# Sensitivity of CLIC at 380 GeV to top FCNC decay $t \to ch$

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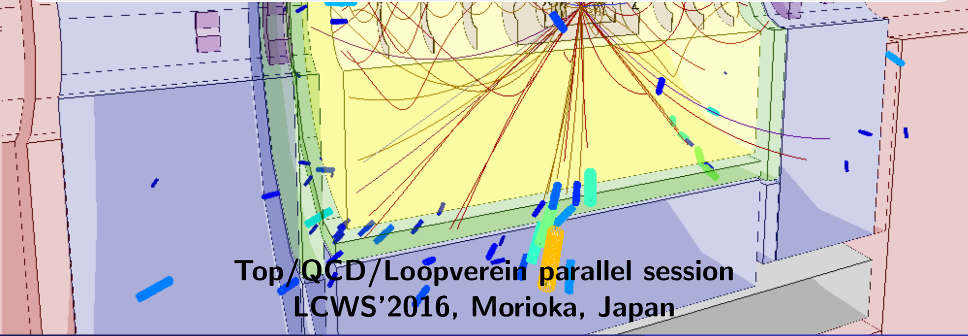
Faculty of Physics, University of Warsaw

presented by Naomi van der Kolk on behalf of the CLICdp collaboration



**Top/QCD/Loopverein parallel session**
**LCWS'2016, Morioka, Japan**

# Outline

# 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} \\
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Any signal is a direct signature of "new physics"...

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LHC (2016):

$BR(t \rightarrow ch) < 0.40\%$ (CMS)

$BR(t \rightarrow ch) < 0.46\%$ (ATLAS)

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

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

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

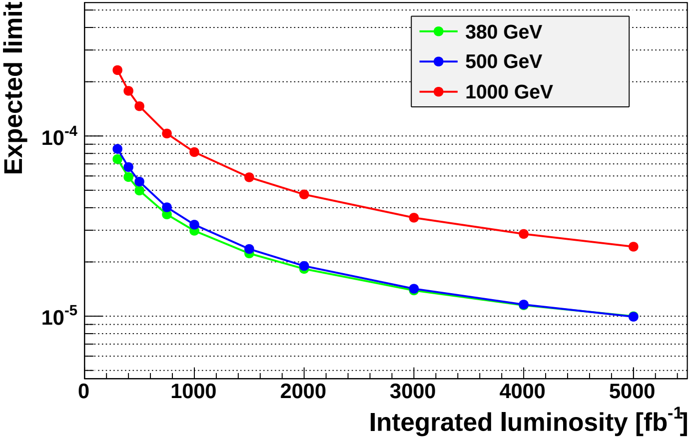
- one of simplest extensions of the SM
- large enhancement both on tree and loop level possible $BR(t \rightarrow c\ h)$ up to $10^{-2}$ and $10^{-4}$, respectively

**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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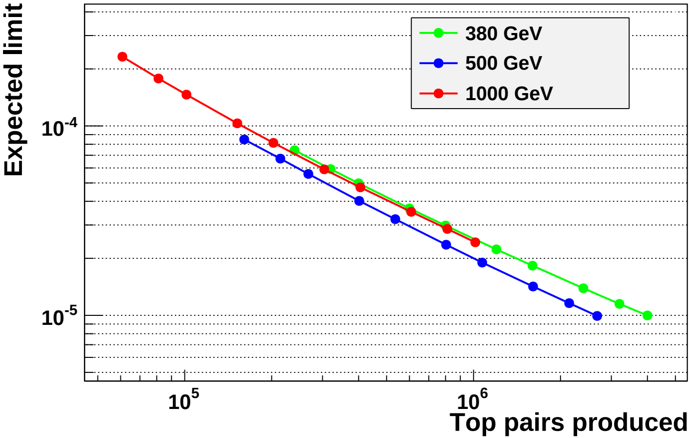

## Signal

Signal sample generated with WHIZARD 2.2.8
Using SARAH implementation of 2HDM(III) model.

Test configuration of the model:

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

Generated samples (10'000 events):

- $e^+e^- \longrightarrow c h_1 \bar{t},\ t \bar{c} h_1$ (FCNC)
- $e^+e^- \longrightarrow t\bar{t}$ (test sample)
  for simulation validation

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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

**Background**

Assume that we can select high purity $t\bar{t}$ sample

$\Rightarrow$ main background to FCNC decays from standard decay channels
in particular from $t \to bW^+$ followed by $W^+ \to c\bar{b}$

Full 6-fermion sample as produced for CLIC $t\bar{t}$ studies, see

https://twiki.cern.ch/twiki/bin/view/CLIC/MonteCarloSamplesForTopPhysics

Total 2034 files processed (out of 2055), 1014966 events in 18 subsamples.

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## Normalisation

Signal and background samples normalised to 500 fb$^{-1}$

Assumed $t\bar{t}$ cross section at 380 GeV: 820 fb
575 fb (LO) $\times$ 1.34 (polarisation) $\times$ 1.4 (NLO) $\times$ 0.76 (spectra + ISR)

## 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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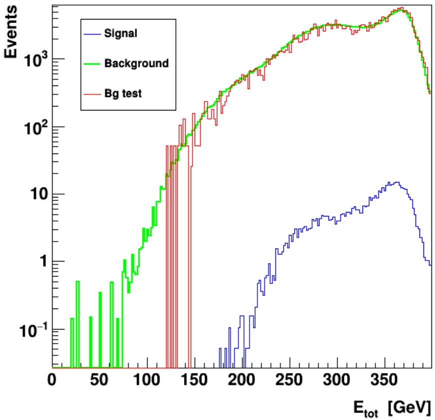
Final analysis in root:

- hadronic decay selection
- pre-selection cuts
- kinematic fit
- final selection

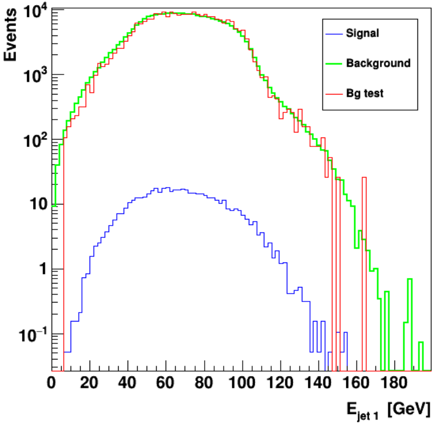
## Control plots

Comparing signal sample with full background and test samples.

Total measured energy




Jet energy (highest *b*-tag)



## Control plots

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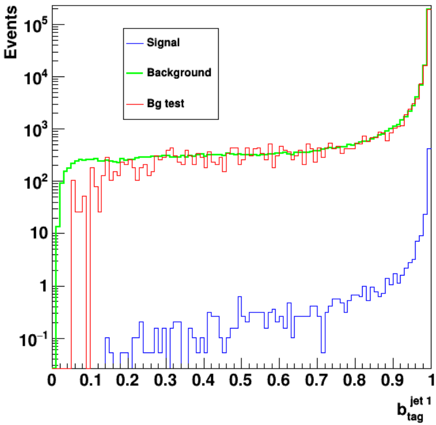
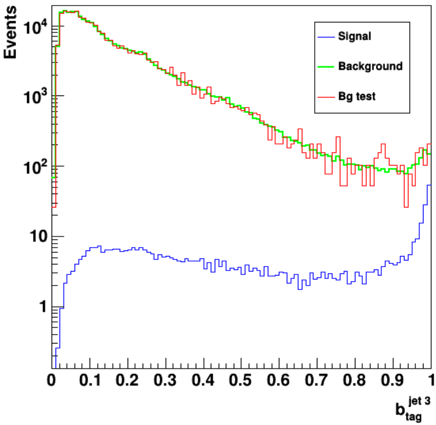
Highest $b$-tag value



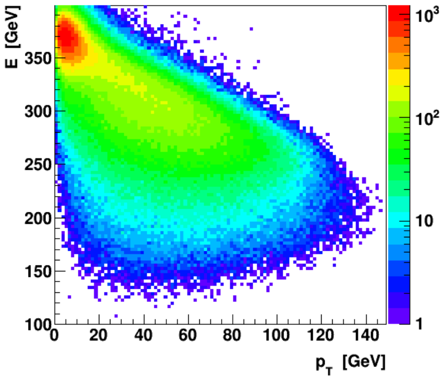

Third $b$-tag value



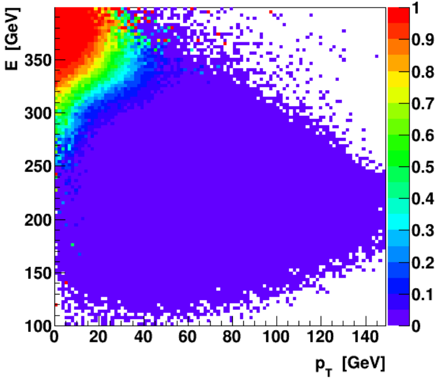
## Hadronic event selection

Trying to improve selection of hadronic top decays by looking at correlation of transverse momentum and total energy

Background event distribution




**Hadronic event fraction**




$\Rightarrow$ best discrimination (in this plane) with cut on $E - 2\,p_T$

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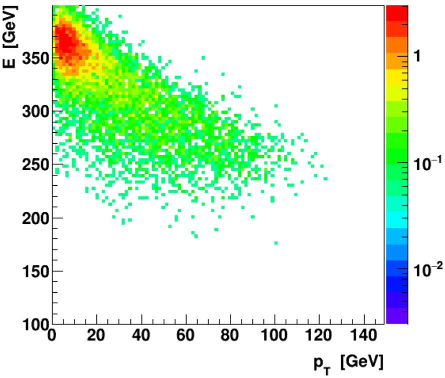


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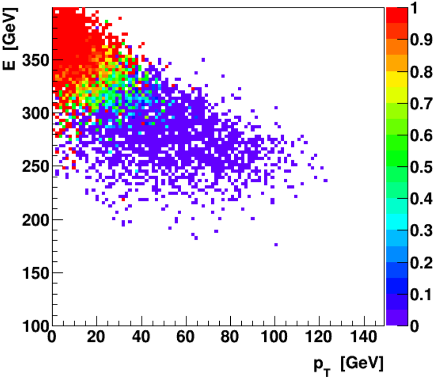


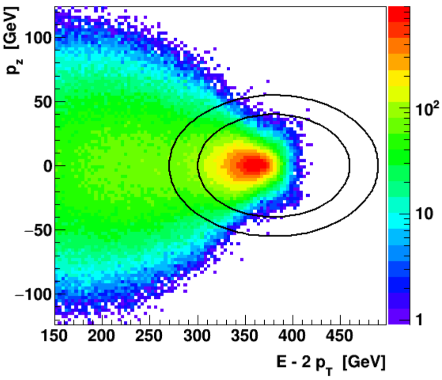

⇒ best discrimination (in this plane) with cut on $E - 2\,p_T$

# Event selection

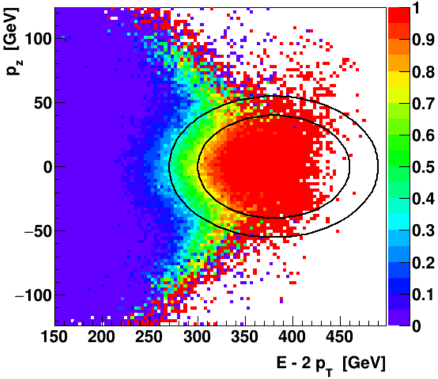
## Hadronic event selection

Energy and transverse momentum correlated with longitudinal momentum

Background event distribution




**Hadronic event fraction**




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

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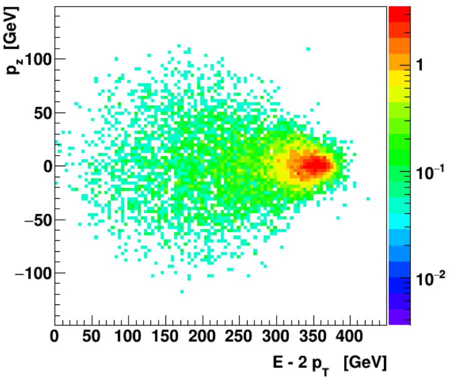


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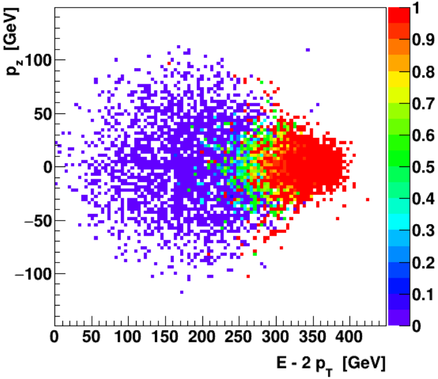


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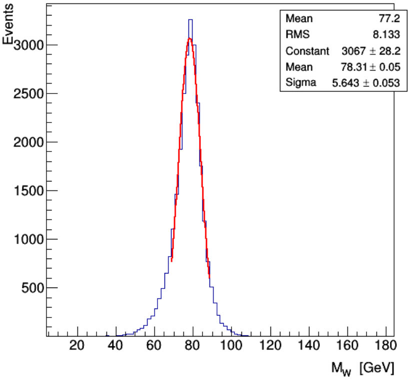
## Mass resolution

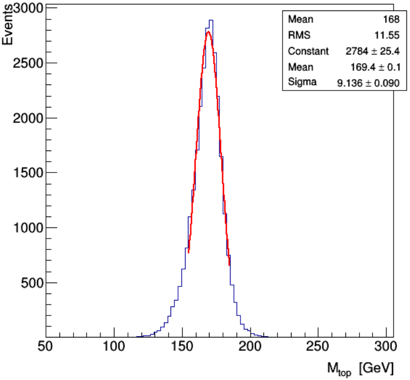
Reconstructed mass distributions for background events (Valencia jets)

For jet combination consistent with parton level configuration

W boson




Top quark



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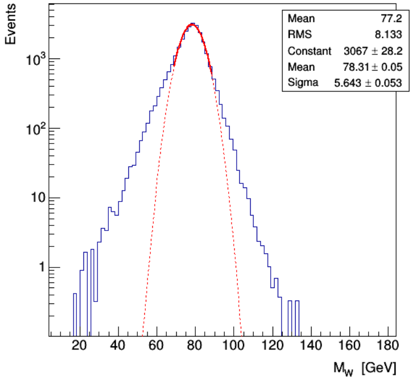


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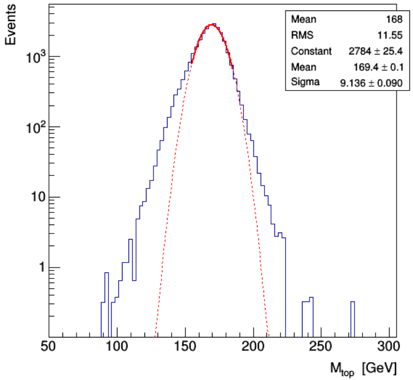
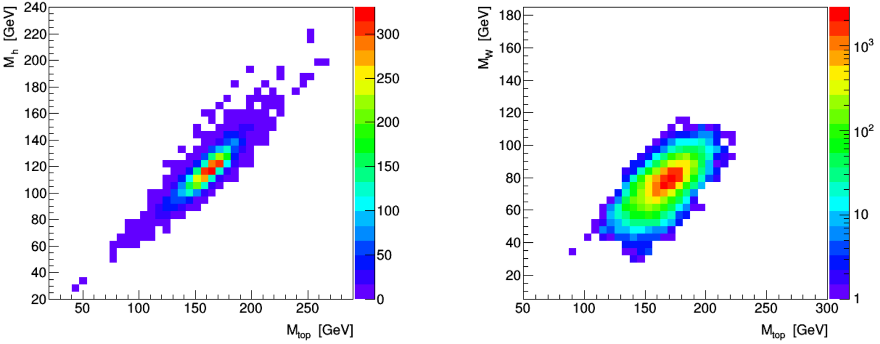


## Mass correlation

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)




$\Rightarrow$ should be taken into account in event selection

# Kinematic fit

**Old $\chi^2$ definition** from previous, parton level study

Used to find best hadronic final state reconstruction (6 jets):

- signal hypothesis $t\bar{t} \to ch\ bW \to 3b + c + 2q$

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

- background hypothesis $t\bar{t} \to bW\ bW \to 2b + 4q$

$$\chi^2_{bg} = \left(\frac{M^{(1)}_{bqq} - m_t}{\sigma_t}\right)^2 + \left(\frac{M^{(1)}_{qq} - m_W}{\sigma_W}\right)^2 + \left(\frac{M^{(2)}_{bqq} - m_t}{\sigma_t}\right)^2 + \left(\frac{M^{(2)}_{qq} - m_W}{\sigma_W}\right)^2$$

Signal and background differ in the last term only!

## New $\chi^2$ 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)

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

# Event selection

**Preselection** (before kinematic fit)

- cut on $E_{balance} < 100$ GeV
  no isolated lepton veto required
- 6 jets reconstructed in LCFI+
  no addition veto cuts required
- 3 jets with $b$-tag value above threshold of 0.4
- additional jet with $b$ or $c$ tag

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**Final selection cuts** (after selecting best signal hypothesis)

- quality of signal hypothesis ($\chi^2_{sig}$)
- the difference of reconstructed top masses ($\Delta M_{top}$)
- product of *b*-tag values for Higgs candidate
- *b*-tag value for *b* from spectator top
- sum of *b*-tag and *c*-tag values for *c* jet candidate
- $\chi^2_{sig}/\chi^2_{bg}$ (final optimisation for best BR limit)

## Expected events

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

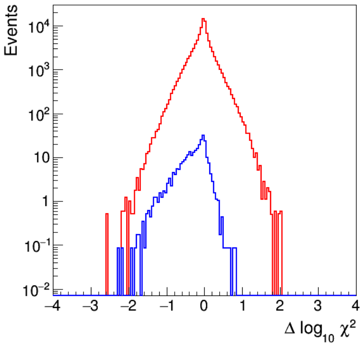
| Analysis level / Selection cut | Expected events $t\bar{t}$ (SM) | Expected events Signal | Efficiency $t\bar{t}$ (SM) | Efficiency Signal |
|---|---|---|---|---|
| All events | 410'000 | 819 | 100% | 100% |
| hadronic events | 170'000 | 543 | 41.5% | 66.3% |
| **Before kinematic fit** | | | | |
| $E_{balance} < 100$ 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% |

## Signal-background discrimination

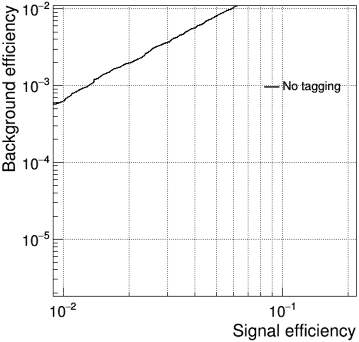
Based on the cut on the difference of $\log_{10}\chi^2$ for two hypothesis

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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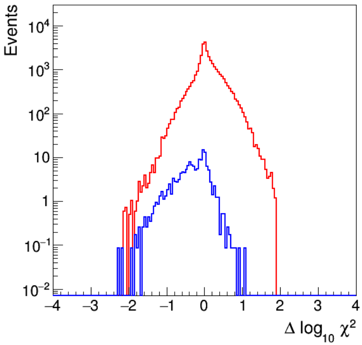


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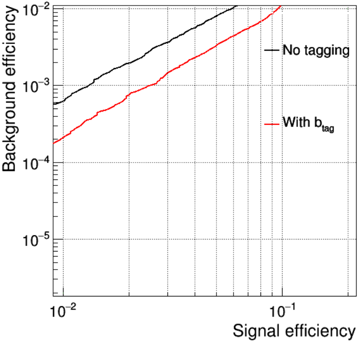


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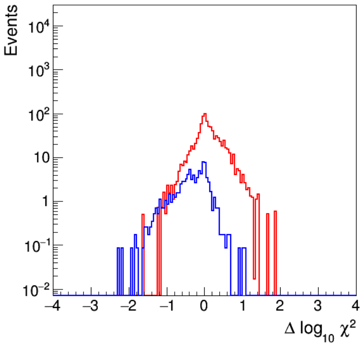


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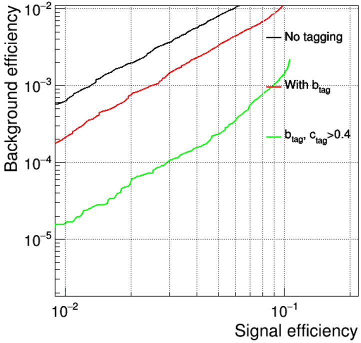


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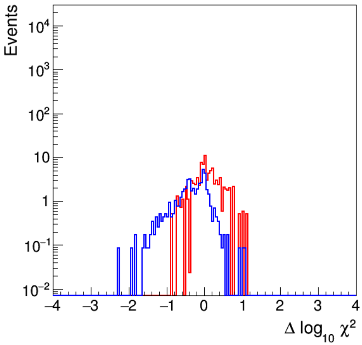


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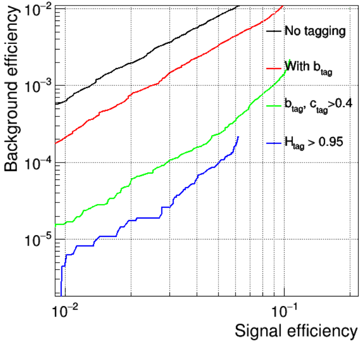


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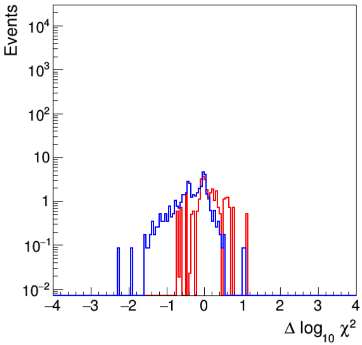


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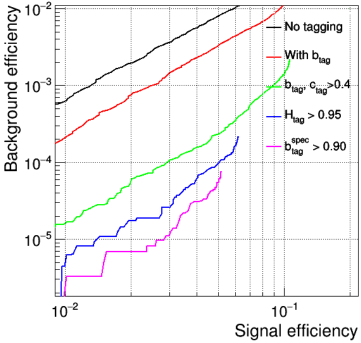


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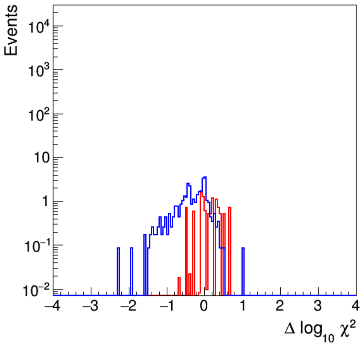


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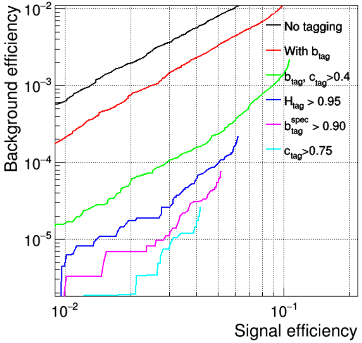


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## Expected limits

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 $\mathrm{fb}^{-1}$ at 380 GeV preliminary

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

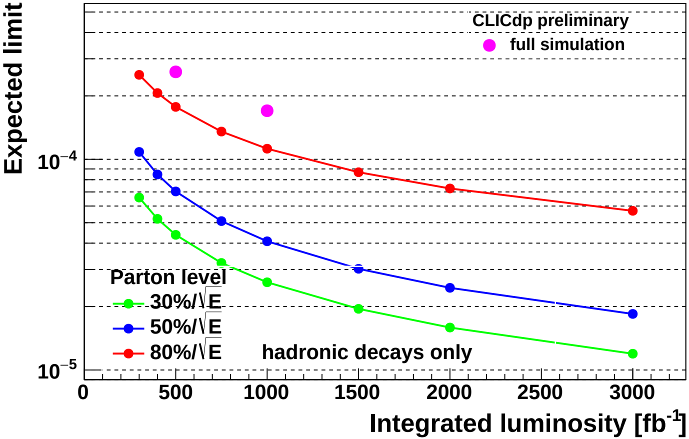
With luminosity of 1000 $\mathrm{fb}^{-1}$ at 380 GeV

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

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

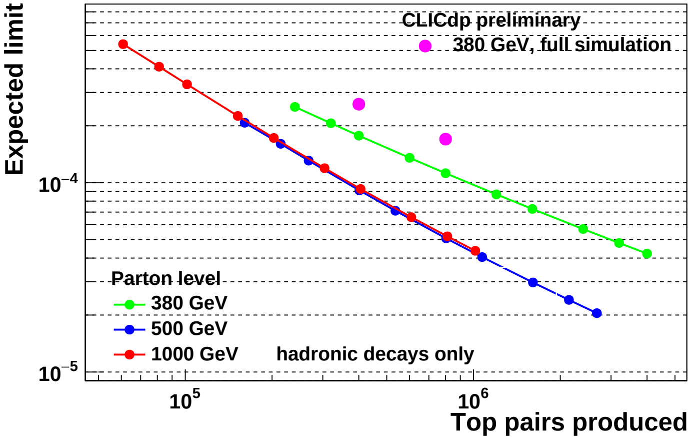
**Expected limits** on $BR(t \to ch) \times BR(h \to b\bar{b})$

Comparison with parton level results, different jet energy resolutions



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

Comparison with parton level results, jet energy resolutions of $80\%/\sqrt{E}$, different energies



**FCNC top decays** $t \to ch$

Preliminary results from full simulation at 380 GeV presented.

Focus on optimizing kinematic reconstruction in the hadronic channel

Expected limit at 500 fb$^{-1}$

$$BR \quad < \quad 2.6 \cdot 10^{-4}$$

# Conclusions

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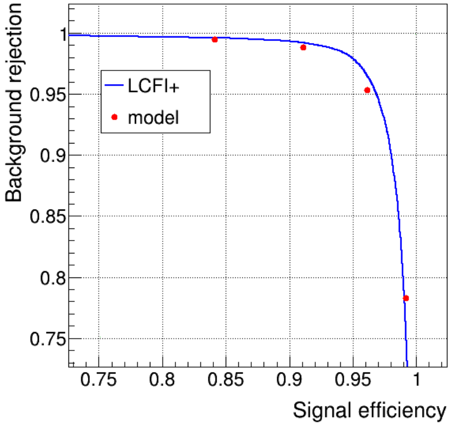
Better reconstruction should be possible at higher energies!

# Backup slides

# LCFI+ performance

Comparison of LCFI+ performance in full simulation analysis with model assumed in the parton level study




Signal: events with 2 $b$ jets (ssubbu) Background: events without $b$ jets (ssussu)

## 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% [GeV$^{1/2}$]

- $b$ tagging (misstagging) efficiencies: (LCFI+ package)

| 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% |