Experimental Physics at Lepton Colliders
CERN Summer Student Lecture, 2019

Lecture 2

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Physics at Lepton Colliders

- **Lecture 1** (Wednesday 31 July, 9:15)
  - Introduction: Why Lepton Colliders?
  - Where we stand: Status of the Standard Model
  - An experimental strategy for the future: $e^+e^-$ colliders
  - Precision Higgs Physics

- **Lecture 2** (Thursday 1 August, 10:25)
  - Electroweak Precision Physics: FCC-ee
  - GigaZ physics: Flavour Physics and Direct Discoveries
  - High Energy $e^+e^-$ Physics: CLIC
  - Instrumentation: Detectors for $e^+e^-$ physics
  - Thinking out of the box: Muon colliders
  - Rounding off: Summary and Conclusions
Electroweak Precision Physics

FCC-ee

![Graph showing luminosity vs. √s (GeV)]

- FCC-ee (Baseline, 2IPs)
- CEPC (2IPs)
- ILC
- CLIC
◆ FCC-ee is the ultimate Z, W, Higgs and top factory
  □ $10^5$ times more Zs and $10^3$ times more Ws than LEP1 and LEP2
    ◆ Potential statistical accuracies are mind-boggling!
◆ Predicting accuracies with 200 times smaller statistical precision than at LEP is hard
  □ Conservatively, use LEP experience for systematics
◆ Example: The uncertainty on $E_{\text{BEAM}}$ (2 MeV) was the dominant uncertainty on $m_Z$, $\Gamma_Z$
  □ Can we do significantly better at FCC-ee?

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### FCC-ee Goals in Numbers

<table>
<thead>
<tr>
<th>Working point</th>
<th>$Z$, years 1-2</th>
<th>$Z$, later</th>
<th>$WW$</th>
<th>$HZ$</th>
<th>$t\bar{t}$ threshold...</th>
<th>... and above</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>88, 91, 94</td>
<td>157, 163</td>
<td>240</td>
<td>340 – 350</td>
<td>365</td>
<td></td>
</tr>
<tr>
<td>Lumi/IP ($10^{34}$ cm$^{-2}$s$^{-1}$)</td>
<td>100</td>
<td>200</td>
<td>25</td>
<td>7</td>
<td>0.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Lumi/year (2 IP)</td>
<td>24 ab$^{-1}$</td>
<td>48 ab$^{-1}$</td>
<td>6 ab$^{-1}$</td>
<td>1.7 ab$^{-1}$</td>
<td>0.2 ab$^{-1}$</td>
<td>0.34 ab$^{-1}$</td>
</tr>
<tr>
<td>Physics goal</td>
<td>150 ab$^{-1}$</td>
<td>10 ab$^{-1}$</td>
<td>5 ab$^{-1}$</td>
<td>0.2 ab$^{-1}$</td>
<td>1.5 ab$^{-1}$</td>
<td></td>
</tr>
<tr>
<td># events</td>
<td>$5 \times 10^{12}$ $Z$</td>
<td>$10^8$ $WW$</td>
<td>$10^6$ $HZ$</td>
<td>$10^6$ $t\bar{t}$</td>
<td>45000 $WW \rightarrow H$</td>
<td></td>
</tr>
<tr>
<td>Run time (years)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>
FCC-ee Precision Physics: Beam Energy (1)

- Measurement of the beam energy at LEP
  - Ultra-precise measurement crucial for $m_Z$, $\Gamma_Z$, ...
  - Unique to circular colliders

![Diagram of electron with momentum $p$ in a uniform vertical magnetic field $B$]

Electron with momentum $p$ in a uniform vertical magnetic field $B$:

$$E \sim p = eBR = \left(\frac{e}{2\pi}\right)BL$$

In real life, $B$ non-uniform, LEP ring not circular

$$E = \frac{e}{2\pi} \int_{\text{LEP}} B \, dl$$

To be measured

The electrons get transversally polarized (i.e., their spin tends to align with $B$)

![Graph showing polarization over time]

Slow process (~ 1 hour to get 10% polarization)

NB. Polarization can be kept in collision (was attempted only once at LEP).
**Measurement of the beam energy at LEP (cont’d)**

- The spin precesses around $B$ with a frequency proportional to $B$ (Larmor precession)
  - Hence, the precession frequency $\nu_S$ for each LEP turn is proportional to $\int B \, dl$

\[
\nu_S = \frac{g_e - 2}{2m_e} \times E_{\text{beam}}
\]

**Resonant depolarization:**

- LEP was colliding 4 bunches of $e^+$ and $e^-$; FCC-ee will have 1,000’s of bunches
  - Use ~10 “single” bunches to measure $E_{\text{BEAM}}$ with resonant depolarization
    - Each measurement gives 100 keV precision, with no extrapolation uncertainty
FCC-ee Precision EW Physics Measurements (1)

- Boils down to measuring cross sections and asymmetries

\[ e^+e^- \rightarrow \mu^+\mu^- \]

- Measure \( \sin^2 \theta_W \) with \( A_{FB} \) at \( \sqrt{s} = m_Z \)
- Measure \( \alpha_{QED}(m_Z) \) with \( A_{FB} \) at \( \sqrt{s} = 87.9 \) and 94.3 GeV

- The dominant experimental uncertainties (still!) come from the beam energy knowledge
**FCC-ee Precision EW Physics Measurements (2)**

- EW precision measurements at FCC-ee (see arXiv:1308.6176 and CDR)

### Z resonance: TeraZ

- Lineshape
  - Exquisite $E_{\text{beam}}$ (unique!)
  - $m_Z$, $\Gamma_Z$ to < 100 keV (2.2 MeV)

- Asymmetries
  - $\sin^2\theta_W$ to $6 \times 10^{-6}$ (1.6 $\times 10^{-4}$)
  - $\alpha_{\text{QED}}(m_Z)$ to $3 \times 10^{-5}$ (1.5 $\times 10^{-4}$)

- Branching ratios $R_L$, $R_b$
  - $\alpha_S(m_Z)$ to 0.0002 (0.002)

### WW threshold scan: OkuW

- Threshold scan
  - $m_W$ to 0.6 MeV (12 MeV)

### tt threshold scan: MegaTop

- Threshold scan
  - $m_{\text{top}}$ to 20 MeV (500 MeV)

- Branching ratios $R_L$, $R_b$:
  - $\alpha_S(m_W)$ to 0.0002

- Radiative return $e^+e^- \rightarrow Z\gamma$
  - $N_\nu$ to 0.001 (0.008)

- EW couplings to 2%
FCC-ee Precision EW Physics Measurements (3)

- Measurements of $t_L t_L Z$ and $t_R t_R Z$ couplings, $g_L$ and $g_R$
  - At FCC-ee@365 GeV, couplings extracted from "top polarization measurement":
    Leptons and b-jet distributions
  - Couplings sensitive to, e.g., composite Higgs models
<table>
<thead>
<tr>
<th>Observable</th>
<th>Measurement</th>
<th>Current precision</th>
<th>FCC-ee stat.</th>
<th>FCC-ee syst.</th>
<th>Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$ (keV)</td>
<td>Z lineshape</td>
<td>91186700 ± 2200</td>
<td>5</td>
<td>100</td>
<td>Beam energy calib</td>
</tr>
<tr>
<td>$\Gamma_Z$ (keV)</td>
<td>Z lineshape</td>
<td>2495200 ± 2300</td>
<td>8</td>
<td>100</td>
<td>Beam energy calib</td>
</tr>
<tr>
<td>$R_l$ ($x10^3$)</td>
<td>Ratio of hadrons to leptons</td>
<td>20767 ± 25</td>
<td>0.01</td>
<td>0.2–1</td>
<td>Acceptance for leptons</td>
</tr>
<tr>
<td>$\alpha_s(m_Z)$ ($x10^4$)</td>
<td>From $R_\ell$</td>
<td>1196 ± 30</td>
<td>0.1</td>
<td>0.4–1.6</td>
<td>ditto</td>
</tr>
<tr>
<td>$R_b$ ($x10^6$)</td>
<td>Ratio of bb to hadrons</td>
<td>216290 ± 660</td>
<td>0.3</td>
<td>&lt; 60</td>
<td>g → bb</td>
</tr>
<tr>
<td>$N_v$ ($x10^3$)</td>
<td>Peak hadronic cross section</td>
<td>2991 ± 7</td>
<td>0.005</td>
<td>&lt; 1</td>
<td>Lumi meast</td>
</tr>
<tr>
<td>$\sin^2\theta_W^{\text{eff}}$ ($x10^6$)</td>
<td>From $A_{FB}^{\mu\mu}$ at Z peak</td>
<td>231480 ± 160</td>
<td>3</td>
<td>2–5</td>
<td>Beam energy calib</td>
</tr>
<tr>
<td>$1/\alpha_{\text{QED}}(m_Z)$ ($x10^3$)</td>
<td>From $A_{FB}^{\mu\mu}$ off-peak</td>
<td>128952 ± 14</td>
<td>4</td>
<td>small</td>
<td>QED corr.</td>
</tr>
<tr>
<td>$A_{FB}^{\text{pol},\tau}$ ($10^4$)</td>
<td>$\tau$ polarization charge asymm</td>
<td>1498 ± 49</td>
<td>0.15</td>
<td>&lt; 2</td>
<td>$\tau$ decay physics</td>
</tr>
<tr>
<td>$m_w$ (MeV)</td>
<td>WW threshold scan</td>
<td>80385000 ± 15000</td>
<td>600</td>
<td>300</td>
<td>Beam energy calib</td>
</tr>
<tr>
<td>$N_v$</td>
<td>$e^+e^-\rightarrow\gamma Z, Z\rightarrow\nu\bar{\nu}, l\ell$</td>
<td>2.92 ± 0.05</td>
<td>0.001</td>
<td>&lt; 0.001</td>
<td>?</td>
</tr>
<tr>
<td>$\alpha_s(m_w)$ ($x10^4$)</td>
<td>From $R_\ell^W$</td>
<td>1170 ± 420</td>
<td>3</td>
<td>small</td>
<td>Lepton acceptance</td>
</tr>
<tr>
<td>$m_{top}$ (MeV)</td>
<td>tt threshold scan</td>
<td>172740 ± 500</td>
<td>20</td>
<td>small</td>
<td>QCD corr</td>
</tr>
<tr>
<td>$\Gamma_{top}$ (MeV)</td>
<td>tt threshold scan</td>
<td>1410 ± 190</td>
<td>40</td>
<td>small</td>
<td>QCD corr</td>
</tr>
<tr>
<td>$\lambda_{top} / \lambda_{top}^{\text{SM}}$</td>
<td>tt threshold scan</td>
<td>1.2 ± 0.3</td>
<td>0.08</td>
<td>small</td>
<td>QCD corr</td>
</tr>
</tbody>
</table>
Extremely Precise EW Consistency Checks

- Combination of all precision electroweak measurements
  - FCC-ee precision allows $m_{top}$, $m_W$, $\sin^2 \theta_W$ to be predicted within the SM
    - ... and to be compared to the direct measurements

- New Physics?
  - Direct measurement (blue ellipse) and indirect constraints (red ellipse) may or may not overlap
Higher-dimensional operators as a parametrization of new physics

Possible corrections to the Standard Model

Standard Model Effective Theories (SMEFT)

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i \]

- scale of new decoupled physics

Electroweak precision measurements

Limits on new physics scale, \( \Lambda \):

Today: \( \Lambda > 4\text{-}10\text{TeV} \)

Sensitivity to new physics scale, \( \Lambda \):

After FCC-ee: \( \Lambda > 20\text{-}70\text{ TeV} \)
SMEFT Fit to FCC-ee Higgs Measurements

- Interpret also precisely measured Higgs couplings (Lecture 1) in terms of higher-dimension operators

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i \]

Higgs precision measurements

Limits on new physics scale, \( \Lambda \):

Today: \( \Lambda > 1-15 \text{ TeV} \)

Sensitivity to new physics scale, \( \Lambda \):

After FCC-ee: \( \Lambda > 1-35 \text{ TeV} \)
Combined FCC-ee SMEFT Fit

- Combine EW precision observables with precise Higgs coupling measurements via higher-dimensional operators

Electroweak + Higgs precision measurements

- The EW and Higgs measurements are highly complementary
  - Together they provide precise constraints on a large number of operators
  - Different New Physics models give different pattern of deviations from SM
    - Pattern provides fingerprint to differentiate among models
GigaZ Physics: Flavour Physics and Direct Discoveries
Flavour Physics at FCC-ee

- $5 \times 10^{12}$ Z decays: $10^{12}$ $b\bar{b}$ events, $1.7 \times 10^{11} \tau^+\tau^-$ events
  - FCC-ee is also the ultimate factory for the study of (heavy) flavours
    - lifetime, branching fractions, rare decays, test of Universality

- Example from b-physics:
  - Current tensions (several 2–3 $\sigma$ deviations) of LHCb data with SM predictions
    - In particular, lepton flavour universality is challenged in $b \rightarrow s \ell^+\ell^-$ transitions
      - For example, the rates of $B^0 (B^+) \rightarrow K^{*0} (K^+) \ell^+\ell^-$ are different for $\ell = e$ and $\ell = \mu$
      - Differences are also observed in the lepton angular distributions
    - This effect, if real, could be enhanced for $\ell = \tau$, in $B \rightarrow K^{(*)} \tau^+\tau^-$
      - With $10^{12}$ $Z \rightarrow bb$, FCC-ee is beyond any foreseeable competition
      - Decay can be fully reconstructed
      - Full angular analysis possible

![Graph showing $B^0 \rightarrow K^{*}(892) \tau^+\tau^-$](image-url)

J.F. Kamenik et al.
arXiv:1705.11106
τ physics

τ Properties and Universality

- τ branching fractions and lifetime provide strong test of Universality of the $\alpha - \nu_\alpha$ CC coupling, $\alpha = e, \mu, \tau$
  - Sensitive to light-heavy neutrino mixing
  - Need also (more) precise mass measurement

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current precision</th>
<th>FCC-ee stat.</th>
<th>Possible syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\tau$ [MeV]</td>
<td>1776.86 ± 0.12</td>
<td>0.004</td>
<td>0.1</td>
</tr>
<tr>
<td>$\tau_\tau$ [fs]</td>
<td>290.3 ± 0.5 fs</td>
<td>0.001</td>
<td>0.04</td>
</tr>
<tr>
<td>$B(\tau \to e\nu\nu)$ [%]</td>
<td>17.82 ± 0.05</td>
<td>0.0001</td>
<td>0.003</td>
</tr>
<tr>
<td>$B(\tau \to \mu\nu\nu)$ [%]</td>
<td>17.39 ± 0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Measurement</th>
<th>Current precision</th>
<th>FCC-ee precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>g_\mu/g_e</td>
<td>$</td>
<td>$\Gamma_\tau\to\mu / \Gamma_\tau\to e$</td>
</tr>
<tr>
<td>$</td>
<td>g_\tau/g_\mu</td>
<td>$</td>
<td>$\Gamma_\tau\to e / \Gamma_\mu\to e$</td>
</tr>
</tbody>
</table>

Visible Z decays
- $3 \times 10^{12}$
- $Z \to \tau^+\tau^-$: $1.3 \times 10^{11}$
- 1 vs. 3 prongs: $3.2 \times 10^{10}$
- 3 vs. 3 prong: $2.8 \times 10^9$
- 1 vs. 5 prong: $2.1 \times 10^8$
- 1 vs. 7 prong: $< 67,000$
- 1 vs 9 prong: ?

Lepton universality with $m_\tau = 1776.86 \pm 0.12$ MeV

M.Dam
arXiv:1811.09408
Direct discoveries from Z decays

- Discover right-handed neutrinos
  - vMSM: Complete particle spectrum with the missing three right-handed neutrinos

  ![Particle Spectrum Diagram]

  ▶ Could explain everything: Dark matter ($N_1$), Baryon asymmetry, Neutrino masses
  - Searched for in very rare $Z \to vN_{2,3}$ decays
  - Followed by $N_{2,3} \to W^*\ell$ or $Z^*v$

  ![Search Diagram]

  Very small $vN$ mixing: long lifetime, detached vertex

  ![Physics at Lepton Colliders Diagram]

  Inverted hierarchy

  CHARM  
  PS191  
  NuTeV  
  BAU  
  BBN  
  FCC-ee $10^{12} Z^0$  
  $1 \text{ mm} < r < 1 \text{ m}$

  FCC-ee $10^{10} Z^0$  
  $100 \mu m < r < 5 \text{ m}$

  SHiP  
  Seesaw  

  A. Blondel et al. arXiv:1411.5230
Direct discoveries (cont’d)

- Discover the dark sector

  - A very-weakly-coupled window to the dark sector is through light “Axion-Like Particles” (ALPs)

  - $\gamma + E_{\text{MISS}}$ for very light $a$
  - $\gamma\gamma$ for light $a$
  - $\gamma\gamma\gamma$ for heavier $a$

- Orders of magnitude of parameter space accessible at FCC-ee
High Energy $e^+e^-$ Physics

CLIC
Why do precision Higgs physics at high $\sqrt{s}$?

- Precision achieved with $e^+e^-$ colliders at $\sqrt{s}=240-500$ GeV: 0.1% - 1%
  - Superior to what can be done at higher energy
    - $\sigma_{HZ}$ decreases, kinematics less favourable, backgrounds increase, ...

However ...

- Some production processes are not directly accessible at low-energy $e^+e^-$ colliders
  - Hence more couplings might become measurable at larger energy
    - $Htt$, $HHH$, $HHHH$, ...

1. **Htt**
   - $\sqrt{s} > 500$ GeV

2. **HHH**
   - $\sqrt{s} > 1$ TeV

Background

Mogens Dam / NBI Copenhagen

Physics at Lepton Colliders

31 July - 1 August, 2019
Precision: Higgs properties at high energy (2)

- Achievable precisions

<table>
<thead>
<tr>
<th>Collider</th>
<th>HL-LHC</th>
<th>CLIC$_{3000}$</th>
<th>FCC-ee</th>
<th>FCC-ee+hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta g_{Htt}/g_{Htt}$</td>
<td>3%</td>
<td>2.6%</td>
<td>10% (*)</td>
<td>1%</td>
</tr>
<tr>
<td>$\Delta g_{HHH}/g_{HHH}$</td>
<td>50%</td>
<td>+11 -7 %</td>
<td>19%</td>
<td>5%</td>
</tr>
</tbody>
</table>

- Combined CLIC Higgs results
  - 380 GeV; 1.5 TeV, 3.0 TeV

Full CLIC program, ~27 yrs of running in total
- Precision of $\mathcal{O}(1\%)$ for most couplings
- Accuracy on Higgs width: ±1.6%

(*) indirect
High-mass searches: peak vs. mass tails

Example: Z' at 3 TeV

- Seeing the “peak”. Mass reach:
  - mass < √s for lepton colliders
  - mass ≲ 0.3–0.5 √s at hadron for couplings ~ weak couplings

- Deviations in high-mass tails:
  - Very well suited for lepton colliders; sensitive to [mass/couplings] ≫ √s

accelerator only goes to $\sqrt{s} = 2.2$ TeV
Direct BSM sensitivity – Example SUSY

- Unique opportunity to directly probe new particles with masses up to 1.5 TeV

- Direct observation of particles coupling to $\gamma^*/Z/W$
  - precision measurement, $O(1\%)$, of new particle masses and couplings

- Wider capability than only SUSY: reconstructed particles can be interpreted as “states of given mass, spin and quantum numbers”

- Very rare processes accessible due to low backgrounds
  - CLIC especially suited for electroweak states

- Polarised electron beam and threshold scans may be useful to constrain the underlying theory
BSM example: $Z'$ sensitivity

Minimal anomaly-free $Z'$ model

$$Q_f = g_Y'(Y_f) + g'_{BL}(B-L)_f$$

Observables:
- Total $e^+e^- \rightarrow \mu^+\mu^-$ cross section
- Forward-backward asymmetry
- Left-right asymmetry
  (with $\pm80\%$ $e^-$ polarisation)

◆ If LHC discovers $Z'$ (e.g. for $M_{Z'} = 5$ TeV)
  - CLIC precision measurement of effective couplings
◆ Otherwise:
  - CLIC discovery reach up to tens of TeV
    (depending on the couplings)

31 July - 1 August, 2019
CLIC Global Sensitivity to BSM Effects

Standard Model

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{c_i}{\Lambda^2} \mathcal{O}_i \]

Scale of new decoupled physics

Dimension-6 operators

Universal EFT fit

Includes CLIC measurements of:
- Higgs
- Top
- WW
- e^+e^→ff

Strong benefits from high-energy running

Note: Here, projections are displayed as \( c_i/\Lambda^2 \) [as compared to \( \Lambda/\sqrt{c_i} \) on slides 12-14]

So, here small is good
Instrumentation

Detectors for $e^+e^-$ physics
We know today how to build a detector for $e^+e^-$ precision physics
- Experience with LEP detectors and 20-years R&D with ILC/CLIC detectors
- Compared to LHC, less challenging w.r.t. radiation damage, pile-up, etc.
- However, need ultimate systematic precision to match the formidable statistical precision
  - Remember, up to $6 \times 10^{12}$ Z decays
**Typical Modern $e^+e^-$ Detector**

**B-field: 2-5 Tesla**
- Limited to 2 Tesla at FCC-ee due to the 30 mrad crossing angle

**Calorimetry:**
- Jet energy ($1/3 \times$ LEP)
  \[
  \frac{\sigma_E}{E} \approx 3 - 4\%
  \]

**Momentum: ($1/10 \times$ LEP)**
- \[
  \sigma_{1/p} < 5 \times 10^{-5} \text{ GeV}^{-1}
  \]

**Impact parameter: ($1/3 \times$ SLD)**
- e.g. b/c-tagging
  \[
  \sigma_{r\phi} = 5 \oplus 10/(p \sin^3 \theta) \mu m
  \]

**Hermetic:** down to $\theta \approx 5$ mrad
- Not possible with 30 mrad crossing angle, however
Thinking out of the box

Muon Colliders
Why muon colliders?

- Muons are leptons (like electrons)
  - Collisions at the full energy, small physics background, \( (E,p) \) conservation
    - Muons can a priori do all what electrons can do

- Muons are heavy (like protons)
  - Negligible synchrotron radiation, no beamstrahlung
    - Small circular colliders, up to large \( \sqrt{s} \)
    - Excellent energy definition (up to a few \( 10^{-5} \))
  - Large direct coupling to the Higgs boson
    - Unique \( s \)-channel Higgs factory at \( \sqrt{s} = 125.093 \text{ GeV} \)

- Muons are naturally longitudinally polarized (100%)
  - Because arising from \( \pi^{\pm} \) decays to \( \mu^{\pm} \nu_{\mu} \)
    - Ultra-precise beam energy and beam energy spread measurement

- Muons eventually decay (in 2.2 \( \mu \text{s} \)) to \( \nu_{\mu} \bar{\nu}_{e} \)
  - Outstanding neutrino physics programme
    - Muon colliders could be the natural successors of neutrino factories?
Muon colliders challenges

- Muons decay: Produce, Collect, Cool, Accelerate and Collide them fast!

- Intense proton driver to get the adequate number of muons
  - At least 4 MW for the desired muon luminosities
- Robust target to not evaporate at the first proton bunch
  - Re-circulating liquid metal
- Efficient muon collector from pion decays
  - Magnetic fields of 20T
- Unique 6D muon cooling
  - To reduce beam sizes and beam energy spread
- Fast acceleration and injection into circular ring(s)

All these aspects are at the level of intense R&D. Will require decades to demonstrate feasibility.
Muon collider challenges since 2014?

- Clever alternative muon source

- Intense $e^+$ beam with $E \approx 45$ GeV
  - 100 kW for the desired muon intensity
- Non-destructive target for $e^+e^- \rightarrow \mu^+\mu^-$
  - Keep the $e^+$ beam in a ring
    - Possible synergy with FCC-ee
    - Energy Recovery Linac is also a possibility
- Production at $\mu^+\mu^-$ threshold ($\sqrt{s} \approx 2 m_\mu$)
  - Quasi-monocromatic muons, much less need for cooling
    - Except for a Higgs factory
  - Not obvious it is possible to cool at 23 GeV anyway??
- Fast acceleration and injection into circular ring(s) remain as in the proton-driver option

If feasible, this design would probably be faster, cheaper, and easier than the proton-driver option.
Muon collider optimal circumference(s)

- **Muon decay:** Minimize the ring circumference
  - To allow the produced muons to collide as many times as possible before they decay
    - Optimal ring size is proportional to $E_\mu$. With 14 T state-of-the-art dipoles:

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>91 GeV</th>
<th>125 GeV</th>
<th>161 GeV</th>
<th>350 GeV</th>
<th>6 TeV</th>
<th>24 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t = \gamma \tau_m$</td>
<td>0.94 ms</td>
<td>1.30 ms</td>
<td>1.67 ms</td>
<td>3.64 ms</td>
<td>62.3 ms</td>
<td>249 ms</td>
</tr>
<tr>
<td>$L = \gamma \beta c \tau_m$</td>
<td>283 km</td>
<td>389 km</td>
<td>501 km</td>
<td>1090 km</td>
<td>18700 km</td>
<td>74000 km</td>
</tr>
<tr>
<td>Ring</td>
<td>100 m</td>
<td>140 m</td>
<td>180 m</td>
<td>390 m</td>
<td>6.6 km</td>
<td>27 km</td>
</tr>
<tr>
<td>$N_{\text{turns}}$</td>
<td>~2800 turns</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- One ring per centre-of-mass energy
  - Two very small rings for precision studies
    - One for Z and H factories (140 m circumference)
    - One for W and top pair thresholds (390 m circumference)
  - Larger ring(s) for the energy frontier
    - $\sqrt{s} = 6$ TeV can fit, for example, in the Tevatron tunnel (6.6 km circumference)
    - $\sqrt{s} = 24$ TeV can fit in the LHC tunnel
  - Plus a number of rings for first stages of fast acceleration
Muons collider as a Higgs factory (1)

**Challenges for the Higgs factory**

- $\Gamma_H$ is small (4.2 MeV in the SM)
  - Similar or smaller beam energy spread is required ($3 \times 10^{-5}$)
    - Fast longitudinal cooling to reduce energy spread
  - Beam energy reproducibility must be at the same level or better

- $\sigma(\mu^+\mu^-\rightarrow H)$ is about 20 pb
  - Luminosity must be at the level of $1.6 \times 10^{32}$ cm$^{-2}$s$^{-1}$ for the same number of Higgs bosons as ILC ...
  - and at the level of $1.6 \times 10^{33}$ cm$^{-2}$s$^{-1}$ for the same number of Higgs bosons as FCC-ee
    - Fast transverse cooling to reduce beam spot dimensions
    - And the Higgs bosons produced are not tagged with a Z anyway ...

- **Problem**
  - Longitudinal and transverse cooling are antagonistic
    - Luminosity is limited (as of today’s knowledge) to a few $10^{31}$ cm$^{-2}$s$^{-1}$
Physics performance of a Higgs factory

- Scan of Higgs resonance in the inclusive $b\bar{b}$ and $WW$ final states
  - Ten years of data taking at $10^{31}$ cm$^{-2}$s$^{-1}$, just count events

- Measure $\Gamma_H$ to 5% in 10 years (cf. 4% at ILC, <1% at FCC-ee)
  - Only way to see a structure in the resonance (several Higgs bosons?)

- Measure $\sigma_{\text{peak}} \sim BR_{\mu\mu}$ to 2-3% in 10 years
- Other expected measurement on the figures
Muon collider as a Higgs factory (3)

- Summary of precision measurements (after ~10 years of running)

<table>
<thead>
<tr>
<th>Error on</th>
<th>(\mu\mu) collider</th>
<th>ILC(_{250})</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_H) (MeV)</td>
<td>0.06</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>(\Gamma_H) (MeV)</td>
<td>0.17</td>
<td>0.11</td>
<td>0.06</td>
</tr>
<tr>
<td>(g_{Hbb})</td>
<td>2.3%</td>
<td>1.8%</td>
<td>0.61%</td>
</tr>
<tr>
<td>(g_{HWW})</td>
<td>2.2%</td>
<td>1.7%</td>
<td>0.43%</td>
</tr>
<tr>
<td>(g_{H\tau\tau})</td>
<td>5%</td>
<td>1.9%</td>
<td>0.80%</td>
</tr>
<tr>
<td>(g_{HYY})</td>
<td>10%</td>
<td>6.4%</td>
<td>3.8%</td>
</tr>
<tr>
<td>(g_{H\mu\mu})</td>
<td>2.1%</td>
<td>13%</td>
<td>8.6%</td>
</tr>
<tr>
<td>(g_{HZZ})</td>
<td>-</td>
<td>0.35%</td>
<td>0.17%</td>
</tr>
<tr>
<td>(g_{Hcc})</td>
<td>-</td>
<td>2.3%</td>
<td>1.2%</td>
</tr>
<tr>
<td>(g_{Hgg})</td>
<td>-</td>
<td>2.2%</td>
<td>1.0%</td>
</tr>
<tr>
<td>(BR_{\text{invis}})</td>
<td>-</td>
<td>&lt;0.5%</td>
<td>&lt;0.1%</td>
</tr>
</tbody>
</table>

- Note: \(BR(H\rightarrow\mu\mu)\) can be also measured with % precision at FCC-hh (Will be already 5% after HL-LHC)

- Not obvious what is the practical use of such high precision on \(m_H\)

- The Higgs width is best measured at ee colliders

- These Higgs couplings are best measured at ee colliders

- The Higgs coupling to muons is the added value of a \(\mu\mu\) collider

- These Higgs couplings are only measured at ee colliders *)
Muon colliders at the energy frontier

- Muon colliders might be a solution for high energy in the (far?) future
  - Many challenges to solve with sustained R&D and innovative thinking, as to
    - Increase luminosity for precision studies
    - Solve the radiation hazard at high energy (decay neutrino interactions in Earth)
  - Target luminosity competitive with CLIC above 2-3 TeV
    - With the possibility of several IPs

![Circular Muons](image1)

![Linear Muons](image2)

![Circular Linear Luminosity](image3)

![Linear Luminosity](image4)
Muon colliders: Summary

- A muon collider may be the best way to get lepton collisions at $\sqrt{s} \geq 3$ TeV
  - Much R&D remain in, e.g., muon cooling/acceleration
- A muon collider at $\sqrt{s} = 125$ GeV is a very pretty Higgs factory ($\mu^+\mu^- \rightarrow H$)
  - But not necessarily the one we need
    - If $H(125)$ is a single particle, the process $e^+e^- \rightarrow HZ$ @ 240 GeV is better suited
      - In particular, the Higgs width can be measured very well in $e^+e^-$ collisions
    - A muon collider can also do that, but much higher luminosity would be necessary
      - At least two orders of magnitude – limited by the proton/positron source
- Several quasi-degenerate Higgs bosons is a strong case for $\mu\mu$ Higgs factory
  - If $\Delta m$ is between 4 MeV ($\Gamma_H$) and ~100 MeV (LHC resolution)
    - Such a situation may occur with two Higgs doublets, and quasi-degenerate H & A
      - Isolate the two peaks and perform nice CP studies!
- A muon collider at $\sqrt{s} > 2 m_H$ provides the only way to \textit{cleanly} probe HHH coupling
  
  ![Diagram](image)

- A muon collider is the natural second step of neutrino factories
- Conclusion: don’t write them off completely, but don’t oversell them!
Rounding off

Summary and Conclusions
Summary & Conclusions (1)

- Since LEP, there has been a dramatic development in e⁺e⁻ accelerator technology
  - Linear colliders: Energy reach up to √s = 3 TeV
  - Circular colliders: Increase of instantaneous luminosity by 4-5 orders of magnitude
    - For √s < 400 GeV, circular colliders provide very high luminosities
      - Repeat of LEP1 programme every ~5 min!
- With the discovery of the light Higgs boson and the non-discovery (so far) of new heavier states, e⁺e⁻ communities are now zooming in on the √s < 400 GeV region
  - ILC: Higgs factory at √s = 250 GeV as first stage (12 years)
    - Possibly later upgraded to √s = 500 GeV (and √s = 1 TeV ?)
  - CLIC: “Affordable” Higgs/top factory at √s = 380 GeV as first stage
    - Later upgraded to √s = 1.5 TeV and possibly √s = 3 TeV
- An e⁺e⁻ Higgs factory with $O(10^6)$ Higgs decays provides sub-% level measurement of (most) Higgs couplings
  - Strong New Physics reach!
- Electroweak precision measurements provide a strong test of SM
  - A e⁺e⁻ collider with 90 < √s < 400 GeV could improve precision of all electroweak parameters by 1 – 2 orders of magnitude
    - Ultimate precision for Z, W, Higgs, and top (and flavour: b and τ)
  - Strong New Physics reach!
Summary & Conclusions (2)

- CLIC programme at $\sqrt{s} = 1.5$ and 3 TeV, has access to complementary measurements
  - Higgs self-coupling to sub-10% level
  - Precise top quark studies
  - Direct (indirect) access to new physics if $m < 1.5$ TeV ($m > 1.5$ TeV)

- In the long-term future, muon colliders may be the way to go for energy frontier lepton colliders
Personal views

- Muon colliders provide a potential interesting option for long-term future high energy lepton colliders
  - Without major technological breakthroughs they unfortunately do not provide sufficient luminosity to be interesting as a Higgs factory
- Very clear physics case for an $e^+e^-$ collider with $90 < \sqrt{s} < 370-500$ GeV
  - Precision Higgs and electroweak physics
    - Strong complementary programmes
- Slightly harder to make physics case for $e^+e^-$ colliders with $\sqrt{s}>370–500$ GeV
  - At least without clear evidence for accessible new particles
    - Produced copiously in $e^+e^-$ or $\gamma\gamma$ collisions
- Exploration of energy frontier seems best done with a hadron collider
  - e.g., the 100 TeV FCC-hh proton-proton collider
The FCC integrated programme

Base the next generation of colliders on a proven model

- **27 km tunnel**

![LEP (e^+e^-) 1989 - 2000](image1)

![LHC (pp) 2009 – 2035?](image2)

- **The next step: 100 km tunnel**

![FCC-ee 100km](image3)

![FCC-hh 100km](image4)
End of the second lecture

Questions...
"No doubt that future high energy colliders are extremely challenging projects. However, the correct approach, as scientists, is not to abandon our exploratory spirit, nor give in to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable."

Fabiola Gianotti, DG CERN
Extra Material
e^+e^- colliders – a field in very rapid development

luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$]

- **FCC-ee 4 IPs**
  - $Z$ 91 GeV
  - WW 160 GeV

- **FCC-ee 2 IPs**

- **CEPC 2 IPs**
  - $Z$H 240 GeV
  - ZHH 500 GeV
  - $ttbar$ 350-365 GeV

- **ILC Baseline**
- **ILC Upgrade 2019**
- **CEPC CDR (2 IPs)**
- **CEPC Upgrade 2019 (2IPs)**
- **CLIC Baseline 2016**
- **CLIC Upgrade 2019**
- **FCC-ee monochr. H (2 IPs)**
- **FCC-ee (4 IPs)**
- **FCC-ee ERL (1 IP)**

- **Physics at Lepton Colliders**

31 July - 1 August, 2019
**e^{+}e^{-} colliders – a field in very rapid development**

**luminosity \([10^{34} \text{ cm}^{-2}\text{s}^{-1}]\)**

- **FCC-ee 4 IPs**
  - Z 91 GeV
  - WW 160 GeV
- **FCC-ee 2 IPs**
- **CEPC 2 IPs**
  - ZH 240 GeV
  - ZHH 500 GeV
  - ttbar 350-365 GeV
- **ILC UG**
  - CLIC Upgrade 2019
- **CLIC UG**
  - CLIC Upgrade 2019
- **FCC-ee monochr. H (2 IPs)**

**10^7 ZH events in 3 years**

**10^4 ZHH events in 3 years**

**c.m. energy [GeV]**

Mogens Dam / NBI Copenhagen

Physics at Lepton Colliders

31 July - 1 August, 2019
The FCC Home

- Optimized length: 97.5 km
  - Accessibility, rock type, shaft depth, etc.
  - Tried different options from 80 to 100 km

- Tunneling
  - Molasse 90% (easy to dig)
  - Limestone 5%, Moraines 5% (tougher)

- Shallow implementation
  - 30m below Leman lakebed
  - Only one very deep shaft (F, 476m)
    - Alternatives studied (e.g. inclined access)
double ring $e^+e^-$ collider ~100 km
follows footprint of FCC-hh, except around IPs
asymmetric IR layout & optics to limit synchrotron radiation towards the detector
presently 2 IPs (alternative layouts with 3 or 4 IPs under study), large horizontal crossing angle 30 mrad, crab-waist optics
synchrotron radiation power 50 MW/beam at all beam energies; tapering of arc magnet strengths to match local energy
top-up injection scheme; requires booster synchrotron in collider tunnel
## FCC-ee Machine Parameters

<table>
<thead>
<tr>
<th>FCC-ee parameters</th>
<th>Z</th>
<th>W⁺W⁻</th>
<th>ZH</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam energy</strong></td>
<td>GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity / IP</td>
<td>10^{34} cm⁻² s⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam current</td>
<td>mA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunches per beam</td>
<td>#</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average bunch spacing</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch population</td>
<td>10^{11}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal emittance $\varepsilon_x$</td>
<td>nm</td>
<td>0.27</td>
<td>0.84</td>
<td>0.63</td>
</tr>
<tr>
<td>Vertical emittance $\varepsilon_y$</td>
<td>pm</td>
<td>1.0</td>
<td>1.7</td>
<td>1.3</td>
</tr>
<tr>
<td>$\beta_x^* / \beta_y^*$</td>
<td>m / mm</td>
<td>0.15 / 0.8</td>
<td>0.2 / 1.0</td>
<td>0.3 / 1.0</td>
</tr>
<tr>
<td>Beam size at IP: $\sigma_x^* / \sigma_y^*$</td>
<td>µm / nm</td>
<td>6.4 / 28</td>
<td>13 / 41</td>
<td>13.7 / 36</td>
</tr>
<tr>
<td>Energy spread: SR / total (w BS)</td>
<td>%</td>
<td>0.038 / 0.132</td>
<td>0.066 / 0.131</td>
<td>0.099 / 0.165</td>
</tr>
<tr>
<td>Bunch length: SR / total</td>
<td>mm</td>
<td>3.5 / 12.1</td>
<td>3 / 6.0</td>
<td>3.15 / 5.3</td>
</tr>
<tr>
<td>Energy loss per turn</td>
<td>GeV</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
</tr>
<tr>
<td>RF Voltage / station</td>
<td>GV</td>
<td>0.1</td>
<td>0.75</td>
<td>2.0</td>
</tr>
<tr>
<td>Longitudinal damping time</td>
<td>turns</td>
<td>1273</td>
<td>236</td>
<td>70.3</td>
</tr>
<tr>
<td>Acceptance RF / energy (DA)</td>
<td>%</td>
<td>1.9 / ±1.3</td>
<td>2.3 / ±1.3</td>
<td>2.3 / ±1.7</td>
</tr>
<tr>
<td>Rad. Bhabha/ actual Beamstr. Lifetime</td>
<td>min</td>
<td>68 / &gt; 200</td>
<td>59 / &gt;200</td>
<td>38 / 18</td>
</tr>
<tr>
<td>Beam-beam parameter $\xi_x / \xi_y$</td>
<td></td>
<td>0.004 / 0.133</td>
<td>0.01 / 0.141</td>
<td>0.016 / 0.118</td>
</tr>
<tr>
<td>Interaction region length</td>
<td>mm</td>
<td>0.42</td>
<td>0.85</td>
<td>0.9</td>
</tr>
</tbody>
</table>
FCC-ee Power consumption

- The RF system needs to compensate for 100 MW SR losses
  - Corresponds to 200 MW electric power with 50% RF power sources (klystrons)
    - Klystron efficiency was ~55% at LEP2
  - Recent (2015) breakthroughs in klystron design promise 90% efficiency
    - Assume 85% will be achieved and take 10 – 20% margins

- For comparison
  - CLIC: 250 MW (at 380 GeV) to 580 MW (at 3 TeV)
figure of merit for lepton colliders

FCC-ee: most efficient from $Z$ to $t\bar{t}$
The predictions of $m_{\text{top}}$, $m_W$, $m_H$, $\sin^2\theta_W$ have theoretical uncertainties which may cancel the sensitivity to new physics.

For $m_W$ and $\sin^2\theta_W$ today, these uncertainties are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_W$</td>
<td>80.3584</td>
<td>$\pm 0.0055 m_{\text{top}} \pm 0.0025 m_Z \pm 0.0018 \alpha_{\text{QED}}$</td>
</tr>
<tr>
<td>$\sin^2\theta_W$</td>
<td>0.231488</td>
<td>$\pm 0.000029 m_{\text{top}} \pm 0.000015 m_Z \pm 0.000035 \alpha_{\text{QED}}$</td>
</tr>
</tbody>
</table>

- Parametric uncertainties and missing higher orders in theoretical calculations:
  - Are of the same order
  - Smaller than experimental uncertainties
Precision electroweak physics at FCC-ee (13)

- Most of the parametric uncertainties will reduce at the FCC-ee
  - New generation of theoretical calculations is necessary to gain a factor 10 in precision
    - To match the precision of the direct FCC-ee measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_W$</td>
<td>80.3584</td>
<td>±0.0001</td>
</tr>
<tr>
<td></td>
<td>80.358</td>
<td>±0.005</td>
</tr>
<tr>
<td>$m_{top}$</td>
<td>±0.0001</td>
<td></td>
</tr>
<tr>
<td>$m_Z$</td>
<td>±0.0003</td>
<td></td>
</tr>
<tr>
<td>$m_H$</td>
<td>±0.0040</td>
<td>theory</td>
</tr>
<tr>
<td>$\alpha_{QED}$</td>
<td>±0.0000</td>
<td></td>
</tr>
<tr>
<td>$\alpha_s$</td>
<td>±0.0000</td>
<td></td>
</tr>
<tr>
<td>$\sin^2 \theta_W^{\text{eff}}$</td>
<td>0.231488</td>
<td>±0.000001</td>
</tr>
<tr>
<td></td>
<td>0.23149</td>
<td>±0.00006</td>
</tr>
<tr>
<td></td>
<td>0.0000006</td>
<td></td>
</tr>
</tbody>
</table>

- Will require calculations up to three or four loops to gain an order of magnitude
  - Might need a new paradigm in the actual computing methods
    - Lots of interesting work for future generations of theorists (you?)
\[ e^- \rightarrow e^+ \quad \mu^- \rightarrow \mu^- \] forward

\[ e^- \rightarrow e^- \quad \mu^- \rightarrow \mu^- \] backward
**Higgs Self-coupling**

- Higgs pair production requires high energy

<table>
<thead>
<tr>
<th></th>
<th>1.4 TeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(\text{HH}e_{\mu}e_{\mu})$</td>
<td>&gt;3σ EVIDENCE = 28%</td>
<td>&gt;5σ OBSERVATION = 7.3%</td>
</tr>
<tr>
<td>$\sigma(\text{ZHH})$</td>
<td>&gt;5σ OBSERVATION</td>
<td></td>
</tr>
<tr>
<td>$g_{\text{HHH}}/g_{\text{SM}}^{\text{SM}}$</td>
<td>1.4 TeV: −34%, +36% rate-only analysis</td>
<td>1.4 + 3 TeV: −7%, +11% differential analysis</td>
</tr>
</tbody>
</table>

Among $e^+e^-$ colliders, unrivalled sensitivity to Higgs self-coupling

$$\Delta g_{\text{HHH}}/g_{\text{HHH}} = +11\% - 7\%$$