Sensitivity to top FCNC decay $t \rightarrow ch$ at future e^+e^- colliders

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

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

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LHC (Moriond 2015):

$$BR(t \rightarrow ch) < 0.56\% \text{ (CMS)}$$
$$BR(t \rightarrow ch) < 0.79\% \text{ (ATLAS)}$$

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Estimated HL-LHC reach:
(Snowmass Top WG report, 2013)

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

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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 $BR(t \to c\ h)$ up to 10^{-2} and 10^{-4}, respectively

Model

Dedicated implementation of 2HDM(III) prepared by Florian Straub.
Many thanks also due to Juergen Reuter and Wolfgang Kilian...

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:

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

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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 $W^+ \to c\bar{b}$

WHIZARD

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⇒ main background to FCNC decays from standard decay channels
in particular from $t \to bW^+$ 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:

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

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%

Running scenarios

Reference setup:

- $\sqrt{s} = 500$ GeV (assumed for initial ILC running), 500 fb^{-1} (unpol.)

Other options:

- $\sqrt{s} = 380$ GeV (initial stage for CLIC running)
- $\sqrt{s} = 1000$ GeV (possible ILC/CLIC upgrade)

Limits calculated for integrated luminosities from 300 to 5000 fb^{-1}

H-20 scenario for ILC

- starting at $\sqrt{s} = 500$ GeV with 500 fb^{-1} in 4 years (polarized!)
- total of 4000 fb^{-1} at $\sqrt{s} = 500$ GeV (after 17 years)

$t\bar{t}$ final state selection

"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

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Event selection cuts for $\sqrt{s} = 500$ GeV, $30\%/\sqrt{E}$ jet energy resolution

Semileptonic:

- Missing $p_t > 20$ GeV
- Single lepton with $p_t > 15$ GeV
- 4 jets with $p_t > 15$ GeV
- 3 jets b-tagged

Fully hadronic:

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

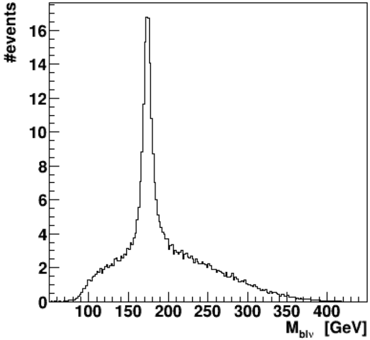
Top reconstruction

Try to group final state objects into two tops

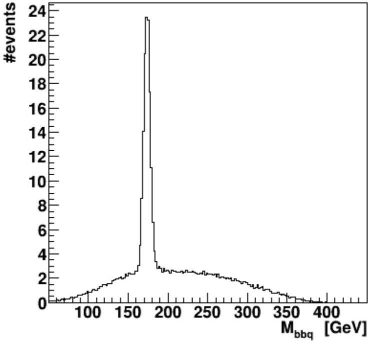
Check invariant mass distributions for all considered combinations

Semileptonic events (signal sample):

Semileptonic "spectator" top decay



Fully hadronic "signal" top decay



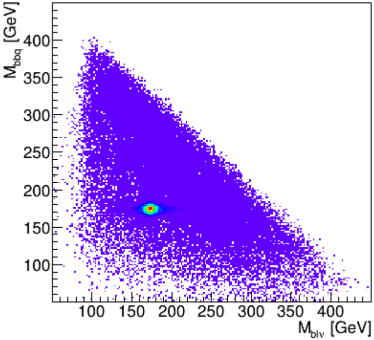
Top reconstruction

Try to group final state objects into two tops

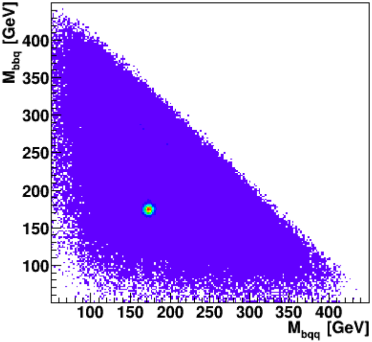
Check invariant mass distributions for all considered combinations

Proper combination can be easily identified

Semileptonic events



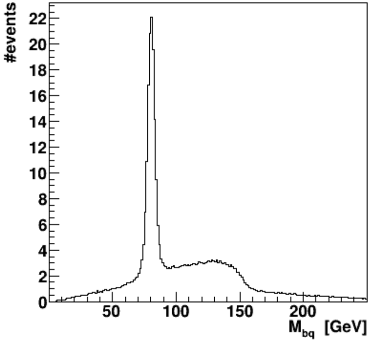
Fully hadronic events



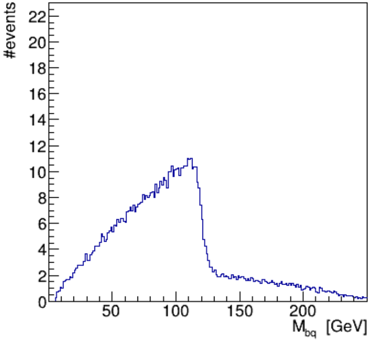
Cut based approach: $W^{\pm}$ veto

Irreducible SM background can be suppressed by reconstructing second W

Invariant mass of two jets from "signal" top - all combinations



$e^+e^- \longrightarrow cb\bar{b}\bar{b}l^+\nu$ (SM)

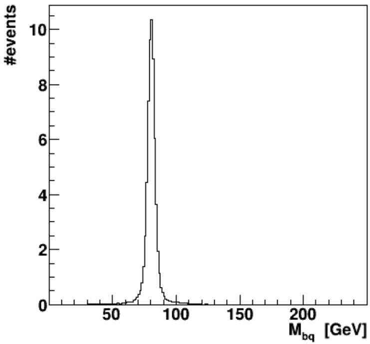


$e^+e^- \longrightarrow ch_1\bar{t},\ t\bar{c}h_1$ (2HDM)

Cut based approach: $W^{\pm}$ veto

Irreducible SM background can be suppressed by reconstructing second W

Invariant mass of two jets from "signal" top - best background fit



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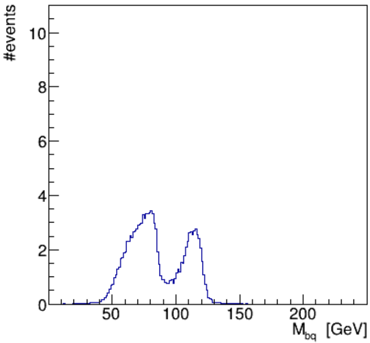
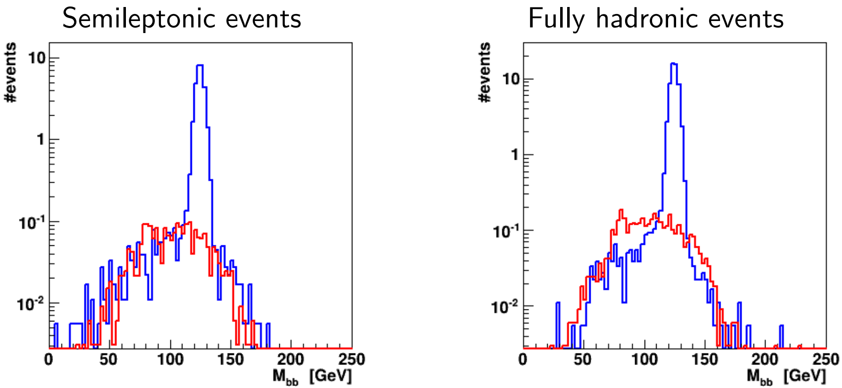


$e^+e^- \longrightarrow ch_1\bar{t},\ t\bar{c}h_1$ (2HDM)

Cut based approach: Higgs candidate events

$W^{\pm}$ veto used: events with $73.5 < M_{bq} < 87.3$ GeV rejected ($\pm 3\sigma$)

Invariant mass of two b-jets jets after $W^{\pm}$ veto: signal vs background



Look for events in the Higgs mass window...

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Alternative approach - compare two hypothesis:

- background hypothesis

$$\chi^2_{bg} = \left(\frac{M_{bl\nu} - m_t}{\sigma_{t,lep}}\right)^2 + \left(\frac{M_{l\nu} - m_W}{\sigma_{W,lep}}\right)^2 + \left(\frac{M_{bbq} - m_t}{\sigma_{t,had}}\right)^2 + \left(\frac{M_{bq} - m_W}{\sigma_{W,had}}\right)^2$$

- signal hypothesis

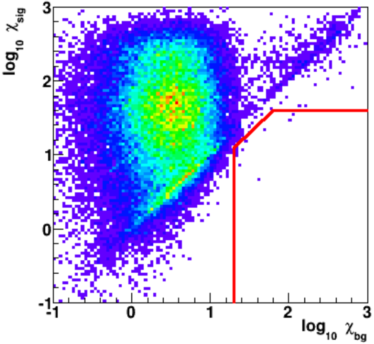
$$\chi^2_{sig} = \left(\frac{M_{bl\nu} - m_t}{\sigma_{t,lep}}\right)^2 + \left(\frac{M_{l\nu} - m_W}{\sigma_{W,lep}}\right)^2 + \left(\frac{M_{bbq} - m_t}{\sigma_{t,had}}\right)^2 + \left(\frac{M_{bb} - m_h}{\sigma_h}\right)^2$$

Independent search for best background and signal combinations

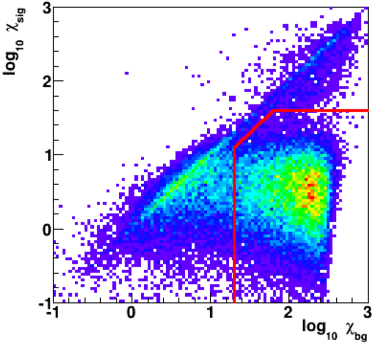
Hypothesis comparison

Correlation of $\log_{10}\chi^2$ for two hypothesis (possible cut indicated)

SM background



Signal events



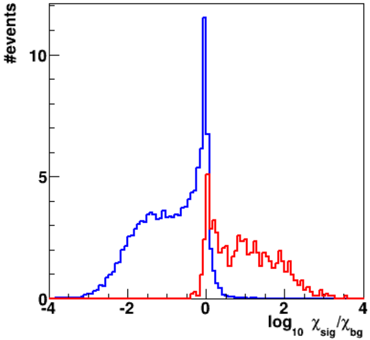
80% *b*-tagging efficiency (scenario B)

Signal selection

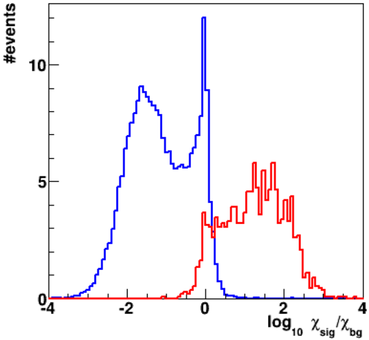
Hypothesis comparison

Difference of $\log_{10} \chi^2$ for two hypothesis: signal vs background

Semileptonic channel



Fully hadronic channel



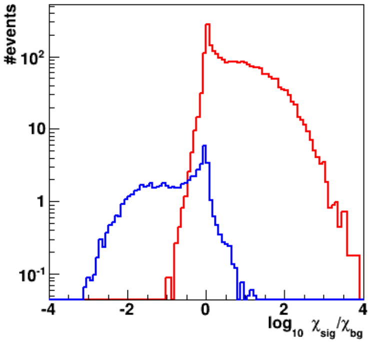
Ideal *b*-tagging

Very efficient background rejection possible

Hypothesis comparison

Difference of $\log_{10}\chi^2$ for two hypothesis: signal vs background

Semileptonic channel



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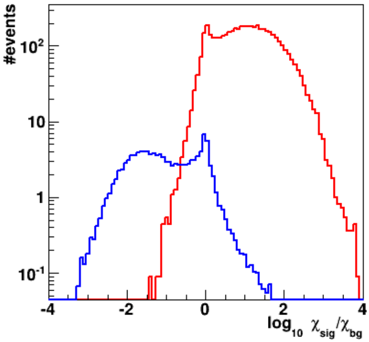


80% *b*-tagging efficiency (scenario B)

Very efficient background rejection possible

Expected events

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

Semileptonic	Ideal b-tagging		Scenario B	
	$t\bar{t}$ (SM)	Signal	$t\bar{t}$ (SM)	Signal
All	268'000	548	268'000	548
Single lepton + $\not{p}_t$	102'000	149	102'000	149
4 jets	75'700	122	75'700	122
3 b-tags	64.3	122	2'480	61.3
W veto	5.44	88.2	24.6	45.1
h mass window	0.88	81.5	3.5	39.3
χ^2 cut	0.72	65.0	0.80	31.2
h mass window	0.38	62.2	0.71	29.6

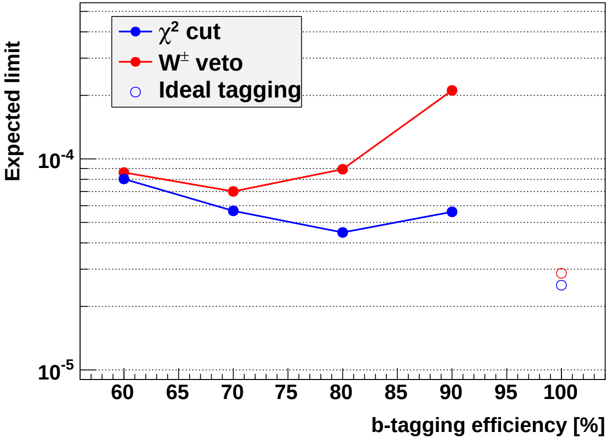
Expected events

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

Fully hadronic	Ideal b-tagging		Scenario B	
	$t\bar{t}$ (SM)	Signal	$t\bar{t}$ (SM)	Signal
All	268'000	548	268'000	548
No leptons, no $\not{p}_t$	112'000	343	112'000	343
6 jets	73'300	236	73'300	236
3 b-tags	130.1	236	4'680	118
W veto	9.7	160	31.3	79.0
h mass window	1.48	152	3.48	70.8
χ^2 cut	1.41	150	1.25	69.2
h mass window	0.68	143	0.89	65.4

Expected limits

Limits on $BR(t \to ch) \times BR(h \to b\bar{b})$ expected for 500 fb^{-1} @ 500 GeV from combined analysis (semileptonic+hadronic channels)

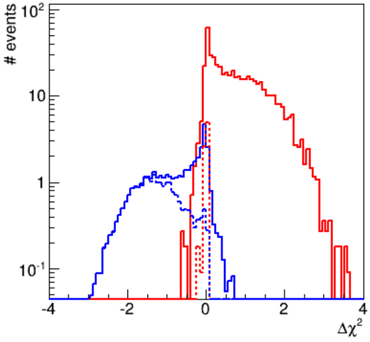


Jet energy resolution

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

Jet energy resolution 30%

Semi-leptonic events



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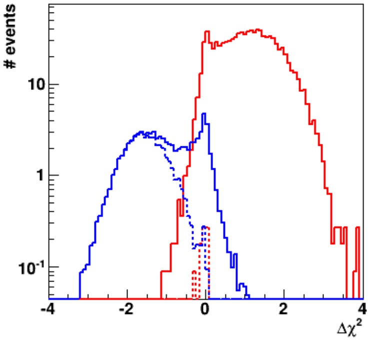
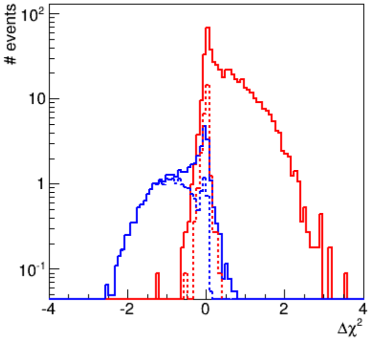


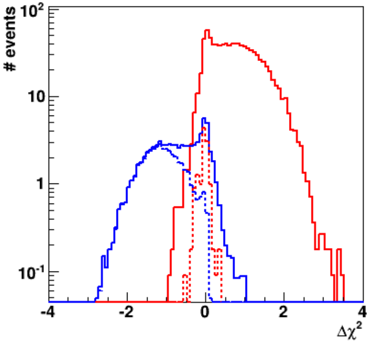
Difference of $\log_{10}\chi^2$ for two hypothesis, for signal and background events
Before (solid) and after (dashed) other selection cuts

Jet energy resolution 50%

Semi-leptonic events



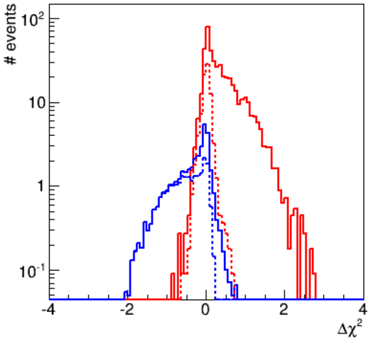
Fully hadronic events



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

Jet energy resolution 80%

Semi-leptonic events



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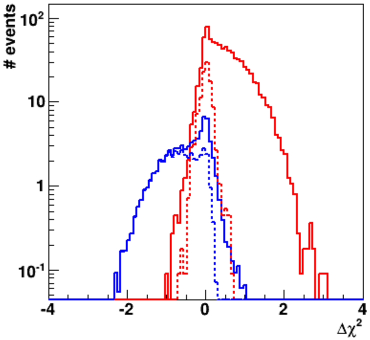
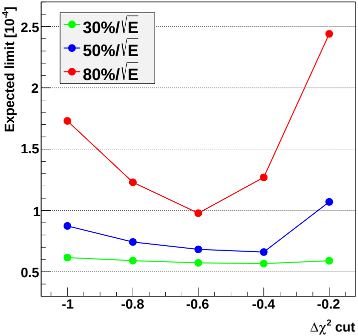


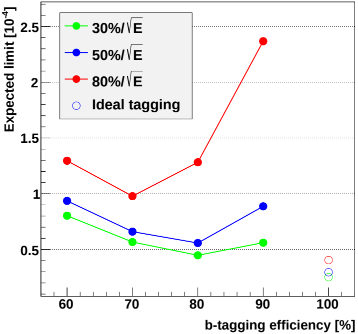
Signal - background separation still possible, but with decreasing efficiency

Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$
for 500 fb^{-1} @ 500 GeV and different jet energy resolutions assumed

For b-tagging efficiency of 70%



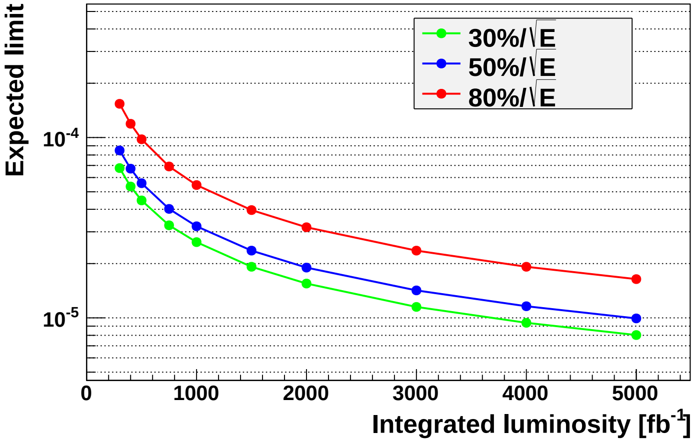
For optimized $\Delta\chi^2$ cut



Worsening jet energy resolution $\Rightarrow$ tighter cuts & b-tagging required

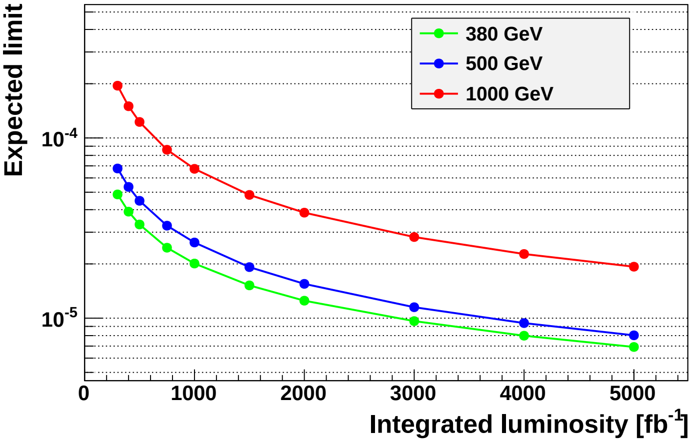
Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Collision energy 500 GeV



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

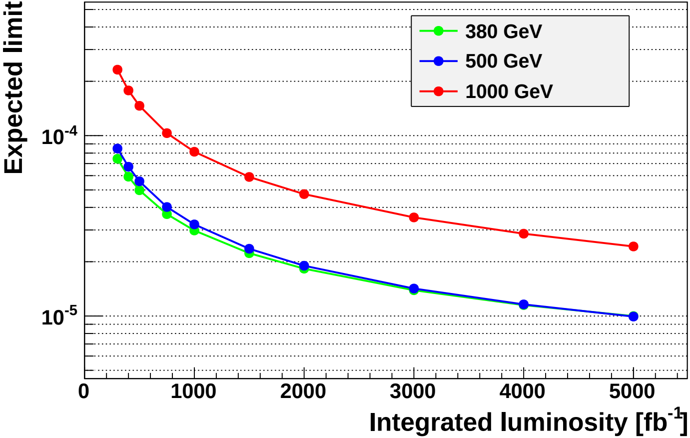
Jet energy resolution 30%



Collision energy and luminosity

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

Jet energy resolution 50%



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

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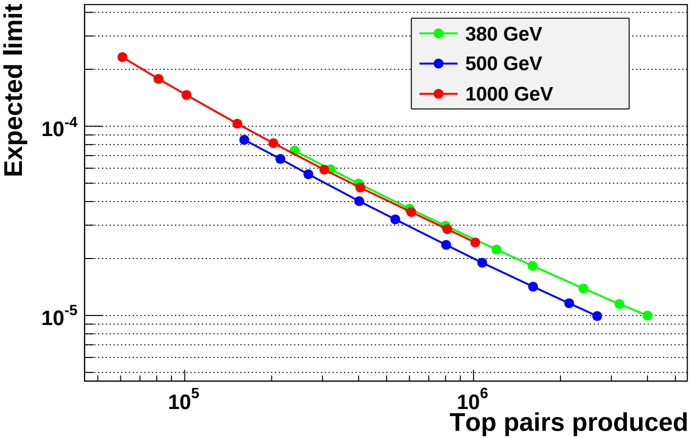

Disclaimer

Sensitivity to $BR(t \to ch)$ estimated with parton level simulation based on very simplified approach:

- only $t\bar{t}$ background considered
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- selection cuts not optizmized (except for $\Delta\chi^2$)

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$\Rightarrow$ Results are just estimates!

Conclusions

Measurement of FCNC top decays at ILC/CLIC studied at parton level.

Expected limits on $BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b})$ from 10^{-4} to 10^{-5}
depending on the energy, luminosity and detector parameters
Limits scale with integrated luminosity approximately as $\mathcal{L}^{-0.8}$

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Selection efficiency strongly depends on the jet energy resolution
At 500 GeV, $30\%/\sqrt{E}$ require 25% less luminosity than $50\%/\sqrt{E}$,
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Flavour tagging preformance crucial for the analysis
$\Rightarrow$ possible benchmark for optimization of detector design

Thank you!

Expected maximal branching rations for different models

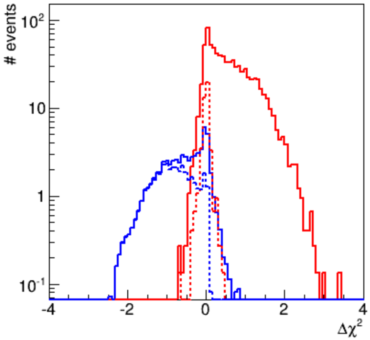
Significant differences between papers - overall limit ranges given

Model	BR($t \to c\ h$)	BR($t \to c\ \gamma$)	BR($t \to c\ g$)	BR($t \to c\ Z$)
SM	$3 \cdot 10^{-15}$	$5 \cdot 10^{-14}$	$5 \cdot 10^{-12}$	10^{-14}
2HDM	10^{-5} - 10^{-4}	10^{-9}	10^{-8}	10^{-10}
2HDM (FV)	10^{-3} - 10^{-2}	10^{-6} - 10^{-7}	10^{-4}	10^{-6}
MSSM	10^{-5} - 10^{-4}	10^{-8} - 10^{-6}	10^{-7} - 10^{-4}	10^{-8} - 10^{-6}
$\not R$ SUSY	10^{-9} - 10^{-6}	10^{-9} - 10^{-5}	10^{-5} - 10^{-3}	10^{-6} - 10^{-4}
Little Higgs	10^{-5}	$1.3 \cdot 10^{-7}$	$1.4 \cdot 10^{-2}$	$2.6 \cdot 10^{-5}$
Quark Singlet	$4.1 \cdot 10^{-5}$	$7.5 \cdot 10^{-9}$	$1.5 \cdot 10^{-7}$	$1.1 \cdot 10^{-4}$
Randal-Sundrum	10^{-4}	10^{-9}	10^{-10}	10^{-3}

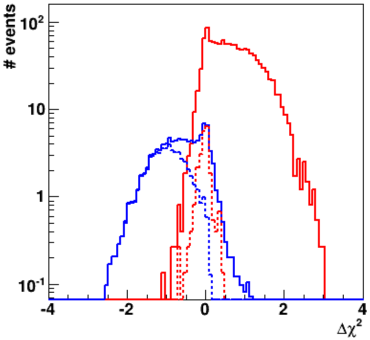
Difference of $\log_{10}\chi^2$ (signal - background) 50% resolution, 70% b-tagging
Before (solid) and after (dashed) additional selection cuts

Collision energy 380 GeV

Semi-leptonic events



Fully hadronic events

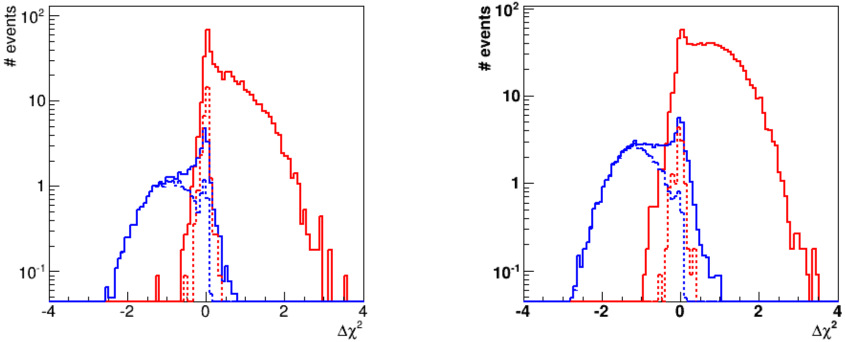


Difference of $\log_{10} \chi^2$ (signal - background) 50% resolution, 70% b-tagging
Before (solid) and after (dashed) additional selection cuts

Collision energy 500 GeV

Semi-leptonic events

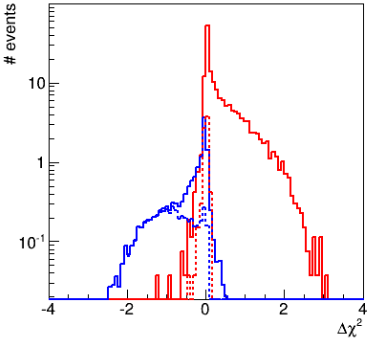
Fully hadronic events



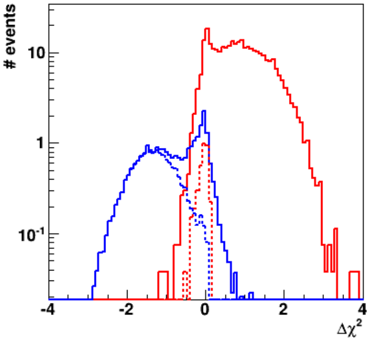
Difference of $\log_{10} \chi^2$ (signal - background) 50% resolution, 70% b-tagging
Before (solid) and after (dashed) additional selection cuts

Collision energy 1000 GeV

Semi-leptonic events



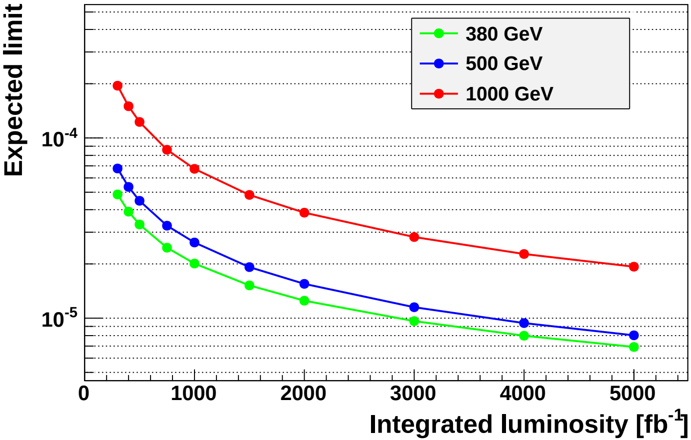
Fully hadronic events



Signal - background separation improves slightly for hadronic events.
Visible loss of efficiency in semi-leptonic channel.

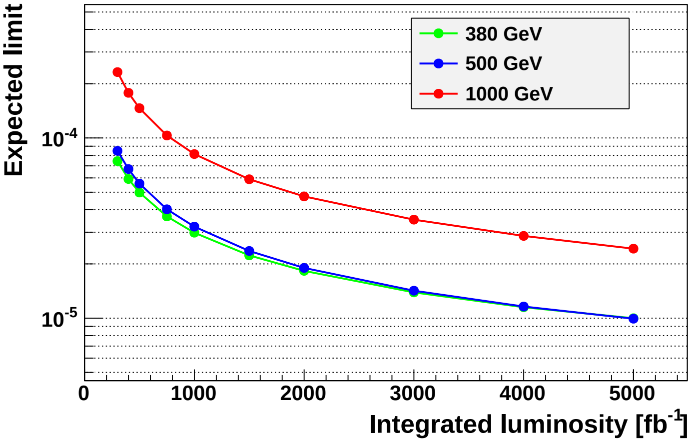
Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Jet energy resolution 30%



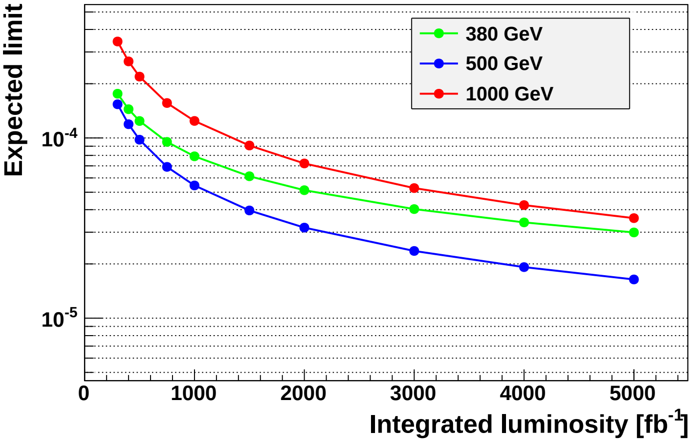
Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Jet energy resolution 50%



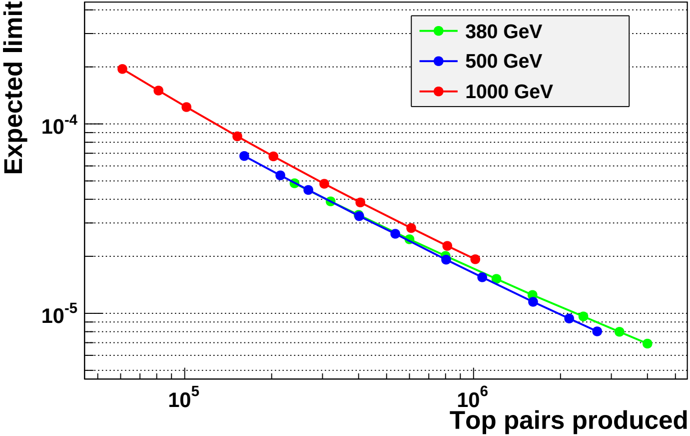
Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Jet energy resolution 80%



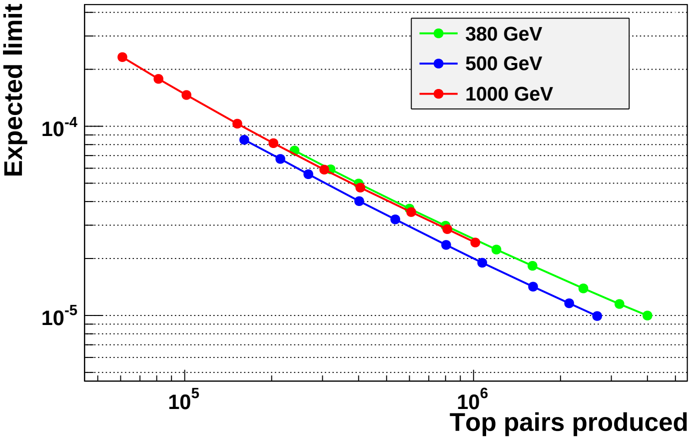
Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Jet energy resolution 30%



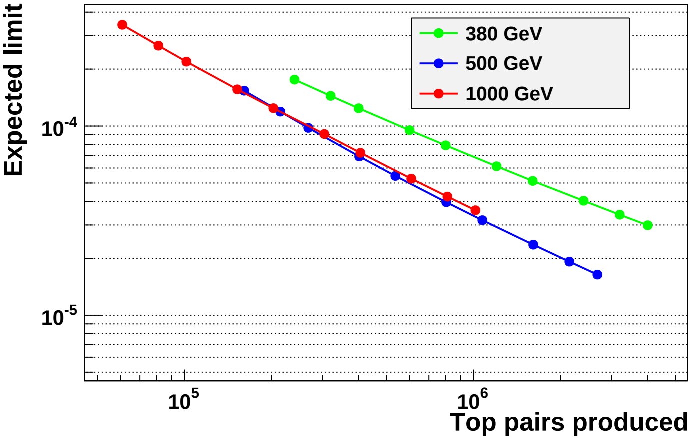
Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Jet energy resolution 50%



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

Jet energy resolution 80%



Expected limit

Expected 95% C.L. limit on the number of signal events calculated as an average limit from multiple "background only" experiments, with number of observed events generated from Poisson distribution.