Me, myself, and VLQs

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Lorenzo Basso

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Myself

- 2007: Graduated in Physics at University of Padova (Italy)
- 2007-2011: PhD in Physics at University of Southampton (UK) within NExT Institute
  Supervisor: Stefano Moretti. Student member of CMS, associated to an experimental supervisor (Claire Shepher-Themistocleous)
  Thesis: *Phenomenology of the minimal B-L extension of the Standard Model at the LHC*
  Defense: 24/05/2011
- 2011-2013: PostDoc at Universtity of Freiburg (Germany) within Graduiertenkolleg (mentoring to ATLAS PhD students)
  Supervisor/Advisors: Prof. Dr. Stefan Dittmaier / Prof. Dr. Karl Jakobs
- 2013-2015: PostDoc at IPHC (ANR BATs@LHC)
  Supervisor: Dr. Caroline Collard
  Non-signing member of CMS collaboration

Summary of competences and work

Phenomenologist (theory): MC parton/detector level event simulation and analysis, analytic computations, model building, model implementations (LanHEP, SARAH, FeynRules), dark matter properties

- PhD on phenomenology at LHC and ILC of a SM$\times U(1)_{B-L}$ model: Z', heavy neutrinos, extra Higgs boson, plus theory constraints (RGEs etc) , first fast sim studies of $pp \to Z' \to \nu_h \nu_h \to 3\ell 2j+$ MET
- Model extented to SUSY version: study of DM and first inspection of scalar sector. Implementation in SARAH
- Extension to include gauged inverse seesaw, study of DM/leptogenesis
- Asymmetries in Z' models, in $t\bar{t}$ and then interplay with $b\bar{b}$ and $\tau^+\tau^-$
- 2HDM: $H^\pm \to W^\pm h$ and $H^\pm \to \tau\nu_\tau$ (parton level)
- other works on LRSSM, fitting of neutrino models to precision data (possible 3σ hint), proposal for seesaw in SLHA, RGE study of $B-L$ model and Hill/HEIDI model
- full QCD+EW NLO corrections to top decay width
- Detector level studies: 13 TeV CMS prospects for top FCNC, resonant mono Higgs (LHC and FCC-ee, on going), and

discovery potential for VLQ $T' \to tZ$ in trilepton channel

Introduction

Vector-like quarks (equal LH and RH couplings) are common to BSM theories:

Extra Dimensions, Little Higgs Models, Composite Higgs Models

At LHC, searched for in pair-production: QCD-like (model-independent)

Single production: model-*dependent*

- allows to access underlying model
- favoured when very heavy resonances

In this talk: LHC discovery potential of singly-produced T' (top-partner)

Simplified model

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

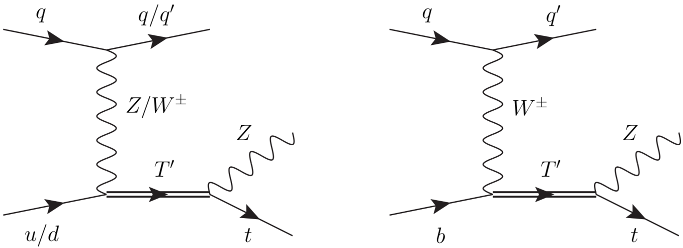
$$\mathcal{L}_{\mathrm{T'}} = g^* \left\{ \sqrt{\frac{R_L}{1+R_L}} \frac{g}{\sqrt{2}} [\overline{T'}_L W_\mu^+ \gamma^\mu d_L] + \sqrt{\frac{1}{1+R_L}} \frac{g}{\sqrt{2}} [\overline{T'}_L W_\mu^+ \gamma^\mu b_L] + \right.$$
$$\left. \sqrt{\frac{R_L}{1+R_L}} \frac{g}{2\cos\theta_W} [\overline{T'}_L Z_\mu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

We allow for generic mixing to 1^{st} 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. Rescaling: $\sigma \propto (g^*)^2$
- R_L, the mixing coupling to first generation quarks. $R_L = 0$ corresponds to coupling to t/b only. Rescaling: by integrating $1^{st} \propto \frac{R_L}{1+R_L}$ and $3^{rd} \propto \frac{1}{1+R_L}$ gen. quark processes independently

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`)
- 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 CSV medium working point: $b-$tag $= 70\%$, mistag $= 1\%$

Cut-and-count

Objects identification

$$p_T(\ell) > 20 \text{ GeV}, \qquad |\eta(e/\mu)| < 2.5/2.4\,,$$
$$p_T(j) > 40 \text{ GeV}, \qquad \Delta R(\ell, j) > 0.4\,,$$
$$|\eta(j)| < 5, \qquad |\eta(b)| < 2.4,$$

Cuts:

$$n_\ell \equiv 3 \qquad \text{suppress } t\bar{t} + X \to \mathbf{0.09\%}$$
$$1 < n_j < 3 \qquad \text{(remove pair-prod.)}$$
$$n_b \equiv 3 \qquad \text{suppress } WZ \to \mathbf{4.2\%}$$
$$|M(\ell^+\ell^-)/\text{ GeV} - M_Z| < 15 \qquad Z \to \ell^+\ell^- \text{ reco}$$
$$10 < M_T(\ell_W \nu)/\text{GeV} < 150 \qquad W \to \ell_W \nu \text{ reco}$$
$$0 < M_T(b\,\ell_W\,\nu)/\text{GeV} < 220 \qquad t \to bW \text{ reco}$$

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

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 (13 variables) output

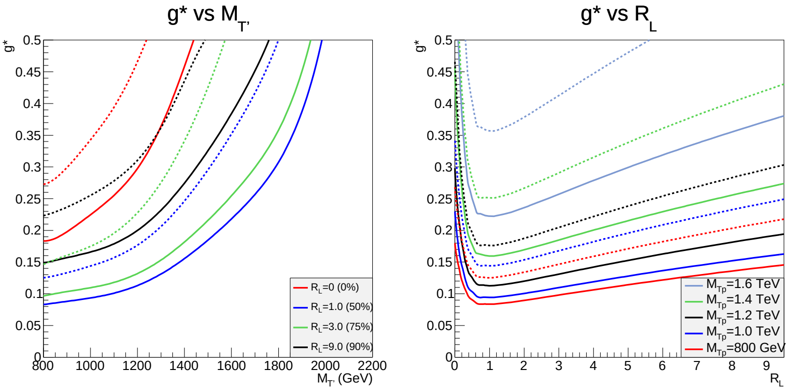
to maximise the significance: $\sigma = S/\sqrt{S+B}$

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

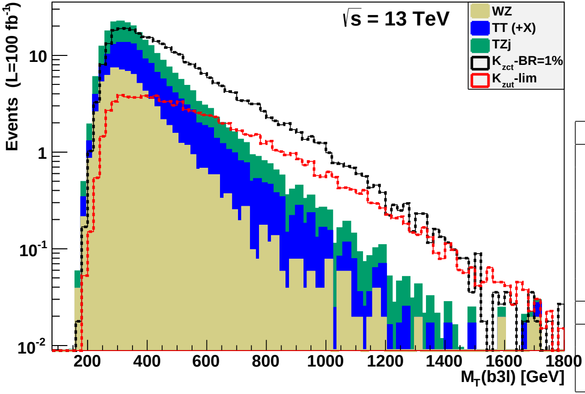


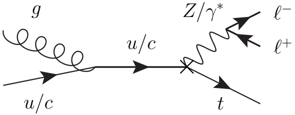
(dashed lines: 5σ, solid lines: 3σ)

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)

Reinterpretation: top anomalous couplings





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

Present limit: BR$(t \to Zq) < 0.05\%$ (inclusive, from $t\bar{t}$)

MVA trained on T' signals: no improvements

In progress: training on the top anomalous signal

Proposal: Vector-like Quarks (VLQ)

VLQ: vector-like quarks, quarks with equal LH and RH chiral couplings

Strong interactions with 3^{rd} generation of quarks: (again) a preferred window to New Physics. However, mixing with 1^{st} generation is also possible

Very common in BSM: simplified Lagrangians for model-independent analyses

Only 4 types couple to SM quarks 1305.4172

$$\begin{aligned}
Q = 5/3 &\quad \Rightarrow \quad X \to W^+t \\
Q = 2/3 &\quad \Rightarrow \quad T \to W^+b,\ Zt,\ Ht \\
Q = -1/3 &\quad \Rightarrow \quad B \to W^-t,\ Zb,\ Hb \\
Q = -4/3 &\quad \Rightarrow \quad Y \to W^-b
\end{aligned}$$

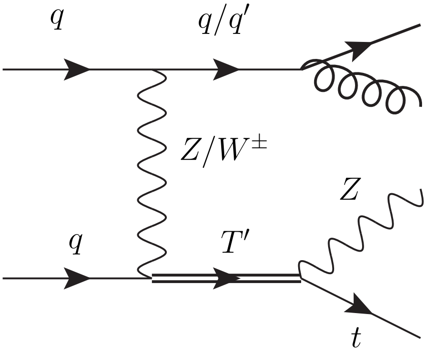
LHC@13 TeV: single prod (model dep) overtakes pair prod (QCD, model ind)

- possibility to access underlying model
- **PROPOSAL**: Wt/b only common decay mode: single analysis in hadronic final state, also comparing boosted techniques

Why NLO-QCD

VLQ are still quarks, hence NLO-QCD correction can be large at the LHC.

Important to investigate modification to forward jet, used in analyses



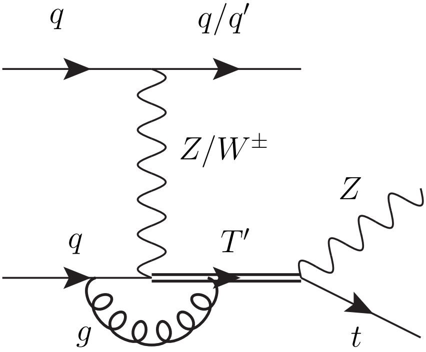
Why NLO-QCD

VLQ are still quarks, hence NLO-QCD correction can be large at the LHC.

Important to investigate modification to forward jet, used in analyses

Model recently implemented in FeynRules v2.1 for automated NLO event generation in MG5_aMC@NLO

Problem under investigation: single-out pure QCD corrections

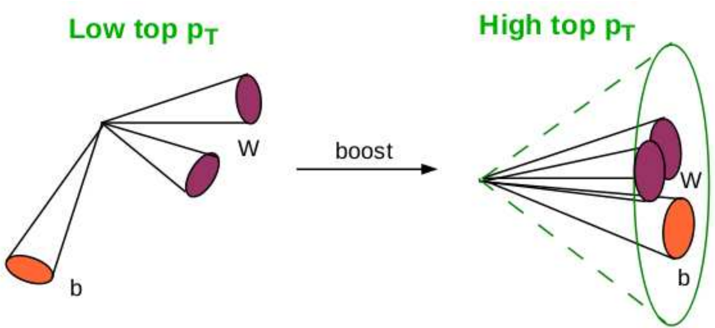


(a) NLO-QCD (b) NLO-EW

Boosted techniques

Present exclusions require $M_{VLQ} \gtrsim 1$ TeV

Final state particles are boosted:



Traditional techniques for reconstructing particles lose efficiency

⇒ "Boosted" techniques/substructures: more efficient (vs. pileup)

Aim of project: compare traditional reconstruction against boosted techniques

Backup slides

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

More simulation details

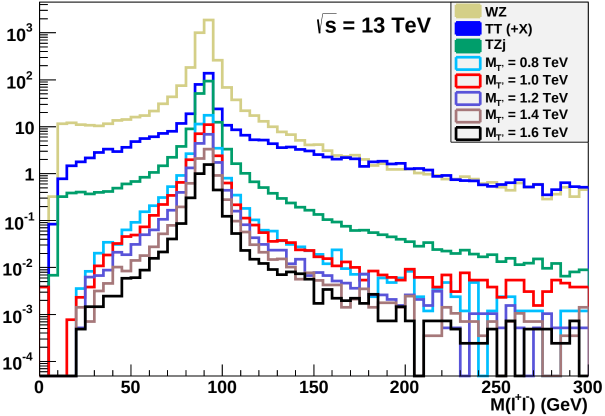
Massive background event generation to gather enough statistics:

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_WZToLLLNu_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_WZToLLLNu_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	WZToLLLNu	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

Cut-based analysis: optimisation

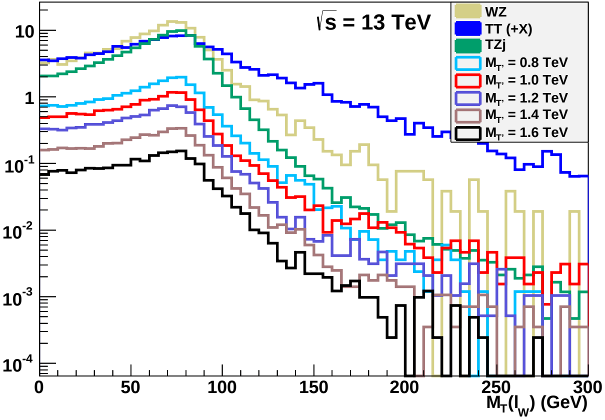
Z-boson reco by minimising distance of OSSF leptons to M_Z



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

Cut-based analysis: optimisation

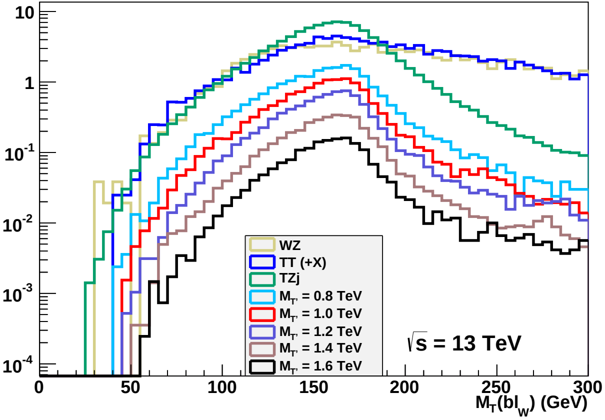
W reco with remaining lepton



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

Cut-based analysis: optimisation

top reco with remaining lepton and b-tagged jet



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

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

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

$$W \to \ell_W \nu \text{ reco} \quad 10 < M_T(\ell_W \nu)/\text{GeV} < 150\,, \tag{5}$$

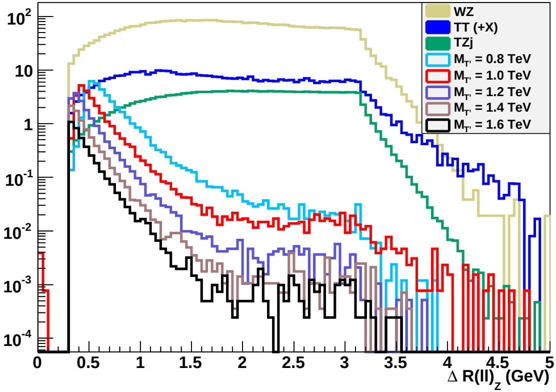
$$t \to bW \text{ reco} \quad 0 < M_T(b\,\ell_W\,\nu)/\text{GeV} < 220\,. \tag{6}$$

Background	$n_b \equiv 1$	Z-reco	W-reco	t-reco
$t\bar{t}(+X)$	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)	$n_b \equiv 1$	Z-reco	W-reco	t-reco
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

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



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

MVA: 13 variables

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

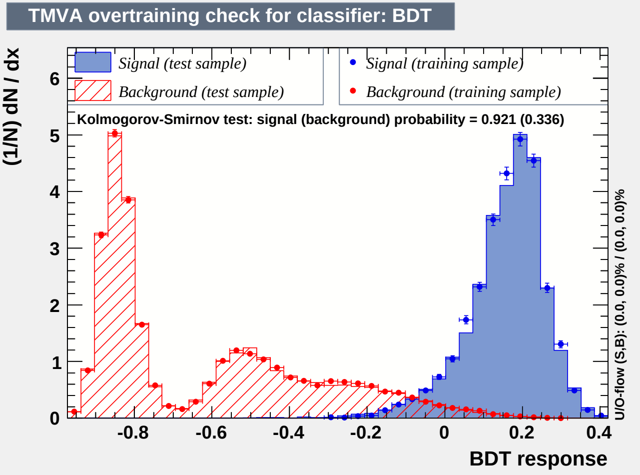
$(\ell\ell|_Z)$: the pair of leptons reconstructing the Z boson

$\eta^{max}(j)$: 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 $M_T(b\,3\ell)$

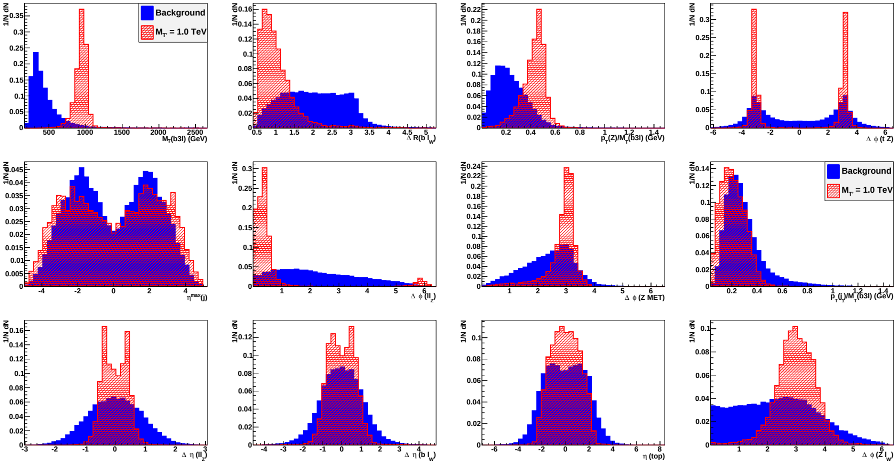
Angular variables from fully reconstructing the neutrino 4-momentum

BDT output



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

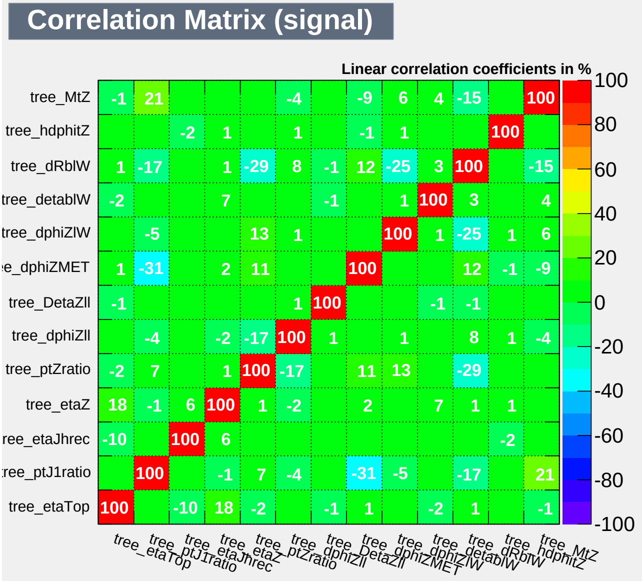
MVA variables



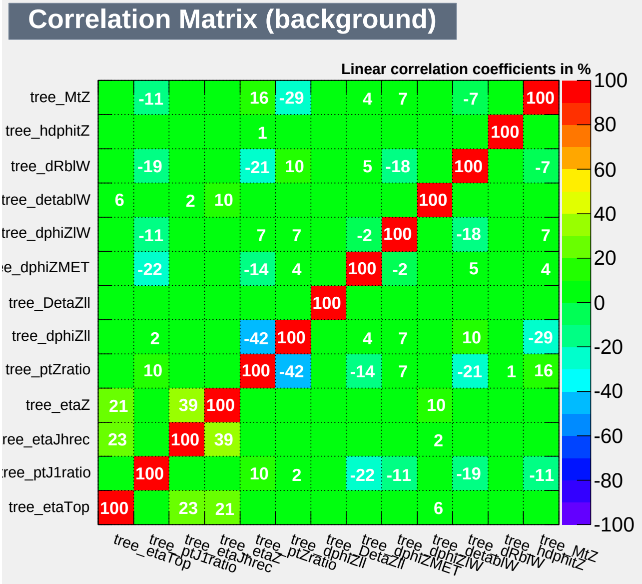
+ η_Z

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

Correlations - $M_{T'} = 1$ TeV

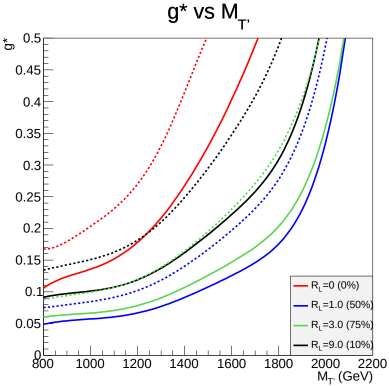


Correlations - Background

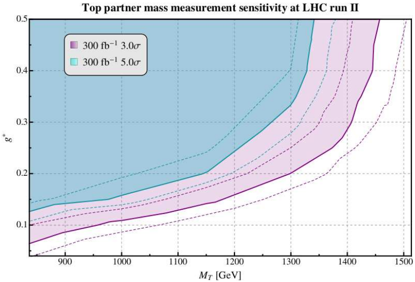


Comparison to dilepton channel

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



J. Reuter and M. Tonini,
JHEP **1501** (2015) 088 [arXiv:1409.6962]



(dashed lines: 5σ, solid lines: 3σ)

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

$200 \div 300$ 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

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

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]

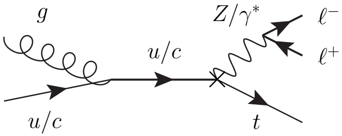
$$\mathcal{L} = \sum_{q=u,c} \frac{g}{\sqrt{2} c_W} \frac{\kappa_{tZq}}{\Lambda} \bar{t} \sigma^{\mu\nu} \left(f_{Zq}^L P_L + f_{Zq}^R P_R \right) q \, Z_{\mu\nu} \, ,$$

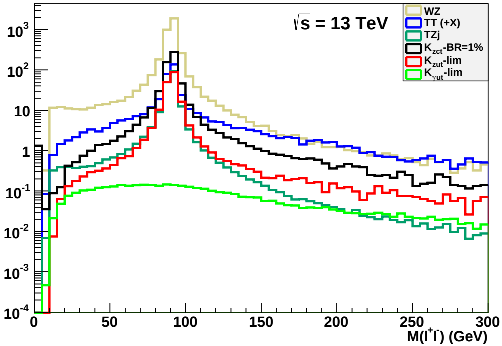
where Λ is the scale of new physics.

Reinterpretation: optimisation

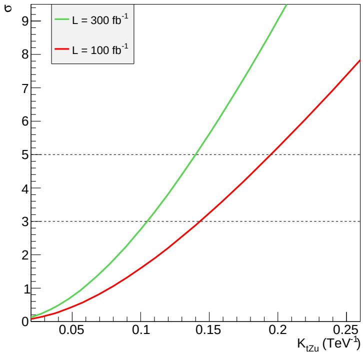
tZq coupling gives similar final state as $T' \to tZ \to t\,\ell^+\ell^-$

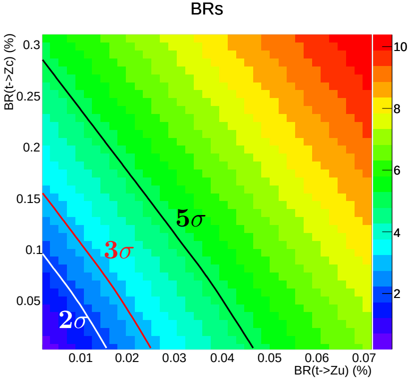
$t\gamma q$ coupling (with γ^*) too. However, the cut around M_Z removes it





Reinterpretation: parameter space





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

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

See CMS-TOP-12-037 and CMS-TOP-12-021, respectively