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Four-top production and $t\bar{t}$ + missing energy events at multi TeV e^+e^- colliders

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Summary. — Four-top production and top pair production in association with missing energy at e^+e^- colliders are sensitive probes of beyond-the-Standard-Model physics. We consider Standard Model extensions containing a new $U(1)'$ which couples preferably to the most massive states of the SM such as the top quark or Dark Matter but has suppressed couplings to all the light states of the SM, as inspired by Randall-Sundrum–like setups or theories of partial fermion compositeness. These simple models are poorly constrained by experimental data but lead to striking new signatures at colliders. In this paper we consider Z' production in association with a top quark pair in 3 TeV e^+e^- collisions at CLIC, leading to interesting four-top final states and $t\bar{t} + E_{\mathrm{miss}}$ events.

PACS `12.60.cn` – Extensions of electroweak gauge sector.
PACS `29.20.db` – Storage rings and colliders.

1. – Theoretical framework

We introduce a very simple effective theory in which the Standard Model is supplemented by a spontaneously broken $U(1)'$ gauge symmetry, the massive gauge boson of which acts as a portal to the Standard Model (SM) by coupling to the top quark. This type of setup arises naturally in models of "partial compositeness" in which the top quark acquires its large mass (after electroweak symmetry breaking) through large mixing with composite states in a new strong sector, as in 4d duals to Randall-Sundrum (RS) Models [1]. The effective Lagrangian contains [2],

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + M^2_{Z'}Z'_{\mu}Z'^{\mu} + \frac{\chi}{2}\hat{F}'_{\mu\nu}\hat{F}^{\mu\nu}_{Y} + g_t^{Z'}\ \bar{t}\gamma^{\mu}P_R Z'_{\mu}t \\ +i\bar{N}\gamma^{\mu}(\partial_{\mu} - ig_N^{Z'}P_R Z'^{\mu})N + M_N\bar{N}N, \tag{1}$$

where N is a Dirac fermion which is a singlet under the SM gauge interactions but is charged under $U(1)'$ and turns out to play the role of a weakly interacting massive particle (WIMP). $F'_{\mu\nu}$ ($F^{Y}_{\mu\nu}$) is the usual Abelian field strength for the Z' (hyper-charge boson), $g_t^{Z'}$ is the Z' coupling to right-handed top quarks, and $g_N^{Z'}$ is the coupling to right-handed WIMPs. M_N is the WIMP mass. One can easily include a coupling to the left-handed top (and bottom). Our choice to ignore such a coupling fits well with typical RS models [1], balancing the need for a large top Yukawa interaction with control over corrections to precision electroweak observables. The parameter χ encapsulates the strength of kinetic mixing between the Z' and SM hyper-charge bosons.

We have included hyper-charge-Z' kinetic mixing through the term proportional to χ. Such a term is consistent with the gauge symmetries, and even if absent in the UV, will be generated in the IR description by loops of top quarks(^{1}). The kinetic mixing parameter χ generates an effective coupling of SM states to the Z', and through electroweak symmetry breaking, mass mixing of the Z' with the SM Z gauge boson resulting in a coupling of N to the SM Z boson.

In this approach, most of the Standard Model is fundamental, but with the WIMP, Higgs, and right-handed top largely composite. The Higgs couples strongly to composite fields, and the amount of admixture in a given SM fermion determines its mass [3]. In this picture, the Z' is one of the higher resonances, built out of the same preons as the WIMP and t_R. RS theories provide a very motivated picture of the UV physics, but more generically, in any theory (not necessarily with approximate scale invariance) containing composite WIMPs and composite top quarks belonging to a common sector one would expect strong couplings between them as a residual of the strong force which binds them, and perhaps negligible coupling to the rest of the Standard Model.

If the Z' mixes with the electroweak bosons, this results in strong constraints from precision data. We circumvent these constraints by considering a Z' whose mixing with the Z is kinetic. At large Z' masses this is not operationally different from the mass-mixing case, but it allows us to consider lower mass Z's which are not ruled out by precision data.

2. – Signals at CLIC

Since the coupling of Z' to light SM fermions is suppressed by the small kinetic mixing factor, the best probe of the dark sector is through the top portal. In particular, the Z' can be produced by being radiated from top quarks, as illustrated in fig. 1. In fig. 2, we show the leading-order cross-section at CLIC for $t\bar{t}Z'$ production, as calculated by CalcHep 2.5.4 [4]. Depending on the masses and couplings, the Z' will predominantly decay into $t\bar{t}$, $N\bar{N}$, or into light fermions. Decays into top quarks lead to four-top events with a very large cross-section compared to the SM four-top rate, which leads to a characteristic same-sign di-lepton signature [5, 6] (see also [7] for studies of a $ttWW$ final state at the LHC). The right-handed nature of the Z' coupling to top quarks implies that top polarisation also provides an interesting observable. When the Z' decays into WIMPs, a $t\bar{t}$ + missing energy final state results, which is particularly compelling at high energy e^+e^- colliders such as CLIC.

We present preliminary results of an analysis aimed at characterising these signals in multi-TeV e^+e^- collisions. Signal events are generated using CalcHep, assuming

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(^{1}) χ can be engineered to vanish in the UV, for example, by embedding $U(1)'$ into a larger gauge group which breaks down at scales of order $M_{Z'}$.

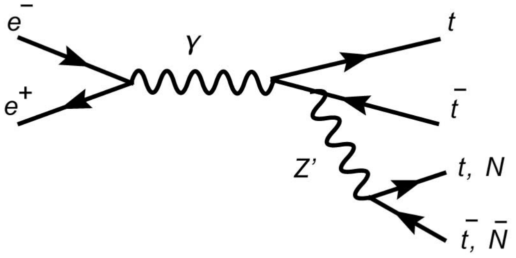

Fig. 1. – Z' mediated production of $t\bar{t}t\bar{t}$ and $t\bar{t} + E_{\text{miss}}$ at CLIC.

$g_t^{Z'} = g_N^{Z'} = 3$, and subsequently hadronised with Pythia 6.125 [8]. We assume the beams to be unpolarised. Events are processed through full detector simulation using the GEANT-4-based MOKKA [9] program and reconstructed with MARLIN-based [10] processors assuming a version of the ILD detector [11], modified for physics at CLIC. The performances most relevant to the analysis of these events are a relative parton energy resolution at 1 TeV $\delta_{90}E/E \simeq 0.08$–$0.10$, charged particle momentum resolution $\delta p_t/p_t^2 = 2 \times 10^{-5}\,\text{GeV}^{-1}$, track extrapolation resolution of $5\ (\mu\text{m}) \oplus \frac{13(\mu\text{m GeV}^{-1})}{p_t(\text{GeV})}$. We perform jet clustering forcing the number of jets to the number of top quarks expected in the signal final state of interest. Jet reconstruction is performed with the Durham algorithm [12]. In this preliminary study we do not account for machine-induced backgrounds and do not attempt to perform a detailed top reconstruction through the identification of its Wb decay, which will need to be evaluated in a more refined analysis. We now discuss both signatures in turn.

2·1. $e^+e^- \to t\bar{t} + E_{\text{miss}}$. – The Standard Model background for $e^+e^- \to t\bar{t} + E_{\text{miss}}$ is dominated by $e^+e^- \to t\bar{t} + \nu_e\overline{\nu}_e$, which, at 3 TeV, has a cross-section of 4.1 fb. By comparison, the signal cross-section for $M_{Z'} = 200\,\text{GeV}$, $M_N = 97\,\text{GeV}$, $\chi = 10^{-3}$ is 16.5 fb (note that this choice of parameters leads to the correct relic density for dark matter [2]). For a higher mass $M_{Z'} = 320\,\text{GeV}$, the cross-section is 7.6 fb. The event selection requires $2 \leq N_{\text{jet}} \leq 6$, where N_{jet} is the number of natural jets obtained with the Durham algorithm for $y_{\text{cut}} = 0.0025$, more than 50 particles with $p_t > 0.5\,\text{GeV}$,

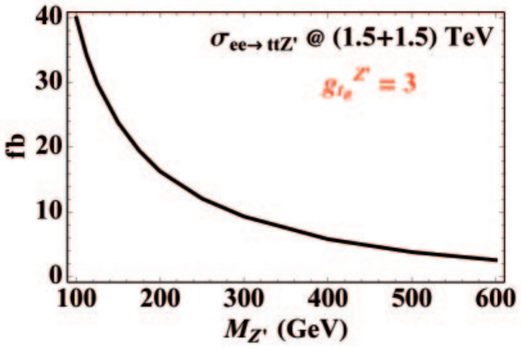

Fig. 2. – $t\bar{t}Z'$ production at CLIC as a function of the Z' mass.

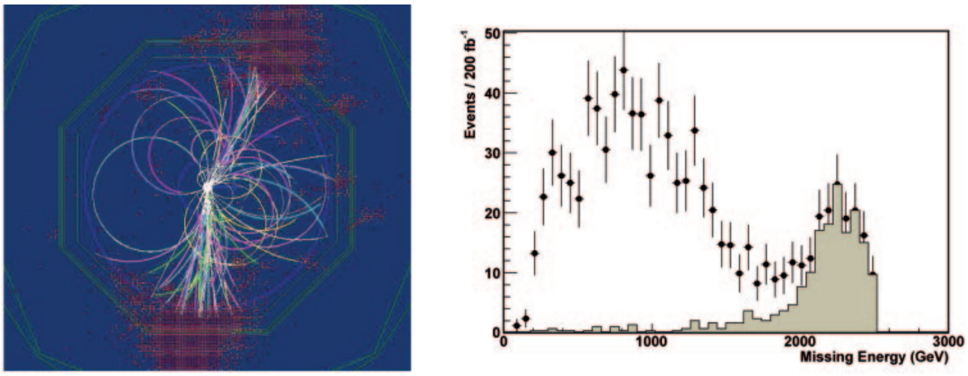

Fig. 3. – Signal $e^+e^- \rightarrow t\bar{t}Z' \rightarrow t\bar{t}N\bar{N}$ events at 3 TeV for $M_{Z'} = 200\,\text{GeV}$, $M_N = 97\,\text{GeV}$. Left: display of a reconstructed event. Right: reconstructed E_{miss} distribution. The points with error bars show the reconstructed events for $200\,\text{fb}^{-1}$ of statistics and the filled histogram the contribution of the SM $t\bar{t}\nu\bar{\nu}$ background after event pre-selection.

total reconstructed energy in the detector larger than 500 GeV, transverse energy larger than 250 GeV, event thrust larger than 0.75 and sphericity lower than 0.30. The missing energy in the event, E_{miss}, appears to be the best discriminating variable against the SM $t\bar{t}\nu\bar{\nu}$ "irreducible" background. Figure 3 shows the E_{miss} distribution for signal and background events. We require $E_{\text{miss}} < 1900\,\text{GeV}$. Events fulfilling these criteria are clustered into two jets. We further require both jets to have $|\cos\theta| < 0.90$, where θ is the polar angle of the jet axis. Next we compute the invariant mass, M_{jet} of each jet. We require the invariant mass of both jets to be in the range $125\,\text{GeV} < M_{\text{jet}} < 225\,\text{GeV}$, around the top quark mass. After this selection, there are 648 signal and 22 SM $t\bar{t}\nu_e\bar{\nu}_e$ background events, for $200\,\text{fb}^{-1}$ of integrated luminosity at 3 TeV. Due to the finite parton energy resolution and the beamstrahlung effects, it is not feasible to reconstruct the Z' mass from the mass of the system recoiling against the $t\bar{t}$ pair. Instead, we can measure the invariant mass of the $t\bar{t}$ system. The upper endpoint of this distribution is well preserved after reconstruction (see fig. 4) and can be used to estimate the Z' mass.

2˙2. $e^+e^- \rightarrow t\bar{t}t\bar{t}$. – The four top quark final state represents a spectacular signature, with minimal background from SM processes (see fig. 5). The analysis of the invariant mass of the di-top system offers a mean of measuring the Z' mass. The main experimental challenge for this analysis is the accurate reconstruction of the twelve parton final state. In this preliminary study, the event selection procedure is similar to that adopted for the $t\bar{t} + E_{\text{miss}}$ channel with the exception that in this case there is no missing energy expected, except through leptonic decays in the top decay chain.

The SM cross-section for $e^+e^- \rightarrow t\bar{t}t\bar{t}$ at 3 TeV is 0.03 fb while the signal cross-section for $M_{Z'} = 360\,\text{GeV}$ is 4.2 fb. The dominant SM background will actually come from $t\bar{t}W$+jets. The cross-section for $t\bar{t}Wjj$ is estimated to 0.4 fb while that for $t\bar{t}WW+N$jets to 0.6 fb(^{2}). We request events to have more 50 particles with $p_t > 0.5\,\text{GeV}$, total reconstructed energy in the detector larger than 2.5 TeV, transverse energy larger than 1 TeV, event thrust larger than 0.96, sphericity lower than 0.50 and more than four jets

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(^{2}) We thank Marcel Vos for providing these estimates.

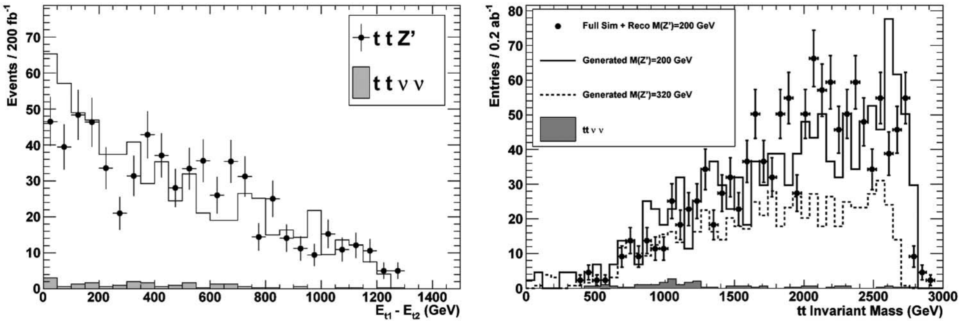

Fig. 4. – (Left) Difference between the energy of the two top quarks. (Right) Invariant mass of the $t\bar{t}$ pair. The points with error bars show the reconstructed events for $200\,\mathrm{fb}^{-1}$ of statistics and the filled histogram the contribution of the SM $t\bar{t}\nu_e\bar{\nu}_e$ background after event selection. The continuous line is the distribution for signal events at generator level. The right panel shows the $t\bar{t}$ invariant mass at generator level for two values of the Z' mass.

using Durham clustering. Events surviving these cuts are forced into four jets and a kinematic fit is applied to improve the parton energy resolution. We use a port of the Pufitc kinematic fit algorithm [13]. Figure 5 shows the $t\bar{t}$ invariant mass distribution for $1\,\mathrm{ab}^{-1}$ of integrated luminosity at 3 TeV. The signal is clearly visible over a negligible SM background. For $M_{Z'} = 360\,\mathrm{GeV}$ there are 240 signal events in the mass peak around the generated Z' mass. The Z' mass can be determined with a statistical accuracy of $\simeq 3.5\,\mathrm{GeV}$.

To conclude, multi-top production is an expected signature for several processes at, and beyond, the TeV frontier. It has the advantage that the irreducible SM background is small so that multi-top detection can provide clean probes of new physics. It also carries experimental challenges from the reconstruction of a large number of partons, with missing energy and leptons. The prospects for studying these signatures at the

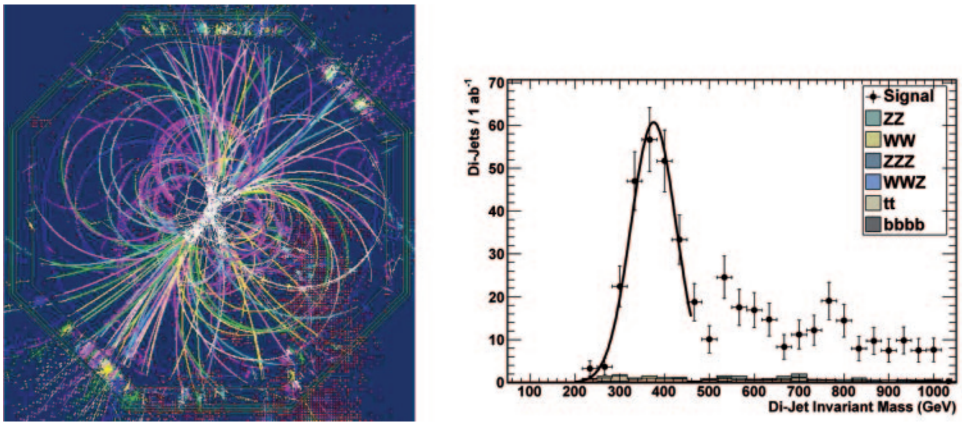

Fig. 5. – Signal $e^+e^- \to t\bar{t}Z' \to t\bar{t}t\bar{t}$ events at 3 TeV. Left: display of a reconstructed event. Right: invariant mass of the pair $t\bar{t}$ of lowest energy in $e^+e^- \to t\bar{t}t\bar{t}$ events after kinematic fit with the SM backgrounds for $1\,\mathrm{ab}^{-1}$ of integrated luminosity and $M_{Z'} = 360\,\mathrm{GeV}$.

LHC are promising [6]. In this contribution, we started investigating these signatures at e^+e^- colliders using a template model but it is clear that this work can be useful to other models having similar final states.

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REFERENCES

[1] Randall L. and Sundrum R., *Phys. Rev. Lett.*, **83** (1999) 3370 [arXiv:hep-ph/9905221]; Agashe K., Delgado A. and Sundrum R., *Ann. Phys. (N.Y.)*, **304** (2003) 145 [arXiv:hep-ph/0212028].

[2] Jackson C. B., Servant G., Shaughnessy G., Tait T. M. P. and Taoso M., *JCAP*, **1004** (2010) 004 [arXiv:0912.0004 [hep-ph]].

[3] Contino R., Nomura Y. and Pomarol A., *Nucl. Phys. B*, **671** (2003) 148 [arXiv:hep-ph/0306259]; Agashe K., Contino R. and Pomarol A., *Nucl. Phys. B*, **719** (2005) 165 [arXiv:hep-ph/0412089]; Agashe K. and Contino R., *Nucl. Phys. B*, **742** (2006) 59 [arXiv:hep-ph/0510164]; Contino R., Kramer T., Son M. and Sundrum R., *JHEP*, **0705** (2007) 074 [arXiv:hep-ph/0612180].

[4] Pukhov A., arXiv:hep-ph/0412191.

[5] Lillie B., Shu J. and Tait T. M. P., *JHEP*, **0804** (2008) 087 [arXiv:0712.3057 [hep-ph]]; Pomarol A. and Serra J., *Phys. Rev. D*, **78** (2008) 074026 [arXiv:0806.3247 [hep-ph]]; Kumar K., Tait T. M. P. and Vega-Morales R., *JHEP*, **0905** (2009) 022 [arXiv:0901.3808 [hep-ph]].

[6] Gauthier L. and Servant G., in preparation.

[7] Contino R. and Servant G., *JHEP*, **0806** (2008) 026 [arXiv:0801.1679 [hep-ph]]; Mrazek J. and Wulzer A., arXiv:0909.3977 [hep-ph].

[8] Sjostrand T., Mrenna S. and Skands P. Z., *JHEP*, **0605** (2006) 026 [arXiv:hep-ph/0603175].

[9] Mora de Freitas P., in *Proceedings of the International Conference on Linear Colliders (LCWS 04)*, Vol. **I** (Ed. de l'Ecole Polytechnique, Paris) 2004, p. 437.

[10] Gaede F., *Nucl. Instrum. Methods A*, **559** (2006) 177.

[11] Stoeck H. *et al.* (The ILD Concept Group), The International Large Detector - Letter of Intent, March 2009.

[12] Catani S., Dokshitzer Y. L., Olsson M., Turnock G. and Webber B. R., *Phys. Lett. B*, **269** (1991) 432.

[13] Abreu P. *et al.* (DELPHI Collaboration), *Eur. Phys. J. C*, **2** (1998) 581.