TLEP

Precision physics at the Electroweak scale
TeraZ, OkuW, MegaHiggs and Megatops
possible long-term strategy

& $e^\pm (120 \text{ GeV}) - p (7, 16 \& 50 \text{ TeV})$ collisions \([(V)\text{HE-}]\text{TLHeC})$

$\geq 50$ years of $e^+e^-$, $pp$, $ep/A$ physics at highest energies
What are the possibilities offered by a circular e+e- machine located in the 80-100 km tunnel that will eventually contain also a 100 TeV pp collider?

-- very powerful machine as you will see

++ offers a feasible multi-step long-term strategy:

-1- the tunnel and TLEP
-2- 100 TeV pp collider with 16 T magnets
-3- e-p, e-ion, p-ion, ion-ion etc...

in 2035 the LEP/LHC tunnel will have been used for 46 years...

the TLEP/VHE-LHC tunnel would be used for > 50 years!
How can one increase over LEP2 (average) luminosity by a factor 500 without exploding the power bill?

Answer is in the B-factory design: a very low vertical emittance ring with higher intrinsic luminosity and a small value of $\beta_y^*$

electrons and positrons have a much higher chance of interacting
  ➞ much shorter lifetime (few minutes)
  ➞ feed beam continuously with a ancillary accelerator

Storage ring has separate beam pipes for e+ and e- for multibunch operation
SuperKEKB – TLEP demonstrator!

beam commissioning will start in early 2015

- $\beta_y^*=300$ $\mu$m (TLEP: 1 mm)
- lifetime 5 min (TLEP: $\sim$15 min)
- $\varepsilon_y/\varepsilon_x=0.25\%$ (~TLEP)
- off momentum acceptance
- $e^+$ production rate
Important properties of circular e+e- machines:

-- luminosity

-- center-of-mass definition

-- beam polarization and energy calibration

-- IP backgrounds, repetition rate etc...
  -- note that at Z peak operate at 40MHz beam Xing
Table 1: TLEP parameters at different energies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TLEP Z</th>
<th>TLEP W</th>
<th>TLEP H</th>
<th>TLEP t</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{\text{beam}}) [GeV]</td>
<td>45</td>
<td>80</td>
<td>120</td>
<td>175</td>
</tr>
<tr>
<td>circumf. [km]</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>1180</td>
<td>124</td>
<td>24.3</td>
<td>5.4</td>
</tr>
<tr>
<td>#bunches/beam</td>
<td>4400</td>
<td>600</td>
<td>80</td>
<td>12</td>
</tr>
<tr>
<td>#e⁻/beam [10^{13}]</td>
<td>1960</td>
<td>200</td>
<td>40.8</td>
<td>9.0</td>
</tr>
<tr>
<td>horiz. emit. [nm]</td>
<td>30.8</td>
<td>9.4</td>
<td>9.4</td>
<td>10</td>
</tr>
<tr>
<td>vert. emit. [nm]</td>
<td>0.07</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>bending rad. [km]</td>
<td>9.0</td>
<td>9.0</td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>(\kappa_{e})</td>
<td>440</td>
<td>470</td>
<td>470</td>
<td>1000</td>
</tr>
<tr>
<td>mom. c. (\sigma_{c}) ([10^{-2}])</td>
<td>9.0</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(P_{\text{loss,SR}}/\text{beam}) [MW]</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>(\beta'_{x}) [m]</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>(\beta'_{y}) [cm]</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>(\sigma_{x}) [\mu m]</td>
<td>124</td>
<td>78</td>
<td>68</td>
<td>100</td>
</tr>
<tr>
<td>(\sigma_{y}) [\mu m]</td>
<td>0.27</td>
<td>0.14</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td>hourglass (F_{\text{hg}})</td>
<td>0.71</td>
<td>0.75</td>
<td>0.75</td>
<td>0.65</td>
</tr>
<tr>
<td>(E_{\text{SR,loss}}/\text{turn}) [GeV]</td>
<td>0.04</td>
<td>0.4</td>
<td>2.0</td>
<td>9.2</td>
</tr>
<tr>
<td>(V_{\text{RF,tot}}) [GV]</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>(\phi_{\text{max}}) [%]</td>
<td>4.0</td>
<td>5.5</td>
<td>9.4</td>
<td>4.9</td>
</tr>
<tr>
<td>(\xi_{x}/\text{IP})</td>
<td>0.07</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>(\xi_{y}/\text{IP})</td>
<td>0.07</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>(f_{\text{c}}) [kHz]</td>
<td>1.29</td>
<td>0.45</td>
<td>0.44</td>
<td>0.43</td>
</tr>
<tr>
<td>(E_{\text{acc}}) [MV/m]</td>
<td>3</td>
<td>3</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>eff. RF length [m]</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>(f_{\text{RF}}) [MHz]</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>(\delta_{\text{rms}}) [%]</td>
<td>0.06</td>
<td>0.10</td>
<td>0.15</td>
<td>0.22</td>
</tr>
<tr>
<td>(\sigma_{\text{rms}}) [cm]</td>
<td>0.19</td>
<td>0.22</td>
<td>0.17</td>
<td>0.25</td>
</tr>
<tr>
<td>(\mathcal{L}_{/\text{IP}}[10^{23}\text{cm}^{-2}\text{s}^{-1}])</td>
<td>5600</td>
<td>1600</td>
<td>480</td>
<td>130</td>
</tr>
<tr>
<td>number of IPs</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>beam lifet. [min]</td>
<td>67</td>
<td>25</td>
<td>16</td>
<td>20</td>
</tr>
</tbody>
</table>

TLEP: A HIGH-PERFORMANCE CIRCULAR \(e^+e^-\) COLLIDER TO STUDY THE HIGGS BOSON


CONSISTENT SET OF PARAMETERS FOR TLEP TAKING INTO ACCOUNT BEAMSTRAHLUNG
**TLEP: PARAMETERS & STATISTICS**

\((e^+e^- \rightarrow ZH, \ e^+e^- \rightarrow W^+W^-, \ e^+e^- \rightarrow Z, [e^+e^- \rightarrow t\bar{t}] )\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TLEP-4 IP, per IP</th>
<th>Stats (4IP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>circumference</td>
<td>80 km</td>
<td></td>
</tr>
<tr>
<td>max beam energy</td>
<td>175 GeV</td>
<td></td>
</tr>
<tr>
<td>no. of IPs</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Luminosity/IP at 350 GeV c.m.</td>
<td>(1.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1})</td>
<td>(10^6) (t\bar{t}) pairs</td>
</tr>
<tr>
<td>Luminosity/IP at 240 GeV c.m.</td>
<td>(4.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1})</td>
<td>(2 \times 10^6) Z events</td>
</tr>
<tr>
<td>Luminosity/IP at 160 GeV c.m.</td>
<td>(1.6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1})</td>
<td>(10^8) WW pairs</td>
</tr>
<tr>
<td>Luminosity/IP at 90 GeV c.m.</td>
<td>(5.6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1})</td>
<td>(10^{12}) Z decays</td>
</tr>
</tbody>
</table>

at the Z pole repeat the LEP physics programme in a few minutes...

Alain Blondel precision measurements at TLEP HEP-EPS Stockholm 2013-07-18
• Luminosity: Crossing point between circular and linear colliders ~ 400 GeV

As pointed out by H. Shopper in ‘The Lord of the Rings’ (Thanks to Superconducting RF...)

• Circular colliders can have several IP’s. Sum scales as $\sim (N_{IP})^{0.5-1}$

use 4 IP machine as more reliable predictions using LEP experience
Beamstrahlung @TLEP is important for machine design but benign for physics:
- particles are either lost or recycled on a synchrotron oscillation.
- some increase of energy spread but no change of average energy
- Little resulting systematic error – cross-check wrt orbit of ‘single’ bunches

Little EM background in the experiment, no issue for luminosity measurement, but shielding against synchrotron radiation has to be designed.
Beam polarization and E-calibration @ TLEP

Precise meast of $E_{\text{beam}}$ by resonant depolarization
$\sim 100$ keV each time the meast is made $\rightarrow$ LEP

At LEP transverse polarization was achieved routinely at Z peak. instrumental in $10^{-3}$ measurement of the Z width in 1993 led to prediction of top quark mass (179+- 20 GeV) in Mar’94

Polarization in collisions was observed (40% at BBTS = 0.04) $\rightarrow$

At LEP beam energy spread destroyed polarization above 61 GeV
$\sigma_E \propto E^2/\sqrt{\rho} \rightarrow$ At TLEP transverse polarization up to at least 81 GeV (WW threshold) to go to higher energies requires spin rotators and siberian snake (see spares)

TLEP: use ‘single’ bunches to measure the beam energy continuously $\rightarrow$ no interpolation errors due to tides, ground motion or trains etc...

$\ll 100$ keV beam energy calibration around Z peak and W pair threshold.
$\Delta m_Z \sim 0.1$ MeV, $\Delta \Gamma_Z \sim 0.1$ MeV, $\Delta m_W \sim 0.5$ MeV

Alain Blondel Higgs and Beyond June 2013 Sendai
EXPERIMENTS ON BEAM-BEAM DEPOLARIZATION AT LEP


PAC 1995

- With the beam colliding at one point, a polarization level of 40 % was achieved. The polarization level was about the same for one colliding and one non colliding bunch.
- It was observed that the polarization level depends critically on the synchrotron tune : when $Q_y$ was changed by 0.005, the polarization strongly decreased.

Experiment performed at an energy of 44.71 GeV the polarization level was 40 % with a linear beam-beam tune shift of about 0.04/IP. This indicates, that the beam-beam depolarization does not scale with the linear beam-beam tune shift at one crossing point. Other parameters as spin tune and synchrotron tune are also of importance.

This was only tried 3 times!
Best result: $P = 40\%$, $\xi_y = 0.04$, one IP
Assuming 4 IP and $\xi_y = 0.01$ ➔

reduce luminosity somewhat, $10^{11} Z @ P=40\%$

Figure 3. Polarization level during third experiment
TERA-Z and Oku-W

Precision tests of the closure of the Standard Model
Precision tests of EWSB

Z pole symmetries, lineshape

WL threshold scan

WW threshold scan

ALEPH
DELPHI
L3
OPAL

\[ \sigma_{had}[nb] \]

average measurements, error bars increased by factor 10

\[ E_{cm}[GeV] \]

TLEP: Repeat the LEP1 physics programme every 15 mn

- Transverse polarization up to the WW threshold
  - Exquisite beam energy determination (10 keV)

- Longitudinal polarization at the Z pole
  - Measure \( \sin^2\theta_W \) to 2.10^{-6} from \( A_{LR} \)
  - Statistics, statistics: \( 10^{10} \) tau pairs, \( 10^{11} \) bb pairs, QCD and QED studies etc...

tt threshold scan
$\Gamma_e = \frac{(1 + \Delta \rho)}{24 \pi \sqrt{2}} \frac{G_F M_Z^3}{(1 + \left(\frac{g_{\nu e}}{g_{\nu e}}\right)^2) (1 + \frac{3}{4} \frac{\alpha}{\pi})}$

$\sin^2 \theta_w \cos^2 \theta_w = \frac{\pi d (M_Z^2)}{\sqrt{2} G_F M_Z^2} \frac{1}{1 + \Delta \rho} \frac{1}{1 - \frac{\epsilon_3}{\cos^2 \theta_w}}$

$M_W^2 = \frac{\pi \alpha (M_Z^2)}{\sqrt{2} G_F \sin^2 \theta_W \cos \theta_W} (1 + \epsilon_2)
\sin^2 \theta_w^{\text{eff}} = \frac{\sin^2 \theta_w}{\sin^2 \theta_W}$

$\Delta \rho = \Delta \alpha - \frac{\cos^2 \theta_W}{\sin^2 \theta_W} \Delta \rho + \frac{2}{\sin^2 \theta_W} G^2 T_W \epsilon_3 + \frac{c^2 - s^2}{s^2} \epsilon_2$

There is much more than the $W$ mass!

EWRCs
relations to the well measured $G_F$ and $M_Z$

At first order:

$\epsilon_3 = \cos^2 \theta_w \frac{\alpha}{9 \pi} \log \left(\frac{m_h}{m_Z}\right)^2$

$\delta_{\nu b} = \frac{20}{13} \frac{\alpha}{\pi} \left(\frac{m_{\text{top}}}{m_Z}\right)^2$

Complete formulae at 2d order including strong corrections are available in fitting codes e.g. ZFITTER, GFITTER

Will need to be improved for TLEP!
Words of caution:

1. TLEP will have $5 \times 10^4$ more luminosity than LEP at the Z peak, $5 \times 10^3$ at the W pair threshold. Predicting achievable accuracies with statistical errors decreasing by 250 is very difficult. *The study is just beginning.*

2. The following table are ‘plausible’ precisions based on my experience and knowledge of the present limitations, most of which from higher order QED corrections (ex. production of additional lepton pairs etc..). Many can have experimental cross-checks and errors may get better.

3. The most serious issue is the luminosity measurement which relies on the calculations/modeling of the low angle Bhabha scattering cross-section. This dominates the measurement of the hadronic cross section at the Z peak thus the determination of $N_v$ (test of the unitarity of the PMNS matrix)

4. The following is only a sample of possibilities. With $10^{12}$ Z decays, there are many, many more powerful studies to perform at TERA-Z e.g. flavour physics with $10^{11}$ $\bar{b}b$, $\bar{c}c$, $10^{10}$ $\tau\tau$ etc…
### A Sample of Essential quantities:

<table>
<thead>
<tr>
<th>X</th>
<th>Physics</th>
<th>Present precision</th>
<th>TLEP target Precision–TBS</th>
<th>TLEP key</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_Z$ (MeV/c^2)</td>
<td>Input</td>
<td>91187.5 ±2.1</td>
<td>&lt;±0.1 MeV/c^2 (solid)</td>
<td>E_cal</td>
<td>QED corrections</td>
</tr>
<tr>
<td>$\Gamma_Z$ (MeV/c^2)</td>
<td>$\Delta \rho \left( T \right)$ (no $\Delta \alpha$!)</td>
<td>2495.2 ±2.3</td>
<td>&lt;±0.1 MeV/c^2 (solid)</td>
<td>E_cal</td>
<td>QED corrections</td>
</tr>
<tr>
<td>$R_{\ell}$</td>
<td>$\alpha_s, \delta_b$</td>
<td>20.767 ±0.025</td>
<td>± 0.002 - 0.0002</td>
<td>Statistics</td>
<td>QED corrections</td>
</tr>
<tr>
<td>$N_v$</td>
<td>Unitarity of PMNS, sterile $\nu$'s</td>
<td>2.984 ±0.008</td>
<td>±0.001 (?)</td>
<td>environment -&gt; lumi meast</td>
<td>QED corrections to Bhabha scat.</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$\delta_b$</td>
<td>0.21629 ±0.00066</td>
<td>±0.00002 - 5</td>
<td>Statistics, small IP</td>
<td>Hemisphere correlations</td>
</tr>
<tr>
<td>$A_{LR}$</td>
<td>$\Delta \rho, \varepsilon_3, \Delta \alpha$ ($T, S$)</td>
<td>0.1514 ±0.0022 (SLD)</td>
<td>±0.000015 (solid)</td>
<td>4 bunch scheme</td>
<td>Polarization in collisions</td>
</tr>
<tr>
<td>$M_W$ (MeV/c^2)</td>
<td>$\Delta \rho, \varepsilon_3, \varepsilon_2, \Delta \alpha$ ($T, S, U$)</td>
<td>80385 ±15</td>
<td>0.5 (solid)</td>
<td>E_cal &amp; Statistics</td>
<td></td>
</tr>
<tr>
<td>$m_{top}$ (MeV/c^2)</td>
<td>Input</td>
<td>173200 ±900</td>
<td>10</td>
<td>E_cal &amp; Statistics</td>
<td></td>
</tr>
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</table>
Measurement of $A_{LR}$

electron bunches

table:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
</table>

positron bunches

table:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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</thead>
</table>

cross sections

tables:

<table>
<thead>
<tr>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
<th>$\sigma_3$</th>
<th>$\sigma_4$</th>
</tr>
</thead>
</table>

event numbers

tables:

<table>
<thead>
<tr>
<th>$N_1$</th>
<th>$N_2$</th>
<th>$N_3$</th>
<th>$N_4$</th>
</tr>
</thead>
</table>

\begin{align*}
\sigma_1 &= \sigma_u (1 - P^- e \wedge_{LR}) \\
\sigma_2 &= \sigma_u (1 + P^+ e \wedge_{LR}) \\
\sigma_3 &= \sigma_u \\
\sigma_4 &= \sigma_u [1 - P^+ e P^- e + (P^+ e - P^- e) \wedge_{LR}] \\
\end{align*}

Verifies polarimeter with experimentally measured cross-section ratios

statistics

\begin{align*}
\Delta A_{LR} &= 0.0025 \text{ with about } 10^6 Z^0 \text{ events,} \\
\Delta A_{LR} &= 0.000015 \text{ with } 10^{11} Z \text{ and 40% polarization in collisions.} \\
\Delta \sin^2 \theta_{W_{\text{eff}}} \text{ (stat)} &= O(2.10^{-6})
\end{align*}
At the moment we do not know for sure what is the most sensible scenario.

LHC offered 3 possible scenarios: (could not lose)

- Discover that there is nothing in this energy range.
  ➔ This would have been a great surprise and a great discovery!

- Discover SM Higgs Boson and that nothing else is within reach.
  ➔ Most Standard scenario great discovery!

- Discover many new effects or particles great discovery!

So far we are here

But....

Keep looking in 13/14 TeV data!

Answer in 2018

High precision

High energy

Also: understand scaling of LHC errors with luminosity

BE PREPARED!
d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available.

CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.

The two most promising lines of development towards the new high energy frontier after the LHC are proton-proton and electron-positron colliders. Focused design studies are required in both fields, together with vigorous accelerator R&D supported by adequate resources and driven by collaborations involving CERN and national institutes, universities and laboratories worldwide. The Compact Linear Collider (CLIC) is an electron-positron machine based on a novel two-beam acceleration technique, which could, in stages, reach a centre-of-mass energy up to 3 TeV. A Conceptual Design Report for CLIC has already been prepared. Possible proton-proton machines of higher energy than the LHC include HE-LHC, roughly doubling the centre-of-mass energy in the present tunnel, and VHE-LHC, aimed at reaching up to 100 TeV in a new circular 80km tunnel. A large tunnel such as this could also host a circular e+e− machine (TLEP) reaching energies up to 350 GeV with high luminosity.
CERN Medium term plan -- June 2013:

- Studies for high-energy proton-proton and electron-positron colliders in a new 80-100 km circular tunnel have already started. The aim is to have available Conceptual Design Reports by the time of the next update of the European Strategy for Particle Physics.

NB. What ICFA decided to discontinue are the ICFA-beam dynamics workshops on Higgs Factories -- not the studies of course!
Design Study: http://tlep.web.cern.ch
can subscribe for work, informations, newsletter, etc…

Global collaboration: collaborators from Europe, US, Japan, China

Next events: TLEP workshops 25-26 July 2013, Fermilab
16-18 October 2013, CERN

+ Joint VHE-LHC+ TLEP kick-off meeting in February 2014
The first 250 subscribers:

Some interesting statistics can be found below. More details can be found on the TLEP web site.

The distribution of the country of origin reflects the youth of the TLEP project and the very different levels of awareness in the different countries.

The audience is remarkably well balanced between Accelerator, Experiment, and Phenomenology.
Conclusions

• Discovery of H(126) focuses studies of the next machine
  – News ideas emerging for Higgs factories and beyond

• A large e+e- storage ring collider seems the best complement to the LHC
  – Couple Permil precision on Higgs Couplings (see P. Janot’s talk)
  – Unbeatable precision on EW quantities ($m_Z$, $\Gamma_Z$, $m_W$, $A_{LR}$, $R_b$ etc, etc.....)
  – Most mature technology and safe luminosity estimates.
  – A first step towards a 100 TeV proton proton collider and a long term vision.

• Results of the LHC run at 14 TeV will be a necessary and precious input
  – Towards an ambitious medium and long term vision
  – In Europe: Decision to be taken by 2018
  -- Design study recommended and being organized: tlep.web.cern.ch

The numbers speak for themselves!
Some guidance from theorists:

New physics affects the Higgs couplings

**SUSY**
\[
\frac{g_{hbb}}{g_{hSMbb}} \approx 1 + 1.7\% \left( \frac{1 \text{ TeV}}{m_A} \right)^2, \text{ for } \tan\beta = 5
\]

**Composite Higgs**
\[
\frac{g_{hff}}{g_{hSMff}} \approx \frac{g_{hVV}}{g_{hSMVV}} \approx 1 - 3\% \left( \frac{1 \text{ TeV}}{f} \right)^2
\]

**Top partners**
\[
\frac{g_{hgg}}{g_{hSMgg}} \approx 1 + 2.9\% \left( \frac{1 \text{ TeV}}{m_T} \right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{hSM\gamma\gamma}} \approx 1 - 0.8\% \left( \frac{1 \text{ TeV}}{m_T} \right)^2
\]

Other models may give up to 5% deviations with respect to the Standard Model

**Sensitivity to “TeV” new physics needs per-cent to sub-per-cent accuracy on couplings for 5 sigma discovery.**

**LHC discovery/(or not) at 13 TeV will be crucial to understand the strategy for future collider projects**

The LHC is a Higgs Factory!

1M Higgs already produced – more than most other Higgs factory projects.
15 Higgs bosons / minute – and more to come (gain factor 3 going to 13 TeV)

Difficulties: several production mechanisms to disentangle and significant systematics in the production cross-sections $\sigma_{\text{prod}}$.

Challenge will be to reduce systematics by measuring related processes.

$$\sigma_{i\rightarrow f}^{\text{observed}} \propto \sigma_{\text{prod}} \frac{(g_{H_i})^2 (g_{H_f})^2}{\Gamma_H}$$

extract couplings to anything you can see or produce from $H \rightarrow i f$ as in $WZ$ with $H \rightarrow ZZ \rightarrow$ absolute normalization

A. Blondel precision measurements at TLEP HEP-EPS Stockholm 2013-07-18
**HL-LHC (≡3 ab\(^{-1}\) at 14 TeV):**

Highest-priority recommendation from European Strategy

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle’s properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier.

The LHC is in a unique position to pursue this programme.

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<thead>
<tr>
<th></th>
<th>LHC</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>End date</td>
<td>2021</td>
<td>2030-35?</td>
</tr>
<tr>
<td>(N_H)</td>
<td>1.7 \times 10^7</td>
<td>1.7 \times 10^8</td>
</tr>
<tr>
<td>(\Delta m_H) (MeV)</td>
<td>100</td>
<td>50</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>
</tr>
<tr>
<td>(\Delta g_{Hgg}/g_{Hgg})</td>
<td>11 – 5.7%</td>
<td>7.5 – 2.7%</td>
</tr>
<tr>
<td>(\Delta g_{Hww}/g_{Hww})</td>
<td>5.7 – 2.7%</td>
<td>4.5 – 1.0%</td>
</tr>
<tr>
<td>(\Delta g_{HZZ}/g_{HZZ})</td>
<td>5.7 – 2.7%</td>
<td>4.5 – 1.0%</td>
</tr>
<tr>
<td>(\Delta g_{HHH}/g_{HHH})</td>
<td>--</td>
<td>&lt; 30%</td>
</tr>
<tr>
<td>(\Delta g_{H\mu\mu}/g_{H\mu\mu})</td>
<td>&lt;30%</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>(\Delta g_{Htt}/g_{Htt})</td>
<td>8.5 – 5.1%</td>
<td>5.4 – 2.0%</td>
</tr>
<tr>
<td>(\Delta g_{Hcc}/g_{Hcc})</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>(\Delta g_{Hbb}/g_{Hbb})</td>
<td>15 – 6.9%</td>
<td>11 – 2.7%</td>
</tr>
<tr>
<td>(\Delta g_{Htt}/g_{Htt})</td>
<td>14 – 8.7%</td>
<td>8.0 – 3.9%</td>
</tr>
</tbody>
</table>

**Coupling measurements with precision:**

- in the range **6-15%** with LHC - 300 fb\(^{-1}\)
- in the range **1-4%** with HL-LHC - 3000 fb\(^{-1}\)

**NB:** at LEP theory errors improved by factor 10 or more....
A. Blondel precision measurements at TLEP HEP-EPS Stockholm 2013-07-18
Conclusions and outlook (my own view)
A project for the next 50 years

The discovery of the $\text{H}(126)$ scalar boson opens the way to precise investigations:

-- HL-LHC
-- A lepton collider of sufficient luminosity and precision
-- Best performance with an $\text{e}^+\text{e}^-$ circular machine TLEP in a large (80km) tunnel

-- First step towards 100 TeV Very Large Hadron Collider
-- Choice when LHC results at 13 TeV available $\rightarrow$ 2017–18

In 2035 the LEP/LHC tunnel will have been used for 46 years...

the TLEP/VHE-LHC tunnel would be used for $>50$ years!
Obtaining longitudinal polarization at higher energies requires a cancellation of depolarization effects by reducing the spin-tune spread associated with the energy spread. Siberian snake solutions [11] invoking combinations of spin rotators situated around the experiments and polarization wigglers are being discussed. They take advantage of the fact that the TLEP arcs have very low fields and can be overruled by polarization wigglers suitably disposed around the ring. These schemes will need to be worked out and simulated before the feasibility of longitudinal polarization in high energy collisions can be asserted.

Figure 6: A possible scheme to obtain longitudinal beam polarization at high energies ($E_{\text{beam}} \gg M_Z/2$) with TLEP: taking advantage of the weakness of the magnetic field in the arcs, the polarization is generated dominantly by strong asymmetric wigglers of opposite polarities (AW1 and AW2) in two halves of the ring. The transverse polarization obtained this way is rotated to longitudinal in the experimental straight sections in detector D1, by 90 degrees spin rotators (SR1L, etc..), and brought back to vertical (but reversed) in the following arc, and similarly for the next experimental straight section, D2. The scheme easily generalizes to the situation with four IPs. This scheme generates a spin transport with an integer part of the spin tune equal to zero. The spin polarization of the electrons is shown. Given separated beam pipes for the $e^+$ and $e^-$ beams, they can be exposed to wigglers of opposite polarity, providing polarization of positrons can be chosen parallel to that of the electrons. In this way highly polarized $e^+e^-$ systems at the collision point can be obtained. Polarization can be reversed by reversing the wiggler polarity. The possibility of depolarizing a fraction of the bunches in this scheme, to provide a normalization of polarimetry from the measured cross-sections, is being investigated.
possible long-term time line

---|---|---|---|---|---|---
HL-LHC | Design, R&D | Constr. | Physics
TLEP | Design, R&D | Constr. | Physics
VHE-LHC | Design, R&D | Constr. | Physics