



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

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Based on LB, J. Andrea, JHEP **1502** (2015) 032  
arXiv:1411.7587 [hep-ph].

# Outline

- Simplified model for  $T'$  analyses
- Analysis
  - Simulation details
  - Cut-based
  - Multi-variate (BDT)
- Results
  - Discovery potential
  - Comparison to dilepton channel
- Reinterpretation for top anomalous couplings
- 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

They are *vector-like* because their LH and RH chiralities couple to the gauge boson vectors in the *same* way

→ LH and RH couplings are equal, as for a vector

# Examples of models

Very quick review: [J. Reuter and M. Tonini, JHEP 1501 \(2015\) 088 \[arXiv:1409.6962\]](#)

Composite Higgs models: Higgs boson is a composite state

Minimal case:  $SO(5)/SO(4) \begin{cases} t_R \sim \mathbf{1}_4, \text{ complete rep. of } SO(4) \\ q_L \sim \text{incomplete rep. of } SO(5) \end{cases}$

New fermions:  $\Psi \begin{cases} \mathbf{1}_4 : T' \\ \mathbf{4}_4 : (T', B'), (X_{5/3}, X_{2/3}) \end{cases}$

Little Higgs models: Higgs is a pseudo-Goldstone boson

from a global spontaneous breaking of  $SU(5)/SO(5)$  (Littlest Higgs model)

A vector-like heavy top is required to cancel loop quadratic divergences

Many models, many similarities  $\rightarrow$  simplified model

Here, **singlet top partner**:  $T'$

Typically,  $\text{BR}(T' \rightarrow qW^\pm) : \text{BR}(T' \rightarrow qZ) : \text{BR}(T' \rightarrow qh) \sim 2 : 1 : 1$

# Simplified model

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

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

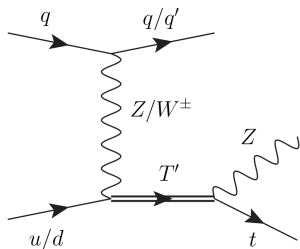
We allow for generic mixing to 1<sup>st</sup> generation quarks

Only 3 parameters:

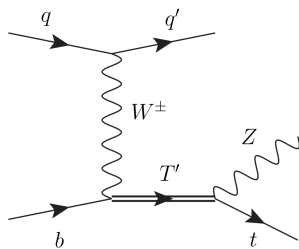
- $M_{T'}$ , the vector-like mass of the top partner
- $g^*$ , the coupling strength to SM quarks, only relevant in single production.  
 $\sigma \propto (g^*)^2$
- $R_L$ , the mixing coupling to first generation quarks.  $R_L = 0$  corresponds to coupling to  $t/b$  only

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

# Single production and $T' \rightarrow tZ$



(a)  $\mathcal{A}_1$



(b)  $\mathcal{A}_3$

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

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

$M_{T'} \text{ (GeV)}$	$\mathcal{A}_1(M_{T'}) \text{ (pb)}$	$\mathcal{A}_3(M_{T'}) \text{ (pb)}$	$\mathcal{B}(M_{T'}) \text{ (\%)}$
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)
- Hadronisation/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

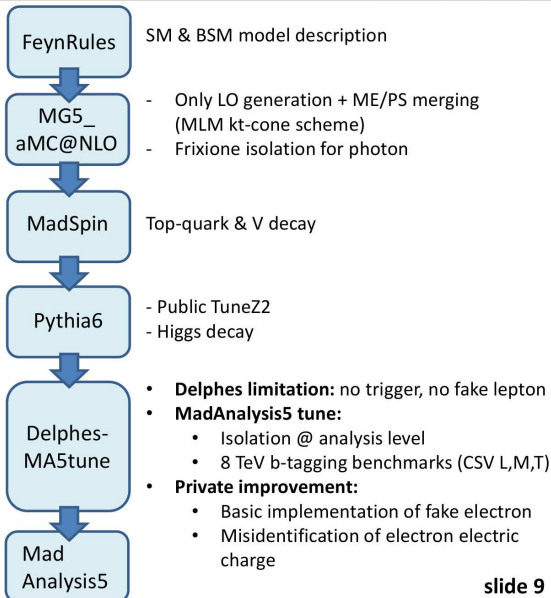
CMS detector emulation

Anti- $k_T$  algorithm with  $R = 0.5$

$b$ -tagging CVS medium working point:  $b$ -tag = 70%, mistag = 1%

## Massive Monte Carlo generation for background

- V + jets with  $V=W,Z,\gamma$
  - H + jets
  - VV + jets
  - VH + jets
  - T + jets
  - TV + jets
  - TH + jets
  - TT + jets
  - TTV + jets
  - TTH + jets
  - TTVV + jets
- K-factor for background are mainly computed with MG\_aMC@NLO
  - K-factor for signal are (now) available in the literature ...





# More simulation details

Massive background event generation to gather enough statistics:

Process	# Files	# Events	Process	# Files	# Events
SingleTop_W_madspin	189	18898481	SingleTop_s_madspin	188	18771372
SingleTop_t_5FS_madspin	83	8299246	TTdilep_WToLNu_madspin	1	64191
TTdilep_WWToLLNuNu_madspin	1	99999	TTdilep_WZToLLNuNu_madspin	1	99991
TTdilep_ZToLL_madspin	1	99989	TTdilep_ZZToLLLL_madspin	1	99993
TTdilep_madspin	200	9427953	TTsemilep_WToLNu_madspin_1	1	59694
TTsemilep_WToLNu_madspin_2	1	59771	TTsemilep_WWToLLNuNu_madspin_1	1	99989
TTsemilep_WWToLLNuNu_madspin_2	1	99997	TTsemilep_WZToLLNuNu_madspin_1	2	199988
TTsemilep_ZToLL_madspin_1	1	99995	TTsemilep_ZToLL_madspin_2	1	99987
TTsemilep_ZZToLLLL_madspin_1	1	99993	TTsemilep_ZZToLLLL_madspin_2	1	99990
TTsemilep_madspin_1	172	8105465	TTsemilep_madspin_2	173	8156688
TZq2_W_trilep1	100	9999157	TZq2_W_trilep2	97	9672987
TZq2_s_trilep	94	9393276	TZq2_t5FS_trilep	97	9699081
WToLNu-0Jet_sm-no_masses	592	52785449	WToLNu-0Jet_sm-no_masses-run2	482	42972689
WToLNu-1Jet_sm-no_masses	586	32827404	WToLNu-2Jets_sm-no_masses	396	15769022
WToLNu-3Jets_sm-no_masses	488	12931463	WWToLLNuNu	194	11221071
WZToLLJJ	5	306339	WZToLLNuNu	120	7666801
WZToLNuNuNu	1	59147	WZToNuNuJJ	1	59420
ZToLL10-50-0Jet_sm-no_masses	1	97701	ZToLL10-50-1Jet_sm-no_masses	1	45361
ZToLL10-50-2Jets_sm-no_masses	1	38998	ZToLL10-50-3Jets_sm-no_masses	1	5690
ZToLL50-0Jet_sm-no_masses	9	784399	ZToLL50-1Jet_sm-no_masses	10	549567
ZToLL50-2Jets_sm-no_masses	9	350088	ZToLL50-3Jets_sm-no_masses_split	8	115396
ZToLL50-4Jets_sm-no_masses_split	1	2884	ZZTo4Nu	1	35808
ZZToLLLL	92	6222800	ZZToLLNuNu	1	64305

Monte Carlo errors below permil: neglected

# Objects selection

## Objects identification

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

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

$$|\eta(j)| < 5, \quad |\eta(b)| < 2.4, \quad (3)$$

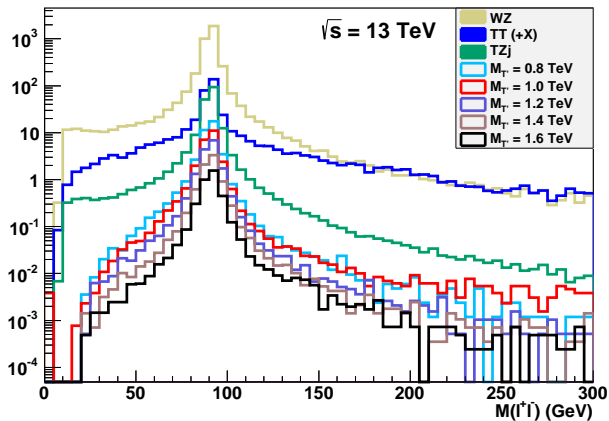
Background	no cuts	$1 \leq n_j \leq 3$	$n_\ell \equiv 3$	$n_b \equiv 1$
$t\bar{t}(+X)$	$7.5 \cdot 10^6$ (100%)	$6.1 \cdot 10^6$ (81.2%)	<b>514.9 (0.09%)</b>	243.8 (47.3%)
$tZj$	<b>3521</b> (100%)	<b>2953</b> (83.9%)	290.6 (9.8%)	170.0 (58.5%)
$WZ$	$1.4 \cdot 10^5$ (100%)	$5.7 \cdot 10^4$ (41.9%)	3883 (6.9%)	<b>164.3 (4.2%)</b>
Total	$7.6 \cdot 10^6$ (100%)	$6.1 \cdot 10^6$ (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: optimisation

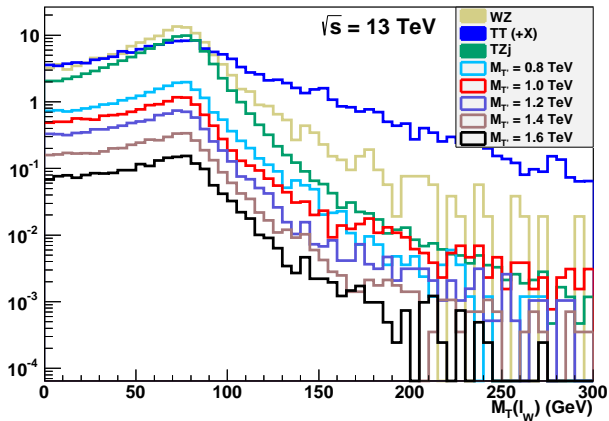
Z-boson reco by minimising distance of OSSF leptons to  $M_Z$



$$|M(\ell^+\ell^-) / \text{GeV} - M_Z| < 15$$

# Cut-based analysis: optimisation

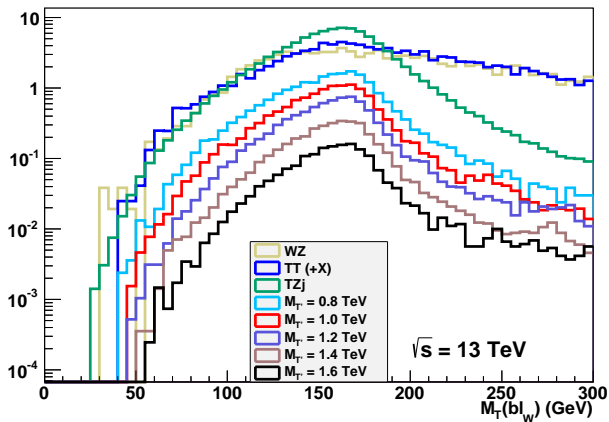
$W$  reco with remaining lepton



$$10 < M_T(l_W)/\text{GeV} < 150$$

# Cut-based analysis: optimisation

top reco with remaining lepton and  $b$ -tagged jet



$$0 < M_T(\ell_W b)/\text{GeV} < 220$$

# Cut-based analysis

## Selections

$$|M(\ell^+\ell^-)/\text{GeV} - M_Z| < 15, \quad (4)$$

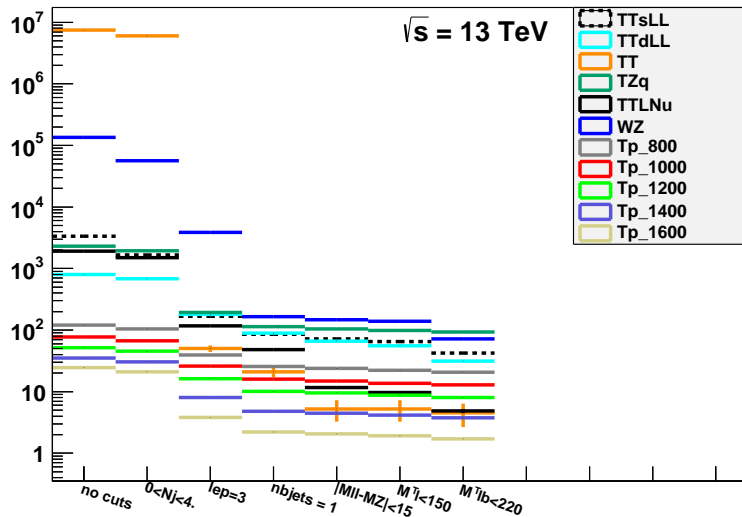
$$10 < M_T(\ell_W)/\text{GeV} < 150, \quad (5)$$

$$0 < M_T(\ell_W b)/\text{GeV} < 220. \quad (6)$$

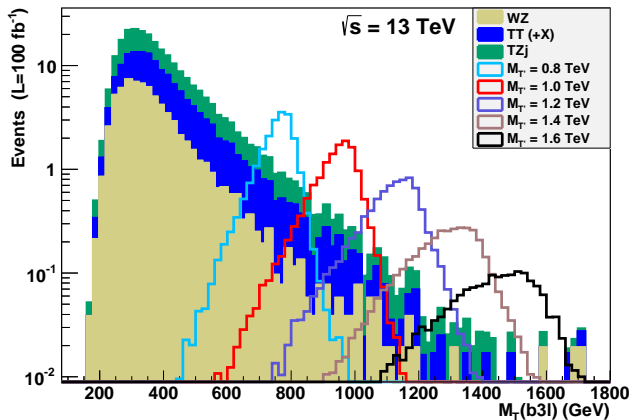
Background	$n_b \equiv 1$	cut (4)	cut (5)	cut (6)
$t\bar{t}(+X)$	243.8 (47.3%)	154.8 (63.5%)	135.1 (87.3%)	83.0 (61.5%)
$tZj$	170.0 (58.5%)	155.6 (67.2%)	148.7 (95.6%)	139.8 (63.7%)
$WZ$	164.3 (4.2%)	146.9 (89.4%)	138.2 (94.1%)	71.5 (51.7%)
Total	578.0 (12.3%)	457.2 (79.1%)	422.0 (92.3%)	294.3 (69.8%)
$M_{T'}$ (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  $\geq 90\%$  of signal

# Cutflow



# $M_T(b3\ell)$



Signal clearly visible over background

Distribution in transverse mass, sharper peaks than invariant mass

Q: can we do better?



# Multi-Variate Analysis (MVA)

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

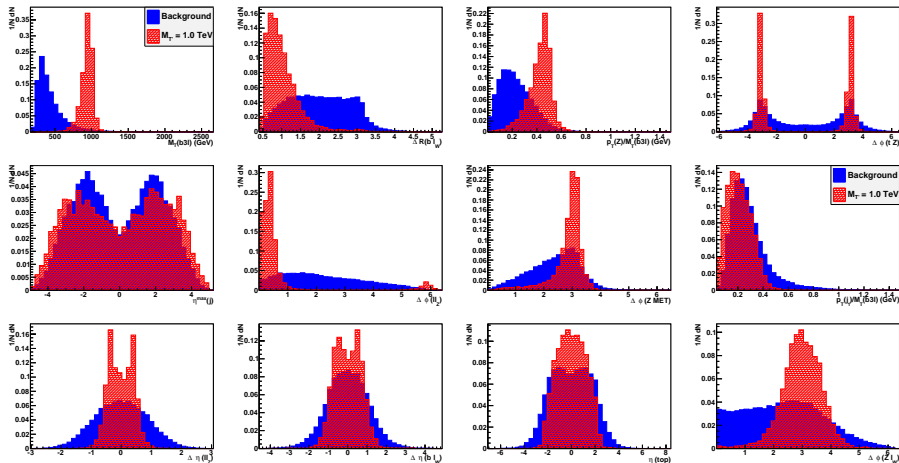
combine several variables using a *multivariate analysis* (MVA) to obtain the best signal/background discrimination

Here we used Boosted Decision Tree (BDT)

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



+  $\eta_Z$

$p_T(Z)/M_T(b3l)$ ,  $p_T(j_1)/M_T(b3l)$ , and  $M_T(b3l)$  are decorrelated



## MVA variables II

Variable	Importance	Variable	Importance
$M_T(b3\ell)$	$2.60 \cdot 10^{-1}$	$\Delta R(b, \ell_W)$	$9.77 \cdot 10^{-2}$
$p_T(Z)/M_T(b3\ell)$	$9.41 \cdot 10^{-2}$	$\Delta\varphi(t, Z)$	$8.17 \cdot 10^{-2}$
$\eta^{max}(j)$	$6.02 \cdot 10^{-2}$	$\Delta\varphi(\ell\ell Z)$	$5.89 \cdot 10^{-2}$
$\Delta\varphi(Z, \not{p}_T)$	$5.37 \cdot 10^{-2}$	$p_T(j_1)/M_T(b3\ell)$	$5.08 \cdot 10^{-2}$
$\Delta\eta(\ell\ell Z)$	$5.05 \cdot 10^{-2}$	$\Delta\eta(b, \ell_W)$	$5.03 \cdot 10^{-2}$
$\eta(t)$	$4.99 \cdot 10^{-2}$	$\Delta\varphi(Z, \ell_W)$	$4.63 \cdot 10^{-2}$
$\eta(Z)$	$4.61 \cdot 10^{-2}$		

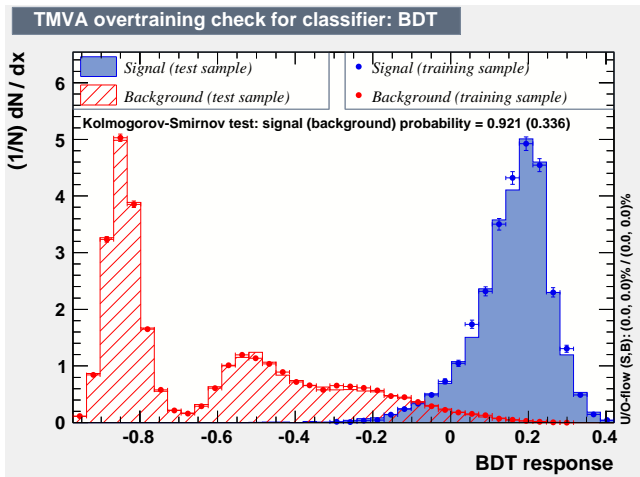
$(\ell\ell|Z)$ : the pair of leptons reconstructing the  $Z$  boson

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

$p_T(j_1)/M_T(b3\ell)$  and  $p_T(Z)/M_T(b3\ell)$  effectively decorrelated from  $M_T(b3\ell)$

Angular variables from fully reconstructing the neutrino 4-momentum

# 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

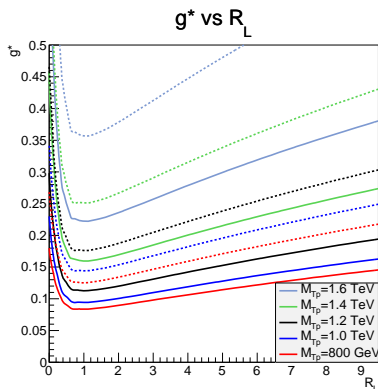
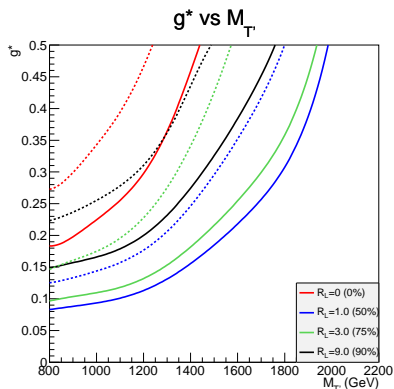
to maximise the significance:  $\sigma = S/\sqrt{S+B}$

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]
S (ev.)	18.00	12.28	7.16	3.40	1.57
C&C B (ev.)	8.90	4.88	1.74	0.90	0.63
$\sigma$	3.47	2.96	2.40	1.64	1.06
MVA cut	0.07	0.08	0.11	0.12	0.12
$\sigma$	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



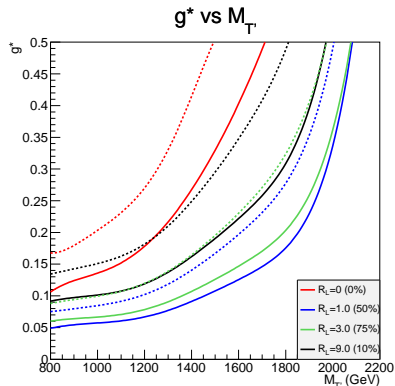
(dashed lines:  $5\sigma$ , solid lines:  $3\sigma$ )

$T'$  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)

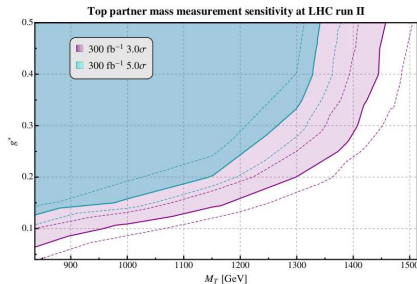
# Comparison to dilepton channel

We set ourselves in similar conditions:  $\mathcal{L} = 300 \text{ fb}^{-1}$ ,  $\kappa_f = 1.14$ ,  $R_L = 0$



J. Reuter and M. Tonini,

JHEP **1501** (2015) 088 [arXiv:1409.6962]



(dashed lines:  $5\sigma$ , solid lines:  $3\sigma$ )

Comparable reach at low  $T'$  masses (no pair-prod. here)

200 ÷ 300 GeV better sensitivity at high  $T'$  masses



# Reinterpretation: top anomalous couplings

The top-quark couplings can be parametrised in an effective field theory

The SM Lagrangian is extended by gauge-invariant (non-renormalisable) operators, obtained by integrating out heavy modes

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i O_i}{\Lambda^2}$$

Here we consider only dimension 6 operators, the first non-vanishing terms in  $1/\Lambda$  expansion: total of 59 operators [W. Buchmuller, D. Wyler, Nucl.Phys. B268 \(1986\) 621](#)

Not all possible dim-6 operators that one can write are independent  
Redundant operators can be reduced by using equation of motions and other relations due to gauge invariance

[J. A. Aguilar-Saavedra, Nucl. Phys. B812, 181 \(2009\) \[0811.3842\]](#)

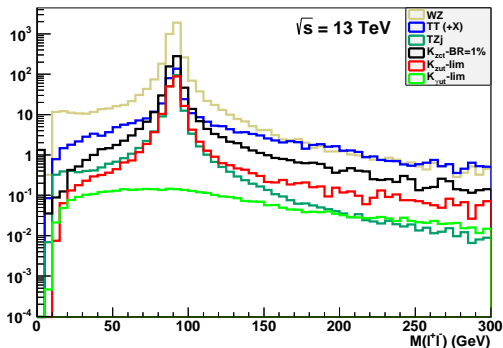
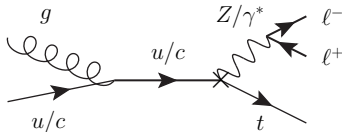
$$\mathcal{L} = \sum_{q=u,c} \frac{g}{\sqrt{2}c_W} \frac{\kappa_{tZq}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_{Zq}^L P_L + f_{Zq}^R P_R) q Z_{\mu\nu},$$

where  $\Lambda$  is the scale of new physics.

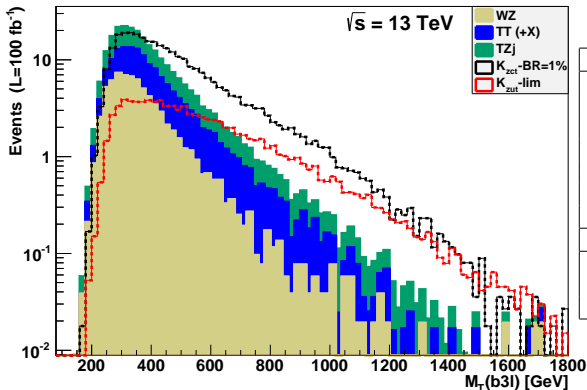
# Reinterpretation: optimisation

$tZq$  coupling gives similar final state as  $T' \rightarrow tZ \rightarrow t\ell^+\ell^-$

$t\gamma q$  coupling (with  $\gamma^*$ ) too. However, the cut around  $M_Z$  removes it



# Reinterpretation: C&C

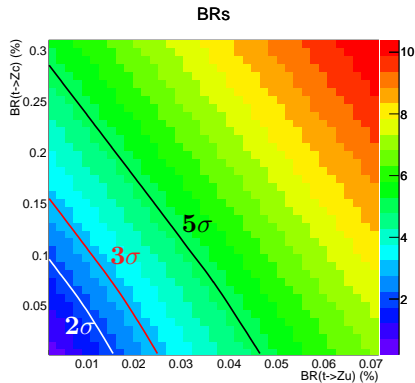
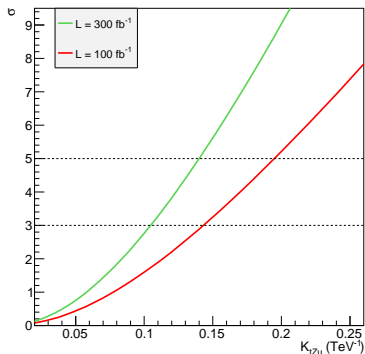


Cut	$\kappa_{tZu}$	$\kappa_{tZc}$
no cuts	2263(100%)	5360(100%)
$1 \leq n_j \leq 3$	1765(78.0%)	4452(83.0%)
$n_\ell \equiv 3$	191.8(10.9%)	623.3(14.0%)
$n_b \equiv 1$	113.8(59.3%)	381.0(61.1%)
cut (4)	103.2(90.7%)	342.7(90.0%)
cut (5)	96.2(93.3%)	323.6(94.4%)
cut (6)	91.1(94.7%)	304.7(94.1%)
$M_T(b3\ell)$	$> 400 \text{ GeV}$	$> 200 \text{ GeV}$
S	68.0	304.5
B	102.9	241.7
$\sigma$	5.2	13.0

MVA trained on  $T'$  signals and applied to top anomalous couplings does not lead to improvements

In progress: training on the top anomalous signal

# Reinterpretation: parameter space



Actual limits:  $\text{BR}(t \rightarrow Zq) < 0.05\%$  (inclusive, from  $t\bar{t}$ )  $\Rightarrow \kappa_{tZu} < 0.2 \text{ TeV}^{-1}$

Otherwise from single top:  $\begin{cases} \text{BR}(t \rightarrow Zu) < 0.51\% \\ \text{BR}(t \rightarrow Zc) < 11.4\% \end{cases}$

See [CMS-TOP-12-037](#) and [CMS-TOP-12-021](#), respectively

# Conclusions

Singlet top partners  $T'$  common to many BSM models trying to address the Higgs stability

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

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

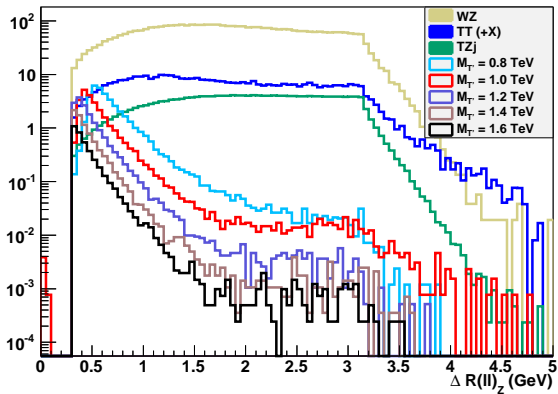
$T'$  masses up to 2.0 TeV and couplings down to  $g^* = 0.1$  can be probed. Large gain if mixing with light generation is accounted for

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

Reinterpretation to top anomalous couplings sharing similar signature

# Backup slides

# $\Delta R(\ell^+\ell^-)$ for $T'$ signals



$T'$  is very massive, hence the decay products are boosted

# Correlations - Background

