Flavor-changing top-quark decays at CLIC

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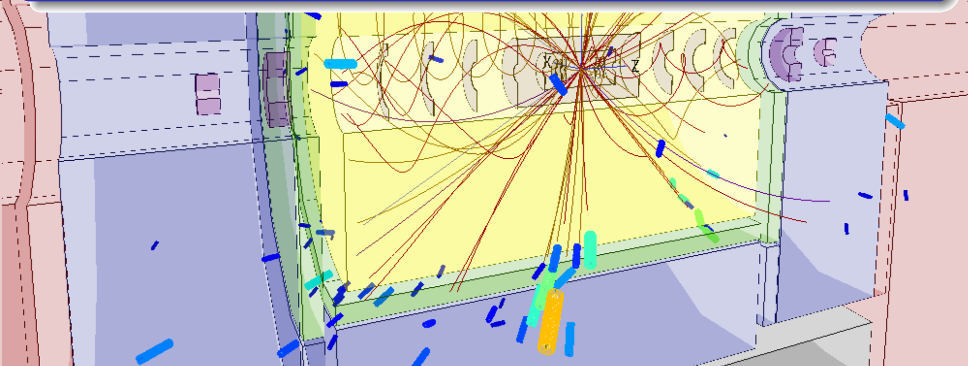
on behalf of the CLICdp Collaboration



Workshop on Top physics at the LC 2018

Outline

Top quark decays

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

$$t \rightarrow W^+ b \quad \text{dominant, BR} = 99.8\%$$
$$t \rightarrow W^+ s/d \quad \text{CKM suppressed}$$

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

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

Motivation

Top quark decays

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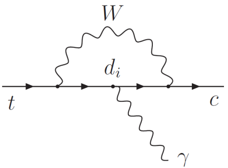
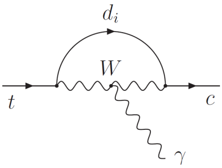
However, leading order diagrams suppressed by CKM matrix unitarity

$t \rightarrow c\,\gamma$





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

Predictions

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

$$
\begin{aligned}
BR(t \rightarrow c\,\gamma) &\sim 5 \cdot 10^{-14} \\
BR(t \rightarrow c\,h) &\sim 3 \cdot 10^{-15} \\
BR(t \rightarrow c\,Z) &\sim 1 \cdot 10^{-14} \\
BR(t \rightarrow c\,g) &\sim 5 \cdot 10^{-12}
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Any signal is a direct signature of "new physics"...

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Any signal is a direct signature of “new physics”...

Significant enhancement possible in many BSM scenarios

Maximum branching fractions possible:

Model	2HDM	MSSM	$\not R$ SUSY	LH	Q singlet	RS
BR($t \rightarrow c\,\gamma$)	10^{-6}	10^{-6}	10^{-5}	10^{-7}	$8 \cdot 10^{-9}$	10^{-9}
BR($t \rightarrow c\,h$)	10^{-2}	10^{-4}	10^{-6}	10^{-5}	$4 \cdot 10^{-5}$	10^{-4}

Motivation

Constraints

95% C.L. limits from LHC experiments

$$BR(t \to c\gamma) \; < \; 0.17\% \;\; \text{(CMS)}$$

$$BR(t \to ch) \; < \; 0.40\% \;\; \text{(CMS)}$$

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Expectations

Limits expected after HL-LHC running (3 ab^{-1} at 14 TeV)

$$BR(t \to c\gamma) < 2.0 - 3.4 \cdot 10^{-4} \text{ (CMS)}$$
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e^+e^- colliders

Can be competitive for selected channels thanks to high statistics of produced top quarks, clean environment and well constrained kinematics.

Framework

Dedicated samples generated with WHIZARD 2.2.8
Background samples generated previously with WHIZARD 1.95

Detailed beam spectra for CLIC and beam induced backgrounds included
Beam polarization of -80%/0% (for e^-/e^+) assumed

Hadronization done in PYTHIA 6.427
quark masses and PYTHIA settings as used for CLIC CDR

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Standard event processing with CLIC_ILD_CDR500 configuration
Analysis based on PandoraPFA objects with loose selection cuts
LooseSelectedPandoraPFANewPFOs

Vertexing, jet reconstruction and flavour tagging with LCFI+
Using Valencia jet algorithm for best mass reconstruction

Event samples

Signal and background samples considered in the analysis.

For -80%/0% polarization, assuming 500 fb^{-1} collected at 380 GeV, FCNC signal normalised to $BR(t \to cX) = 10^{-3}$

Sample	Cross section	Expected events	MC event sample
FCNC signal	1.79 fb	895	99 301
6 fermion	938 fb	469 000	1 014 966
4 fermion	21 pb	10 500 000	7 067 836
quark pair	26 pb	13 000 000	2 968 551

Analysis has to focus on reduction of huge non-$t\bar{t}$ backgrounds

Search for $t \to c\gamma$

Signature assuming hadronic decay of "spectator" top

- high energy isolated photon ($E_\gamma = 50 - 140$ GeV)
- high energy c-quark jet ($E_{c-jet} = 50 - 140$ GeV)
- one b-quark jet and a pair of light jets from spectator top

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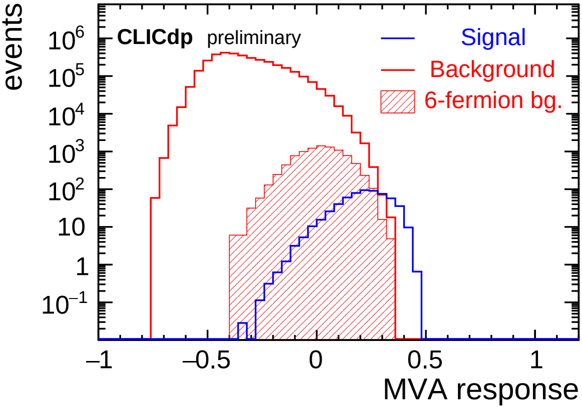
Analysis

- require isolated photon with $E_\gamma > 50$ GeV (preselection)
- reconstruct top pair decay kinematics
  caclulate χ^2 for signal and background (SM $t\bar{t}$) hypothesis
- multivariate analysis (BDT) for final signal-background discrimination
  Combining all available information on the event: photon properties, jet properties, flavour tagging, results of kinematic reconstruction (χ^2, invariant masses etc.). Total of 42 input variables.

Signal-background discrimination

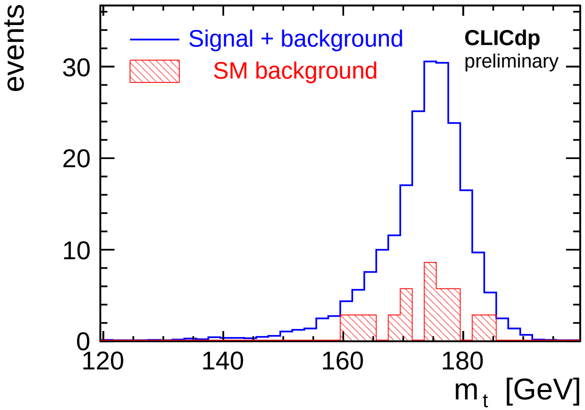
Comparison of BDT response distribution for SM background events and FCNC signal, assuming $BR(t \to c\gamma) = 10^{-3}$



Kinematic reconstruction

For signal events after BDT selection cut (BDT > 0.29)

Reconstructed $c\gamma$ invariant mass



Selection efficiency

Cut	FCNC signal	6 fermion	4 fermion	quark pairs
Preselection	92%	2.7%	16%	24%
BDT >0.29	28%	0.14%	0.003%	$< 10^{-5}$
Total efficiency	26%	$3.8 \cdot 10^{-5}$	$4.8 \cdot 10^{-6}$	-
Expected events	170	13	33	-

Expected limit

CLICdp preliminary

The expected 95% C.L. limit calculated using the $\mathrm{CL_s}$ approach:

$$\mathrm{BR}(t \to c\gamma) \quad < \quad 4.7 \cdot 10^{-5}$$

for 500 fb^{-1} collected at 380 GeV

Search for $t \to ch$

Signature assuming Higgs decay channel $h \to b\bar{b}$

- final state compatible with SM $t\bar{t}$ events
  both hadronic ($6q$) and semi-leptonic ($4q\ l\nu$) events considered
- three b-quark jets in the finals state + c-quark jet
- invariant mass of two b-quark jets consistent with h mass

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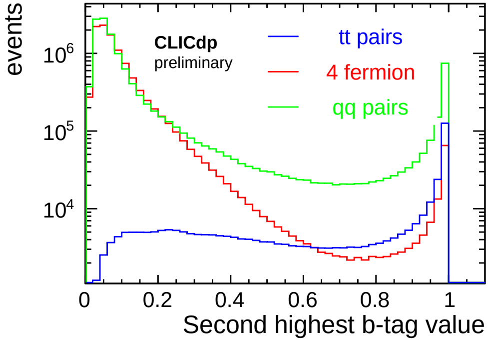
Analysis

- event classification (into hadronic, semi-leptonic, leptonic samples)
- pre-selection cuts (loose cuts on kinematics and flavour tagging)
- kinematic fit (for signal and background hypothesis)
- final selection based on multivariate analysis

Initial selection cut

To suppress non-$t\bar{t}$ background contribution, two jets are required to have b-tag of at least 0.2 (from 6-jet or from 4-jet final state reconstruction)



Removes 80% of $q\bar{q}$ events and 92% of 4-fermion sample.
FCNC signal efficiency of about 98% (90% for SM $t\bar{t}$ sample).

Two signal channels: fully hadronic and semi-leptonic decays

Event classification

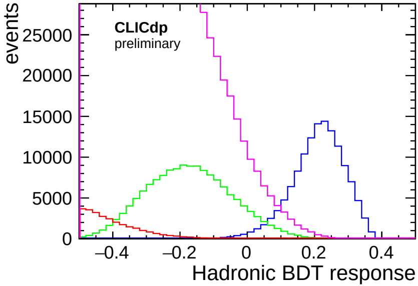
two BDTs used for selection of hadronic and semi-leptonic samples

15 input variables: total energy-momentum, event shape and jet parameters, lepton ID

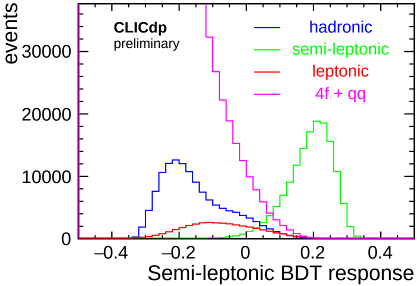
$\Rightarrow$ improved efficiency/purity, compared to cut-based approach

efficient rejection of non-$t\bar{t}$ background

Hadronic sample selection



Semi-leptonic sample selection



Signal hypothesis: three jets are required to have b-tag > 0.4
fourth jet required to have c-tag $+$ b-tag > 0.4

Kinematic fit χ^2 definition for hadronic events

Mass ratios used to reduce influence of mass correlations

- signal hypothesis — top boost as additional constraint

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

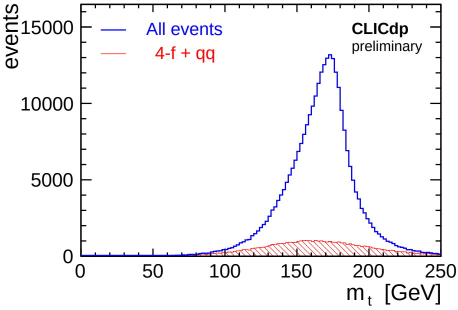
- similar for background hypothesis ($t\bar{t}$ hadronic decays)

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

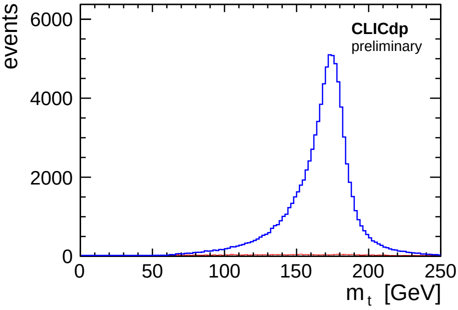
Kinematic fit

Reconstructed invariant mass for the hadronic top-quark decays

Hadronic $t\bar{t}$ selection



Semi-leptonic $t\bar{t}$ selection



Multivariate analysis

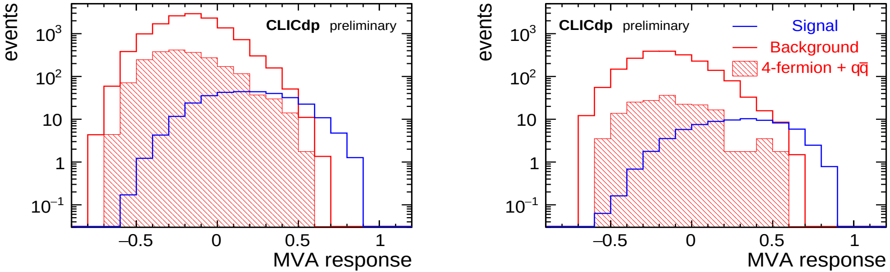
Used for final signal vs background discrimination

11 input variables: classification results, flavour tagging and kinematic fit

One BDT trained on both samples

Hadronic sample

Semi-leptonic sample



Selection efficiencies

Cut	FCNC signal	6 fermion	4 fermion	quark pairs
Preselection	99%	88%	8.5%	19.9%
Classification	99%	90%	5.1%	1.1%
Signal selection	45%	3.6%	2.8%	3.3%
BDT >0.4	25%	0.51%	0.96%	0.90%
Total efficiency	11%	$1.4 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$	$6.7 \cdot 10^{-7}$
Expected events	98	68	12	9

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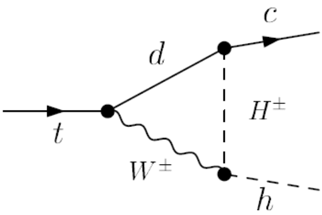
Expected limit 95% CL **CLICdp** preliminary

Calculated from BDT response distributions using $\mathrm{CL_s}$ method

$$BR(t \to ch) \times BR(h \to b\bar{b}) \quad < \quad 1.2 \cdot 10^{-4}$$

Scenario



In 2HDM enhancement of the $t \rightarrow ch$ decay can be due to loop contributions including new charged higgs boson.

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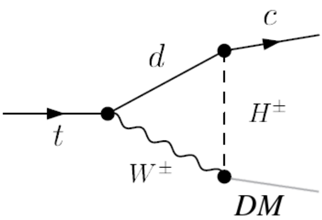

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Similar diagram could result in the decay to new, stable (or long-lived) heavy particle (Dark Matter candidate).

Can we set limits on such scenario?

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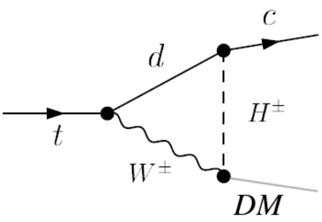

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2HDM(III) used to generate dedicated samples with $t \to ch$ decay but with the Higgs boson defined as a stable particle in PYTHIA (and thus invisible in the detector)

Samples were generated for $m_{DM} = 25, 50, 75, 100, 125$ and 150 GeV.

Preselection

We look for the final state consisting of four jets with only one b quark (c + hadronic decay of second top quark)

Dominant background contribution expected from four fermion processes (mainly WW production), but also from quark pair production.

Following preselection cuts are applied:

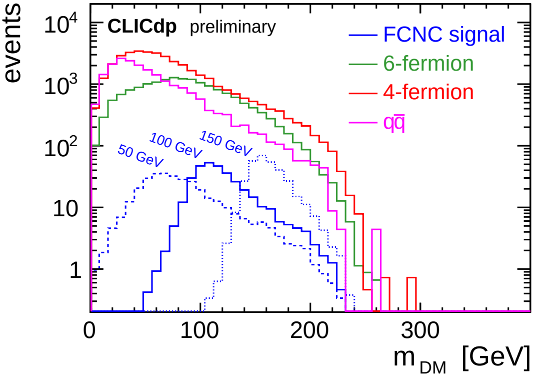
- b-tag value for b-jet > 0.6
- b-tag values for other jets < 0.4
- Transverse momentum > 20 GeV
- Long. momentum $|p_z| < 100$ GeV
- Total invariant mass > 140 GeV

Preselection efficiency for signal events between 35 and 42%
Depending on the assumed mass

Final state reconstruction

Take jet with highest c-tag value as the c-jet $\Rightarrow$ no ambiguity

Distribution of the reconstructed invariant mass of the invisible decay product, after preselection (for $m_{DM} = 50$, 100 and 150 GeV)



Search for $t \to c+$ missing energy

Signal-background discrimination

Independent BDTs trained for selection of signal events for low mass scenarios (below 100 GeV) high mass scenarios (100 GeV and above).

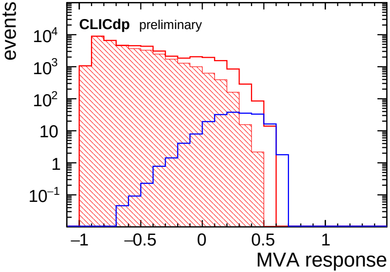
Same set of variables used: general event properties (E_{tot}, p_T, M_{inv}, M_{miss}, S, A), clustering parameters (y_{min}, y_{max}), reconstructed top and invisible scalar masses, χ^2 value from the kinematic fit.

Signal-background discrimination

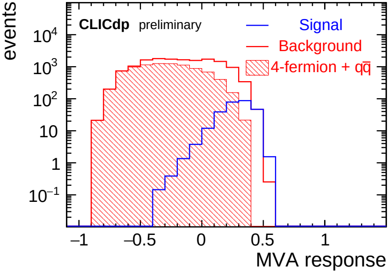
Independent BDTs trained for selection of signal events for low mass scenarios (below 100 GeV) high mass scenarios (100 GeV and above).

For each considered value of the invisible scalar particle mass the BDT response distribution was plotted for events in the ±30 GeV window in the reconstructed particle mass ⇒ used for limit setting

$m_{DM} = 50$ GeV

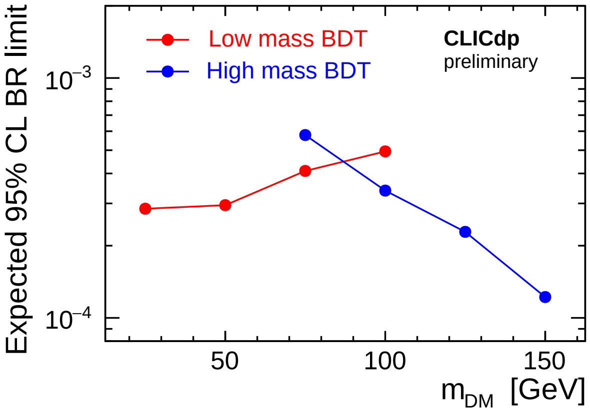


$m_{DM} = 125$ GeV



Results

Expected limits for 500 fb^{-1} collected at 380 GeV CLIC
calculated using the CL_s approach



Limits on top FCNC decays from CLIC at 380 GeV

based on full detector simulation **CLICdp preliminary**

$t \rightarrow c\gamma$

Analysis of hadronic channel only, first estimate of 95% C.L. limit:

$$BR(t \rightarrow c\gamma) \quad < \quad 4.7 \cdot 10^{-5}$$

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$t \rightarrow ch$

Combined analysis of hadronic and semi-leptonic channel,
expected 95% C.L. limit (CL_s method):

$$BR(t \rightarrow ch) \times BR(h \rightarrow b\bar{b}) \quad < \quad 1.2 \cdot 10^{-4}$$

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$t \rightarrow c\not{E}$

Only hadronic channel can be used, expected 95% C.L. limit (CL_s):

$$BR(t \rightarrow c\not{E}) \quad < \quad 1.2 - 4.1 \cdot 10^{-4}$$

depending on the assumed scalar mass

Not covered by the current analysis

$t \to cZ$

Direct search possible only for leptonic Z decays (limited efficiency).
$\Rightarrow$ use indirect constraints from single top production $e^+e^- \to t\bar{c},\ c\bar{t}$

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Search for single top production $e^+e^- \rightarrow t\bar{c},\ c\bar{t}$ can be also used to set constraints on $\mathrm{BR}(t \rightarrow c\gamma)$. Direct limits slightly better in this case...

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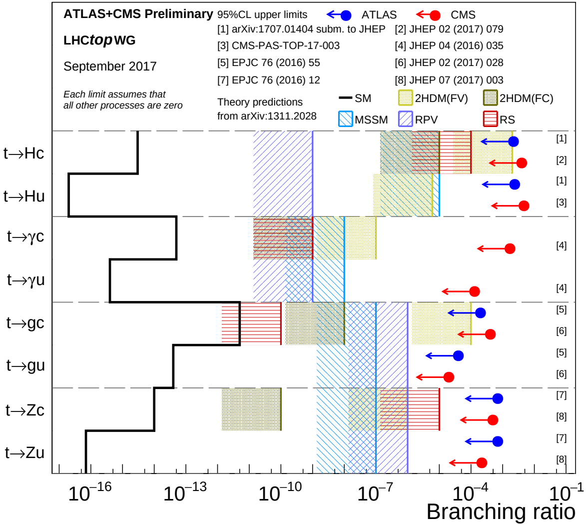
$t \rightarrow cg$

Very difficult for direct reconstruction,
mainly due to higher-order QCD effects (eg. $g \rightarrow q\bar{q}$).

Better sensitivity at LHC using single top production, eg. $gu \rightarrow t$

Thank you!

Results from the LHC top Working Group September 2017



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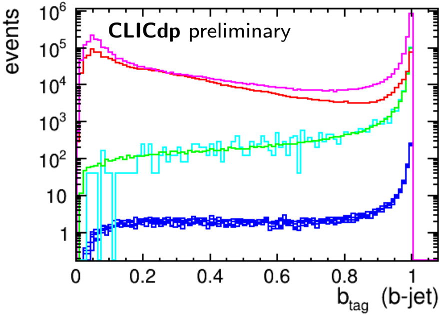
Dominant background contribution expected from four fermion processes (mainly WW production), but also from quark pair production.



b-tag value for b-jet > 0.6

Expected distribution for 500 fb^{-1}:
— FCNC signal $BR = 10^{-3}$
— 6-fermion ($t\bar{t}$) sample
— 4-fermion sample
— quark-pair sample

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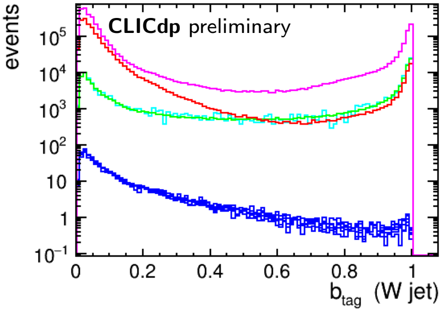

b-tag value for other jets < 0.4

Expected distribution for 500 fb^{-1}:
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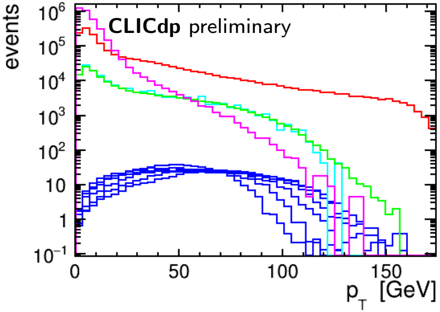

Transverse momentum > 20 GeV

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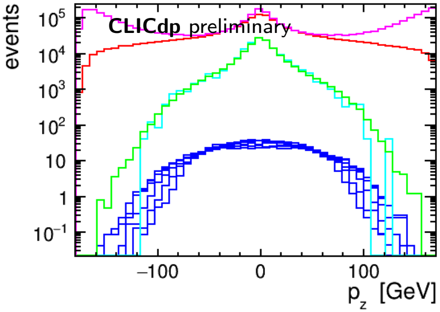

Long. momentum $|p_z| < 100$ GeV

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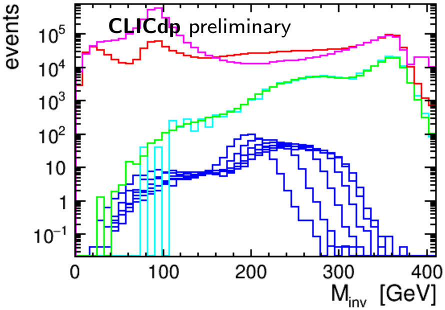

Total invariant mass > 140 GeV

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— quark-pair sample

Results

Summary of cross section values, selection efficiencies and numbers of events expected for two selected masses

Sample	σ	$\epsilon_{Pre.}$ (%)	$\epsilon_{BDT>0.25}$ (%)	$N_{BDT>0.25}$
Low mass selection, $m_{DM} = 50$ GeV				
FCNC	1.79 fb	41	29	105
6-fermion	938 fb	4.0	3.3	635
4-fermion	21 pb	0.35	0.17	64
quark pairs	26 pb	0.16	0.11	22
High mass selection, $m_{DM} = 125$ GeV				
FCNC	1.79 fb	40	51	181
6-fermion	938 fb	4.0	4.0	731
4-fermion	21 pb	0.35	0.20	76.3
quark pairs	26 pb	0.16	0.042	8.8