A feasibility study of top-quark Yukawa coupling measurement in $e^+e^- \rightarrow ttH$ at $\sqrt{s}=500\text{GeV}$

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for
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Introduction

- Unique role of the top quark for Electroweak symmetry breaking (EWSB) studies
  - Top mass is by far the largest and approximates the EWSB scale
  - Suggests top couples strongly to the physics that breaks the EW symmetry
  - Important to investigate properties of the top in detail, for the purpose of probing the EWSB physics as well as to gain deeper understanding of the origin of the flavor structure
  - Measurement of top-quark Yukawa coupling will be the most decisive test of the mass generation mechanism for matter particles!

- Goal of our study: evaluate measurement accuracy for the direct measurement of the top Yukawa coupling at 500GeV
  - Need to demonstrate its feasibility in the first phase of the ILC project!

If the Higgs boson is the one to give masses to all the SM particles, we need to observe proportionality between mass and coupling.

Might see two or more lines if the Higgs sector is non-minimal!
Measurement of top Yukawa coupling

- **LHC (2 x 300 fb⁻¹)**
  - Cross section for Gluon fusion → H
    \[ \sigma_{ggH} = \alpha_{ggH} \cdot g_t^2 \]
    - Cross section for Gluon fusion → ttH (seems difficult...)
    \[ \sigma_{ttH} = \alpha_{ttH} \cdot g_t^2 \]
    - Branching ratio for H → γ γ
      \[ \text{BR}(H \rightarrow \gamma \gamma) = \frac{(\beta_{\gamma W} \cdot g_W - \beta_{\gamma t} \cdot g_t)^2}{\Gamma_H} \]

From J. Tanaka (U. Tokyo/ICEPP)'s slide
Measurement of top Yukawa coupling

- **ILC**: indirect measurement
  - Higgs exchange between tops affects the potential near ttbar threshold
  - 11 points ttbar threshold scan
    => $\sigma_{tt}$ ($m_H, g_Y$)
  - Need theoretical progress in the predictions of ttbar threshold observables
Measurement of top Yukawa coupling

- **ILC: indirect measurement**
  - Higgs exchange between the potential near ttbar state
  - 11 points ttbar threshold scan
  => $\sigma_{tt}(m_H, g^t)$
  - Need theoretical progress in the predictions of ttbar threshold observables

  ![Graph showing ttbar threshold scan]

- **ILC: direct measurement**
  - Most of the past studies were done assuming at $\sqrt{s} \sim 700 \text{GeV}$ since the cross section for $e^+e^- \rightarrow ttH$ attains its maximum around this energy region
  - However, pointed out that the NRQCD threshold correction enhances the cross section significantly and might open the possibility of directly measuring $g^t$ at $\sqrt{s} = 500 \text{GeV}$

  ![Graph showing direct measurement]

**top Yukawa effect at tt threshold quickly vanishes as $M_{Higgs}$ goes up from 110 GeV to 120 GeV!**
$e^+e^- \rightarrow ttH$ event display

- Dense 8-fermion ($H\rightarrow bb$) and/or 10-fermion ($H\rightarrow WW^*$) events
- Challenging for correct jet-parton association w/ quad b-tagging
  - Di-jet & Tri-jet invariant masses: $M_{W(jj)}, M_{c(bjj)}$ & $M_H(bb)$ for background events rejection
**Signal processes: e^+e^- -> ttH**

- In this study: concentrate on the **dominant decay mode** H(120GeV) -> bb (68%)
  - ttH (-> bW^+bW^- bb) signal events can be classified into 3 groups
    - 8-jets, 1-lepton + 6-jets, and 2-leptons + 4-jets

\[ \sigma_{ttH} \propto (g_{Yt})^2 \]

- Dominant contribution to ttH production at \( \sqrt{s} = 500\text{GeV} \) is \( \gamma/Z \) exchange (= very small contribution from Higgs radiated off the Z)
  - Can determine \( g_{Yt} \) by just counting the number of signal events
  - But the **signal cross section** is sub-fb order...

- Initial state radiation (ISR) and Beamstrahlung
  - \( \sigma_{ttH} \) decreases by a factor \( \approx 2 \) at \( \sqrt{s} = 500\text{GeV} \)

- **NRQCD threshold correction** (to ttbar system)
  - Enhances \( \sigma_{ttH} \) significantly: \( \sigma_{ttH} = 0.45\text{fb} \) (with no beam pol.)
Possible BGs (Interfering)

- Interfering BGs (same final state: $ttbb \rightarrow bqql \nu bb$)
  - Electroweak: $ttZ \rightarrow ttbb$ ($Z \rightarrow bb$: 15%) $\sim 0.2fb$ with no beam polarization
    - NRQCD threshold correction enhances $\sigma_{ttz}$ from 0.7fb to 1.3fb
    - Dangerous if $M_{Higgs}(120GeV)$ is close to $M_{bb}$
  - Electroweak: $W^*W^*/ZZ^* \rightarrow ttbb$: small contribution ($< 0.01fb$)
  - QCD: $ttg \rightarrow ttbb$ ($g \rightarrow bb$: dominant) $\sim 0.7fb$ with no beam polarization
    - Not so dangerous when $M_{bb} < M_{Higgs}(120GeV)$
Possible BGs (Non-interfering)

- Non-interfering BGs (but, **huge cross sections**)
  - $t\bar{t}$bar $\sim$ 500fb with no beam polarization
    - Hard gluon emission from bottom quarks
    - Small fraction of mis-reconstruction and/or failure in b-tagging may lead to significant BG contamination
  - qq (5 flavors) $\sim$ 4pb: negligible <= 1-isolated lepton + 6-jets (w/ quad b-tagging)
  - WW $\sim$ 8pb: negligible w/ quad b-tagging / ZZ $\sim$ 0.58pb: not huge = negligible

![Graph showing Cross Section vs. $\sqrt{s}$ (GeV) for various processes with and without QCD corrections.](image-url)
Analysis framework

- Event generator
  - **physsim** package: based on full helicity amplitudes (6 or 8-fermion final states) calculated with **HELAS** including gauge boson decays (correctly taking into account angular distribution of the decay products)
  - **BASES/SPRING**: MC phase pace integration / 4-momenta of the final-state quarks and leptons
  - Included **ISR & Beamstrahlung**
  - NRQCD threshold enhancement to the ttbar system (ttH/ttZ)

- Parton shower / Hadronization
  - **Pythia 6.4**

- Detector simulator / energy flow reconstruction
  - **JSFQuickSim** (smearing based fast MC simulator) / Track-cluster matching

<table>
<thead>
<tr>
<th>Detector</th>
<th>Performance</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex detector</td>
<td>$\sigma_b = 7.0 \oplus (20.0/p)/\sin^{3/2} \theta \mu m$</td>
<td>$</td>
</tr>
<tr>
<td>Central drift chamber</td>
<td>$\frac{\sigma_{T}}{P_T} = 1.1 \times 10^{-4} P_T \oplus 0.1%$</td>
<td>$</td>
</tr>
<tr>
<td>EM calorimeter</td>
<td>$\sigma_E/E = 15%/\sqrt{E} \oplus 1%$</td>
<td>$</td>
</tr>
<tr>
<td>Hadron calorimeter</td>
<td>$\sigma_E/E = 40%/\sqrt{E} \oplus 2%$</td>
<td>$</td>
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</tbody>
</table>

Katsumasa Ikematsu (KEK) / ALCPG LCWA09
Event selection

- Concentrate on 1-lepton + 6-jets mode as our first step
  - not so low branching ratio: 35% where the lepton is required to be either $e^\pm$ or $\mu^\pm$
  - not so high jet multiplicities

- Signatures of the 1-lepton + 6-jets mode
  - 1 isolated energetic $e^\pm$ or $\mu^\pm$
  - 6 jets including 4 b-jets, 2 of which form a Higgs
  - Remaining 2-jets being consistent with a $W$
  - 1 of the 2 unused b-jets together with this $W$ candidate comprising a top

Reconstructed mass dists. using generator information (Cheated jet-finder = perfect jet-parton association)
Reduction of huge $t\bar{t}$ BGs

1) Finding and eliminating an energetic isolated lepton
2) Force the events to cluster into 6 jets by choosing an appropriate $Y_{cut}$ value on the event-by-event basis (force 6-jet clustering)
3) $Y_{cut}$ cut
   - $Y_{cut}$ value for a $t\bar{t}$ BG event to form 6-jets should be lower than the one for a signal ($t\bar{t}H \rightarrow t\bar{t}bb$)
   - Effective $t\bar{t}$ BG rejection by cutting $Y_{cut}$ values at 0.002

4) Jet-parton association $\Rightarrow$ Mass cut
   - Looping over all the 2-jet combinations $\Rightarrow$ Look for a pair having an invariant mass $\Rightarrow \pm 15$GeV from $M_w(80.0\text{GeV})$
   - From the remaining 4-jets $\Rightarrow$ Pick up one and attach it to the pair making a W candidate $\Rightarrow \pm 25$GeV from $M_t(175\text{GeV})$
   - Search a pair from the 3-jets left over $\Rightarrow \pm 15$GeV from $M_{H}(120\text{GeV})$
   - Chance to have multiple combinations since these mass window cuts are rather loose
   - Select the combination with the smallest $\chi^2$

$$\chi^2 = \left( \frac{M_{2\text{-jet}(w)} - M_w}{\sigma_{M_w}} \right)^2 + \left( \frac{M_{3\text{-jet}(t/\bar{t})} - M_t}{\sigma_{M_t}} \right)^2 + \left( \frac{M_{2\text{-jet}(H)} - M_H}{\sigma_{M_H}} \right)^2$$
Reduction of huge tt BGs (cont’d)

- For the tt BG rejection, **quad b-tagging is very powerful** since ttH has 4 b-jets, while tt BG has only 2 b-jets.
- Use ordinary **n-sig method** for the quad b-tagging for the moment.
- Defined **tight b-tagging** \((n_{\sigma b}, \#_{\text{off-vtx-trk}}) = (3.0, 2)\) / **loose b-tagging** \((n_{\sigma b}, \#_{\text{off-vtx-trk}}) = (2.0, 2)\)
- Require all of the 4 b-jet candidates have to satisfy the loose b-tagging condition and there has to be at least one tight b-tagged jet from each of the H and t/tbar candidates.

**Mass dists. after using both mass cut and the quad b-tagging**

- **ttZ** \((Z\rightarrow bb)\) and **ttg** \((g\rightarrow bb)\) BGs have similar signature as a ttH
  - can be separated only with the invariant mass of the H candidate.
**Final cut statistics**

- Normalized to integrated luminosity: $1 \text{ ab}^{-1}$
  - # generated events: $5\text{M}$ for tt / $50\text{k}$ for ttH, ttZ, ttg (g->bb)

<table>
<thead>
<tr>
<th>Beam Polarization Processes</th>
<th>$\bar{t}tH$</th>
<th>$\bar{t}tZ$</th>
<th>$\bar{t}t$</th>
<th>$\bar{t}\bar{t}g$ (bb)</th>
<th>$\bar{t}tH$</th>
<th>$\bar{t}tZ$</th>
<th>$\bar{t}t$</th>
<th>$\bar{t}\bar{t}g$ (bb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Cut</td>
<td>449.0</td>
<td>1340.0</td>
<td>514040.5</td>
<td>697.5</td>
<td>759.0</td>
<td>2407</td>
<td>863500.4</td>
<td>1159.6</td>
</tr>
<tr>
<td>$N_{iso.lep}=1$</td>
<td>159.4</td>
<td>435.9</td>
<td>209718.4</td>
<td>242.2</td>
<td>269.4</td>
<td>783.0</td>
<td>303879.0</td>
<td>397.7</td>
</tr>
<tr>
<td>$Y_{cut}$ (6 jets) &gt; 0.002</td>
<td>139.2</td>
<td>307.8</td>
<td>22851.3</td>
<td>152.5</td>
<td>235.4</td>
<td>552.9</td>
<td>38477.2</td>
<td>249.6</td>
</tr>
<tr>
<td>btag &amp; mass cut</td>
<td>23.0</td>
<td>12.2</td>
<td>11.9</td>
<td>6.9</td>
<td>38.9</td>
<td>21.8</td>
<td>19.7</td>
<td>11.3</td>
</tr>
</tbody>
</table>

Mass dists. (cumulative) for the final selected samples for the beam polarization combination: $(e^-, e^+) = (-0.8, +0.3)$

Clear evidence of signal events over the background

<table>
<thead>
<tr>
<th>Beam pol. combination</th>
<th>No beam pol.</th>
<th>$(e^-, e^+) = (-0.8, +0.3)$</th>
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</thead>
<tbody>
<tr>
<td>Significance</td>
<td>$4.1,\sigma$</td>
<td>$5.4,\sigma$</td>
</tr>
<tr>
<td>$\Delta g\gamma^t / g\gamma^t$</td>
<td>$\pm0.12$</td>
<td>$\pm0.093$</td>
</tr>
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</table>
Summary

- Performed a feasibility study of measuring the top-quark Yukawa coupling at $\sqrt{s} = 500\text{GeV}$, taking advantage of the NRQCD threshold enhancement to the t-tbar sub-system
- Implemented the threshold correction in the ttH and ttZ event generators in the physsim package
- For 1-lepton + 6-jets mode of $e^+e^- \rightarrow \text{ttH}$ process, signal significance $4.1\sigma$ without beam polarization, and $5.4\sigma$ with the beam polarization combination: $(e^-, e^+) = (-0.8, +0.3)$ for an integrated luminosity of 1 ab$^{-1}$
- Measurement accuracy for the top-quark Yukawa coupling about 10% using only 1-lepton + 6-jets mode at $\sqrt{s} = 500\text{GeV}$, which is the energy already available in the first stage of the ILC

Future prospects

- Increase signal statistics by analyzing 8-jets mode (45%)
- Introduce a multivariate analysis instead of cut-bases analysis
- Derive measurement accuracy for $\sqrt{s}$ dependence
- Apply full MC detector simulator => realistic particle flow algorithm
- Adopt a high performance flavor tagging by using LCFIVertex package
- Do full SM backgrounds scan