Top FCNC decays: review of theoretical expectations

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Standard Model

On the tree level only charged current top decays are allowed in the Standard Model

$$t \rightarrow W^+ b \quad \text{dominant, BR} = 91\%$$
$$t \rightarrow W^+ s/d \quad \text{CKM suppressed}$$

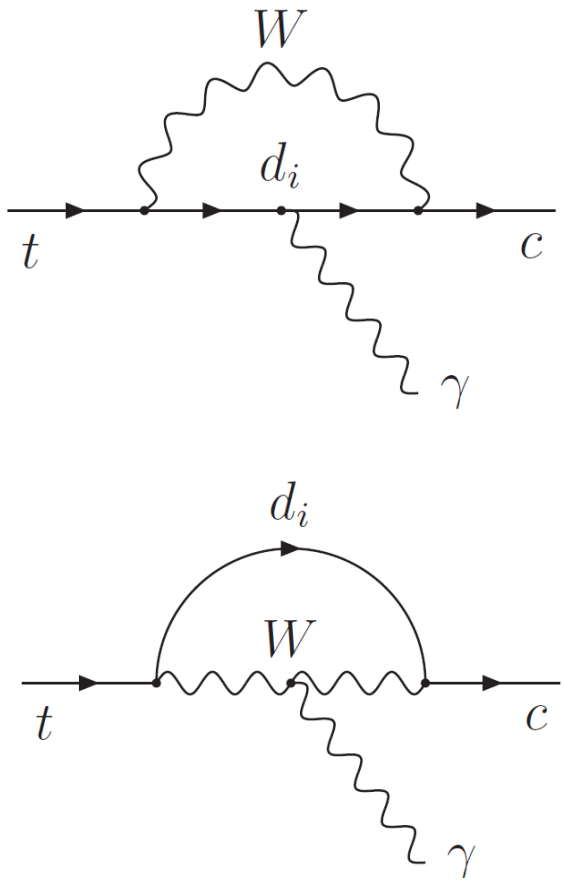
FCNC top decays are only possible on loop level.
Four two-particle final states can be considered:

$$t \rightarrow q\gamma \,,\; qZ \,,\; qg \,,\; qH \qquad q = u, c$$

Current experimental limits are (RPP2014):

$$BR(t \rightarrow \gamma\, q) < 5.9 \cdot 10^{-3} \quad 95\%\ \text{CL}$$
$$BR(t \rightarrow Z\, q) < 2.1 \cdot 10^{-3}$$

Leading order diagrams for FCNC decay $t \to c\,\gamma$



When neglecting down quark masses, the decay amplitude is suppressed (GIM):

$$\mathcal{M} \;\sim\; \sum_{d_i} V^{\star}_{td_i} V_{cd_i} \;=\; 0$$

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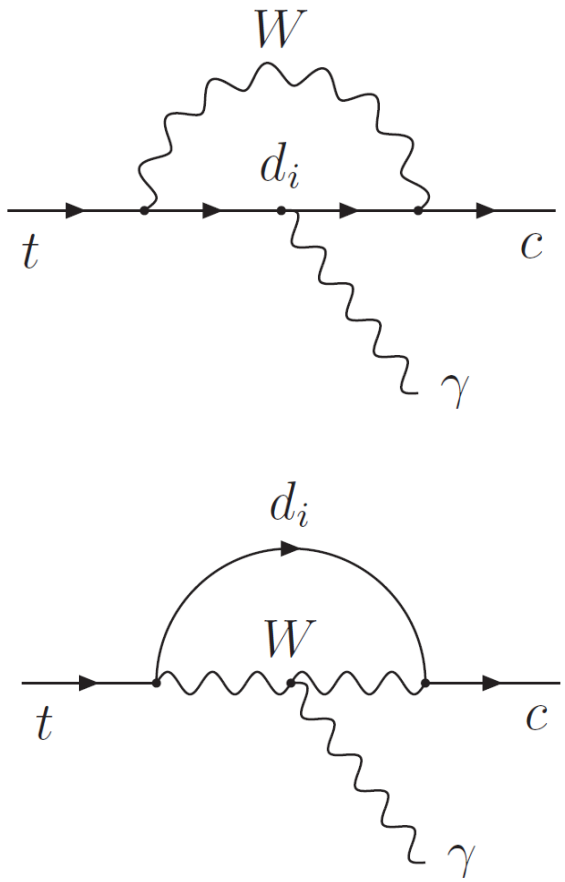

However, taking into account quark masses, GIM cancelation is not perfect

$$\mathcal{M} \sim \sum_{d_i} V^{\star}_{td_i} V_{cd_i}\, \mathcal{F}(x_{d_i})$$

$$x_{di} = \frac{m^2_{d_i}}{M^2_W}$$

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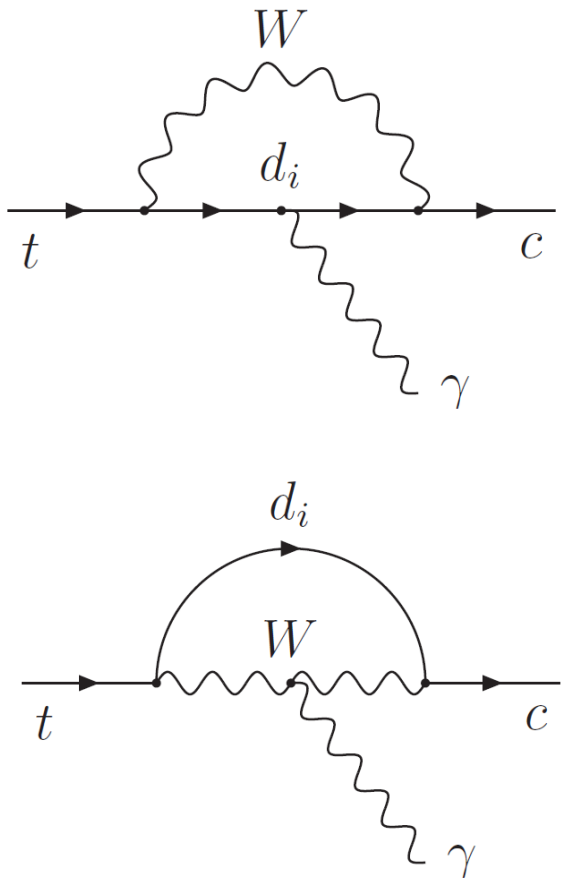

Assuming $m_d = m_s \ll m_b$ the leading contribution is:

$$\mathcal{M} \sim V_{tb}^{\star} V_{cb} \left[\mathcal{F}(x_b) - \mathcal{F}(0)\right]$$

Resulting decay width:

$$\Gamma(t \to c\,\gamma) \sim |V_{bc}|^2\, \alpha_{em}^3\, m_t \left(\frac{m_b}{M_W}\right)^4$$

Double suppression due to

- CKM: $|V_{bc}| \sim 0.04$
- GIM: $\frac{m_b}{M_W} \sim 0.04$

Standard Model

Standard Model expectations for the FCNC top decays (Snowmass 2013):

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

Same suppression mechanism in all channels (CKM+GIM).

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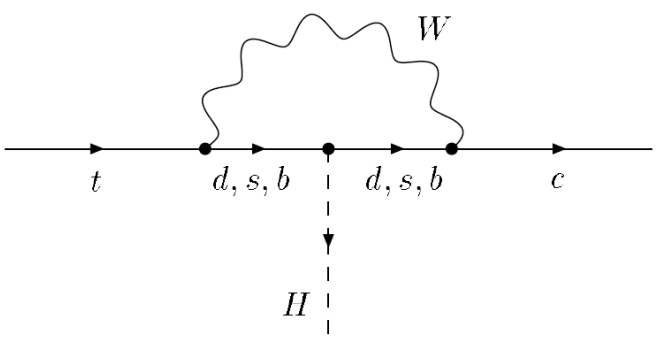


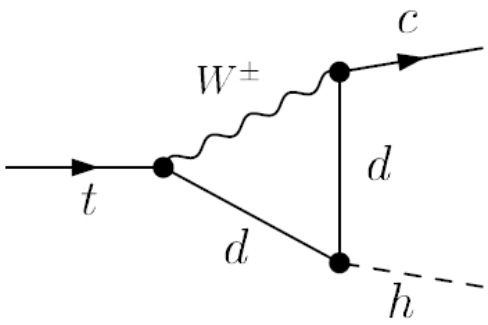
Only for $t \to c\,H$ channel, GIM mechanism is not applicable (in one of the diagrams) due to Higgs coupling proportional to mass.

But the contribution of this diagram is still suppressed by $\frac{m_b}{M_W}$ (Higgs coupling)

Two Higgs Doublet Model

Probably the simplest possible extension of the SM.

Decay channel $t \to c\ h$ is affected by modified Higgs couplings:



hdd :

$$g = g_{SM} \times (\sin(\beta-\alpha) - \tan\beta \cdot \cos(\beta-\alpha))$$

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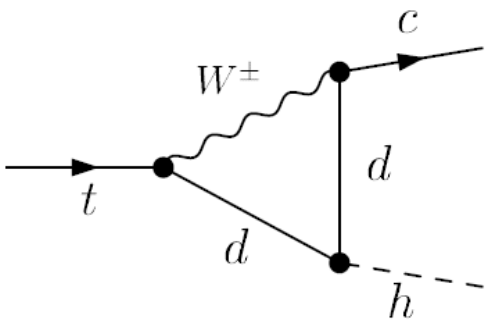

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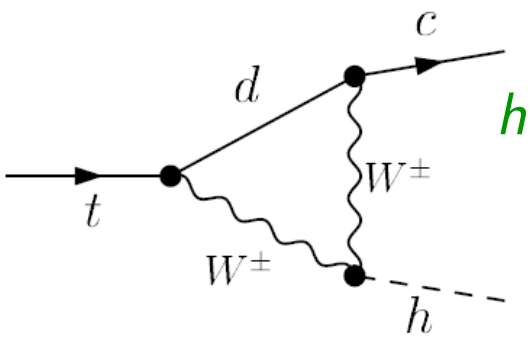


hWW :

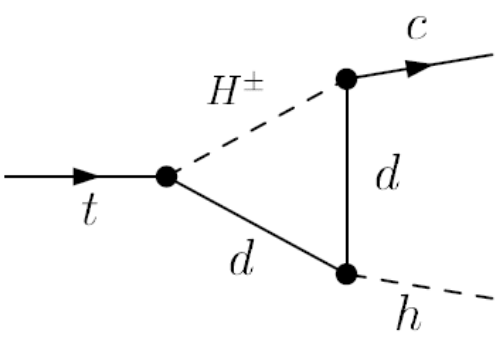
$$g = g_{SM} \times \sin(\beta-\alpha)$$

no enhancement possible

Two Higgs Doublet Model

New contributions to $t \to c\, h$ (as well as to $t \to c\gamma,\ cZ,\ cg$) from diagrams with $H^\pm$ in the loop (instead of $W^\pm$).

In case of 2HDM(II) (as an example):



$H^+ b\bar{t}$:

$$\frac{ig}{2\sqrt{2}M_W}\, V_{tb}\, [m_b(1+\gamma_5)\tan\beta + m_t(1-\gamma_5)\cot\beta]$$

$\tan\beta$ in all 3 vertexes !

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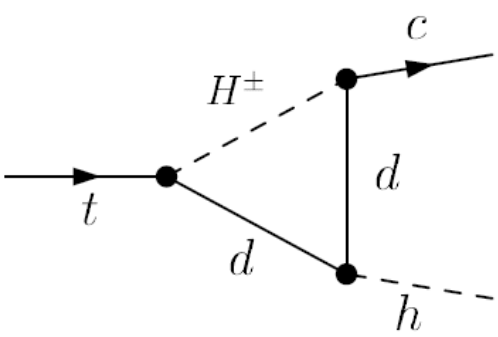

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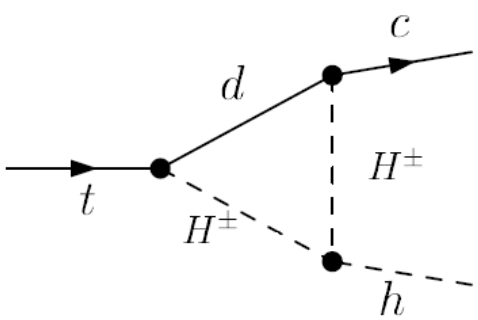


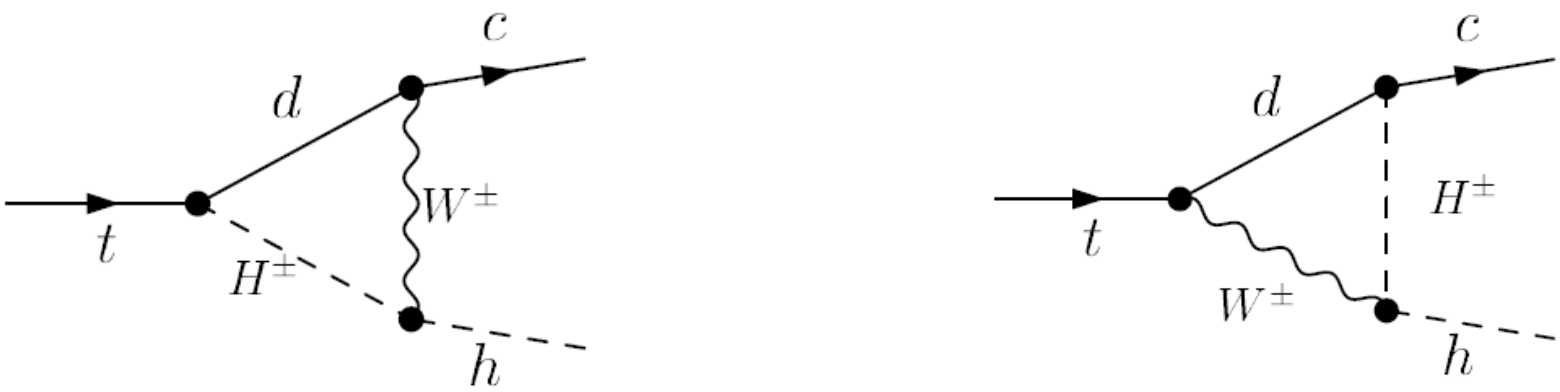
$H^\pm H^\pm h$:

$$\frac{-ig}{M_W}\left[\frac{M_h^2}{\sin 2\beta}\left(\cos^3\beta\cos\alpha - \sin^3\beta\sin\alpha\right) - M_{H^+}^2\sin(\alpha-\beta)\right]$$

enhancement possible for both large and small $\tan\beta$

Two Higgs Doublet Model

One also has to consider diagrams with both $H^{\pm}$ and $W^{\pm}$:



In the "standard" 2HDM scenarios, loop contributions can be enhanced significantly. However, FCNC remain suppressed at the tree level due to assumed flavour diagonal Higgs couplings.

However, one can also consider "non standard" scenarios, as 2HDM(III) or "Top 2HDM", where one of Higgs doublets couple to top quark only, where tree level FCNC couplings are possible!...

Expectations

Expected maximal branching rations for different scenarios

Significant differences between different 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}
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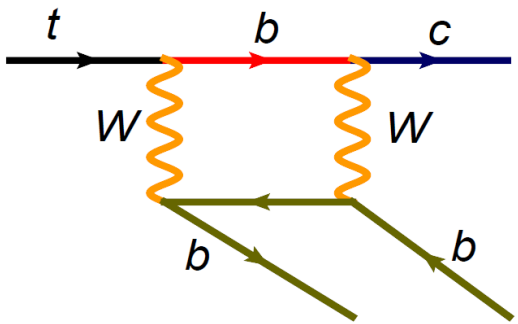
Little Higgs	10^{-5}	$1.3 \cdot 10^{-7}$	$1.4 \cdot 10^{-2}$	$2.6 \cdot 10^{-5}$
Quark Singlet	$4.1 \cdot 10^{-5}$	$7.5 \cdot 10^{-9}$	$1.5 \cdot 10^{-7}$	$1.1 \cdot 10^{-4}$
Randal-Sundrum	10^{-4}	10^{-9}	10^{-10}	10^{-3}

Remark

For both $t \to c\ h$ and $t \to c\ Z$ channels, non-resonant (box) diagrams have to be considered for each final state, in addition to the resonant channels.



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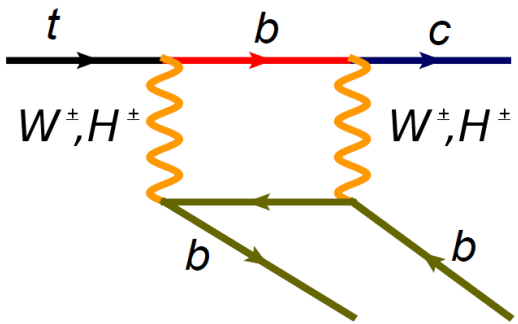

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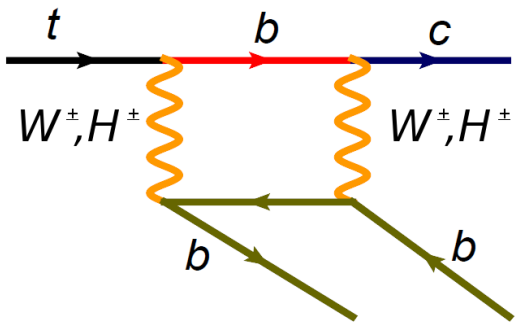

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For hadronic channels, one also has to consider dominant $t \to bW^+$ decay.

For the $cb\bar{b}$ final state all contributions should be considered together:

$$
\begin{aligned}
t &\to c\ h \to c\ b\bar{b} \\
t &\to c\ Z \to c\ b\bar{b} \\
t &\to b\ W^+ \to b\ c\bar{b} \\
t &\to c\ b\bar{b} \quad \text{(non-resonant)}
\end{aligned}
$$

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Depending on the model, all Higgs FCNC decay channels can be enhanced to the level which should be measurable at high luminosity colliders.

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Decay $t \to c\ h$ in 2HDM is an interesting scenario, allowing for very large enhancement of signal with minimal extension of the model and no new final states - well suited for the case study.

Model

WHIZARD includes 2HDM model with possible FCNC tree level couplings.
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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 at $\sqrt{s}$=500 GeV

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

2HDM events generated with CIRCE1 spectra, but no ISR (!)
All results on parton level only! No hadronization or detector efects.

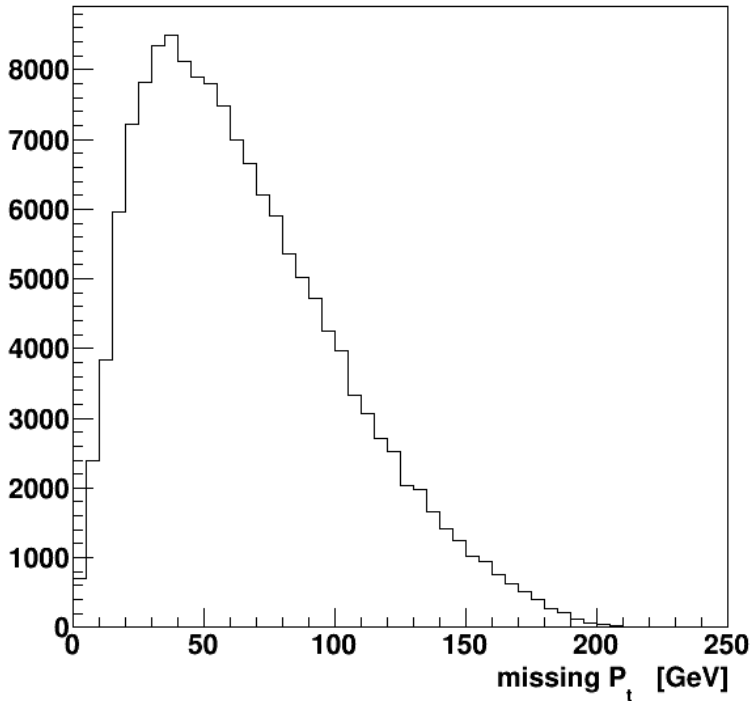
All results VERY PRELIMINARY

Final state selection

Considered final state: 4 jets + lepton + missing p_t

$t \to ch_1$ + higgs decay to $b\bar{b}$ + leptonic $W^{\pm}$ decay for second top

- Missing $p_t > 15$ GeV



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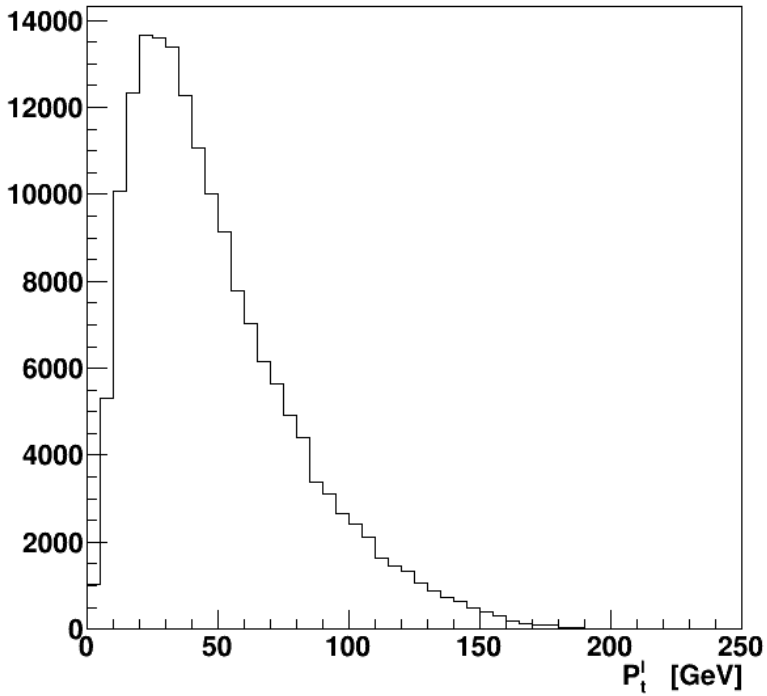
- Lepton with $p_t > 15$ GeV
  $|\cos\theta_l| < 0.995$



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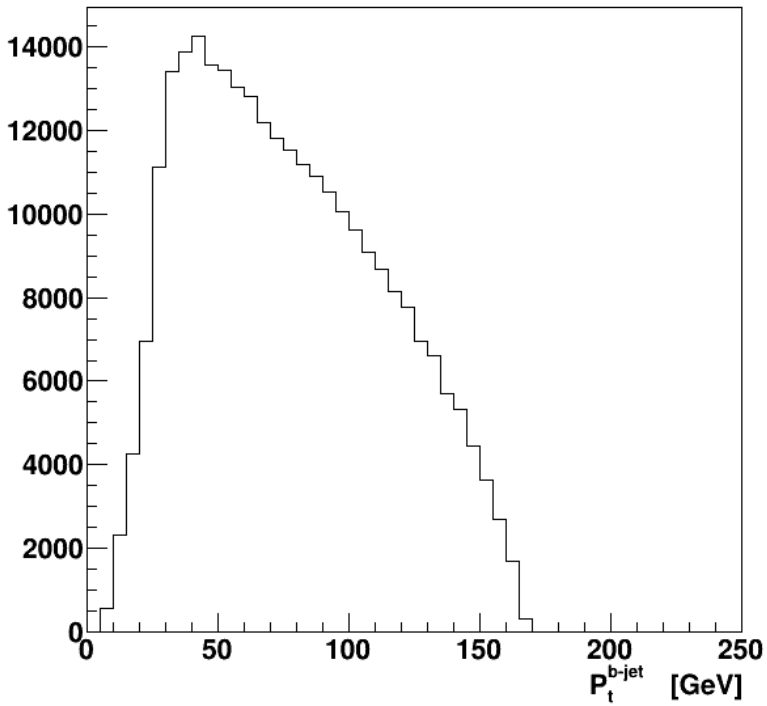

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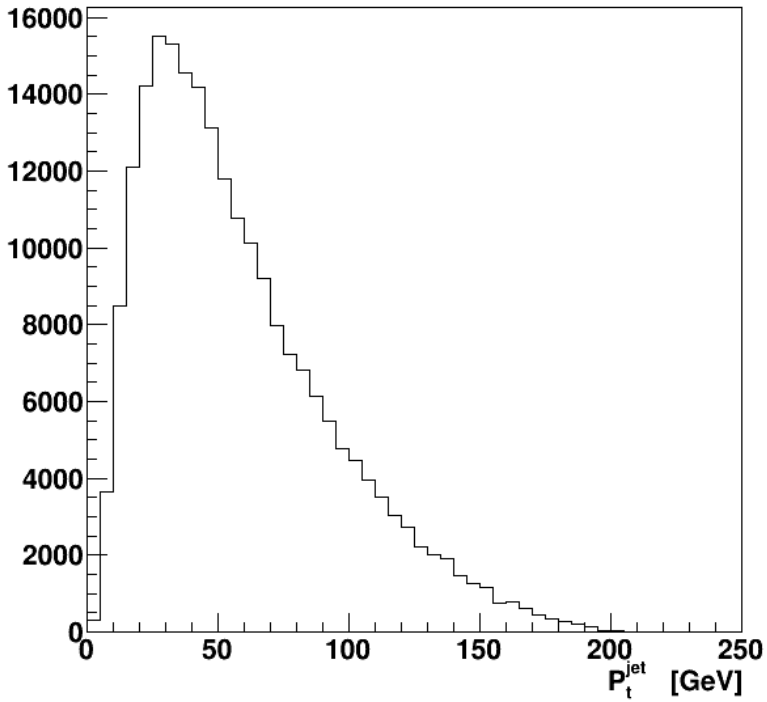

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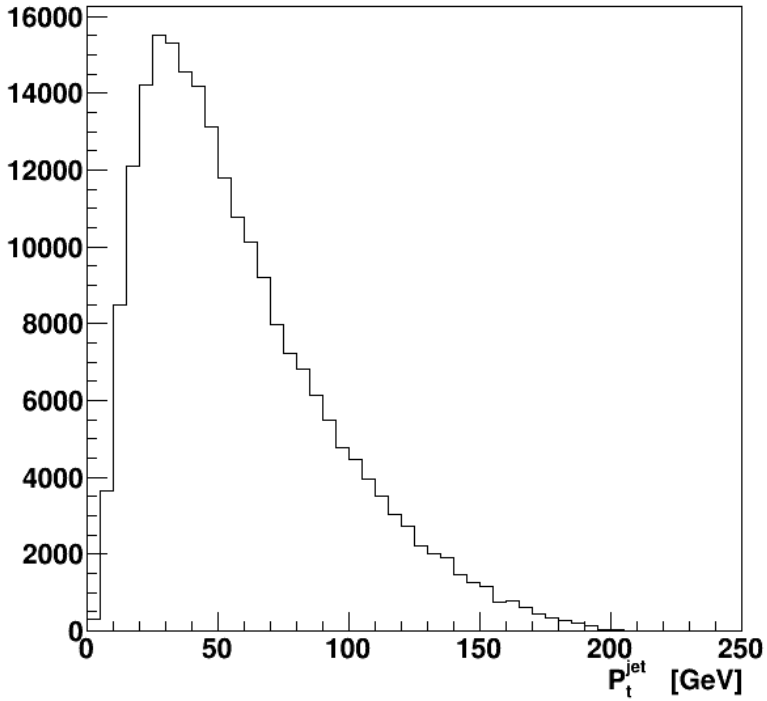
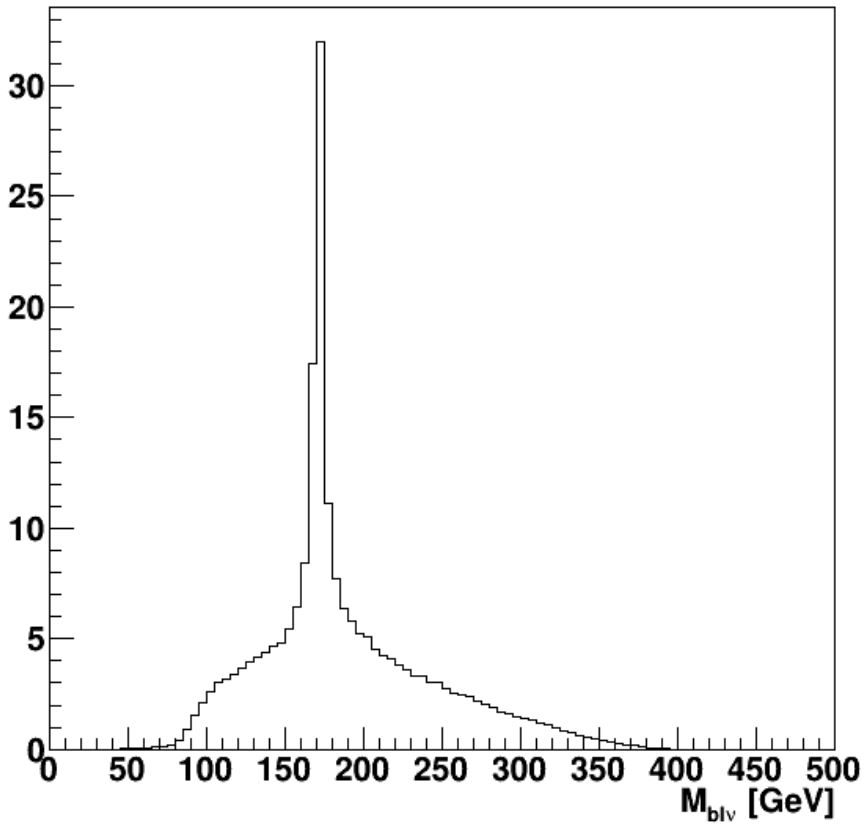


Cut efficiency for considered final state ~75% (without detector effects!)

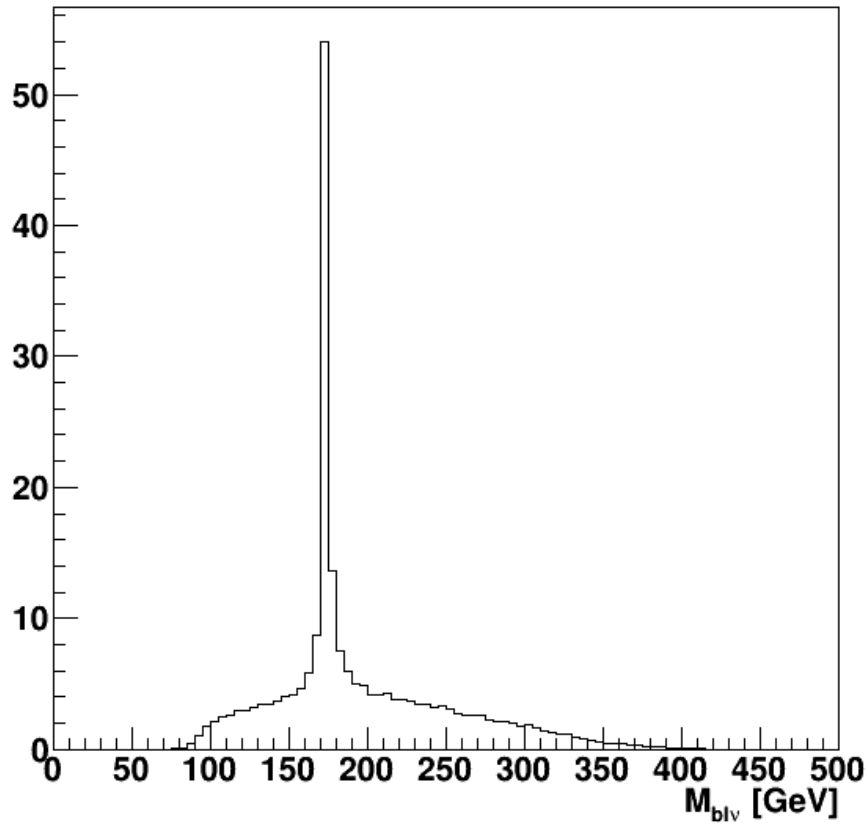
Top reconstruction

With 3 jets b-tagged, there are 3 possible quark combination.

Reconstruction of $t \to bl\nu$



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



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

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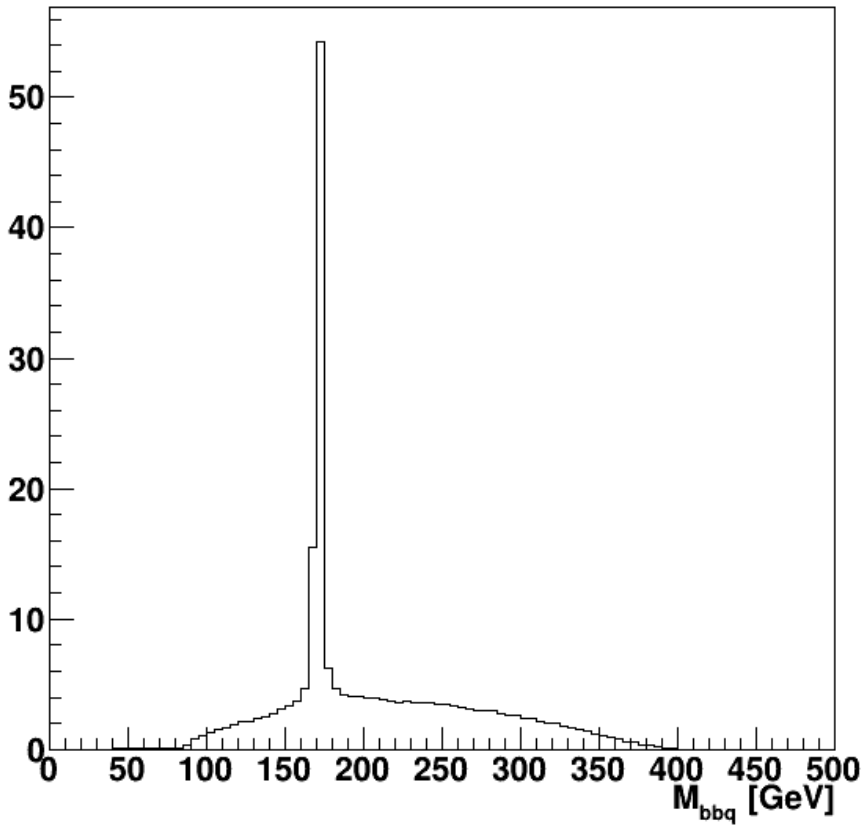
Reconstruction of $t \to b\bar{b}c$



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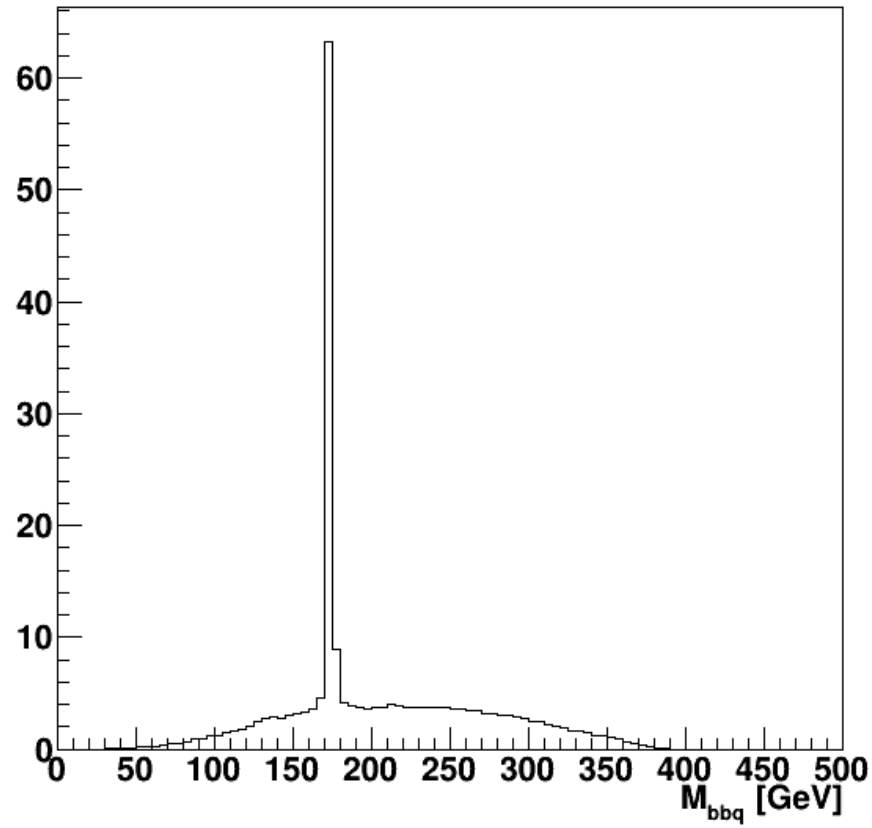

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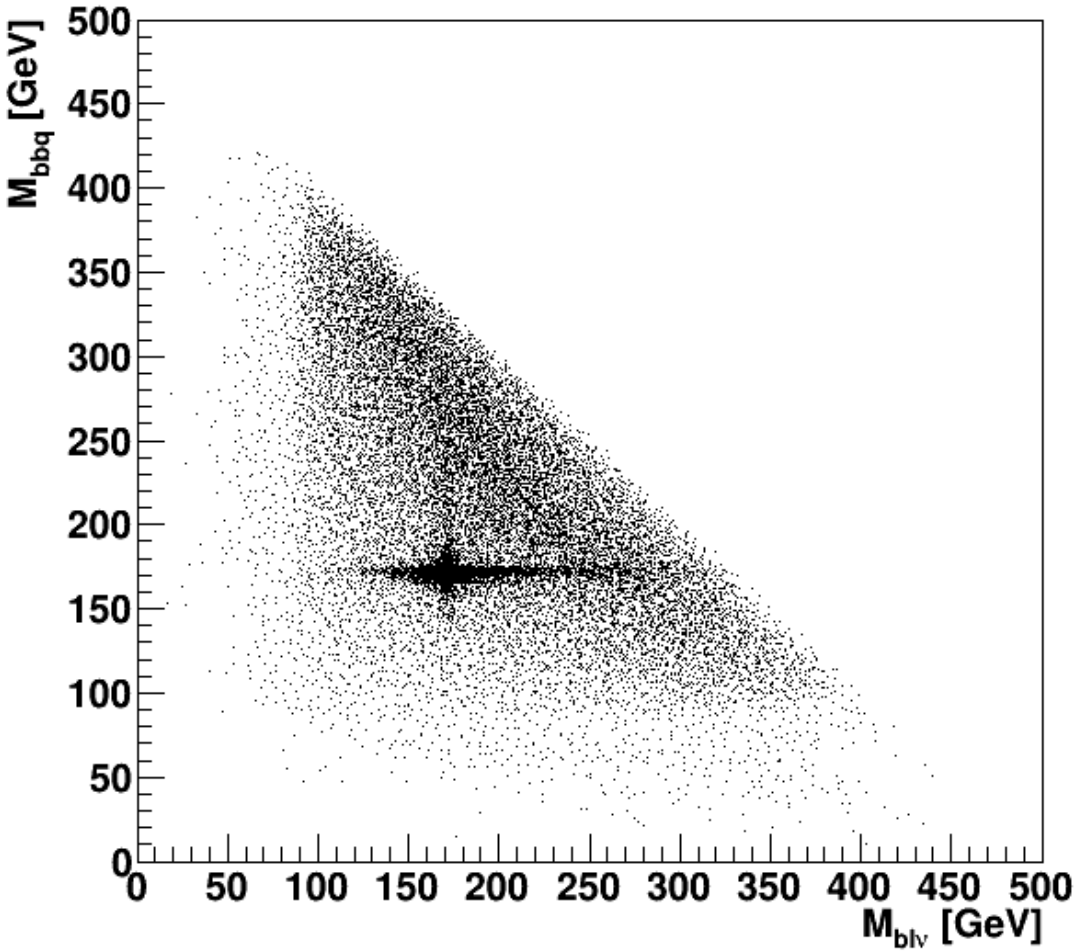
Top reconstruction

Best matching of b-jets to top and anti-top can be selected by minimizing the χ^2 of mass constraint.

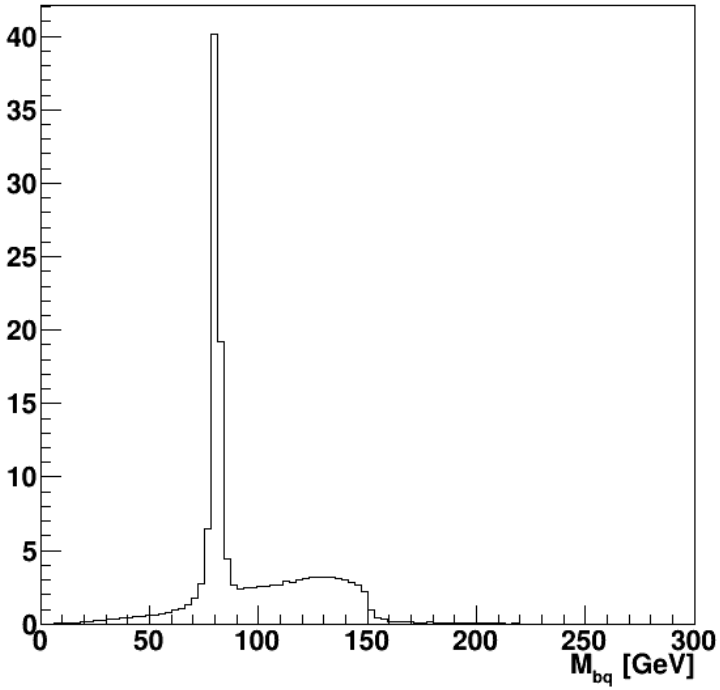


Event selection

$W^{\pm}$ veto

Irreducible SM background can be suppressed by reconstructing second W

Invariant mass of two jets from hadronic top decay (one b-tagged)



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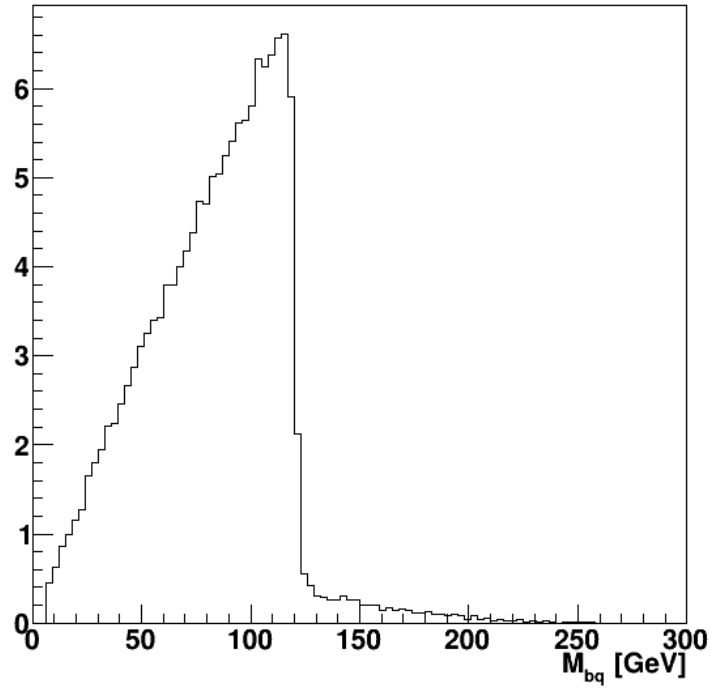

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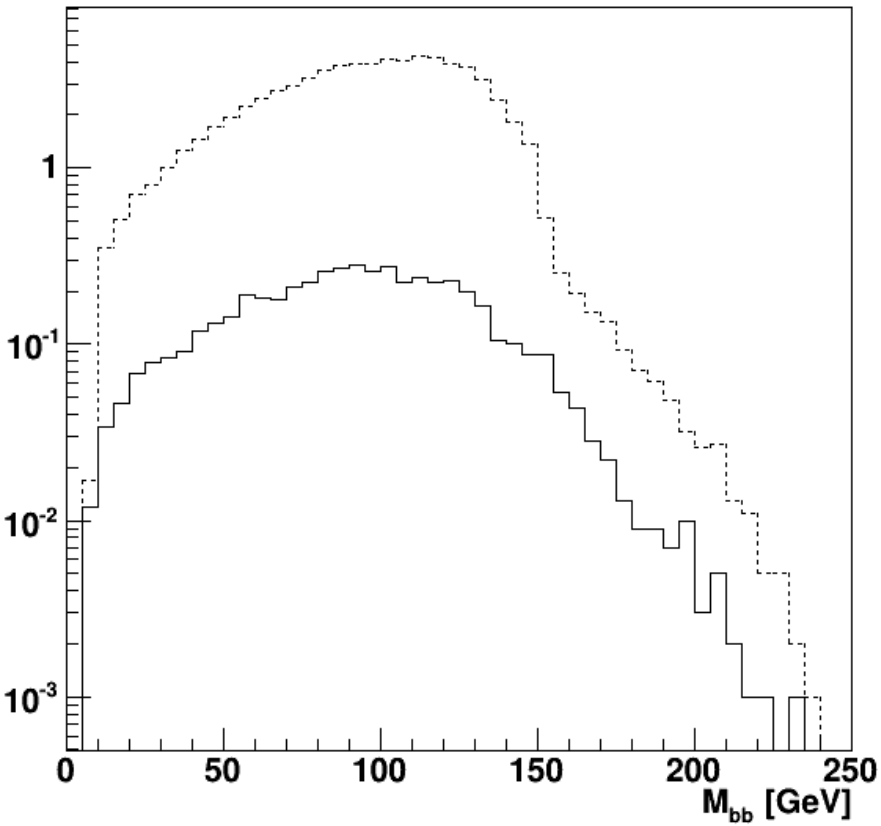
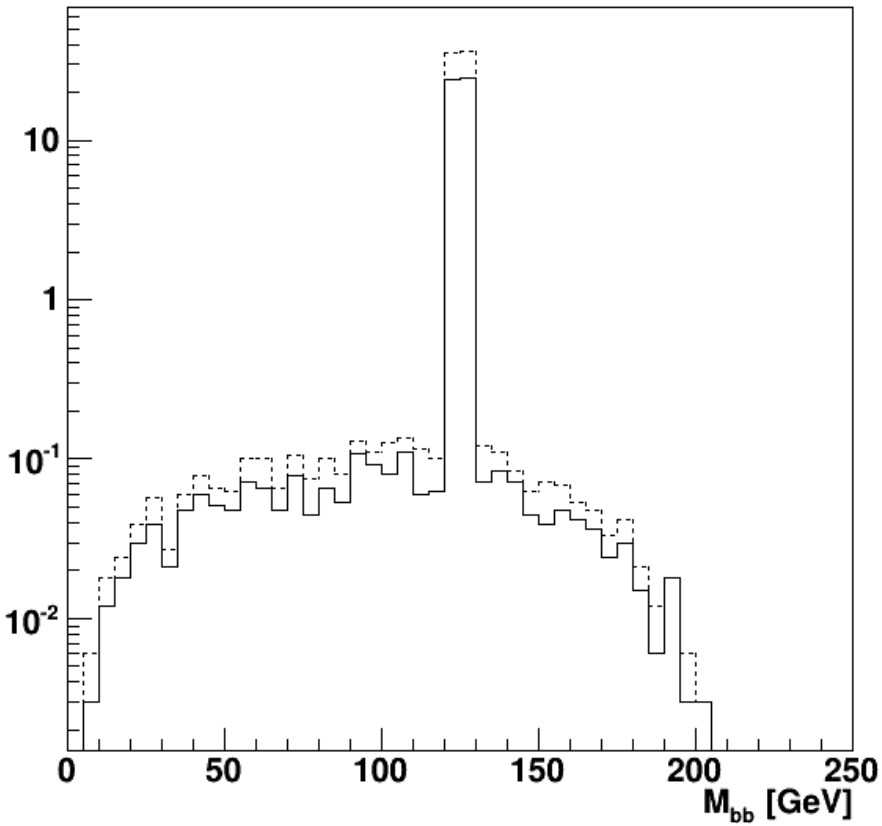
Event selection

Candidate events

$W^{\pm}$ veto used: events with $70 < M_{bq} < 90$ GeV rejected

Invariant mass of two b-jets jets before (dashed) and after (solid) $W^{\pm}$ veto





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

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

Expected events

For 500 fb^{-1}, after taking into account BR($h \to b\bar{b}$) $\approx$ 57% for signal

	Background SM	Signal 2HDM(III)
All	272'000	300
Semi-leptonic	108'000	85
4 jets, 3 b-tags	73	75
W veto	5.0	50.6
H mass $\pm$10 GeV	0.8	48.9

Total of about 540 FCNC top decays expected in the considered model, 180 with leptonic decay of second top, 105 with $h \to b\bar{b}$.

$\Rightarrow$ cut efficiency $\sim$45% overall efficiency $\sim$10 %

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Fully hadronic channel is more challenging, but with 3 b-tagged jets background suppression should still be possible.

References

Selected references for theoretical BR estimates in different models:

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