Physics at TLEP (and LEP3)

- **Outline**
  - Introduction: The SMS sent by LHC
  - What precision for future measurements?
  - Possible paths towards the future
  - Measurements at TLEP/LEP3 and comparative study
    - Higgs Factory mode (and top threshold)
    - TeraZ and MegaW modes
  - Upgradeability at higher energies
  - Other issues: detectors, cost, timescale, ...
  - Possible work packages
  - Conclusions
Bibliography

[21] Electroweak fits run by M. Gruenewald (private communication, Nov. 2012)
[23] A. Blondel, “Possibilities and conditions for very high precision electroweak measurements”, talk given at the 3rd TLEP3 day (Jan. 2013)
Introduction: The SMS sent by LHC (1)

- A new boson with mass \( \sim 126 \text{ GeV} \), and with SMS properties
  - Example: \( H(126) \rightarrow ZZ \rightarrow 4 \) leptons in CMS
    - \( 4\sigma \) exp., \( 3.2\sigma \) obs.
    - \( \mu = 0.72^{+0.45}_{-0.33} \)

- \( H(126) \) couples to the Z boson (important for e\(^+\)e\(^-\) colliders)
- All couplings compatible with those of the Standard Model Scalar
- Scalar hypothesis favoured over pseudo-scalar or spin-2 particle
- \( m_H \) known to \( \sim 400 \text{ MeV} \)
- A factor 100 luminosity will bring the statistical uncertainty on \( \mu \) to a couple %.

\[ [1,2,3] \]
Introduction: The SMS sent by LHC (2)

- No sign of new physics below a scale of several 100’s GeV
  - Supersymmetry (ATLAS)
  - Exotics (CMS)

Data at higher $\sqrt{s}$ will extend the mass reach to ~500 GeV for SUSY

- Will know more after the next LHC run at 14 TeV (2015-2017)
If no new physics is found, what next?

- Once $m_H$ is known, the standard model has nowhere to go!

- Very strong incentive to revisit and improve all precision measurements
  - Z pole, WW threshold
  - Higgs couplings
  - Top quark properties
  - Rare decays ($B_s \rightarrow \mu\mu$, etc.)

- ... and find indirect effects of new physics at larger scales
What is the precision needed? (1)

- Example: Precision for Higgs measurements
  - Does H(126)
    - Couple to fermions?
    - Account for fermion masses?
    - Fully account for EWSB?
    - Has SM coupling to gauge bosons?
    - Decay to new, visible, particles?
    - Decay to invisible particles?
    - Have the "proper" mass and width?
    - Show any sign of new physics?

- What is the precision needed to answer all these questions in a useful manner?
  - Simple answer: measure as precisely as possible
    - Not very informative
What is the precision needed? (2)

- Example: Precision for Higgs couplings
  - Maximal deviations with respect to SM couplings, as a function of new physics scale
    - SUSY: $\frac{g_{hbb}}{g_{h_{SM}bb}} \approx 1 + 1.7\% \left( \frac{1 \text{ TeV}}{m_A} \right)^2$, for $\tan\beta = 5$
    - Composite Higgs: $\frac{g_{hff}}{g_{h_{SM}ff}} \approx \frac{g_{hVV}}{g_{h_{SM}VV}} \approx 1 - 3\% \left( \frac{1 \text{ TeV}}{f} \right)^2$
    - Top partners: $\frac{g_{hgg}}{g_{h_{SM}gg}} \approx 1 + 2.9\% \left( \frac{1 \text{ TeV}}{m_T} \right)^2$, $\frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \approx 1 - 0.8\% \left( \frac{1 \text{ TeV}}{m_T} \right)^2$
  - Other models may give up to 5% deviations with respect to the Standard Model
    - Maximal deviations for the new physics scale still allowed by LHC results

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Delta hVV$</th>
<th>$\Delta htt$</th>
<th>$\Delta hbb$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed-in Singlet</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Composite Higgs</td>
<td>8%</td>
<td>tens of %</td>
<td>tens of %</td>
</tr>
<tr>
<td>Minimal Supersymmetry</td>
<td>&lt; 1%</td>
<td>3%</td>
<td>10%$^a$, 100%$^b$</td>
</tr>
</tbody>
</table>

- Strongly influences the strategy for Higgs factory projects
  - Need at least a per-cent accuracy on couplings for a $5\sigma$ “observation”
    - And sub-percent precision if new physics is at or beyond the TeV scale
Paths towards the future: (HL-)LHC (1)

- **Executive summary (See Leandro’s presentation this morning)**

  **Approved LHC, 300 fb⁻¹ at 14 TeV:**
  - Higgs mass at 100 MeV
  - Disentangle Spin 0 vs Spin 2 and main CP component in γγ/ZZ*
  - Coupling precision / Experiment
    - Z, W
    - b, τ
    - t, µ
    - γγ, gg
    - 5-6%
    - 10-15%
    - 3-2σ effect
    - 5-11%

  **HL-LHC, 3000 fb⁻¹ at 14 TeV:**
  - Higgs mass at 50 MeV
  - More precise studies of Higgs CP sector
  - Coupling precision / Experiment
    - Z, W
    - b, τ, t, µ
    - γγ and gg
    - HH
    - 1-5%
    - 3-10%
    - 2-7%
    - >3σ (2 Expts)

*Assuming sizeable reduction of theory errors*

[11,12]
Paths towards the future: HL-LHC (2)

- Graphic representation of HL-LHC projected performance

- Much better than originally expected before LHC started
  - Will need vigorous upgrade of CMS and ATLAS detectors
  - Per-cent to sub-percent precision will require new collider(s)

Assumptions:
1. No new decay
2. $\Gamma_H$ from SM (or BR(cc) from SM)

In bold, theory uncertainty are assumed to be divided by a factor 2, experimental uncertainties are assumed to scale with $1/\sqrt{L}$, and analysis performance are assumed to be identical as today.

Patrick Janot  
Higgs Factory Mini Workshop  
Frascati, 14 Feb 2013
Several options for Higgs factories are being studied.

Studied for decades

This talk

See presentation of Marco Zanetti

e^+e^- colliders have largest potential as Precision Higgs Factories

Not encouraged by European Strategy
Precision Higgs Factories in $e^+e^-$ collisions (1)

- Physics case not driven by the fact that the collider is linear or circular
  - Scan of the HZ threshold: $\sqrt{s} = 210-240$ GeV
  - Maximum of the HZ cross section: $\sqrt{s} = 240-250$ GeV
  - Just below the $t\bar{t}$ threshold: $\sqrt{s} \sim 340-350$ GeV

Need 100’s fb$^{-1}$

[7]
A few specificities:

- $e^-(e^+)$ beam polarization is easy at the source (possible) for a linear collider.
  - Not critical for Higgs studies.
- No beam disruption from Beamstrahlung for a circular collider ($\sigma_y \sim 300 \text{ nm vs. } 5 \text{ nm } @ \text{ ILC}$)
  - No EM backgrounds in the detector (photons, $e^+e^-$ pairs);
  - No beam energy smearing – energy spectrum perfectly known (lumi measurement)
  - Negligible pile-up from $\gamma\gamma$ interactions

No drastic requirements for the detector and the background simulation

Possibility of operating several IP’s simultaneously in circular collider
  - vs. only one IP in linear collider

[13, 14]
### Precision Higgs Factories in $e^+e^-$ collisions (3)

- **Number of Higgs bosons produced at $\sqrt{s} = 240$-$250$ GeV**

<table>
<thead>
<tr>
<th></th>
<th>ILC-250</th>
<th>LEP3-240</th>
<th>TLEP-240</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi / IP / 5 years</td>
<td>250 fb$^{-1}$</td>
<td>500 fb$^{-1}$</td>
<td>2.5 ab$^{-1}$</td>
</tr>
<tr>
<td># IP</td>
<td>1</td>
<td>2 - 4</td>
<td>2 - 4</td>
</tr>
<tr>
<td>Lumi / 5 years</td>
<td>250 fb$^{-1}$</td>
<td>1 - 2 ab$^{-1}$</td>
<td>5 - 10 ab$^{-1}$</td>
</tr>
<tr>
<td>Beam Polarization</td>
<td>80%, 30%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$L_{0.01}$ (beamstrahlung)</td>
<td>86%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Number of Higgs</td>
<td>70,000</td>
<td>400,000</td>
<td>2,000,000</td>
</tr>
<tr>
<td>Upgradeable to</td>
<td>ILC 1 TeV</td>
<td>HE-LHC</td>
<td>SHE-LHC</td>
</tr>
<tr>
<td></td>
<td>CLIC 3 TeV</td>
<td>33 TeV</td>
<td>100 TeV</td>
</tr>
</tbody>
</table>

- **LEP3** : 4-8 times more luminosity and 3-6 times more Higgs bosons than ILC
- **TLEP** : 20-40 times more luminosity and 15-30 times more Higgs bosons than ILC

- In a given amount of time, Higgs coupling precisions scale like
  - 2% for ILC : 1% for LEP3 : 0.3% for TLEP
  - One year of TLEP = five years of LEP3 = 15-30 years of ILC (at 240 GeV)
Higgs measurements at $\sqrt{s} \sim 240$ GeV (1)

- With $e^+e^- \rightarrow ZH \rightarrow e^+e^-X$ and $\mu^+\mu^-X$ events
  - Measure HZ cross section in a model independent way
    - Find $m_H$ peak from the leptons and $E_p$ conservation
    - Determine spin with three-point threshold scan
      - $10$ fb$^{-1}$/point suffice
    - Determine $\sigma_{HZ}$ and $g_{HZZ}$ coupling at 240 GeV
      - $3\%$ ($1.5\%$) precision on $\sigma_{HZ}$ ($g_{HZZ}$) with 250 fb$^{-1}$
  - Good tracker needed, but details mildly depend on the actual performance
    - Plots below with ILD@ILC and CMS@LEP3

Frascati, 14 Feb 2013

Patrick Janot

[[9,10,11]]

$e^+e^- \rightarrow ZH \rightarrow e^+e^-X$ and $\mu^+\mu^-X$

$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^-X$

$\Delta p/p \sim 0.2\%$

$\Delta p/p \sim 2\%$

$e^+e^- \rightarrow ZH \rightarrow e^+e^-X$ and $\mu^+\mu^-X$
Higgs measurements at $\sqrt{s} \sim 240$ GeV (2)

- **With ZH $\rightarrow$ e$^+$e$^-$X and $\mu^+\mu^-$X events (cont’d)**
  - Measure invisible decay branching ratio ($X =$ nothing)
    - Precision on $\text{BR}_{\text{INV}} \sim 1\%$ with 250 fb$^{-1}$
    - Or exclude $\text{BR}_{\text{INV}} > \sim 2\%$ at 95% C.L.

- **Measure other $\sigma_{HZ} \times \text{BR}(H \rightarrow ff, VV)**
  - With exclusive selections of Z and H decays
    - Precision of 1.5% to 8% with 250 fb$^{-1}$ for the copious decays (bb, WW, gg, $\tau\tau$, cc)
    - Need more luminosity for rare decays ($\gamma\gamma$, Z$\gamma$, $\mu\mu$)
      - Particle flow, b and c tagging, lepton and photon capabilities needed

- **ZH $\rightarrow$ qqbb, 250 fb$^{-1}$**
- **ZH $\rightarrow$ llWW $\rightarrow$ llvqq, 500 fb$^{-1}$**
- **ZH $\rightarrow$ X$\gamma\gamma$, 500 fb$^{-1}$**
- **ZH $\rightarrow$ X$\mu\mu$, 2 ab$^{-1}$**
Higgs measurements at $\sqrt{s} \sim 240$ GeV (3)

- Higgs width from the $H\nu\nu$ final state
  - From $\sigma_{WW\rightarrow H}$ and $\text{BR}(H\rightarrow WW)$
    - $\sigma_{WW\rightarrow H} \sim g^2_{HWW}$
    - $\text{BR}(H\rightarrow WW) = \Gamma_{H\rightarrow WW}/\Gamma_H \sim g^2_{HWW}/\Gamma_H$
    - $\Gamma_H \sim \sigma_{WW\rightarrow H}/\text{BR}(H\rightarrow WW)$
  - Contribution to $H\nu\nu$ from $HZ \sim 40$ pb
    - Known from $ZH \rightarrow e^+e^-X$ and $\mu^+\mu^-X$
  - Contribution from WW fusion $\sim 6$ pb
    - To be measured
  - Select $\nu\nu bb$ events from ZH and WW fusion
    - Needs adequate $b$ tagging and particle flow
  - Fit the missing mass distribution for $N_{WW\rightarrow H\rightarrow bb}$
    - $\sigma_{HZ} \times \text{BR}(H\rightarrow bb)$ known to $\sim 1.5\%$ or better
    - $\sigma_{WW\rightarrow H} = N_{WW\rightarrow H\rightarrow bb}/\text{BR}(H\rightarrow bb)$
      - Precision on $\sigma_{WW\rightarrow H} \sim 14\%$ with $250$ fb$^{-1}$
      - $\Gamma_H \sim \sigma_{WW\rightarrow H}/\text{BR}(H\rightarrow WW)$, measured up to $15\%$ precision with $250$ fb$^{-1}$
Higgs measurements at $\sqrt{s} \sim 240$ GeV (4)

- **Higgs width from the ZZZ final state**
  - Number of ZZZ events $\sim \sigma_{HZ} \times \text{BR}(H \rightarrow ZZ)$
    - $\sigma_{HZ} \sim g_{HZZ}^2$
    - $\text{BR}(H \rightarrow ZZ) = \Gamma_{H \rightarrow ZZ}/\Gamma_H \sim g_{HZZ}^2 / \Gamma_H$
    - Number of ZZZ events $\sim g_{HZZ}^4 / \Gamma_H$
  - Select $l^+l^- \, l^+l^- \, X$ events ( ~ background and $H \rightarrow WW$ free)
    - Number of events in 250 fb$^{-1}$ at 240 GeV:
      - $250 \text{ fb}^{-1} \times 200 \text{ fb} \times \text{BR}(H \rightarrow ZZ) \times \text{BR}(Z \rightarrow ll)^2 \times 3$
      - About 40 events, of which ~25 selected
  - Hence measure the total width $\Gamma_H$ with a precision of 21%
    - Reduced to 12% in combination with WW fusion measurement
      - Could be further reduced with other Z decays
        (Need full simulation and WW/ZZ simultaneous fit)
  - Note: Precision of a few % can be reached on $\Gamma_H$ if one assumes no exotic Higgs decays
### Linear vs Circular at $\sqrt{s} \sim 240$ GeV

- **Precision on H(125) branching fractions, width, mass, ... after 5 years**

<table>
<thead>
<tr>
<th></th>
<th>ILC</th>
<th>LEP3 (4)</th>
<th>TLEP (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{Hz}$</td>
<td>2.5%</td>
<td>1.3%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$\sigma_{Hz} \times \text{BR}(H \rightarrow bb)$</td>
<td>1.0%</td>
<td>0.5%</td>
<td>0.1%</td>
</tr>
<tr>
<td>$\sigma_{Hz} \times \text{BR}(H \rightarrow cc)$</td>
<td>6.9%</td>
<td>4% (*)</td>
<td>1.3%</td>
</tr>
<tr>
<td>$\sigma_{Hz} \times \text{BR}(H \rightarrow gg)$</td>
<td>8.5%</td>
<td>4.5% (*)</td>
<td>1.4%</td>
</tr>
<tr>
<td>$\sigma_{Hz} \times \text{BR}(H \rightarrow WW^*)$</td>
<td>8.0%</td>
<td>3.0%</td>
<td>0.9%</td>
</tr>
<tr>
<td>$\sigma_{Hz} \times \text{BR}(H \rightarrow \tau\tau)$</td>
<td>5.0%</td>
<td>3.0%</td>
<td>0.9%</td>
</tr>
<tr>
<td>$\sigma_{Hz} \times \text{BR}(H \rightarrow ZZ^*)$</td>
<td>28%</td>
<td>7.1%</td>
<td>3.1%</td>
</tr>
<tr>
<td>$\sigma_{Hz} \times \text{BR}(H \rightarrow \gamma\gamma)$</td>
<td>27%</td>
<td>6.8%</td>
<td>3.0%</td>
</tr>
<tr>
<td>$\sigma_{Hz} \times \text{BR}(H \rightarrow \mu\mu)$</td>
<td>–</td>
<td>28%</td>
<td>13%</td>
</tr>
<tr>
<td>$\sigma_{WW \rightarrow H}$</td>
<td>12%</td>
<td>5% (*)</td>
<td>2.2%</td>
</tr>
<tr>
<td>$\Gamma_H, \Gamma_{INV}$</td>
<td>10% , $&lt; 1.5%$</td>
<td>4% , $&lt; 0.7%$</td>
<td>1.8% , $&lt; 0.3%$</td>
</tr>
<tr>
<td>$m_H$</td>
<td>40 MeV</td>
<td>26 MeV</td>
<td>8 MeV</td>
</tr>
</tbody>
</table>

- LEP3 numbers obtained from a CMS simulation $\times 4$, except (*) extrapolated from ILC
- Need a refined vertex detector for gg and cc BR accurate measurements
- TLEP numbers extrapolated from LEP3 column

[10,15,16]
Measurements at $\sqrt{s} \sim 350$ GeV (ILC/TLEP)

- Luminosity similar for ILC and TLEP
  - At each IP: 350 fb$^{-1}$ over 5 years
  - With possibly 4 detectors at TLEP
  - More study of the $H\nu\nu$ final state with $H \to bb$
    - Contribution from $HZ: \sim 25$ fb
    - Contribution from $WW \to H: \sim 25$ fb

<table>
<thead>
<tr>
<th></th>
<th>ILC (250+350)</th>
<th>TLEP (240+350)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{WW \to H}$</td>
<td>12% $\to$ 4%</td>
<td>2.2% $\to$ 1.5%</td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>10% $\to$ 5.5%</td>
<td>1.8% $\to$ 1.3%</td>
</tr>
</tbody>
</table>

- Small improvement for other $\sigma \times BR$'s
- Measure CP mixture to $\sim 5\%$
- Scan of the $tt$ threshold
  - From the cross section
    - Top mass and width to 50 MeV or better
    - Probe the $ttH$ coupling to 30%

No beamstrahlung is a advantage
- Study rare top decays
Same assumptions as for HL-LHC for a sound comparison
- No exotic decay, Standard Model decay width

\[
\sigma_{HZ} \propto g_{HZZ}^2, \text{ and } \sigma_{HZ} \times BR(H \rightarrow XX) \propto \frac{g_{HZZ}^2 g_{HXX}^2}{\Gamma_H}
\]

ILC250 would be a good complement to LHC ($\Gamma_H, \Gamma_{inv}, g_{Hcc}, g_{Hbb}$)

[11,16]
Same assumptions as for HL-LHC for a sound comparison

- No exotic decay, Standard Model decay width

$$\sigma_{HZZ} \propto g_{HZZ}^2$$, and $$\sigma_{HZZ} \times \text{BR}(H \rightarrow XX) \propto g_{HZZ}^2 g_{HXX}^2 / \Gamma_H$$

ILC250/350 would be a good complement to LHC ($\Gamma_H, \Gamma_{\text{inv}}, g_{Hcc}, g_{Hbb}$)
Same assumptions as for HL-LHC for a sound comparison

- No exotic decay, Standard Model decay width

\[ \sigma_{HZ} \propto g_{HZ}^2, \text{ and } \sigma_{HZ} \times \text{BR}(H \rightarrow XX) \propto g_{HZ}^2 g_{HXX}^2 / \Gamma_H \]

\[ \sigma_{HZ} \propto g_{HZ}^2, \text{ and } \sigma_{HZ} \times \text{BR}(H \rightarrow XX) \propto g_{HZ}^2 g_{HXX}^2 / \Gamma_H \]

- LEP3 would be an advantageous back-up: larger lumi, several IP, smaller cost
Higgs couplings for Precision Higgs Factories (4)

- Same assumptions as for HL-LHC for a sound comparison
  - No exotic decay, Standard Model decay width

\[ \sigma_{HZ} \propto g_{HZZ}^2, \text{ and } \sigma_{HZ} \times \text{BR}(H \rightarrow XX) \propto g_{HZZ}^2 g_{HXX}^2 / \Gamma_H \]

- TLEP would be a superior option (see zoom next page)
Higgs couplings for Precision Higgs Factories (5)

- Same assumptions as for HL-LHC for a sound comparison
  - No exotic decay, Standard Model decay width

$$\sigma_{HZ} \propto g_{HZZ}^2$$, and $$\sigma_{HZ} \times \text{BR}(H \rightarrow XX) \propto g_{HZZ}^2 g_{HXX}^2 / \Gamma_H$$

- TLEP: sub-percent precision, needed for NP sensitivity beyond 1 TeV

Patrick Janot
Higgs Factory Mini Workshop
Frascati, 14 Feb 2013

[11, 16, 17, 18]
Higgs couplings for Precision Higgs Factories (6)

- Same conclusion when $\Gamma_H$ is a free parameter in the fit
  - Plot shown only for ILC350 and TLEP, with an accurate width measurement

$$\sigma_{HZ} \propto g_{HZZ}^2, \text{ and } \sigma_{HZ} \times BR(H \rightarrow XX) \propto g_{HZZ}^2 g_{HXX}^2 / \Gamma_H$$

- TLEP: sub-percent precision, adequate for NP sensitivity beyond 1 TeV

Patrick Janot  
Higgs Factory Mini Workshop  
Frascati, 14 Feb 2013
### Table 2.1: Expected performance on the Higgs boson couplings from the LHC and $e^+e^-$ colliders, as compiled from the Higgs Factory 2012 workshop. CLIC numbers from Ref [11-12].

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC</th>
<th>Full ILC</th>
<th>CLIC</th>
<th>LEP3, 4 IP</th>
<th>TLEP, 4 IP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Quantity</td>
<td>300 fb(^{-1})/expt</td>
<td>3000 fb(^{-1})/expt</td>
<td>250 GeV</td>
<td>250+350+1000 GeV</td>
<td>350 GeV (500 fb(^{-1}))</td>
<td>240 GeV</td>
<td>240 GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 yrs</td>
<td>5 yrs each</td>
<td>10 ab(^{-1}) (*)</td>
<td>10 ab(^{-1}) 5 yrs (*)</td>
</tr>
<tr>
<td>(N_H)</td>
<td>(1.7 \times 10^7)</td>
<td>(1.7 \times 10^8)</td>
<td>(6 \times 10^4) ZH</td>
<td>(10^5) ZH</td>
<td>(1.4 \times 10^5) Hvv</td>
<td>(4 \times 10^2) ZH</td>
<td>(2 \times 10^6) ZH</td>
</tr>
<tr>
<td>(m_H) (MeV)</td>
<td>100</td>
<td>50</td>
<td>35</td>
<td>35</td>
<td>~70</td>
<td>26</td>
<td>7</td>
</tr>
<tr>
<td>(\Delta \Gamma_H / \Gamma_H)</td>
<td>Indirect (30%?)</td>
<td>Indirect (10%?)</td>
<td>10%</td>
<td>3%</td>
<td>6%</td>
<td>4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>(\Delta \Gamma_{inv} / \Gamma_H)</td>
<td>--</td>
<td>--</td>
<td>1.5%</td>
<td>1.0%</td>
<td>--</td>
<td>0.35%</td>
<td>0.15%</td>
</tr>
<tr>
<td>(\Delta g_{H\gamma \gamma} / g_{H\gamma \gamma})</td>
<td>6.5 – 5.1%</td>
<td>5.4 – 1.5%</td>
<td>--</td>
<td>5%</td>
<td>N/A</td>
<td>3.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>(\Delta g_{Hgg} / g_{Hgg})</td>
<td>11 – 5.7%</td>
<td>7.5 – 2.7%</td>
<td>4.5%</td>
<td>2.5%</td>
<td>N/A</td>
<td>2.2%</td>
<td>0.7%</td>
</tr>
<tr>
<td>(\Delta g_{HHW} / g_{HHW})</td>
<td>5.7 – 2.7%</td>
<td>4.5 – 1.0%</td>
<td>4.6%</td>
<td>1%</td>
<td>1%</td>
<td>1.5%</td>
<td>0.25%</td>
</tr>
<tr>
<td>(\Delta g_{HZZZ} / g_{HZZZ})</td>
<td>5.7 – 2.7%</td>
<td>4.5 – 1.0%</td>
<td>1.3%</td>
<td>1.5%</td>
<td>1%</td>
<td>0.65%</td>
<td>0.2%</td>
</tr>
<tr>
<td>(\Delta g_{HHHH} / g_{HHHH})</td>
<td>--</td>
<td>&lt; 30% (2 expts)</td>
<td>--</td>
<td>~30%</td>
<td>~20%</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>(\Delta g_{Huu} / g_{Huu})</td>
<td>&lt; 30%</td>
<td>&lt; 10%</td>
<td>--</td>
<td>--</td>
<td>15%</td>
<td>14%</td>
<td>7%</td>
</tr>
<tr>
<td>(\Delta g_{Htt} / g_{Htt})</td>
<td>8.5 – 5.1%</td>
<td>5.4 – 2.0%</td>
<td>3.5%</td>
<td>2.5%</td>
<td>3%</td>
<td>1.5%</td>
<td>0.4%</td>
</tr>
<tr>
<td>(\Delta g_{Hcc} / g_{Hcc})</td>
<td>--</td>
<td>--</td>
<td>3.7%</td>
<td>2%</td>
<td>4%</td>
<td>2.0%</td>
<td>0.65%</td>
</tr>
<tr>
<td>(\Delta g_{bHb} / g_{bHb})</td>
<td>15 – 6.9%</td>
<td>11 – 2.7%</td>
<td>1.4%</td>
<td>1%</td>
<td>2%</td>
<td>0.7%</td>
<td>0.22%</td>
</tr>
<tr>
<td>(\Delta g_{Ht} / g_{Ht})</td>
<td>14 – 8.7%</td>
<td>8.0 – 3.9%</td>
<td>--</td>
<td>15%</td>
<td>3%</td>
<td>--</td>
<td>30%</td>
</tr>
</tbody>
</table>

[20]
The 80 km tunnel envisioned for TLEP can also host a hadron collider (TLHC). This might well be the future of particle physics in Europe.

I will now discuss the estimates of Higgs measurement capabilities of these machines and the conversion of those estimates to measurement errors on the Higgs couplings.

It will be obvious that - weighting all claims equally - TLEP has the best capabilities. It has the highest luminosity, can plausibly support multiple detectors, and can reach energies well above the Higgs threshold. In the following, I will omit the comparison with TLEP in the figures. The final errors would in any event be tiny on the graphs that I will show. These are given in a table at the end of the lecture.
Measurements at smaller $\sqrt{s}$ (1)

- Larger luminosity at smaller $\sqrt{s}$ for circular colliders
  - Use the RF power to accelerate more bunches: $L \sim 1/E^4$
  - Crossing point with ILC at $\sqrt{s} \sim 350$ GeV
Measurements at smaller $\sqrt{s}$ (2)

- Revisit and improve the LEP precision measurements
  - Can do the entire LEP1 physics programme
    - In 5 minutes (TLEP) ; in 1h (LEP3); or in a week (ILC)
  - Huge potential in a year of TLEP (LEP3) at $\sqrt{s} = m_Z$ or $2m_W$

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>LEP</th>
<th>ILC</th>
<th>LEP3</th>
<th>TLEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} \sim m_Z$</td>
<td>MegaZ</td>
<td>GigaZ</td>
<td>~TeraZ</td>
<td>TeraZ</td>
</tr>
</tbody>
</table>
| Lumi (cm$^{-2}$s$^{-1}$) | Few $10^{31}$ | Few $10^{33}$ | Few $10^{35}$ | $10^6$
| #Z / IP / year | 2x10$^7$ | Few $10^9$ | Few $10^{11}$ | $10^{12}$ |
| Polarization vs LEP1 | no | easy | maybe | maybe |
| Polarization 1 | ~5-10 | ~50 | ~100 |

<table>
<thead>
<tr>
<th>$\sqrt{s} \sim 2m_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi (cm$^{-2}$s$^{-1}$)</td>
</tr>
<tr>
<td>Lumi / IP / year</td>
</tr>
<tr>
<td>Error on $m_W$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\sqrt{s} \sim 200-250$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi (cm$^{-2}$s$^{-1}$)</td>
</tr>
<tr>
<td>Lumi / IP / 5 years</td>
</tr>
<tr>
<td>Error on $m_W$</td>
</tr>
</tbody>
</table>

Asymmetries, Lineshape

WW threshold

[15,16]
Would open a whole new book in EWSB precision measurements

- Case 1: Only SM physics in EW Radiative Corrections

  - With TeraZ and $m_W$ to 0.3 MeV at TLEP:
    - Predicts $m_{top}$ to 100 MeV (SM) - was 10 GeV at LEP.
  
  - With $m_{top}$ and $m_H$ measured at TLEP240/350:
    - SM accurate closure test

- Case 2: Some weakly interacting new physics in the loops?

  - Will cause inconsistency between the various observables
Measurements at smaller $\sqrt{s}$ (4)

- **Experimental challenges are numerous : TLEP(Z)**
  - At TLEP(Z), the hadronic Z event rate will be 30 kHz
    - Same rate of bunch crossings as at LHC (40 MHz)
    - CMS current high-level trigger rate is about 1 kHz
      - (But hadronic Z events typically 20 times smaller than typical LHC event)
    - Need to design a detector and a DAQ system able to cope with these rates
      - A clever mixture of LHC detector (rate) and ILC detector (precision)
        Need to study what is the precision needed for each sub-detectors
        Is a CMS-like detector sufficient? (~OK for Higgs studies)
  - Small angle Bhabha event rate (lumi measurement) will be even larger
    - Essential to measure cross sections, hence the Z lineshape ($m_Z, \Gamma_z$)
      - Negligible beamstrahlung is a great advantage
        No background in the luminometers
        Energy spectrum perfectly known (hence Bhabha cross section)
        Will need theoretical developments to understand $\sigma_{e^+e^-}$ to better than $5 \times 10^{-5}$
  - Limiting uncertainties on $\alpha_{\text{QED}}(m_Z)$ and $\alpha_s(m_Z)$ must be overcome
    - Possible with the billions of $e^+e^- \rightarrow e^+e^-\gamma$, $\mu^+\mu^-\gamma$ and $q\bar{q}g$ events?
      - Will affect all Z peak asymmetries, and $m_Z$ vs $m_W$ interpretation
Experimental challenges are numerous: TLEP(Z)

- Z lineshape needs a precise beam energy measurement
  - Resonant depolarization unique @ circular machines
    - Intrinsic precision ~ 100 keV (LEP1) / measurement
      Decreases like $1 / \sqrt{\text{#(Measurements)}}$
  - Requires beam transverse polarization
    - In one non-colliding bunch, during operations
      Continuous energy measurement
      No extrapolation needed (tides, trains, rain...)
    - Will require installation of polarization wigglers
      - Natural polarization time ~ 150 h at TLEP...

- Polarized asymmetry ($A_{LR}$) requires longitudinal polarization
  - Hence spin rotators and polarimeters at each IP
    - Then need to keep polarization in collisions
      That’s the main unknown
      Dedicated operations with lower luminosity?
  - Dedicated study is needed here
Measurements at smaller $\sqrt{s}$ (6)

- Experimental challenges are numerous: $m_w$ at TLEP(W) and TLEP(H) [22]
  - With $2.5 \text{ ab}^{-1}$ at TLEP(W) and $10^7 \text{ WW events/expt}$ at threshold: $\sigma(m_w) \sim 0.4 \text{ MeV}$
  - With $2.5 \text{ ab}^{-1}$ at TLEP(H), $4 \times 10^7 \text{ W pairs/expt}$: $\sigma(m_w) \sim 0.2 \text{ MeV}$

- Need to know beam energy to few $0.1 \text{ MeV}$, but no beam polarization at these energies
  - Use the precision Z mass measurement from the Z pole
    - With $5 \times 10^7 \text{ Z(\gamma) events (Z } \rightarrow \text{ e}^+\text{e}, \mu^+\mu^-) / \text{ expt at TLEP(W)}$
    - With $2 \times 10^6 \text{ Z pairs and } 5 \times 10^6 \text{ Z(\gamma) events (Z } \rightarrow \text{ e}^+\text{e}, \mu^+\mu^-) / \text{ expt at TLEP(H)}$

Can reach combined statistical precision on $E_{beam}$ of $0.2 \text{ MeV}$ and $0.4 \text{ MeV}$

- Need to understand all systematic effects that would affect the measurement
  - Both theoretical and experimental
Upgradeability at larger $\sqrt{s}$ (1)

- All existing proposals have access to larger $\sqrt{s}$
  - To discover New Physics in a direct manner
  - To measure more difficult Higgs couplings: $g_{Htt}$ and $g_{HHH}$
    - ILC350 can be upgraded to ILC500/ILC1TeV, or even to CLIC (3 TeV)
    - LEP3 can be upgraded to (or preceded by) HE-LHC (33 TeV)
    - TLEP can be upgraded to SHE-LHC (100 TeV)

Cross sections in $e^+e^-$ collisions

Cross sections in pp collisions
Summary for Htt and HHH couplings

- Other Higgs couplings benefit marginally from high energy

For similar new physics reach, similar ttH/HHH precision with pp and e⁺e⁻ colliders
For LEP3, obvious detectors are CMS and ATLAS
- CMS demonstrated to be adequate with today’s design + upgraded pixel detector
  - Phase 2 upgrades: LEP3 could be seen as an alternative to HL-LHC
  - Tunnel By-passes need to be dug out for the accelerating ring

For TLEP, new detectors are in order (used CMS for Higgs studies in this talk)
- Holistic view: design caverns and detectors to be re-used in pp collisions (as new)
  - TeraZ sets the scale for DAQ (2600 bunches) + forward EM calorimetry (lumi)
  - TLEP(H) sets the scale for precision (tracker, ECAL, particle flow, b tagging)
  - SHE-LHC sets the scale for magnetic field, calorimeter depths, tracker p_T reach
  - Could envision a staged approach
Basic requirements (examples)

- Vertex detector with impact parameter resolution $\sim 5 \mu m$ (CMS : $20 \mu m$)
  - For b and c tagging
    - Very large number of channels (cf ILC)
- Tracker detector with $\sigma(p_T)/p_T^2 \sim 10^{-5}$ (CMS : $10^{-4}$)
  - For precise recoil mass determination in $(Z \rightarrow l^+l^-) + H$ and in $H \rightarrow \mu^+\mu^-$
    - All silicon, with large number of channels
- ECAL resolution of the order of 1% at 60 GeV (same as CMS)
  - For $H \rightarrow \gamma\gamma$ (and all decays with electrons : WW, ZZ, $\tau\tau$)
- ECAL and HCAL with decent transverse and longitudinal segmentation, inside the coil
  - For Particle Flow towards HZ and WW $\rightarrow H$ discrimination (and precise jets, $p_{\text{miss}}$)
    - Study trade-offs between ILC proposals and CMS crystals
- Efficient and pure muon Id
  - For $H \rightarrow ZZ, W^+W^-, \mu^+\mu^-, \tau^+\tau^-$
- Extremely fast DAQ
  - Detector with $\sim 10^{10}$ channels
    - TLEP-H : low occupancy, zero suppression, read out each BX (100 kHz)

Simple trigger needed for TeraZ (40 MHz -> 100 kHz)
Possible Timescales

- Similar timescales for TLEP and LEP3

- TLEP
  - Design study : 2013-2017
  - Next European Strategy Workshop : 2017-2018
  - Decision to go and start digging : 2018-2019
  - Start installation in parallel with HL-LHC running : 2023 - ...
  - Start running at the end of HL-LHC running : 2030 - ...

- LEP3
  - Design study : 2013-2017 (spin-off of TLEP design study)
  - Next European Strategy Workshop : 2017-2018
  - Decision to go : 2018-2019
  - Start installation at the end of LHC running : 2022 - ...
    - Tunnel probably irradiated at the end of HL-LHC
      - LEP3 is an alternative of HL-LHC, and could be followed by HE-LHC in 2040
  - Start running when ready : 2027 - ...

Frascati, 14 Feb 2013
Cost (can be wrong by a factor 2)

- **LEP3 : A cost-effective option**
  - Tunnel : 0 $ - Cryoplant : 0$
  - Two detectors : 0$ - Four detectors : 1 G$
  - RF + Magnets + Injector Ring : 1 G$
  - 100,000 Higgs boson / detector / 5 years @ 240 GeV : 5 k$ / Higgs boson
  - Total : 1 – 2 G$

- **TLEP : A long-term vision**
  - Tunnel : 3 G$ - Cryoplant : 1 G$
  - Four detectors : 2 G$
  - RF + Magnet + Injector Ring : 1 G$
  - Total : 7 G$
  - of which 6 G$ in common with SHE-LHC
  - 500,000 Higgs boson / detector / 5 years @ 240 GeV : < 3.5 k$ / Higgs boson

- **Comparison with ILC**
  - Total Cost : ~ 10 G$
  - 70,000 Higgs boson / 5 years @ 240 GeV : 150 k$ / Higgs boson
Possible Work Packages

TLEP design study – preliminary structure for discussion

Institutional board

Steering group web site, mailing lists, speakers board, etc.

International Advisory board

Accelerator
1. Optics, low beta, alignment and feedbacks
2. Beam beam interaction
3. Magnets and vacuum
4. RF system
5. Injector system
6. Integration w/(SHE)-LHC
7. Interaction region
8. Polarization & E-calib.
9. Elements of costing

Experiments
1. H(126) properties
2. Precision EW measurements at the Z peak and W threshold
3. Top quark physics
4. Experimental environment
5. Detector design
6. Online and offline computing

Physics
1. Theoretical implications and model building
2. Precision measurements, simulations and monte-carlos
3. Combination + complementarity with LHC and other machines; global fits
Possible Work Packages

**WP4 Experiments**
1. H(126) properties
2. Precision EW measurements at the Z peak and W threshold
3. Top quark physics
4. Experimental environment
5. Detector design
6. Online and offline computing

**WP5 Physics**
1. Theoretical implications and model building
2. Precision measurements, simulations and monte-carlos
3. Combination + complementarity with LHC and other machines; global fits
Conclusions (1)

- A very much SM-like Higgs boson was discovered at the LHC
  - So far with no evidence of BSM Physics or of an extended Higgs sector
    - Up to a scale of several hundred GeV to 1 TeV

- A sub-per-cent precision Higgs factory will be critical
  - For establishing whether the SM-like boson is THE Higgs boson
  - To see whether there is any evidence for small deviations from SM predictions
  - To provide hints for the energy scale of the BSM physics that couples to the Higgs boson
  - To possibly unravel an extended Higgs sector

- Adequately high-statistics Z and W factories will also be important
  - To do the ultimate closure test of the SM from the knowledge of $m_{\text{top}}$ and $m_H$
  - To probe Weakly-Interacting New Physics beyond to TeV scale
Conclusions (2)

- The LHC run at 13 TeV may revolutionize the current physics perspective
  - New discoveries will strongly influence the strategy for future collider projects
    - And so will absence of new discoveries, possibly even more strongly
      ➔ We will know much more in 2015-2017

- Future projects should therefore encompass
  - A high-precision Higgs factory
    - Including high-statistics Z, W, and possibly top, factories
  - A high-energy-frontier facility able to study the new physics discovered at the LHC
    - And to probe much higher scales

- It is probably too early (and maybe imprudent) to decide now
  - The European Strategy Group encourages studies of $e^+e^-$ and pp colliders at CERN
    - The TLEP + SHE-LHC package is a (the?) long term vision for Europe
    - The LEP3 + HE-LHC package would be a cost-effective back-up solution