

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

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

$$BR(t \rightarrow c \gamma) \sim 5 \cdot 10^{-14}$$

$$BR(t \rightarrow c Z) \sim 1 \cdot 10^{-14}$$

$$BR(t \rightarrow c g) \sim 5 \cdot 10^{-12}$$

$$BR(t \rightarrow c h) \sim 3 \cdot 10^{-15}$$

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

## Model

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

Test configuration of the model:

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

Generated samples:

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



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

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

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

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

- $b$  tagging (mis-tagging) 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),  $500 \text{ fb}^{-1}$  (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  $5000 \text{ fb}^{-1}$

## H-20 scenario for ILC

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

## $t\bar{t}$ final state selection

“Signal” top:  $t \rightarrow ch_1 + \text{higgs decay to } b\bar{b} \Rightarrow 2 \text{ } b \text{ tags}$

“Spectator” top: SM top decay  $\Rightarrow 1 \text{ } b \text{ tag}$

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  $\sqrt{s} = 500 \text{ GeV}$ , 30%/ $\sqrt{E}$  jet energy resolution

Semileptonic:

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

Fully hadronic:

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

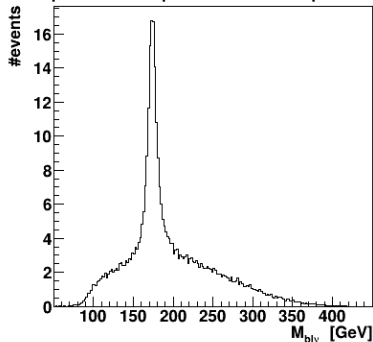
## Top reconstruction

Try to group final state objects into two tops

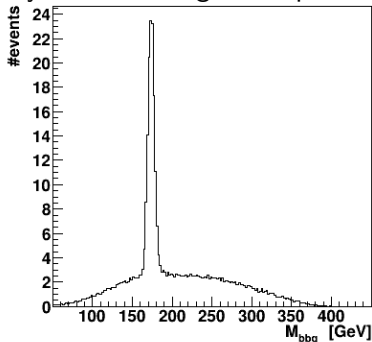
Check invariant mass distributions for all considered combinations

Semileptonic events (signal sample):

Semileptonic “spectator” top decay



Fully hadronic “signal” top decay



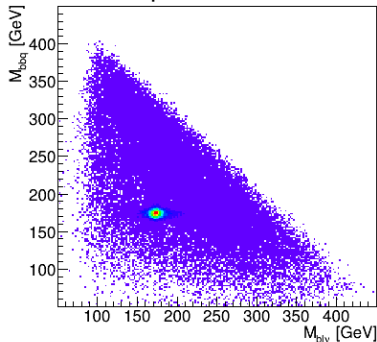
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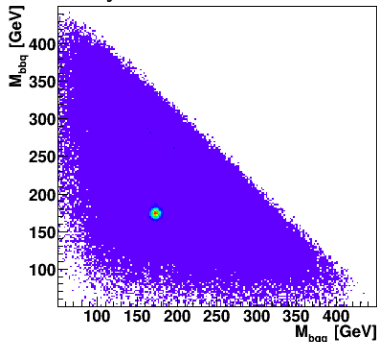
Check invariant mass distributions for all considered combinations

Proper combination can be easily identified

Semileptonic events



Fully hadronic events

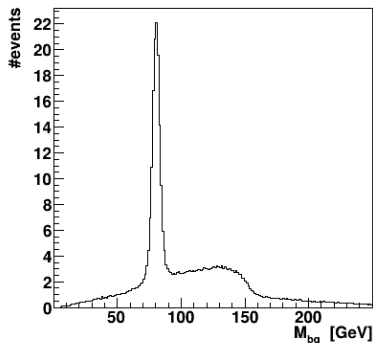




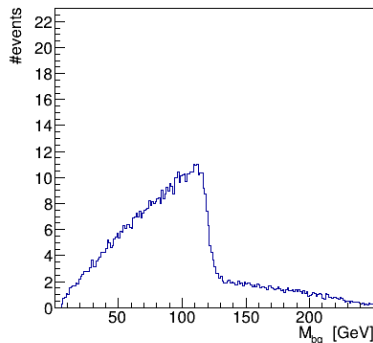
## Cut based approach: $W^\pm$ veto

Irreducible SM background can be suppressed by reconstructing second  $W$

Invariant mass of two jets from “signal” top - all combinations



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

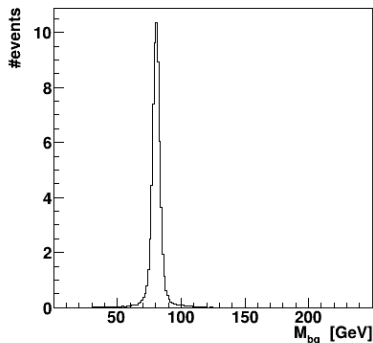


$$e^+e^- \longrightarrow ch_1\bar{t}, t\bar{c}h_1 \text{ (2HDM)}$$

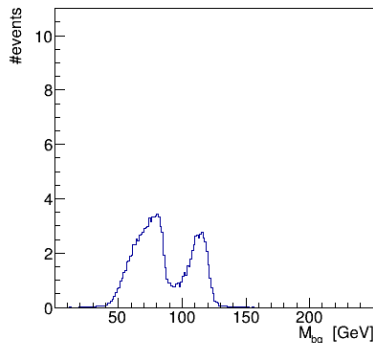
## Cut based approach: $W^\pm$ veto

Irreducible SM background can be suppressed by reconstructing second  $W$

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



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

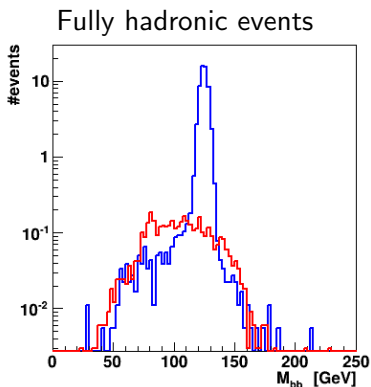
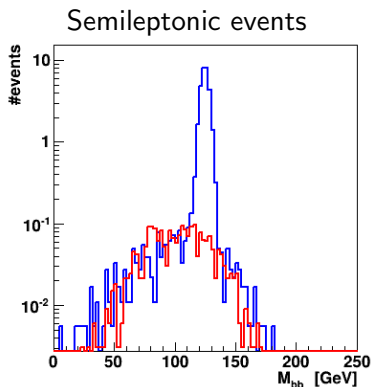


$$e^+e^- \longrightarrow ch_1\bar{t}, t\bar{c}h_1 \text{ (2HDM)}$$

## 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 after  $W^\pm$  veto: **signal** vs **background**



Look for events in the Higgs mass window...

Alternative approach - compare two hypothesis:

- background hypothesis

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

- signal hypothesis

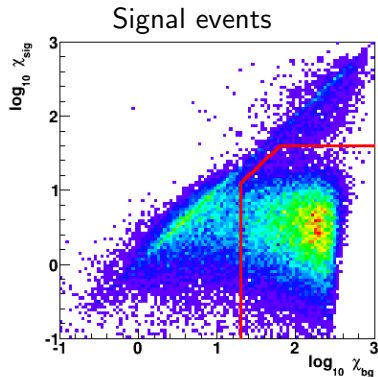
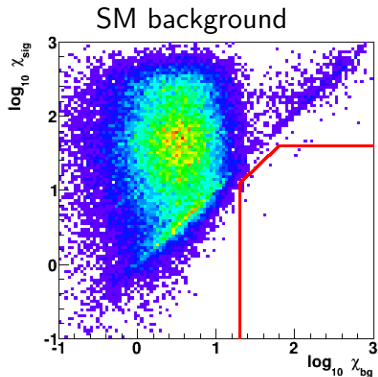
$$\chi_{sig}^2 = \left( \frac{M_{bl\nu} - m_t}{\sigma_{t,lep}} \right)^2 + \left( \frac{M_{l\nu} - m_W}{\sigma_{W,lep}} \right)^2 + \left( \frac{M_{bbq} - m_t}{\sigma_{t,had}} \right)^2 + \left( \frac{M_{bb} - m_h}{\sigma_h} \right)^2$$

Independent search for best background and signal combinations

## Hypothesis comparison

Correlation of  $\log_{10} \chi^2$  for two hypothesis

(possible cut indicated)

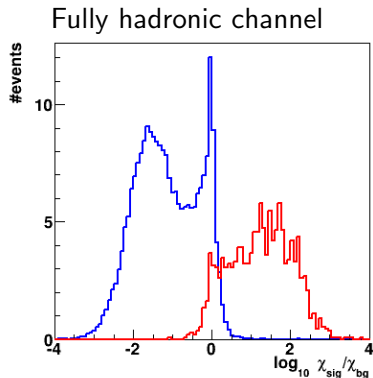
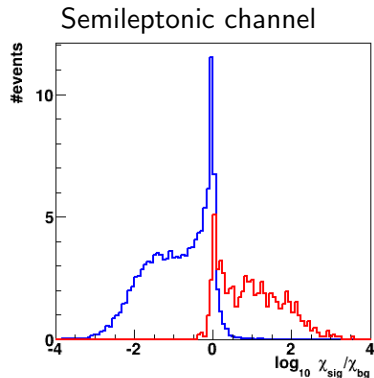


80% *b*-tagging efficiency (scenario B)

# Signal selection

## Hypothesis comparison

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



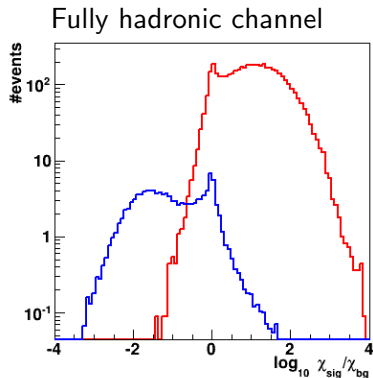
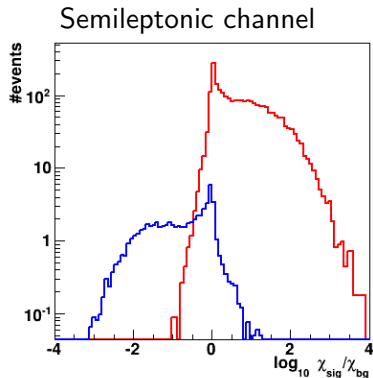
Ideal *b*-tagging

Very efficient background rejection possible

# Signal selection

## Hypothesis comparison

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



80% *b*-tagging efficiency (scenario B)  
 Very efficient background rejection possible

## Expected events

For 500  $fb^{-1}$ , assuming  $BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b}) \approx 10^{-3}$  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 + $\cancel{p}_t$	102'000	149	102'000	149
4 jets	75'700	122	75'700	122
<b>3 b-tags</b>	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
$\chi^2$ cut	0.72	65.0	0.80	31.2
h mass window	0.38	62.2	0.71	29.6



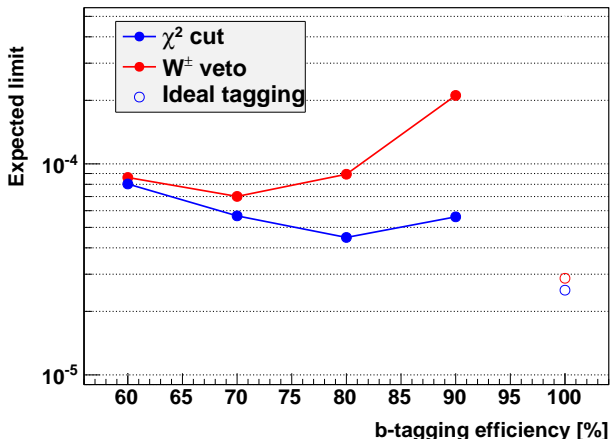
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For 500  $fb^{-1}$ , assuming  $BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b}) \approx 10^{-3}$  for signal

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 $\cancel{p}_t$	112'000	343	112'000	343
6 jets	73'300	236	73'300	236
<b>3 b-tags</b>	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
$\chi^2$ cut	1.41	150	1.25	69.2
h mass window	0.68	143	0.89	65.4

## Expected limits

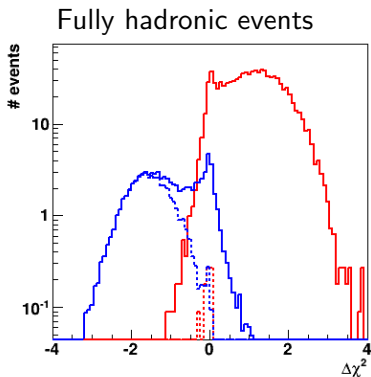
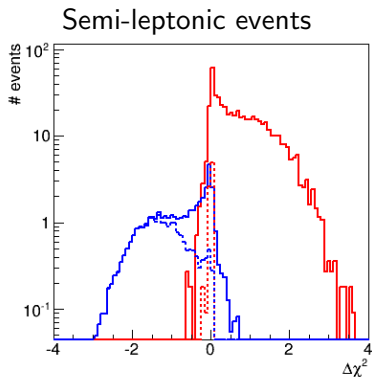
Limits on  $BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b})$  expected for  $500 \text{ fb}^{-1}$  @ 500 GeV  
from combined analysis (semileptonic+hadronic channels)



# 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%

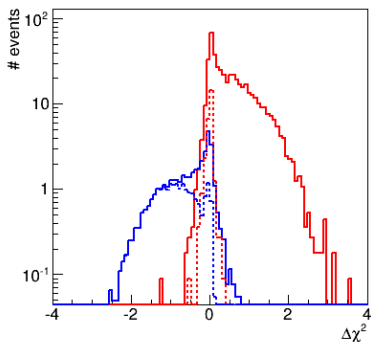


# Jet energy resolution

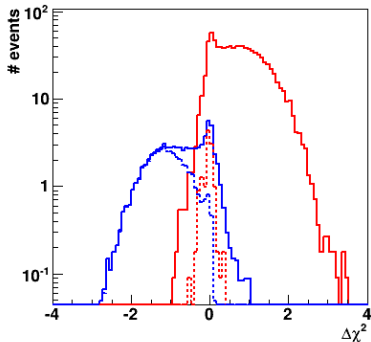
Difference of  $\log_{10} \chi^2$  for two hypothesis, for **signal** and **background** events  
 Before (solid) and after (dashed) other selection cuts

Jet energy resolution 50%

Semi-leptonic events



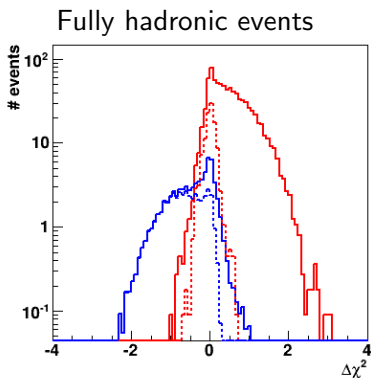
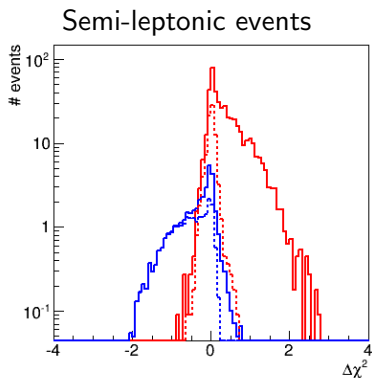
Fully hadronic events



# 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 80%

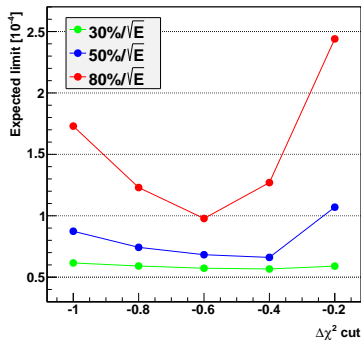


Signal - background separation still possible, but with decreasing efficiency

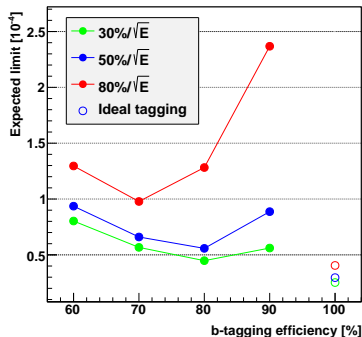
# Jet energy resolution

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

For b-tagging efficiency of 70%



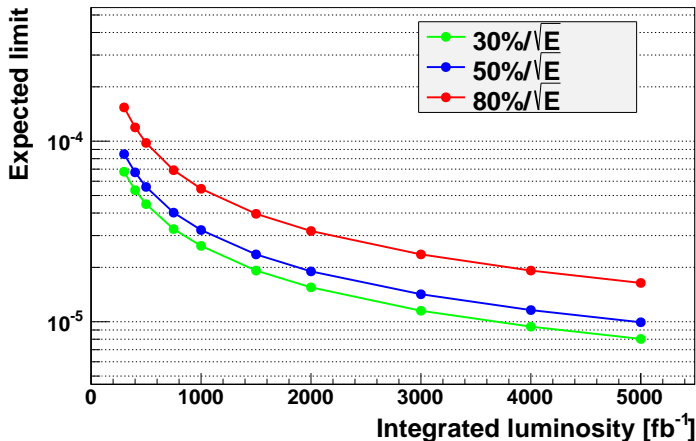
For optimized  $\Delta\chi^2$  cut



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

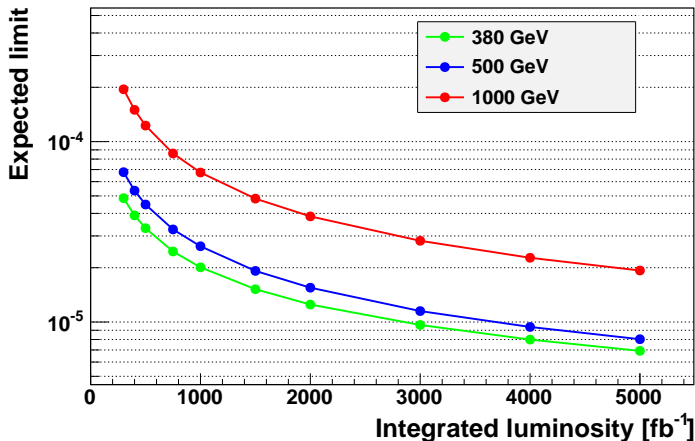
**Expected limits** on  $BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b})$

Collision energy 500 GeV



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

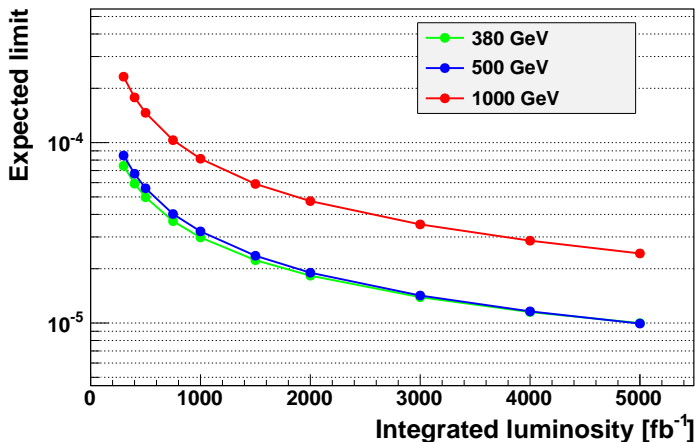
Jet energy resolution 30%





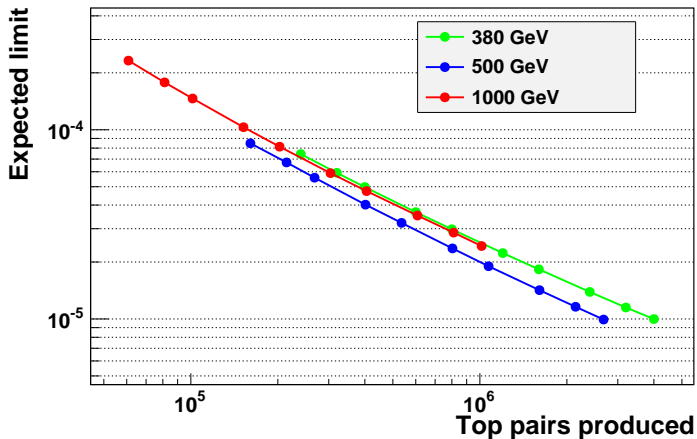
**Expected limits** on  $BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b})$

Jet energy resolution 50%



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Jet energy resolution 50%



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

- only  $t\bar{t}$  background considered
- no effects of hadronization/decays ( $\tau$ ,  $B\dots$ )
- very rough description of detector effects

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- angular distributions not taken into account
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⇒ Results are just estimates!

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 performance crucial for the analysis

⇒ possible benchmark for optimization of detector design

Thank you!

Expected maximal branching ratios for different models

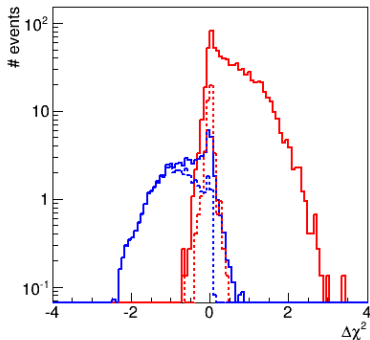
Significant differences between papers - overall limit ranges given

Model	$BR(t \rightarrow c h)$	$BR(t \rightarrow c \gamma)$	$BR(t \rightarrow c g)$	$BR(t \rightarrow c Z)$
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	$10^{-5} - 10^{-4}$	$10^{-8} - 10^{-6}$	$10^{-7} - 10^{-4}$	$10^{-8} - 10^{-6}$
$\mathcal{R}$ 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	$10^{-4}$	$10^{-9}$	$10^{-10}$	$10^{-3}$

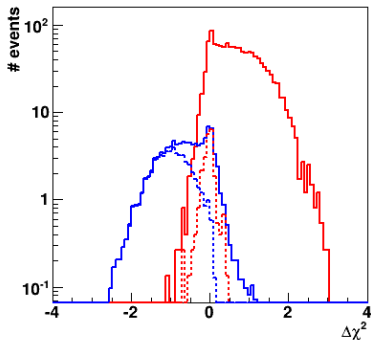
Difference of  $\log_{10} \chi^2$  (signal - background) 50% resolution, 70% b-tagging  
Before (solid) and after (dashed) additional selection cuts

Collision energy 380 GeV

Semi-leptonic events



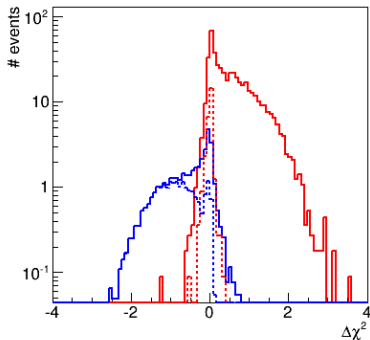
Fully hadronic events



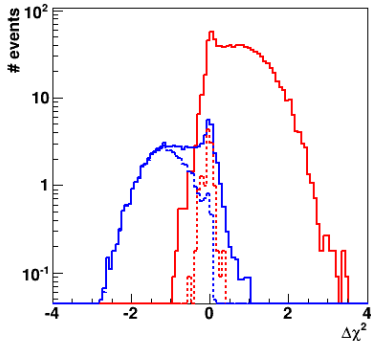
Difference of  $\log_{10} \chi^2$  (signal - background) 50% resolution, 70% b-tagging  
Before (solid) and after (dashed) additional selection cuts

Collision energy 500 GeV

Semi-leptonic events

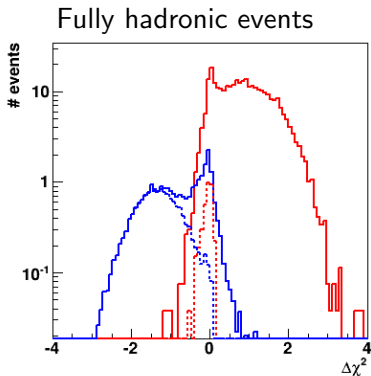
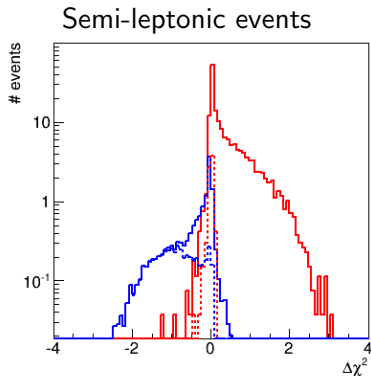


Fully hadronic events



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

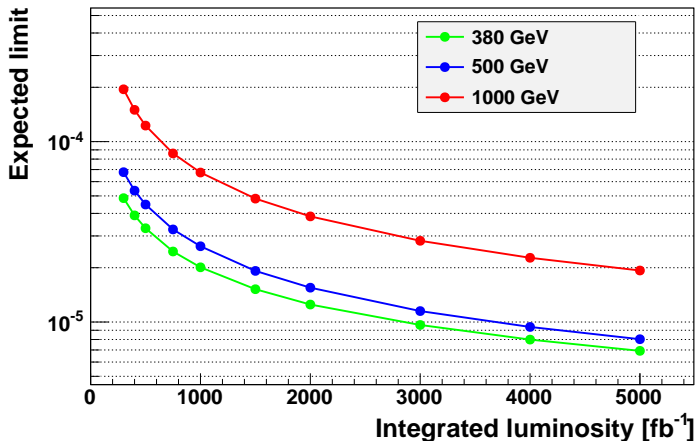
Collision energy 1000 GeV



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

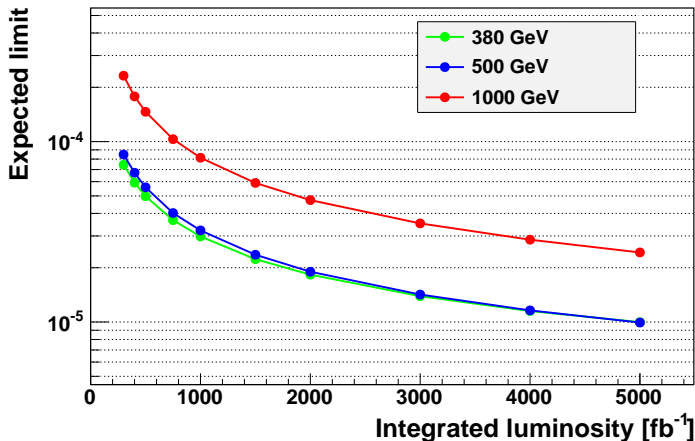
**Expected limits** on  $BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b})$ 

Jet energy resolution 30%



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

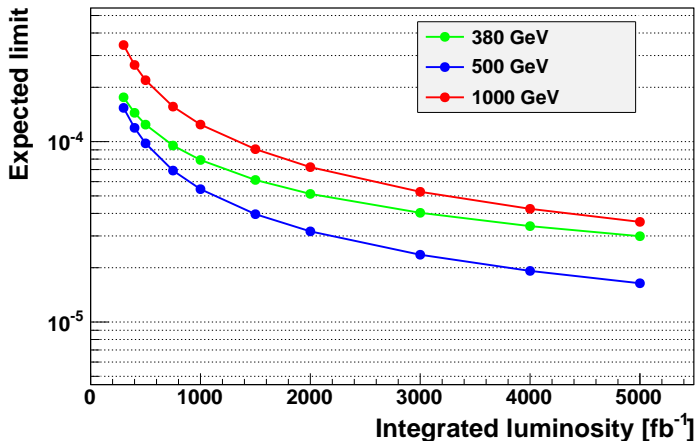
Jet energy resolution 50%





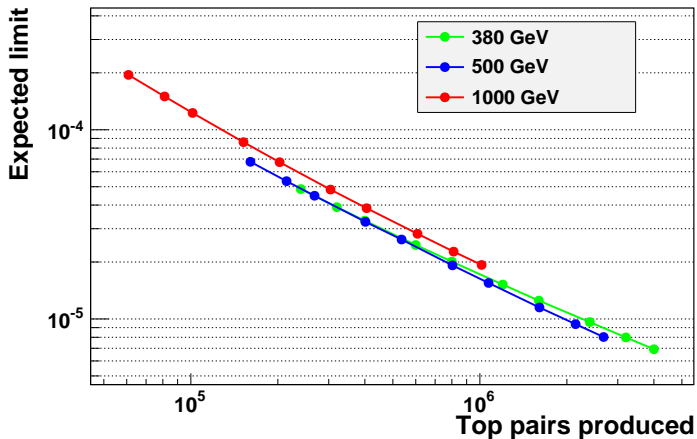
## Expected limits on $BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b})$

Jet energy resolution 80%



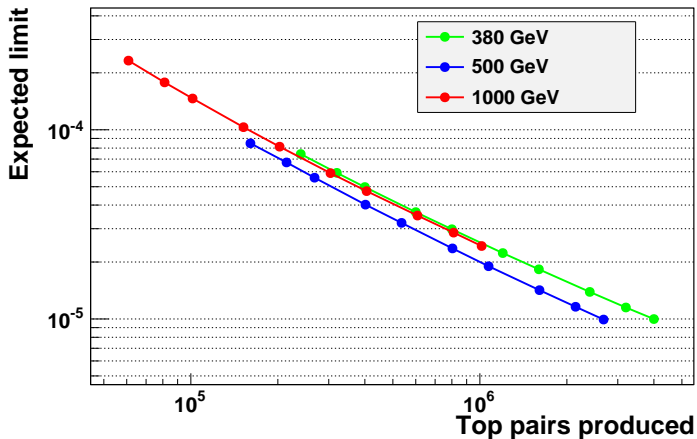
**Expected limits** on  $BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b})$ 

Jet energy resolution 30%



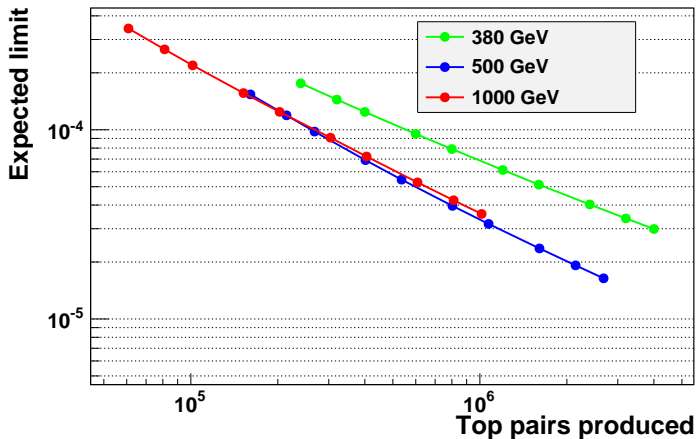
**Expected limits** on  $BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b})$ 

Jet energy resolution 50%



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

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.

