Searching for top FCNC decay $t \rightarrow ch$ at future e^+e^- colliders

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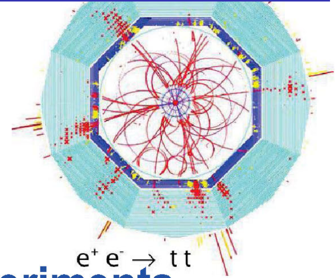
Outline

1. Introduction
   - Projects
   - Top measurements
   - CLIC staging
   - ILC running scenario
2. FCNC top decays
   - SM predictions
   - FCNC in 2HDM
   - Model expectations
3. Simulation study
   - WHIZARD simulation
   - Event analysis
   - Results
4. Conclusions

Outline

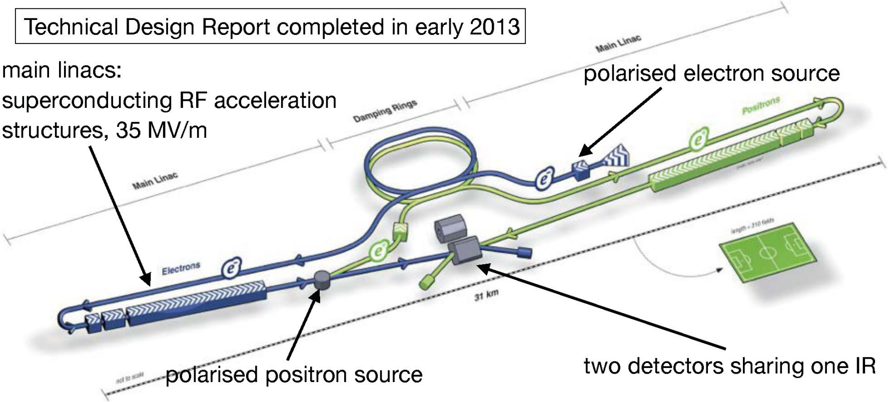

$e^+e^- \rightarrow t\bar{t}$

- Introduction
- Motivation
- Future colliders and experiments
- Prospects for precise measurements
  - threshold scan and top mass
  - Yukawa coupling
  - EW couplings

ILC - The International Linear Collider

- Currently the most advanced concept for a future energy frontier collider
  - e^+e^- collider, baseline energy 500 GeV, high luminosity: 2 x 10^{34} $cm^{-2}s^{-1}$
    - staged construction, starting from 250 GeV / 350 GeV
    - upgrade to 1 TeV possible (extension of linacs), luminosity upgrade by rate increase

Technical Design Report completed in early 2013



main linacs:
superconducting RF acceleration structures, 35 MV/m

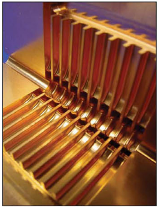
polarised electron source

polarised positron source

two detectors sharing one IR

CLIC - The Compact Linear Collider

- A possible future energy frontier collider at CERN
  - e^+e^- collisions at up to 3 TeV with high luminosity (~ 6 x 10^{34} $cm^{-2}s^{-1}$ at 3 TeV)
  - Staged construction 350 - 500 GeV, ~ 1.5 TeV, 3 TeV - detailed energies under study, based on physics and technical considerations
  - Based on two-beam acceleration: gradients of 100 MV/m
  - Development phase until ~2018 - CDR completed in 2012



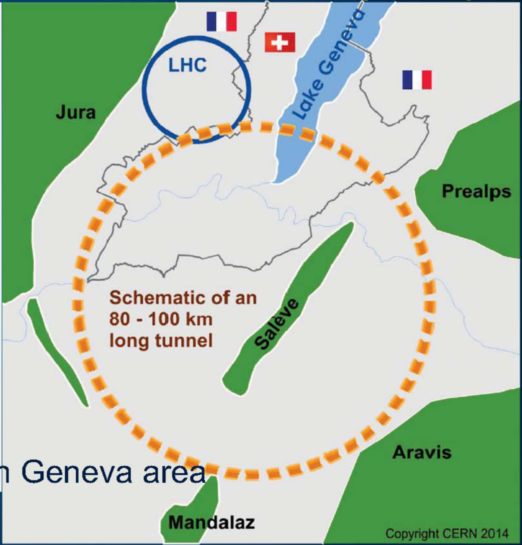
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

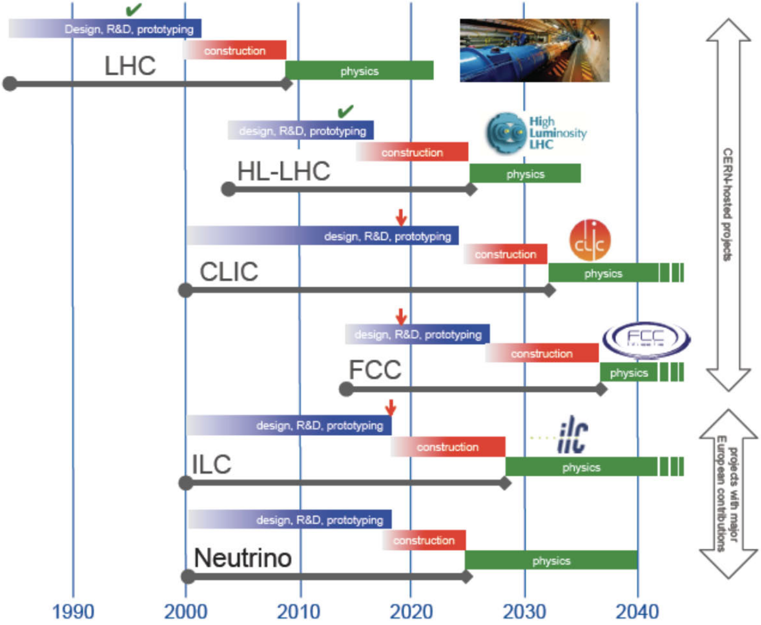
- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



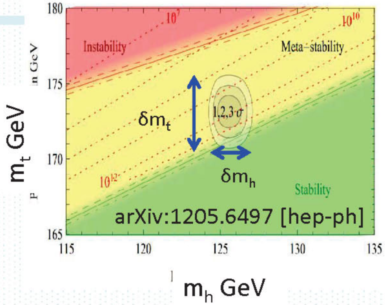
timeline: (HL-)LHC and future collider options



arXiv:1205.6497 [hep-ph]

Target around 350GeV

- **Top mass(m_t)**
  - Important input parameter
  - $\overline{\text{MS}}$ scheme mass ($m_t^{\overline{\text{MS}}}$)
    - ✓ $m_t^{\overline{\text{MS}}} = 160^{+5}_{-4}$ GeV (PDG)
  - Potential subtracted mass (m_t^{PS})
- **Decay width(Γ_t)**
  - anomalous coupling
  - exotic decay
- **Top yukawa coupling(y_t)**
  - Test of higgs mechanism
- α_s
- QCD wave function



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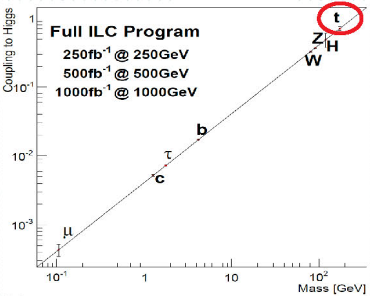
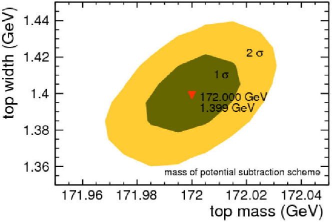
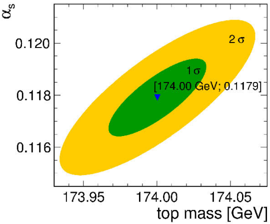


Fitting for the top mass

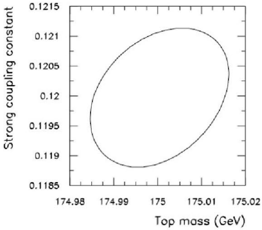
Horiguchi et al., arXiv:1310.0563



Seidel, Simon, Tesar, Poss, EPJ C73 (2013)



Martinez, Miquel, EPJ C27, 49 (2003)



Several authors have applied multi-parameter fits to cross-section obtained in scan (+ other distributions)

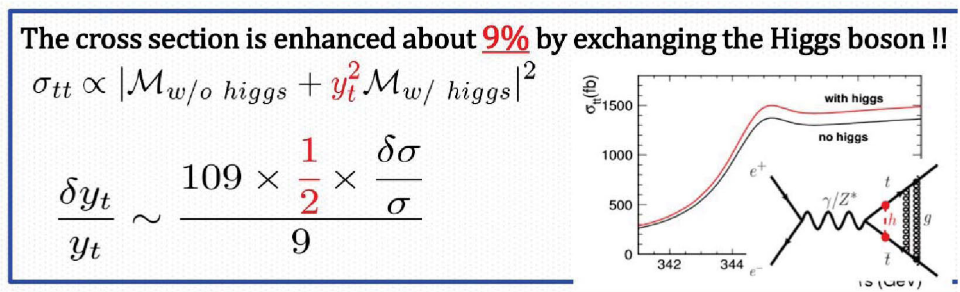
Minor differences between ILC, CLIC and FCC-ee

Statistical precision on 1S or PS mass for 10 x 10/fb:

16 – 30 MeV

(range of results can be understood from assumptions and fit details)

Top Yukawa coupling at threshold



The cross section is enhanced about 9% by exchanging the Higgs boson !!

$$\sigma_{tt} \propto \left|\mathcal{M}_{w/o\ higgs} + y_t^2 \mathcal{M}_{w/\ higgs}\right|^2$$

$$\frac{\delta y_t}{y_t} \sim \frac{109 \times \frac{1}{2} \times \frac{\delta\sigma}{\sigma}}{9}$$

$\int \mathcal{L}dt = 100\ \text{fb}^{-1}$

	(2 + 1) param fit	3 param fit
mt	19 MeV	29 MeV
Γt	38 MeV	39 MeV
yt	4.6%	5.9%

Stat. Uncertainties
'add'
Theoretical
uncertainties ~70 MeV

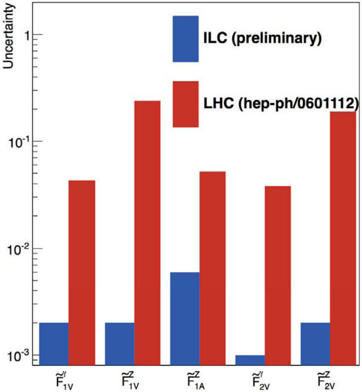
T. Horiguchi

Results of full simulation study for DBD at $\sqrt{s}$ = 500 GeV

IFICLAL ArXiv: 1307.8102

Precision: cross section ~ 0.5%, Precision A_{FB} ~ 2%, Precision λ_t ~ 3-4%

Accuracy on CP conserving couplings



- ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV, 300 fb^{-1})
  Disentangling of vector/axial vectol couplings for ILC
  One variable at a time For LHC
  However LHC projections from 8 years old study

- Need to control experimental (e.g. Top angle) and theoretical uncertainties (e.g. Electroweak corrections)
  -> Dedicated work has started

- Potential for CP violating couplings at ILC under study
  (However CP violation would rather show up at threshold)

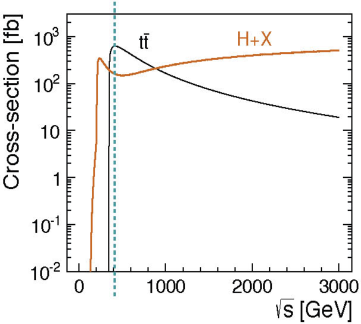
ILC will be indeed high precision machine for electroweak top couplings

CLIC staging

CLIC Physics Landscape

CLIC is foreseen as a staged machine:

- ★ First stage focuses on precision SM physics
  - ~350-375 GeV : Higgs and top

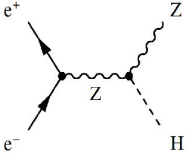


- ★ Not the peak of Higgs cross section
  - But, luminosity scales with √s
- ★ 250 GeV and 350 GeV give similar precision for coupling measurements
- ★ With >350 GeV as a first stage:
  - provides access to top physics

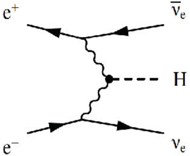
- ★ Energies of subsequent stages motivated by physics
  - results from ~14 TeV LHC operation
  - direct dark matter searches,

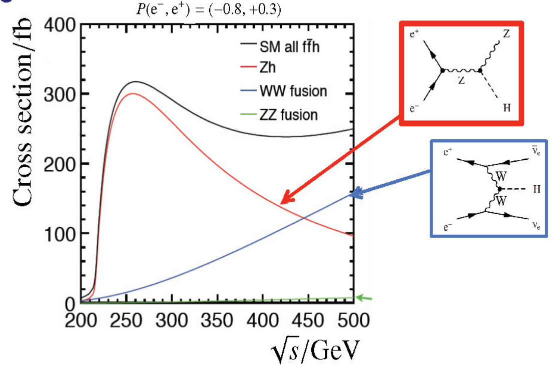
Standard Model Higgs

- A number of SM Higgs processes accessible at CLIC
- Below $\sqrt{s}$ ~ 300 GeV
  Higgs-strahlung dominates



- Above $\sqrt{s}$ ~ 500 GeV
  WW fusion dominates

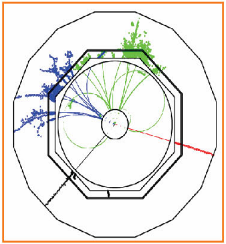


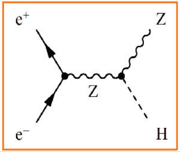


- At $\sqrt{s}$ ~ 350-450 GeV both contribute

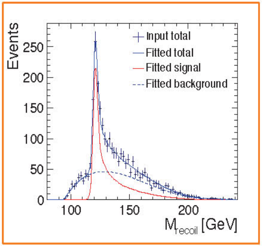
HZ Cross Section revisited

- ★ During first stage of CLIC: study the Higgs-strahlung process





- ★ <u>Model independent</u> analysis
  - Select Higgs from mass recoiling against leptonically decaying Z
  - Measure Higgs BRs



- ★ Measure Higgs production cross section independent of Higgs decay
  - Sensitive to invisible Higgs decay modes
  - **Absolute measurement of HZ coupling**

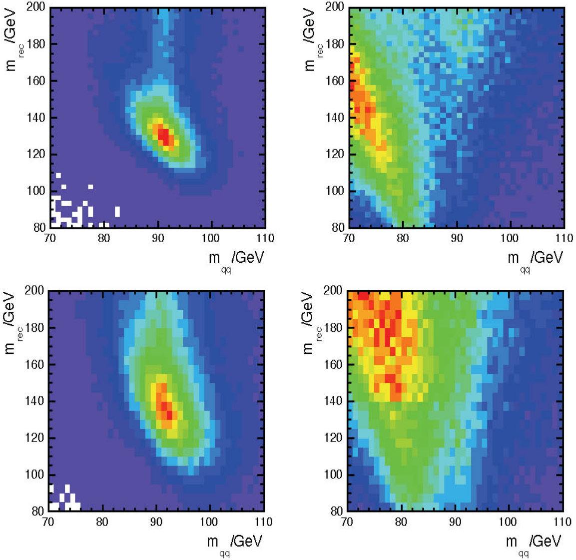
- ★ Recent studies demonstrated:

  MI measurements with $Z \rightarrow q\bar{q}$

Full Simulation

350 GeV

420 GeV

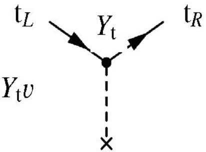


Top Physics

★ **The top quark appears to be special**

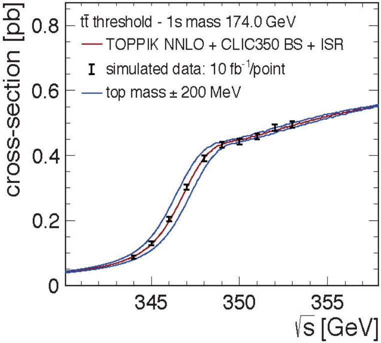
- fermion mass at the electroweak scale
- Yukawa coupling suspiciously close to 1

$$m_t = \frac{1}{\sqrt{2}} Y_t v$$



★ **CLIC @ √s > 350 GeV ⇨ precision top physics**

- e.g. top quark mass from threshold scan



★ **Scan with modest lumi (10 fb^{-1}/pt):**

⇨ $\boxed{m_t \ : \ \pm 33 \,\text{MeV (stat.)}}$

- measurement relatively easy to interpret – “know what you are measuring”
- theory uncertainties relatively small

Conclusions

HZ production

⇨ $\sqrt{s} \sim 250\text{-}450$ GeV

Top at theshold

⇨ $\sqrt{s} > 350$ GeV

Recoil Mass

⇨ $\sqrt{s} < 400$ GeV

Top pair production

⇨ $\sqrt{s} > 360$ GeV

Top pair BSM

⇨ $\sqrt{s} > 360$ - ? GeV

⇨ **$\sqrt{s} \sim 380$ GeV**

Still good for HZ
Provides valid top quark program

ILC running scenario

Construct 500 GeV from start

- 500 GeV scenarios study
  - TDR Baseline
  - Emphasizes higher energy - strength of ILC
- Study parameters
  - assume 20 years of operation
  - compare 3 scenarios (studied more)
    - G20, H20, I20
  - Snowmass white paper studied also for comparison
    - arXiv:1310.0763 [hep-ph]
- Draft report: http://pages.uoregon.edu/jimbrau/temp/parameters-draft-150419.pdf - comments welcome!

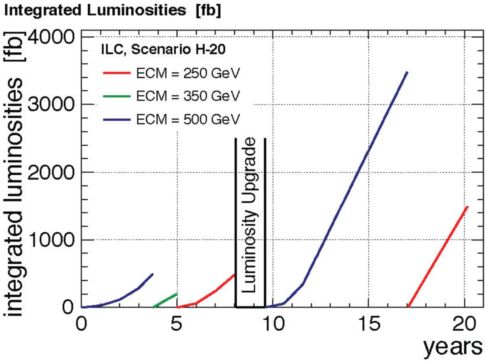
Assumptions

- Full calendar year is assumed to be 8 months at a 75% efficiency (the RDR assumption). This corresponds to Y = 1.6 x 10^7 seconds of integrated running. (significantly higher than a Snowmass year of 10^7 seconds.)
- A **ramp-up** of luminosity performance is in general assumed after:
  - (a) initial construction and after 'year 0' commissioning;
  - (b) after a downtime for a luminosity upgrade;
  - (c) a change in operational mode which may require some learning curve (e.g. going to 10-Hz collisions).
- For initial physics run *after construction and year 0 commissioning*, the RDR ramp of 10%, 30%, 60% and 100% is assumed over the first four years.
- The ramp *after the shutdowns for installation of the luminosity upgrade* is assumed slightly shorter (10%, 50%, 100%) with no year 0.
- *Going down in centre of mass energy* from 500 GeV to 350 GeV or 250 GeV is assumed to have no ramp, since there is no machine modification.
- *Going to 10-Hz operation at 50% gradient* does assume a ramp (25%, 75%, 100%), since 10-Hz affects the entire machine.
- A major 18 month shutdown is assumed for the luminosity upgrade.
- Unlike TDR: 10-Hz and 7-Hz operation assumed at 250 GeV and 350 GeV

H-20 Luminosity profile

	$\sqrt{s}$	$\int \mathcal{L} dt$	L_{peak}	Ramp				T	T_{tot}	Comment	inst. $\mathcal{L}$
	[GeV]	[fb^{-1}]	[fb^{-1}/a]	1	2	3	4	[a]	[a]		[10^{34} cm^{-2}s^{-1}]
Physics run	500	500	288	0.1	0.3	0.6	1.0	3.7	3.7	TDR nominal at 5 Hz	1.8
Physics run	350	200	160	1.0	1.0	1.0	1.0	1.3	5.0	TDR nominal at 5 Hz	1.0
Physics run	250	500	240	0.25	0.75	1.0	1.0	3.1	8.1	operation at 10 Hz	1.5
Shutdown								1.5	9.6	Luminosity upgrade	
Physics run	500	3500	576	0.1	0.5	1.0	1.0	7.4	17.0	TDR lumi-up at 5 Hz	3.6
Physics run	250	1500	480	1.0	1.0	1.0	1.0	3.2	20.2	lumi-up operation at 10 Hz	3.0

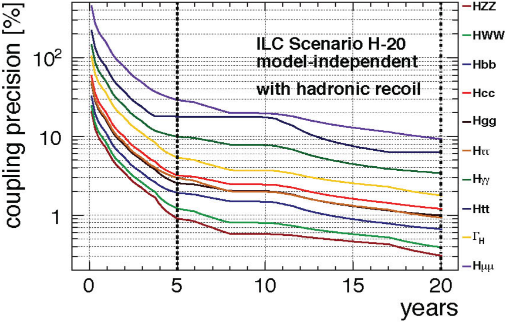
Table 7: Scenario H-20: Sequence of energy stages and their real-time conditions.



- Briefer initial 500 GeV operation than G-20
- Return to 250 GeV operation after lumi upgrade

Higgs couplings (H-20)

- H-20 preferred for
  - slightly better early precision (compared to G-20)
  - current best reliability of m_h and $\sigma(e^+e^- \rightarrow Zh)$ measurements when done at 250 GeV
- Model independent
  - Higgs recoil from hadronic decaying Z is nearly model independent
- Recommended H-20 to ILC PAC last week



FCNC top decays

Standard Model

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

$$\begin{array}{lcll} t & \rightarrow & W^+ \, b & \text{dominant, BR} = 91\% \\ t & \rightarrow & W^+ \, s/d & \text{CKM suppressed} \end{array}$$

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

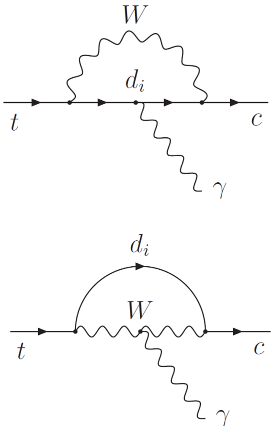
$$t \rightarrow q\gamma \, , \; qZ \, , \; qg \, , \; qH \qquad q = u, c$$

RPP2014 experimental limits:

$$\begin{array}{lcll} BR(t \rightarrow \gamma \, q) & < & 5.9 \cdot \; 10^{-3} & 95\% \text{ CL} \\ BR(t \rightarrow Z \, q) & < & 2.1 \cdot 10^{-3} & \end{array}$$

Standard Model

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

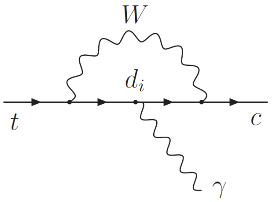


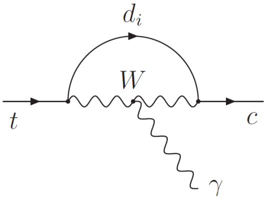
When neglecting down quark masses, the decay amplitude is suppressed (GIM):

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

Standard Model

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





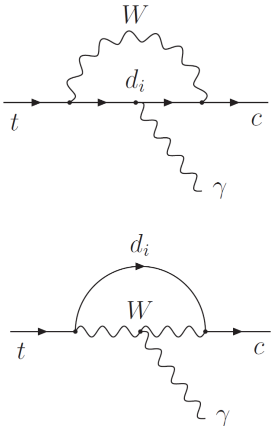
However, taking into account quark masses, GIM cancelation is not perfect

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

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

Standard Model

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



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

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

Resulting decay width:

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

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):

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

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

Standard Model

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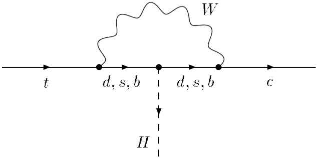


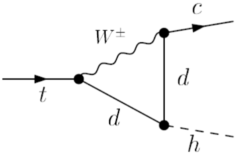
Only for $t \to c\ H$ channel, GIM mechanism is not applicable (in one of the diagrams) due to Higgs coupling proportional to mass.

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 :

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

possible enhancement at large $\tan\beta$

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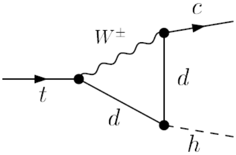

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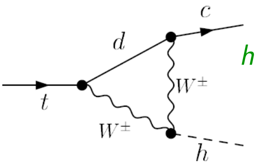
possible enhancement at large tan β



hWW :

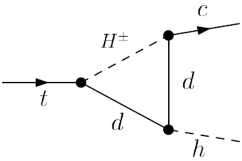
$$g = g_{SM} \times \sin(\beta-\alpha)$$

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):



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

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

$\tan\beta$ in all 3 vertexes !

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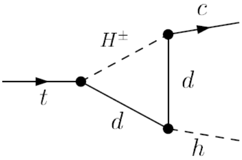
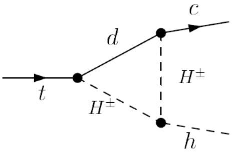


$H^+ b\bar{t}$:

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

tan β in all 3 vertexes !



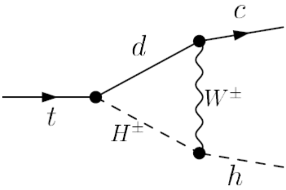
$H^\pm H^\pm h$:

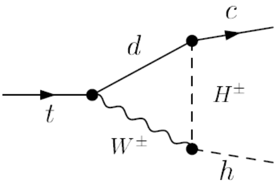
$$\frac{-ig}{M_W}\ \left[\frac{M_h^2}{\sin 2\beta}\left(\cos^3\beta\cos\alpha - \sin^3\beta\sin\alpha\right) - M_{H^+}^2\sin(\alpha-\beta)\right]$$

enhancement possible for both large and small tan β

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}
2HDM	10^{-5} - 10^{-4}	10^{-9}	10^{-8}	10^{-10}

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2HDM (FV)	10^{-3} - 10^{-2}	10^{-6} - 10^{-7}	10^{-4}	10^{-6}

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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}

Expectations

Expected maximal branching rations for different scenarios

Significant differences between different papers - overall limit ranges given

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$\not{R}$ 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}

Model expectations

Decay $t \to c\ h$ in 2HDM is an interesting scenario:

- large enhancement both on tree and loop level
- well constrained kinematics
- seems to be most difficult for LHC

Limits on top FCNC decays from LHC (Moriond 2015):

$$\begin{array}{rcll}
BR(t \to qZ) & < & 0.05\% & \text{(CMS)} \\
BR(t \to c\gamma) & < & 0.18\% & \text{(CMS)} \\
BR(t \to u\gamma) & < & 0.016\% & \text{(CMS)} \\
BR(t \to cg) & < & 0.016\% & \text{(ATLAS)} \\
BR(t \to ug) & < & 0.0031\% & \text{(ATLAS)}
\end{array}$$

$$\begin{array}{rcll}
BR(t \to ch) & < & 0.56\% & (\text{CMS, } 20\ \text{fb}^{-1}) \\
BR(t \to ch) & < & 0.79\% & (\text{ATLAS, } 25\ \text{fb}^{-1})
\end{array}$$

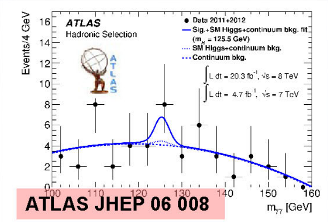
Top FCNC Searches (cont.)

Search for $t \to Hq$ decays

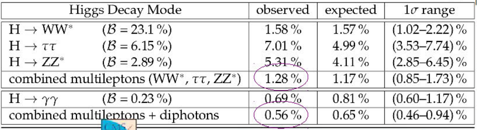
- ATLAS (direct search)
  - Using **7+8 TeV** data on $H \to \gamma\gamma$

    $\mathcal{B}(t \to cH) < 0.79\%$ (exp. 0.51%)
- CMS (two approaches)
  - Re-interpret from **SUSY** mult.-lep. Studies
    - Combining $H \to \gamma\gamma$ $\mathcal{B}(t \to cH) < 0.56\%$
  - Direct search
    - Multi-lepton ch. $H \to WW, ZZ, \tau\tau$
      - Using **8 TeV** data with 19.7/fb
      - Tri-lepton & same-sign di-lep.
      - Major bkg. from **non-prompt**

        $\mathcal{B}(t \to cH) < 0.93\%$ (exp. 0.89%)

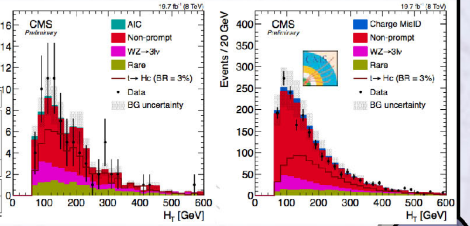


ATLAS JHEP 06 008



Higgs Decay Mode		observed	expected	1σ range
$H \to WW^*$	($\mathcal{B}$ = 23.1 %)	1.58 %	1.57 %	(1.02–2.22) %
$H \to \tau\tau$	($\mathcal{B}$ = 6.15 %)	7.01 %	4.99 %	(3.53–7.74) %
$H \to ZZ^*$	($\mathcal{B}$ = 2.89 %)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons (WW^*, $\tau\tau$, ZZ^*)		1.28 %	1.17 %	(0.85–1.73) %
$H \to \gamma\gamma$	($\mathcal{B}$ = 0.23 %)	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons		0.56 %	0.65 %	(0.46–0.94) %

CMS PAS TOP-13-034



CMS PAS TOP-13-017

WHIZARD

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
- $\mathrm{BR}(t \to ch_1) = 10^{-3}$
- $\mathrm{BR}(h \to b\bar{b}) = 100\%$

Generated samples at $\sqrt{s}$=500 GeV

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

Assume that we can select high purity $t\bar{t}$ sample
⇒ main background to FCNC decays from standard decay channels

All events generated with CIRCE1 spectra + ISR
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:

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

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

- 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%

Pandora LC Event Reconstruction

Traditional calorimetric approach:

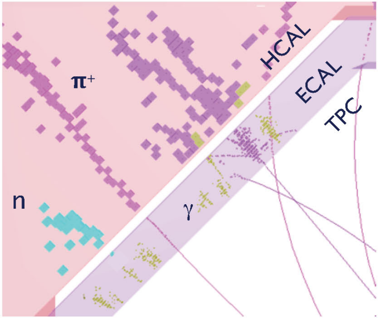
- Measure all components of jet energy in ECAL/HCAL
- Approximately 70% of energy measured in HCAL: $\sigma_E/E \approx 60\% / \sqrt{E(\text{GeV})}$

Particle Flow Calorimetry:

- Trace paths of individual particles through the detector.
- Charged particle momentum measured in tracker (essentially perfectly)
- Photon energies measured in ECAL: $\sigma_E/E < 20\% / \sqrt{E(\text{GeV})}$
- Only neutral hadron energies (10% of jet energy) measured in HCAL.

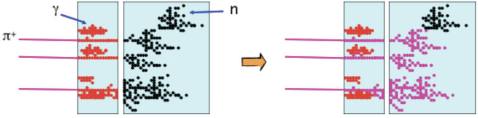
Particle Flow Calorimetry requires:

- Fine-granularity calorimeters
- Sophisticated software algorithms



Traditional calorimetry

Particle flow calorimetry

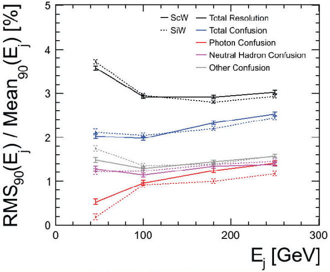


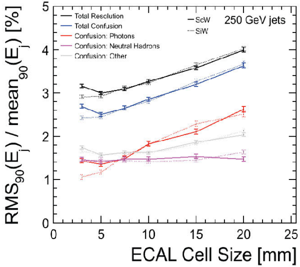
$E_{JET} = E_{ECAL} + E_{HCAL}$

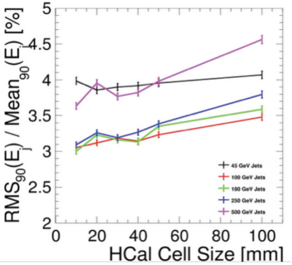
$E_{JET} = E_{TRACK} + E_{\gamma} + E_n$

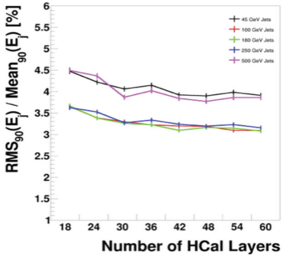
Pandora Detector Optimisation

- Physics motivation for particle flow calorimetry:
  Jet energy resolution: $\sigma_E/E < 3.5\%$
- Benchmark performance using jet energy resolution in Z decays to light quarks.
- Use jet energy resolution as figure of merit for extensive detector optimisation studies.
- **Publication currently under construction.**

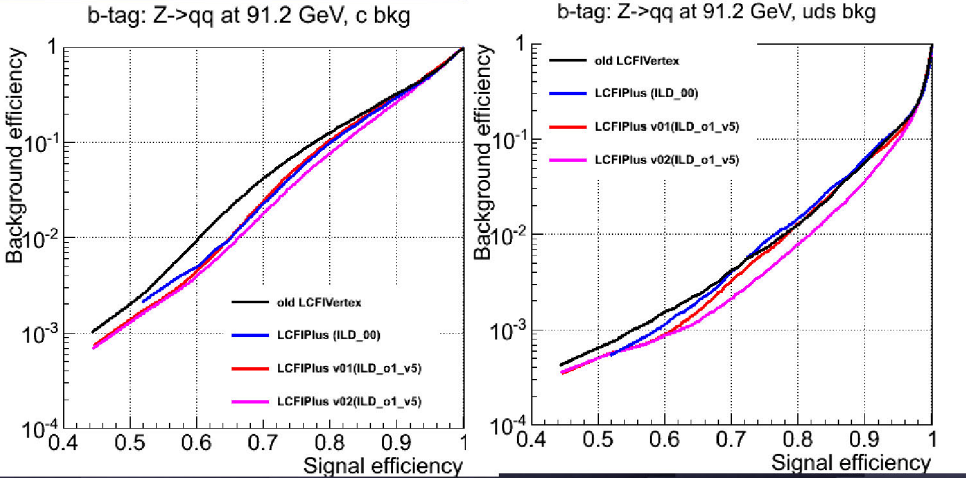








b-tag performance: Z-pole qq



old LCFIVertex -> LCFIPlus improvement seen in all region
ILD_00 & ILD_o1_v5 give similar performance
v02 is better than v01 in all region: use v02!

Event selection

$t\bar{t}$ 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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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

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

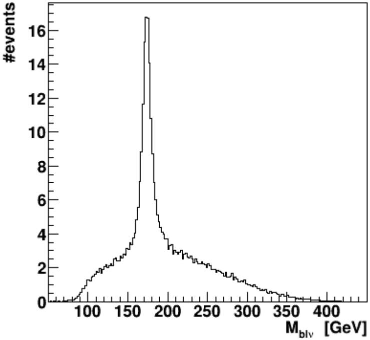
Event analysis

Top reconstruction

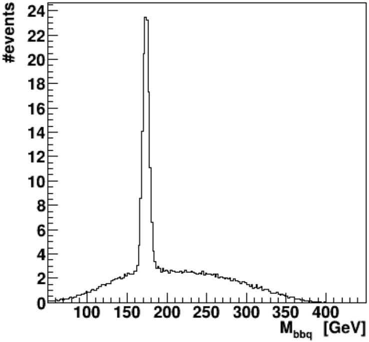
Try to group final state objects into two tops
Check invariant mass distributions for all considered combinations

Semileptonic events (signal sample):

Semileptonic "spectator" top decay



Fully hadronic "signal" top decay



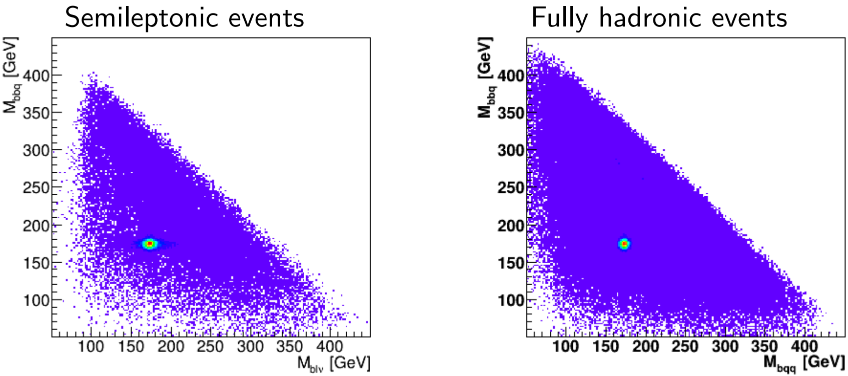
Event analysis

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

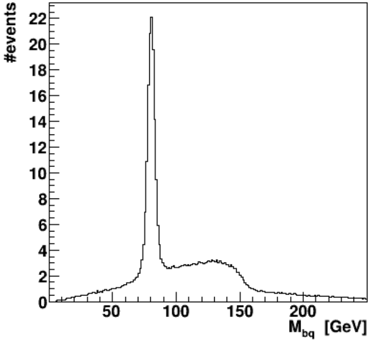


Signal selection

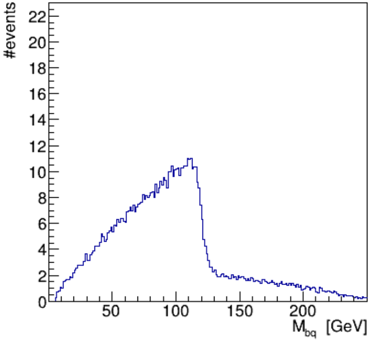
Cut based approach: $W^\pm$ veto

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)



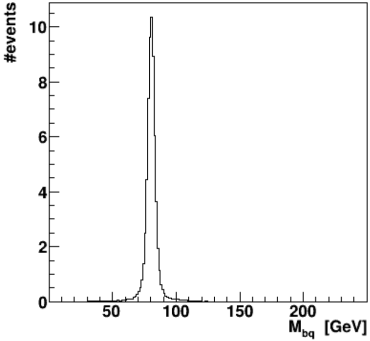
$e^+e^- \longrightarrow ch_1\bar{t},\ t\bar{c}h_1$ (2HDM)

Signal selection

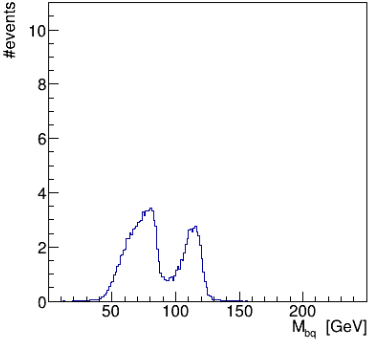
Cut based approach: $W^{\pm}$ veto

Irreducible SM background can be suppressed by reconstructing second W

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



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



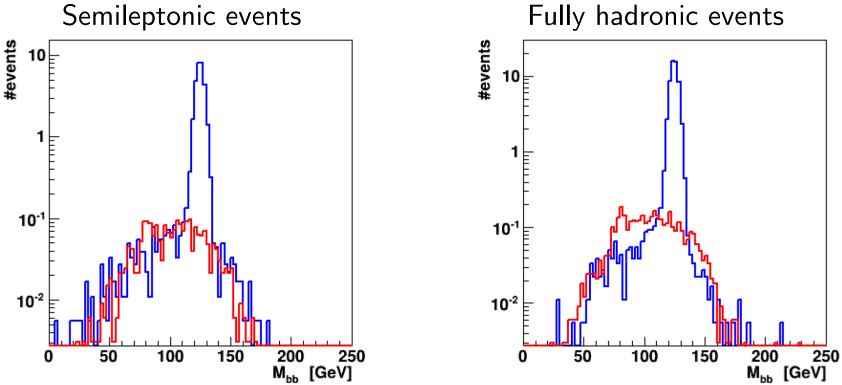
$e^{+}e^{-} \longrightarrow ch_1\bar{t},\ t\bar{c}h_1$ (2HDM)

Signal selection

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...

Signal selection

Alternative approach - compare two hypothesis:

- background hypothesis

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

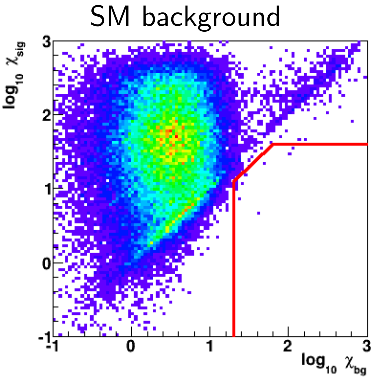
- signal hypothesis

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

Independent search for best background and signal combinations

Hypothesis comparison

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



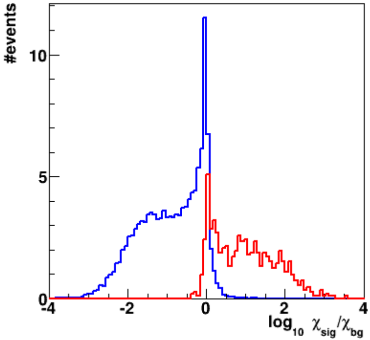
80% *b*-tagging efficiency (scenario B)

Signal selection

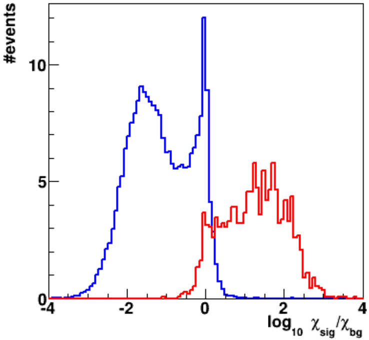
Hypothesis comparison

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

Semileptonic channel



Fully hadronic channel



Ideal *b*-tagging

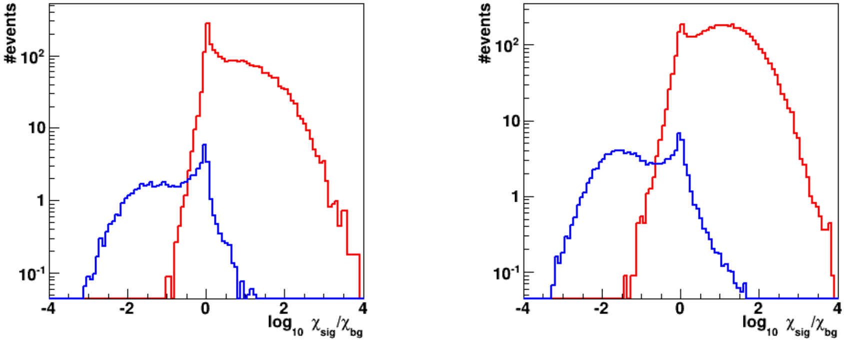
Very efficient background rejection possible

Signal selection

Hypothesis comparison

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

Semileptonic channel   Fully hadronic channel



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

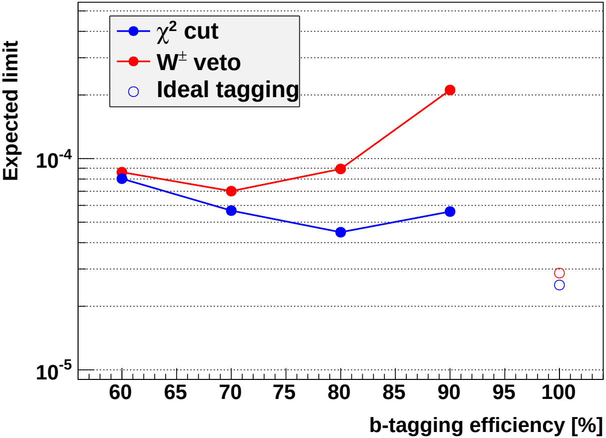
Expected events

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

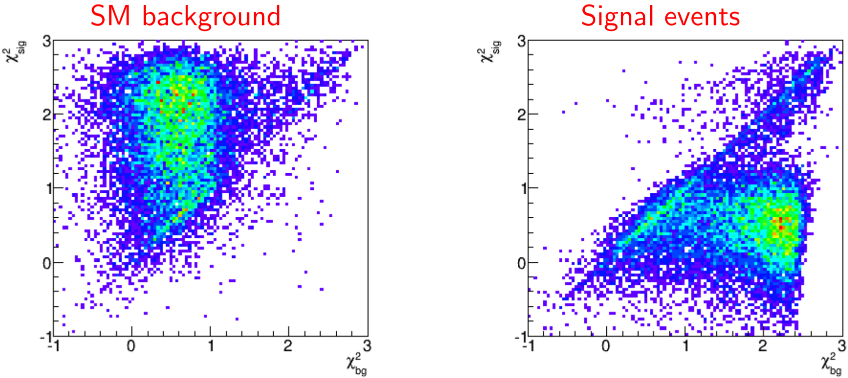
Limits on $BR(t \to ch) \times BR(h \to b\bar{b})$ expected for 500 fb^{-1} @ 500 GeV
from combined analysis (semileptonic+hadronic channels)



Jet energy resolution

Correlation of $\log_{10}\chi^2$ for two hypothesis for hadronic events @ 500 GeV

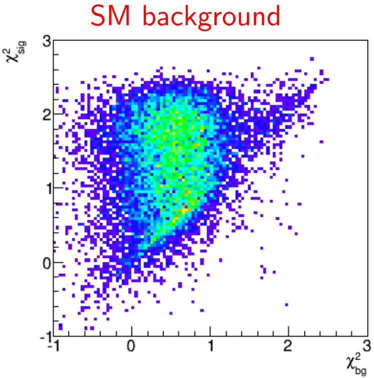
Jet energy resolution 30%



Jet energy resolution

Correlation of $\log_{10} \chi^2$ for two hypothesis for hadronic events @ 500 GeV

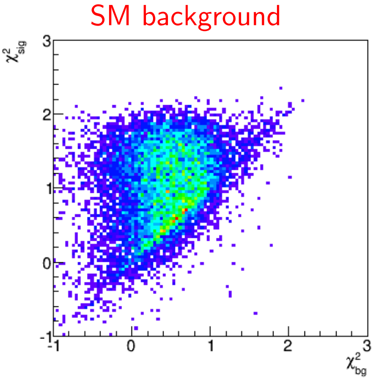
Jet energy resolution 50%

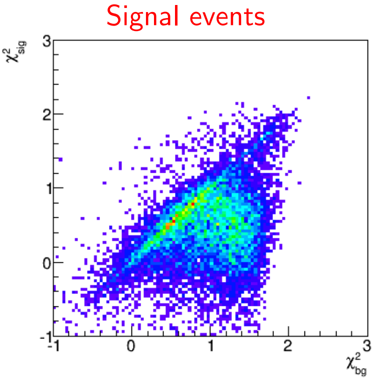


Jet energy resolution

Correlation of $\log_{10}\chi^2$ for two hypothesis for hadronic events @ 500 GeV

Jet energy resolution 80%

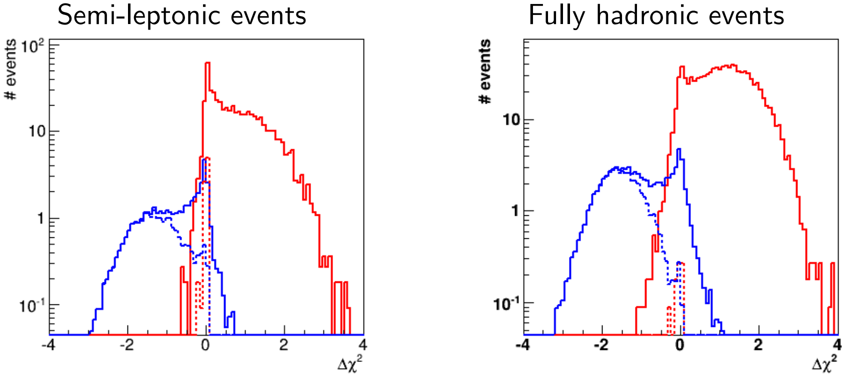

SM background


Signal 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 30%

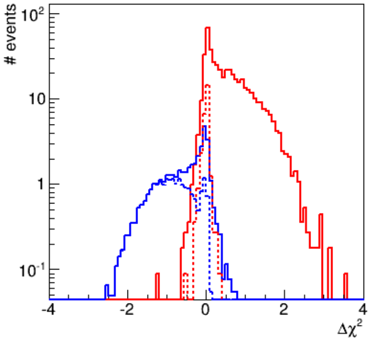


Jet energy resolution

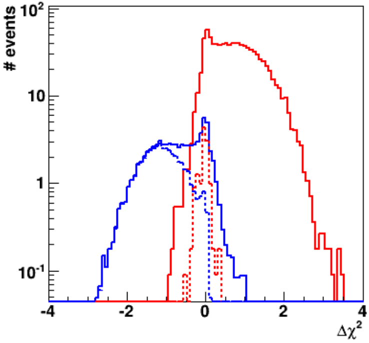
Difference of $\log_{10}\chi^2$ for two hypothesis, for signal and background events
Before (solid) and after (dashed) other selection cuts

Jet energy resolution 50%

Semi-leptonic events



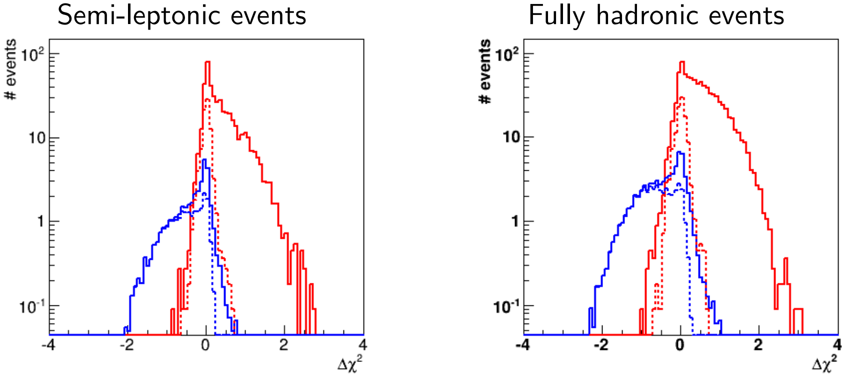
Fully hadronic events



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%



Semi-leptonic events

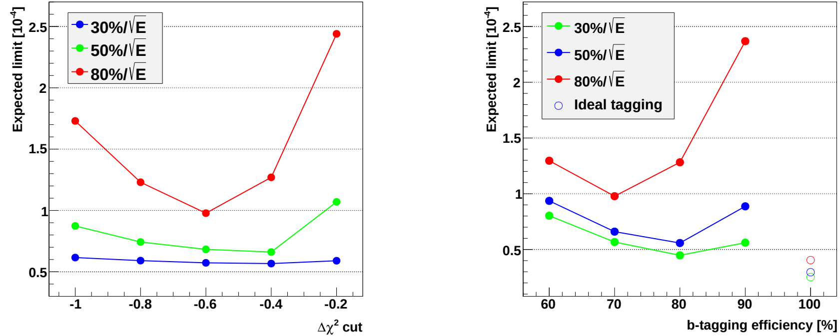
Fully hadronic events

Signal - background separation still possible, but with decreasing efficiency

Jet energy resolution

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

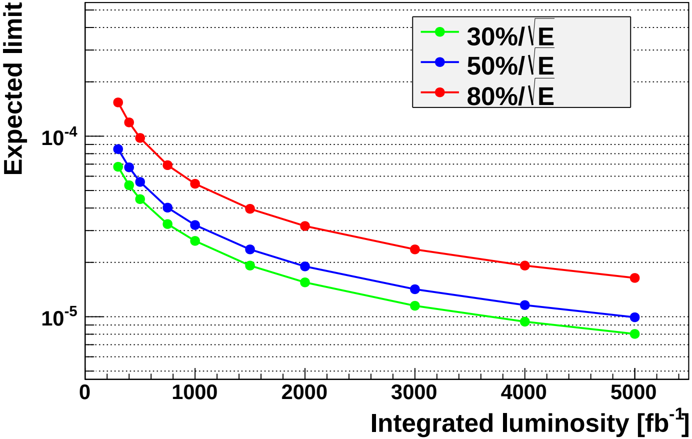


Worsening jet energy resolution ⇒ tighter cuts & b-tagging required

Jet energy resolution and luminosity

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

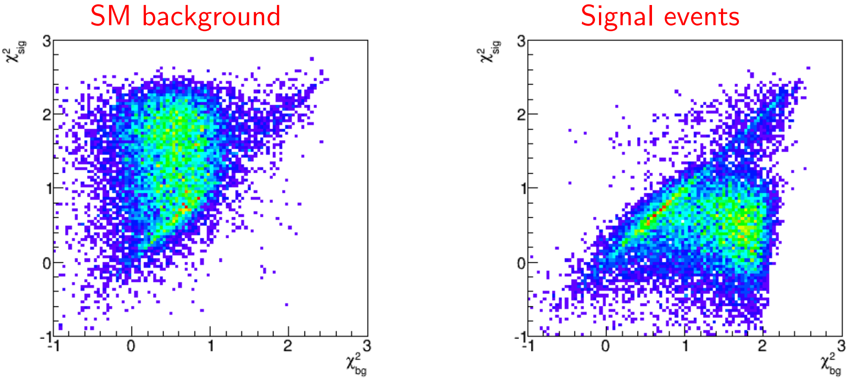
Collision energy 500 GeV



Collision energy

Correlation of $\log_{10} \chi^2$ for hadronic events, 50% resolution, 70% b-tagging

Collision energy 500 GeV

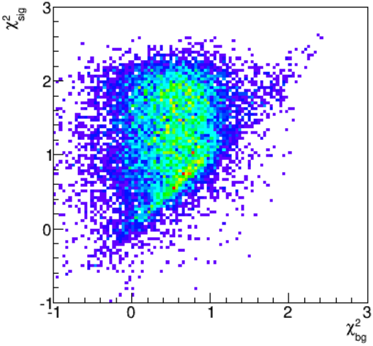


Collision energy

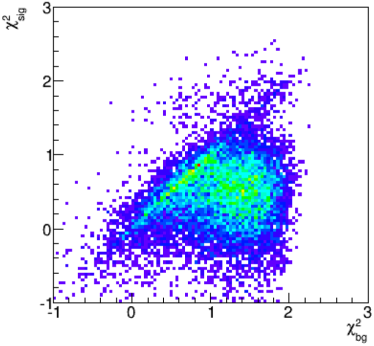
Correlation of $\log_{10} \chi^2$ for hadronic events, 50% resolution, 70% b-tagging

Collision energy 380 GeV

SM background



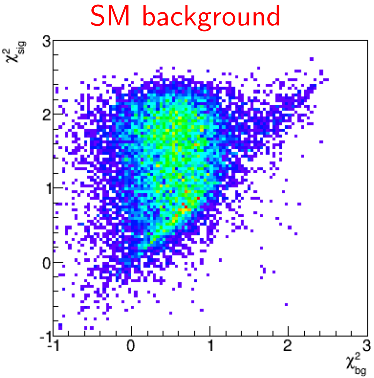
Signal events



Collision energy

Correlation of $\log_{10}\chi^2$ for hadronic events, 50% resolution, 70% b-tagging

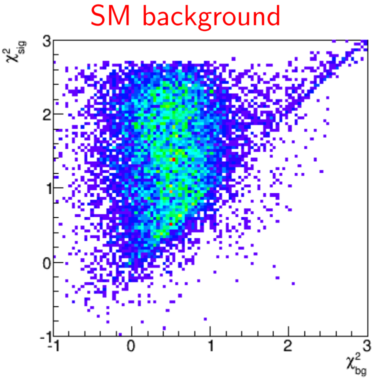
Collision energy 500 GeV



Collision energy

Correlation of $\log_{10}\chi^2$ for hadronic events, 50% resolution, 70% b-tagging

Collision energy 1000 GeV


SM background

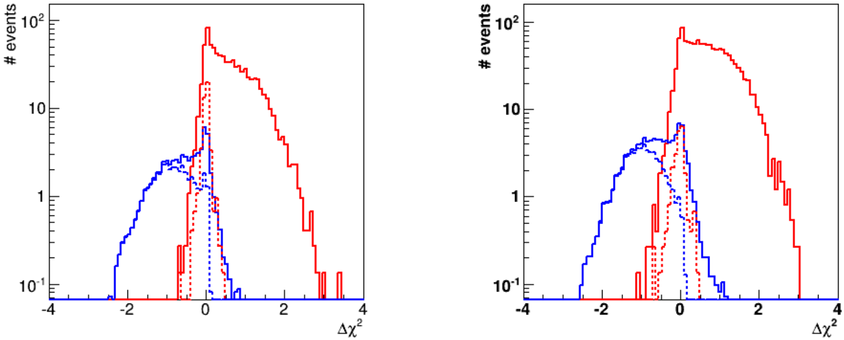
Signal events

Collision energy

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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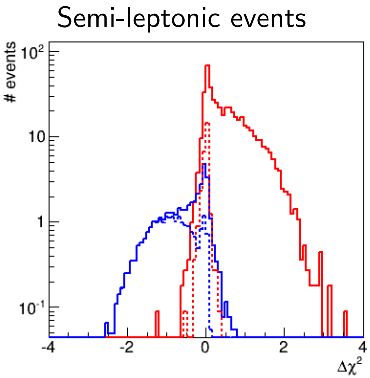

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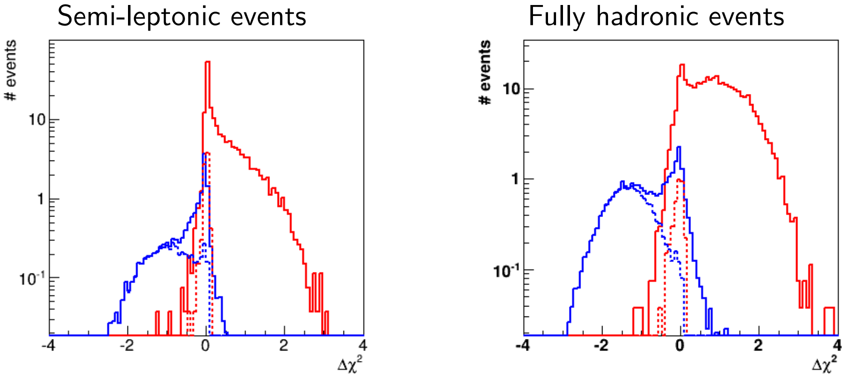
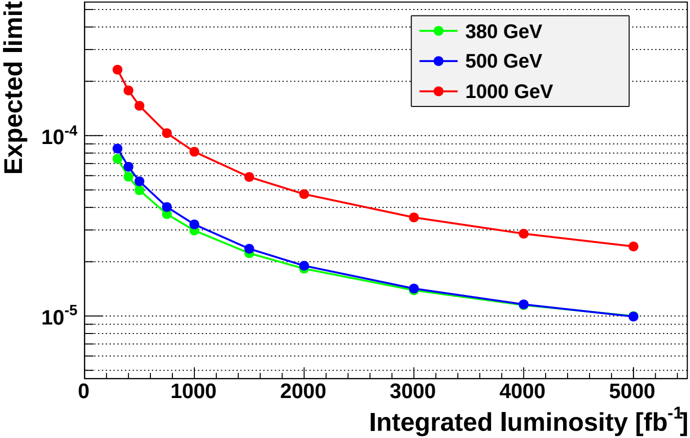


Signal - background separation improves slightly for hadronic events.
Visible loss of efficiency in semi-leptonic channel.

Collision energy and luminosity

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

Jet energy resolution 50%



Collision energy and statistics

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

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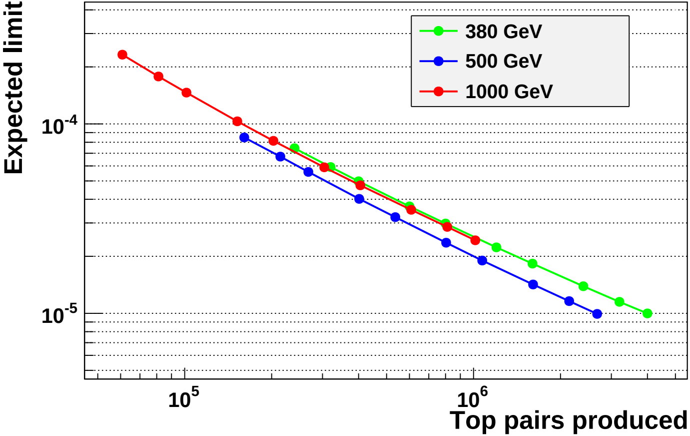

Reminder

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

- only $t\bar{t}$ background considered
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Results are just estimates!

Conclusions

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

Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$ 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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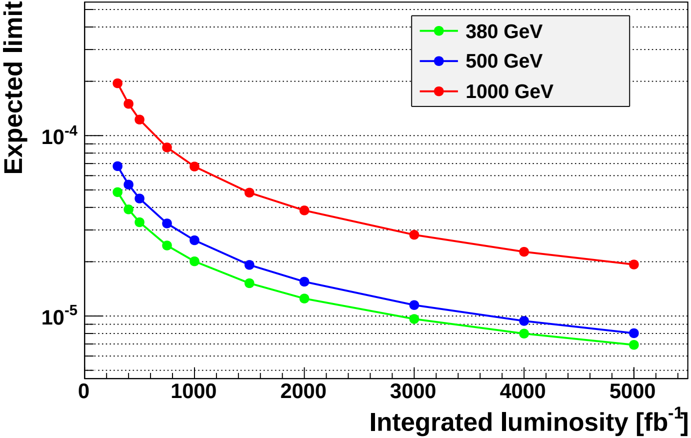
Flavour tagging preformance crucial for the analysis
⇒ possible benchmark for optimization of detector design

Backup

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

Jet energy resolution 30%



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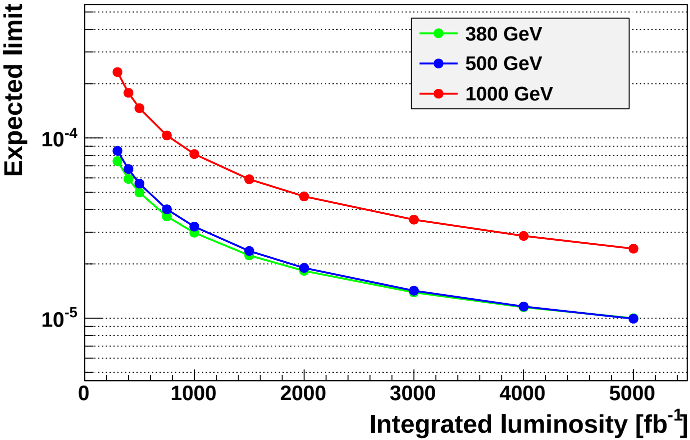
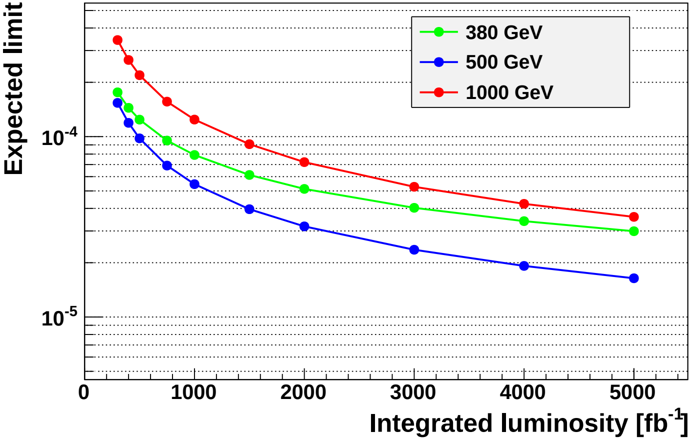


Backup

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

Jet energy resolution 80%



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

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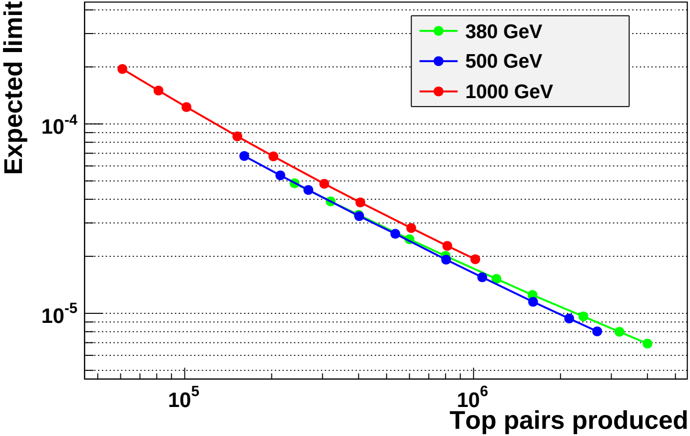

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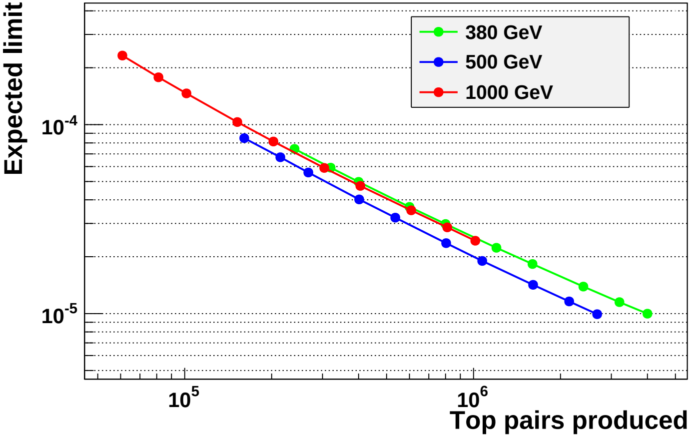

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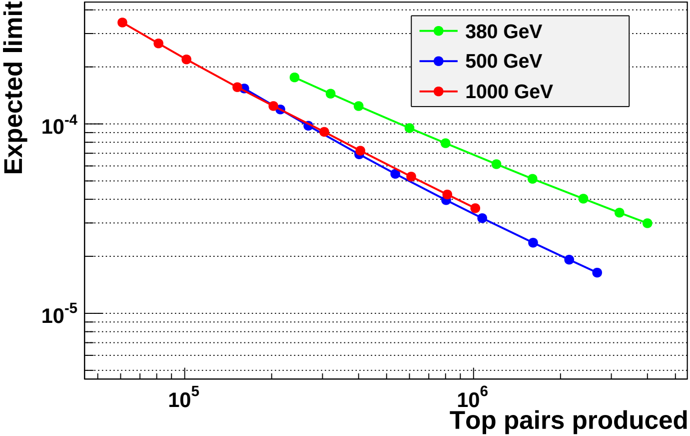

Backup

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.