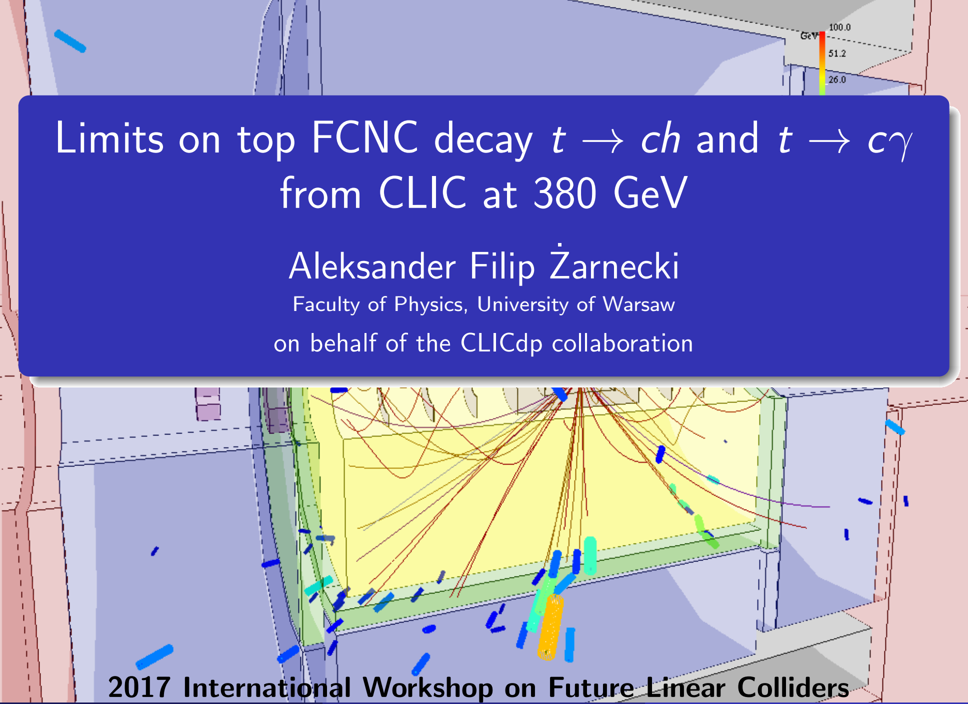
Limits on top FCNC decay $t \to ch$ and $t \to c\gamma$ from CLIC at 380 GeV

Aleksander Filip Żarnecki

Faculty of Physics, University of Warsaw

on behalf of the CLICdp collaboration



2017 International Workshop on Future Linear Colliders

Outline

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"...

Predictions

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

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

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($t \to c\,\gamma$)	10^{-6}	10^{-6}	10^{-5}	10^{-7}	$8 \cdot 10^{-9}$	10^{-9}
BR($t \to c\,h$)	10^{-2}	10^{-4}	10^{-6}	10^{-5}	$4 \cdot 10^{-5}$	10^{-4}

Constrains

95% C.L. limits from LHC experiments

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

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

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

Motivation

Constrains

95% C.L. limits from LHC experiments

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

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

Expectations

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

$$BR(t \to c\gamma) \quad < \quad 2.0 - 3.4 \cdot 10^{-4} \quad \text{(CMS)}$$
$$BR(t \to ch) \quad < \quad 2 \cdot 10^{-4} \quad \text{(ATLAS)}$$

Constrains

95% C.L. limits from LHC experiments

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

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

Expectations

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

$$BR(t \to c\gamma) < 2.0 - 3.4 \cdot 10^{-4} \quad \text{(CMS)}$$
$$BR(t \to ch) < 2 \cdot 10^{-4} \quad \text{(ATLAS)}$$

CLIC

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

Full simulation for CLIC @ 380 GeV

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^+)

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

Full simulation for CLIC @ 380 GeV

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^+)

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

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 algorithm for best mass reconstruction

Signal and background samples normalised to 500 fb^{-1} at 380 GeV

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

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

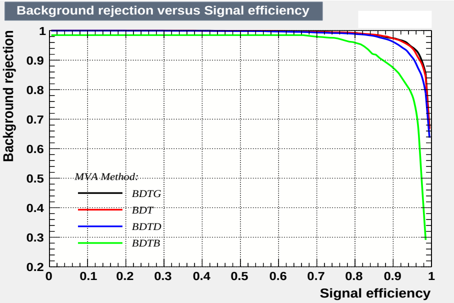
Analysis

- 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

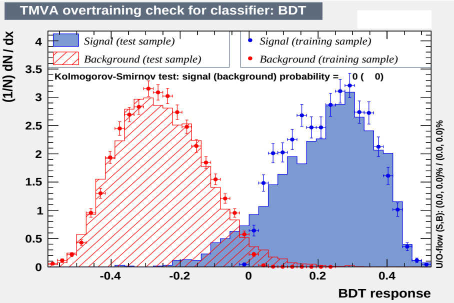
Multivariate analysis TMVA

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



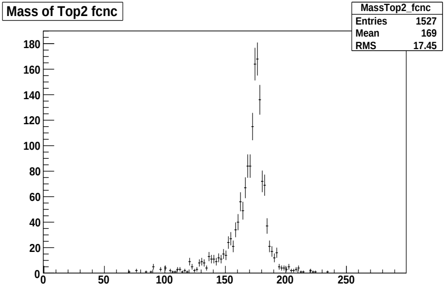
Work in Progress

Kinematic reconstruction

For signal events after final selection cut (BDT > 0.20)

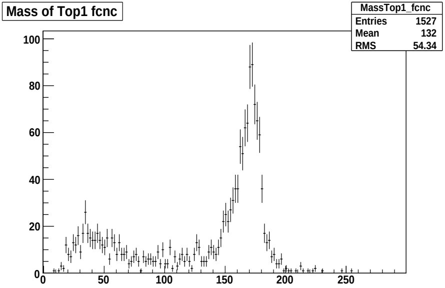
Signal top invariant mass

$t \to c\, \gamma$



Spectator top invariant mass

$t \to b\, q\, \bar{q}'$



Work in Progress

Selection efficiency

	Signal	SM $t\bar{t}$
isolated photon	0.92	0.052
BDT $>$ 0.20	0.60	0.0018
Total	0.55	0.000094

Expected limits

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

$$N_{bg} = 37.4$$

$t\bar{t}$ background events are expected after all selection cuts.

Expected 95% C.L. limit:

$$BR(t \to c\gamma) < 3 \cdot 10^{-5}$$

Analysis of other background channels still ongoing

Work in Progress

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

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

Analysis

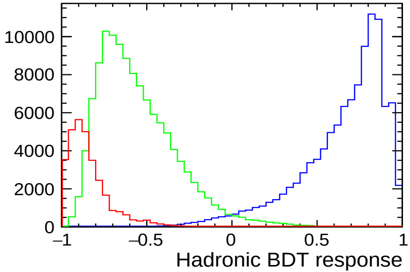
- event classification (into hadronic, semi-leptonic, leptonic samples)
- pre-selection cuts (loose cuts on kinematics and flavour tagging)
- kinematic fit (for signal and background hypothesis)
- estimate of event reconstruction “quality”
- final selection based on multivariate analysis

Event classification

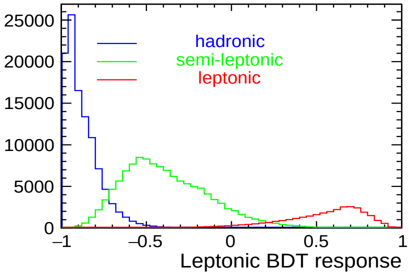
Two independent selections based on total event energy-momentum, event shape variables, isolated lepton information, jet reconstruction parameters.

BDTs trained on background (SM $t\bar{t}$) samples:

Selection of hadronic events



Selection of leptonic events



$\Rightarrow$ hadronic and semi-leptonic samples selected for analysis

$+$ isolated lepton (e or μ) required for semi-leptonic events

Search for $t \to ch$

Pre-selection: three jets are required to have b-tag > 0.4
fourth jet required to have c-tag $+$ b-tag > 0.4 (LCFI+)

Kinematic fit χ^2 definition for hadronic events

Mass ratios used to reduce influence of mass correlations

- signal hypothesis — top boost as additional constrain

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

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

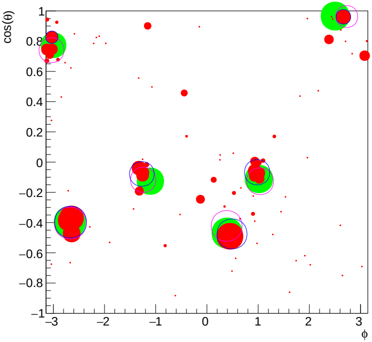
- similar for background hypothesis ($t\bar{t}$ hadronic decays)

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

Event quality estimate

Reconstructed PFOs and the clustering results compared to parton level

"good" event



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

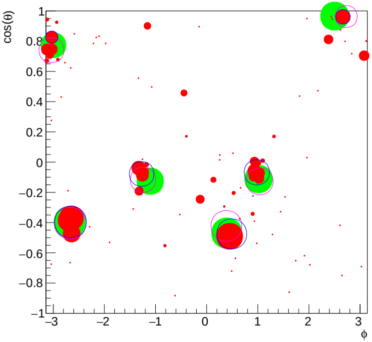
size reflects energy (log scale)

⇒ Kinematic fit works OK!

Event quality estimate

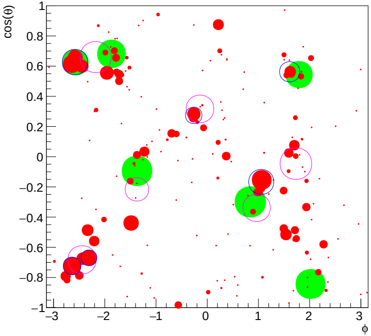
Reconstructed PFOs and the clustering results compared to parton level

"good" event



⇒ Kinematic fit works OK!

"bad" event



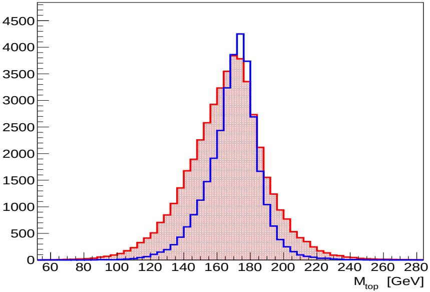
⇒ Can not discriminate between signal and background...

Event quality estimate

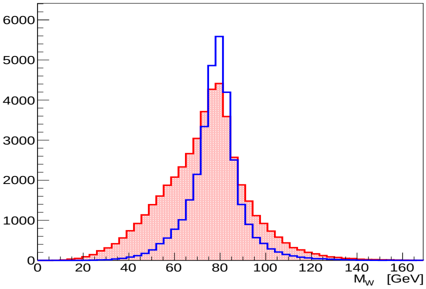
Dedicated BDT implemented to recognize events with "bad" clustering based on jet variables and comparison of different jet algorithms

Kinematic fit result for hadronic sample (after preselection)
for "good" events (BDT > 0.2) and "bad" events (BDT < 0.2)

Top quark mass



W boson mass



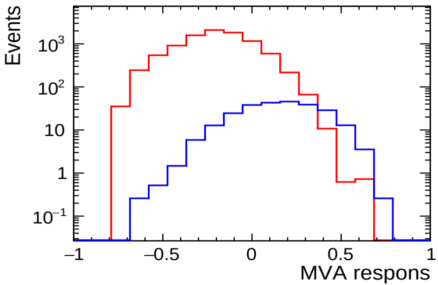
Multivariate analysis TMVA

Used for final signal vs background discrimination

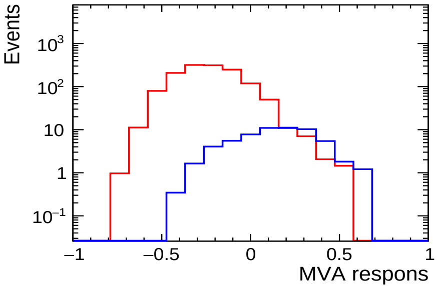
Based on: event variables, flavour tagging, kinematic fit and event quality

Independent BDTs trained for:

Hadronic decays



Semi-leptonic decays



Background sample normalized to 500 fb^{-1}, signal sample to BR$= 10^{-3}$

Work in Progress

Selection efficiency

	Hadronic		Semi-leptonic	
	Signal	SM $t\bar{t}$	Signal	SM $t\bar{t}$
Classification	0.66	0.42	0.19	0.28
Flavour tagging	0.54	0.059	0.42	0.013
Event quality	0.89	0.90	0.92	0.90
Final MVA cut	0.23	0.0038	0.44	0.013
Total	0.072	0.000086	0.032	0.000044

Selection efficiency

	Hadronic		Semi-leptonic	
	Signal	SM $t\bar{t}$	Signal	SM $t\bar{t}$
Classification	0.66	0.42	0.19	0.28
Flavour tagging	0.54	0.059	0.42	0.013
Event quality	0.89	0.90	0.92	0.90
Final MVA cut	0.23	0.0038	0.44	0.013
Total	0.072	0.000086	0.032	0.000044

Expected limits

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

Hadronic and semi-leptonic samples combined (based on S/B distribution)

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

Work in Progress

Limits on top FCNC decays from CLIC at 380 GeV

Based on full detector simulation. **Work in Progress**

$t \rightarrow c\gamma$

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

$$BR(t \rightarrow c\gamma) \quad < \quad 3 \cdot 10^{-5}$$

for integrated luminosity of 500 fb^{-1}

Limits on top FCNC decays from CLIC at 380 GeV

Based on full detector simulation. **Work in Progress**

$t \to c\gamma$

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

$$BR(t \to c\gamma) \quad < \quad 3 \cdot 10^{-5}$$

for integrated luminosity of 500 fb^{-1}

$t \to ch$

Combined analysis of hadronic and semi-leptonic channel, expected 95% C.L. limit

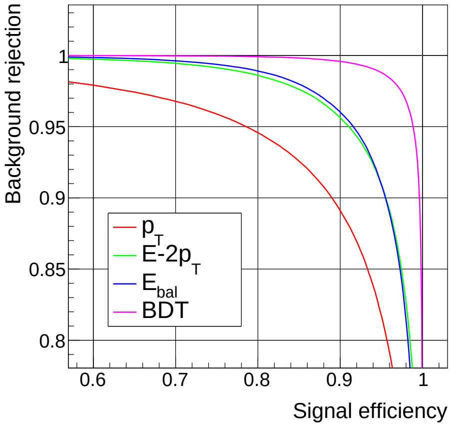
$$BR(t \to ch) \times BR(h \to b\bar{b}) \quad < \quad 1.6 \cdot 10^{-4}$$

Other FCNC processes still to be considered in details.

Thank you!

Event classification

Comparison of different approaches to selection of hadronic $t\bar{t}$ decays
(for background sample)



Results from the LHC top Working Group September 2017