Measurement of the top quark mass and couplings at Linear Colliders

Ignacio García García
IFIC (UV-CSIC)

On behalf of the ILC Physics and Detector Study and CLICdp
1. Introduction
   International Linear Collider (ILC)
   Compact Linear Collider (CLIC)
   Motivation

2. Top quark mass measurement at threshold
   Precision in the measurement of the top quark mass
   The $t\bar{t}$ threshold
   Event generation, detector simulation and reconstruction
   Measurement of the $m_t$ and $\alpha_s$ at CLIC and ILC

3. Top quark electroweak couplings
   Top quark electroweak couplings at ILC
   Event generation, detector simulation and reconstruction
   Observables
   Sensitivities for the top electroweak couplings at ILC

4. Summary and conclusions
International Linear Collider (ILC)

Electron positron collisions

Superconducting acceleration technology

$E_{\text{cms}}$ tuneable between 200 GeV and 500 GeV, possible upgrade to 1 TeV

Integrated $\mathcal{L} = 500$ fb$^{-1}$ (2 years of running)

Beams are polarised:

$P(e^-) \approx \pm 80\%$, $P(e^+) \approx \pm 30\%$

About 31 km site length

ILD and SiD detectors are optimised for:

Particle Flow Algorithm (PFLOW)

The energy of charged hadrons will be measured by the tracking detectors

The energy of photons will be measured by the electromagnetic calorimeter

The hadronic calorimeter is then used only to measure the energy of neutral hadrons
Compact Linear Collider (CLIC)

Electron-positron collider in the **multi-TeV** energy range

About **48 km** site length

The c.o.m. energy: \( \sqrt{s} = 3 \text{ TeV} \) (default design)

500 GeV - 1.5 TeV

Luminosity: \( \mathcal{L} = 2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \)

Intense R&D in the CLIC collaboration to fully develop two-beam acceleration at high gradients

A **CLIC_ILD** and **CLIC_SiD** detector concepts have been developed from the ILD and SiD detector concepts for ILC

Modifications motivated by the **more challenging experimental conditions** at CLIC and by the **higher collision energy**
Motivation

**Top quark mass**

- A small change in $M_h$ and $M_t$ can **drastically modify** the conclusions regarding **vacuum stability**

- $M_t$ must be characterised well

**Top quark electroweak couplings**

- **Learn about BSM** physics from the deviations observed on Higgs and top EW couplings.

- LHC cannot achieve enough accuracy in the measurement of the coupling deviations -> **ILC accuracies** are needed to access to **fully significant deviations**

arXiv:1403.2893
Precision in the measurement of the top quark mass

• **Hadron colliders** achieve precisions in the measurement of the top mass of $\sim 0.76$ GeV

  Historical result, first ever LHC/Tevatron Combination [arXiv:1403.4427]

• At **linear colliders** there are **two techniques** to determine the mass of the top quark

  1. **Direct reconstruction of top from its decay products** (above threshold)

     Experimentally well-defined but the generated mass is **not well-defined theoretically** and non-perturbative corrections could be substantial

  2. **A scan of the top pair production threshold**

     **High degree of precision** using a **theoretically** well-defined top mass (**1S mass**, can be transformed into other mass schemes). Precise top mass measurement with **well-controlled theory uncertainties**

     See details about the **1S mass scheme**: arXiv:hep-ph/9904468v2
The $t\bar{t}$ threshold

- Top mass input $174 \text{ GeV}$ in the $1S$ mass scheme and $\alpha_s = 0.118$

- NNLO calculations provided by the code TOPPIK

- Corrections for ISR and luminosity spectrum

- These corrections result in a smearing of the cross section peak at threshold

- The smearing is due to the statistical efficiency, reduced by the luminosity spectra. Not affected by systematics.
Event generation, detector simulation and reconstruction

\[ e^+e^- \rightarrow t\bar{t} \] production at threshold CLIC@352 GeV

1. Generated events (signal + background)
   - **Pythia**: \( e^+e^- \rightarrow t\bar{t}, WW, ZZ \)
   - **WHIZARD**: \( e^+e^- \rightarrow q\bar{q}, q\bar{q}e^+e^-, q\bar{q}e\nu \)

2. Simulation of the detector
   - Full simulation with high level of realism

3. Reconstruction
   - Standard algorithms
   - **Kinematic fitting**: Grouping W-bosons and b-jets into top quarks

\[ m_t = 174.0 \text{ GeV} \]
\[ \Gamma_t = 1.37 \text{ GeV} \]

Katja Seidel, Frank Simon, Michal Tesar, StephanePoss
Top mass measurement in a threshold scan

- The **cross-section depends on** the **top mass**, so measuring the cross-section the top mass can be extracted (Also the $\alpha_s$, Yukawa coupling, top width…)

- Inclusion of **higher-order QCD contributions** are needed for a correct description of the cross section

- Determination of **event selection efficiency** and **background contamination**

- Threshold scan with **10 energy points** spaced by 1 GeV from 344 GeV to 353 GeV with an integrated **luminosity of 10 fb$^{-1}$**
The cross section for ILC rises faster due to the luminosity peak is narrower

But it does not result in a significant difference of the precision of the top quark mass measurement.
Measurement of the top mass and $\alpha_s$ at CLIC and ILC

- **Statistical uncertainty of top mass around 30 MeV** (CLIC ~ 20% larger than ILC due to different luminosity spectrum)

- In addition: **Experimental and theoretical systematics**, and uncertainties from the conversion to the $\overline{\text{MS}}$ mass scheme. **Total uncertainty below 100 MeV** within reach.
Top quark electroweak couplings at the ILC

- The process $e^+e^- \to t\bar{t}$ involves only $t\bar{t}Z_0$ and $t\bar{t}\gamma$ primary vertices
- A way to describe the current at the $t\bar{t}X$ vertex:

$$\Gamma^{ttX}_{\mu}(k^2, q, \bar{q}) = i e \left\{ \gamma_\mu \left( \widetilde{F}_{1V}^X(k^2) + \gamma_5 \widetilde{F}_{1A}^X(k^2) \right) + \frac{(q - \bar{q})_\mu}{2m_t} \left( \widetilde{F}_{2V}^X(k^2) + \gamma_5 \widetilde{F}_{2A}^X(k^2) \right) \right\}$$

where:
- $V = $ Vector coupling
- $A = $ Axial coupling
- $X = Z, \gamma$

Non CP violating top quark couplings
**Event generation, detector simulation and reconstruction**

\[ e^+e^- \rightarrow t\bar{t} \text{ semi-leptonic channel at ILC@500 GeV} \]

1. **Generated events (signal)**

   **WHIZARD**: Generate 6 fermions final state \( e^+e^- \rightarrow q\bar{q}b\bar{b}\nu \)

   **Pythia**: Parton shower and hadronisation

   + *WbWb and beam backgrounds added*

   **Beams are polarised**

   (2 samples)

   1. \( e^-_L e^+_R \) \( P(e^-) \approx -80\% , P(e^+) \approx +30\% \)
   2. \( e^-_R e^+_L \) \( P(e^-) \approx +80\% , P(e^+) \approx -30\% \)

2. **Simulation of the detector**

   Full realistic simulation of the ILD detector concept

Three-dimensional image of a 500-GeV \( t\bar{t} \) event simulated in the ILD detector

M.S. Amjad, M. Boronat, et al
http://www-flc.desy.de/lcnotes/
LC-REP-2013-007

ICHEP Valencia 2-9 July 2014
3. Reconstruction

Standard algorithms for event selection

Signal reconstruction: combination of $b$ quark jet and $W$ boson that minimises the following equation:

$$d^2 = \left( \frac{m_{\text{cand.}} - m_t}{\sigma_{m_t}} \right)^2 + \left( \frac{E_{\text{cand.}} - E_{\text{beam}}}{\sigma_{E_{\text{cand.}}}} \right)^2 + \left( \frac{p_b^* - 68}{\sigma_{p_b^*}} \right)^2 + \left( \frac{\cos \theta_{bW} - 0.23}{\sigma_{\cos \theta_{bW}}} \right)^2$$

Efficiency of selection

- **51.9%** for $P, P' = -1, +1$ (Left-handed electrons)
- **55.0%** for $P, P' = +1, -1$ (Right-handed electrons)
**Total cross section (\(\sigma\))**

**The Forward-Backward Asymmetry (\(A_{FB}^{top}\))**

**The slope of the distribution of the helicity angle (\(\lambda_t\))**

<table>
<thead>
<tr>
<th>Observables</th>
<th>(e^{-}e^{+}_R)</th>
<th>(e^{-}e^{+}_L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma(\text{fb}))</td>
<td>1564</td>
<td>724</td>
</tr>
<tr>
<td>(A_{FB})</td>
<td>0.38</td>
<td>0.47</td>
</tr>
<tr>
<td>(F_R = (1 + \lambda_t)/2)</td>
<td>0.25</td>
<td>0.76</td>
</tr>
</tbody>
</table>

But actually there are 6 independent observables = 3 observables x 2 polarisations

So we can obtain the following **CP conserving 6 couplings of the top to Z and \(\gamma\)**

\[
\begin{align*}
\sigma(+) & \quad A_{FB}(+) & \quad \lambda_{hel}(+) & \quad (+ = e^-_R) \\
\sigma(-) & \quad A_{FB}(-) & \quad \lambda_{hel}(-) & \quad (- = e^-_L)
\end{align*}
\]

\[
\begin{pmatrix}
F_{1V}^\gamma & F_{1A}^\gamma & F_{2V}^\gamma \\
F_{1V}^Z & F_{1A}^Z & F_{2V}^Z
\end{pmatrix}
\]

* \(F_{1A}^\gamma = 0\) because of the gauge invariance
Measurement of observables

The cross section

The cross section can be measured to

0.5% (stat. + lumi)

The Forward-Backward Asymmetry

\[ A_{FB}^t = \frac{N(\cos \theta > 0) - N(\cos \theta < 0)}{N(\cos \theta > 0) + N(\cos \theta < 0)} \]

2% (stat. + syst.)

The helicity angle

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta_{hel}} = \frac{1 + \lambda_t \cos \theta_{hel}}{2} = \frac{1}{2} + (2F_R - 1) \cos \theta_{hel} \]

~4% (stat. + syst.)
Sensitivities for the electroweak couplings

500/fb at 500 GeV yields 1-2 orders of magnitude better sensitivity than the LHC (300/fb at 14 TeV)

<table>
<thead>
<tr>
<th>Coupling</th>
<th>SM value</th>
<th>LHC [1] ( \mathcal{L} = 300 \text{ fb}^{-1} )</th>
<th>( e^+e^-[ILC\ DBD] ) ( \mathcal{L} = 500 \text{ fb}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \tilde{F}_{1V}^\gamma )</td>
<td>0.66</td>
<td>+0.043</td>
<td>+0.002</td>
</tr>
<tr>
<td>( \Delta \tilde{F}_{1V}^Z )</td>
<td>0.23</td>
<td>+0.240</td>
<td>+0.003</td>
</tr>
<tr>
<td>( \Delta \tilde{F}_{1A}^Z )</td>
<td>-0.59</td>
<td>+0.052</td>
<td>+0.005</td>
</tr>
<tr>
<td>( \Delta \tilde{F}_{2V}^\gamma )</td>
<td>0.015</td>
<td>+0.038</td>
<td>+0.003</td>
</tr>
<tr>
<td>( \Delta \tilde{F}_{2V}^Z )</td>
<td>0.018</td>
<td>+0.270</td>
<td>+0.006</td>
</tr>
</tbody>
</table>


LHC studies (Snowmass 2005)

Present study denoted as ILC DBD
Summary

Top mass at threshold

Statistical uncertainty of top mass around 30 MeV
(CLIC ~ 20% larger than ILC due to different luminosity spectrum).

Total uncertainty below 100 MeV in reach, expected to be dominated by theory systematics.

Top electroweak couplings

Log scale

Uncertainty

$\tilde{f}_{1V}$  $\tilde{f}_{1V}$  $\tilde{f}_{1A}$  $\tilde{f}_{2V}$  $\tilde{f}_{2V}$

ILC (preliminary)
LHC (hep-ph/0601112)
Conclusions

• In a **threshold scan**, the **top mass** can be determined in a **theoretically well defined** way, using 1S mass scheme

• These studies confirm the expectation that a **linear e⁺e⁻ collider** will be capable of measuring the mass of the top quark with **30 MeV error**

• **Polarisation** allows to **double the number of observables**

• **It is a powerful tool for analysis** because it also allows **full separation** between **axial and vectorial couplings** and between **ttZ and ttγ vertices**

• In LC with polarised beams we can measure the top quark couplings with **accuracies** one or two orders of magnitude **better than LHC**
THANK YOU FOR YOUR ATTENTION
Tunnel implementations (laser straight)

Central MDI & Interaction Region
ILC@Japan

Planned construction candidate site for the International linear collider and main surrounding facilities


This entire area is a prominent producer of a wide variety of agricultural products including high quality rice, beef, vegetables, and apples.
$e^+ e^- \rightarrow t\bar{t}$ gives three different final states:

**Fully leptonically (10.3%)**
2 jets + 2 leptons + 2 neutrinos

**Semi-leptonically (43.5%)**
4 jets + lepton + neutrino

**Fully hadronically (46.2%)**
6 jets at final state