Top and Heavy quark studies at linear colliders

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on behalf of the ILC International Development Team Working Group 3

EPS-HEP Hamburg July 2021
Linear Electron positron colliders

Energy: 0.1 - 1 TeV
Electron (and positron) polarisation
TDR in 2013
+ DBD for detectors
Footprint 31 km

Under discussion in Japanese Government and international community

Initial Energy 250 GeV – Footprint ~20km

Energy: 0.4 - 3 TeV

CDR in 2012
Update 2016

Footprint 48km

Initial Energy 380 GeV

Possible future project of CERN
An enigmatic couple

- Higgs and top quark are intimately coupled! Top Yukawa coupling O(1)!
  => Top mass important SM Parameter

- New physics by compositeness?
  Higgs and top composite objects?

- e+e- collider perfectly suited to decipher both particles

Courtesy of S. Rychkov
Anomalies in LEP/SLD data

Most precise single Individual determination of $\sin^2 \theta_{\text{eff}}^\ell$ from SLC
- Left-right asymmetry of leptons

Most precise measurement of $\sin^2 \theta_{\text{eff}}^\ell$ from forward backward asymmetry $A_{FB}^b$ in $ee \rightarrow bb$ at LEP:
- Requires verification
- Heavy quark effect, effect on all quarks/fermions, no effect at all?
Two fermion processes

Differential cross sections for (relativistic) di-fermion production*

\[ \frac{d\sigma}{d\cos \theta}(e^-e^+ \rightarrow f\bar{f}) = \Sigma_{LL}(1 + \cos \theta)^2 + \Sigma_{LR}(1 - \cos \theta)^2 \]

\[ \frac{d\sigma}{d\cos \theta}(e^-e^+ \rightarrow f\bar{f}) = \Sigma_{RL}(1 + \cos \theta)^2 + \Sigma_{RR}(1 - \cos \theta)^2 \]

*add term \( \sim \sin^2 \theta \) in case of non-relativistic fermions e.g. top close to threshold

\( \Sigma_{IJ} \) are helicity amplitudes that contain couplings \( g_L, g_R \) (or \( F_{V'}, F_{A'} \))

\( \Sigma_{IJ} \neq \Sigma_{I'J'} \Rightarrow \) (characteristic) asymmetries for each fermion

Forward-backward in angle, general left-right in cross section

**All four** helicity amplitudes for all fermions **only available with polarised beams**

Here we focus on tt, bb and cc pair production
Elements of top quark reconstruction

Three different final states:
1) Fully hadronic (46.2%) → 6 jets
2) Semi leptonic (43.5%) → 4 jets + 1 charged lepton and a neutrino
3) Fully leptonic (10.3%) → 2 jets + 4 leptons

$$t\bar{t} \rightarrow (bW)(bW) \rightarrow (bq')(bl\nu)$$

Final state reconstruction uses all detector aspects
Results shown in the following are based on full simulation of LC Detectors
Cross section around threshold is affected by several properties of the top quark and by QCD

- Top mass, width Yukawa coupling
- Strong coupling constant

- Effects of some parameters are correlated:
  - Dependence on Yukawa coupling rather weak,
  - Precise external $\alpha_s$ helps

F. Simon, Top@LC15 Valencia
Optimising of scanning points

Optimisation of threshold scan using “Non dominated sorting genetic algorithm”

arxiv: 2103.00522

Standard scan scenario

Optimised scenario for mass a width

Precision on top mass ...

100 fb\(^{-1}\) for 10 equally distributed points

- Optimisation of threshold scan yield 25% statistical precision of top mass compared with scan using equally distributed scan points
- Choice of measurement points with optimal sensitivity to desired quantity
- For breakdown of systematic errors see backup
A new(er) idea to measure the top mass in a theoretically well-defined scheme in high-energy running above the threshold can provide 5σ evidence for scale evolution ("running") of the top quark MSR mass from ILC500 data alone.

<table>
<thead>
<tr>
<th>cms energy</th>
<th>CLIC, $\sqrt{s} = 380$ GeV</th>
<th>ILC, $\sqrt{s} = 500$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity $[fb^{-1}]$</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>statistical</td>
<td>140 MeV</td>
<td>90 MeV</td>
</tr>
<tr>
<td>theory</td>
<td>46 MeV</td>
<td>55 MeV</td>
</tr>
<tr>
<td>lum. spectrum</td>
<td>20 MeV</td>
<td>20 MeV</td>
</tr>
<tr>
<td>photon response</td>
<td>16 MeV</td>
<td>85 MeV</td>
</tr>
<tr>
<td>total</td>
<td>150 MeV</td>
<td>110 MeV</td>
</tr>
</tbody>
</table>
Top quark polar angle spectrum at 500 GeV

- Integrated Luminosity 4 fb$^{-1}$
- Exact reproduction of generated spectra
- Statistical precision on cross section: ~0.1%
- Statistical precision on $A_{FB}$: ~0.5%
- Can expect that systematic errors will match statistical precision (but needs to be shown)
Measurement of bottom and top observables delivers complementary information for EFT operators.

- **ILC@250 GeV comparable to LEP in terms of cross section** => Constrain on $g_{Lb}$
- **ILC@250 GeV drastically better than LEP in terms of AFB** => Constrain on $g_{Rb}$

How would the picture look with GigaZ precisions?

*From cross section*

*From forward-backward asymmetry*
Precision on electroweak form factors and couplings

Arxiv:1709.04289, ILD Paper in progress

Couplings are order of magnitude better than at LEP

- e+e- collider way superior to LHC (√s = 14 TeV)
- Final state analysis at FCCee
  - Also possible at LC => Redundancy

- Two remarks:
  - 500 GeV is nicely away from QCD Matching regime
  - Less systematic uncertainties
  - Axial form factors are ~ and benefit therefore from higher energies

Full disentangling of helicity structure for all fermions only possible with polarised beams!!
Electroweak top couplings EFT-operators

Mapping between FF and EFT Coefficients

\[ F_{1V} = \frac{1}{2} \left( 1 - \frac{2}{3} s_W^2 \right) - \frac{m_t^2}{s_W c_W^2} \frac{1}{\Lambda^2} \left[ C_{\phi q}^{C_{\phi q}} + (C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)}) \right], \]

\[ F_{1A} = -\frac{1}{4} \frac{m_t^2}{s_W c_W^2} \frac{1}{\Lambda^2} \left[ C_{\phi q}^{A(33)} + (C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)}) \right], \]

\[ F_{2V} = 4 \frac{m_t^2}{\Lambda^2} \left[ C_{uZ}^R = \text{Re} \left\{ C_{uW}^{(33)} - s_W^2 C_{uB}^{(33)} \right\} / s_W c_W \right], \]

\[ F_{2A} = 4 \frac{m_t^2}{\Lambda^2} \left[ C_{uZ}^I = \text{Im} \left\{ C_{uW}^{(33)} - s_W^2 C_{uB}^{(33)} \right\} / s_W c_W \right], \]

- Translation of results into EFT language confirm superiority of e+e- w.r.t. LHC
- Several operators benefit already from 250 GeV running
- Top specific operators constrained by running at 500 GeV

arxiv:1907.10619

arxiv:1807.02121
Effects at higher energies

Development of EFT Operators

GUT Inspired GHU Model

- Effects amplified at higher energies
- Different patterns for different beam polarisations (L, U, R)
- Different patterns for different fermions

Increased sensitivity to operators representing four-fermion interactions
Summary and outlook

- Linear colliders are ideally suited for precision measurements of two-fermion final states

- Measurement of top mass to a precision of ~50 MeV in clean environment
  - Flexibility in energy allow for complementary methods
  - Threshold scan and radiative events
  - Watch our for new ideas later today

- Linear colliders will have the answer whether new physics acts on heavy doublet (t,b) only or on all fermions

- Will/would probe helicity structure of electroweak fermion couplings over at least one order of magnitude in energy (Z-Pole -> ~1 TeV)
  - Achievable experimental precisions ~0.1 - 1%
  - Effects may become already visible at 250 GeV stage for b quark and c quarks (and other light fermions)
  - Amplification of effects at higher energies
  - Clear and unique pattern thanks to polarised beams

- Active phenomenological studies in terms of global analyses (EFT) and concrete models

- Main challenge at future machines will be the control of systematic errors
  - Experimentally
    - Vertex charge and particle ID
    - PFO for final state jets
  - Theoretically (not discussed)
    - Need at least NLO electroweak predictions (and MC programs) for correct interpretation of results
Backup
Linear colliders physics program

All Standard Model particles within reach of planned linear colliders

High precision tests of Standard Model over wide range to detect onset of New Physics

Machine settings can be “tailored” for specific processes
  • Centre-of-Mass energy
  • Beam polarisation (straightforward at linear colliders)

\[ \sigma_{P,P'} = \frac{1}{4} \left[ (1 - PP') (\sigma_{LR} + \sigma_{RL}) + (P - P') (\sigma_{RL} - \sigma_{LR}) \right] \]

Background free searches for BSM through beam polarisation
Experimental challenges - Flavor tagging and charge measurement

- **Flavor tagging**
  - Indispensable for analyses with final state quarks

- **Quark charge measurement**
  - Important for top quark studies,
  - Indispensable for $ee\rightarrow bb$, $cc$, $ss$, ...

- **Control of migrations:**
  - Correct measurement of vertex charge
  - Kaon identification by $dE/dx$ (and more)

- **Future detectors can base the entire measurements on double Tagging and vertex charge**
  - LEP/SLC had to include single tags and Semi-leptonic events

PhD thesis: S. Bilokin
A. Irles
Cross sections

$e^+e^- \rightarrow \bar{t}t : \quad 500 \text{ GeV}$

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma_{\text{unpol}}$ (fb)</th>
<th>$\sigma_{+,+}$ (fb)</th>
<th>$\sigma_{-,-}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{t}t$</td>
<td>572</td>
<td>1564</td>
<td>724</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>456</td>
<td>969</td>
<td>854</td>
</tr>
<tr>
<td>$\sum_{q=\text{up,down}}\bar{q}q$</td>
<td>2208</td>
<td>6032</td>
<td>2793</td>
</tr>
<tr>
<td>$\bar{b}b$</td>
<td>372</td>
<td>1212</td>
<td>276</td>
</tr>
<tr>
<td>$\gamma Z^0$</td>
<td>11185</td>
<td>25500</td>
<td>19126</td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>6603</td>
<td>26000</td>
<td>150</td>
</tr>
<tr>
<td>$Z^0 Z^0$</td>
<td>422</td>
<td>1106</td>
<td>582</td>
</tr>
<tr>
<td>$Z^0 W^+W^-$</td>
<td>40</td>
<td>151</td>
<td>8.7</td>
</tr>
<tr>
<td>$Z^0 Z^0 Z^0$</td>
<td>1.1</td>
<td>3.2</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Single $t$ for $e^+e^- \rightarrow e^-\bar{\nu}_e tb \quad [11]$:

$\sigma_{\text{unpol}} \approx 3.1 \quad \sigma_{+,+} \approx 10.0 \quad \sigma_{-,-} \approx 1.7$

$e^+e^- \rightarrow b\bar{b} : \quad 250 \text{ GeV}$

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma_{\text{unpol}}$ (fb)</th>
<th>$\sigma_{L}$ (fb)</th>
<th>$\sigma_{R}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}$</td>
<td>1756</td>
<td>5629</td>
<td>1394</td>
</tr>
<tr>
<td>$\gamma b\bar{b}$ (Z return)</td>
<td>7860</td>
<td>18928</td>
<td>12512</td>
</tr>
<tr>
<td>$Z\bar{Z}$ hadronic with $b\bar{b}$</td>
<td>196</td>
<td>549</td>
<td>236</td>
</tr>
<tr>
<td>HZ hadronic with $b\bar{b}$</td>
<td>98</td>
<td>241</td>
<td>152</td>
</tr>
</tbody>
</table>

$e^+e^- \rightarrow c\bar{c} : \quad 250 \text{ GeV}$

$\sigma(P_{e^-} = -1, P_{e^+} = +1) \approx 8518 \text{ fb}$

$\sigma(P_{e^-} = +1, P_{e^+} = -1) \approx 3565 \text{ fb}$

$\sigma_{\text{unpol}} \approx 3020 \text{ fb}$
Detector requirements

e+e- detector concepts for linear colliders
Preferred solution Particle Flow Detectors

CLIC Detector
B= 4T
Central tracking with silicon

SiD
B= 5T
Highly granular calorimeters
Inner tracking with silicon

ILD
B= 3.5T
Central tracking with TPC
Detector requirements

Track momentum: \( \sigma_{1/p} < 5 \times 10^{-5}/\text{GeV} \) (1/10 \( \times \) LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: \( \sigma_{d0} < \left[ 5 \oplus 10/(p[\text{GeV}]\sin^{3/2}\theta) \right] \mu\text{m} \) (1/3 \( \times \) SLD)

(Quark tagging c/b)

Jet energy resolution: \( dE/E = 0.3/(E[\text{GeV}])^{1/2} \) (1/2 \( \times \) LEP)

(W/Z masses with jets)

Hermeticity: \( \theta_{\min} = 5 \text{ mrad} \)

(for events with missing energy e.g. SUSY)

Final state will comprise events with a large number of charged tracks and jets(6+)

- High granularity
- Excellent momentum measurement
- High separation power for particles

Particle Flow Detectors

Detector Concepts: ILD, SiD and CLICdp
Typical efficiencies

\[ e^+e^- \rightarrow b\bar{b} : \ 250 \text{ GeV} \]

- Individual efficiency for correct b-tag and charge measurements using Vtx and Kaon charge
- Final efficiency ~20% from combination of Vtx and Kaon charge in different/same jets

**Total cross section**
- Typical efficiency 75%
- Independent of beam polarisation

**Differential cross section**
- Note, difference for different beam polarisations
- Left hand polarisation more vulnerable to migrations
- Requires information from hadronic final state
- Vtx, Kaon as in bb-case
Why lighter quarks? – e.g. GUT Inspired Grand Higgs Unification Model

- Model parameter is Hosotani angle $\theta_H$ yielding the Higgs-Potential as consequence of Aharanov-Bohm Phase in 5th dimension

- Model defined in Randall-Sundrum warped extra dimensions
  - KK excitations of gauge bosons and new bosons modify fermion couplings

- Predictions for ILC
  - $m_{KK} = 13$ TeV and $\theta_H = 0.1$

- Deviations from SM of the order of a few %
  - Effects measurable already at 250 GeV
  - Effects amplified by beam polarisations
  - Effects for $tt$, $bb$ and $cc$ (and other light fermions)

- One concrete example for importance to measure full pattern of fermion couplings
  - Full pattern only available with beam polarisation
Decomposing $\text{ee} \rightarrow \text{bb}$ – Differential cross section

- Full simulation study (with ILD concept), Benchmark reaction
- Long lever arm in $\cos \theta_b$ to extract from factors or couplings

- Note that the precision will reach the per-mill level -> requires full control over detector performance
- Background can be reduced to a negligible level (see backup) but requires careful treatment of e.g. radiative return events

- Discussion of all experimental aspects deserves dedicated talk!!!
Top pair production at threshold

“Bound states” at tt threshold
Hydrogen atom of strong interaction

- Size $O(10^{-17} \text{m})$, smallest non-elementary object known in particle physics
Small scale => Free of confinement effects => Ideal premise for precision calculations
Measurement of (a hypothetical) $1^3S_1$ State

- Decay of top quark smears out resonances in a well defined way
Sensitivity and error breakdown

<table>
<thead>
<tr>
<th>Error Source</th>
<th>$\Delta m_t^{\text{PS}}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>stat. error (200 fb$^{-1}$)</td>
<td>13</td>
</tr>
<tr>
<td>theory (NNNLO scale variations, PS scheme)</td>
<td>40</td>
</tr>
<tr>
<td>parametric ($\alpha_s$, current WA)</td>
<td>35</td>
</tr>
<tr>
<td>non-resonant contributions (such as single top)</td>
<td>$&lt; 40$</td>
</tr>
<tr>
<td>residual background / selection efficiency</td>
<td>10 – 20</td>
</tr>
<tr>
<td>luminosity spectrum uncertainty</td>
<td>$&lt; 10$</td>
</tr>
<tr>
<td>beam energy uncertainty</td>
<td>$&lt; 17$</td>
</tr>
<tr>
<td>combined theory &amp; parametric</td>
<td>30 – 50</td>
</tr>
<tr>
<td>combined experimental &amp; backgrounds</td>
<td>25 – 50</td>
</tr>
<tr>
<td>total (stat. + syst.)</td>
<td>40 – 75</td>
</tr>
</tbody>
</table>

- Detailed evaluation of systematic uncertainties
- Multi-parameter fits (mass, width, $\alpha_s$, yt), scan optimization...
Precision on couplings and helicity amplitudes and physics reach

Example b-couplings (same observation for c-couplings, arxiv:2002.05805)

- Couplings are order of magnitude better than at LEP
  - In particular right handed couplings are much better constrained

New physics can also influence the Zee vertex
  - in 'non top-philic' models

Full disentangling of helicity structure for all fermions only possible with polarised beams!!

ILD Preliminary

- ILC250, 2000 fb⁻¹
- ILC GigaZ
- LEP1

Stat + syst unc. [%]

10
1
10⁻¹
10⁻²
10⁻³

LeLb, LeRb, ReLb, ReRb, LeZ, ReZ

Impressive sensitivity to new physics in Randall Sundrum Models with warped extra dimensions

- Complete tests only possible at LC
- Discovery reach O(10 TeV)@250 GeV and O(20 TeV)@500 GeV

Pole measurements critical input
- Only poorly constrained by LEP
How can the Z-Pole help?

On the Z-pole

- Sensitivity to $Z/Z'$ mixing
- Sensitivity to vector (and tensor) couplings of the Z
  *the photon does not “disturb”

Above the Z-pole

- Sensitivity to interference effects of $Z$ and photon!!
- Measured couplings of photon and $Z$ can be influenced by new physics effects
- Interpretation of result is greatly supported by precise input from $Z$ pole

More on ILC GigaZ Program in EF04 Meeting on Friday 19/6/20
And tomorrow?

**ee --> ss: SLD Analysis at Z Pole**

- Extend the heavy quark analyses to light quarks to get full picture.
- Optimise vertexing and particle ID (i.e., Kaon ID with full simulation studies.)
Beam polarisation and disentangling

With two beam polarisation configurations

\[ P(e^-) = \pm 80\% \quad P(e^+) = \mp 30\% \]

There exist a number of observables sensitive to chiral structure, e.g.

\[ \sigma_I \]
\[ A_{FB,I} = \frac{N(\cos \theta > 0) - N(\cos \theta < 0)}{N(\cos \theta > 0) + N(\cos \theta < 0)} \]
\[ (F_R)_I = \frac{(\sigma_{tR})_I}{\sigma_I} \]

\( x \)-section

Forward backward asymmetry

Fraction of right handed top quarks

\[ F_{1V}, F_{1Z}, F_{1A} = 0, \quad F_{1A} \]

or equivalently

\[ g_L^\gamma, g_R^\gamma, g_L^Z, g_R^Z \]

Extraction of relevant unknowns

EPS 2021
~3σ in heavy quark observable $A_{FB}^b$

- Is tension due to underestimation of errors or due to new physics?

- High precision e+e- collider will give final word on anomaly

- In case it will persist polarised beams will allow for discrimination between effects on left and right handed couplings (Remember $Zb_l b_l$ is protected by cross section)

- Note that also B-Factories report on anomalies EPS 2021
What about lighter quarks – Differential cross section $ee \rightarrow cc$

Full simulation study (with ILD concept)
Long lever arm in $\cos \theta_c$ to extract from factors or couplings

arxiv:2002.05805
Top pair production at threshold

Fit uncertainty:
- ILC: 28.5 MeV (18 MeV stat)
- CLIC: 31 MeV (21 MeV stat)
- FCC-ee: 27 MeV (15 MeV stat)

Scale uncertainty:
- ILC: 40 MeV
- CLIC: 42 MeV
- FCC-ee: 40 MeV
ee-->bb – Signal and background

- Background levels can be kept at very small level
- However, these type of analyses seek per-mille level precision