Search for top FCNC decay $t \to cH$ at 380 GeV CLIC

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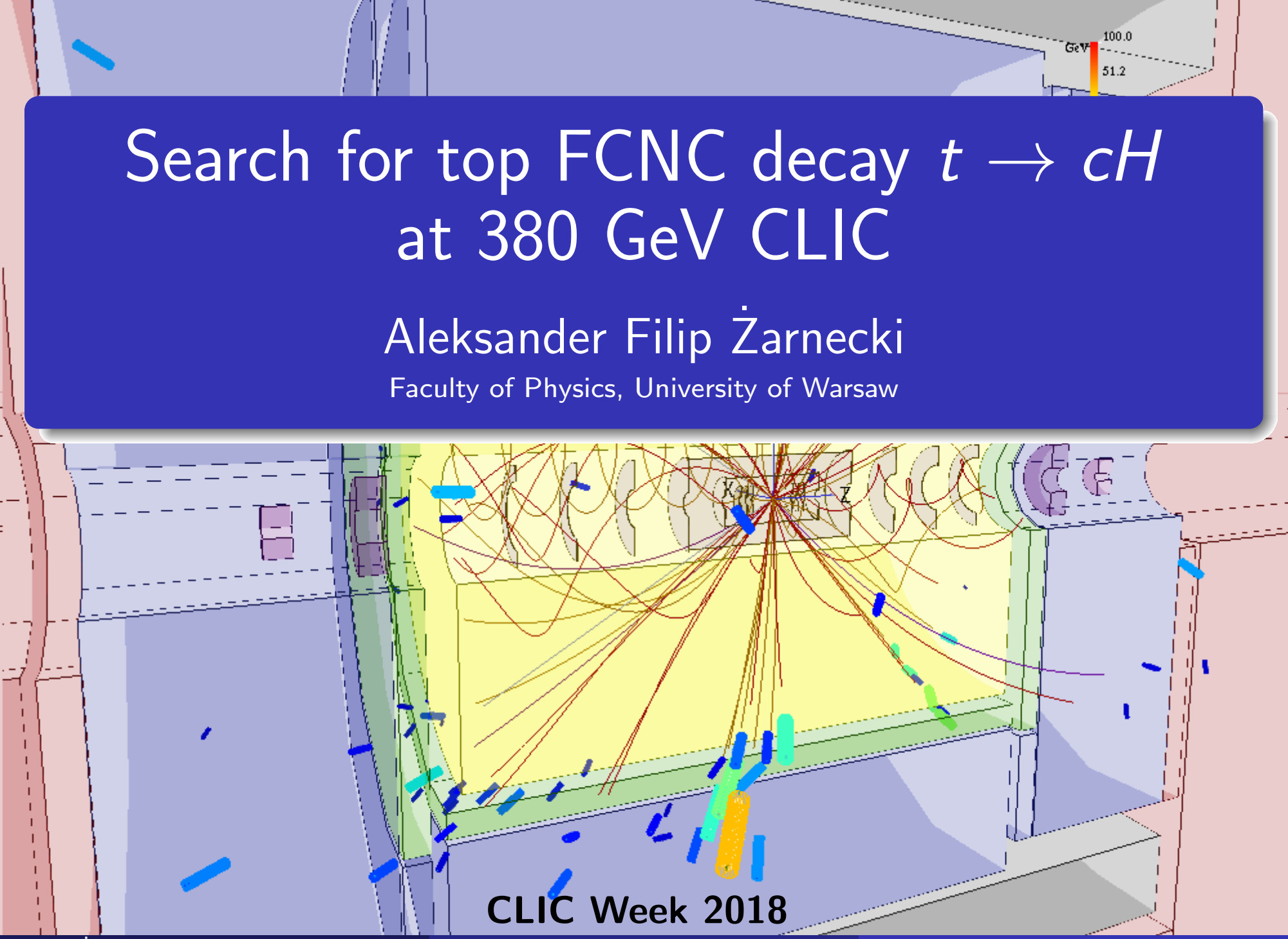

CLIC Week 2018

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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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)

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 $e^+e^- \longrightarrow cH\bar{t},\ t\bar{c}H$
  Higgs boson decay restricted to $H \to b\bar{b}$
- full 6-fermion sample as produced for CLIC $t\bar{t}$ studies
- 4-fermion and quark-pair samples (recently included in the analysis)

Event samples

Signal and background samples considered in the analysis.

All samples processed with standard CLICdp simulation and analysis chain.
Assuming 500 fb^{-1} collected at 380 GeV, with polarization of -80%/0%.
FCNC signal for $BR(t \to cH) \times BR(H \to b\bar{b}) = 10^{-3}$

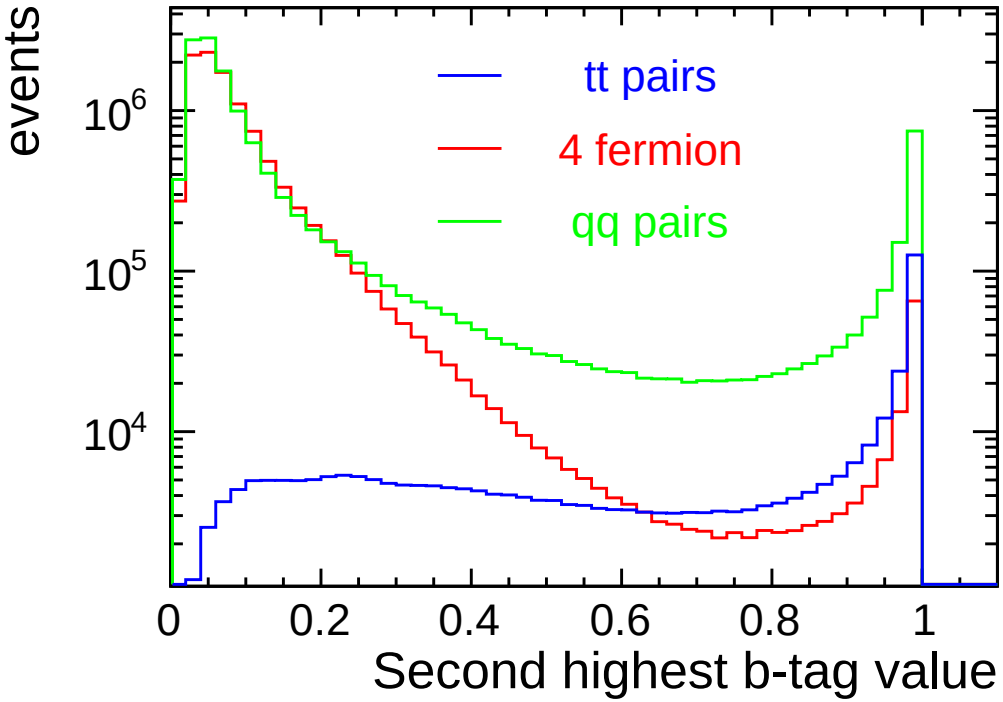
Sample	Cross section	Expected events	MC event sample
FCNC signal	1.64 fb	819	99 301
6 fermion	820 fb	410 000	1 014 966
4 fermion	21 pb	10 500 000	7 067 836
quark pair	26 pb	13 000 000	2 968 551

First analysis stage focused on reduction of huge non-$t\bar{t}$ backgrounds

Event classification

Initial selection cut based on LCFI+ flavour tagging

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 $t\bar{t}$ events

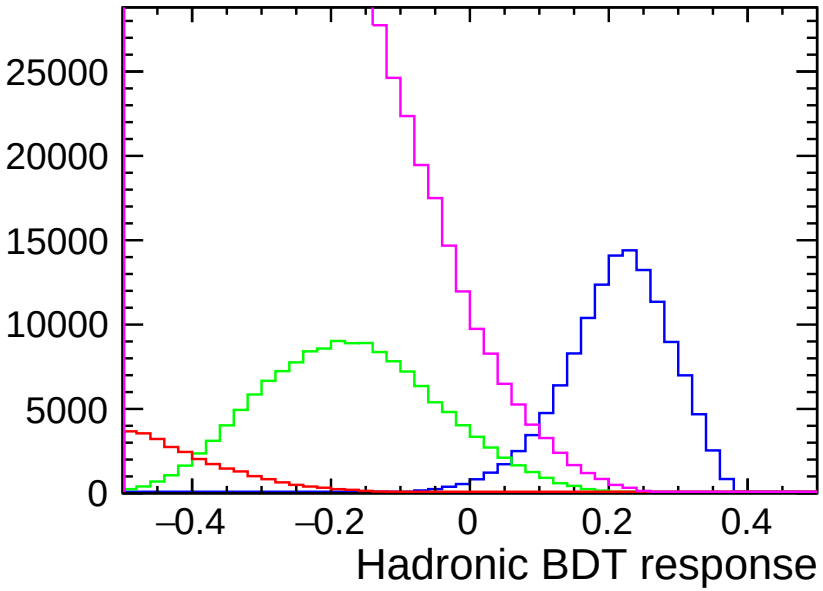
Classificantion:

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

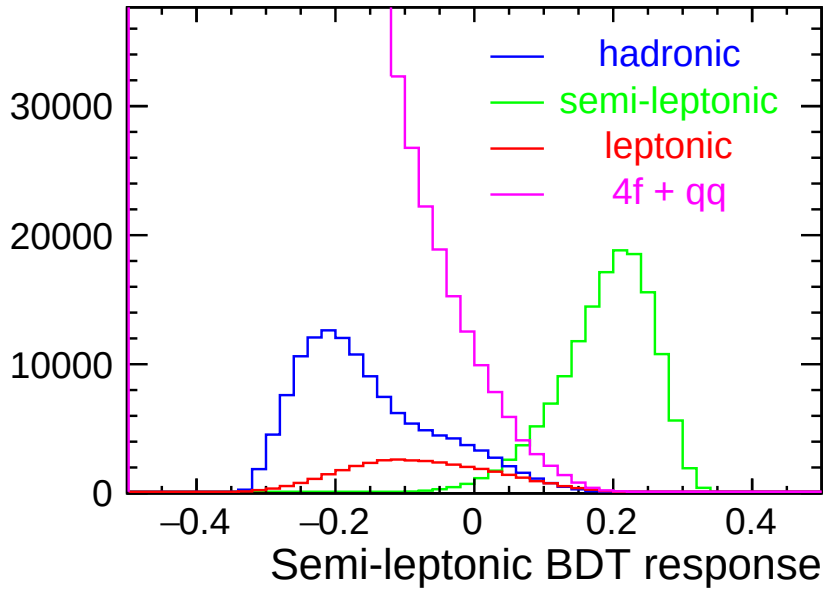
based on total energy-momentum, event shape and jet parameters (y_{min}, y_{max}), lepton ID

$\Rightarrow$ improved efficiency/purity, efficient rejection of non-$t\bar{t}$ background

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

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

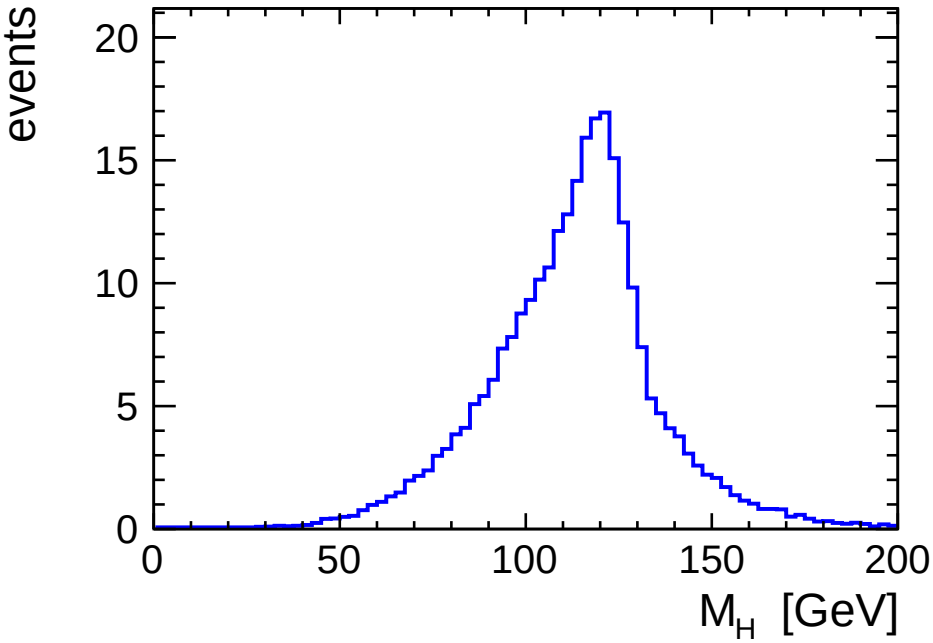
- similar for background hypothesis ($t\bar{t}$ hadronic decays)

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

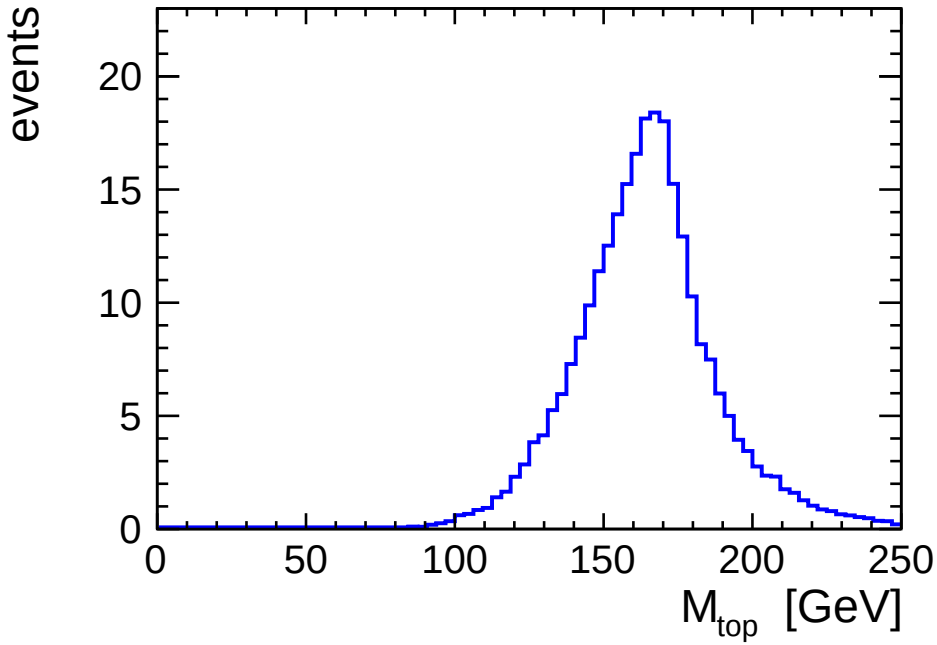
Results

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

Higgs boson mass



Top quark mass



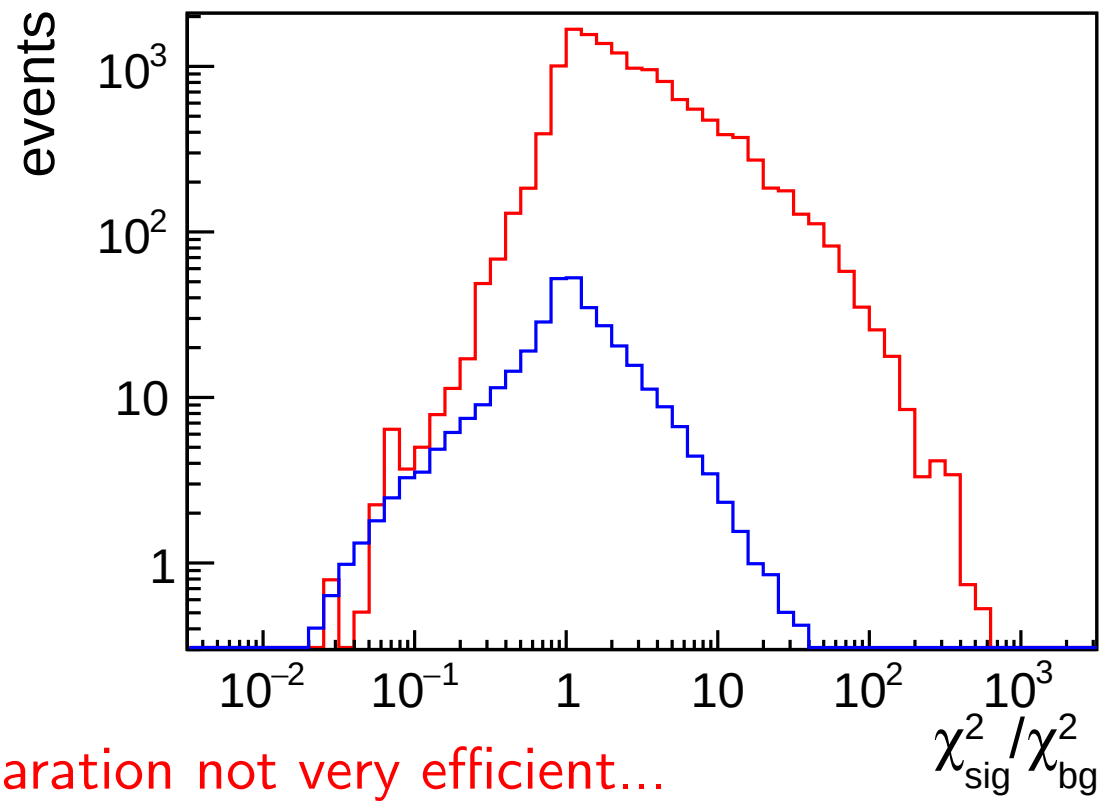
Invariant mass distributions significantly wider than expected !?...

Significant contribution of events with "poor" clustering, mainly due to higher order QCD effects...

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



Kinematic separation not very efficient...

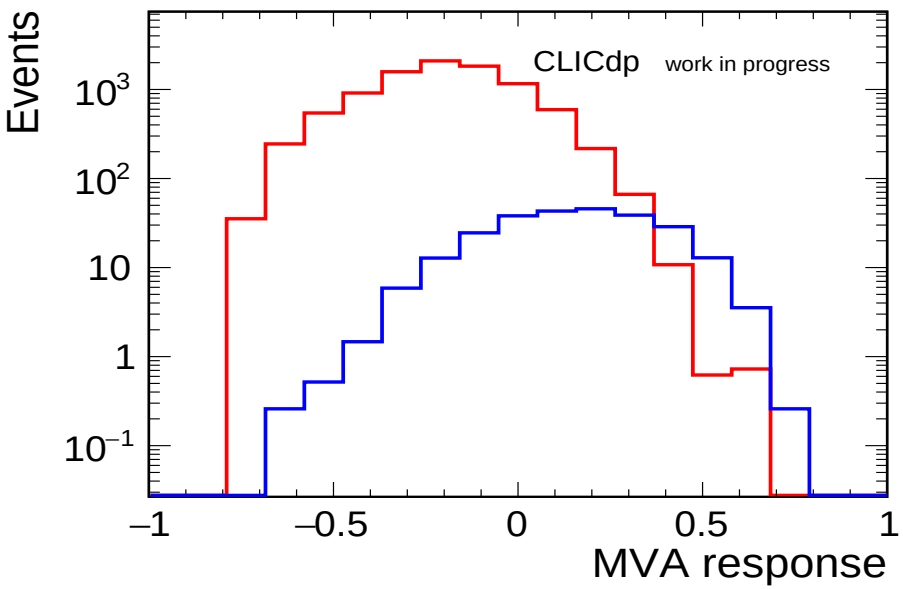
Event classification with MVA

Used for efficient signal vs background discrimination

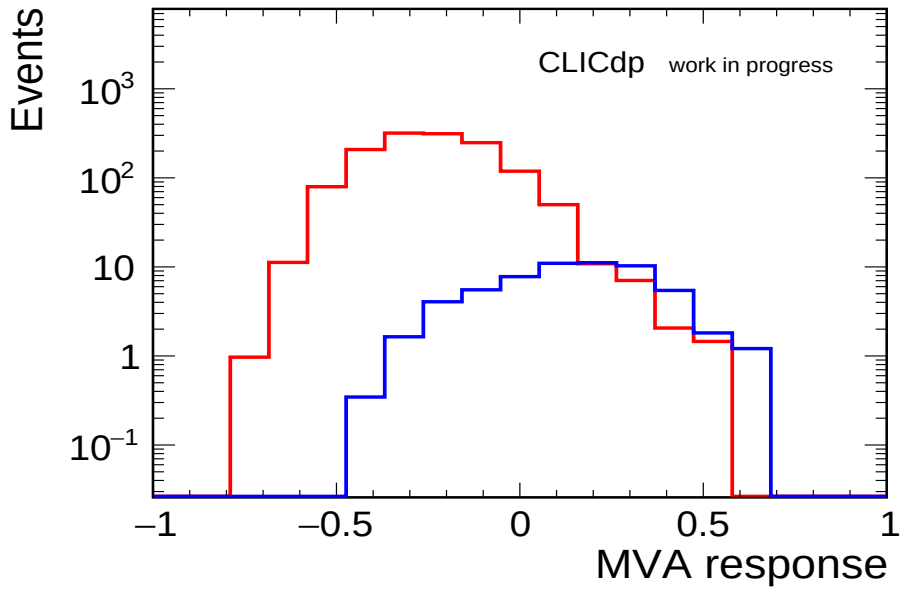
Based on: event variables, flavour tagging and kinematic fit

LCWS'2017 results: independent BDTs trained for

Hadronic decays



Semi-leptonic decays



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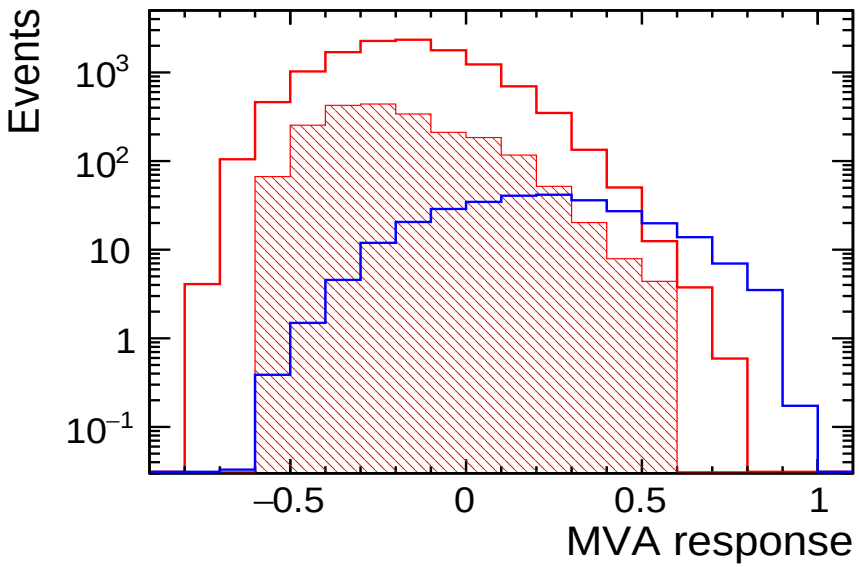
New results: one BDT trained on both samples (!)

Hadronic decays



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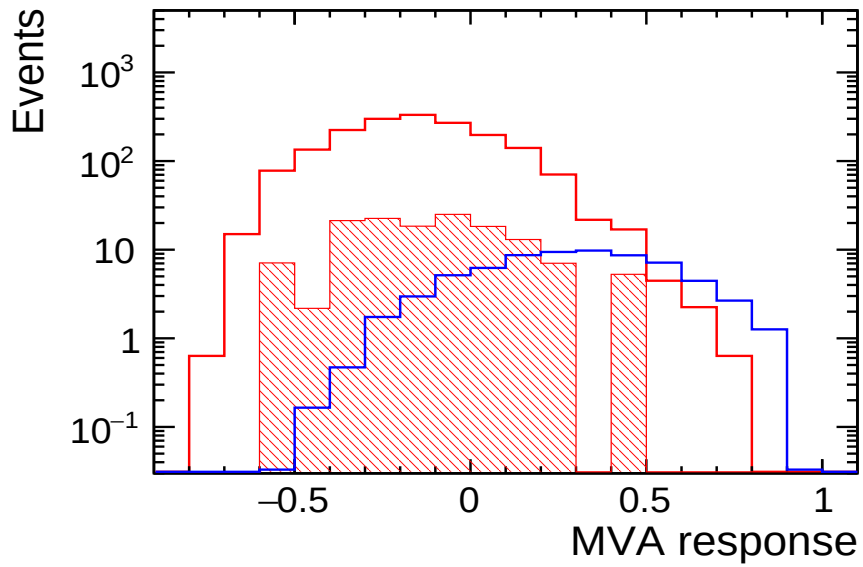

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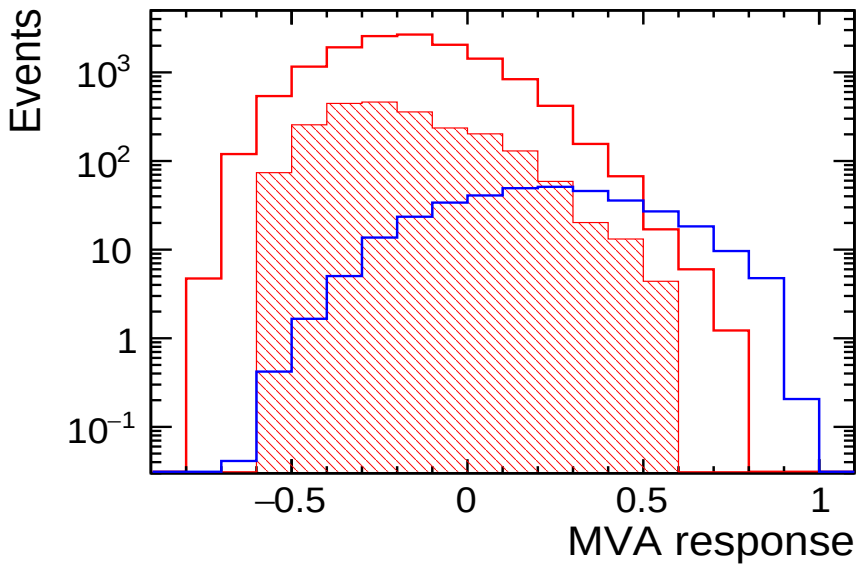
Hadronic and semi-leptonic decays



⇒ avoid complicated procedure for combining limits from both channels

Selection efficiencies

Cut	FCNC signal	$t\bar{t}$/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 events and signal efficiency of 7.3%

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

in agreement with results presented at LCWS'2017. Now considered final.

Thank you!

Backup

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

Feasibility study with very simple detector modelling. Estimated limit:

$$BR(t \to cH) \times BR(H \to b\bar{b}) < 5 \cdot 10^{-5} \text{ (500 fb}^{-1} \text{ @ 380 GeV)}$$

LCWS'2016 results CLICdp-Conf-2017-005 [arXiv:1703.05007]

Cut based analysis using full simulation samples. Only hadronic final state, only 6-fermion background samples considered. Expected 95% C.L. limit:

$$BR(t \to cH) \times BR(H \to b\bar{b}) < 2.6 \cdot 10^{-4}$$

LCWS'2017 results CLICdp-Conf-2018-001 [arXiv:1801.04585]

Analysis based on BDT algorithms. Both hadronic and semi-leptonic final states considered. Only 6-fermion background samples included:

$$BR(t \to cH) \times BR(H \to b\bar{b}) < 1.6 \cdot 10^{-4}$$

This presentation

Including 6-fermion, 4-fermion and $q\bar{q}$ background samples.

Improved (and simplified) analysis: limit setting with single BDT

Event processing

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

- Using LooseSelectedPandoraPFANewPFOs as input collection
- Isolated lepton identification IsolatedLeptonFinder
- LcfiPlus
  - primary and secondary vertex finder
  - jet finding with Valencia algorithm
  - vertex corrections and flavour taging

Event analysis on root level:

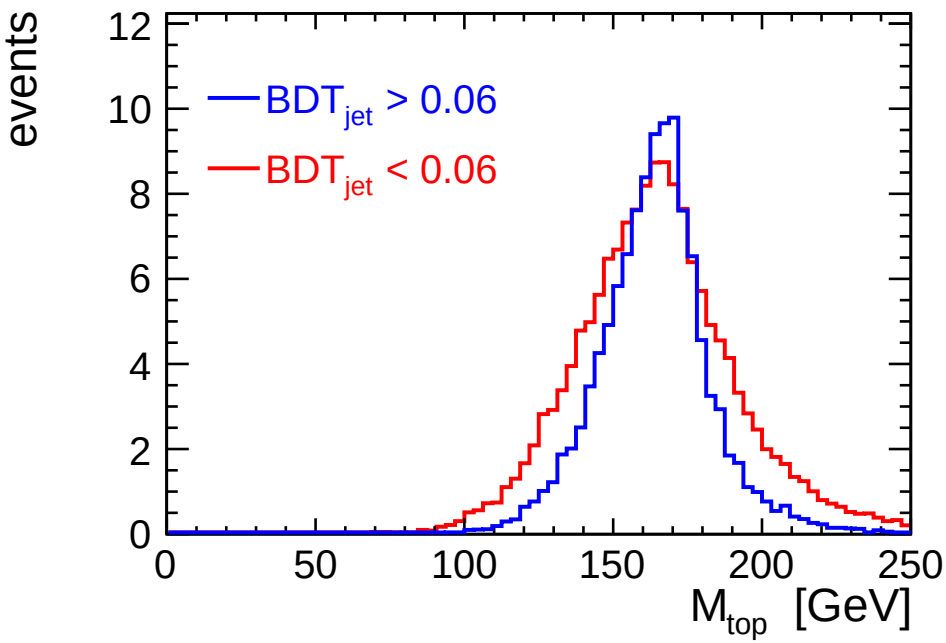
- pre-selection and event classification
  selection hadronic and semi-leptonic $t\bar{t}$ candidates
- kinematic fit
- final signal-background discrimination

Clustering quality estimate

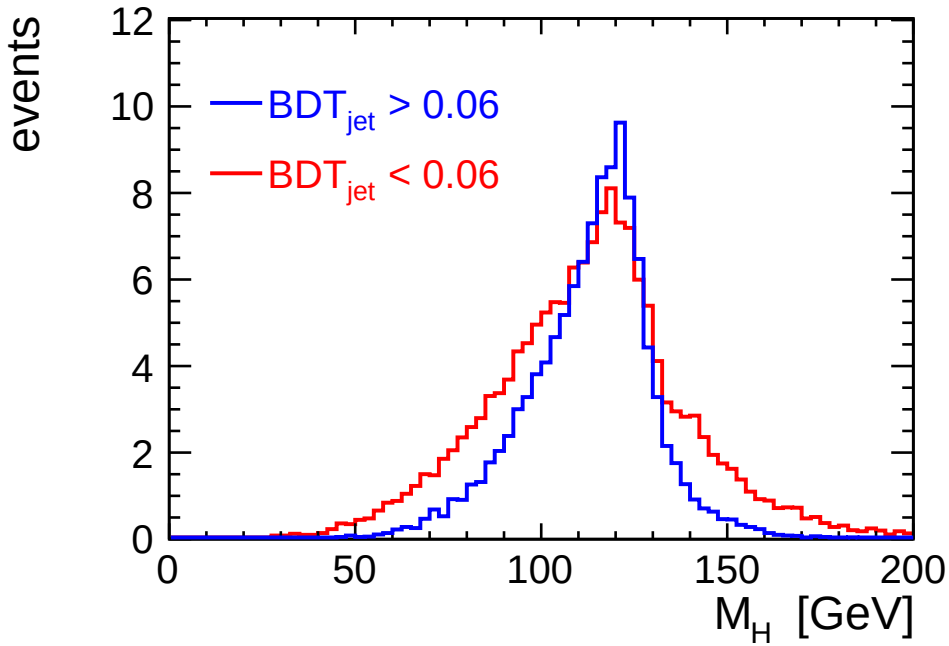
Dedicated BDT implemented to recognize events with "bad" clustering based on jet variables and comparison of different jet algorithms

Kinematic fit result for FCNC sample (signal top decays)

Top quark mass



Higgs boson mass



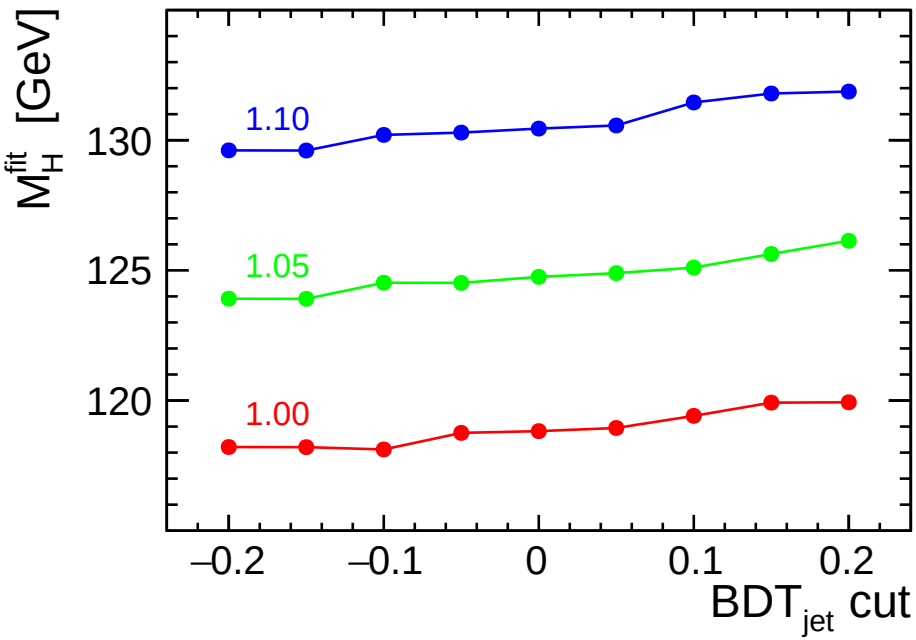
b-jet energy correction

No visible shift in $W^{\pm}$ boson invariant mass (two light quark jets).
Significant shift in reconstructed Higgs boson and top quark masses.

$\Rightarrow$ additional 5% energy correction for *b*-jets

Higgs boson reconstruction

Maximum position vs quality cut



Reconstructed mass distribution