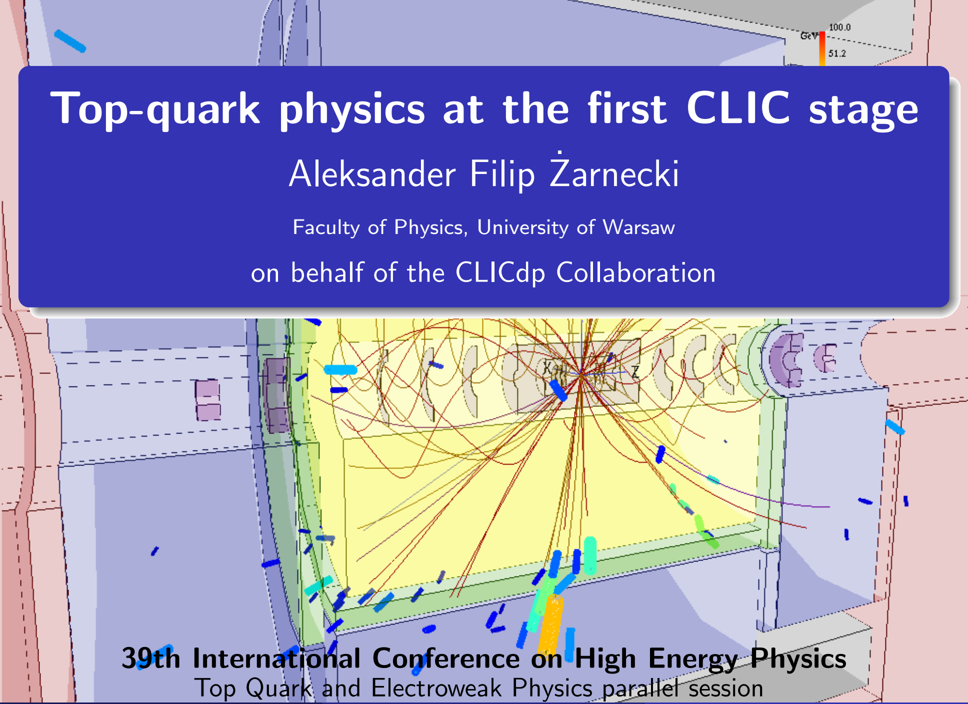


Top-quark physics at the first CLIC stage

Aleksander Filip Żarnecki

Faculty of Physics, University of Warsaw

on behalf of the CLICdp Collaboration

39th International Conference on High Energy Physics

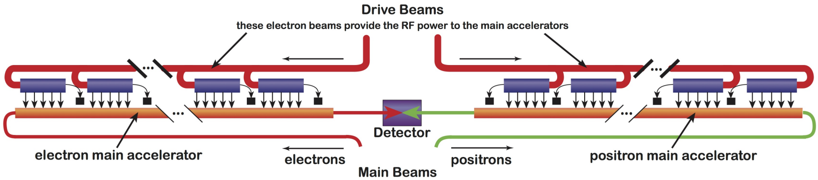
Top Quark and Electroweak Physics parallel session

Outline

1. Introduction
2. Top-quark mass measurements
3. Top-quark couplings
4. Top-quark FCNC decays
5. Conclusions

For details see:
H.Abramowicz et al. (CLICdp Collaboration),
Top-Quark Physics at the CLIC Electron-Positron Linear Collider,
CLICdp-Pub-2018-003, prepared for submission to JHEP

Compact LInear Collider



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

- high gradient, two-beam acceleration scheme
- staged implementation plan with energy from 380 GeV to 3 TeV
- footprint of 11 to 50 km
- e^- polarisation

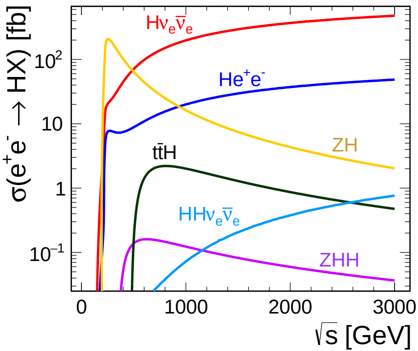
For details refer to: D.Schulte, *The CLIC accelerator project status and plans*, parallel session Accelertor: Physics, Perforamnce, and R&D for Future Facilities

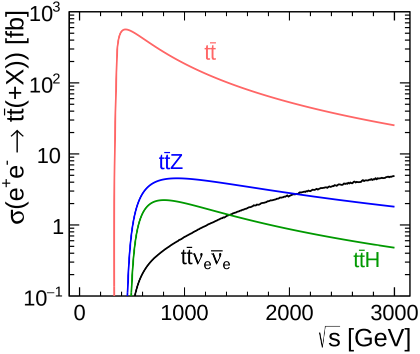
CLIC running scenario

CERN-2016-004

Three construction stages (each 5 to 7 years of running)
for an optimal exploitation of its physics potential

- $\sqrt{s} = 380$ **GeV** with 500 fb^{-1} $+$ 100 fb^{-1} at $t\bar{t}$ threshold
  focus on precision Standard Model physics,
  in particular Higgs and **top-quark measurements**





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Presented results based on detailed detector-level simulations

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- $\sqrt{s} = 1.5$ TeV with 1500 fb^{-1}
- $\sqrt{s} = 3$ TeV with 3000 fb^{-1}
  focus on direct and indirect BSM searches,
  but also additional Higgs boson and top-quark studies

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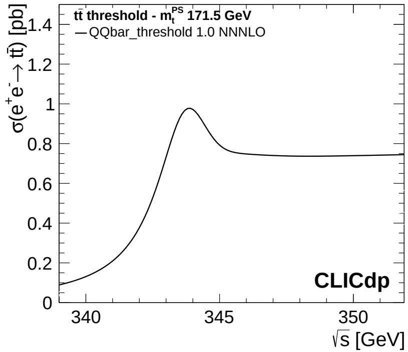
Other CLICdp contributions to ICHEP'2018 parallel sessions:

- Ulrike Schnoor, *Top-quark physics at high-energy CLIC operation* (yesterday)
- Matthias Artur Weber, *Higgs physics at CLIC* (Higgs Physics)
- Roberto Franceschini, *BSM searches at CLIC* (Beyond the Standard Model)
- Eva Sicking, *The CLIC detector* (Detector R&D for present and future...)

Threshold scan

Top pair production cross section around threshold
is very sensitive to top-quark mass, width and other model parameters



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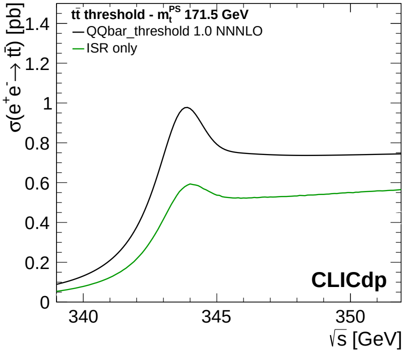
The dependence is smeared by ISR



Threshold scan

Top pair production cross section around threshold
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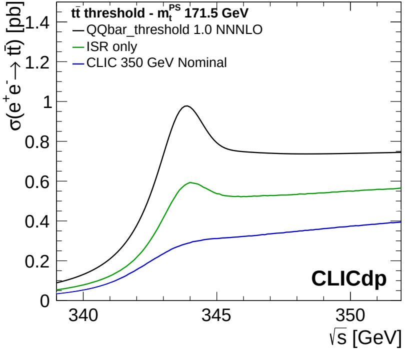
The dependence is smeared by ISR and CLIC luminosity spectra.



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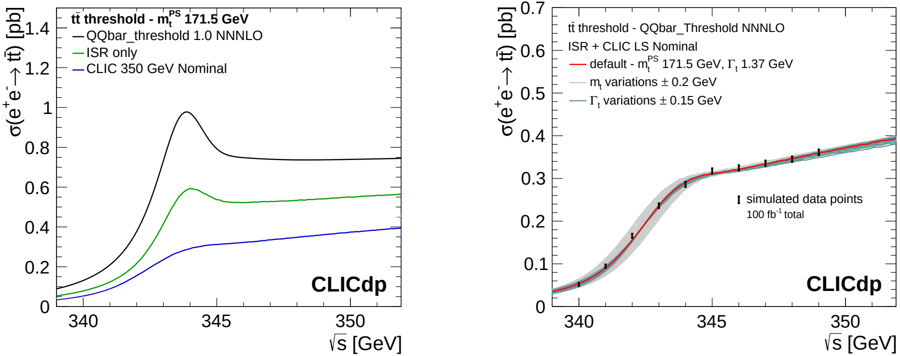

Expected statistical uncertainty for 100 fb^{-1} is 23 MeV

Top-quark mass

Threshold scan

Top pair production cross section around threshold
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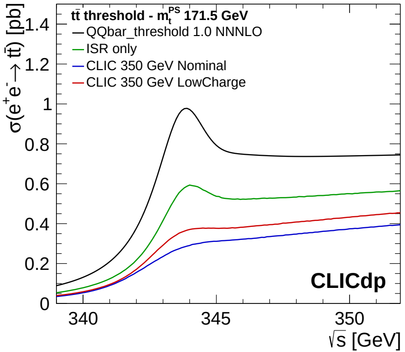
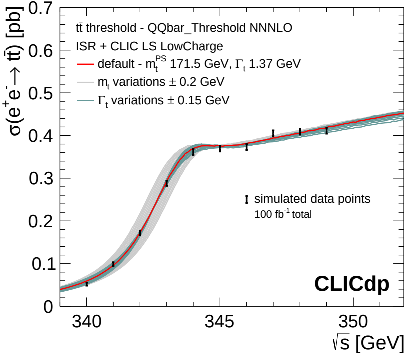
The dependence is smeared by ISR and CLIC luminosity spectra.



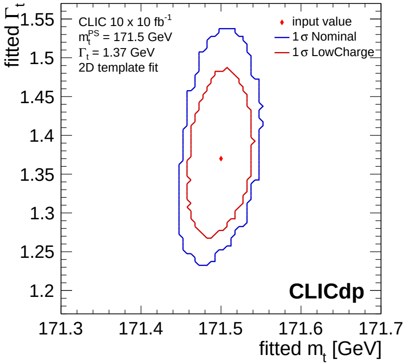


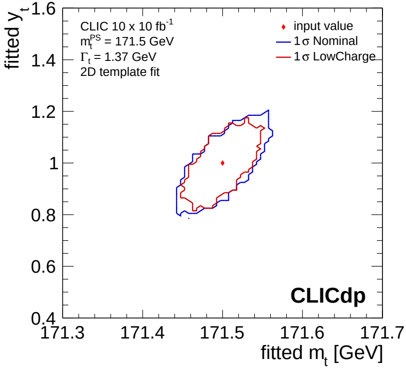
Expected statistical uncertainty for 100 fb^{-1} is 19 MeV (dedicated spectra)

Threshold scan

Dedicated luminosity spectra also reduces uncertainties on the extracted

top-quark width and Yukawa coupling





Energy scan: 10 cross section measurements, 10 fb^{-1} each

Threshold scan

Top-quark mass extracted in a theoretically well-defined approach.
Ultimate precision dominated by systematic effects:

- beam energy and the luminosity spectrum,
- selection efficiencies and residual background levels,
- non-resonant contributions,

  combined experimental systematic uncertainties: 25 MeV to 50 MeV

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Top-quark mass extracted in a theoretically well-defined approach.
Ultimate precision dominated by systematic effects:

- beam energy and the luminosity spectrum,
- selection efficiencies and residual background levels,
- non-resonant contributions,

  combined experimental systematic uncertainties: 25 MeV to 50 MeV

- parametric uncertainties from α_s,
- theoretical uncertainties from QCD scale variations.

  combined theoretical and parametric uncertainties: 30 MeV to 50 MeV
  depending on assumptions on the expected improvement

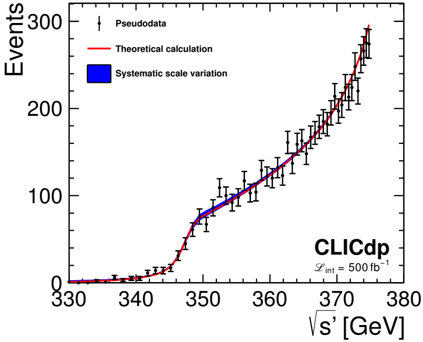
$\Rightarrow$ total uncertainty on top-quark mass of around 50 MeV feasible

Radiative events

When running at 380 GeV, the top-quark mass can be still extracted from the cross section of radiative events:

$$e^+e^- \rightarrow t\,\bar{t} + \gamma_{ISR}$$

Expected distribution of the reconstructed $t\bar{t}$ invariant mass



with lumionsity spectra taken into account

Top-quark mass:

statistical precision of about 100 MeV

total uncertainty of about 150 MeV

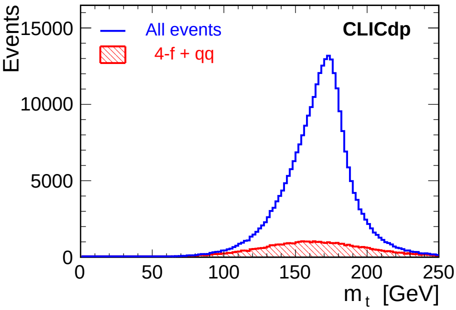
Direct reconstruction

Possible for all energies above the threshold (continuum)

Largest statistics expected at the first CLIC stage

Expected distribution of the reconstructed invariant mass
for hadronic top-quark decays, for 500 fb^{-1} at 380 GeV CLIC

Hadronic $t\bar{t}$ events



⇒ statistical uncertainty: 42 MeV

Direct reconstruction

Possible for all energies above the threshold (continuum)

Largest statistics expected at the first CLIC stage

Expected distribution of the reconstructed invariant mass
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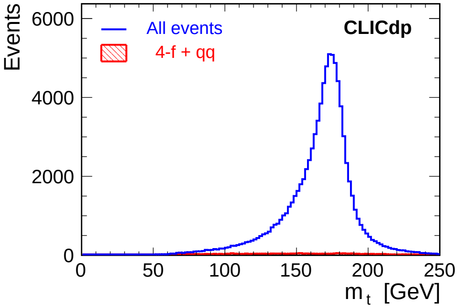
Semi-leptonic $t\bar{t}$ events



⇒ statistical uncertainty: 56 MeV

Direct reconstruction

Possible for all energies above the threshold (continuum)

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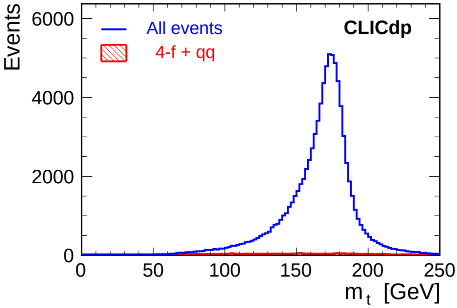

Combined statistical uncertainty on the top-quark mass: 40 MeV

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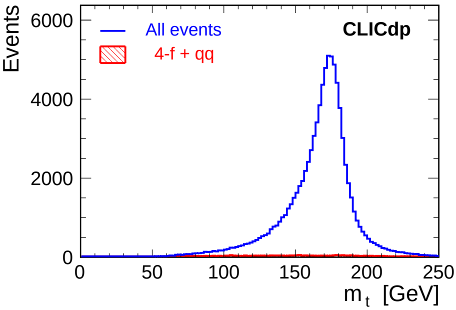


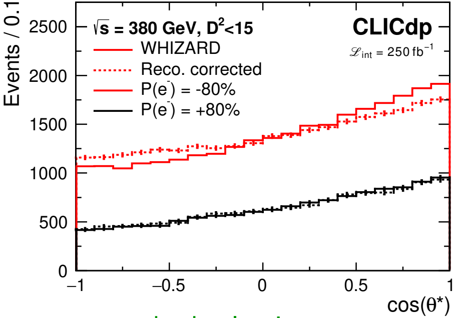
Combined statistical uncertainty on the top-quark mass: 40 MeV

Reconstruction of the top-quark to W boson mass ratio
⇒ 60 MeV statistical uncertainty on the top-quark mass

Asymmetry measurement

Precise measurements of $t\bar{t}$ production cross section and top-quark forward-backward asymmetry with different beam polarisation
$\Rightarrow$ constrain top-quark couplings to the photon and the Z-boson

Forward-backward asymmetry can be directly extracted from the measured top-quark angular distribution for the semi-leptonic events



standard selection

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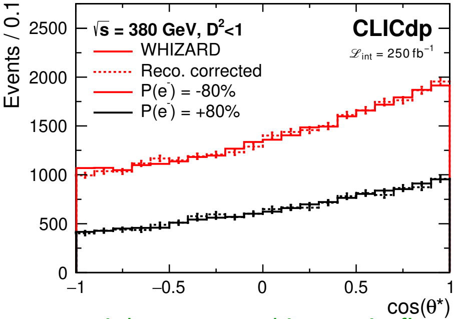
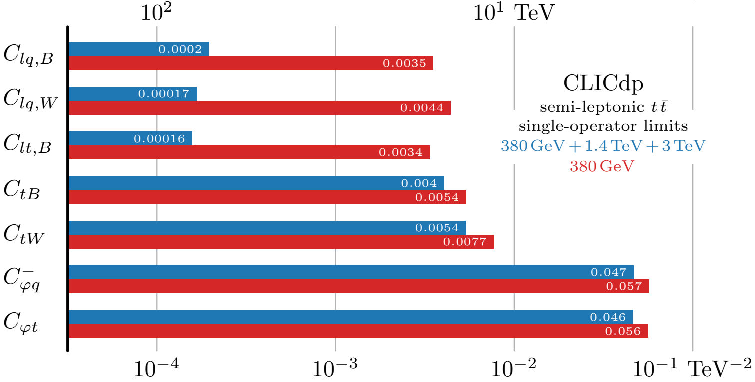


tighter cut on kinematic fit quality ⇒ avoid bias

EFT interpretation

Possible BSM effects induced by heavy new physics (above the direct reach of CLIC) are universally described by Effective Field Theory (EFT)

Top-quark measurements at CLIC can be used to constrain 7 operators:



First CLIC stage crucial for constraining 4 operators

Top-quark FCNC decays

Predictions

FCNC top-quark decays are strongly suppressed in SM (CKM+GIM):

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

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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}

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95% C.L. limits from LHC experiments

$BR(t \rightarrow c\gamma) < 0.17\%$ (CMS) $BR(t \rightarrow cH) < 0.16\%$ (ATLAS)

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Limits expected after HL-LHC running

$BR(t \to c\gamma) < 2.0 - 3.4 \cdot 10^{-4}$(CMS) $BR(t \to cH) < 2 \cdot 10^{-4}$(ATLAS)

Signatures

$t \to c\gamma$ 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

Signatures

$t \rightarrow c\gamma$ 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

$t \rightarrow cH$ assuming Higgs decay channel $h \rightarrow b\bar{b}$

- 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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- three b-quark jets in the finals state + c-quark jet
- invariant mass of two b-quark jets consistent with h mass

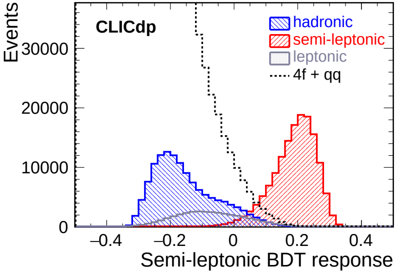
$t \to c+$ missing energy assuming hadronic decay of "spectator" top

- c-quark jet
- large missing transverse momentum
- one b-quark jet and a pair or light jets from spectator top

Analysis procedure

- event classification and pre-selection
  based on flavour tagging, lepton and photon identification, global event properties and jet clustering results

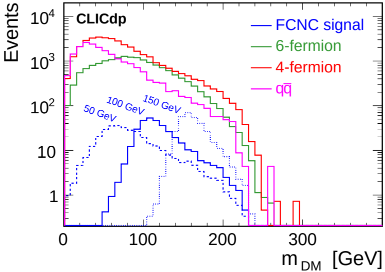
Event classification for $t \to cH$



Analysis procedure

- event classification and pre-selection
  based on flavour tagging, lepton and photon identification, global event properties and jet clustering results
- kinematic fit (for signal and background hypothesis)

Reconstructed missing mass for $t \to c + \not{E}$



for $BR(t \to c + \not{E}) = 10^{-3}$

Analysis procedure

- event classification and pre-selection
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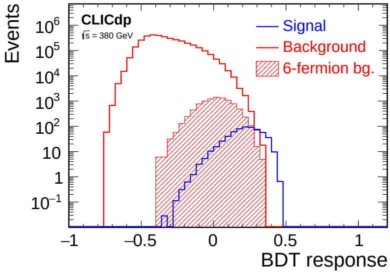
- kinematic fit (for signal and background hypothesis)
- final selection based on multivariate analysis (BDT)

BDT response distribution for $t \to c\gamma$



for $\mathrm{BR}(t \to c\gamma) = 10^{-3}$

Top-quark FCNC decays

Results

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

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

$$2.0 - 3.4 \cdot 10^{-4} \quad \text{(CMS@HL-LHC)}$$

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

$$\mathrm{BR}(t \to cH) \times \mathrm{BR}(H \to b\bar{b}) < 1.2 \cdot 10^{-4}$$

$$2 \cdot 10^{-4} \qquad \text{(ATLAS@HL-LHC)}$$

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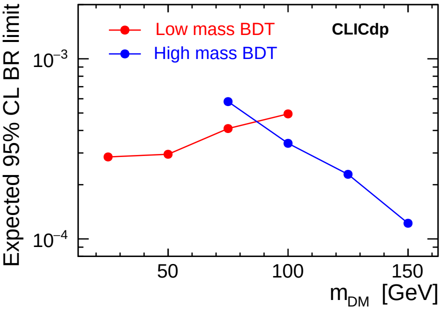
$$\mathrm{BR}(t \to c\not{E}) < 1.2 - 4.1 \cdot 10^{-4}$$



Conclusions

The initial stage of CLIC optimal for top-quark measurements

Dedicated pair production threshold scan:

- top-quark mass extraction with precision of around 50 MeV,
- also constraining top-quark width and Yukawa coupling.

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Cross section and asymmetry measurements constrain top-quark couplings, crucial for the general EFT analysis of CLIC data.

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- also constraining top-quark width and Yukawa coupling.

Complementary mass measurements at 380 GeV:

- from direct reconstruction of hadronic top-quark decays,
- from the energy spectrum of ISR photons.

Cross section and asymmetry measurements constrain top-quark couplings, crucial for the general EFT analysis of CLIC data.

The large number of top quarks produced allows competitive searches for FCNC decays with charm quarks in the final state

Thank you!

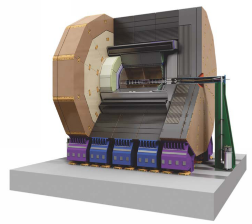
Introduction

Detector Requirements

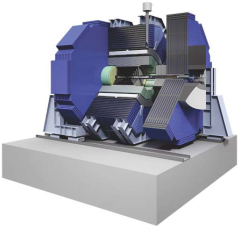
- Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m\ \frac{1\ \mathrm{GeV}}{p\ \sin^{3/2}\Theta}$
- Jet energy resolution: $\sigma_E/E = 3 - 4\%$ (highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

Three detailed LC detector concepts:

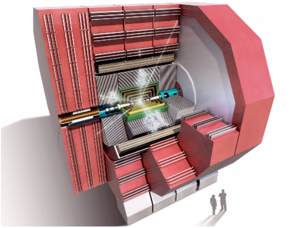
ILD



SiD



CLIC



Prospects for top-quark physics @ CLIC

Presented results based on detailed simulation studies

- signal and background processes generated with WHIZARD
  up to six particles in the final state
- luminosity spectra and beam induced backgrounds taken into account
- fragmentation and hadronisation simulated with PYTHIA 6.4
- GEANT 4 detector simulation using MOKKA and CLIC toolkits
  CLIC_ILD and CLIC_SiD detector concepts considered for presented results
- clustering and particle flow reconstruction is using PandoraPFA
  PFOs selection with loose timing cuts assumed for first CLIC stage
- jet clustering with FASTJET, best reconstruction with VLC algorithm
- flavour tagging with LCFIPLUS package

Direct reconstruction: fully hadronic and semi-leptonic events

Event classification

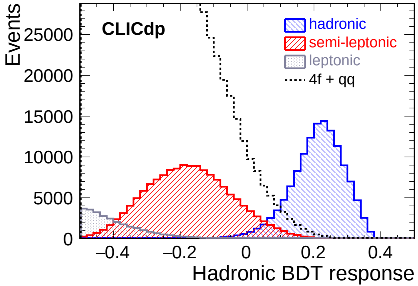
two BDTs used for selection of hadronic and semi-leptonic samples

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

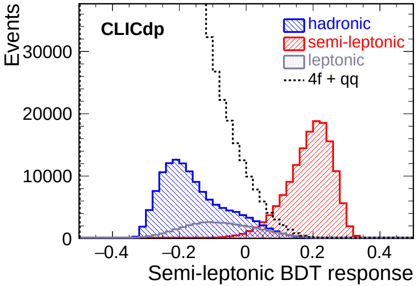
⇒ improved efficiency/purity, compared to cut-based approach

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

Hadronic sample selection



Semi-leptonic sample selection



Direct reconstruction

Possible for all energies above the threshold (continuum)
Largest statistics expected at the first CLIC stage

Expected statistical precision on top-quark mass: 40 MeV
taking into account both the hadronic and the semi-leptonic channels
corrected for dilution due to the use of the fixed mass jet pairing

Require jet energy scale controlled at the level of 0.025% (!)

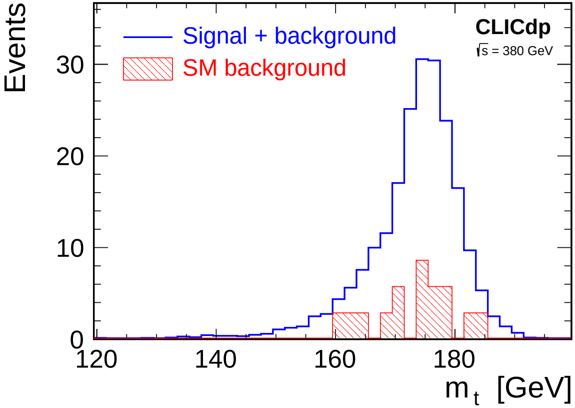
JES effects significantly reduced by relating the top-quark mass to W mass
$\Rightarrow$ expected uncertainty on the reconstructed mass ratio
corresponds to the top-quark mass uncertainty of about 60 MeV

not sensitive to the absolute jet enery scale
energy scale dependence on the quark flavour has to be understood to about 0.1%

Kinematic reconstruction

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

Reconstructed $c\gamma$ invariant mass



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)

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

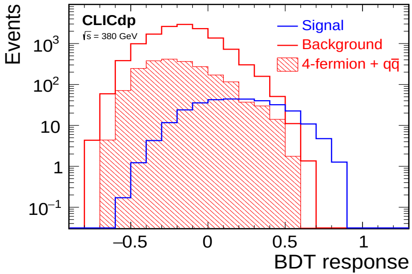
Multivariate analysis

Used for final signal vs background discrimination

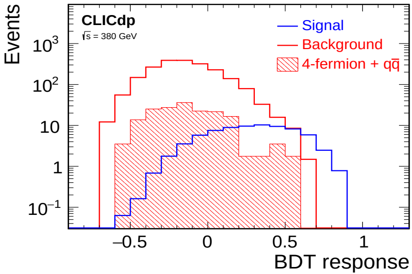
11 input variables: classification results, flavour tagging and kinematic fit

One BDT trained on both samples

Hadronic sample



Semi-leptonic sample



Search for $t \to c +$ missing energy

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

Results from the LHC top Working Group

May 2018