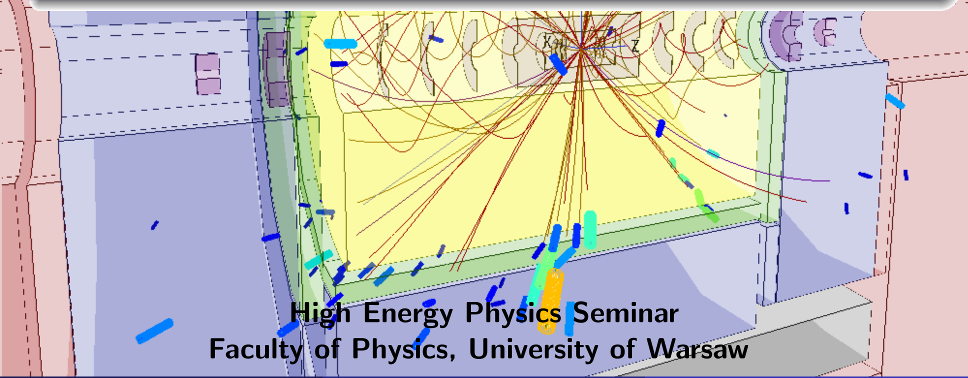
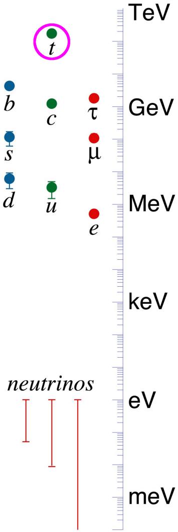
Limits on top quark FCNC decays from CLIC at 380 GeV

Aleksander Filip Żarnecki



High Energy Physics Seminar
Faculty of Physics, University of Warsaw

Outline



Credit: Hitoshi Murayama

Top quark

- the heaviest known elementary particle
- Yukawa coupling to Higgs boson $y_t \sim 1$
  $\Rightarrow$ key to understanding of EWSB
- decays before hadronizing:
  the only "naked" quark
  $\Rightarrow$ test ground for QCD
- large loop contributions to many precision measurements
- sensitive to many BSM scenarios
  $\Rightarrow$ a window to "new physics"

Top quark decays

On the tree level only charged current top decays are allowed in the Standard Model

$$t \rightarrow W^+ b \quad \text{dominant, BR} = 99.8\%$$
$$t \rightarrow W^+ s/d \quad \text{CKM suppressed}$$

FCNC top decays are only possible on loop level.
Four two-particle final states can be considered in SM:

$$t \rightarrow q\gamma\ ,\ qZ\ ,\ qg\ ,\ qH \qquad q = u, c$$

Motivation

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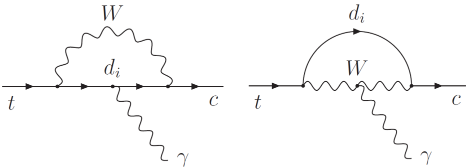
$$t \rightarrow q\gamma \,,\; qZ \,,\; qg \,,\; qH \qquad q = u, c$$

However, leading order diagrams suppressed by CKM matrix unitarity

$t \rightarrow c\,\gamma$



$$\mathcal{M} \sim \sum_{d_i} V^{\star}_{td_i} V_{cd_i} = 0$$

Predictions

In the Standard Model, FCNC top decays are strongly suppressed (CKM+GIM):

$$\begin{aligned} BR(t \rightarrow c\,\gamma) &\sim 5 \cdot 10^{-14} \\ BR(t \rightarrow c\,h) &\sim 3 \cdot 10^{-15} \\ BR(t \rightarrow c\,Z) &\sim 1 \cdot 10^{-14} \\ BR(t \rightarrow c\,g) &\sim 5 \cdot 10^{-12} \end{aligned}$$

Any signal is a direct signature of "new physics"...

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Any signal is a direct signature of "new physics"...

Significant enhancement possible in many BSM scenarios

Maximum branching fractions possible:

Model	2HDM	MSSM	$\not{R}$ SUSY	LH	Q singlet	RS
BR($t \rightarrow c\,\gamma$)	10^{-6}	10^{-6}	10^{-5}	10^{-7}	$8 \cdot 10^{-9}$	10^{-9}
BR($t \rightarrow c\,h$)	10^{-2}	10^{-4}	10^{-6}	10^{-5}	$4 \cdot 10^{-5}$	10^{-4}

Constrains

95% C.L. limits from LHC experiments

$$BR(t \to c\gamma) < 0.17\% \text{ (CMS)}$$

$$BR(t \to ch) < 0.40\% \text{ (CMS)}$$
$$BR(t \to ch) < 0.22\% \text{ (ATLAS)}$$

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Expectations

Limits expected after HL-LHC running (3 ab^{-1} at 14 TeV)

$$BR(t \to c\gamma) < 2.0 - 3.4 \cdot 10^{-4} \text{ (CMS)}$$

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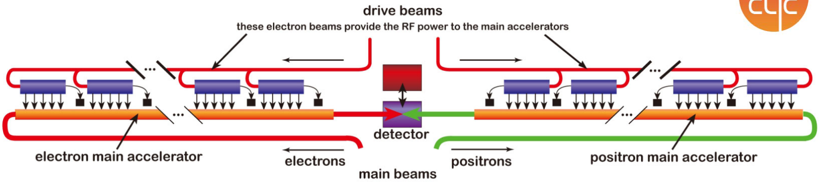
e^+e^- colliders

Can be competitive for selected channels thanks to high statistics of produced top quarks, clean environment and well constrained kinematics.

Compact LInear Collider



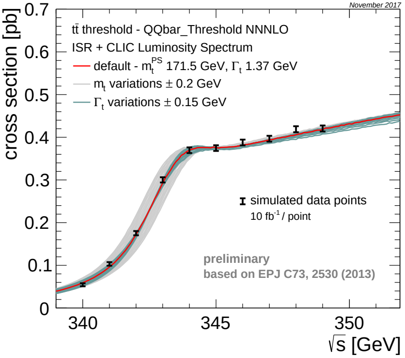
Conceptual Design (CDR) presented in 2012 CERN-2012-007

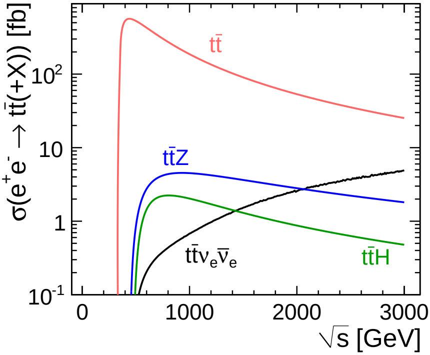
- high gradient, two-beam acceleration scheme
- staged implementation plan with c.m.s energy from 380 GeV to 3 TeV
- footprint of 11 to 50 km
- e^- polarisation, e^+ polarisation as possible upgrade
- ongoing R&D and large-scale system tests

CLIC running scenario

Three construction stages (each 5 to 7 years of running)

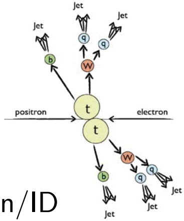
- $\sqrt{s} = 380$ GeV with 500 fb^{-1} $+$ 100 fb^{-1} at $t\bar{t}$ threshold
  selected as an optimal choice for precision Higgs and top physics
- $\sqrt{s} = 1.5$ TeV with 1500 fb^{-1}
- $\sqrt{s} = 3$ TeV with 3000 fb^{-1}





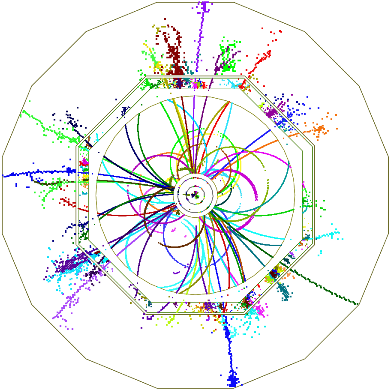
Detector Requirements

Jet reconstruction and jet energy measurement based on "Particle Flow" concept



Single particle reconstruction/ID
$\Rightarrow$ high calorimeter granularity

Benchmark reaction
$e^+e^- \to t\bar{t} \to 6j$



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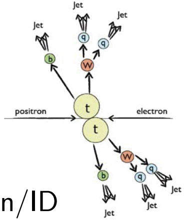

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Best possible jet energy estimate
$\Rightarrow$ precise momentum measurement

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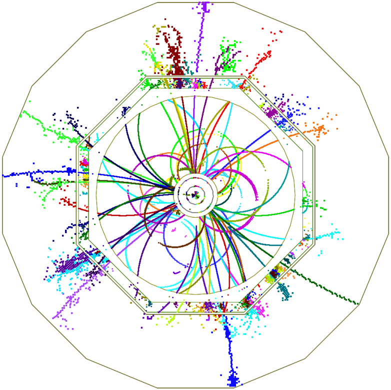

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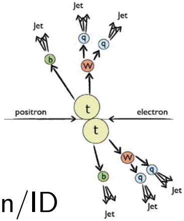

Single particle reconstruction/ID
⇒ high calorimeter granularity

Best possible jet energy estimate
⇒ precise momentum measurement

Very efficient flavour tagging
⇒ high precision vertex detector

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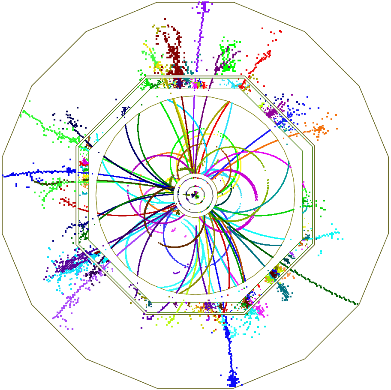

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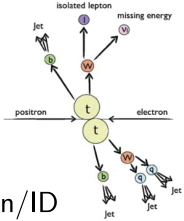


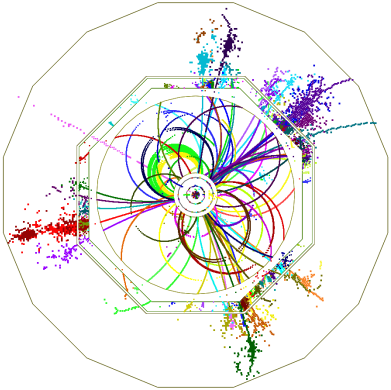
Single particle reconstruction/ID
⇒ high calorimeter granularity

Best possible jet energy estimate
⇒ precise momentum measurement

Very efficient flavour tagging
⇒ high precision vertex detector

Missing energy measurement
⇒ hermecity

Benchmark reaction
$e^+e^- \rightarrow t\bar{t} \rightarrow 4j + l + \nu$

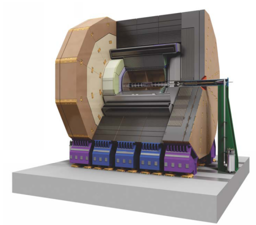


Detector Requirements

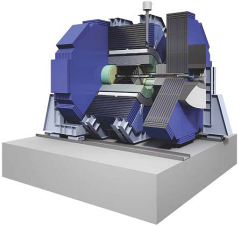
- Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m \, \frac{1\ \mathrm{GeV}}{p\ \sin^{3/2}\Theta}$
- Jet energy resolution: $\sigma_E/E = 3 - 4\%$ (highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

Three detailed detector concepts for CLIC:

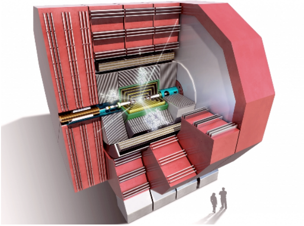
ILD-like



SiD-like



CLIC detector



Full simulation for CLIC @ 380 GeV

Framework

Dedicated samples generated with WHIZARD 2.2.8
Background samples generated previously with WHIZARD 1.95

Detailed beam spectra for CLIC and beam induced backgrounds included
Beam polarization of -80%/0% (for e^-/e^+) assumed

Hadronization done in PYTHIA 6.427
quark masses and PYTHIA settings adjusted to CLIC CDR

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Standard event processing with CLIC_ILD_CDR500 configuration
Analysis based on PandoraPFA objects with loose selection cuts
LooseSelectedPandoraPFANewPFOs

Vertexing, jet reconstruction and flavour tagging with LCFI+
Using Valencia jet algorithm for best mass reconstruction

Event samples

Signal and background samples considered in the analysis.

Assuming 500 fb^{-1} collected at 380 GeV, with polarization of -80%/0%.
FCNC signal normalised to $BR(t \to cX) = 10^{-3}$

Sample	Cross section	Expected events	MC event sample
FCNC signal	1.79 fb	895	99 301
6 fermion	938 fb	469 000	1 014 966
4 fermion	21 pb	10 500 000	7 067 836
quark pair	26 pb	13 000 000	2 968 551

Analysis has to focus on reduction of huge non-$t\bar{t}$ backgrounds

Search for $t \to c\gamma$

Signature assuming hadronic decay of "spectator" top

- high energy isolated photon ($E_\gamma = 50$ – 140 GeV)
- high energy c-quark jet ($E_{c-jet} = 50$ – 140 GeV)
- one b-quark jet and a pair of light jets from spectator top

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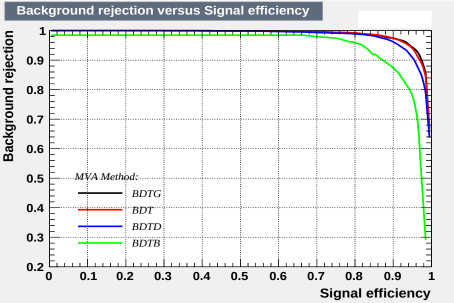
Analysis

- require isolated photon with $E_\gamma > 50$ GeV
- reconstruct top pair decay kinematics
  caclulate χ^2 for signal and background (SM $t\bar{t}$) hypothesis
- multivariate analysis (BDT) for final signal-background discrimination

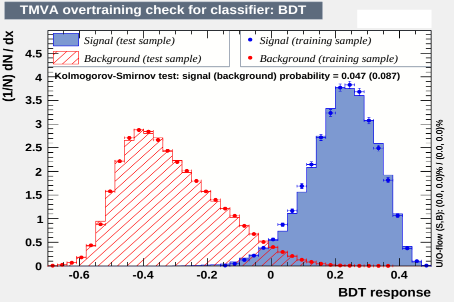
Multivariate analysis TMVA

Combining all available information on the event:
photon properties, jet properties, flavour tagging, results of kinematic reconstruction (χ^2, invariant masses etc.). Total of 42 input variables.

Comparison of MVA methods



Response distribution for BDT

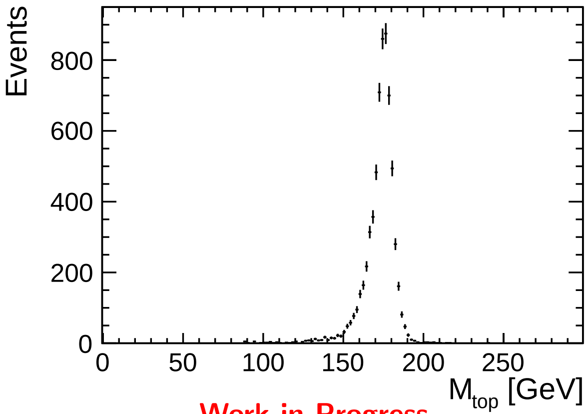


Work in Progress

Kinematic reconstruction

For signal events after BDT selection cut ($BDT > 0.28$)

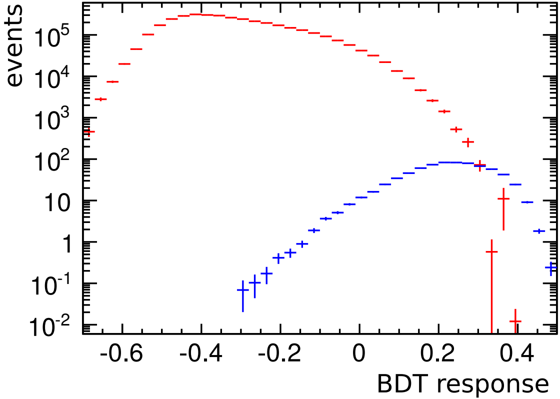
Signal top invariant mass



Work in Progress

Signal-background discrimination

Comparison of BDT response distribution for SM background events and FCNC signal, assuming $BR(t \to c\gamma) = 10^{-3}$



Work in Progress

Selection efficiency

	Signal	SM bg
isolated photon	0.92	0.21
BDT > 0.28	0.30	0.00016
Total	0.28	0.000034

Expected limits

For 500 fb^{-1} collected at 380 GeV

$$N_{bg} \approx 570$$

background events are expected after BDT response cut optimised for $S/\sqrt{S+B}$

Corresponds to 95% C.L. limit:

$$BR(t \to c\gamma) < 3 \cdot 10^{-4}$$

Work in Progress

proper limit extraction still missing

Search for $t \to ch$

Signature assuming Higgs decay channel $h \to b\bar{b}$

- final state compatible with SM $t\bar{t}$ events
  both hadronic ($6q$) and semi-leptonic ($4q\ l\nu$) events considered
- three b-quark jets in the finals state + c-quar jet
- invariant mass of two b-quark jets consistent with h mass

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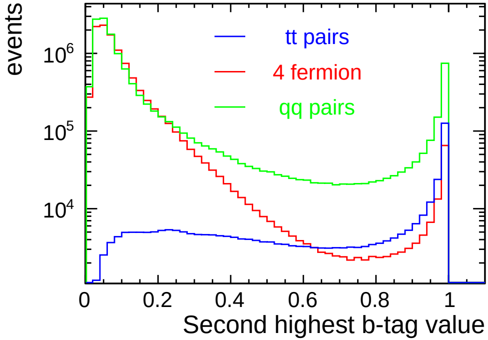
Analysis

- event classification (into hadronic, semi-leptonic, leptonic samples)
- pre-selection cuts (loose cuts on kinematics and flavour tagging)
- kinematic fit (for signal and background hypothesis)
- final selection based on multivariate analysis

Initial selection cut

To suppress non-$t\bar{t}$ background contribution, two jets are required to have b-tag of at least 0.2 (from 6-jet or from 4-jet final state reconstruction)



Removes 80% of $q\bar{q}$ events and 92% of 4-fermion sample.
FCNC signal efficiency of about 98% (90% for SM $t\bar{t}$ sample).

Event classification

Two signal channels: fully hadronic and semi-leptonic decays

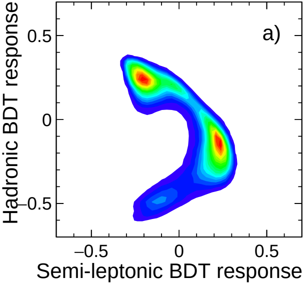
Event selection:

used two BDTs for event classification: "hadronic" and "semi-leptonic"

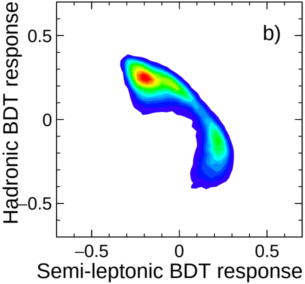
based on total energy-momentum, event shape and jet parameters (y_{min}, y_{max}), lepton ID

$\Rightarrow$ improved efficiency/purity, compared to cut-based approach

SM $t\bar{t}$ sample



FCNC $t\bar{t}$ decays



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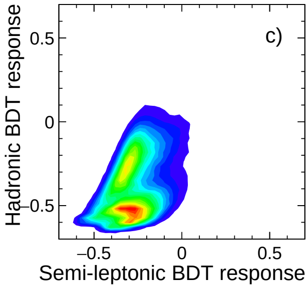
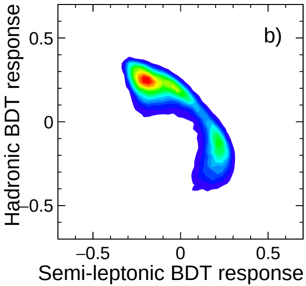
SM 4-fermion sample



FCNC $t\bar{t}$ decays



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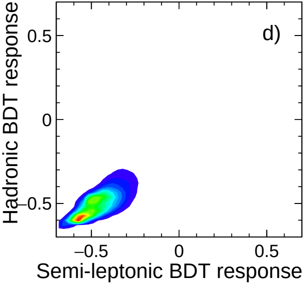
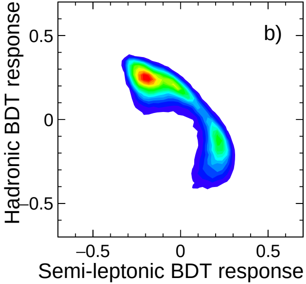
SM $q\bar{q}$ sample



FCNC $t\bar{t}$ decays



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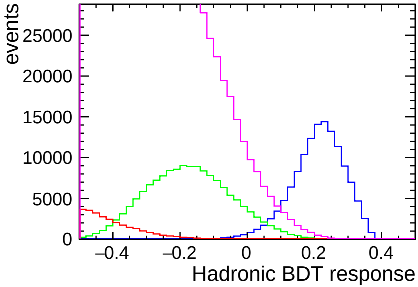
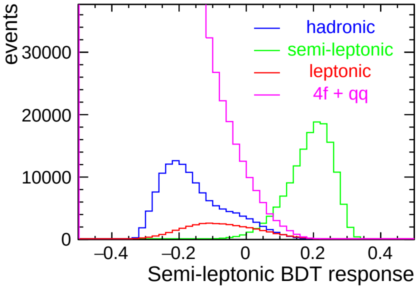
Hadronic sample selection



Semi-leptonic sample selection



Kinematic fit

Signal hypothesis: three jets are required to have b-tag > 0.4
fourth jet required to have c-tag $+$ b-tag > 0.4

χ^2 definition for hadronic events

Mass ratios used to reduce influence of mass correlations

- signal hypothesis top boost as additional constrain

$$\chi^2_{sig} = \left(\frac{M_{bqq} - m_t}{\sigma_t}\right)^2 + \left(\frac{M_{bbc} - m_t}{\sigma_t}\right)^2 + \left(\frac{\frac{E_{bqq}}{M_{bqq}} - \gamma_t}{\sigma_\gamma}\right)^2 + \left(\frac{\frac{E_{bbc}}{M_{bbc}} - \gamma_t}{\sigma_\gamma}\right)^2$$

$$+ \left(\frac{\frac{M_{qq}}{M_{bqq}} - \frac{m_W}{m_t}}{\sigma_{R_W}}\right)^2 + \left(\frac{\frac{M_{bb}}{M_{bbc}} - \frac{m_h}{m_t}}{\sigma_{R_h}}\right)^2$$

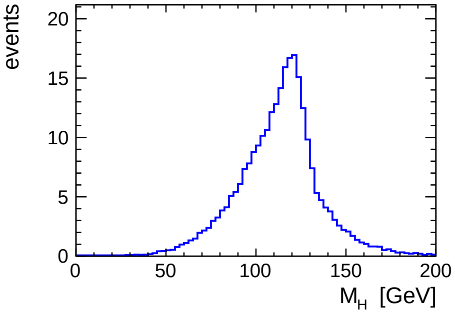
- similar for background hypothesis ($t\bar{t}$ hadronic decays)

$$\chi^2_{bg} = \quad \ldots \quad + \left(\frac{\frac{M_{qq}}{M_{bqq}} - \frac{m_W}{m_t}}{\sigma_{R_W}}\right)^2 + \left(\frac{\frac{M_{bq}}{M_{bqq}} - \frac{m_W}{m_t}}{\sigma_{R_W}}\right)^2$$

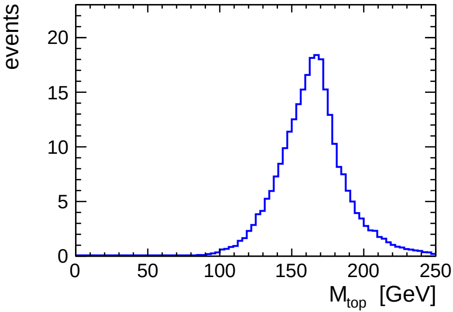
Results

Distributions of reconstructed invariant masses for FCNC event sample, "signal" top decay reconstruction

Higgs boson mass



Top quark mass

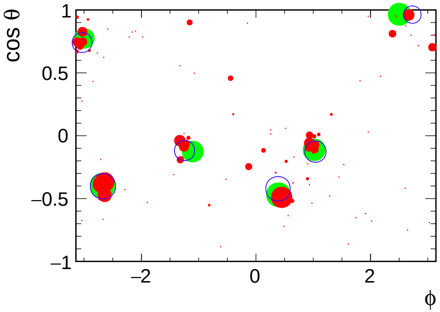


Invariant mass distributions wider than expected !?...

Clustering quality

Reconstructed PFOs and the clustering results compared to parton level

"good" event



- partons
- reconstructed particles (PFOs)
- Valencia jets (LCFI+)
- anti-k_T jets

size reflects energy (log scale)

⇒ Kinematic fit works OK!

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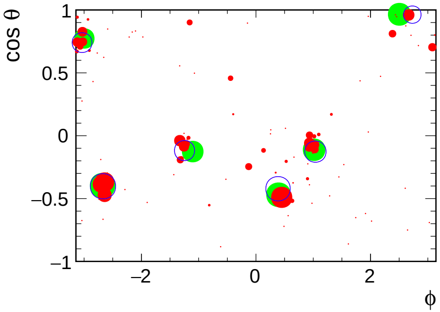
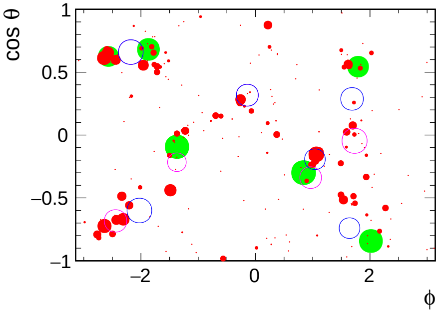


"bad" event



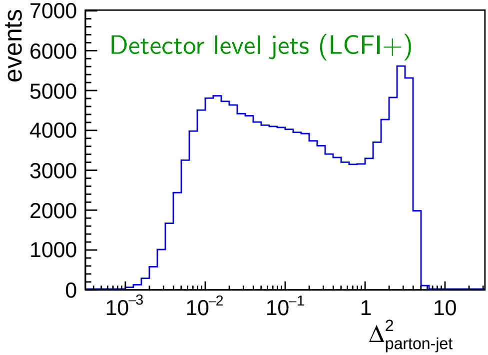
⇒ Kinematic fit works OK!

⇒ Can not discriminate between signal and background...

Clustering quality

"Distance" Δ^2 defined to quantify the agreement between generator level partons and particle or detector level jets

$$\Delta^2_{\text{parton-jet}} = \min_{\text{all combinations}} \sum [\sphericalangle(\vec{p}_{jet}, \vec{p}_{parton})]^2$$

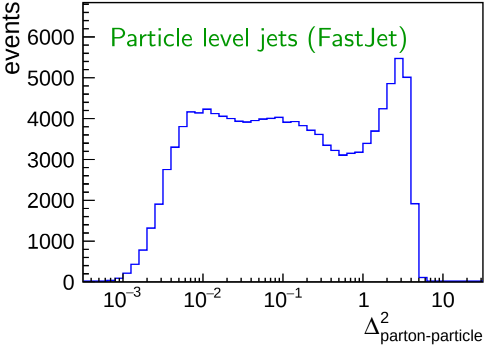


Kinematic fit

Clustering quality

"Distance" Δ^2 defined to quantify the agreement between generator level partons and particle or detector level jets

$$\Delta^2_{\text{parton-jet}} = \min_{\text{all combinations}} \sum [\sphericalangle(\vec{p}_{jet}, \vec{p}_{parton})]^2$$



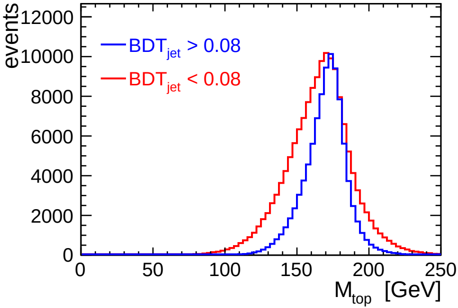
Contribution of poorly reconstructed events ($\Delta^2 > 1$) already on MC level

Clustering quality estimate

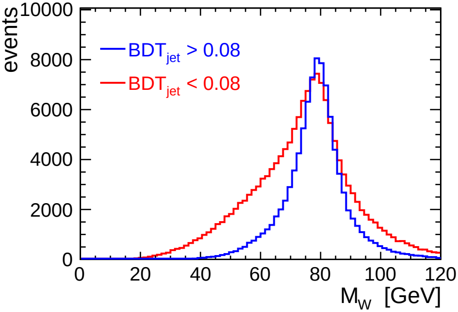
Dedicated BDT implemented to recognize events with “bad” clustering
based on jet variables and comparison of different jet algorithms

Kinematic fit result for SM $t\bar{t}$ background sample

Top quark mass



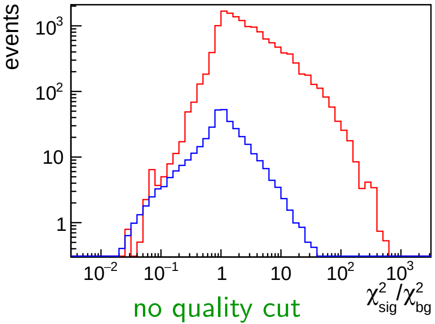
W boson mass



Signal/background discrimination

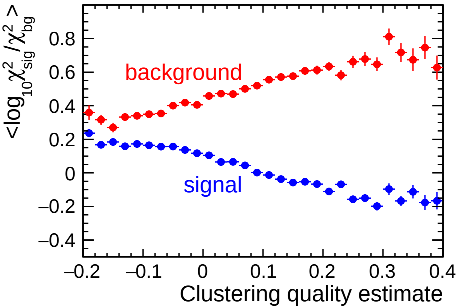
Kinematic fits for two hypotheses (FCNC signal and SM background) can be compared to discriminate between signal and background events.

χ^2 ratio for two hypotheses



no quality cut

average χ^2 ratio vs quality estimate



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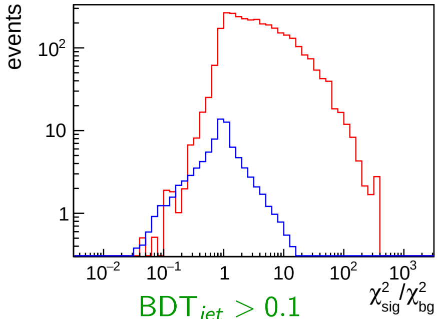
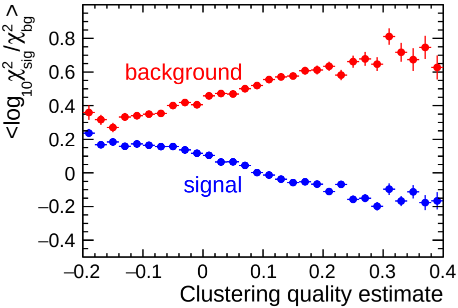


$\text{BDT}_{jet} > 0.1$

average χ^2 ratio vs quality estimate



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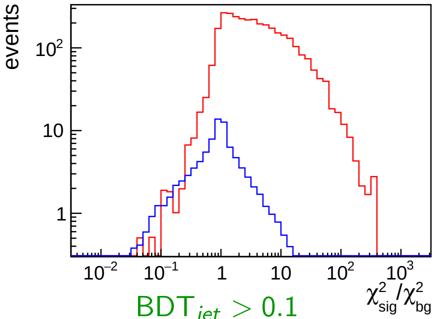

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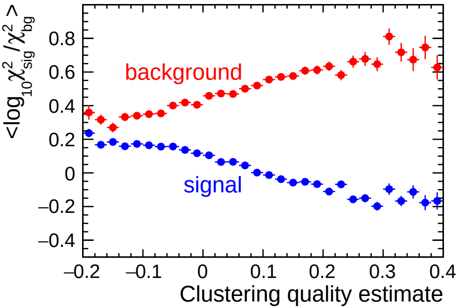


Kinematic separation not very efficient, event with quality cut...

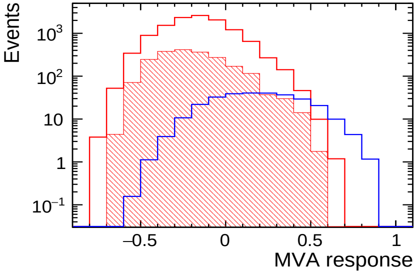
Multivariate analysis TMVA

Used for final signal vs background discrimination

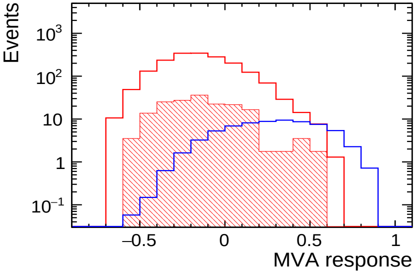
Based on: event variables, flavour tagging and kinematic fit

One BDT trained on both samples

Hadronic decays



Semi-leptonic decays



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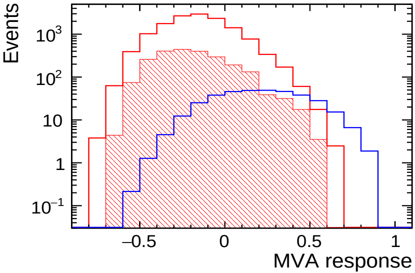
Hadronic and semi-leptonic decays



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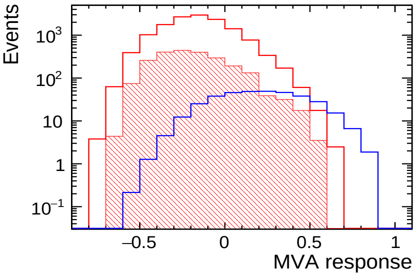

⇒ avoid complicated procedure for combining limits from both channels

Selection efficiencies

Cut	FCNC signal	6 fermion	4 fermion	quark pairs
Preselection	98.6%	88%	8.5%	19.9%
Classification	98.9%	90%	5.1%	1.1%
Signal selection	45%	3.6%	2.8%	3.3%
BDT response	16.6%	0.17%	$<$0.1%	0.5%
Total	7.3%	$4.8 \cdot 10^{-5}$	$< 10^{-7}$	$3 \cdot 10^{-7}$

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Expected limit 95% CL

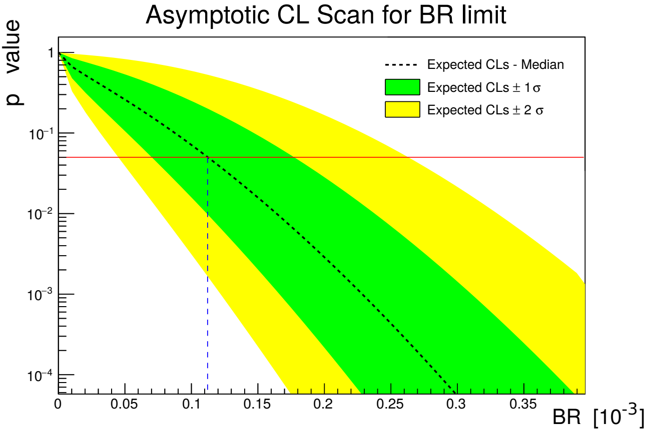
With estimated background of 24.2 events and signal efficiency of 7.3%

$$BR(t \to ch) \times BR(h \to b\bar{b}) \quad < \quad 1.6 \cdot 10^{-4}$$

based on simple event counting after BDT cut

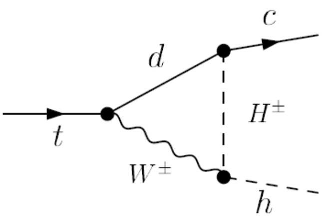
Limit setting

Final limits calculated from BDT response distributions using CL_s method



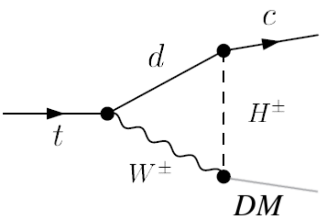
$$BR(t \to ch) \times BR(h \to b\bar{b}) \quad < \quad 1.2 \cdot 10^{-4} \qquad \text{(Freq.)}$$

Scenario



In 2HDM enhancement of the $t \to ch$ decay can be due to loop contributions including new charged higgs boson.

Scenario



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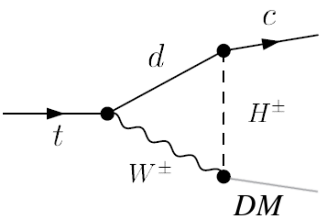
In models with inert doublet, the scalar particle coupling to $W^{\pm}$ and $H^{\pm}$ can be stable (Dark Matter candidate).

Can we set limits on such scenario?

Scenario



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Can we set limits on such scenario?

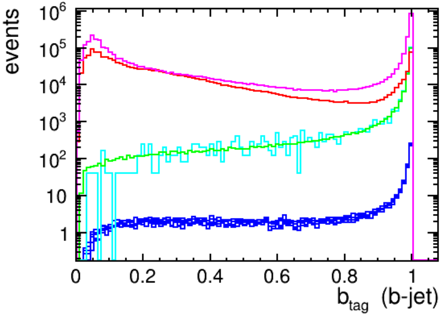
2HDM(III) used to generate dedicated samples with $t \to ch$ decay but with the Higgs boson defined as a stable particle in PYTHIA (and thus invisible in the detector)

Samples were generated for $m_{DM} = 25$, 50, 75, 100, 125 and 150 GeV.

Preselection

We look for the final state consisting of four jets with only one b quark (c + hadronic decay of second top quark)

Dominant background contribution expected from four fermion processes (mainly WW production), but also from quark pair production.



b-tag value for b-jet > 0.6

Expected distribution for 500 fb^{-1}:

— FCNC signal $BR = 10^{-3}$

— 6-fermion ($t\bar{t}$) sample

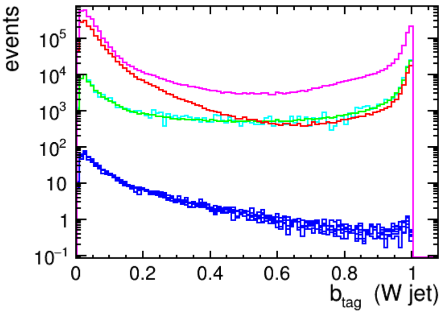
— 4-fermion sample

— quark-pair sample

Preselection

We look for the final state consisting of four jets with only one *b* quark
(c + hadronic decay of second top quark)

Dominant background contribution expected from four fermion processes (mainly *WW* production), but also from quark pair production.



b-tag value for other jets < 0.4

Expected distribution for 500 fb^{-1}:
— FCNC signal $BR = 10^{-3}$
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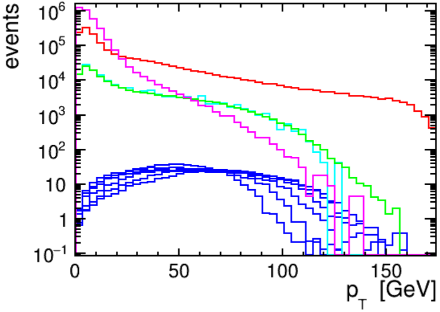

Transverse momentum > 20 GeV

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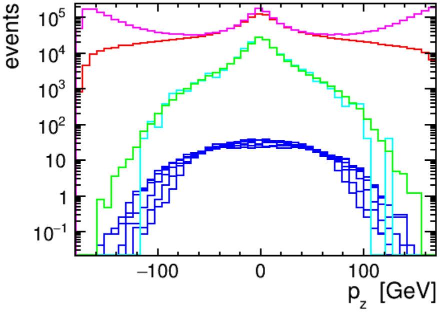

Long. momentum $|p_z| < 100$ GeV

Expected distribution for 500 fb^{-1}:
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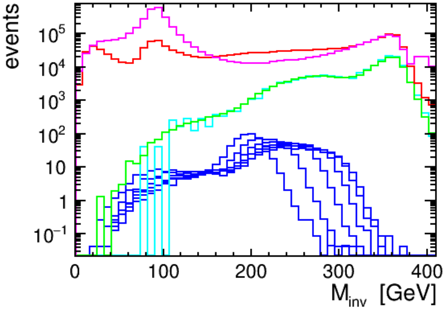


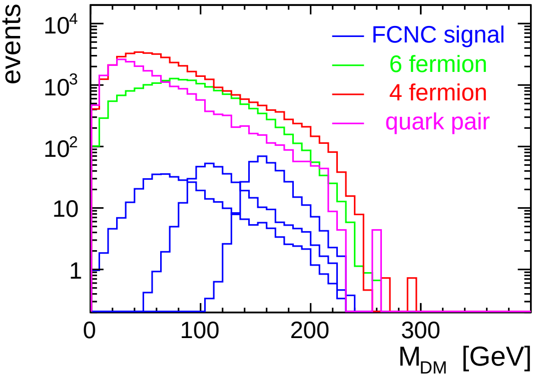
Total invariant mass > 140 GeV

Expected distribution for 500 fb^{-1}:
— FCNC signal $BR = 10^{-3}$
— 6-fermion ($t\bar{t}$) sample
— 4-fermion sample
— quark-pair sample

Final state reconstruction

Take jet with highest c-tag value as the c-jet $\Rightarrow$ no ambiguity

Distribution of the reconstructed invariant mass of the invisible decay product, after preselection (for $m_{DM} = 50$, 100 and 150 GeV)



Pre-selection efficiency for signal events between 35 and 42%

Signal-background discrimination

Independent BDTs trained for selection of signal events for low mass scenarios (below 100 GeV) high mass scenarios (100 GeV and above).

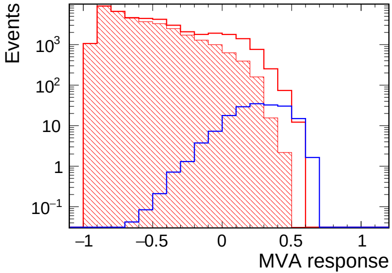
Same set of variables used: general event properties (E_{tot}, p_T, M_{inv}, M_{miss}, S, A), clustering parameters (y_{min}, y_{max}), reconstructed top and invisible scalar masses, χ^2 value from the kinematic fit.

Signal-background discrimination

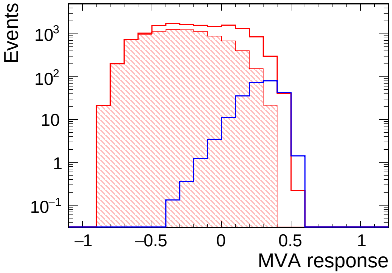
Independent BDTs trained for selection of signal events for low mass scenarios (below 100 GeV) high mass scenarios (100 GeV and above).

For each considered value of the invisible scalar particle mass the BDT response distribution was plotted for events in the ±30 GeV window in the reconstructed particle mass ⇒ used for limit setting

$m_{DM} = 50$ GeV



$m_{DM} = 125$ GeV



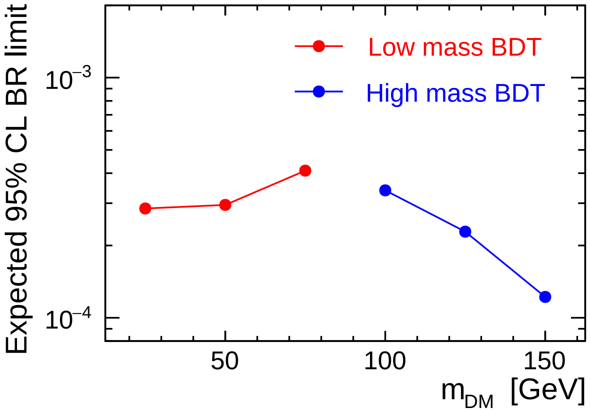
Results

Summary of cross section values, selection efficiencies and numbers of events expected for two selected masses

Sample	σ	$\epsilon_{Pre.}$ (%)	$\epsilon_{BDT>0.25}$ (%)	$N_{BDT>0.25}$
Low mass selection, $m_{DM} = 50$ GeV				
FCNC	1.79 fb	41	29	105
6-fermion	938 fb	4.0	3.3	635
4-fermion	21 pb	0.35	0.17	64
quark pairs	26 pb	0.16	0.11	22
High mass selection, $m_{DM} = 125$ GeV				
FCNC	1.79 fb	40	51	181
6-fermion	938 fb	4.0	4.0	731
4-fermion	21 pb	0.35	0.20	76.3
quark pairs	26 pb	0.16	0.042	8.8

Results

Expected limits for 500 fb^{-1} collected at 380 GeV CLIC
calculated using the CL_s approach



Limits on top FCNC decays from CLIC at 380 GeV

Detailed studies of three FCNC scenarios based on full detector simulation.

$t \rightarrow c\gamma$ **Work in Progress**

Analysis of hadronic channel only, first estimate of 95% C.L. limit:

$$BR(t \rightarrow c\gamma) \quad < \quad 3 \cdot 10^{-4}$$

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Combined analysis of hadronic and semi-leptonic channel,
expected 95% C.L. limit (CL_s method):

$$BR(t \to ch) \times BR(h \to b\bar{b}) \quad < \quad 1.2 \cdot 10^{-4}$$

Conclusions

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$t \rightarrow c\not{E}$

Only hadronic channel can be used, expected 95% C.L. limit (CL_s):

$$BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b}) \quad < \quad 1.2 - 4.1 \cdot 10^{-4}$$

depending on the assumed scalar mass

Conclusions

Results to be published soon

PREPARED FOR SUBMISSION TO JHEP

Top-Quark Physics at the CLIC Electron-Positron Linear Collider

CLICdp Collaboration

E-mail: clicdp-top-paper-editors@cern.ch

ABSTRACT: The Compact Linear Collider (CLIC) is a proposed future high-luminosity linear electron-positron collider operating at three energy stages, with nominal centre-of-mass energies $\sqrt{s} = 380\,\text{GeV}$, 1.5 TeV, and 3 TeV. Its aim is to explore the energy frontier, providing sensitivity to physics beyond the Standard Model (BSM) and precision measurements of Standard Model processes with an emphasis on Higgs boson and top-quark physics. The opportunities for top-quark physics at CLIC are discussed in this paper. The initial stage of operation focuses on top-quark production measurements, as well as the search for rare flavour-changing neutral current (FCNC) top-quark decays. It also includes a top-quark pair production threshold scan around 350 GeV which provides a precise measurement of the top-quark mass in a well-defined theoretical framework. At the higher-energy stages, studies are made of top-quark pairs produced in association with other particles. A study of $t\bar{t}H$ production including the extraction of the top Yukawa coupling is presented as well as a study of vector boson fusion (VBF) production which gives direct access to the high-energy electroweak physics of the top quark. Operation at $\sqrt{s} > 1\,\text{TeV}$ leads

Conclusions

Not covered by the current analysis

$t \rightarrow cZ$

Direct search possible only for leptonic Z decays (limited efficiency).
$\Rightarrow$ use indirect constraints from single top production $e^+e^- \rightarrow t\bar{c},\ c\bar{t}$

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Search for single top production $e^+e^- \to t\bar{c},\ c\bar{t}$ can be also used to set constraints on $\mathrm{BR}(t \to c\gamma)$. Direct limits slightly better in this case...

$t \to cg$

Very difficult for direct reconstruction,
mainly due to higher-order QCD effects (eg. $g \to q\bar{q}$).

Better sensitivity at LHC using single top production, eg. $gu \to t$

Thank you!

Results from the LHC top Working Group September 2017