Precision top quark physics at a future linear $e^+e^-$ collider

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on behalf of the LC community
Outline

• Future $e^+e^-$ colliders
• Detectors
• Top quark mass
• Top quark couplings

Reference documents prepared by the LC community:
- Tesla TDR (2001) part III on physics
- 2004 Report on the complementarity of LC and LHC
- CLIC physics report
- Letter Of Intent of the ILC experiments (2009) SiD and ILD
- Conceptual Design Report (2012) of the CLIC detectors
- Soon: Detailed Baseline Design for the ILC experiments
Future $e^+e^-$ colliders

- Superconducting RF cavities are in the industrialization phase and routinely reach gradients well over 30 MV/m. ILC is shovel-ready.
- Still higher gradient (~100 MV/m) can be achieved using drive beam concept. CLIC can open up the multi-TeV regime.

\[ \text{R&D around the globe} \]
\[ \text{Non-exhaustive list of test facilities:} \]
- ATF@KEK, nm size, low emittance beams
- CESR/IT@Cornell (electron cloud)
- CTF3@CERN, drive beam
- XFEL@DESY, cavities

\[ \text{Contributions on 07/07 in TR14:} \]
- Steinar Stapnes, the CLIC project
- Phil Burrows, beam feedback
- Jenny List, polarimetry
- Tony Hartin, spin tracking

LC technology exists for a low-energy machine ($\sqrt{s} \sim 250-500$ GeV)
R&D is ongoing for $\sqrt{s} \sim 1-3$ TeV
LC detectors

LC environment and detector R&D allow for a big leap in performance

- Signal and bkg x-sections of similar magnitude
- Well-defined initial state (CM energy, polarization)
- Triggerless read-out
- Background confined to innermost detectors

Particle Flow: highly granular calorimetry inside a large 3.5-5 Tesla solenoid allows to follow every single visible particle produced in the collisions from the cradle to the grave → best possible estimate of the jet energy: $\Delta E/E \sim 3-5\%$

Transparent and precise tracking/vertexing:
\[ \Delta(1/p_t) \sim 10^{-5} \text{ GeV}^{-1} \]
\[ \Delta(d_0) \sim 5 \oplus 10-20 / (p \sin^{3/2} \theta) \]

Detailed Geant4 model and sophisticated reconstruction software allow realistic estimates of performance

Contributions on 07/07 in TR13:
Tomohiko Tanabe on ILD
Andy White on SiD
Frank Simon on CLIC detectors
Top Quark Mass – Hadron Colliders

Compare the mass of the top quark decay products to a template from a generator and identify the best fit result with the quark pole mass

Tevatron: total error below 1 GeV
LHC already systematics dominated:
ATLAS $l + \text{jets} (1/fb)$: $174.5 \pm 0.6 \text{ (stat)} \pm 2.3 \text{ (syst)} \text{ GeV}$
CMS $\mu + \text{jets} (5/fb)$: $172.6 \pm 0.4 \text{ (stat)} \pm 1.2 \text{ (syst)} \text{ GeV}$

Main disadvantage: no rigorous interpretation in scheme

Pair production cross-section measurement at the LHC yields a top quark mass determination

Precision of this procedure seems to be limited:

$$\frac{\Delta \sigma_{t \bar{t}}}{\sigma_{t \bar{t}}} \approx 5 \frac{\Delta m_t}{m_t}$$
The shape of the top quark pair production cross section around threshold offers sensitivity to top quark mass, top quark width and the strong coupling constant $\alpha_s$.

Threshold shape is partially washed out by ISR and beam energy spread. Larger beam energy spread at CLIC has $\sim 15\%$ effect on precision of the fit.

See: Peter Marquard's contribution in this track.
Top quark mass

New results corroborate old studies and extend these findings to a machine with a very different technology.

Measurement in the continuum ($\sqrt{s} = 500$ GeV) is possible with a statistical error $\sim 50$-100 MeV (ILD/SiD, CLIC CDR). This measurement is affected by the same type of systematic uncertainties as Tevatron/LHC.

A precise measurement $O(100$ MeV$)$ with a rigorous interpretation is achievable at a low energy linear collider.
Top quark mass – what do we learn?

Measure fundamental parameters of the Standard Model as precisely as possible

If (now that?) a Higgs-like object is observed, use precise measurements of the masses of the top quark, the W boson and the new state to test internal consistency of the Standard Model
Top quark couplings

Asymmetries in the production of third generation quarks has been an interesting area for decades


\[ \sigma \approx 0.6 \text{ pb} \]
\[ \text{at } \sqrt{s} = 500 \text{ GeV} \]
\[ \approx 0.2 \text{ pb} \]
\[ \text{at } \sqrt{s} = 1 \text{ TeV} \]
\[ \approx 0.1 \text{ pb} \]
\[ \text{at } \sqrt{s} = 3 \text{ TeV} \]

Detailed study of tt production at LC may greatly enhance the sensitivity to BSM physics

Example: Warped Extra Dimensions at LC 3 TeV

F. Corradeschi, LCWS10, arXiv:1202.0660
M. Battaglia, LCWS11
Top quark couplings

\[ \Gamma_{t\bar{t}(\gamma,Z)}^{\mu} = ie \left[ \gamma^{\mu} \left[ F_{1V}^{\gamma,Z} + F_{1A}^{\gamma,Z} \gamma^5 \right] + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_t} \left[ F_{2V}^{\gamma,Z} + F_{2A}^{\gamma,Z} \gamma^5 \right] \right] \]

Parton-level studies show how measurements on \( t\bar{t} \) production at LC (\( \sigma, A_{FB}, A_{LR}, \ldots \)) can constrain the form factors \( F \)

<table>
<thead>
<tr>
<th>Form factor</th>
<th>SM value</th>
<th>LC prospects ( \sqrt{s} = 500 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{1V}^{\gamma,Z} )</td>
<td>1</td>
<td>1.9%</td>
</tr>
<tr>
<td>( F_{1A}^{\gamma,Z} )</td>
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<td>( F_{2V}^{\gamma,Z} = (g-2)_\gamma^{\gamma,Z} )</td>
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<td>( \text{Re } d_t^{\gamma} )</td>
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<tr>
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<tr>
<td>( \text{Im } F_{2A}^{\gamma} )</td>
<td>0</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

TESLA TDR, to be explored in complete studies with detailed simulation

Control over beam polarization is vital!!
Top quark couplings

Fully hadronic $t\bar{t}$ events are a benchmark channel in SiD and ILD LOI

**Basic selection:**
- visible energy
- number of (charged) particles
- $y_{\text{min}}$ (6 jets)
- $W$-boson mass
- $b$-tagging

*Efficiency: 51%*
*Purity: 69 %*

**Kinematic fit:**
- $m_t = m_t$
- $m_W = 80.4$ GeV
- $E_{\text{vis}} = 500$ GeV
- $P_x = P_y = P_z = 0$

*Efficiency: 31%
Purity: 86%*

Excellent flavour tagging, vertex charge and jet charge determination allow to reconstruct the $A_{FB}^{t\bar{t}}$ (and that of $b$-quarks in $t\bar{t}$ events) to $\sim 5%$

Lepton + jets final state offers better distinction of $t$ and $t$ directions
Work in progress

Revisiting the parton-level study for the Detailed Baseline Design

Assumptions:
LC: $\sqrt{s} = 500$ GeV, $L = 500$/fb
$P(e^-) = 80\%$, $P(e^+) = 30\%$

LHC: 14 TeV, 300/fb

LAL/IFIC preliminary

Full simulation in ILD concept to understand experimental challenges and estimate systematic errors. Preliminary: migrations due to ambiguities in $tt$ reconstruction can be controlled at an LC

Helicity angle

true

reconstructed

LAL/IFIC preliminary

true

reconstructed

top polar angle
Summary

New results from detailed studies on two highlights of the LC precision top quark physics program:

- $\Delta m_t \sim 100$ MeV
  
  Threshold scan yields a precise top quark mass measurement in a well-defined scheme
  Continuum measurement yields a similar statistical precision

- $\delta F_{1V}^{\gamma,Z}, \delta F_{1A}^{\gamma,Z} \sim 1\%$
  
  Polarization allows to disentangle $\gamma$ and $Z$
  Couplings to $Z$ and characterized couplings at the % level
  $A_{FB}(tt)$ to 5% in fully hadronic final state! Much better in lepton+jets (preliminary)

More results expected soon!!