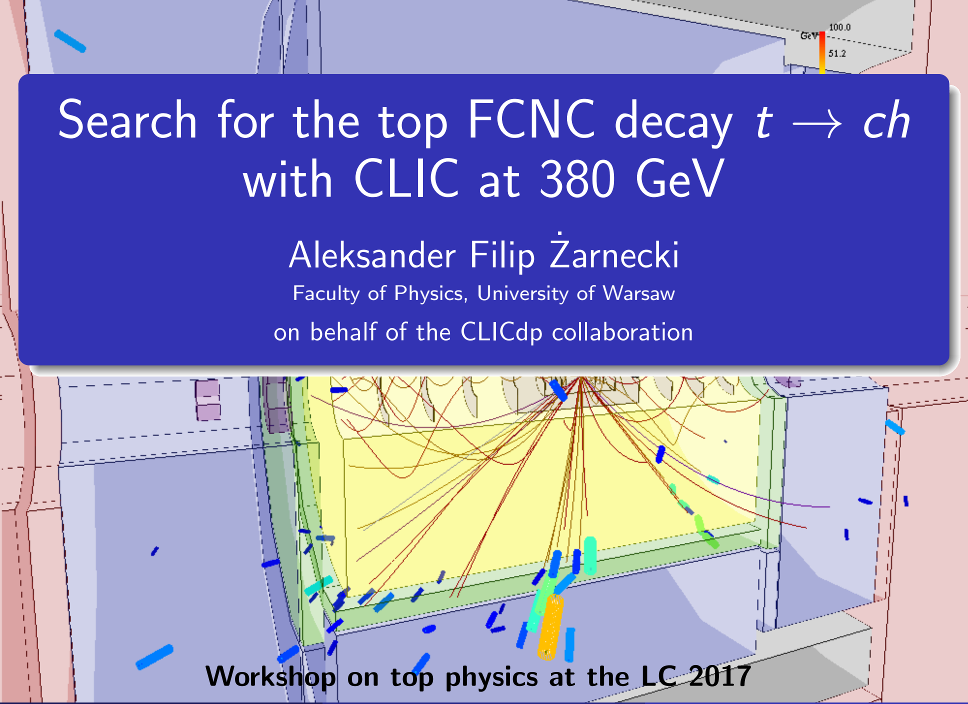

Search for the top FCNC decay $t \to ch$ with CLIC at 380 GeV

Aleksander Filip Żarnecki
Faculty of Physics, University of Warsaw
on behalf of the CLICdp collaboration

Workshop on top physics at the LC 2017

Outline

1. Motivation
2. Simulation
3. LCWS'2016 results
4. Recent progress
5. Conclusions

Motivation

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

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

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

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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:

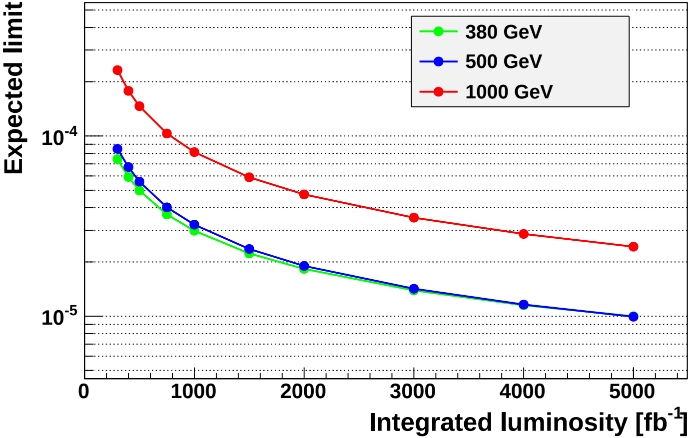
- one of simplest extensions of the SM
- $BR(t \to c\ h)$ up to 10^{-2} (tree level) and 10^{-4} (loop level)

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)



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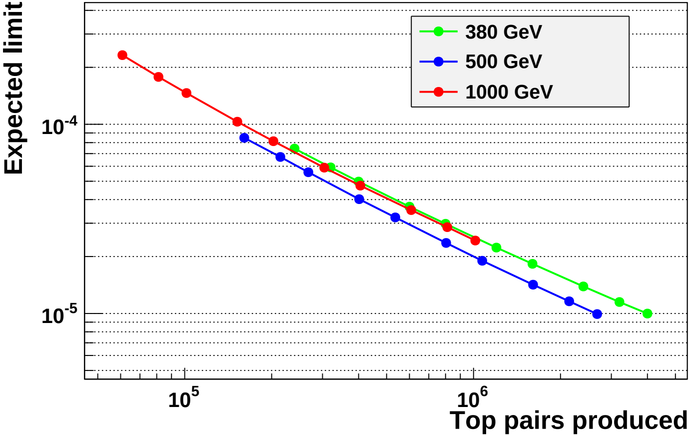

Full simulation for CLIC @ 380 GeV

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

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
  default weights used (no tuning), but seem to work OK
- root TTree writing

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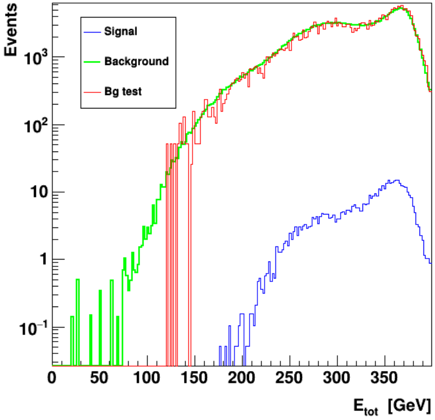
Final analysis in root:

- hadronic decay selection
- pre-selection cuts (loose cuts on flavour tagging)
- kinematic fit
- final selection (cuts or BDT)
  optimised for best BR limit

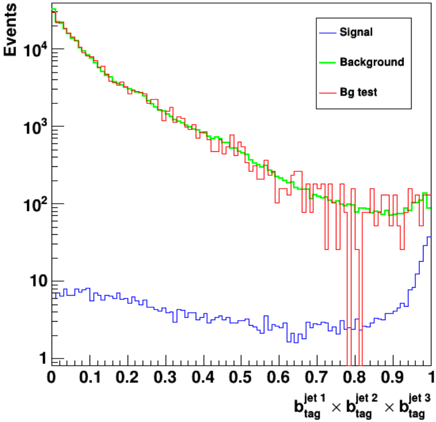
Control plots

Comparing signal sample with full background and test samples.

Total measured energy



Product of three highest *b*-tag value

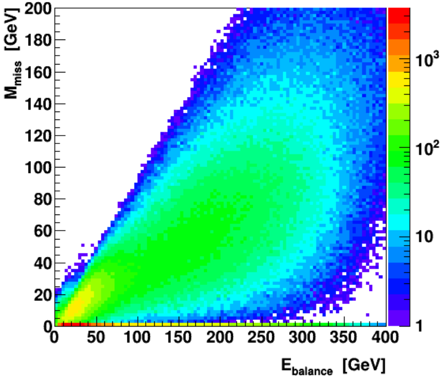


Two event samples: fully hadronic and semi-letopnic $t\bar{t}$ decays

Initial selection based on two variables:

$E_{balance} = \sqrt{(E - 2\ p_T - \sqrt{s})^2\ +\ 4\ p_Z^2}$ and $M_{miss} = \sqrt{\left(\sqrt{s} - E\right)^2 - p^2}$

Distribution for background events



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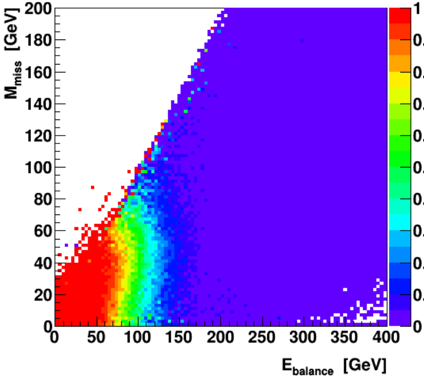
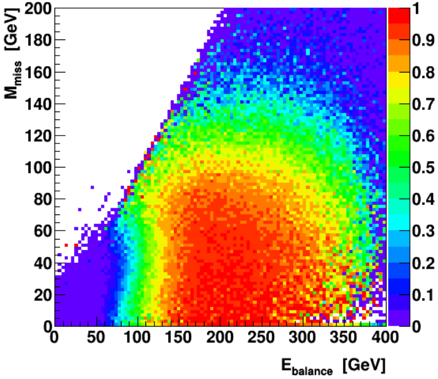
Fraction of hadronic decays



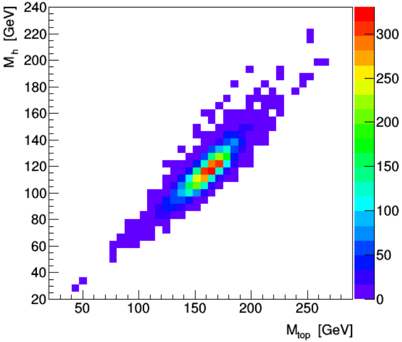
Fraction of semi-leptonic decays



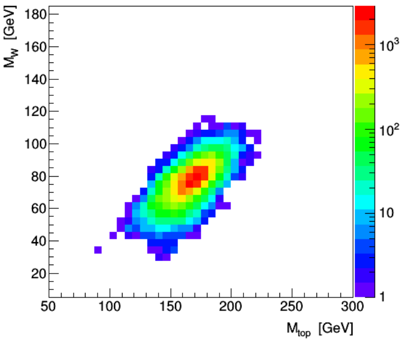
Mass correlation

Significant correlations observed between reconstructed masses of top (3 jets) and its decay product (2 jets)

Higgs and top (signal)



W boson and top (background)



⇒ should be taken into account in event selection

New 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)

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

Expected events in six-jet final state

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

Analysis level / Selection cut	Expected events $t\bar{t}$ (SM)	Expected events Signal	Efficiency $t\bar{t}$ (SM)	Efficiency Signal
All events	410'000	819	100%	100%
hadronic events	170'000	543	41.5%	66.3%
Before kinematic fit				
$E_{balance} < 100$ GeV	167'000	499	40.6%	60.9%
3 b jets tagged ($b_{tag} > 0.4$)	13'280	300	3.24%	36.6%
c jet tagged ($b_{tag}+c_{tag} > 0.4$)	9640	276	2.35%	33.8%
After kinematic fit				
Good fit ($\chi^2_{sig}<14$, $\Delta M_t<45$ GeV)	894	87	0.22%	10.7%
b-tag for higgs jets ($b_1 \times b_2 > 0.95$)	89.5	50.8	0.022%	6.2%
b and c tags ($b_3>0.9$, $c_4+b_4>0.75$)	10.7	34.1	$2.6 \cdot 10^{-5}$	4.2%
$\chi^2_{sig}/\chi^2_{bg} < 1.38$ (optimised for limit)	4.89	31.8	$1.2 \cdot 10^{-5}$	3.9%

LCWS'2016 results

Expected limits — only hadronic channel considered !

Cuts were optimised for the best expected BR limit.

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

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

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

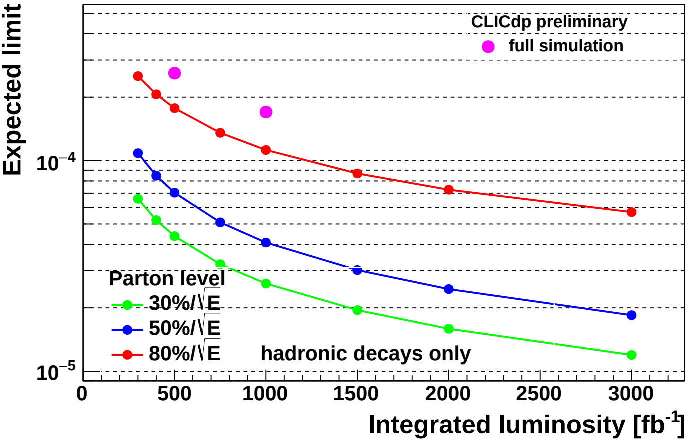
$$BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b}) \quad < \quad 1.7 \cdot 10^{-4}$$

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

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

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

Comparison with parton level results, different jet energy resolutions

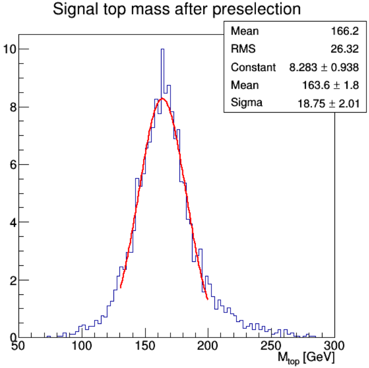


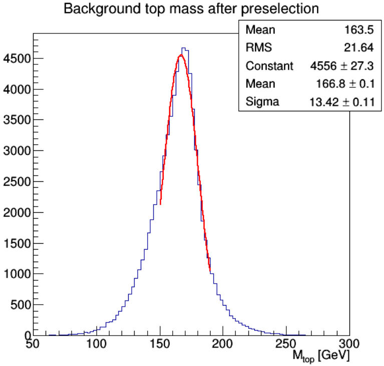
Kinematic fit

Preliminary limits much weaker than expected from parton level study.

The main reason for is poor performance of the kinematic fit!

Background rejection mainly based on flavour tagging.





Mass resolution much worse than expected.

Signal reconstruction much worse than for background events...

Jet matching

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

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

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To quantify the level of correspondence between different levels:

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

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)

Valencia algorithm Phys Lett B 750 (2015) 95

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

VLC algorithm arXiv:1607.05039

Extension of Valencia algorithm, with more general distance definition:

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

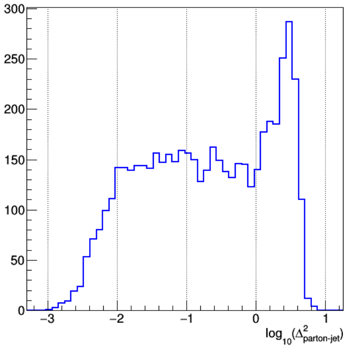
This definition was implemented in FastJet (ValenciaPlugin)

VLC with $\beta = \gamma$ is NOT the same as Valencia ! There is factor of 2...

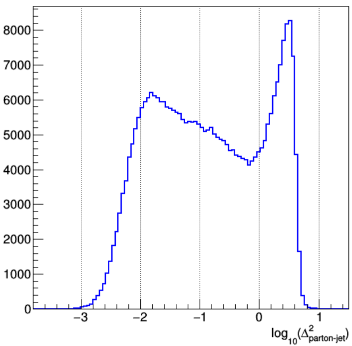
Jet matching

Distance between parton level and detector level jets

Signal events



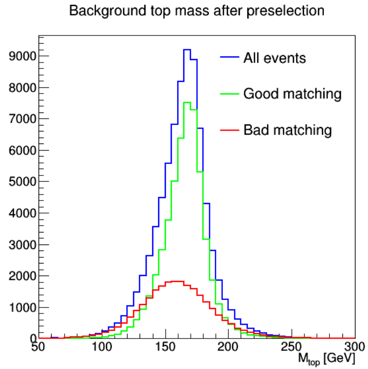
Background ($t\bar{t}$) events



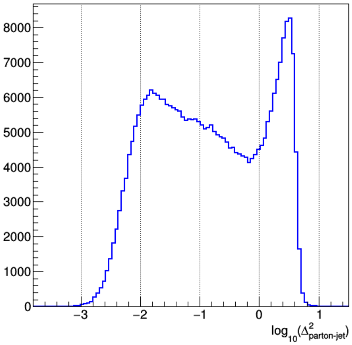
For significant fraction of events reconstructed detector-level jets have nothing to do with the generated fermion configuration!

Jet matching

Distance between parton level and detector level jets



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

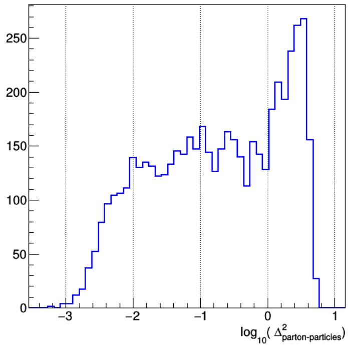


For significant fraction of events reconstructed detector-level jets have nothing to do with the generated fermion configuration!

Jet matching

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

Signal events



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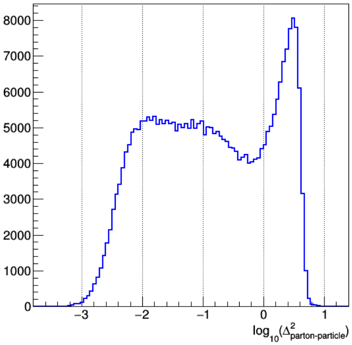
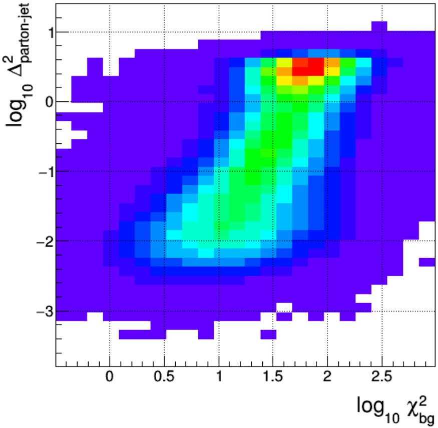


In most cases, information about the partonic final state is already lost on particle level!

How can we suppress such event?!

Kinematic fit quality

"Problematic" clustering also results in poorer quality of kinematic fit
⇒ we can reduce influence of such events in standard $t\bar{t}$ selection...



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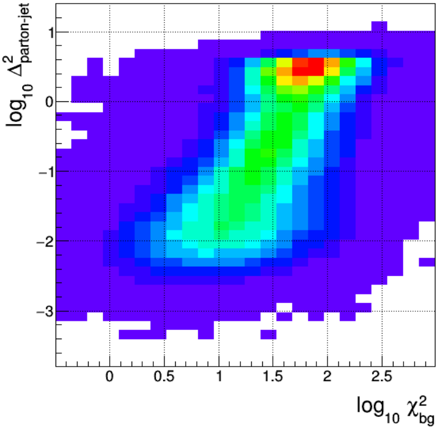
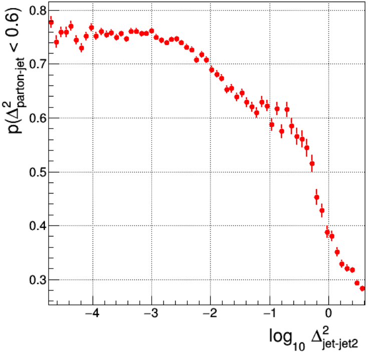


We can not do it, if χ^2 used to discriminate background and signal!

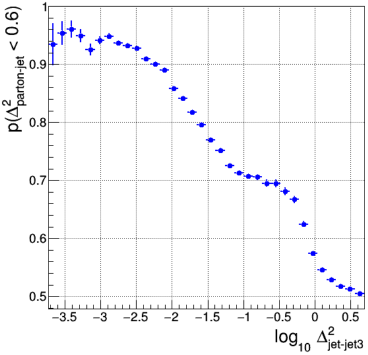
Comparison of jet algorithms

Fraction of properly reconstructed events $(\Delta^2_{\text{parton-jet}} < 0.6)$
as a function of distance squared to Valencia jets $R = 1.2$ (default)

Valencia R=0.85



Angular clustering R=1.0



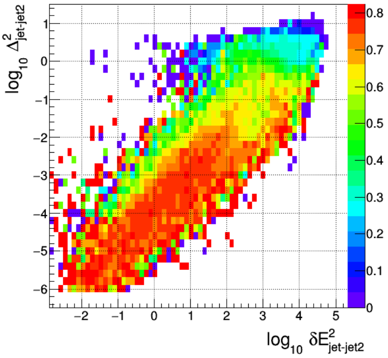
⇒ possible tool for selecting properly reconstructed events...

Comparison of jet algorithms

Fraction of properly reconstructed events ($\Delta^2_{\text{parton-jet}} < 0.6$)

as a function of angular and energy matching to Valencia jets $R = 1.2$

Valencia R=0.85



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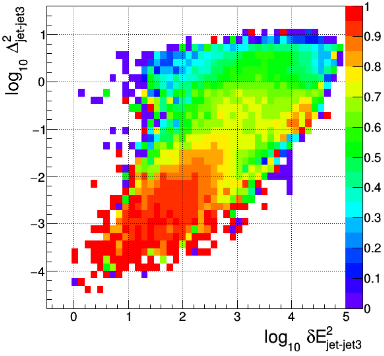
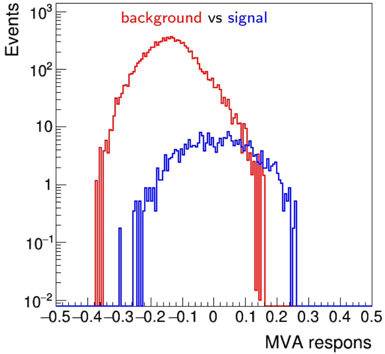
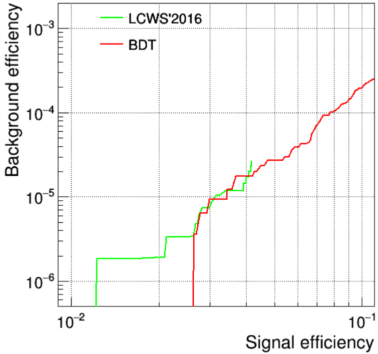


⇒ possible tool for selecting properly reconstructed events...

Including new variables

Final signal event selection based on BDT algorithm (TMVA).
Selection based on BDT response, compared to LCWS'2016 (cut based)





Limits based on BDT similar to cut based (for the same variable set)

Including new variables

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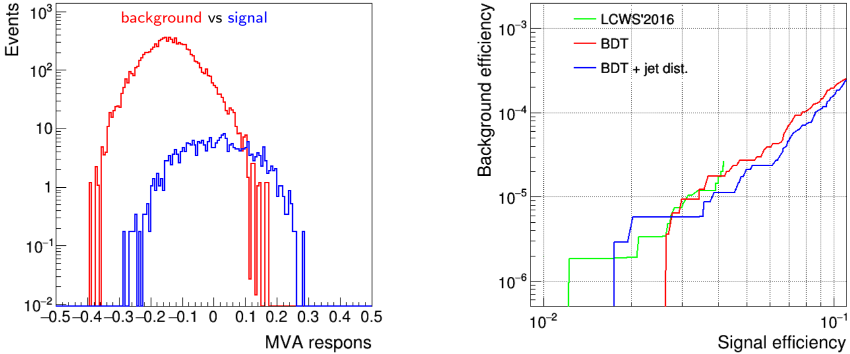
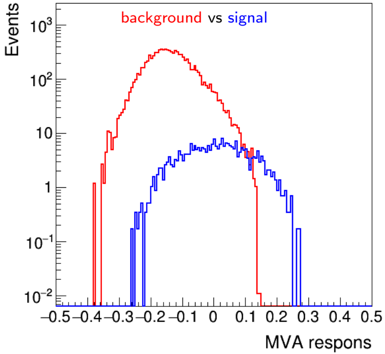


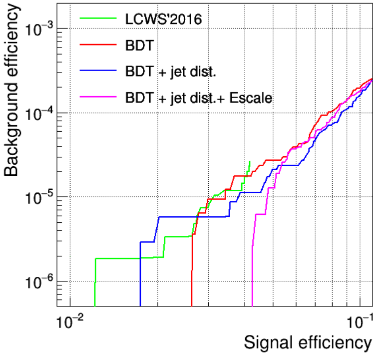
Including jet distance parameters improves background rejection

Including new variables

Final signal event selection based on BDT algorithm (TMVA).

Selection based on BDT response, compared to LCWS'2016 (cut based)





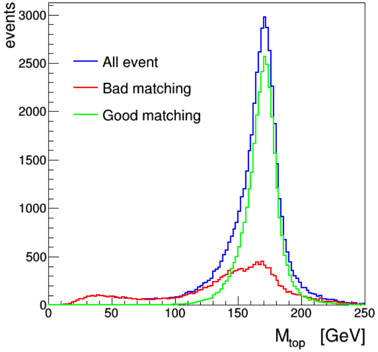
Tight selection also improved with jet energy correction (?!)

First look at semi-leptonic channel

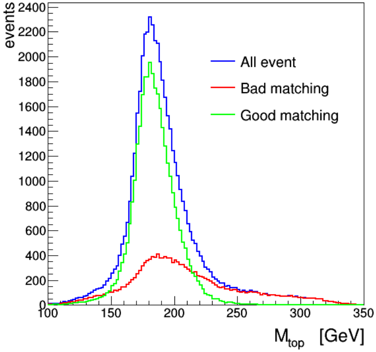
Top mass reconstruction for background sample

Also affected by problem with hadronic final state clustering

Hadronic top decay



Leptonic top decay



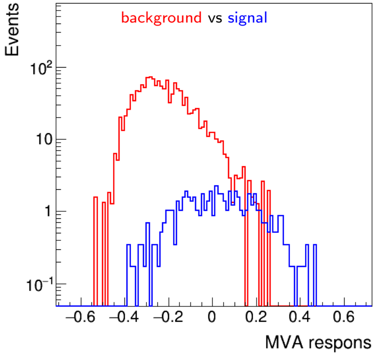
Bad matching: $\Delta^2_{\text{parton-jet}} > 0.4$

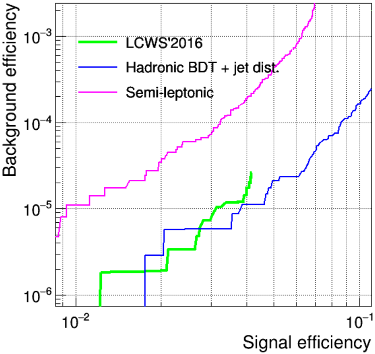
Good matching: $\Delta^2_{\text{parton-jet}} < 0.4$

First look at semi-leptonic channel

Selection based on same BDT variables as for hadronic channel (!)

Needs to be optimised...





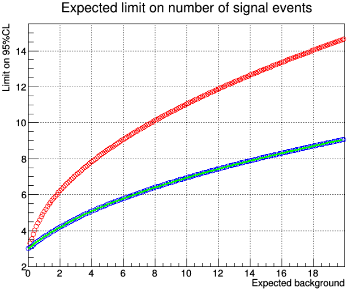
Note: "Signal efficiency" includes top branching ratio !

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

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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this value will be excluded in (about) 50% of experiments

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

Updated limit from LCWS'2016 analysis:

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

Updated results

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

- hadronic channel

$$BR \quad < \quad 1.4 \cdot 10^{-4}$$

- leptonic channel very preliminary!

$$BR \quad < \quad 3.9 \cdot 10^{-4}$$

- combined

$$BR \quad < \quad 1.3 \cdot 10^{-4}$$

Total selection efficiency about 7% (9% hadronic, 5% 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
Focus on identification of events with “wrong” jet clustering
Limits based on BDT response

Expected combined limit at 500 fb^{-1}

$$BR(t \to ch) \times BR(h \to b\bar{b}) \quad < \quad 1.3 \cdot 10^{-4}$$

Conclusions

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Some improvements probably still possible

- optimising variable choice for BDT
- using jet trimming

Thank you!

Parton Level study

Two Higgs Doublet Model (2HDM) type III used as a test scenario.
Implemented in SARAH ⇒ WHIZARD 2 thanks to Florian Staub, many thanks also due to Juergen Reuter and Wolfgang Kilian...

WHIZARD 2.2.5 used to generate signal and background samples.

Test configuration of the model:

- $m_{h_1} = 125$ GeV
- $\mathrm{BR}(t \to ch_1) = 10^{-3}$
- $\mathrm{BR}(h \to b\bar{b}) = 100\%$

Generated samples:

- $e^+e^- \longrightarrow t\bar{t}$ (2HDM/SM)
- $e^+e^- \longrightarrow ch_1\bar{t},\ t\bar{c}h_1$ (2HDM)
- $e^+e^- \longrightarrow cb\bar{b}\bar{t},\ t\bar{c}b\bar{b}$ (SM)

Assume that main background to FCNC decays comes from standard decay channels, including $t \to bW^+$ followed by $W^+ \to c\bar{b}$

All events generated with CIRCE1 spectra + ISR. No polarization.
Only t, W and h defined to be unstable. No hadronization/decays.
No generator-level cuts imposed.

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:

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

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%

Event selection: $t\bar{t}$ final state

"Signal" top: $t \rightarrow ch_1$ + higgs decay to $b\bar{b} \Rightarrow 2\ b$ tags
"Spectator" top: SM top decay $\Rightarrow 1\ b$ tag

Considered final states (resulting from $W^{\pm}$ decay channels):

- semileptonic: 4 jets + lepton + missing p_t
- fully hadronic: 6 jets, no leptons, no missing p_t

Event selection cuts for $\sqrt{s} = 500$ GeV, $50\%/\sqrt{E}$ jet energy resolution

Semileptonic:

- Missing $p_t > 25$ GeV
- Single lepton with $p_t > 15$ GeV
- 4 jets with $p_t > 15$ GeV
- 3 jets b-tagged

Fully hadronic:

- Missing $p_t < 15$ GeV
- No lepton with $p_t > 10$ GeV
- 6 jets with $p_t > 15$ GeV
- 3 jets b-tagged

Signal selection

After pre-selection cuts, compare two hypothesis:

- signal hypothesis hadronic final state

$$\chi^2_{sig} = \left(\frac{M_{bqq} - m_t}{\sigma_t}\right)^2 + \left(\frac{M_{qq} - m_W}{\sigma_W}\right)^2 + \left(\frac{M_{bbq} - m_t}{\sigma_t}\right)^2 + \left(\frac{M_{bb} - m_h}{\sigma_h}\right)^2$$

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

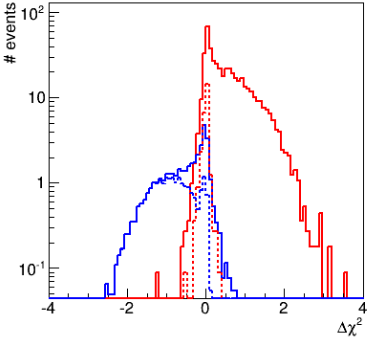
$$\chi^2_{bg} = \left(\frac{M_{bqq} - m_t}{\sigma_t}\right)^2 + \left(\frac{M_{qq} - m_W}{\sigma_W}\right)^2 + \left(\frac{M_{bbq} - m_t}{\sigma_t}\right)^2 + \left(\frac{M_{bq} - m_W}{\sigma_W}\right)^2$$

Independent search for best background and signal combinations
Difference in the last term only: h vs W mass discrimination crucial!

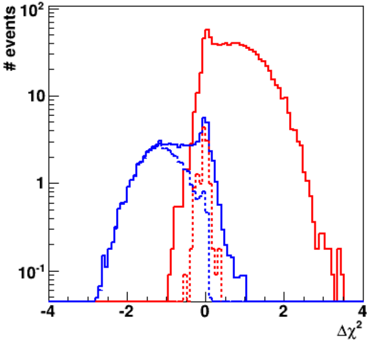
Signal selection

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

Semi-leptonic events



Fully hadronic events



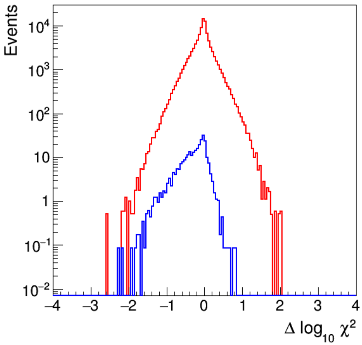
500 GeV, jet energy resolution 50%, 70% *b*-tagging efficiency
Background rejection strongly depends on the detector performance

Signal-background discrimination

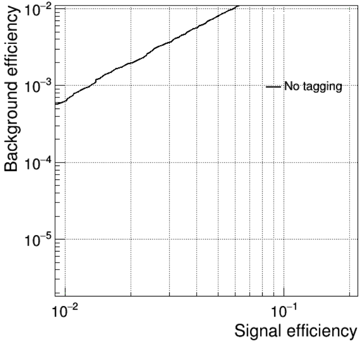
Based on the cut on the difference of $\log_{10}\chi^2$ for two hypothesis

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

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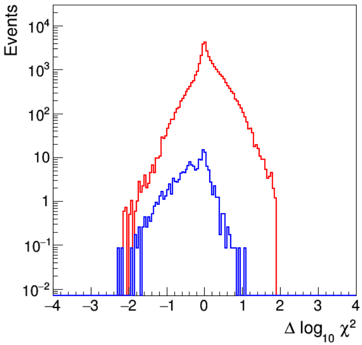

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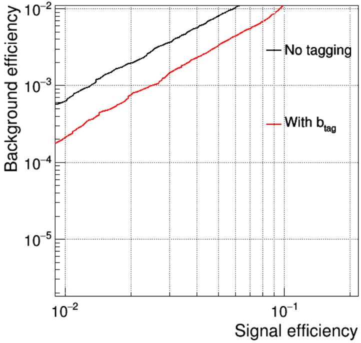

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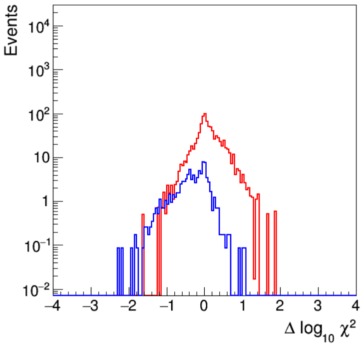

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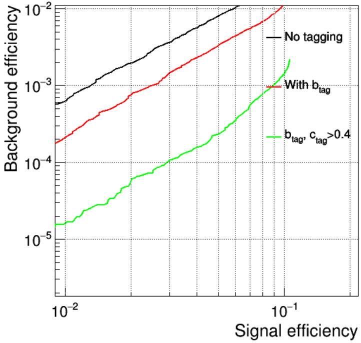

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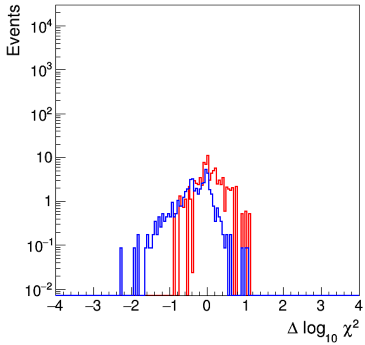

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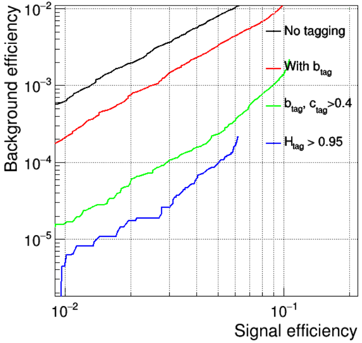

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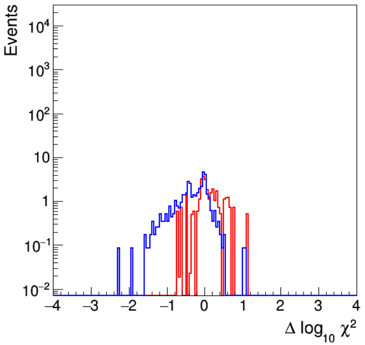

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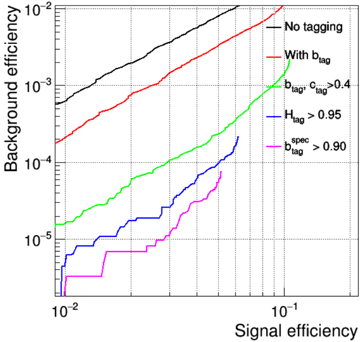

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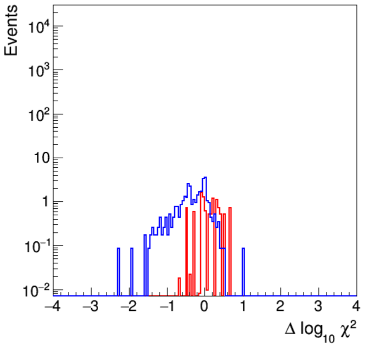

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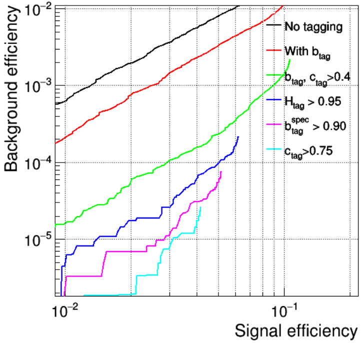
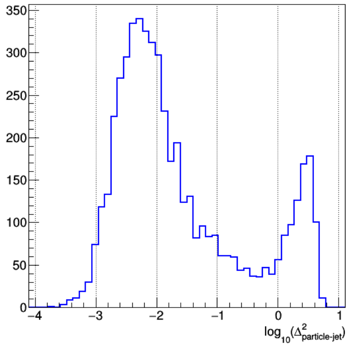


normalized to all decay channels

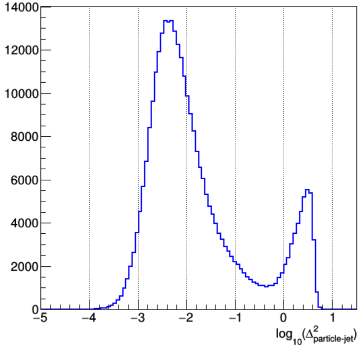
Jet matching

Distance between particle level jets and detector level jets

Signal events



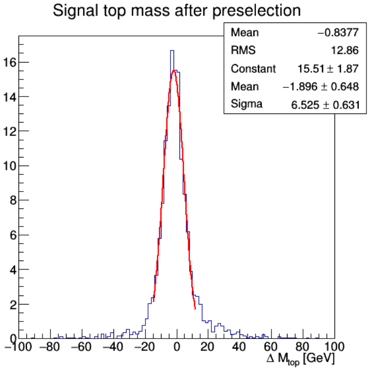
Background ($t\bar{t}$) events

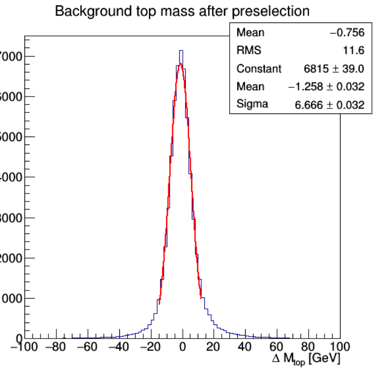


For most events reconstructed detector-level jets follow closely the particle level configuration...

Mass resolution

Difference between top candidate mass reconstructed on particle level and detector level (for events with good matching)





$\Rightarrow$ very good detector performance confirmed

problem is most likely due to particle migrations between jets...