Impact of beam polarization on the LC physics potential for a staged approach

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What is the motivation?

- We have a Higgs!  
  That’s great.
- Why do we need to know all its properties with best precision?  
  Because that’s the bridge between ‘micro’ and ‘macro’ cosmos.
- We have the Top!  
  That’s great.
- Why do we need to know all its properties with best precision?  
  Because that’s the bridge to understand dynamics of EWSB.
- Excellent top physics at LHC (and HL-LHC)  
  That’s great!
- Do we really also need the LC?
  ...a great chance might just be ahead....
Possible Timeline

July 2013
- Non-political evaluation of 2 Japanese candidate sites complete, followed by down-selecting to one

End 2013
- Japanese government announces its intent to bid

2013-2015
- Inter-governmental negotiations
- Completion of R&Ds, preparation for the ILC lab.

~2015
- Inputs from LHC@14TeV, decision on whether to bid

2015-16
- Construction begins (incl. bidding)

2026-27
- Commissioning

ILC might start @ times HL-LHC!
Preface

• Discovery of a SM-like Higgs around $m_H \sim 125$ GeV
  – Is an absolute revolution!
  – Completely new type
  – Not clear whether a SM-Higgs

• In short -- some LC capabilities:

  As e.g. $\Delta m_{\text{top}} \sim 0.1$ GeV, $\text{coup}_{\text{ttH}} \sim 3\%$, $H$: BR’s~1(b)-7(c)\%, $\Gamma_H \sim 5\%$, $\Delta \lambda \sim 17\%$

• Very active: many new LC studies and reports….
  – ILC TDR (since June 12, 2013)
  – CLIC CDR 2012
  – Collection of LC notes (DESY123h) online
  – 2 more LC reviews under work

‘The properties of the Higgs boson, to be discovered at the LHC, must be thoroughly investigated in a good condition at the ILC’
(K. Kawagoe, Feb 12)

Further improvement via lumi-upgrade, see Tians’talk!

Focus of my talk (in p. 1st article in Desy123h, 1210.0202)
The LC physics offer

• Staged approach:
  – $\sqrt{s}=250 \text{ GeV}, \text{`Higgs cross section, mass + couplings'}$
  – $\sqrt{s}=350 \text{ GeV}, \text{`Higgs width + top mass'}$
  – $\sqrt{s}=500 \text{ GeV}, \text{`Special Higgs- and top couplings+BSM'}$
  – $(\sqrt{s}=91 \text{ GeV}, \text{`Precision frontier + indirect BSM frontier'}})$
  – $\sqrt{s}\geq1000 \text{ GeV}, \text{`Closing the Higgs picture+more BSM?'}$

• `New’ features, impact on ‘quality’ (and ‘quantity’):
  – Flexible precise energy
  – Perform threshold scans
  – Polarized e- and e+ beams
Technical remarks beam polarization

- $P(e^-) \sim 80\text{-}90\%$

- $P(e^+) \ (\text{always yield } \geq 1.5 \text{ imposed, i.e. ‘full’ lumi})$:  
  - $\sqrt{s}=240 \text{ GeV}: P(e^+)=40\%$
  - $\sqrt{s}=350 \text{ GeV}: P(e^+)=56\%$
  - $\sqrt{s}=500 \text{ GeV}: P(e^+)=59\%$
  - $\sqrt{s}=1 \text{ TeV}: P(e^+)=54\%$

- **Measurement of polarization:**
  - Compton polarimetry (up- and down-stream): $\delta P/P=0.25\%$
  - Via WW-process (lumi-weighted!): $\delta P/P(e^-)\sim0.1\%$, $\delta P/P(e^+)\sim0.2\text{-}0.3\%$

A. Ushakov, LC note

See talk by J. List

I. Marchesini, A. Rosca

Marchesini, A.  Ushakov, LC note

I. Marchesini, A. Rosca
**$P_{\text{eff}}$ and $L_{\text{eff}}$ for the staged approach**

- With the listed parameters:

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$P(e^-)$</th>
<th>$P(e^+)$</th>
<th>$P_{\text{eff}}$</th>
<th>$L_{\text{eff}}/L$</th>
<th>$\frac{1}{x} \Delta P_{\text{eff}} / P_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>total range</td>
<td>$\mp 80%$</td>
<td>$0%$</td>
<td>$\mp 80%$</td>
<td>$1$</td>
<td>$1$</td>
</tr>
<tr>
<td>250 GeV</td>
<td>$\mp 80%$</td>
<td>$\pm 40%$</td>
<td>$\mp 91%$</td>
<td>$1.3$</td>
<td>$0.43$</td>
</tr>
<tr>
<td>$\geq 350$ GeV</td>
<td>$\mp 80%$</td>
<td>$\pm 55%$</td>
<td>$\mp 94%$</td>
<td>$1.4$</td>
<td>$0.30$</td>
</tr>
<tr>
<td>total range</td>
<td>$\mp 90%$</td>
<td>$0%$</td>
<td>$\mp 90%$</td>
<td>$1$</td>
<td>$1$</td>
</tr>
<tr>
<td>250 GeV</td>
<td>$\mp 90%$</td>
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<td>$0.43$</td>
</tr>
<tr>
<td>$\geq 350$ GeV</td>
<td>$\mp 90%$</td>
<td>$\pm 55%$</td>
<td>$\mp 97%$</td>
<td>$1.5$</td>
<td>$0.29$</td>
</tr>
</tbody>
</table>

- Just by switching on $P(e^+)$!

Gain in polarization! (Almost 100%)
Gain in number of interactions!
Gain in precision by more than a factor 3! (large N)

No gain!
‘New tools’: Qualitative $P(e^\pm)$ effects

- **Access to chirality**
  Practically in all new physics models
  - Chirality of particles/interactions has to be identified
  - Since for $E>>m$: chirality = helicity = polarization

- **Access to specific asymmetries** ($\bar{\nu}$, heavy leptons, ..., see later)

- **Exploitation of transversely-polarized beams** ($\sim P_{e^-}P_{e^+}$)
  - Access to tensor-like interactions (Extra dimensions, etc.)
  - Access to CP-violating phenomena
  - Access to specific triple gauge couplings
  - Optimize top quark polarization
Top production at the LC

- Top very special role: heaviest fundamental fermion
  - most strongly coupled to EWSB sector,
  - Intimately related to the dynamics behind the SB mechanism
  - $M_{\text{top}}$ affects $M_H$, $M_W$, $M_Z$ via radiative corrections

- At LHC/Tevatron: $\Delta m_{\text{top}} \sim 1$ GeV
  - Crucial: relation between measured mass to a well-defined parameter that is a suitable theoretical input, as MS mass
  - Relation affected by non-perturbative contr. = limiting factor

- At the LC, $e^+e^- \rightarrow t\bar{t}$: measure ‘threshold mass’
  - Relation to well-defined $m_{\text{top}}$, theoret. well under control
  - Threshold scan: $\Delta m_{\text{top}} \sim 100$ MeV (incl. theo+exp. uncertainties!)
**Top mass**

- **Threshold scan:**
  - Important shift due to non-logarithmic NNNLO terms
  - LC: Peak position remains stable: $\Delta m_t = 100$ MeV
  - Includ. exp uncertainty of ~30 MeV + theo. uncertainty ~70 MeV
  - Expected accuracy confirmed by full simulation studies!
  - Dedicated threshold scan required with about ~100 fb$^{-1}$
Top electroweak coupling

- $\sqrt{s}=500 \text{ GeV}$: chiral structure of ew top couplings:
  - expected to be sensitive to BSM sources
  - Measurement of $'g_{\text{ttZ}}'$ and $'g_{\text{tt\gamma}}'$ rather unique for a LC!

- Use different observables
  - Cross section
  - $A_{\text{FB}}$
  - helicity angle

- Couplings measurable at %-level thanks to the different observables
  - runs with different beam polarization configurations $P(e^-), P(e^+)$

→ Powerful test of the chiral structure!
Top electroweak coupling

Results of full simulation study for DBD at $\sqrt{s} = 500$ GeV

Precision: $\times$ section $\sim 0.5\%$

Precision $A_{FB} \sim 2\%$

Precision $\lambda_h \sim 4\%$

$\Rightarrow$

ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s} = 14$ TeV, 300 fb$^{-1}$)
Top Yukawa coupling

- \( \sqrt{s}=500 \text{ GeV} \): top-Yukawa couplings:
  - At this energy: \( ttH \) is close to threshold
  - But thanks to threshold effects: \( \sigma \) enhancement by factor 2!
  - Key role in dynamics of ew symmetry-breaking

- Direct measurement of Yukawa couplings: \( g_{ttH} \)
  - With \( P(e^-,e^+)=(-80\%,+30\%) \) and 1600 fb \(^{-1}\)
    \[ \Delta g_{ttH} / g_{ttH} < 16\% \]
    but model-independent!

- \( \sqrt{s}=1000 \text{ GeV} \):
  - With \( P(e^-,e^+)=(-80\%,+20\%) \) and 2500 fb \(^{-1}\)
    \[ \Delta g_{ttH} / g_{ttH} < 4\% \]

- In combination: \( \Delta g_{ttH} / g_{ttH} < 2\% \)

LHC estimates: about \( \Delta g_{ttH} \sim 10\% \) at HL-LHC (14 TeV, 3000fb\(^{-1}\))

See J. Tian’s talk!
Top FCNC

- Flavour-changing neutral couplings
  - Relevant for many BSM
  - Can be studied in top pair or single top production
  - Using polarized beams (3σ, based on 300-500 fb⁻¹) :

|          | unpolarized beams | $|P_{e^-}| = 80\%$ | $(|P_{e^-}|, |P_{e^+}|) = (80\%, 45\%)$ |
|----------|-------------------|-------------------|-------------------------------------|
|          | $\sqrt{s} = 500\text{ GeV}$ | $\sqrt{s} = 800\text{ GeV}$ |
| $BR(t \to Zq)(\gamma_{\mu})$ | $6.1 \times 10^{-4}$ | $3.9 \times 10^{-4}$ | $2.2 \times 10^{-4}$ |
| $BR(t \to Zq)(\sigma_{\mu\nu})$ | $4.8 \times 10^{-5}$ | $3.1 \times 10^{-5}$ | $1.7 \times 10^{-5}$ |
| $BR(t \to \gamma q)$ | $3.0 \times 10^{-5}$ | $1.7 \times 10^{-5}$ | $9.3 \times 10^{-6}$ |
| $BR(t \to Zq)(\gamma_{\mu})$ | $5.9 \times 10^{-4}$ | $4.3 \times 10^{-4}$ | $2.3 \times 10^{-4}$ |
| $BR(t \to Zq)(\sigma_{\mu\nu})$ | $1.7 \times 10^{-5}$ | $1.3 \times 10^{-5}$ | $7.0 \times 10^{-6}$ |
| $BR(t \to \gamma q)$ | $1.0 \times 10^{-5}$ | $6.7 \times 10^{-6}$ | $3.6 \times 10^{-6}$ |

- At the LC: sensitivity up to $10^{-6}$ to FCNC couplings!

Exceeding LHC!
Top polarization

- Top=3rd generation:
  - polarization = analyzing tool for SM/BSM couplings

- With beam polarization:
  - $P_{\text{top}}$ can be tuned maximal/minimal
  - Left-right asymmetry (at NLO):
    - $P_{\text{top}}=\text{max}$ for $P_{\text{eff}} \sim 1$
      - $P_{\text{eff}} = -1$ favoured (more stable)
    - $P_{\text{top}}=0$ for $P_{\text{eff}} \sim 0.4$
Effects of transverse beams \( \sqrt{s}=500 \, \text{GeV} \)

- Transversely-polarized beams in e+e- -> tt
  - probe scalar- and tensor-like interactions
- Parametrization via eff. four-Fermi operators:

\[
\mathcal{L}^{4F} = \sum_{i,j=L,R} \left[ S_{ij}(eP_ie)(tP_jt) + T_{ij}(e\frac{\sigma_{\mu\nu}}{\sqrt{2}} P_ie)(t\frac{\sigma_{\mu\nu}}{\sqrt{2}} P_jt) \right]
\]

- Use angular distributions with \( P^T_{e+} P^T_{e+} \)
  - Sensitive to azimuthal angle: specific asymmetries
  - Assumed 100% beams
- Sensitive to small S-, T-admixtures

<table>
<thead>
<tr>
<th>( \sqrt{s} )</th>
<th>Case</th>
<th>Coupling</th>
<th>Individual limit from asymmetries</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 GeV</td>
<td>ReS</td>
<td></td>
<td>( 2.3 \times 10^{-1} , \text{TeV}^{-2} )</td>
</tr>
<tr>
<td></td>
<td>ReT</td>
<td></td>
<td>( 1.2 \times 10^{-3} , \text{TeV}^{-2} )</td>
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<tr>
<td></td>
<td>ImT</td>
<td></td>
<td>( 1.2 \times 10^{-1} , \text{TeV}^{-2} )</td>
</tr>
<tr>
<td>++</td>
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<td></td>
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<td></td>
<td>( 5.2 \times 10^{-3} , \text{TeV}^{-2} )</td>
</tr>
</tbody>
</table>
**Other exotics: heavy Leptons**

- **Study: e+e- -> W+W-**
  - Very sensitive to leptonic vertices and trilinear gauge couplings
  - New heavy neutral boson or heavy leptons can contribute
  - E.g., E6 inspired model are consistent with Z’s but also new heavy leptons (SU(2))
- **Model identification = exclusion of competitive models (incl. SM)**
  - Double polarization asymmetries very useful:

\[
A_{\text{double}} = P_1 P_2 \frac{(\sigma^{RL} + \sigma^{LR}) - (\sigma^{RR} + \sigma^{LL})}{(\sigma^{RL} + \sigma^{LR}) + (\sigma^{RR} + \sigma^{LL})}.
\]

Sensitive to effects from such models and model distinction already at 500 GeV!
What if nothing else than $H$ is found now?

The exciting Higgs story has just started....

• Since $m_H$ is free parameter in SM at tree level
  – Crucial relations exist, however, between $m_{\text{top}}, m_W$ and $\sin^2\theta_{\text{eff}}$
  – If nothing else appears in the electroweak sector, these relations have to be urgently checked

• Which strategy should one aim?
  – exploit precision observables and check whether the measured values fit together at quantum level
  – $m_Z, m_W, \alpha_{\text{had}}, \sin^2\theta_{\text{eff}}$ and $m_{\text{top}}$

• Exploit `GigaZ’ option: high lumi run at $\sqrt{s} = 91$ GeV
  – $P_e^- = 80\%$ and $P_e^+ = 60\%$ required!
    (If only $P_e^- = 90\%$ : precision ~factor 4 less!)
Higgs story has just started … $\sqrt{s}$=91 GeV

**LEP:**
\[ \sin^2 \theta_{\text{eff}}(A_{FB}^{b}) = 0.23221 \pm 0.00029 \]

**SLC:**
\[ \sin^2 \theta_{\text{eff}}(A_{LR}) = 0.23098 \pm 0.00026 \]

**World average:**
\[ \sin^2 \theta_{\text{eff}} = 0.23153 \pm 0.00016 \]

**Goal GigaZ:** $\Delta \sin \theta = 1.3 \times 10^{-5}$

### Uncertainties from input parameters: $\Delta m_Z$, $\Delta \alpha_{\text{had}}$, $m_{\text{top}}$, ...

- $\Delta m_Z = 2.1$ MeV:
- $\Delta \alpha_{\text{had}} \sim 10$ (5 future) x $10^{-5}$:
- $\Delta m_{\text{top}} \sim 1$ GeV (Tevatron/LHC):
- $\Delta m_{\text{top}} \sim 0.1$ GeV (ILC):

\[ \Delta \sin^2 \theta_{\text{eff}} \text{para} \sim 1.4 \times 10^{-5} \]
\[ \Delta \sin^2 \theta_{\text{eff}} \text{para} \sim 3.6 \ (1.8 \text{ future}) \times 10^{-5} \]
\[ \Delta \sin^2 \theta_{\text{eff}} \text{para} \sim 3 \times 10^{-5} \]
\[ \Delta \sin^2 \theta_{\text{eff}} \text{para} \sim 0.3 \times 10^{-5} \]
What else could we learn? \( \sqrt{s} = 91 \text{ GeV} \)

- Assume only Higgs@LHC but no hints for SUSY:
  - Really SM?
  - Help from \( \sin^2 \theta_{\text{eff}} \)?

- If GigaZ precision:
  - i.e. \( \Delta m_{\text{top}} = 0.1 \text{ GeV} \)...
  - Deviations measurable

\( \sin^2 \theta_{\text{eff}} \) can be the crucial quantity to reveal effects of NP!
To close the story... GigaZ \( \sqrt{s}=91 \text{ GeV} \)

- Measure \( \sin^2\theta_{\text{eff}} \) via \( A_{LR} \) with high precision: \( \Delta \sin\theta=1.3 \ 10^{-5} \)

**World average \( \rightarrow \) happy with both!**

**Central value has large impact !!!**

\[ \text{LEP value disfavours both, SM+MSSM} \]

\[ \text{SLD value disfavours SM} \]

\[ \text{GigaZ precision!} \]
Top + EW Physics at the LC

• The LC offers new tools and a staged approach:
  – $\Delta m_{\text{top}}=100$ MeV (incl. exp+theo uncertainties), ew coupling @%-level
  – complements and extends the HL-LHC capabilities
  – sensitiv to quantum effects of the top and to BSM@top

• LC allows to fully exploit GigaZ! …keeping our ‘savety margin’

Physics case is well justified!

Shouldn’t we shake the hands?