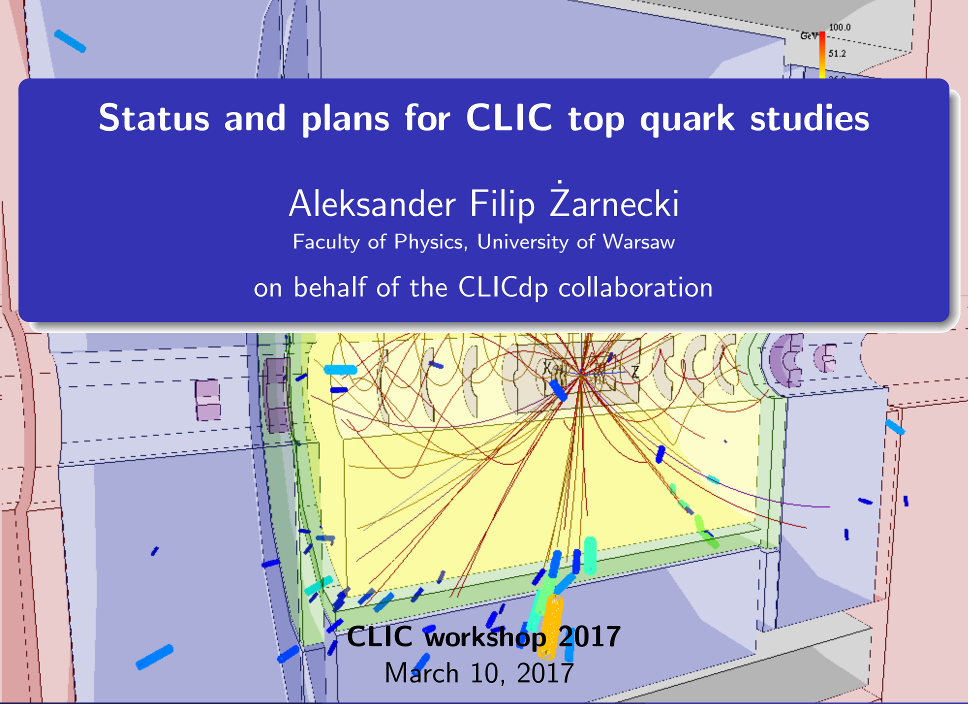
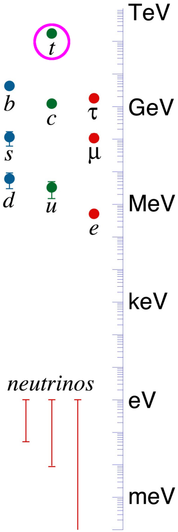
Status and plans for CLIC top quark studies

Aleksander Filip Żarnecki
Faculty of Physics, University of Warsaw
on behalf of the CLICdp collaboration



CLIC workshop 2017
March 10, 2017



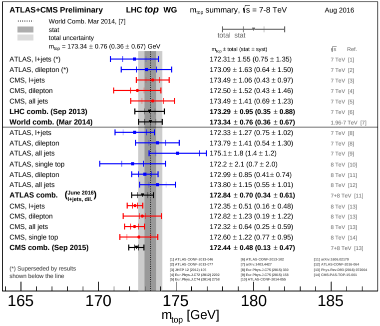
Credit: Hitoshi Murayama

Top quark

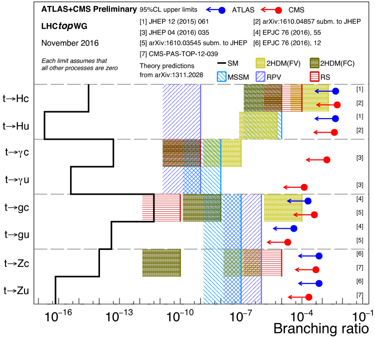
- the heaviest known elementary particle
- Yukawa coupling to Higgs boson $y_t \sim 1$
  $\Rightarrow$ key to understanding of EWSB
- decays before hadronizing:
  the only "naked" quark
  $\Rightarrow$ test ground for QCD
- large loop contributions to many precision measurements
- sensitive to many BSM scenarios
  $\Rightarrow$ a window to "new physics"

LHC Run I data demonstrated that both ATLAS and CMS experiments are capable of making very precise measurements of copiously produced tops.

Top mass



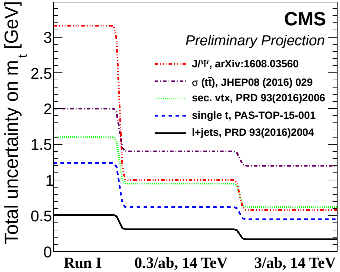
FCNC decays



LHC Run I data demonstrated that both ATLAS and CMS experiments are capable of making very precise measurements of copiously produced tops.

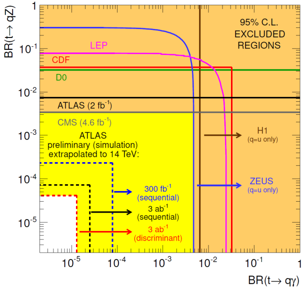
The HL-LHC will provide much larger samples for precision top physics
$\sim$ 3 billion top-quark pairs produced, $\sim$1 billion tops produced singly

Top mass



"mass scheme" uncertainty not included
CMS CR-2017/029

FCNC decays



ATL-PHYS-PUB-2012-001

Most measurements will be systematics limited

Assumed running scenario   CERN-2016-004

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}

with $\pm$80% electron beam polarisation (baseline design)

Full simulation studies

CDR detector models based on the SiD and ILD concepts for the ILC

dedicated detector concept, CLICdet, implemented recently

Luminosity spectra and overlay events taken into account

Event reconstruction with the "Particle Flow" approach

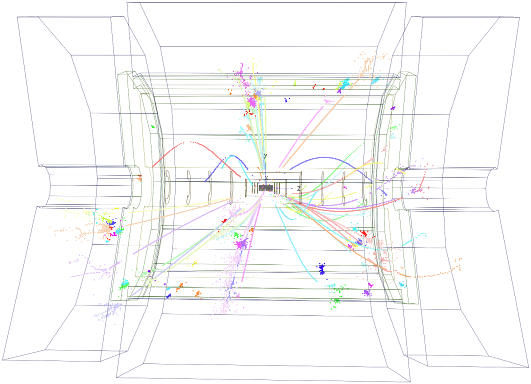
Excellent flvour tagging possible with a high precision pixel vertex detector

see presentation by Dominik Dannheim for more details

Presented in this contribution

1. Top reconstruction
2. Top mass and width measurement
3. Electroweak couplings
4. Yukawa coupling
5. Rare decays

Final state



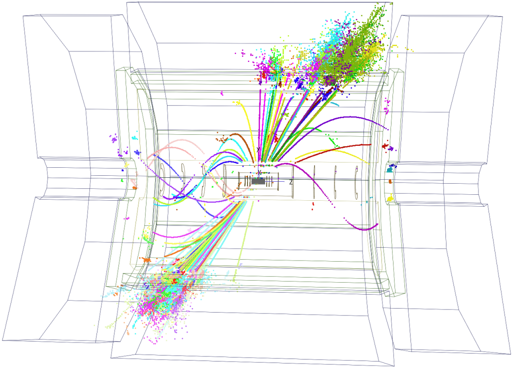
At low energy stage, top decay products (jets) well separated.

Direct reconstruction of the decay kinematics possible.

Crucial for efficient background suppression

$e^+e^- \longrightarrow t\bar{t} \longrightarrow 6\,j$ at $\sqrt{s} = 380$ GeV

Final state



$e^+e^- \longrightarrow t\bar{t} \longrightarrow 6\,j$ at $\sqrt{s} = 3$ TeV

At higher energy stages, top quarks produced with large boost.

Decay products cluster in two "fat" jets.

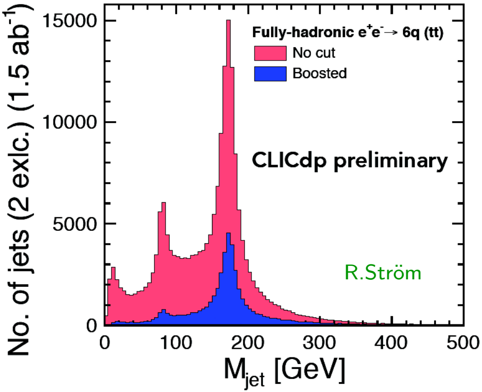
⇒ dedicated tools needed to discriminate between top and background events

Top event reconstruction

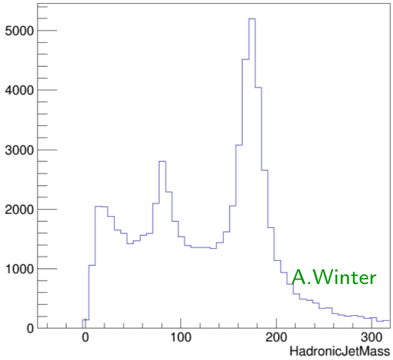
Final state

Invariant mass for "fat jets" (events clustered into 2 jets) $\sqrt{s} = 1.4$ TeV

$t\bar{t} \longrightarrow 6j$



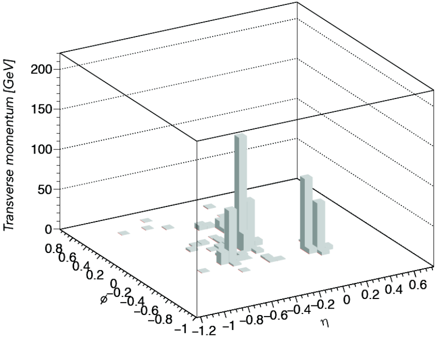
$t\bar{t} \longrightarrow 4j\ l\ \nu$



Two analyses ongoing

Using jet substructure

to distinguish boosted top jets from light-quark and gluon jets using
Method proposed in Kaplan et al. Phys. Rev. Lett. 101, 142001



Structure of a single top jet

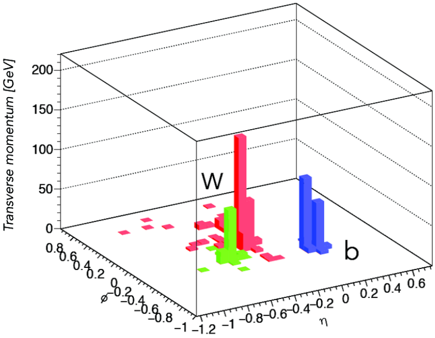
Cluster event into two jets, top candidates

Try to recluster candidate jet into three subjets to reconstruct decay kinematics

Using jet substructure

to distinguish boosted top jets from light-quark and gluon jets using

Method proposed in Kaplan et al. Phys. Rev. Lett. 101, 142001



Structure of a single top jet

Cluster event into two jets, top candidates

Try to recluster candidate jet into three subjets to reconstruct decay kinematics

Impose kinematic constraints

Look also at relative angles, jet multiplicity...

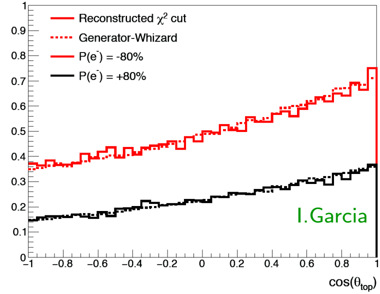
Reconstruction of top production angle

In semi-leptonic decay channel: $e^+e^- \longrightarrow t\bar{t} \longrightarrow 4j\ l\ \nu$

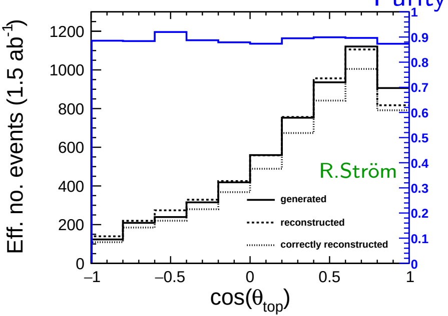
$\Rightarrow$ determination of Forward-Backward asymmetry

important observable for top coupling determination

500 fb^{-1} at 380 GeV



1.5 ab^{-1} at 1.4 TeV



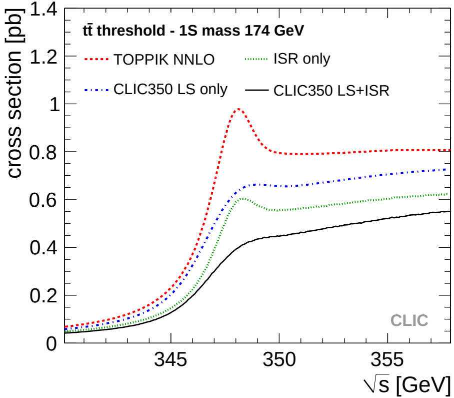
Tight quality cuts required to assure proper charge determination

corrected for event selection efficiency

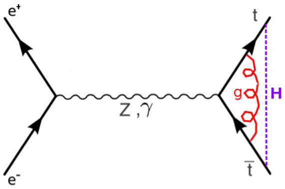
Top pair production cross section around threshold:

resonance-like structure corresponding to narrow $t\bar{t}$ bound state.

Very sensitive to top properties and model parameters:



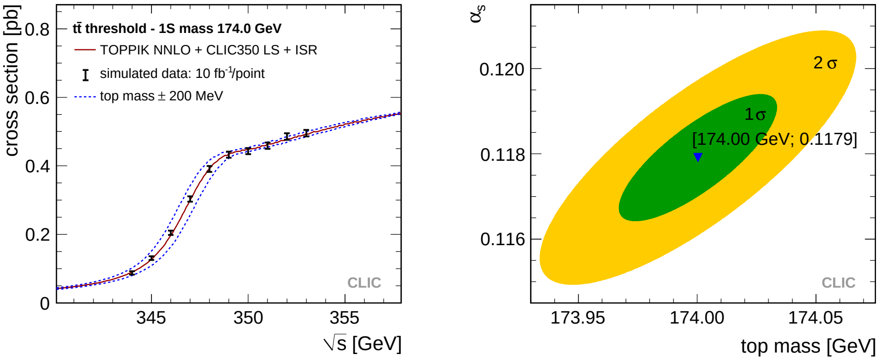
- top quark mass m_t
- top quark width Γ_t
- strong coupling α_s
- top Yukawa coupling y_t



Significant cross section smearing due to luminosity spectra and ISR

Already 100 fb^{-1} at the threshold sufficient for top mass measurement

Energy scan: 10 cross section measurements, 10 fb^{-1} each (to be optimised)



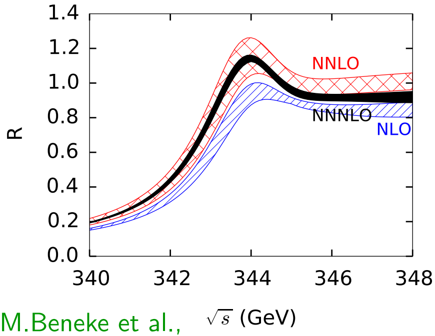
K.Seidel et al., Eur. Phys. J. C73 (2013) 2530

Expected statistical uncertainty on top mass: 15–20 MeV

on top width: ∼40 MeV

Threshold scan

Main advantage: mass well defined from theoretical point of view
Enormous progress in precision of theoretical calculations



M.Beneke et al.,
Phys. Rev. Lett. 115, 192001 (2015)

Estimates for top mass
systematic uncertainties:

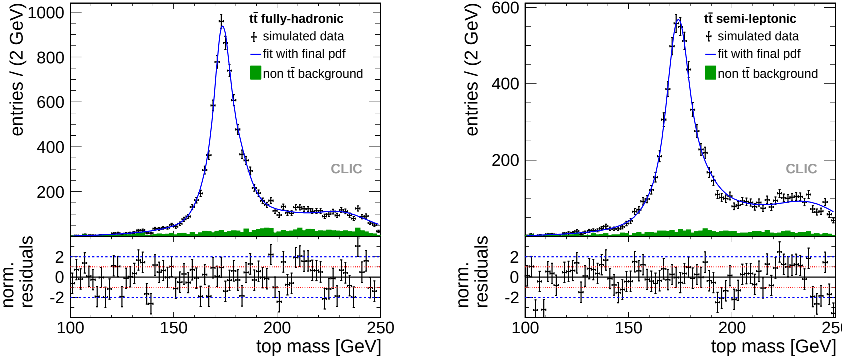
- theoretical predictions (NNNLO):
  $\sim$40 MeV
- parametric α_s uncertainty:
  $\sim$30 MeV (for today's WA)
- other uncertainties
  (backgrounds, spectra, etc.):
  on 10–20 MeV level

$\Rightarrow$ total uncertainty on the top mass of $\sim$50 MeV feasible
dominated by systematics

Direct reconstruction

Possible for all energies above the threshold (continuum)

High statistical precision: 80 MeV estimated for 100 fb^{-1} at 500 GeV



K.Seidel et al., Eur. Phys. J. C73 (2013) 2530

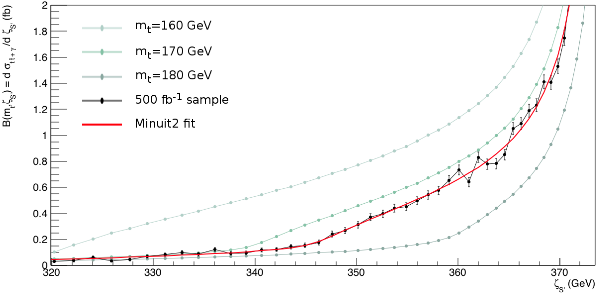
Suffers from significant theoretical uncertainties when converting to particular mass scheme (as in LHC).

Radiative events

M.Boronat @ CLIC'2016

At higher energies, we are still sensitive to $t\bar{t}$ threshold in radiative events.
When measuring the ISR photon, we can calculate "true" collision energy.

Reconstructed energy spectra

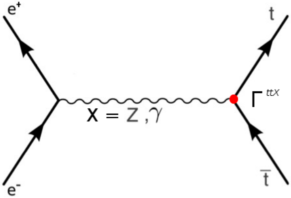


Particle level
$\sqrt{s} = 380$ GeV
$\zeta_{s'} = \sqrt{s'}$

Parton and particle level studies indicate that statistical uncertainty of $\sim$100 MeV can be obtained by combining the ISR and FSR measurements
Full simulation study is under development

Pair production: direct access to top electroweak couplings

Possible higher order corrections
⇒ sensitive to "new physics"



Form factor approach:

$$\Gamma_{\mu}^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2)+\gamma_5 F_{2A}^X(k^2)\right)\right\}$$

Electroweak couplings

Pair production: direct access to top electroweak couplings

Possible higher order corrections
⇒ sensitive to "new physics"

Couplings can be constrained through measurement of:

- total cross-section
- forward-backward asymmetry
- helicity angle in top decays

Form factor approach:

$$\Gamma_{\mu}^{t\bar{t}X}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2)\right)\right\}$$

Electroweak couplings

Pair production: direct access to top electroweak couplings

Possible higher order corrections
⇒ sensitive to "new physics"

Couplings can be constrained through measurement of:

- total cross-section
- forward-backward asymmetry
- helicity angle in top decays

Alternative, more universal approach: effective field theory (EFT)

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

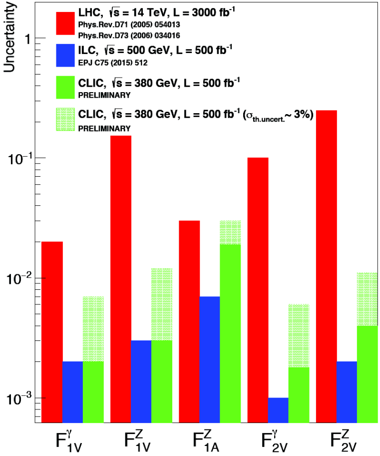
⇒ allows to connect different physics processes (sharing same operator)
⇒ allows to combine/compare different experiments
⇒ includes additional terms (i.e. four-fermion contact interactions)

Under development. Focus on 2-fermion and 4-fermion dim-6 operators.

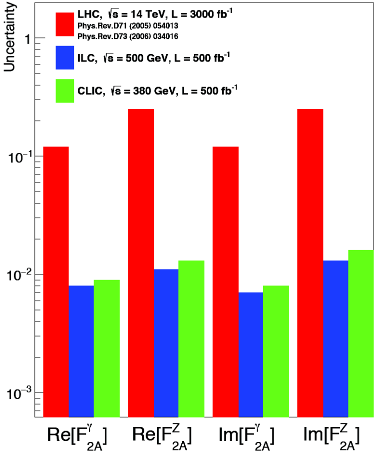
Electroweak couplings

Expected coupling precision at LHC, ILC (500 GeV) and CLIC (380 GeV)
initial stage

CP conserving couplings



CP violating couplings

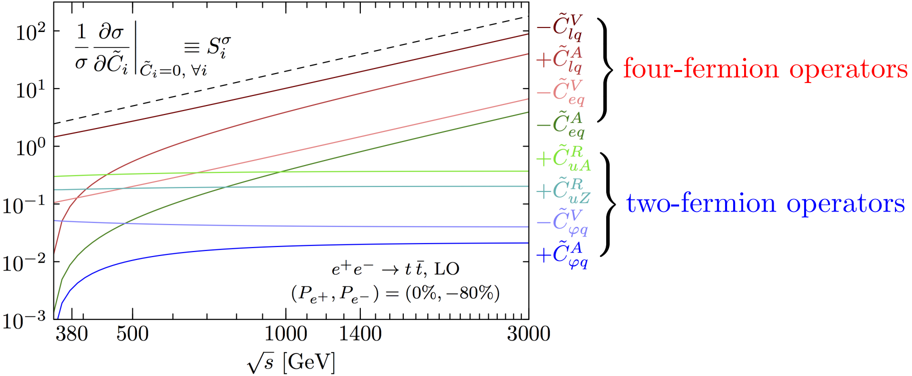


IFIC-LAL Collaboration, M.Perello @ ECFA LC'2016

EFT prospects

M.Perello, this workshop

Sensitivity of $\sigma(e^+e^- \to t\bar{t})$ to dimension-6 operators



Multi-TeV operation gives high sensitivity to four-fermion operators

High sensitivity to two-fermion operators at the initial stage

Threshold scan

ILC: A.Ishikawa @ TopLC'2015

Pair production at threshold: 9% Higgs exchange contribution

$\Rightarrow$ y_t can be extracted with statistical uncertainty $\sim$6% (100 fb^{-1})

assuming α_s can be constrained from other measurements

large theoretical uncertainties ($\sim$20%) need to be reduced

Threshold scan

ILC: A.Ishikawa @ TopLC'2015

Pair production at threshold: 9% Higgs exchange contribution

⇒ y_t can be extracted with statistical uncertainty ∼6% (100 fb^{-1})

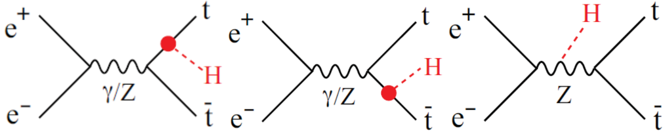
assuming α_s can be constrained from other measurements

large theoretical uncertainties (∼20%) need to be reduced

Direct measurement

for energies above 500 GeV

y_t can be extracted from the measured $e^+e^- \rightarrow t\bar{t}H$ cross section



Difficult measurement: very low statistics and large backgrounds.

Statistical uncertainty of 4.4% expected for 1.5 ab^{-1} at 1.4 TeV

CLICdp-Note-2015-001

New: analysis looking at CP violation in the *ttH* vertex at 1.4 TeV

FCNC top decays

Strongly suppressed in the Standard Model (GIM mechanism + CKM):

$BR(t \to c\,\gamma) \sim 5 \cdot\ 10^{-14}, \quad BR(t \to c\,Z) \sim 1 \cdot 10^{-14}, \quad BR(t \to c\,H) \sim 3 \cdot 10^{-15}$

Significant enhancement possible in many "new physics" scenarios

FCNC top decays

Strongly suppressed in the Standard Model (GIM mechanism + CKM):

$BR(t \to c\,\gamma) \sim 5 \cdot\ 10^{-14}, \quad BR(t \to c\,Z) \sim 1 \cdot 10^{-14}, \quad BR(t \to c\,H) \sim 3 \cdot 10^{-15}$

Significant enhancement possible in many “new physics” scenarios

Two channels under study for CLIC at 380 GeV

$t \to c\ h$

- enhancement up to 10^{-5}–10^{-2}
- test of Higgs boson couplings
- well constrained kinematics
- seems most difficult for LHC
  Run II: $BR < 0.46\%$
  HL-LHC: $BR < 2 \cdot 10^{-4}$

$t \to c\ \gamma$

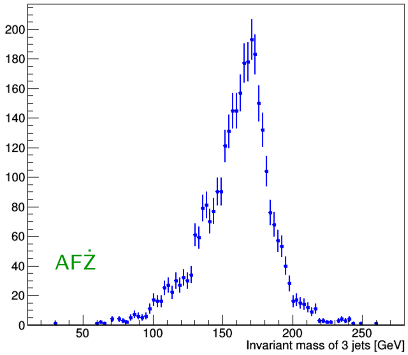
- enhancement up to 10^{-7}–10^{-5}
- clear signature
- less constrained kinematics
- expected limits from HL-LHC
  $BR < 2.5 \cdot 10^{-5}$

Reconstruction of FCNC events

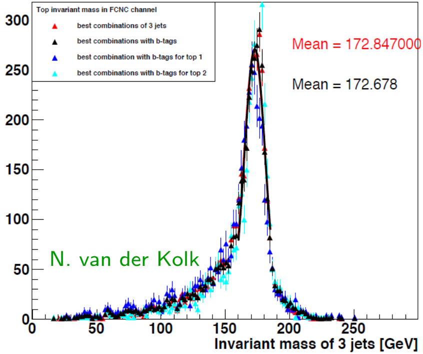
Preliminary results from the full simulation study for $\sqrt{s} = 380\,GeV$

Invariant mass distributions for "spectator" top candidates (SM decay)

$t \to c\ h$ events

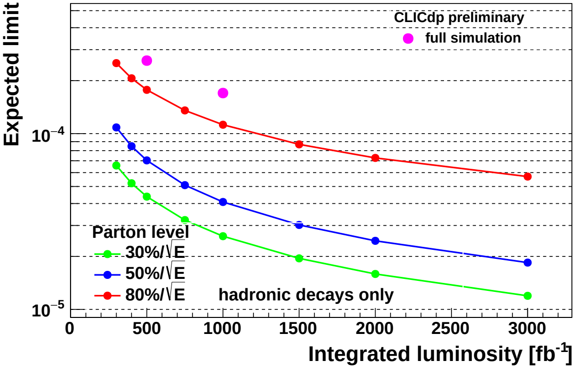


$t \to c\ \gamma$ events



Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$ at $\sqrt{s} = 380$ GeV

Comparison with parton level results, different jet energy resolutions



AFŻ @ LCWS'16

Kinematic fit performance still to be optimised

Background reduction primarily based on flavour tagging!

Summary of activities

	Threshold	380 GeV	1.4 TeV	3 TeV
Top reconstruction	✓	✓	➠	➠
Top mass	✓	✓		
EW couplings		✓	➠	➠
Yukawa coupling + CP	✗		✓➠	
FCNC decays		➠		
Single top/V_{tb}			➠	✗
Top squark production				➠?

✓ - available, ➠ - under study, ✗ - missing

The goal is to prepare the complete top paper draft before the end of 2017

Conclusions

Precise determination of top parameters is crucial for validation of the Standard Model (or any alternative BSM theory)

Wide range of top related measurements under study for CLIC
Most of it can be addressed already at the initial stage!

Top threshold scan gives unique oportunities for precise mass, width and coupling determination

Direct measurement of Yukawa coupling requires higher beam energies

Most of processes studied in details, based on full simulation results.

A lot of ongoing activities, focus mainly on high energy stages and optimization of the detector performance.

$\Rightarrow$ towards the top paper draft by the end of 2017

Invitation
to Workshop on top physics at the LC 2017 (TopLC17)

TopLC workshops gather theorists and experimentalists to study the potential of future lepton colliders in the area of top quark physics.

TopLC17 will be held at CERN on 7-9 June 2017

For details see:

http://indico.cern.ch/event/595651/

Registration is already opened

Thank you!

Many thanks to all authors contributing their results to this presentation.

CLICdp top study group:
Marca Boronat, Tom Coates, Juan Fuster, Ignacio Garcia, Pablo Gomis, Victoria Martin, Philipp Roloff, Martin Perello Rosello, Frank Simon, Lars Rickard Strom, Naomi van der Kolk, Marcel Vos, Alasdair Winter, Yixuan Zhang, Aleksander Filip Żarnecki