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

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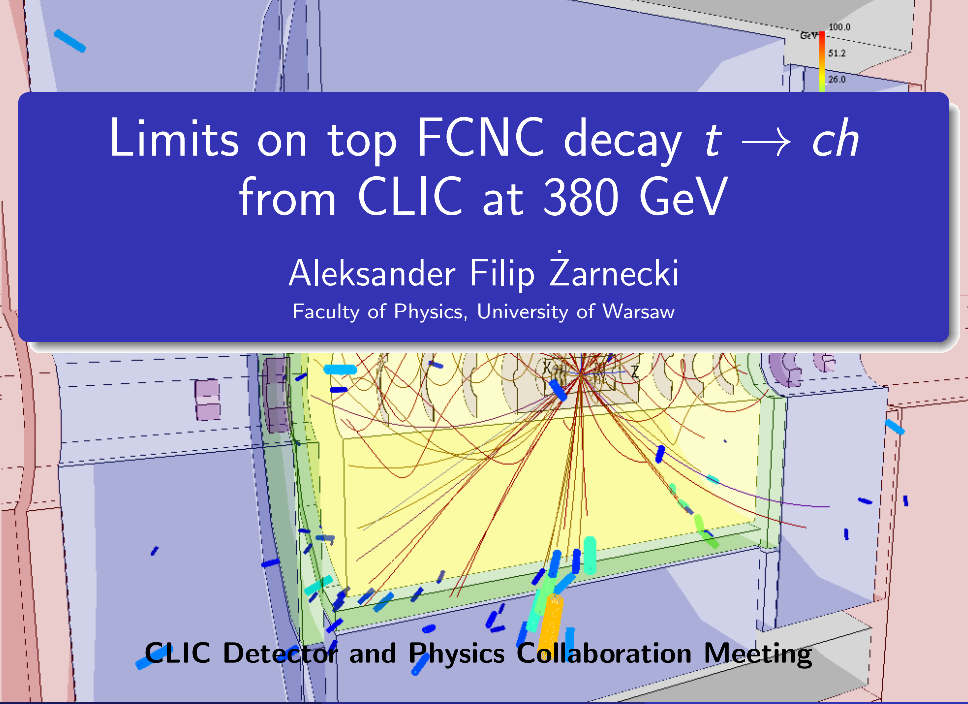

CLIC Detector and Physics Collaboration Meeting

Outline

Motivation

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

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

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

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

Any signal is a direct signature of “new physics”...

Decay $t \to c\ h$ is most interesting:

- well constrained kinematics
- test of Higgs boson couplings
- seems to be most difficult for LHC

Estimated HL-LHC reach:
(Snowmass 2013/ATLAS 2016)

$$BR(t \to qh) \sim 2 \cdot 10^{-4}$$

Two Higgs Doublet Model (2HDM) as a test scenario:

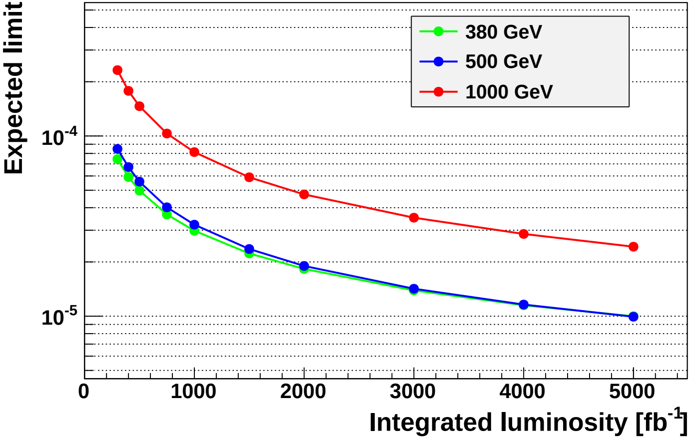
- one of simplest extensions of the SM
- $BR(t \to c\ h)$ up to 10^{-2} (tree level) and 10^{-4} (loop level)

Parton level study presented at TopLC'2015 [arXiv:1604.08122]

Promising results on the feasibility of the measurement

Estimated limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Assumed jet energy resolution $\sigma_E = 50\%/\sqrt{E}$ (5% above 100 GeV)



LCWS'2016 results

Expected limits for hadronic channel

Preliminary results based on CLIC full simulation @ 380 GeV

Final signal selection efficiency: 3.9% (5.9% of hadronic decays)
Background suppression: $1.2 \cdot 10^{-5}$

Expected 95% C.L. limit for 500 fb^{-1} at 380 GeV preliminary

$$BR(t \to ch) \times BR(h \to b\bar{b}) \; < \; 2.6 \cdot 10^{-4}$$

With luminosity of 1000 fb^{-1} at 380 GeV

$$BR(t \to ch) \times BR(h \to b\bar{b}) \; < \; 1.7 \cdot 10^{-4}$$

assuming $t\bar{t}$ cross section at 380 GeV of 820 fb

see: http://hep.fuw.edu.pl/u/zarnecki/talks/afz_lcws2016.pdf

Full simulation for CLIC @ 380 GeV

Dedicated samples generated with WHIZARD 2.2.8
Signal: SARAH implementation of 2HDM(III), BR($t \to ch_1$) = 10^{-3}

Beam spectra for CLIC taken from file (350 GeV scaled to 380 GeV)
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

Samples considered in the study

- dedicated FCNC signal sample $e^+e^- \longrightarrow ch_1\bar{t},\ t\bar{c}h_1$
- test sample of SM background $e^+e^- \longrightarrow t\bar{t}$ for simulation validation
- full 6-fermion sample as produced for CLIC $t\bar{t}$ studies

Signal and background samples normalised to 500 fb^{-1}
Assumed $t\bar{t}$ cross section at 380 GeV: 820 fb

Event processing

DST files processed with MARLIN, ilcsoft v01-17-09 (ilcDIRAC)

- Using LooseSelectedPandoraPFANewPFOs as input collection
- LCFI+ primary and secondary vertex finder
- LCFI+ jet finding with Valencia algorithm
- LCFI+ vertex corrections and flavour taging

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Final analysis in root:

- event classification

  into hadronic, semi-leptonic, leptonic samples
- pre-selection cuts (loose cuts on flavour tagging)
- kinematic fit
- final selection based on BDT optimised for best BR limit

Event processing

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Final analysis in root: **Recent progress:**

- event classification — Improved
- clustering "quality" estimate — NEW!
- pre-selection cuts (loose cuts on flavour tagging)
- kinematic fit — *b*-jet energy correction
- final selection based on BDT optimised for best BR limit

Two signal channels: fully hadronic and semi-leptonic $t\bar{t}$ decays

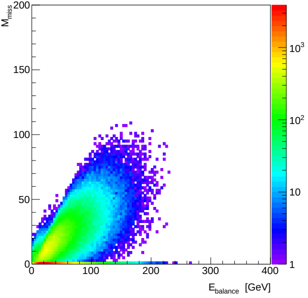
Background: fully hadronic, semi-leptonic and leptonic $t\bar{t}$ events

Different selection algorithms considered previously, based on:

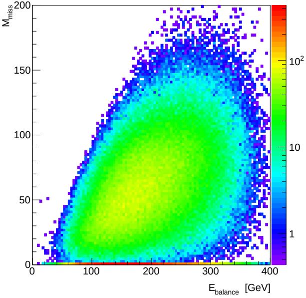
p_T, $E - 2p_T$, missing invariant mass M_{miss}, energy balance

$$E_{balance} = \sqrt{(E - 2\,p_T - \sqrt{s})^2 + 4\,p_Z^2}$$

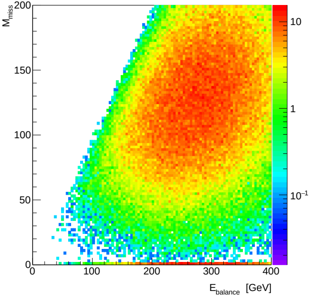
hadronic



semi-leptonic



leptonic



Event classification

Two signal channels: fully hadronic and semi-leptonic $t\bar{t}$ decays
Background: fully hadronic, semi-leptonic and leptonic $t\bar{t}$ events

New approach:

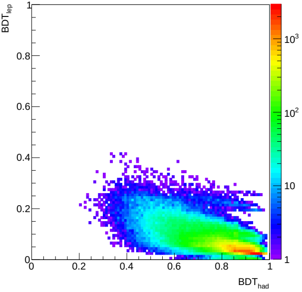
used two BDTs for event classification: "hadronic" and "leptonic" tags

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

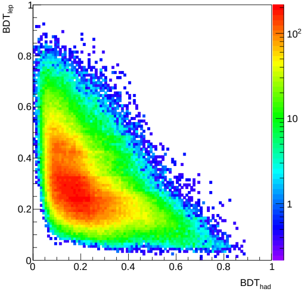
$\Rightarrow$ much improved efficiency/purity

note logarithmic scale

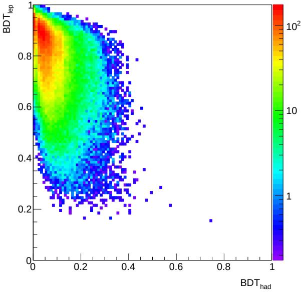
hadronic



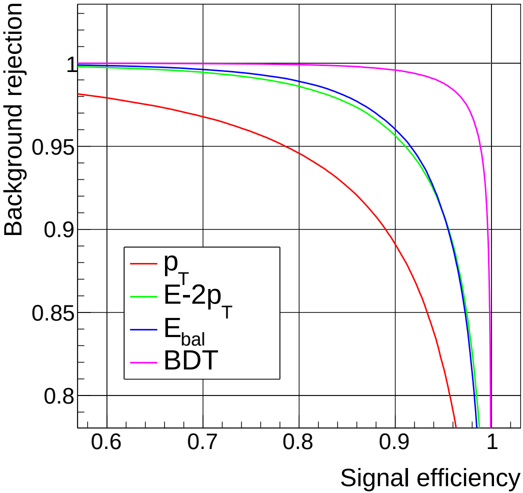
semi-leptonic



leptonic



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



Clustering quality estimate

Jet distance

To understand top reconstruction better, event kinematics was compared between different levels (for hadronic final state):

- parton level: six fermion final state (as generated by WHIZARD)
- particle level: result of PYTHIA hadronisation
  MCParticles clustered in six jets (Valencia algorithm)
- LCFIPlus jet level: six jet final state, after detector simulation
  (clustering with Valencia algorithm)
- alternative algorithms: six jet final state reconstructed with different jet algorithm (Valencia with different settings, angular, anti-k_T)

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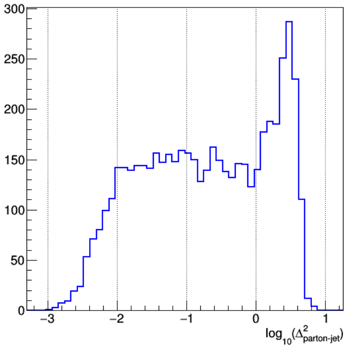
"Distance" Δ^2 reflects the agreement between different levels, eg.:

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

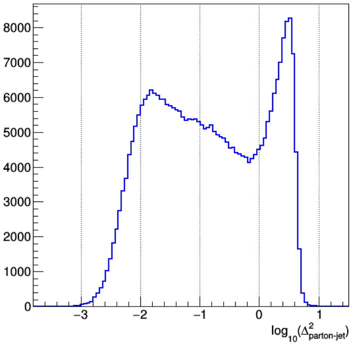
Jet distance

Distance between parton level and detector level jets

Signal events



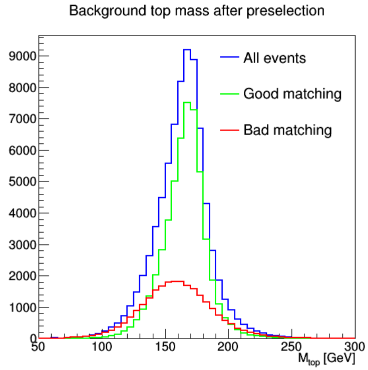
Background ($t\bar{t}$) events



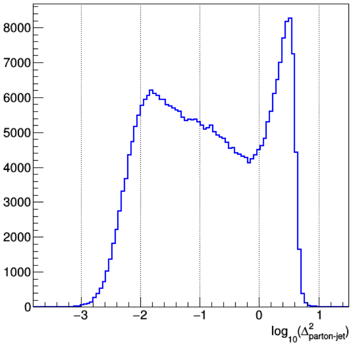
For significant fraction of events detector-level jets do not correspond to the fermion configuration!

Jet distance

Distance between parton level and detector level jets



Background ($t\bar{t}$) events



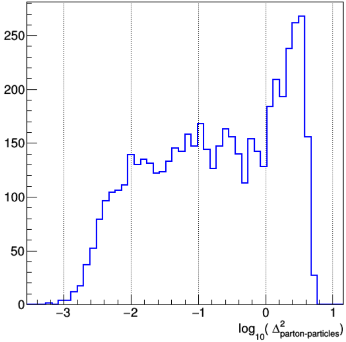
For significant fraction of events detector-level jets do not correspond to the fermion configuration! ⇒ mass reconstruction significantly worse

Clustering quality estimate

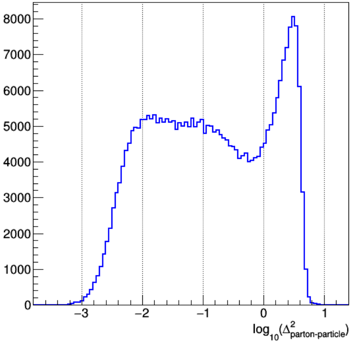
Jet distance

Distance between parton level and particle level jets (no detector involved)

Signal events



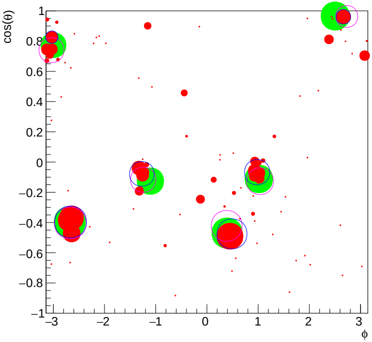
Background ($t\bar{t}$) events



In most cases, information about the partonic final state is already lost on particle level! How can we suppress such event?!

Examples Reconstructed PFOs and the clustering results

Event with $\Delta^2_{\text{parton-jet}} = 0.03$



- partons
- PFOs
- LCFIPlus jets (Valencia)
- anti-k_T jets

size reflects energy (log scale)

Clustering quality estimate

Examples Reconstructed PFOs and the clustering results

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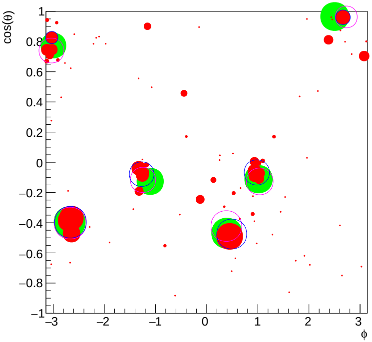
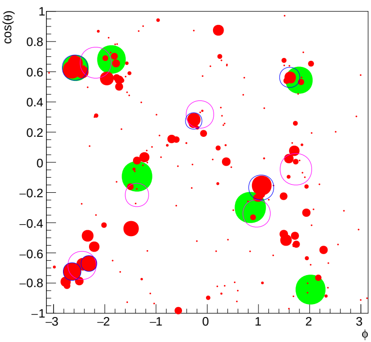


Event with $\Delta^2_{\text{parton-jet}} = 3.80$

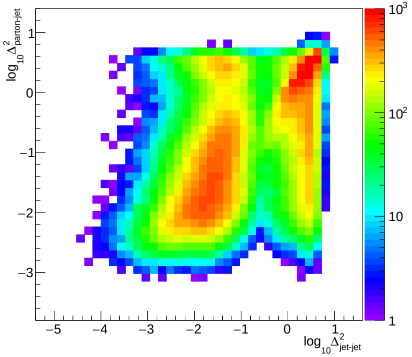


Events with "bad matching" seem to be related to higher order QCD corrections/Parton Shower...

Comparison of jet algorithms

Distance between different jet can be used to estimate “event quality”

parton-jet vs jet-jet distance



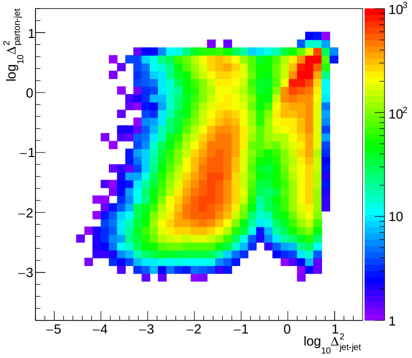
Valencia vs angular clustering

Comparison of jet algorithms

Distance between different jet can be used to estimate "event quality"

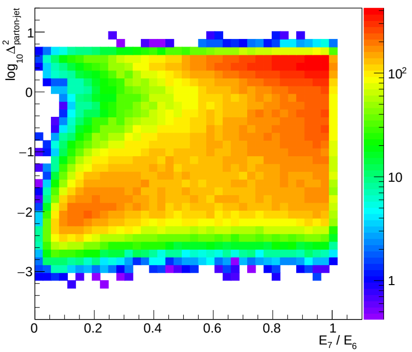
one can also look at other jet related variables...

parton-jet vs jet-jet distance



Valencia vs angular clustering

parton-jet distance vs energy ratio



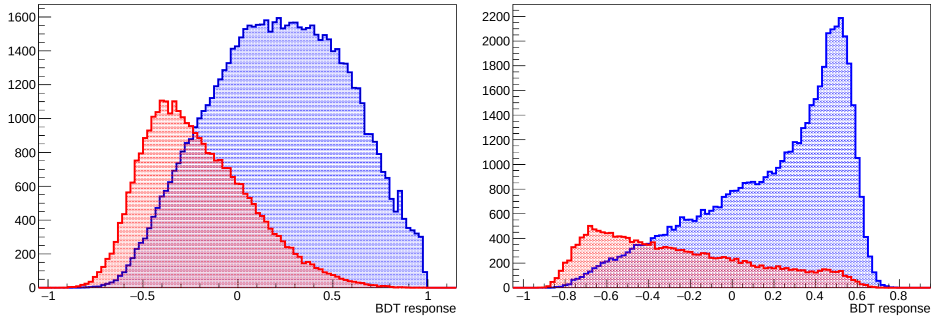
Energy ratio of 7th to 6th jet

BDT response

Separate BDTs were trained to estimate event quality for hadronic and semi-leptonic events, based on comparison of different jet algorithms

Response distribution for "good" ($\Delta^2 < 0.6$) and "bad" ($\Delta^2 > 0.6$) events

Hadronic sample (6 jet) Semi-leptonic sample (4 jet)



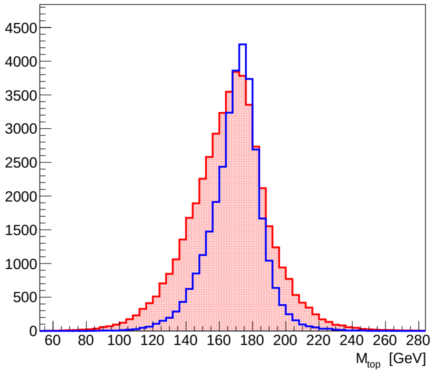
Quality estimate based on background sample only (6 fermion) !

Influence on kinematic fit

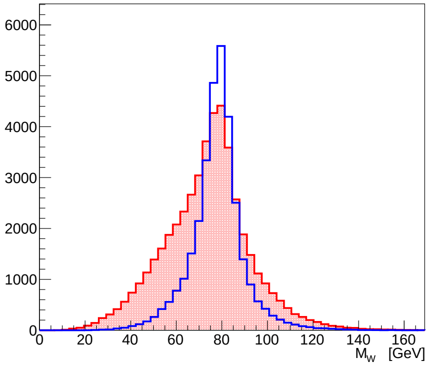
Comparison of invariant mass distributions for BDT < 0.2 and BDT > 0.2

Kinematic fit result for hadronic sample (after preselection)

Top quark mass

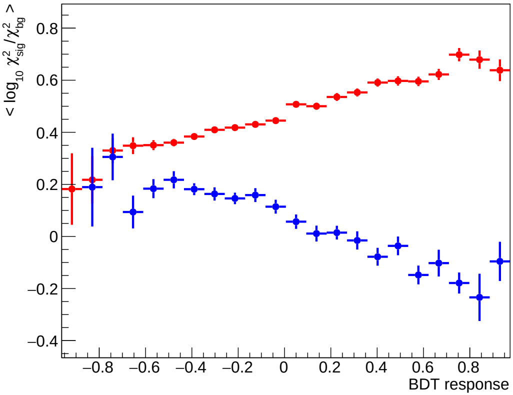


W boson mass



Influence on signal/background discrimination

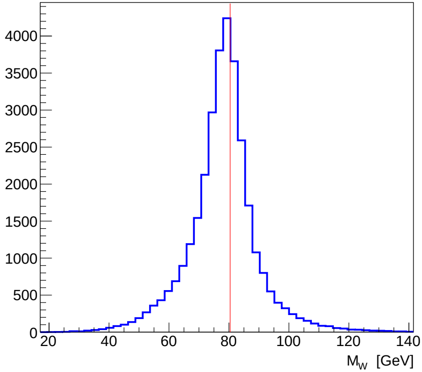
Average χ^2 ratio for signal and background hypothesis, for signal (FCNC) and background (6 fermion) samples



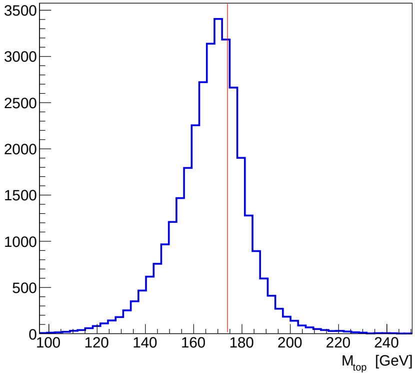
Reconstructed masses background events, hadronic decays

Without energy correction

$W^{\pm}$ bosons



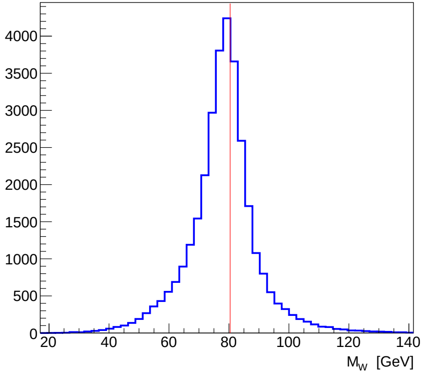
top quarks



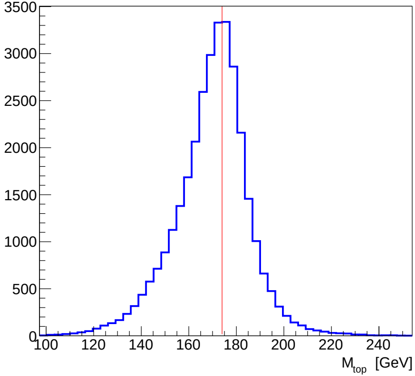
Reconstructed masses background events, hadronic decays

With 5% energy correction for b jets

$W^{\pm}$ bosons



top quarks

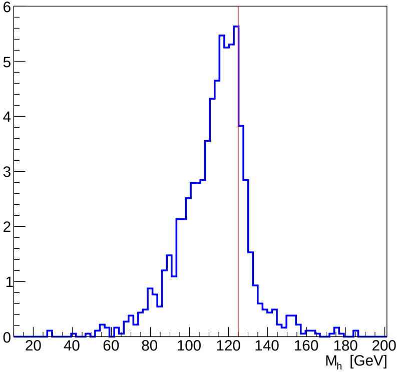


Energy correction for b jets

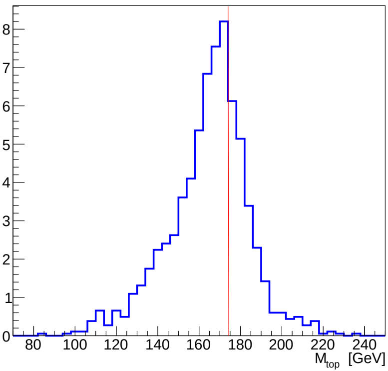
Reconstructed masses signal events, hadronic decays

Without energy correction

Higgs boson



Spectator top quark

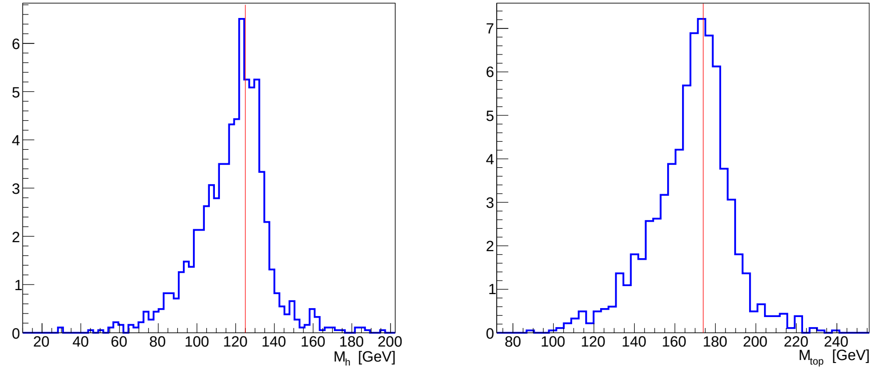


Reconstructed masses signal events, hadronic decays

With 5% energy correction for *b* jets

Higgs boson

Spectator top quark



Expected events in hadronic (6 jet) channel

For 500 fb^{-1}, assuming $BR(t \to ch) \times BR(h \to b\bar{b}) = 10^{-3}$ for signal

	Expected events		Efficiency	
Generator level	$t\bar{t}$ (SM)	Signal	$t\bar{t}$ (SM)	Signal
All events	410'000	819	100%	100%
hadronic events	170'000	543	41%	66%

Preselection cuts

$\text{BDT}_{had} > -0.07$	174'000	543	42%	66%
3 b jets tagged ($b_{tag} > 0.4$)	14'100	320	3.4%	39%
c jet tagged ($b_{tag}+c_{tag} > 0.4$)	10'330	295	2.5%	36%

Preselection cuts improve signal to background ratio by order of magnitude

Updated results

Expected events in semi-leptonic (4 jet + lepton) channel

For 500 fb^{-1}, assuming $BR(t \to ch) \times BR(h \to b\bar{b}) = 10^{-3}$ for signal

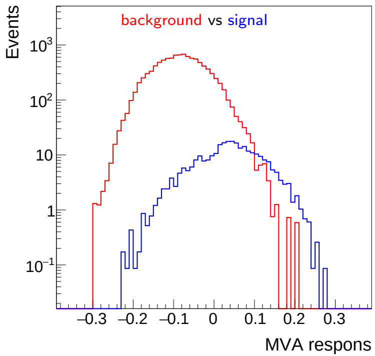
	Expected events		Efficiency	
Generator level	$t\bar{t}$ (SM)	Signal	$t\bar{t}$ (SM)	Signal
All events	410'000	819	100%	100%
semi-leptonic events	191'100	276	47%	34%

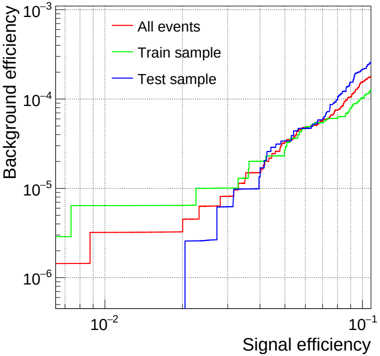
Preselection cuts

$\mathrm{BDT}_{had} < -0.07$, $\mathrm{BDT}_{lep} > -0.05$	178'400	255	44%	31%
One isolated lepton (e or μ)	115'200	157	28%	19%
3 b jets tagged ($b_{tag} > 0.4$)	4'690	84.8	1.1%	10%
c jet tagged ($b_{tag}+c_{tag} > 0.4$)	1'516	65.9	0.37%	8.0%

Hadronic channel

Final signal event selection based on BDT algorithm response



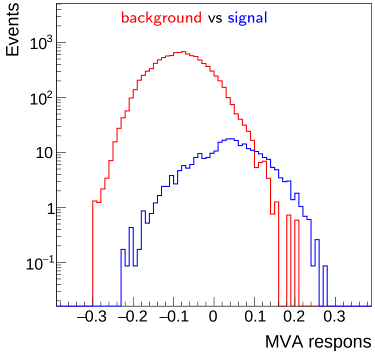


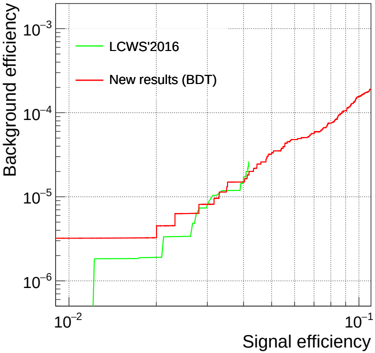
Similar results for train and test samples $\Rightarrow$ no overtraining

Hadronic channel

Final signal event selection based on BDT algorithm response

Results compared to LCWS'2016 (cut based)

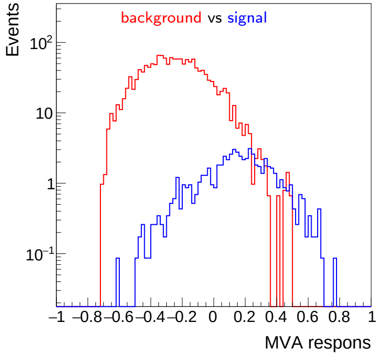


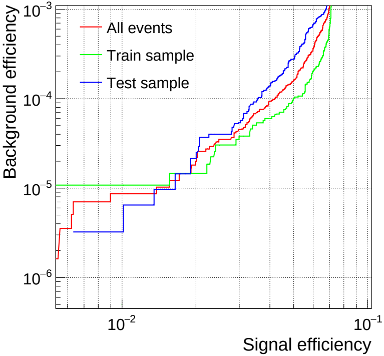


Results based on BDT similar to cut based (?!)

Semi-leptonic channel

Final signal event selection based on BDT algorithm response

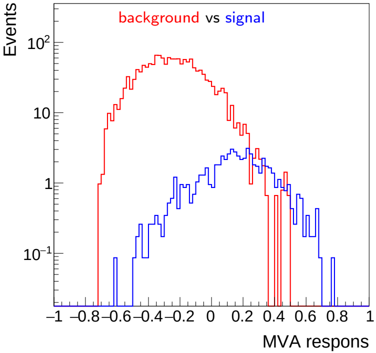


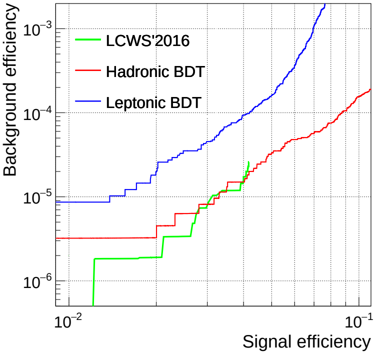


Note: "Signal efficiency" includes top branching ratio !

Semi-leptonic channel

Final signal event selection based on BDT algorithm response compared to hadronic channel





Semi-leptonic channel suppressed by factor of ~ 3 (21% vs 68%)

Note: "Signal efficiency" includes top branching ratio !

Final limits

Limits resulting from the new BDT[5] analysis (500 fb^{-1} @ 380 GeV)

- hadronic channel

$$BR \quad < \quad 1.7 \cdot 10^{-4}$$

- leptonic channel

$$BR \quad < \quad 3.8 \cdot 10^{-4}$$

- combined

$$BR \quad < \quad 1.6 \cdot 10^{-4}$$

Limits calculated from the test event sample! (half of statistics)

Total selection efficiency about 10% (7% hadronic + 3% semi-leptonic)

Conclusions

FCNC top decays $t \to ch$ with CLIC at 380 GeV

Updated results for 380 GeV, including hadronic and semi-leptonic channel
Improved identification of events with “wrong” jet clustering
Analysis based on multiple BDT classifications

Expected combined limit at 500 fb^{-1}

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

FCNC top decays $t \to ch$ with CLIC at 380 GeV

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Expected combined limit at 500 fb^{-1}

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

Some checks still to be done, but results seem stable

$\Rightarrow$ most likely they are final

Thank you!

Very simplified detector description

- detector acceptance for leptons: $|\cos\theta_l| < 0.995$
- detector acceptance for jets: $|\cos\theta_j| < 0.975$
- jet energy smearing:

$$\sigma_E = \begin{cases} \frac{S}{\sqrt{E}} & \text{for} \quad E < 100\,GeV \\ \frac{S}{\sqrt{100\ GeV}} & E > 100\,GeV \end{cases}$$

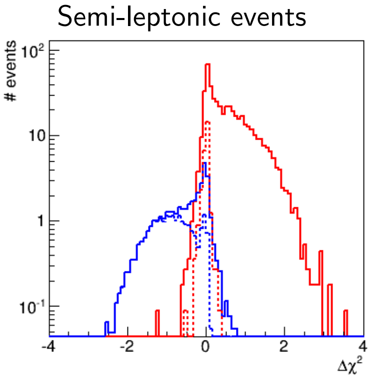
with S = 30%, 50% and 80% $[\mathrm{GeV}^{1/2}]$

- *b* tagging (misstagging) efficiencies: (as expected for LCFI+)

Scenario	b	c	uds
Ideal	100%	0%	0%
A	90%	30%	4%
B	80%	8%	0.8%
C	70%	2%	0.2%
D	60%	0.4%	0.08%

Signal selection

Difference of $\log_{10} \chi^2$ for two hypothesis, for signal and background events
Before (solid) and after (dashed) other selection cuts

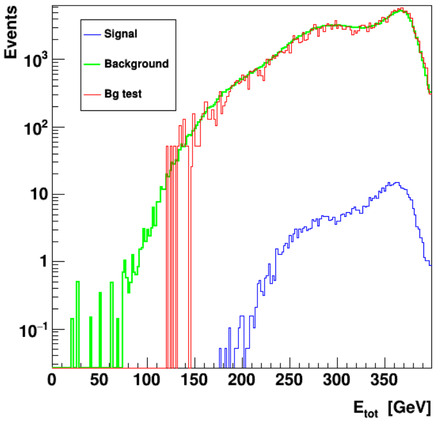


500 GeV, jet energy resolution 50%, 70% *b*-tagging efficiency
Background rejection strongly depends on the detector performance

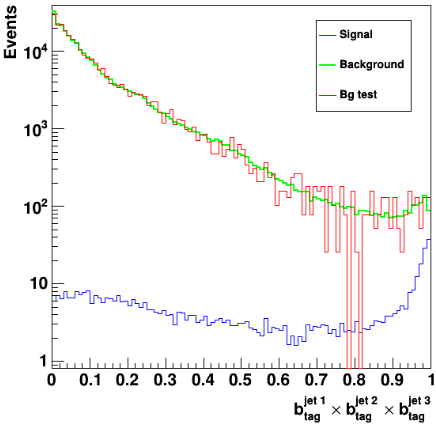
Control plots

Comparing signal sample with full background and test samples.

Total measured energy



Product of three highest *b*-tag value

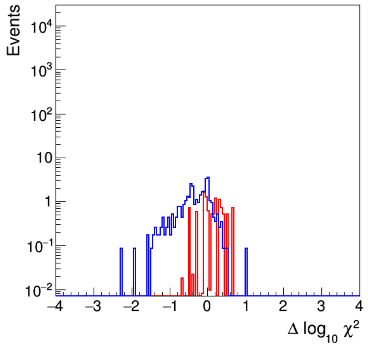


Signal-background discrimination

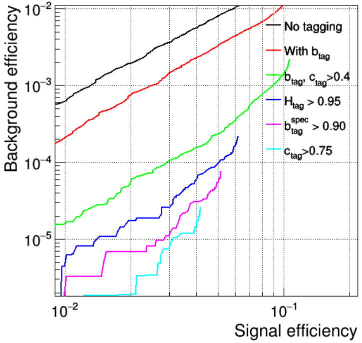
Based on the cut on the difference of $\log_{10}\chi^2$ for two hypothesis

Events with "good" fit of signal hypothesis ($\chi^2_{sig} < 14$, $|\Delta M_{top}| < 45$ GeV)

$\Delta \log_{10}\chi^2$ distribution for signal and background



Background vs signal efficiency after subsequent cuts



normalized to all decay channels

Jet algorithm

Valencia algorithm Phys Lett B 750 (2015) 95

New, robust, background resistant jet reconstruction algorithm.
Distance criterion based on energy and polar angle:

$$d_{ij} = \min\left(E_i^{2\beta}, E_j^{2\beta}\right) \frac{(1-\cos\theta_{ij})}{R^2} \quad \text{and} \quad d_{iB} = E_i^{2\beta} \sin^{2\beta}\theta_{iB}$$

This definition was implemented in LCFI+ package (v00-07)

VLC algorithm arXiv:1607.05039

Extension of Valencia algorithm, with more general distance definition:

$$d_{ij} = 2\min\left(E_i^{2\beta}, E_j^{2\beta}\right) \frac{(1-\cos\theta_{ij})}{R^2} \quad \text{and} \quad d_{iB} = E_i^{2\beta} \sin^{2\gamma}\theta_{iB}$$

This definition was implemented in FastJet (ValenciaPlugin)

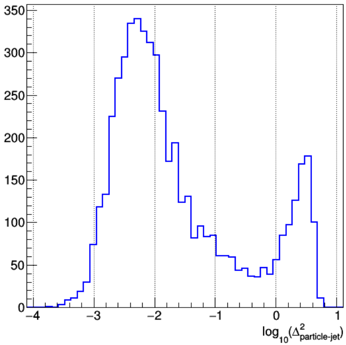
There is factor of 2 in R definition between VLC with $\beta = \gamma$ and Valencia !

Event reconstruction

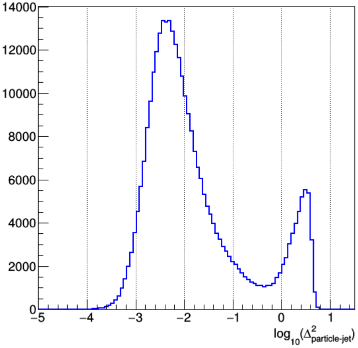
Jet matching

Distance between particle level jets and detector level jets

Signal events



Background ($t\bar{t}$) events



For most events reconstructed detector-level jets follow closely the particle level configuration...

χ^2 definition

Using mass ratios to reduce influence of mass correlations:

- signal hypothesis

use also top boost as additional constrain

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

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

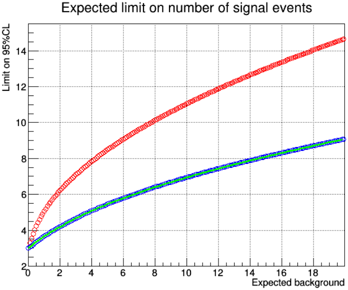
- similar for background hypothesis ($t\bar{t}$ hadronic decays)

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

New limit definition

Expected 95% C.L. limits calculated for the parton-level study and for LCWS'2016 results were too conservative!
Calculated as the BR value which can be excluded in 95% of experiments...

Expected limits should be defined as the average 95% C.L. limit resulting from the background-only experiments
this value will be excluded in (about) 50% of experiments



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$\Rightarrow$ previous limits too strong by a factor of about 1.5

Updated limit from LCWS'2016 analysis:

$$BR(t \to ch) \times BR(h \to b\bar{b}) \quad < \quad 1.7 \cdot 10^{-4}$$