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

Aleksander Filip Żarnecki

FACULTY OF PHYSICS
WARSAW UNIVERSITY

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Outline

1. Motivation
2. Collider and Experiment
3. WHIZARD Simulation
4. Full simulation
5. Event selection
6. Results
7. Conclusions

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

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

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LHC (ATLAS 2016):

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

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

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

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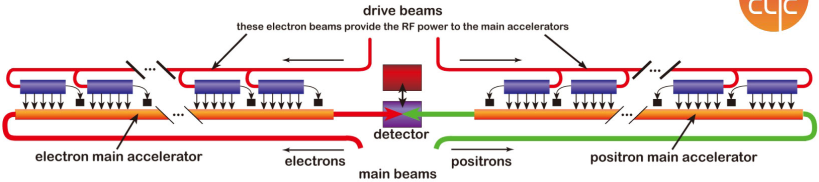
Two Higgs Doublet Model (2HDM) as a test scenario:

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

Compact LInear Collider

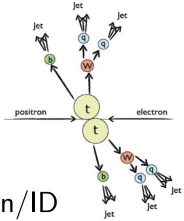


Conceptual Design (CDR) presented in 2012 CERN-2012-007

- high gradient, two-beam acceleration scheme
- staged implementation plan with c.m.s energy from 380 GeV to 3 TeV
- footprint of 11 to 50 km
- e^- polarisation, e^+ polarisation as possible upgrade
- ongoing R&D and large-scale system tests

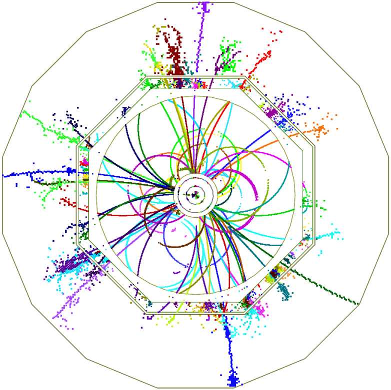
Detector Requirements

Jet reconstruction and jet energy measurement based on "Particle Flow" concept



Single particle reconstruction/ID
$\Rightarrow$ high calorimeter granularity

Benchmark reaction
$e^+e^- \rightarrow t\bar{t} \rightarrow 6j$



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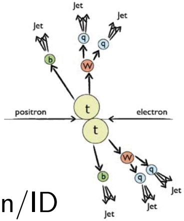

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Best possible jet energy estimate
$\Rightarrow$ precise momentum measurement

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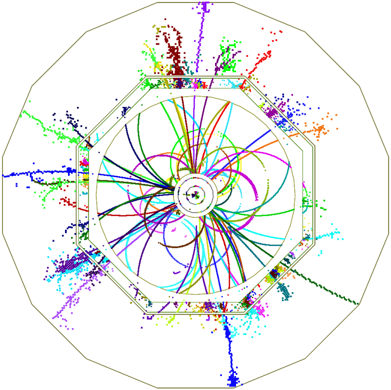

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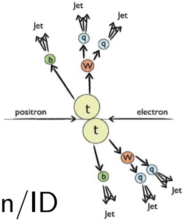

Single particle reconstruction/ID
⇒ high calorimeter granularity

Best possible jet energy estimate
⇒ precise momentum measurement

Very efficient flavour tagging
⇒ high precision vertex detector

Benchmark reaction
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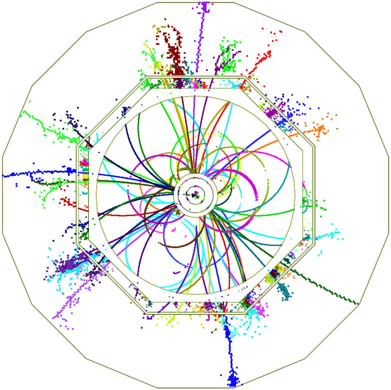
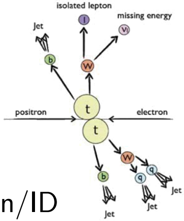


Experiments

Detector Requirements

Jet reconstruction and jet energy measurement based on "Particle Flow" concept



Single particle reconstruction/ID
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Best possible jet energy estimate
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Very efficient flavour tagging
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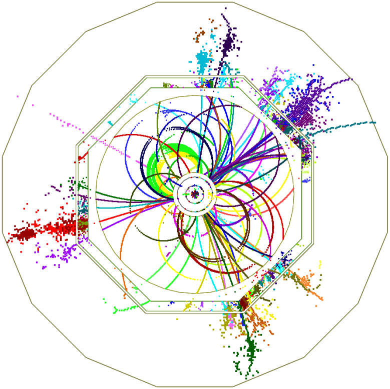
Missing energy measurement
$\Rightarrow$ hermecity

Benchmark reaction
$e^+e^- \rightarrow t\bar{t} \rightarrow 4j + l + \nu$

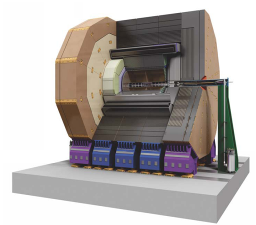


Detector Requirements

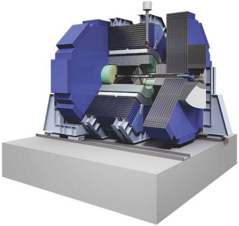
- Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m \frac{1\ \mathrm{GeV}}{p\ \sin^{3/2}\Theta}$
- Jet energy resolution: $\sigma_E/E = 3 - 4\%$ (highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

Three detailed detector concepts:

CLIC-ILD



CLIC-SiD



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Three detector concepts in detail:

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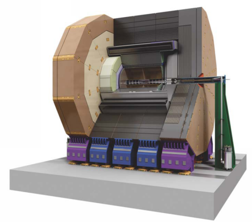

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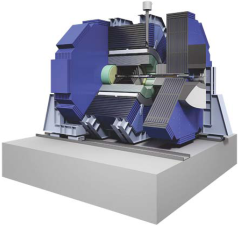
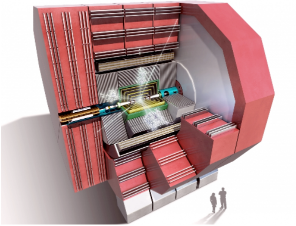


CLIC 2016



CLIC running scenario

Assume three construction stages (each 5 to 7 years of running)

- $\sqrt{s} = 380$ GeV with 500 fb^{-1} + 100 fb^{-1} at $t\bar{t}$ threshold
  selected as an optimal choice for precision Higgs and top physics
- $\sqrt{s} = 1.5$ TeV with 1500 fb^{-1}
- $\sqrt{s} = 3$ TeV with 3000 fb^{-1}

WHIRZARD

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:

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

Dedicated samples:

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

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

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Parton level study

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%

Signal selection

Compare two reconstruction 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

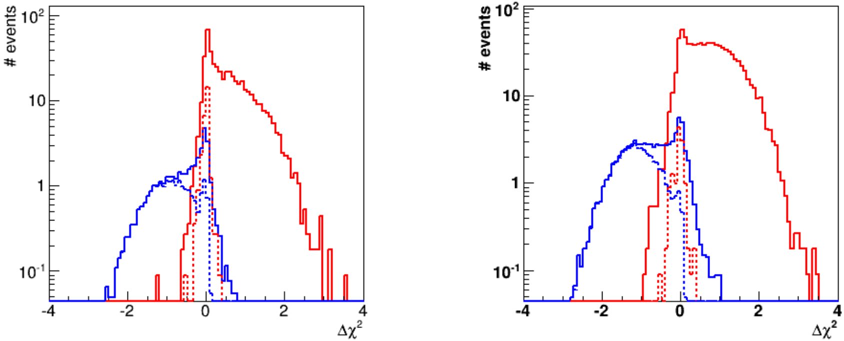
Result

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%

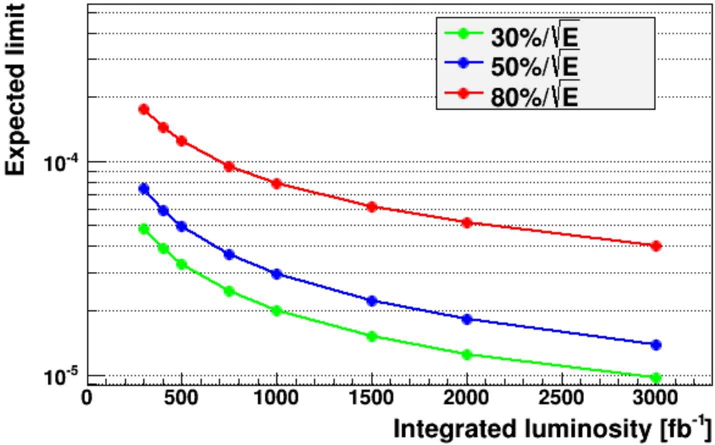
Semi-leptonic events   Fully hadronic events



Jet energy resolution and luminosity

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

Collision energy 380 GeV



Full simulation

Signal sample

10'000 events generated with WHIZARD 2.2.8

- THDMIII model from SARAH, tuned for $BR(t \to ch) = 10^{-3}$
- generated processes: $e^+e^- \longrightarrow t\bar{c}h$ and $e^+e^- \longrightarrow ch\bar{t}$
- beam spectra from file (350 GeV scaled to 380 GeV)
- quark masses and PYTHIA settings adjusted to CLIC CDR
- polarization of -80%/0% (for e^-/e^+)
- corrected treatement of ISR

Standard event processing with CLIC_ILD_CDR500 configuration

Background samples

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

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

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

Event analysis

DST files processed with MARLIN, ilcsoft v01-17-09 (ilcDIRAC)

- Using LooseSelectedPandoraPFANewPFOs as input collection
- LCFI+ primary and secondary vertex finder
- LCFI+ jet finding with Valencia algorithm
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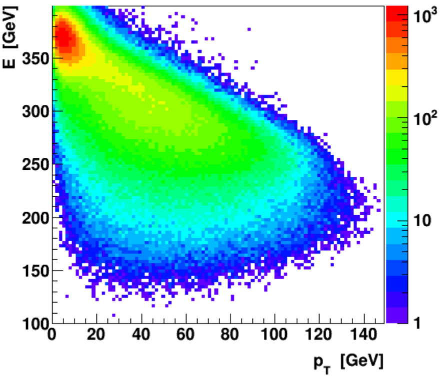
Final analysis in root:

- event pre-selection cuts
- kinematic fit
- final selection

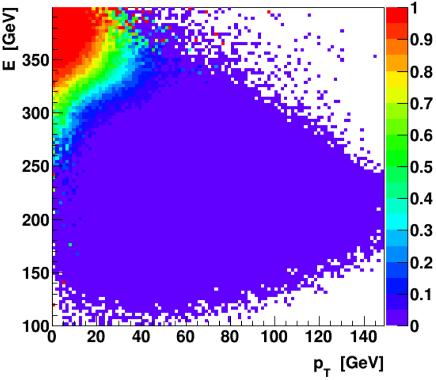
Hadronic event selection

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

Background event distribution



Hadronic event fraction



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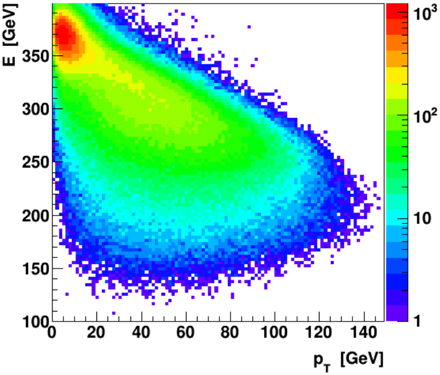

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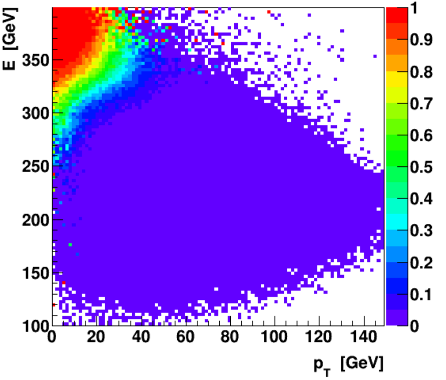

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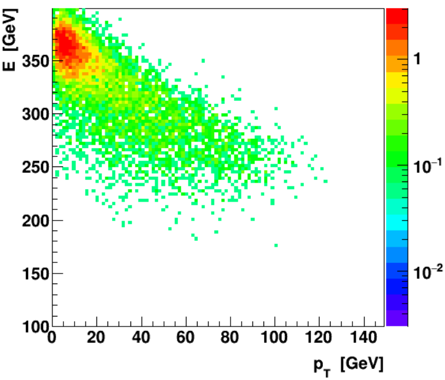

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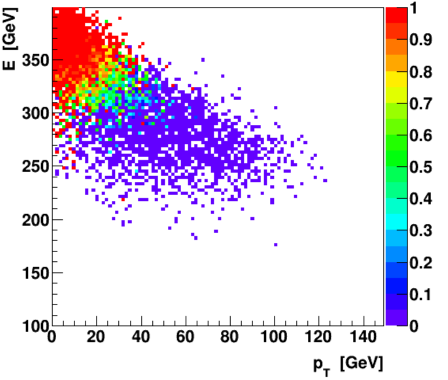
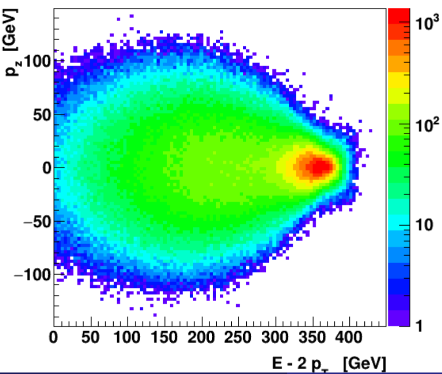


Selection

Hadronic event selection

Energy and transverse momentum balance can also be correlated with longitudinal momentum

Background event distribution



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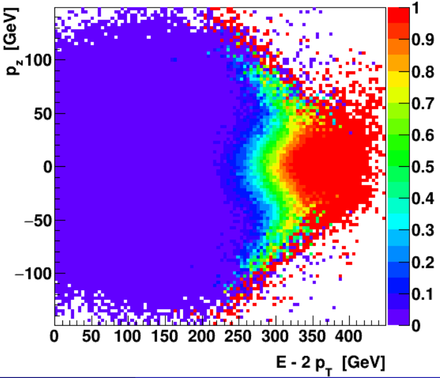

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$\Rightarrow$ cut on $E_{balance} = \sqrt{(E - 2\ p_T - \sqrt{s})^2\ +\ 4\ p_Z^2}$

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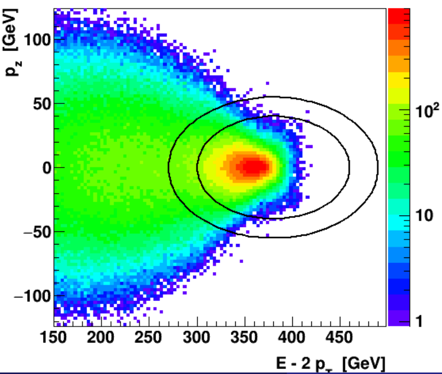

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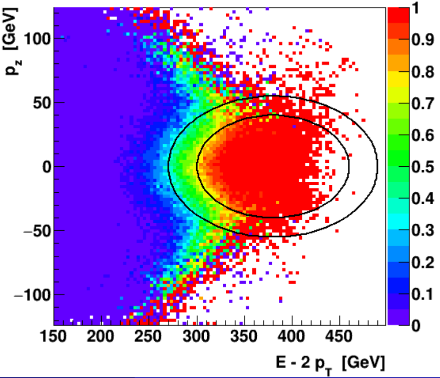

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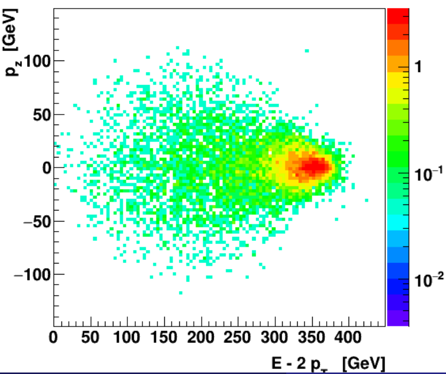

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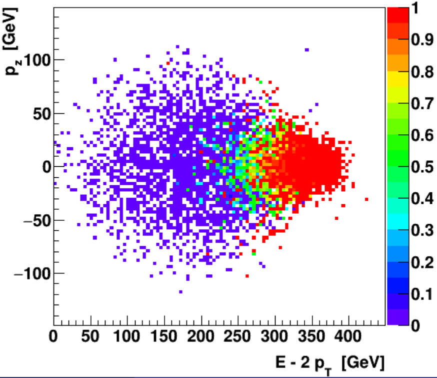
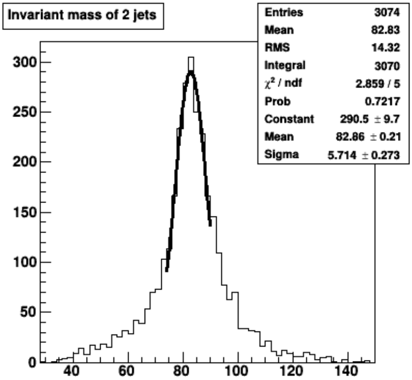


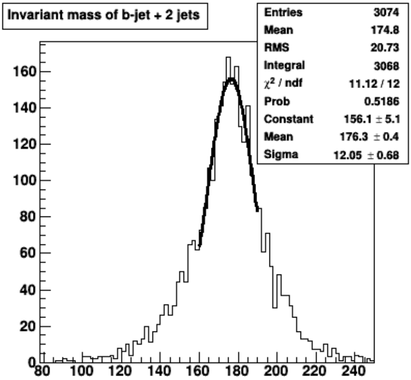
Mass resolution

Reconstructed mass distributions for signal events (Valencia jets)

W boson



"spectator" top



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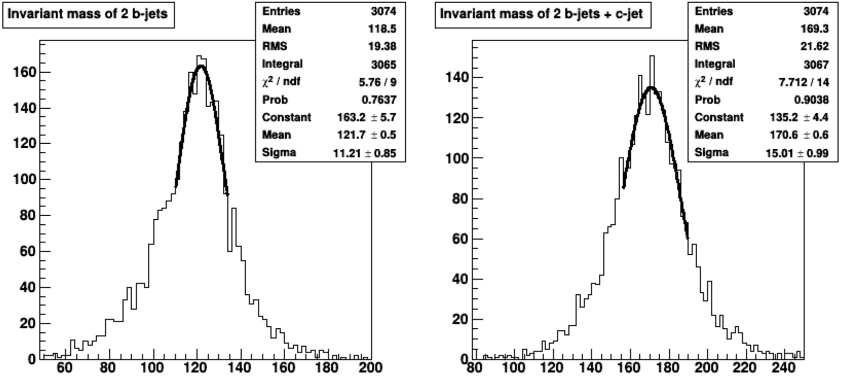
Higgs "signal" top

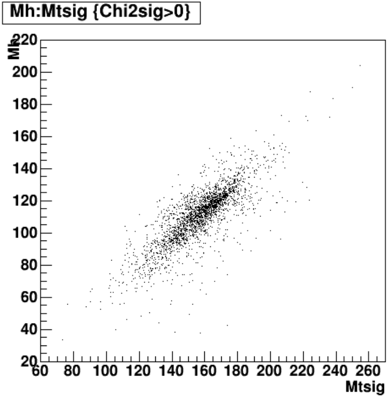


Relatively poor mass reconstruction for b-jets?...

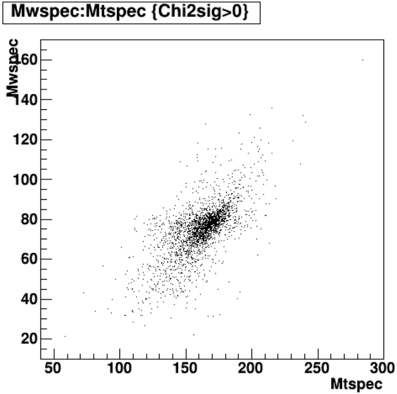
Mass correlation

Significant correlation observed between reconstructed masses of

Higgs and "signal" top



W boson and "spectator" top



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

New χ^2 definition

- signal hypothesis hadronic final state

$$\chi^2_{sig} = \left(\frac{M_{bqq} - m_t}{\sigma_t}\right)^2 + \left(\frac{M_{bbc} - m_t}{\sigma_t}\right)^2 + \left(\frac{\frac{E_{bqq}}{M_{bqq}} - \gamma_t}{\sigma_\gamma}\right)^2 + \left(\frac{\frac{E_{bbc}}{M_{bbc}} - \gamma_t}{\sigma_\gamma}\right)^2$$
$$+ \left(\frac{\frac{M_{qq}}{M_{bqq}} - \frac{m_W}{m_t}}{\sigma_{R_W}}\right)^2 + \left(\frac{\frac{M_{bb}}{M_{bbc}} - \frac{m_h}{m_t}}{\sigma_{R_h}}\right)^2$$

- similar for background hypothesis ($t\bar{t}$ hadronic decays)

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

Preselection (before kinematic fit)

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

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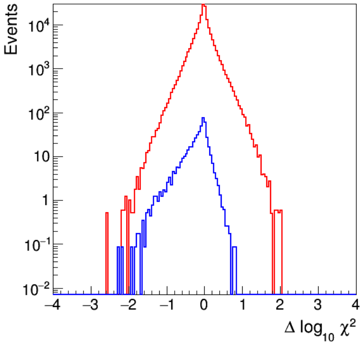
Final selection (after selecting best signal hypothesis)

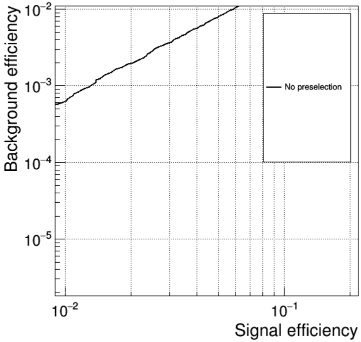
- cut on χ^2_{sig}
- cut on difference of reconstructed top masses
- cut on product of b-tag values for Higgs candidate
- cut on b-tag value for spectator b
- cut on sum of b-tag and c-tag for c jest candidate
- cut on χ^2_{sig}/χ^2_{bg}

Influence of selection cuts

Difference of $\log_{10}\chi^2$ for two hypothesis, for signal and background events

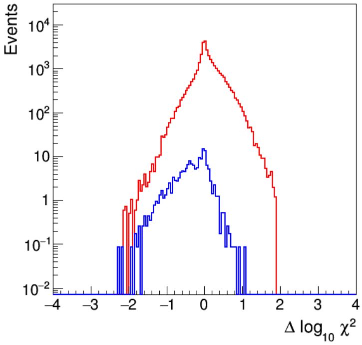


Background vs signal efficiency (normalized to all decay channels) after all cuts



Influence of selection cuts

Difference of $\log_{10} \chi^2$ for two hypothesis, for signal and background events



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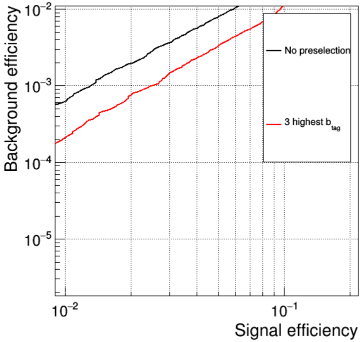

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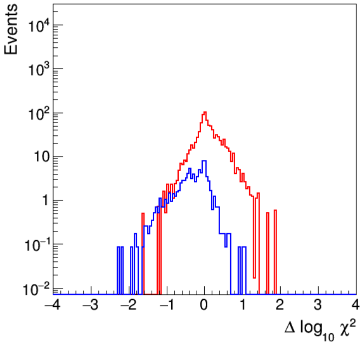

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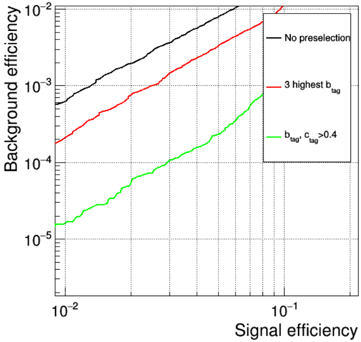

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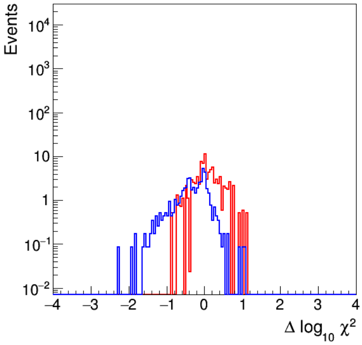

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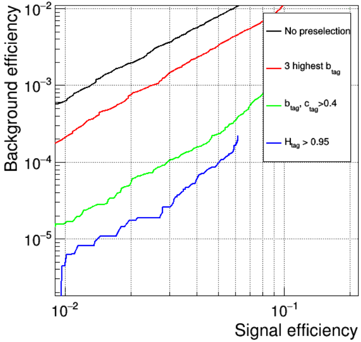

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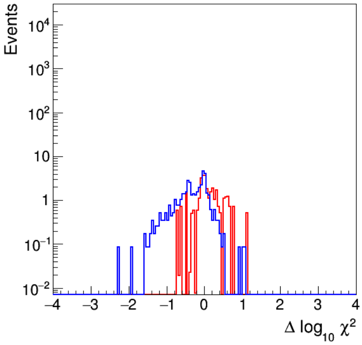

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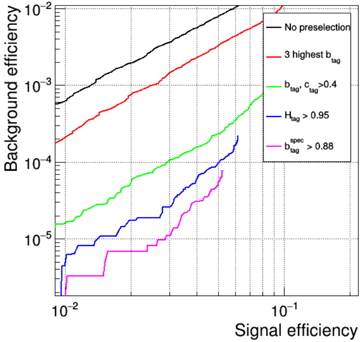

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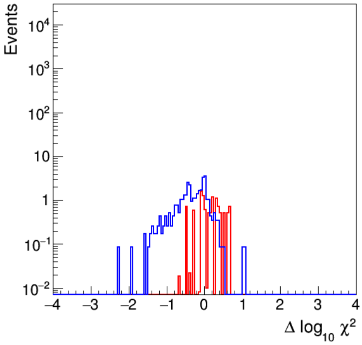

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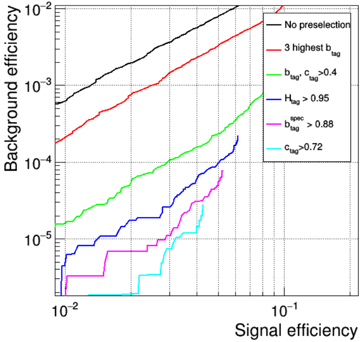
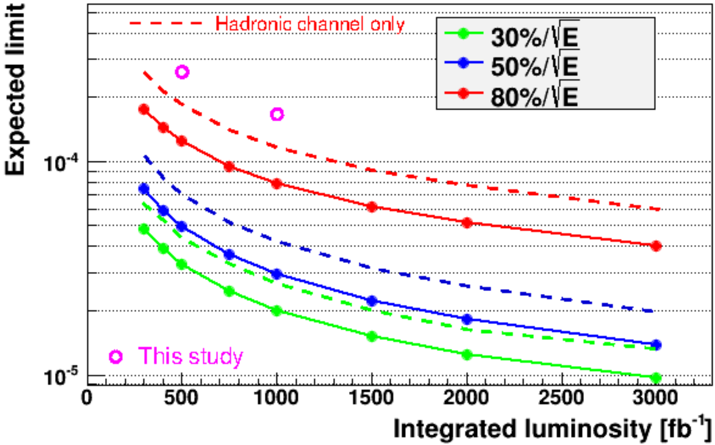


Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Collision energy 380 GeV, different jet energy resolutions



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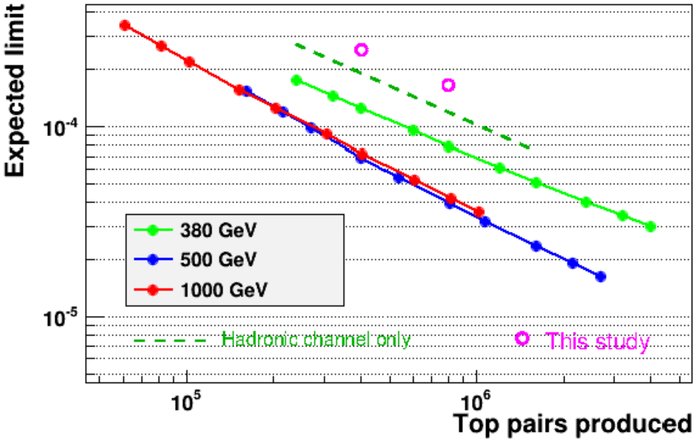
Jet energy resolutions of $80\%/\sqrt{E}$, different energies



FCNC top decays $t \rightarrow ch$

Preliminary results from full simulation at 380 GeV presented.

Focus on optimizing kinematic reconstruction in the hadronic channel

Expected limit at 500 fb^{-1}

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

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Better reconstruction should be possible at higher energies!

Backup slides

LCFI+ performance