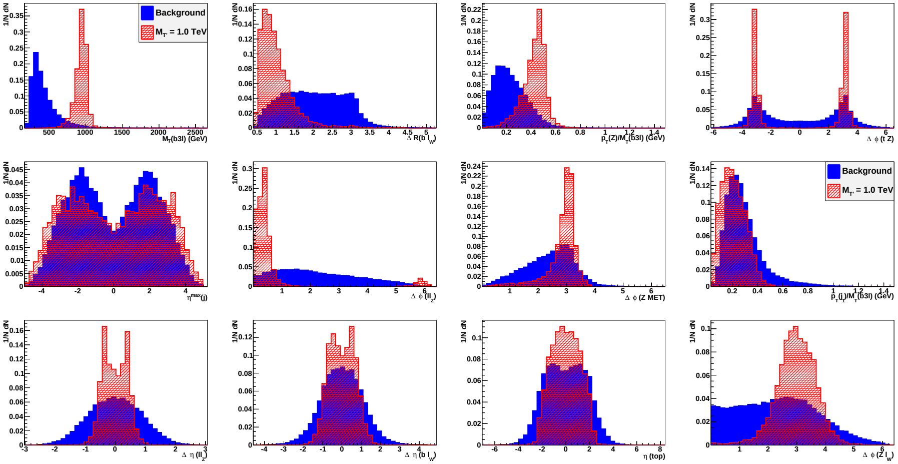
combine several variables using a *multivariate analysis* (MVA) to obtain the best signal/background discrimination

Here we used Boosted Decision Tree (BDT)

Variables drawn after Z mass cut: $M_T(\ell_W)$, $M_T(\ell_W\, b)$; MET, H_T, S_T; p_T, η; $\Delta\eta$, $\Delta\phi$, angular correlations, ...

Some variables correlated, like $p_T(Z)$ and $p_T(\ell_1)$: choose a reduced and uncorrelated set with still large sensitivity

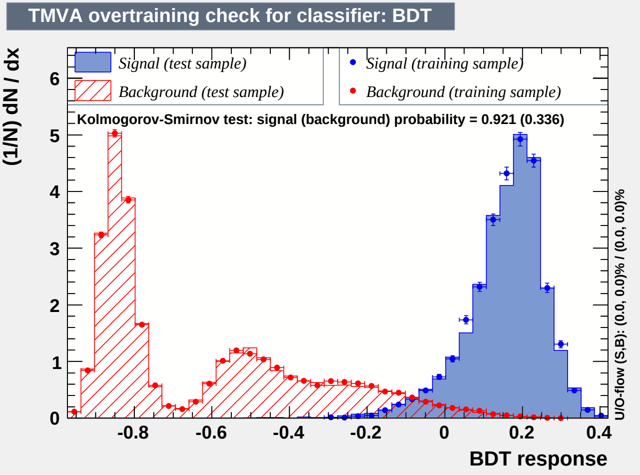
MVA variables



+ η_Z

$p_T(Z)/M_T(b\,3\ell)$, $p_T(j_1)/M_T(b\,3\ell)$, and $M_T(b\,3\ell)$ are <u>decorrelated</u>

BDT output



Allows to check for “overtraining”: 2 random samples, one used for training and the other one for comparison, should get similar output

Discovery power: benchmarks

Surviving events and significances for signal benchmark points ($g^* = 0.1$, $R_L = 0.5$)

- C&C: select a window around the peak in $M_T(b3\ell)$
- MVA: perform a LH cut on BDT output

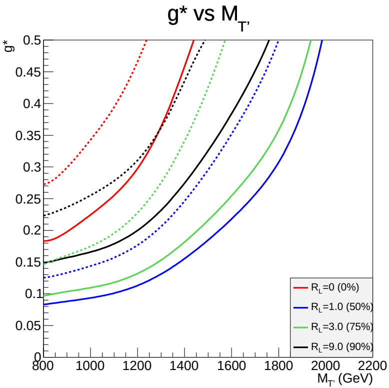
to maximise the significance: $\sigma = S/\sqrt{S+B}$

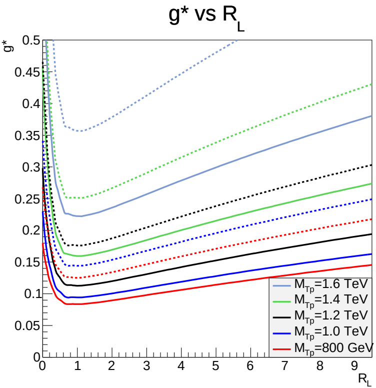
Analysis		$M_{T'} = 0.8$ TeV	$M_{T'} = 1.0$ TeV	$M_{T'} = 1.2$ TeV	$M_{T'} = 1.4$ TeV	$M_{T'} = 1.6$ TeV
$M_T(b3\ell)$ cut (GeV)		$[800 - 860]$	$[840 - 1200]$	$[1000 - 1340]$	$[1120 - 1640]$	$[1200 - 1800]$
C&C	S (ev.)	18.00	12.28	7.16	3.40	1.57
	B (ev.)	8.90	4.88	1.74	0.90	0.63
	σ	3.47	2.96	2.40	1.64	1.06
MVA	cut	0.07	0.08	0.11	0.12	0.12
	σ	3.64	3.10	2.50	1.62	1.15

MVA: non-significant improvement (5%–8%)

Significance depends on g^* and R_L per fixed T' mass

Discovery power: parameter space





(dashed lines: 5σ, solid lines: 3σ)

T' masses up to 2 TeV can be observed

Increased reach when R_L is non-vanishing (maximum for $R_L \simeq 1$, corresponding to 50%–50% mixing)

Conclusions

Singlet top partners T' common to many BSM models

Simplified model: only 3 parameters, simple rescaling to cover whole phase space

$T' \to tZ$: study of the trilepton signature at $\sqrt{s} = 13$ TeV in single production mode

T' masses up to 2.0 TeV and couplings down to $g^* = 0.1$ can be probed. Large gain if mixing with light generation is accounted for

Results from cut-based analysis: simple *and* effective, no substantial improvements from MVA

Backup slides

MVA variables II

Variable	Importance	Variable	Importance
$M_T(b\,3\ell)$	$2.60\,10^{-1}$	$\Delta R(b,\,\ell_W)$	$9.77\,10^{-2}$
$p_T(Z)/M_T(b\,3\ell)$	$9.41\,10^{-2}$	$\Delta\varphi(t,\,Z)$	$8.17\,10^{-2}$
$\eta^{max}(j)$	$6.02\,10^{-2}$	$\Delta\varphi(\ell\ell\vert_Z)$	$5.89\,10^{-2}$
$\Delta\varphi(Z,\,\not{p}_T)$	$5.37\,10^{-2}$	$p_T(j_1)/M_T(b\,3\ell)$	$5.08\,10^{-2}$
$\Delta\eta(\ell\ell\vert_Z)$	$5.05\,10^{-2}$	$\Delta\eta(b,\,\ell_W)$	$5.03\,10^{-2}$
$\eta(t)$	$4.99\,10^{-2}$	$\Delta\varphi(Z,\,\ell_W)$	$4.63\,10^{-2}$
$\eta(Z)$	$4.61\,10^{-2}$		

$(\ell\ell|_Z)$: the pair of leptons reconstructing the Z boson

$\eta^{max}(j)$: jet with largest rapidity (to account for associated jet)

$p_T(j_1)/M_T(b\,3\ell)$ and $p_T(Z)/M_T(b\,3\ell)$ effectively decorrelated from $M_T(b\,3\ell)$

Angular variables from fully reconstructing the neutrino 4-momentum

Correlations