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

Aleksander Filip Żarnecki

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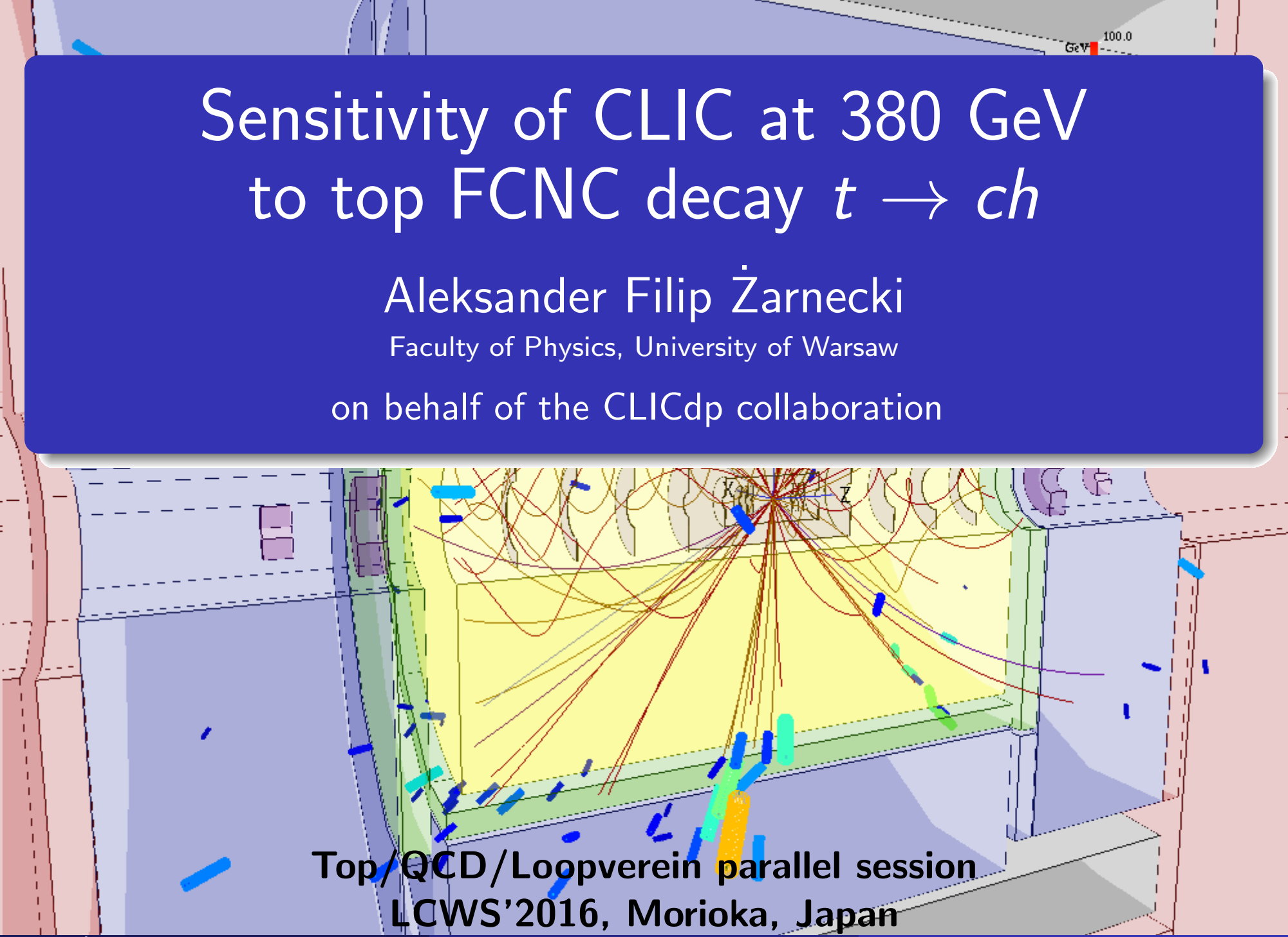
on behalf of the CLICdp collaboration



Top/QCD/Loopverein parallel session

LCWS'2016, Morioka, Japan

Outline

Motivation

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

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

Any signal is a direct signature of "new physics"...

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

- well constrained kinematics
- test of Higgs boson couplings
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LHC (2016):

$BR(t \to ch) < 0.40\%$ (CMS)

$BR(t \to ch) < 0.46\%$ (ATLAS)

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

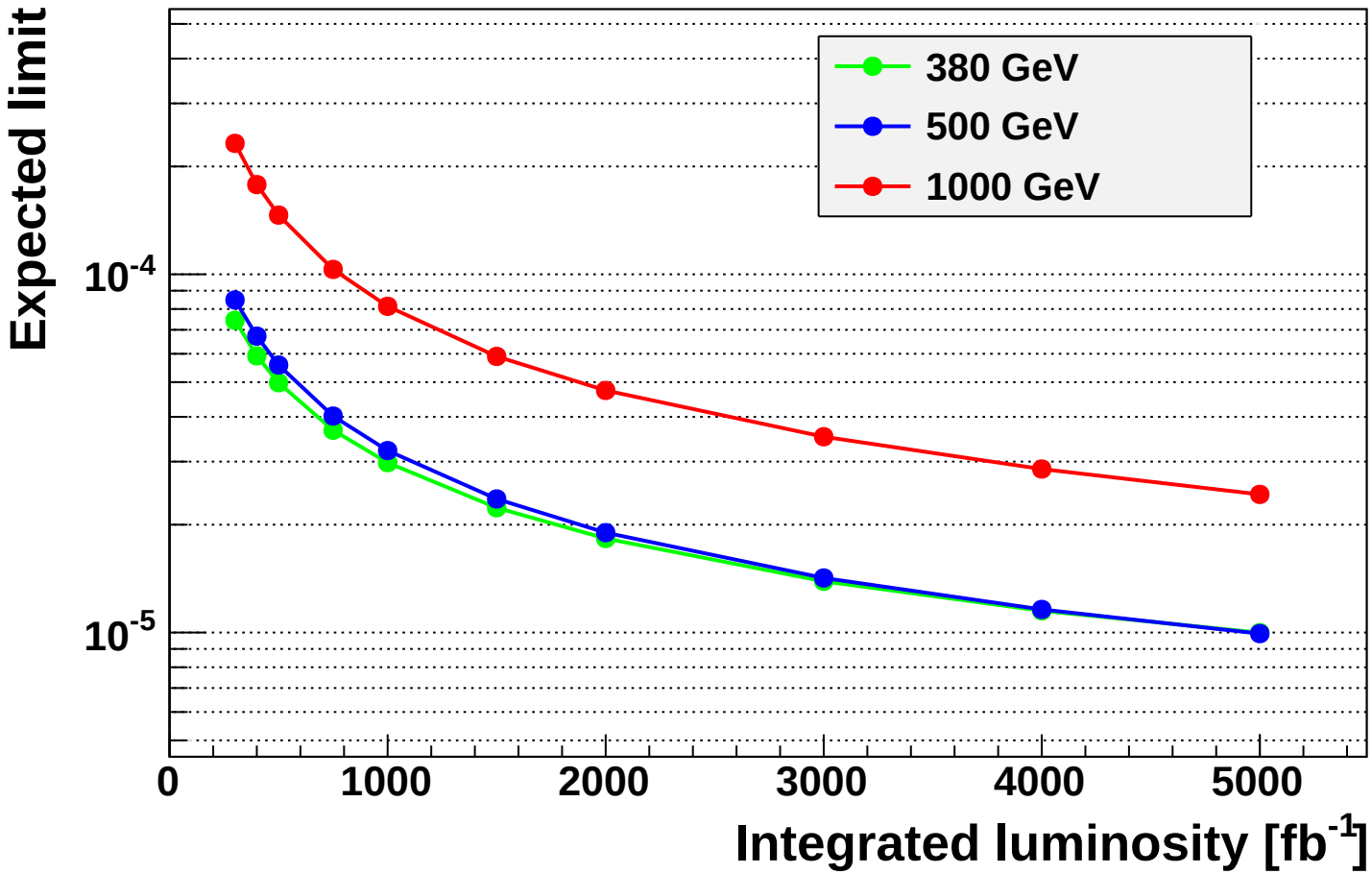
Motivation

Parton level study presented at TopLC'2015 [arXiv:1604.08122]

Promising results on the feasibility of the measurement

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

Assumed jet energy resolution $\sigma_E = 50\%/\sqrt{E}$ (5% above 100 GeV)



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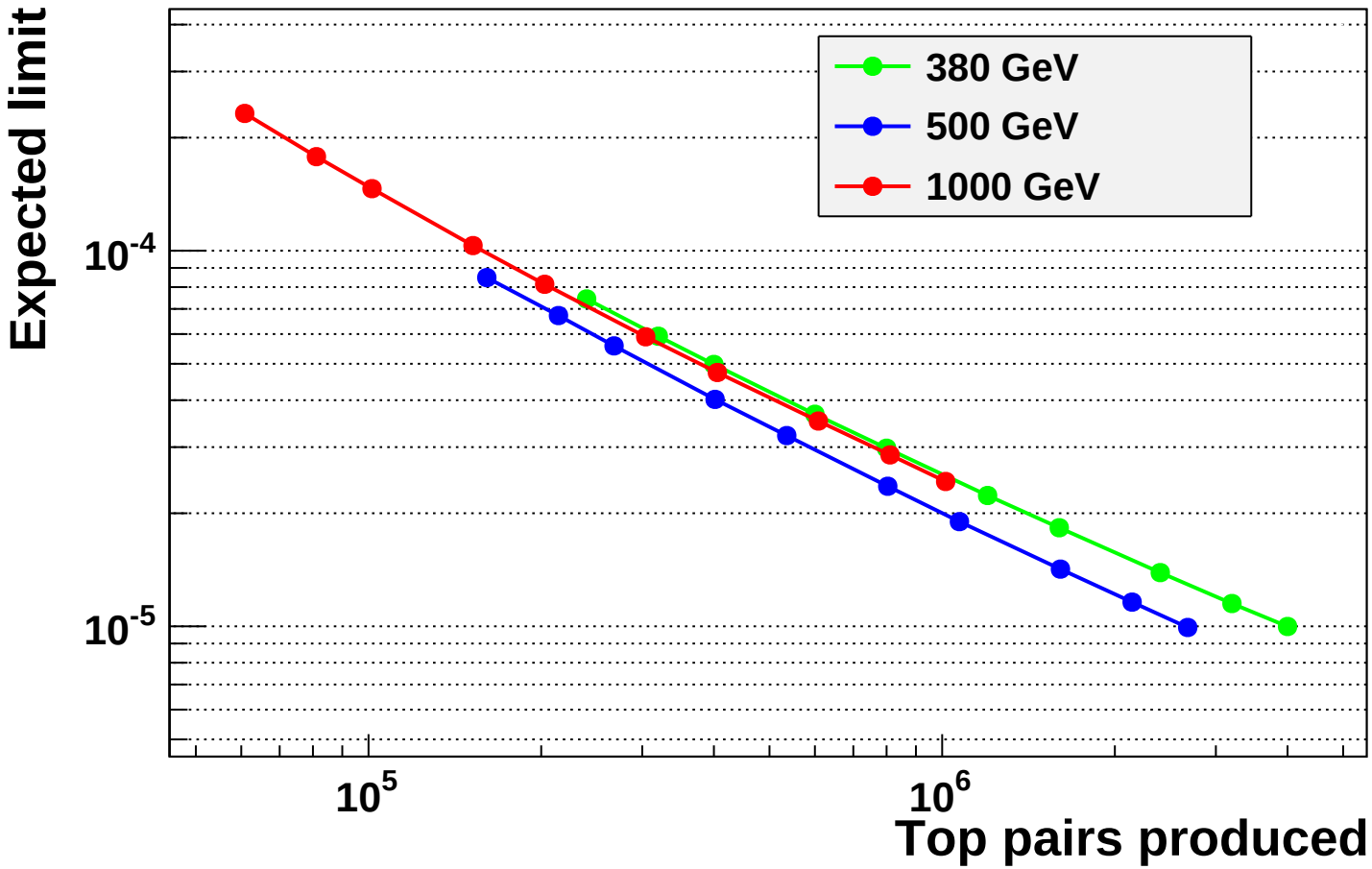

Signal

Signal sample generated with WHIZARD 2.2.8
Using SARAH implementation of 2HDM(III) model.

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 (10'000 events):

- $e^+e^- \longrightarrow ch_1\bar{t},\ t\bar{c}h_1$ (FCNC)
- $e^+e^- \longrightarrow t\bar{t}$ (test sample)
  for simulation validation

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Beam spectra for CLIC taken from file (350 GeV scaled to 380 GeV)

Beam polarization of -80%/0% (for e^-/e^+)

Hadronization done in PYTHIA 6.427
quark masses and PYTHIA settings adjusted to CLIC CDR

Standard event processing with CLIC_ILD_CDR500 configuration

Simulation

Background

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

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 in 18 subsamples.

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Normalisation

Signal and background samples normalised to 500 fb^{-1}

Assumed $t\bar{t}$ cross section at 380 GeV: 820 fb

575 fb (LO) $\times$ 1.34 (polarisation) $\times$ 1.4 (NLO) $\times$ 0.76 (spectra + ISR)

Event processing

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
- LCFI+ vertex corrections and flavour taging
  default weights used (no tuning), but seem to work OK
- root TTree writing

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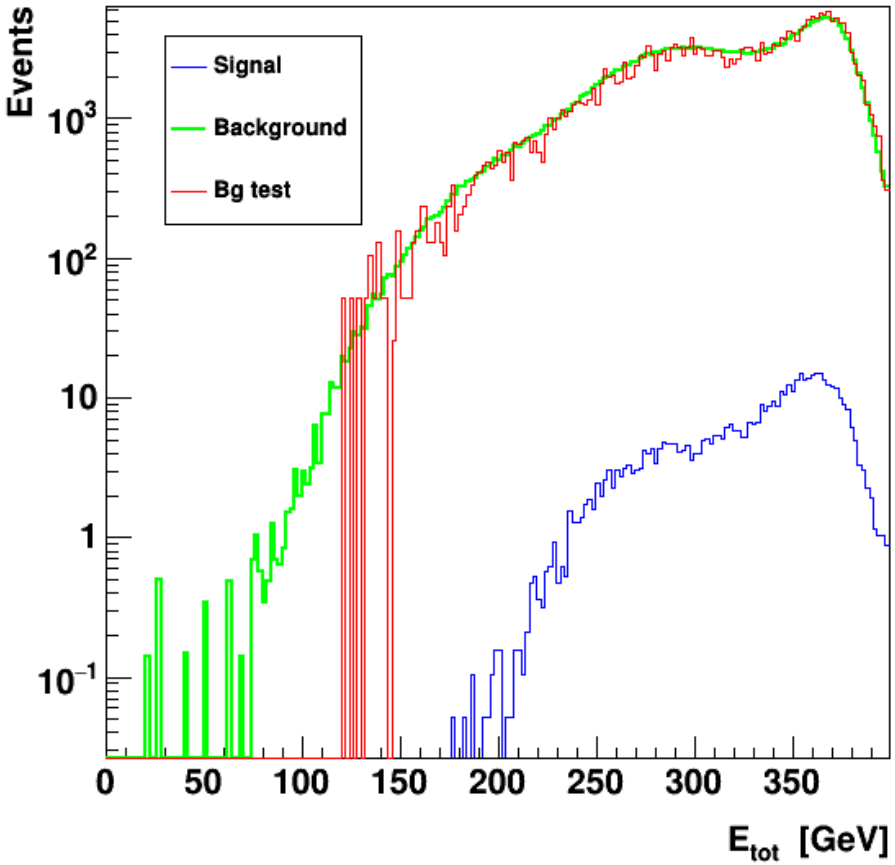
Final analysis in root:

- hadronic decay selection
- pre-selection cuts
- kinematic fit
- final selection

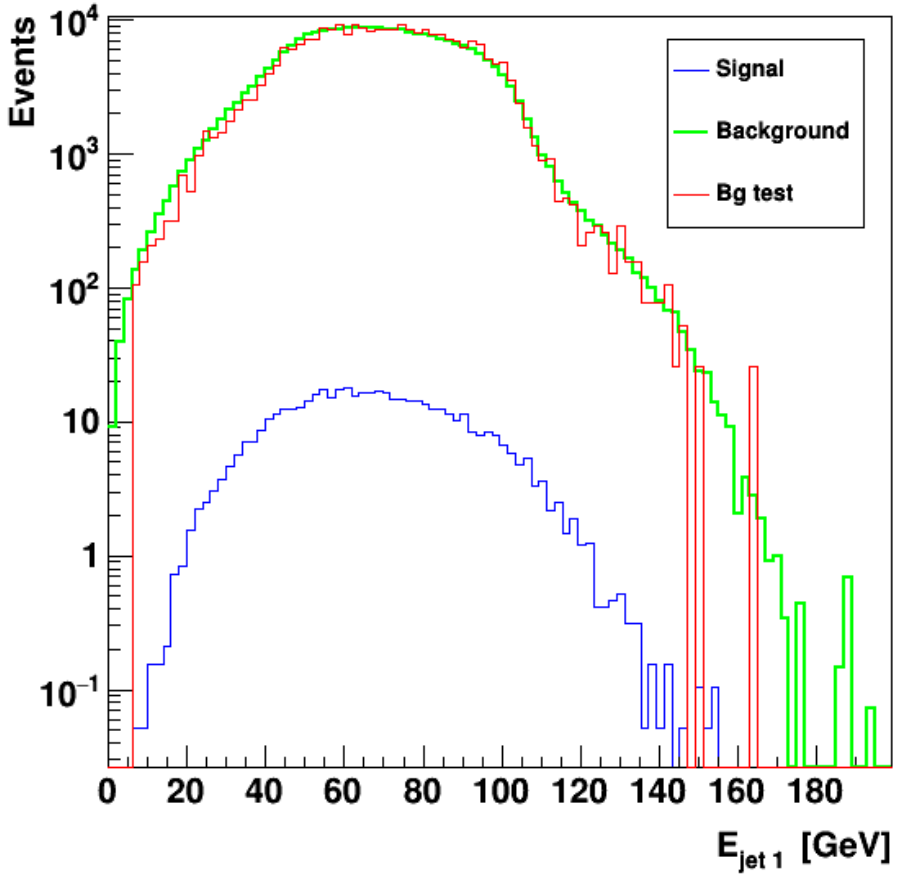
Control plots

Comparing signal sample with full background and test samples.

Total measured energy



Jet energy (highest b-tag)



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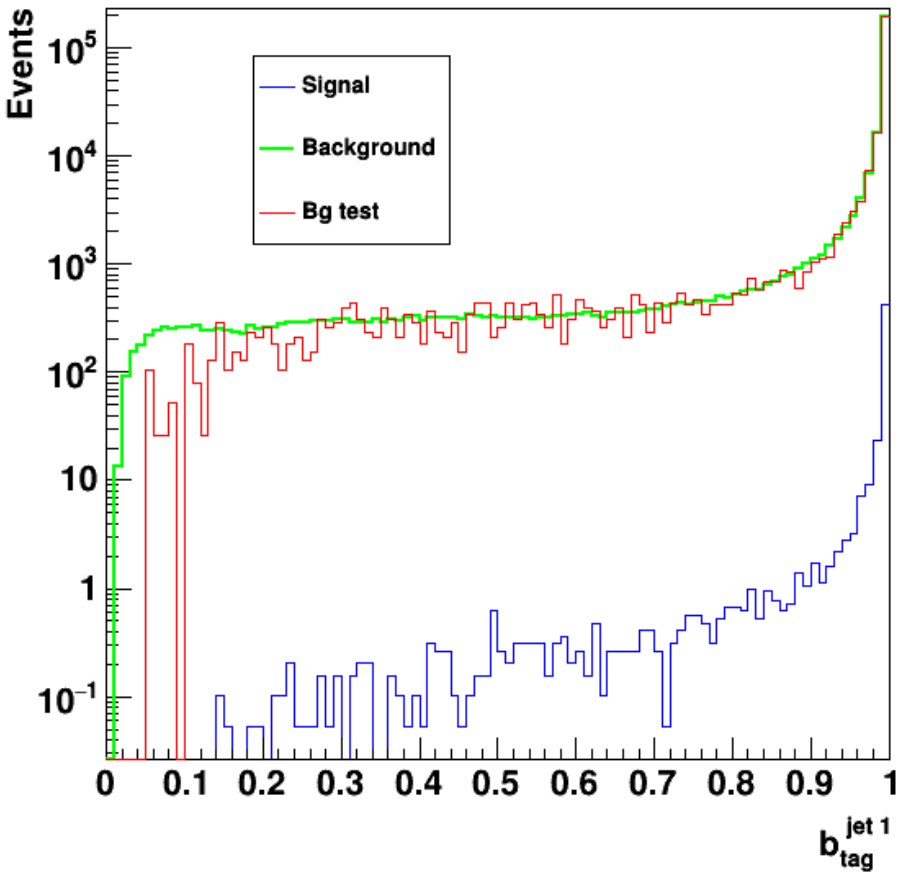
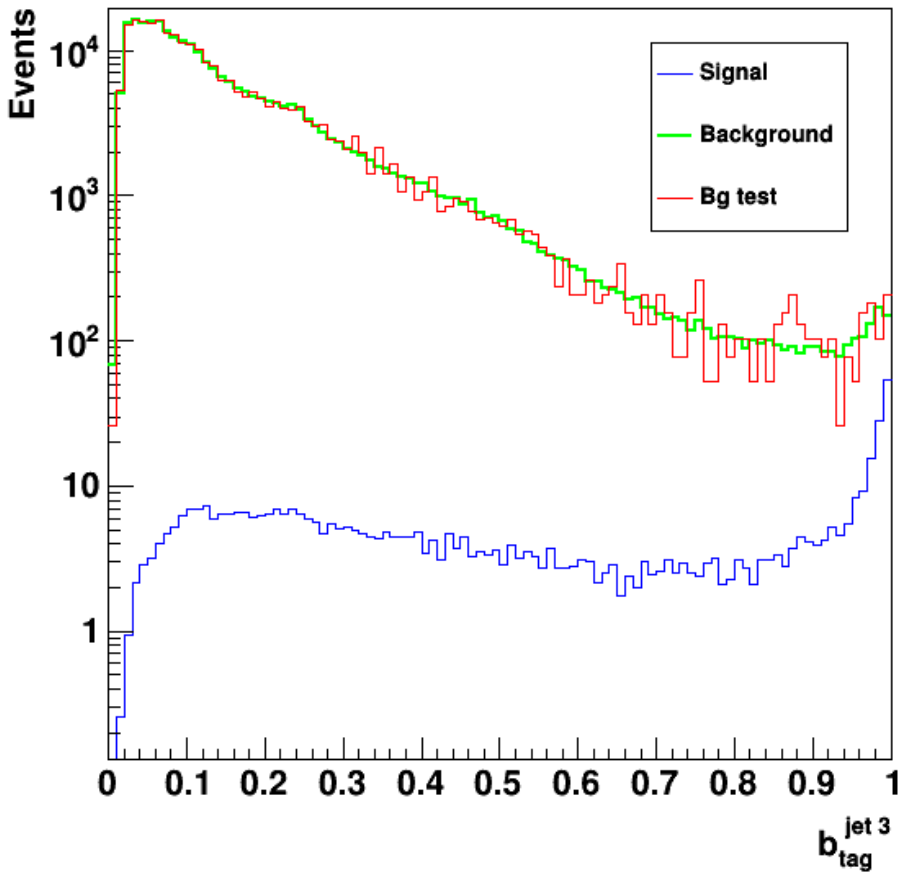
Highest b-tag value



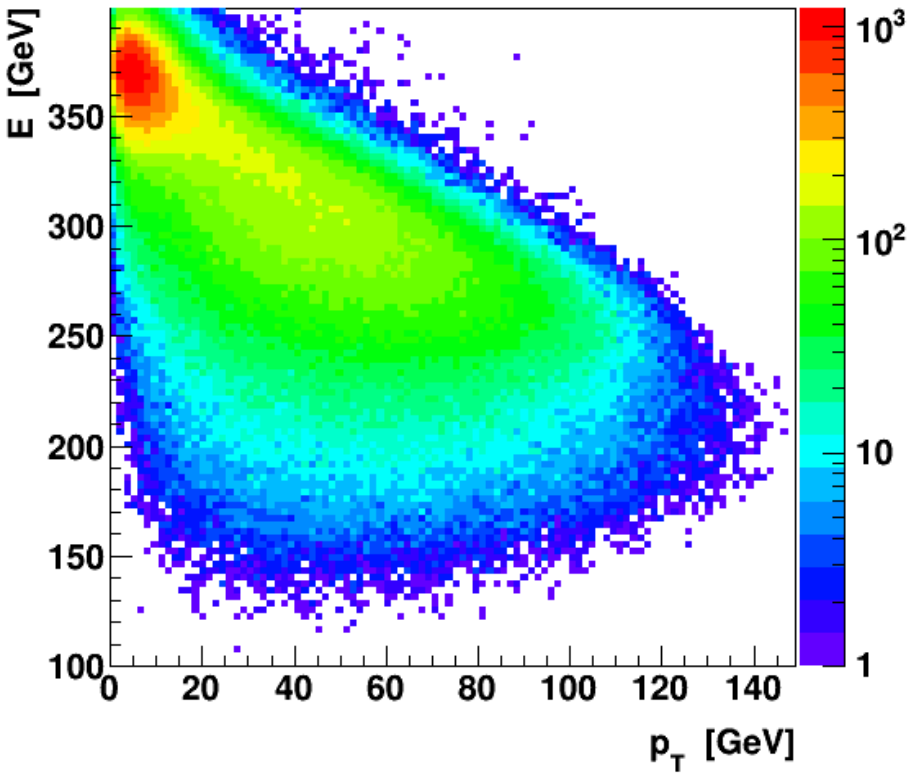
Third b-tag value



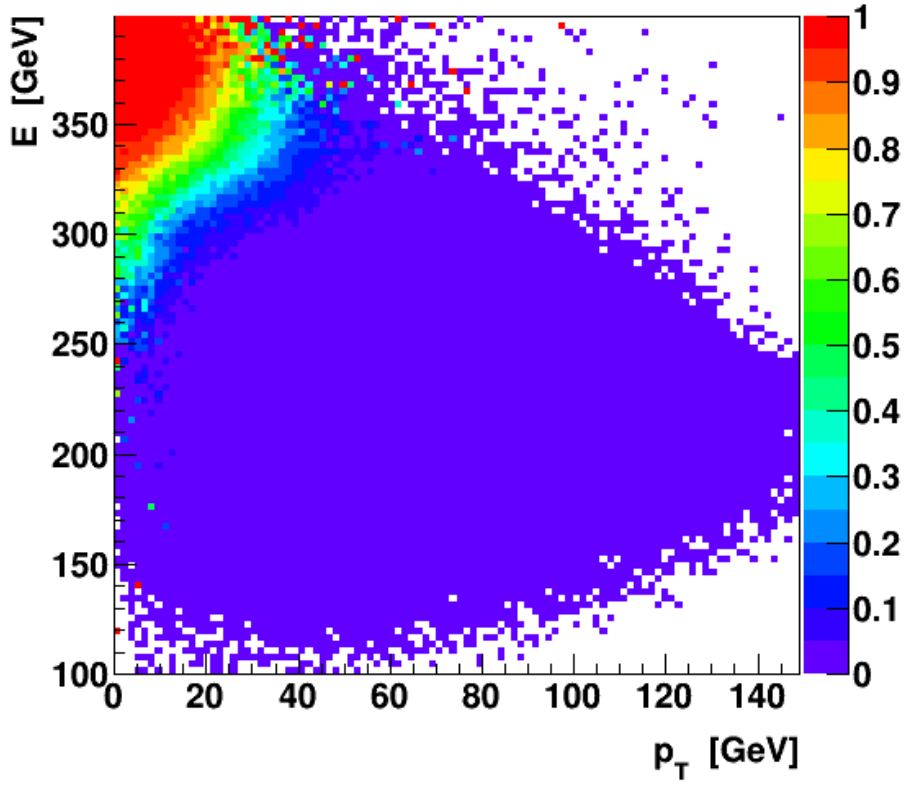
Hadronic event selection

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

Background event distribution



Hadronic event fraction



$\Rightarrow$ best discrimination (in this plane) with cut on $E - 2\,p_T$

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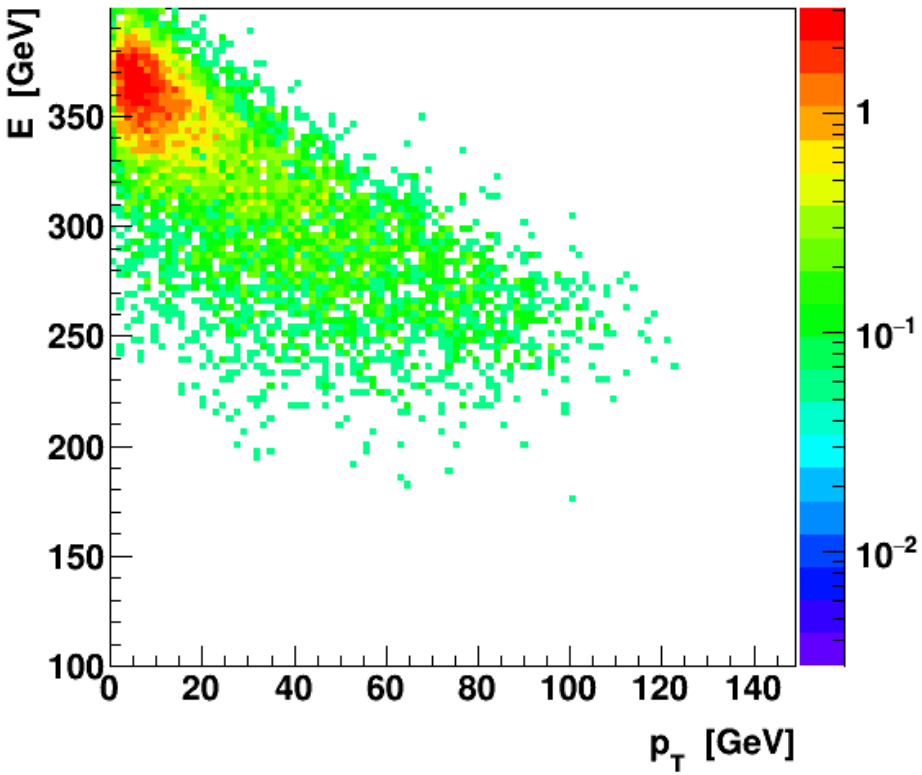

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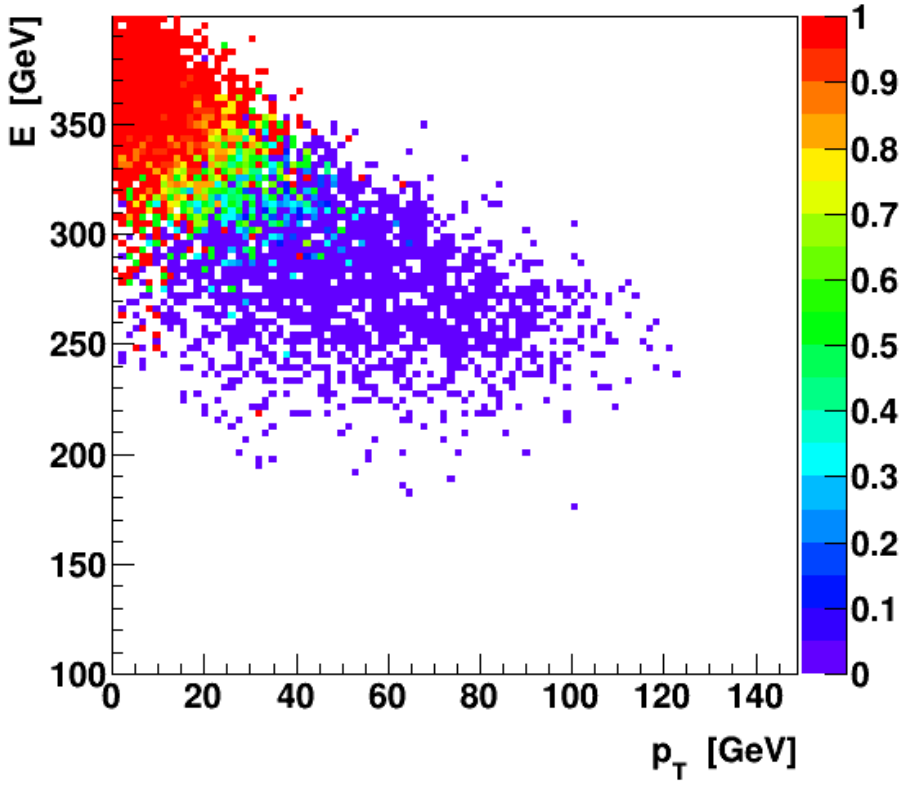

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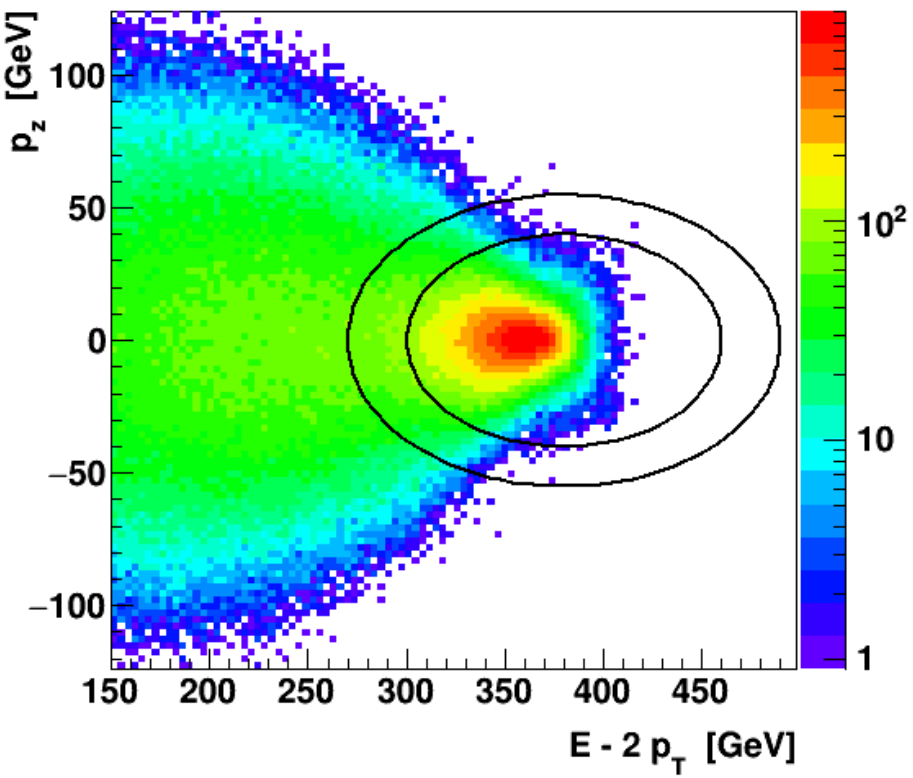
Hadronic event selection

Energy and transverse momentum correlated with longitudinal momentum

Background event distribution



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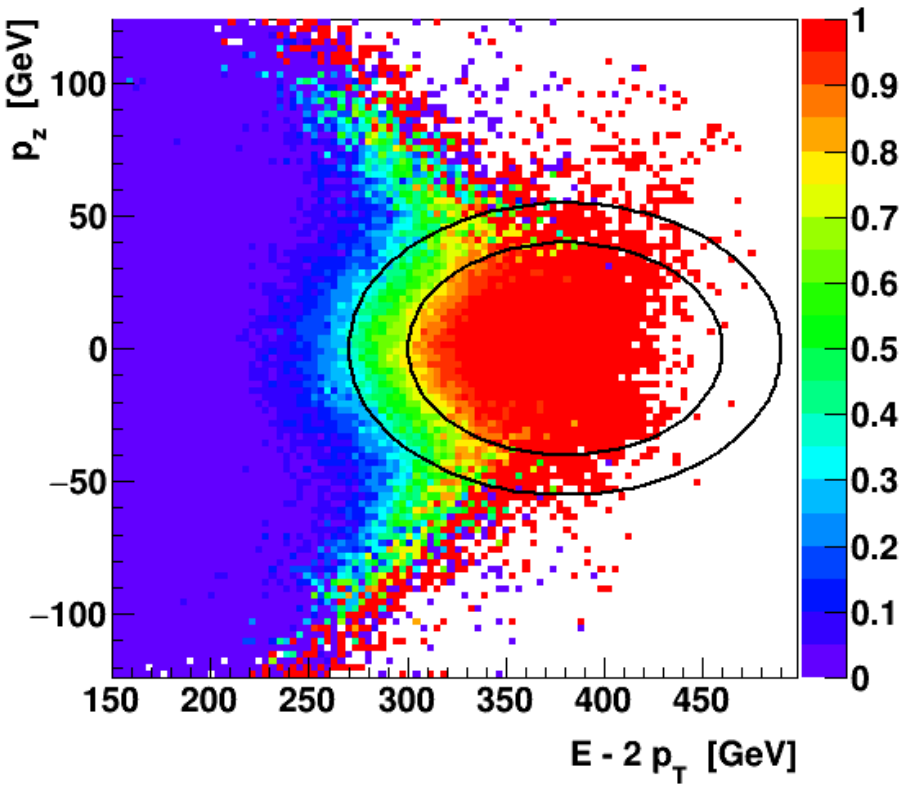

$\Rightarrow$ Use cut on $E_{balance} = \sqrt{(E - 2\,p_T - \sqrt{s})^2 + 4\,p_Z^2}$

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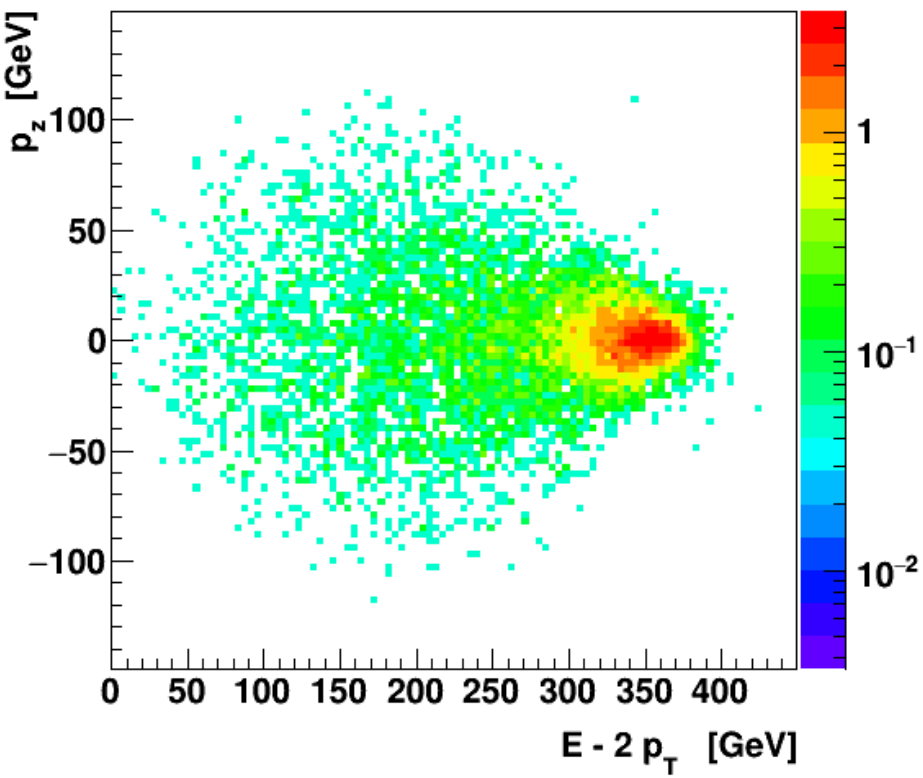

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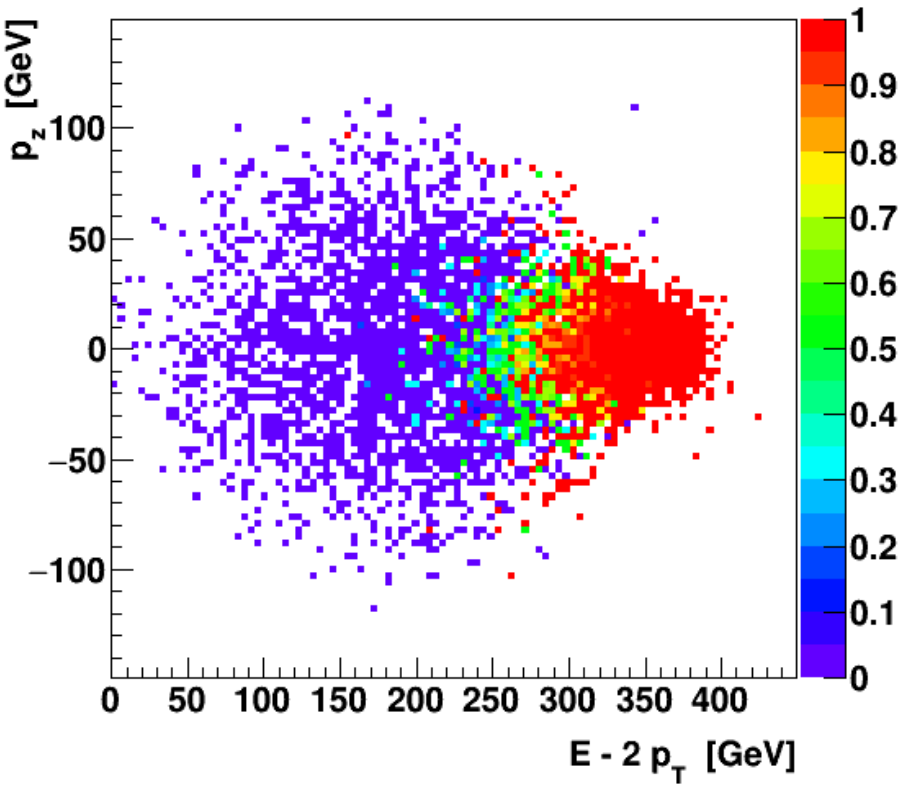

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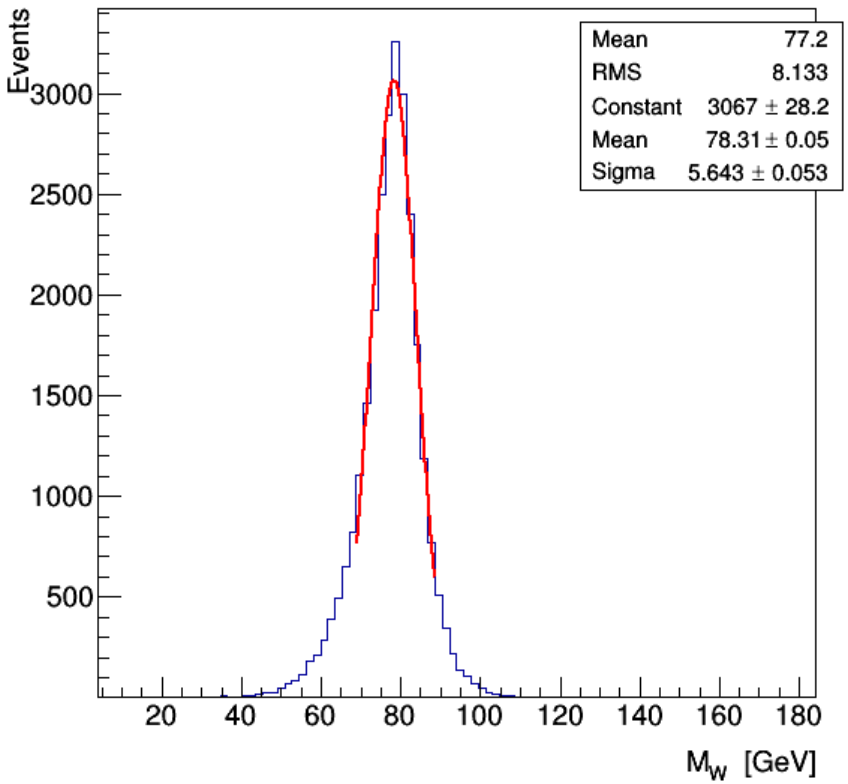
Mass resolution

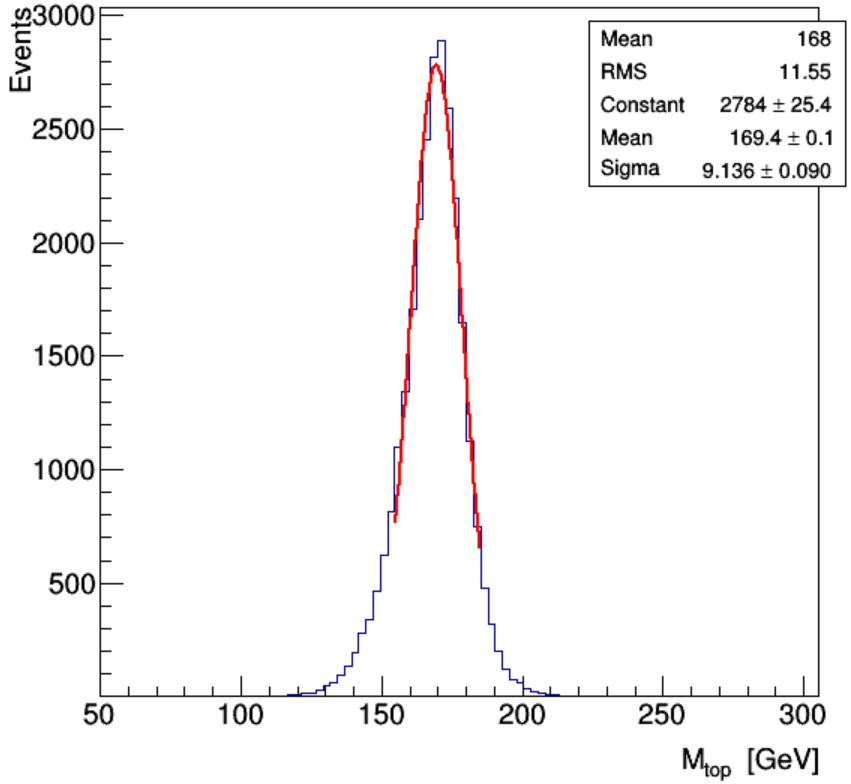
Reconstructed mass distributions for background events (Valencia jets)

For jet combination consistent with parton level configuration

W boson



Top quark



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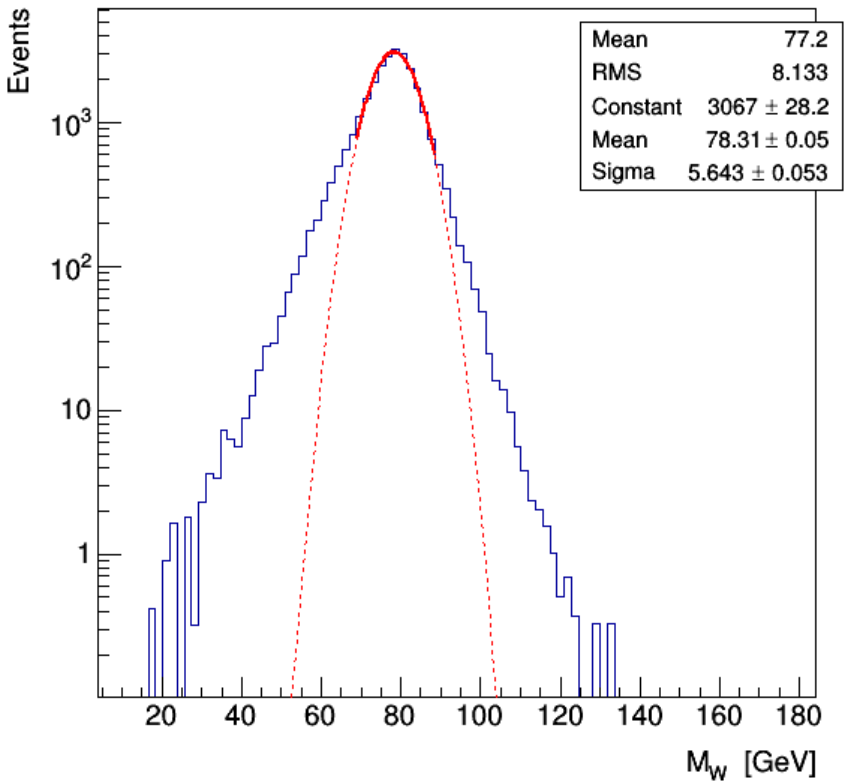

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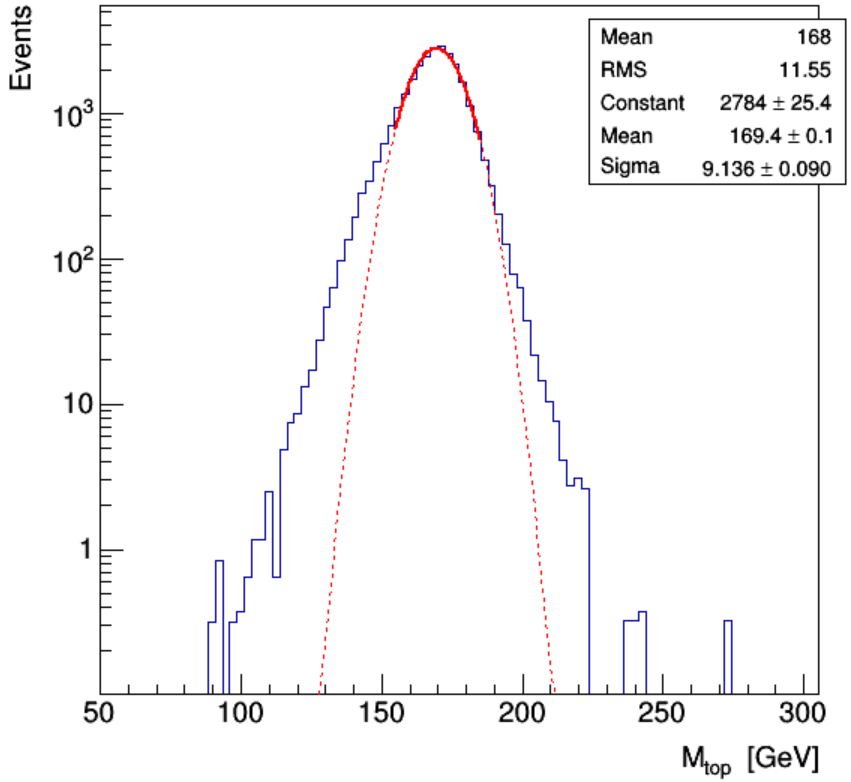
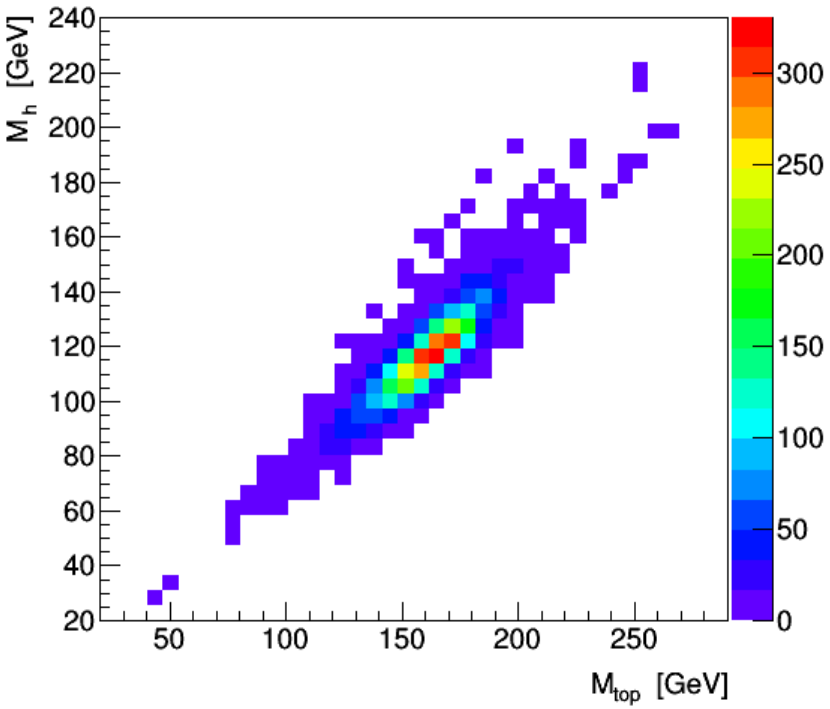


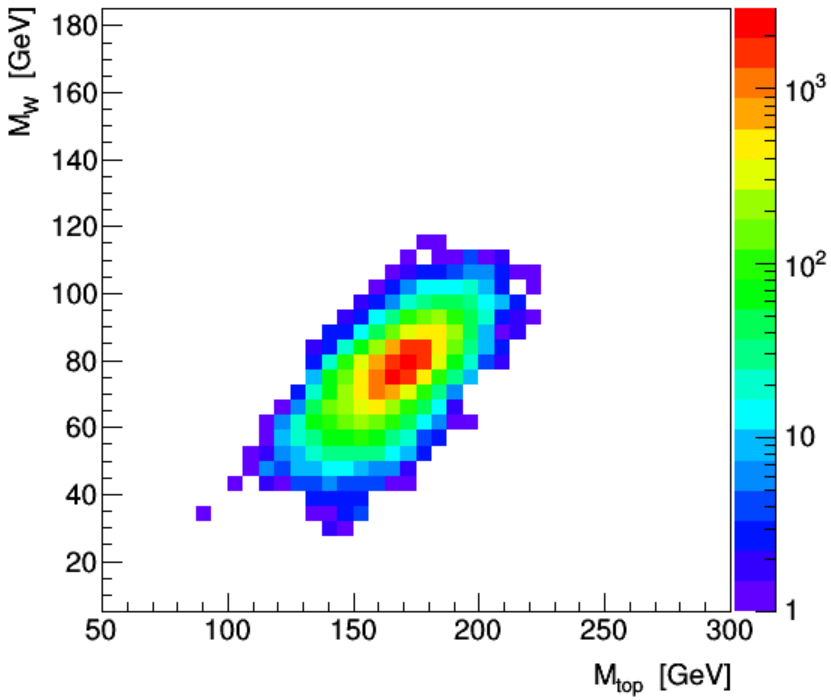
Mass correlation

Significant correlations observed between reconstructed masses of top (3 jets) and its decay product (2 jets)

Higgs and top (signal)



W boson and top (background)



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

Kinematic fit

Old χ^2 definition from previous, parton level study

Used to find best hadronic final state reconstruction (6 jets):

- background hypothesis $t\bar{t} \to bW\ bW \to 2b + 4q$

$$\chi^2_{bg} = \left(\frac{M^{(1)}_{bqq} - m_t}{\sigma_t}\right)^2 + \left(\frac{M^{(1)}_{qq} - m_W}{\sigma_W}\right)^2 + \left(\frac{M^{(2)}_{bqq} - m_t}{\sigma_t}\right)^2 + \left(\frac{M^{(2)}_{qq} - m_W}{\sigma_W}\right)^2$$

- signal hypothesis $t\bar{t} \to ch\ bW \to 3b + c + 2q$

$$\chi^2_{sig} = \left(\frac{M_{bqq} - m_t}{\sigma_t}\right)^2 + \left(\frac{M_{qq} - m_W}{\sigma_W}\right)^2 + \left(\frac{M_{bbc} - m_t}{\sigma_t}\right)^2 + \left(\frac{M_{bb} - m_h}{\sigma_h}\right)^2$$

Signal and background differ in the last term only!

New χ^2 definition

Using mass ratios to reduce influence of mass correlations:

- signal hypothesis — use also top boost as additional constrain

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

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

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

Event selection

Preselection (before kinematic fit)

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

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Final selection cuts (after selecting best signal hypothesis)

- quality of signal hypothesis (χ^2_{sig})
- the difference of reconstructed top masses (ΔM_{top})
- product of b-tag values for Higgs candidate
- b-tag value for b from spectator top
- sum of b-tag and c-tag values for c jet candidate
- χ^2_{sig}/χ^2_{bg} (final optimisation for best BR limit)

Expected events

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

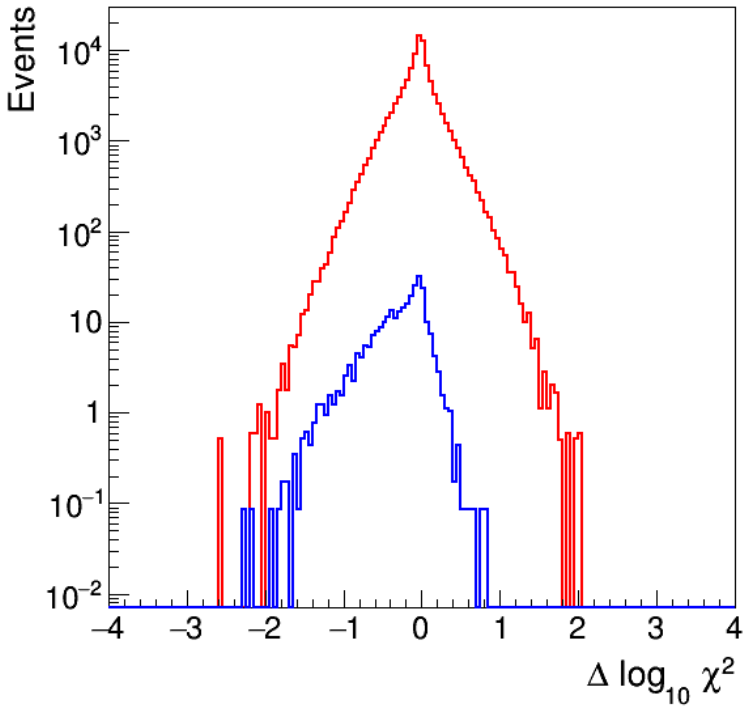
Analysis level / Selection cut	Expected events		Efficiency	
	$t\bar{t}$ (SM)	Signal	$t\bar{t}$ (SM)	Signal
All events	410'000	819	100%	100%
hadronic events	170'000	543	41.5%	66.3%
Before kinematic fit				
$E_{balance} < 100$ GeV	167'000	499	40.6%	60.9%
3 b jets tagged ($b_{tag} > 0.4$)	13'280	300	3.24%	36.6%
c jet tagged ($b_{tag}+c_{tag} > 0.4$)	9640	276	2.35%	33.8%
After kinematic fit				
Good fit ($\chi^2_{sig}<14$, $\Delta M_t<45$ GeV)	894	87	0.22%	10.7%
b-tag for higgs jets ($b_1 \times b_2 > 0.95$)	89.5	50.8	0.022%	6.2%
b and c tags ($b_3>0.9$, $c_4+b_4>0.75$)	10.7	34.1	$2.6 \cdot 10^{-5}$	4.2%
$\chi^2_{sig}/\chi^2_{bg} < 1.38$ (optimised for limit)	4.89	31.8	$1.2 \cdot 10^{-5}$	3.9%

Signal-background discrimination

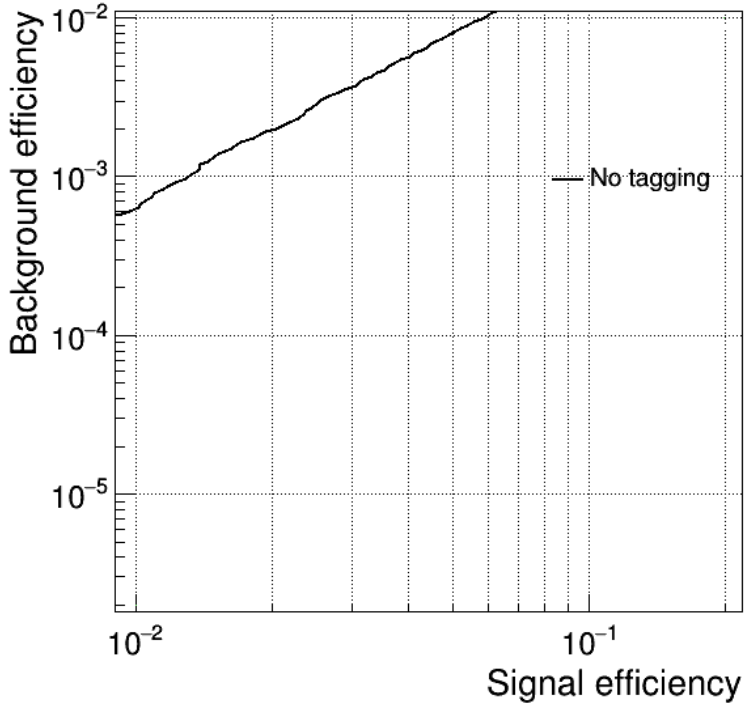
Based on the cut on the difference of $\log_{10}\chi^2$ for two hypothesis

Events with "good" fit of signal hypothesis ($\chi^2_{sig} < 14$, $|\Delta M_{top}| < 45$ GeV)

$\Delta \log_{10}\chi^2$ distribution for signal and background



Background vs signal efficiency after subsequent cuts



normalized to all decay channels

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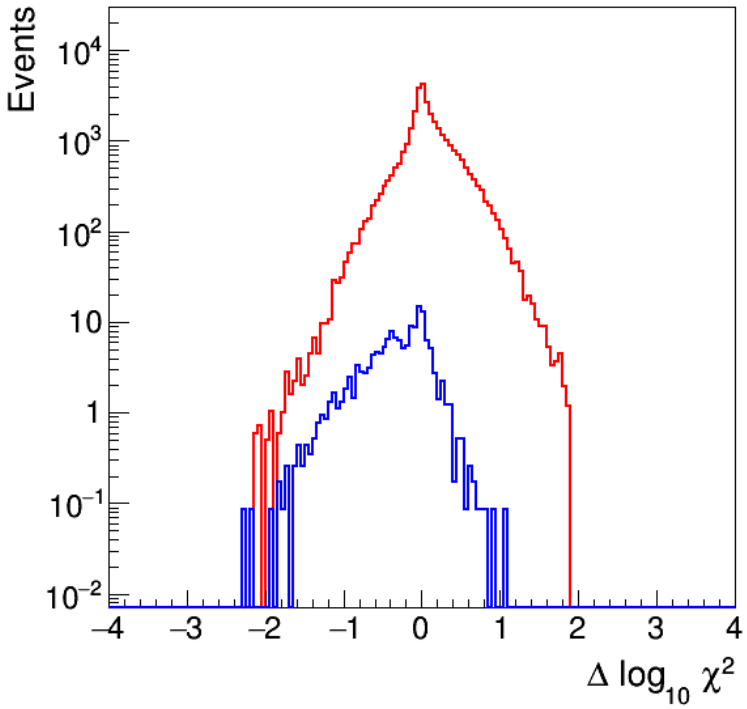

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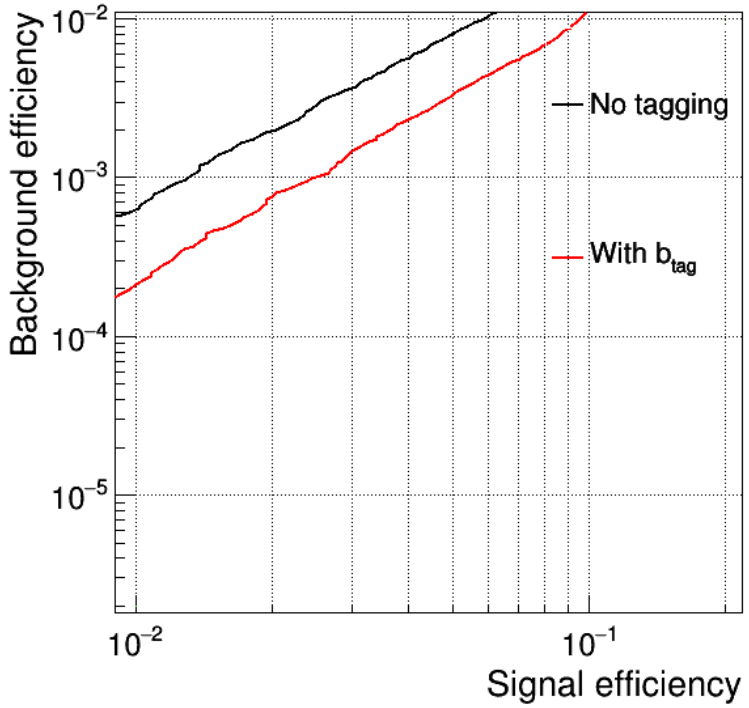

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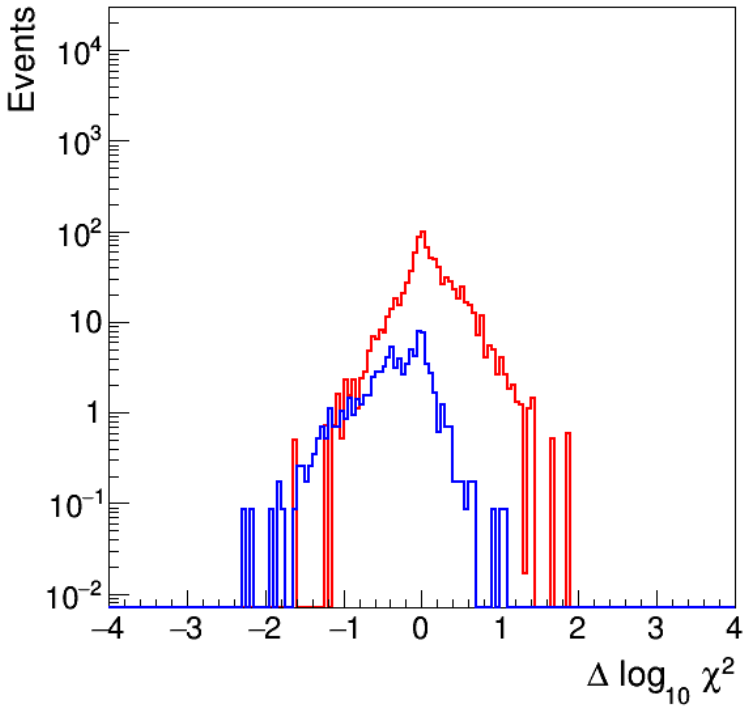

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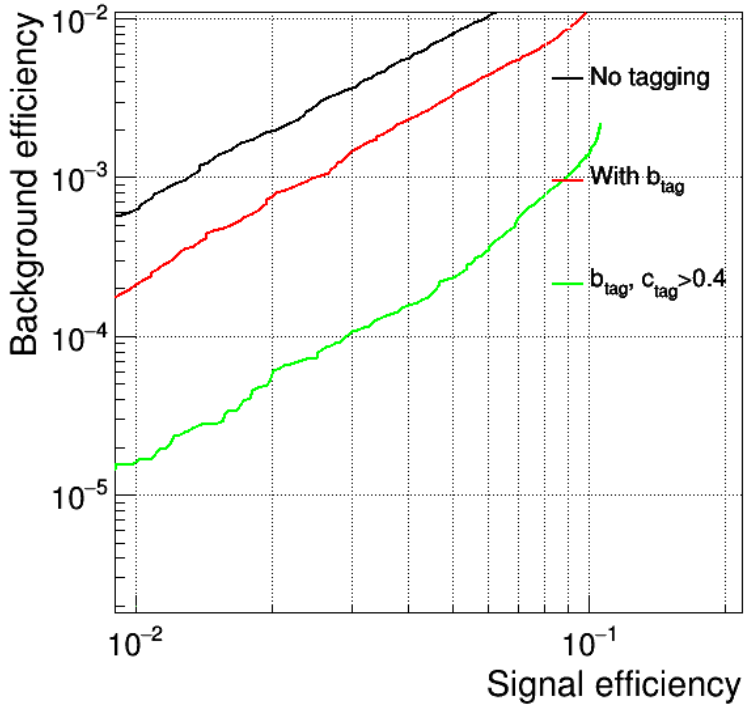

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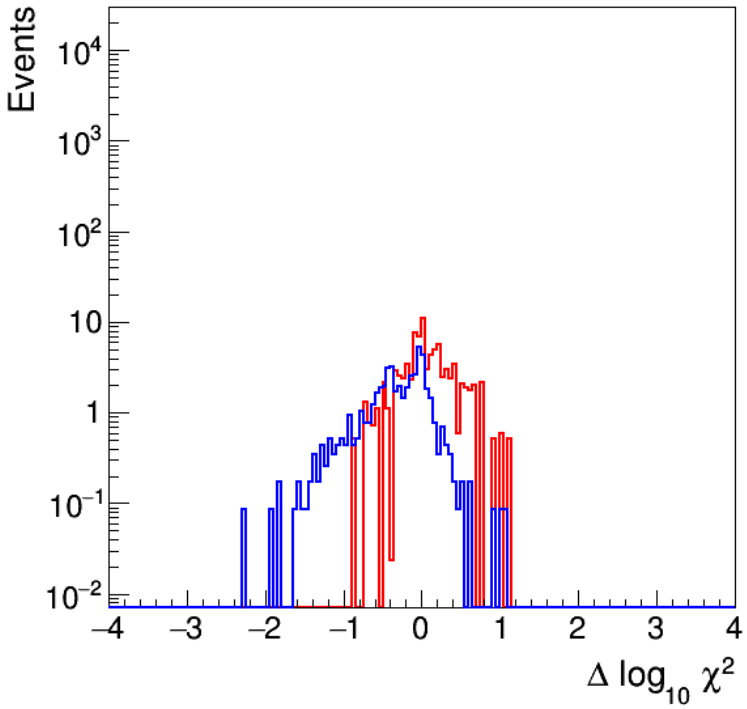

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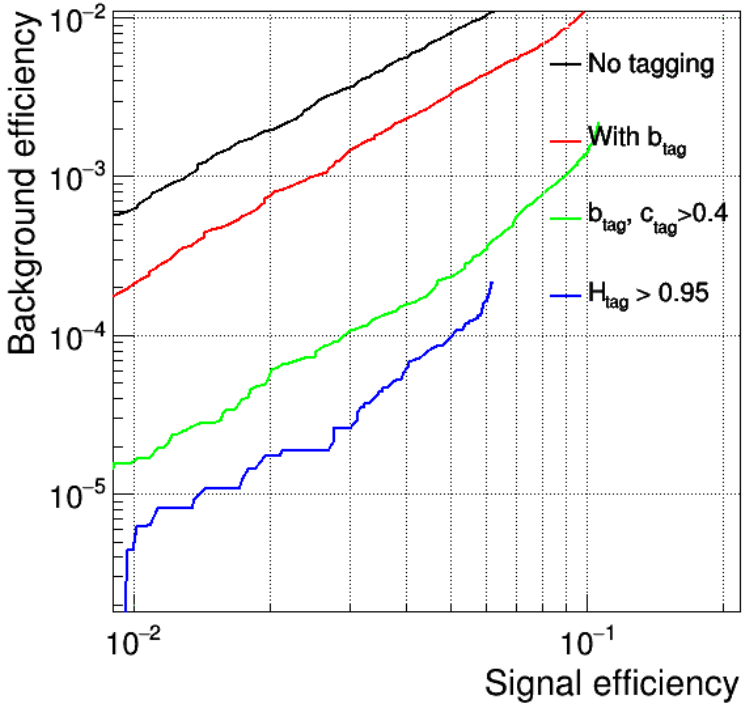

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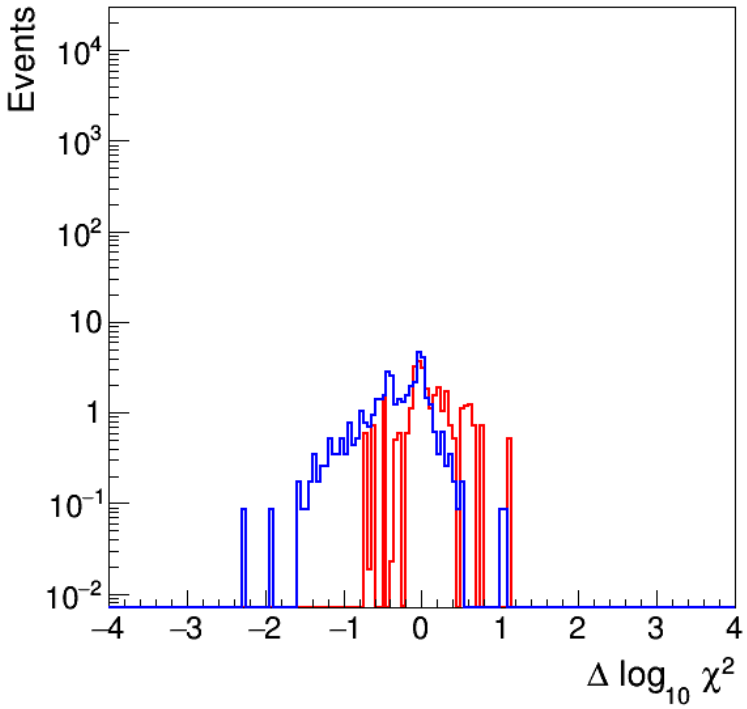
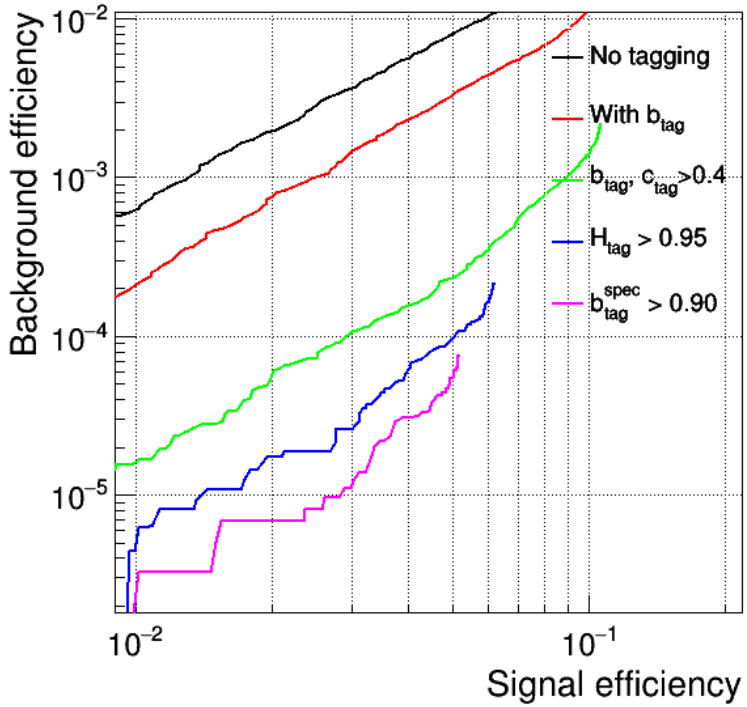


Background vs signal efficiency after subsequent cuts



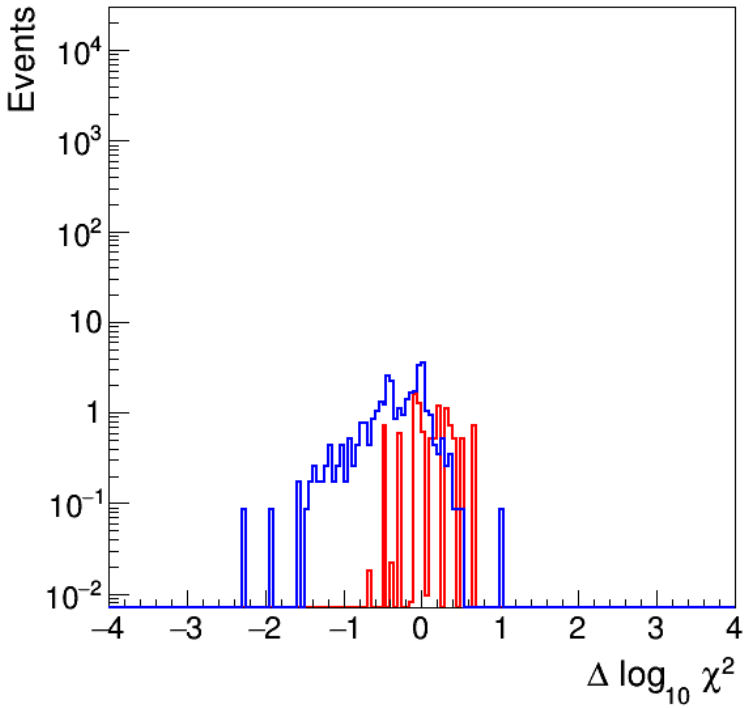
normalized to all decay channels

Signal-background discrimination

Based on the cut on the difference of $\log_{10}\chi^2$ for two hypothesis

Events with "good" fit of signal hypothesis ($\chi^2_{sig} < 14$, $|\Delta M_{top}| < 45$ GeV)

$\Delta \log_{10}\chi^2$ distribution for signal and background



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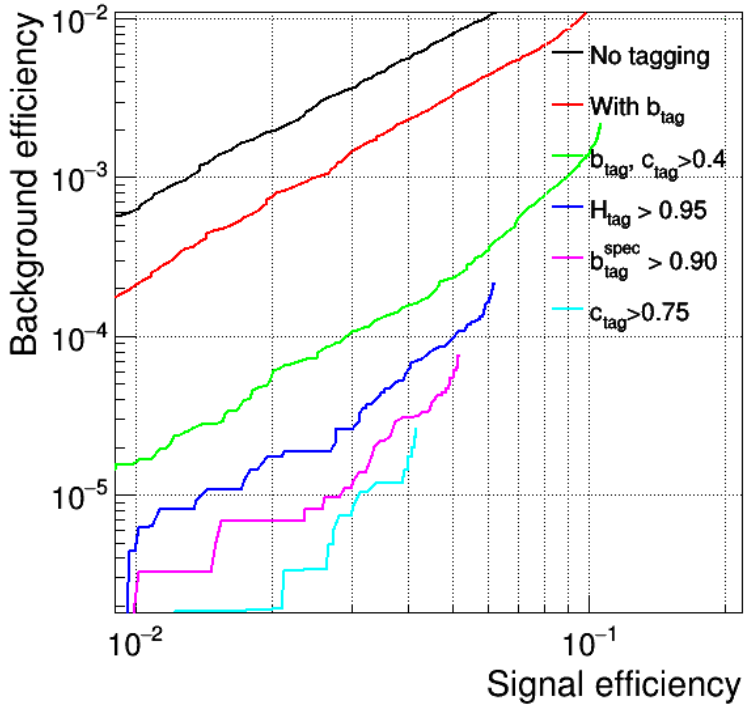


normalized to all decay channels

Expected limits

Cuts were optimised for the best expected BR limit.

Final signal selection efficiency: 3.9% (5.9% for hadronic decays)
Background suppression: $1.2 \cdot 10^{-5}$

Expected 95% C.L. limit for 500 fb^{-1} at 380 GeV

$$BR(t \to ch) \times BR(h \to b\bar{b}) \quad < \quad 2.6 \cdot 10^{-4}$$

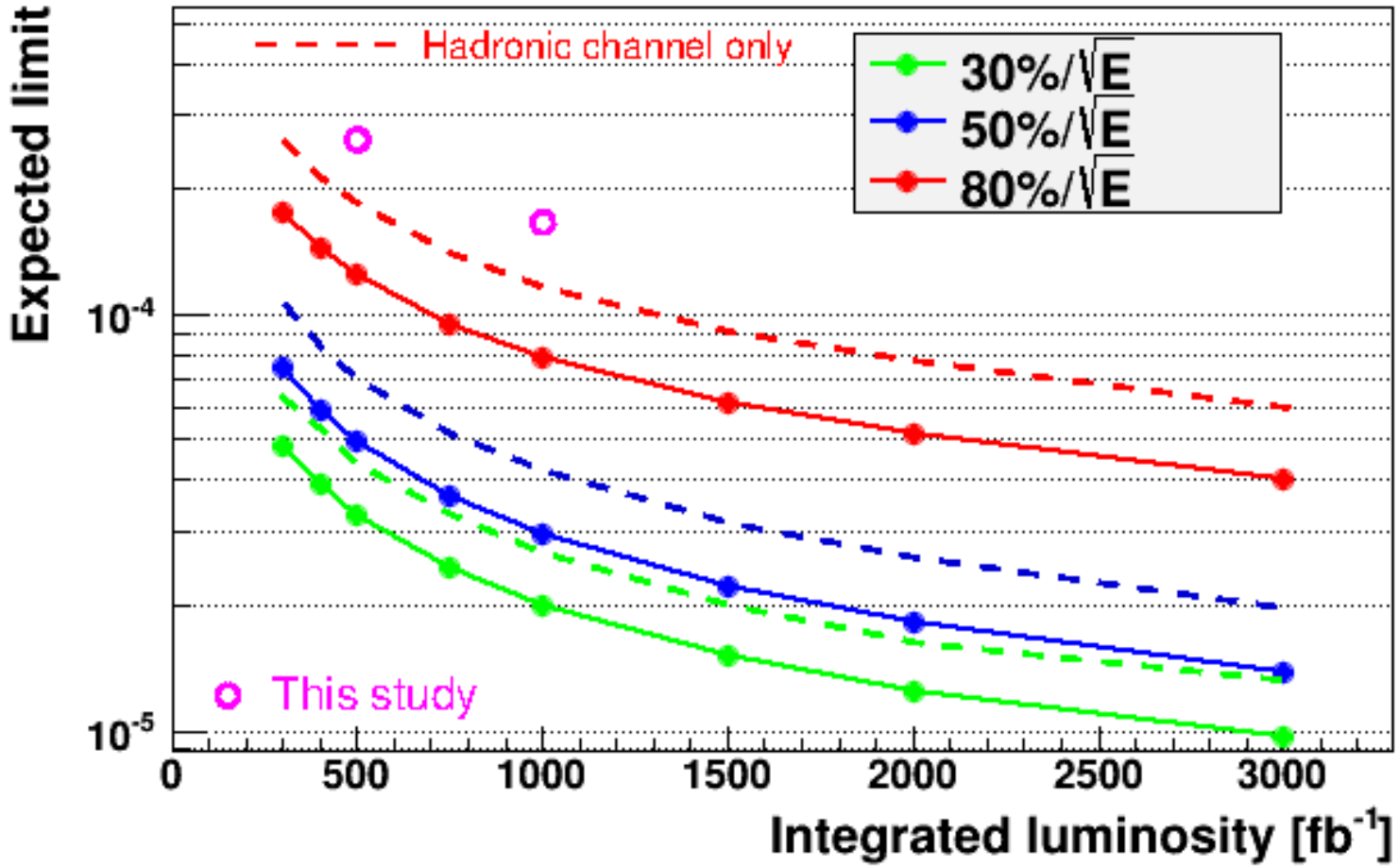
With luminosity of 1000 fb^{-1} at 380 GeV

$$BR(t \to ch) \times BR(h \to b\bar{b}) \quad < \quad 1.7 \cdot 10^{-4}$$

assuming $t\bar{t}$ cross section at 380 GeV of 820 fb

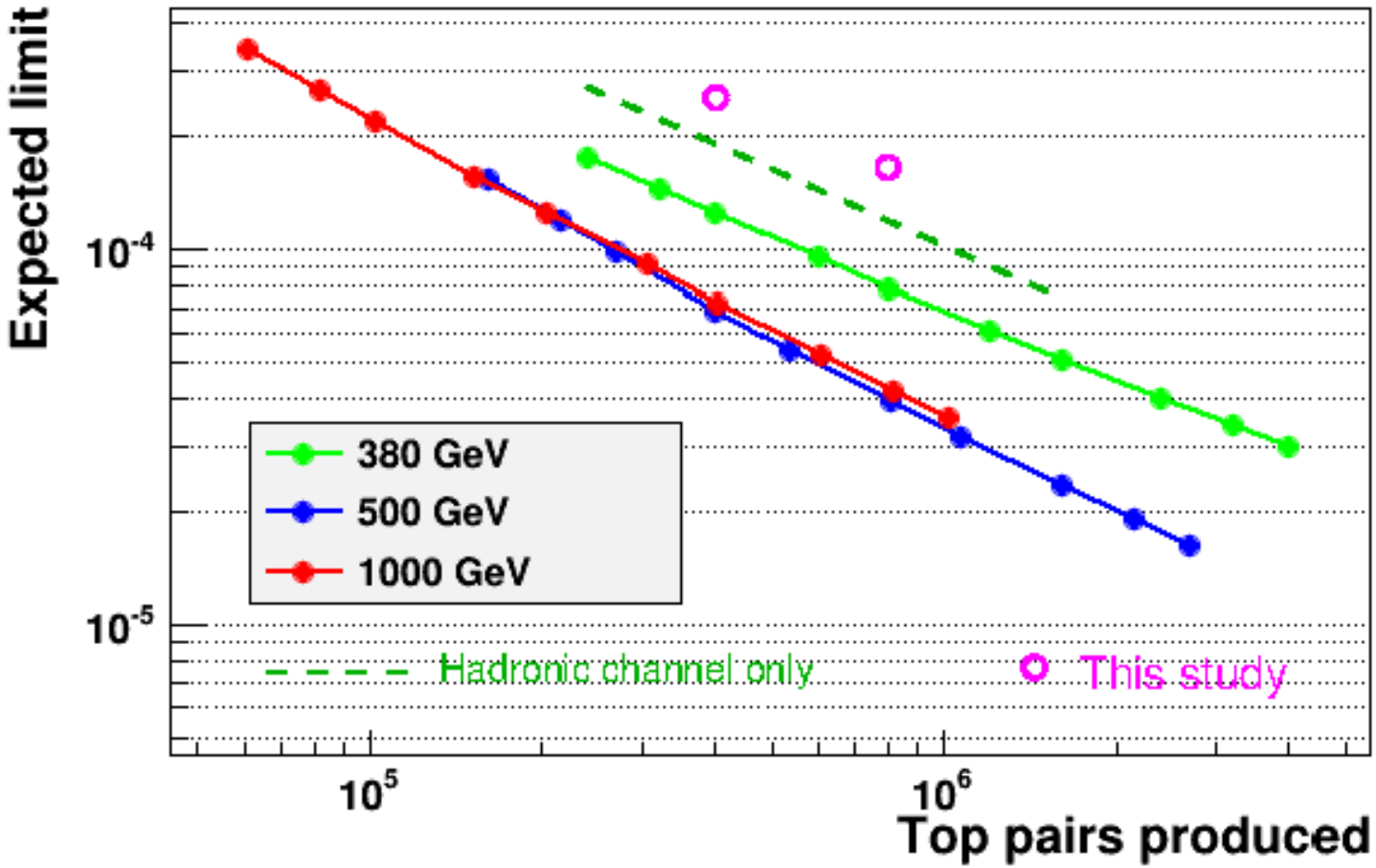
Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Comparison with parton level results, different jet energy resolutions



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

Comparison with parton level results, jet energy resolutions of $80\%/\sqrt{E}$, different energies



Conclusions

FCNC top decays $t \to ch$

Preliminary results from full simulation at 380 GeV presented.

Focus on optimizing kinematic reconstruction in the hadronic channel

Expected limit at 500 fb^{-1}

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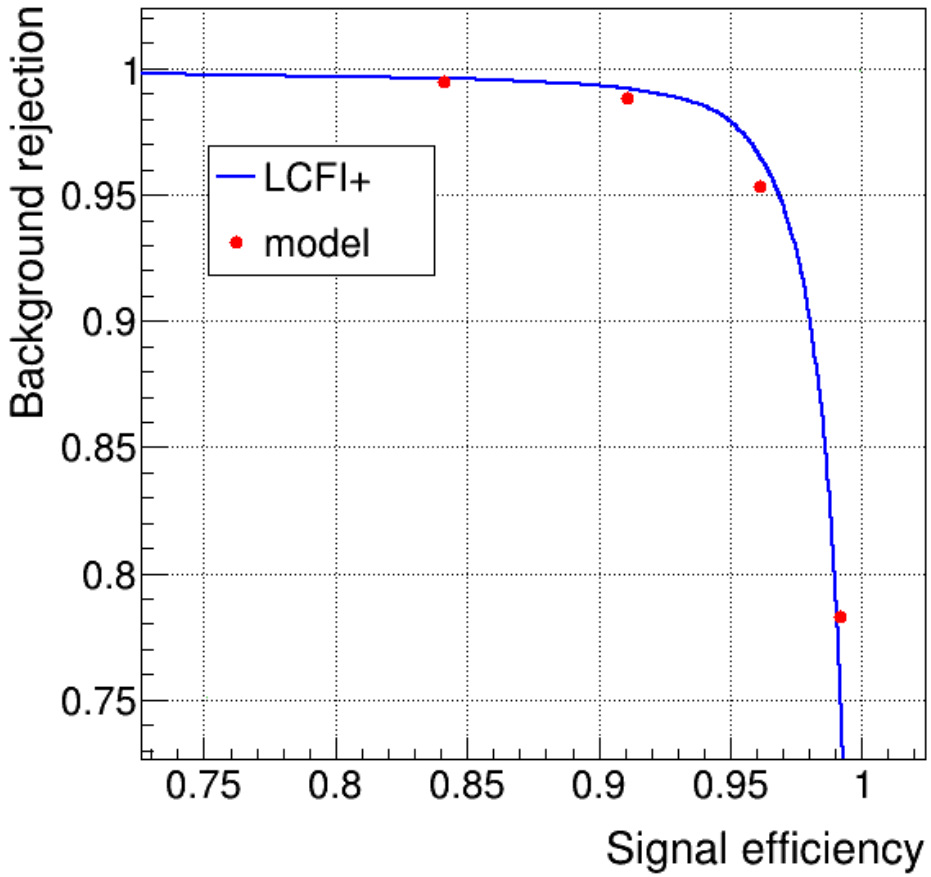
Better reconstruction should be possible at higher energies!

Backup slides

LCFI+ performance

Comparison of LCFI+ performance in full simulation analysis with model assumed in the parton level study



Signal: events with 2 b jets (ssubbu) Background: events without b jets (ssussu)

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%