Physics at Future Colliders

- **Lecture 1** (Wednesday 2 August, 10:25)
  - An historical perspective (1964-2017): The need for precision and energy
  - A strategy for the future: Towards the precision and energy frontier
  - The short-term perspectives (2020-2035): The HL-LHC

- **Lecture 2** (Thursday 3 August, 10:25)
  - The quest for precision (2030-2050): Linear or circular?

- **Lecture 3** (Thursday 3 August, 11:35)
  - The energy frontier (2045-2080): Leptons or hadrons?
  - Thinking out of the box: Muon collider
  - Towards the next European Strategy update (2019-2020)
Lecture 2

Mid-term perspectives (2030-2050):
The quest for precision: Linear or Circular

FCC (100 km)
First step: FCC-ee (88-400 GeV)
[Use the tunnel ultimately aimed at FCC-hh]
Historically, $e^+e^-$ colliders have been used for precision measurements.

- The accuracy of $e^+e^-$ colliders led to predictions at higher scales ($m_{top}$, $m_H$, limits on NP).
- And to [unexpected] discoveries (e.g., $c$ quark, gluon, tau lepton, neutrino tau ...)

Circular? (FCC-ee, CEPC)
Linear? (ILC, CLIC)
The dilemma is not new

“An $e^+e^-$ storage ring in the range of a few hundred GeV in the centre-of-mass can be built with present technologies [...] would seem to be [...] the most useful project on the horizon”

B. Richter (1976)

Why are $e^+e^-$ colliders the tool of choice for precision anyway?

- Electrons are not protons, i.e., do not interact strongly: no pile-up collisions
  - Corollary #1: Final state is clean and cosy, triggering is easy (100% efficient)

Corollary #2: No huge QCD cross section: All events are signal.
Why are $e^+e^-$ colliders the tool of choice for precision anyway?

- Corollary #1: Final state is clean and cosy, triggering is easy (100% efficient)

- Corollary #2: No huge QCD cross section: All events are signal.
Why are $e^+e^-$ colliders the tool of choice for precision anyway? (cont’d)

- Electrons are leptons, i.e., elementary particles: no underlying event
  - Corollary #3: Final state has known energy and momentum: $(\sqrt{s}, 0, 0, 0)$

- Example: an $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$ candidate
  - Four jets in the event and nothing else
  - Total energy and momentum are conserved
    - $E_1 + E_2 + E_3 + E_4 = \sqrt{s}$
    - $p_1^{x,y,z} + p_2^{x,y,z} + p_3^{x,y,z} + p_4^{x,y,z} = 0$
  - Jet directions ($\beta_i = p_i/E_i$) are very well measured

\[
\begin{bmatrix}
1 & 1 & 1 & 1 \\
\beta_1^x & \beta_2^x & \beta_3^x & \beta_4^x \\
\beta_1^y & \beta_2^y & \beta_3^y & \beta_4^y \\
\beta_1^z & \beta_2^z & \beta_3^z & \beta_4^z \\
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_3 \\
E_4 \\
\end{bmatrix}
= \begin{bmatrix}
\sqrt{s} \\
0 \\
0 \\
0 \\
\end{bmatrix}
\]

- Jet energies (and di-jet masses, $m_W$) determined analytically by inverting the matrix
  - No systematic uncertainty related to jet energy calibration
  - A lot of $Z$ are available anyway to calibrate and align everything
Why are $e^+e^-$ colliders the tool of choice for precision anyway? (cont’d)

- Electroweak observables can be calculated/predicted with precision
- And are sensitive to heavier particles through quantum corrections
  - At the $Z$ pole

- Specific correction for $Z$ decay to $b\bar{b}$

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})}$$

- $W$ mass

$m_{top}$ dependence
Weak $m_H$ dependence

No $m_H$ dependence

Different admixture of $m_{top}$ and $m_H$ dependence
Why are $e^+e^-$ colliders the tool of choice for precision anyway? (cont’d)

- Electroweak observables can be calculated/predicted with precision
  - And are sensitive to heavier particles through quantum corrections
    - Different observables – different dependence on $m_{\text{top}}$ and $m_{H}$
      - Disentangle to get prediction for $m_{\text{top}}$ and $m_{H}$
Current status of precision measurements

- With $m_{\text{top}}$, $m_W$ and $m_H$ known, the standard model has nowhere to go

Strong incentive to significantly improve the precision of all measurements

- Towards being sensitive to 100 TeV new physics through quantum corrections
e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.

The European Strategy update in 2013 does not say otherwise.

Precision with $e^+e^-$ colliders (8)
Linear or Circular? (1)

- For 20 years, there was only one such project on the market
  - A 500 GeV $e^+e^-$ linear collider, now called “ILC”, proposed in the early 1990’s

Why not a 500 GeV circular collider?
Linear or Circular? (2)

- Why not a 500 GeV circular collider?
  - Synchrotron radiation in circular machines
    - Energy lost per turn grows like \( \Delta E \propto \frac{1}{R} \left( \frac{E}{m} \right)^4 \), e.g., 3.5 GeV/turn at LEP2
      - Must compensate with R and accelerating cavities → Cost grows like \( E^4 \) too

- A 500+ GeV e⁺e⁻ collider can only be linear. Cost of a circular collider is prohibitive
  - “Up to a centre of mass energy of 350 GeV at least, a circular collider with superconducting accelerating cavities is the cheapest option”
   
   H. Schopper, 2014
Interest for circular collider projects grew up again after first LHC results

- The Higgs boson is light – LEP2 almost made it: only moderate vs increase needed

- Need to go up to the top-pair threshold (350+ GeV) anyway to study the top quark

- There seems to be no heavy new physics below 500 GeV
  - The interest of vs = 500 GeV (and even 1 TeV) is now very much debated

- Way out: study with unprecedented precision the Z, W, H bosons and the top quark
  - Highest possible luminosities at 91, 160, 240 and 350 GeV are needed
Linear or Circular? (4)

- The ILC is designed for $\sqrt{s} = 500$ GeV (works OK at $\sqrt{s} = 250$ GeV)
  - It is supported by 20 years of R&D and innovation
    - With a complete technical design report delivered in 2013
      - In principle, ready for construction as soon as decision is taken
  - This machine has many technological challenges
    - A 24 km-long, high-gradient (31 MV/m), RF system
    - A very low $\beta^*$ optics delivering small beam spot sizes at high intensity
      - Not yet demonstrated to be achievable
    - A positron source with no precedent
      - Its performance cannot be verified before the construction is complete
    - A green-field project
  - It can deliver data to only one detector at a time
  - It is in principle upgradeable to $\sqrt{s} = 1$ TeV
    - And possibly more: CLIC or Plasma acceleration in the same tunnel (?)
  - But there is no design to run at the Z pole
Linear or Circular? (5)

- The FCC-ee is designed to be a Z, W, H, and top factory ($\sqrt{s} = 88-370$ GeV)
  - It is a project in its infancy: less than four years old
    - Lots of progress has been already made
      - Technology ready... on paper
  - This machine has at least as many technological challenges
    - A high-power (200 MW), high-gradient (10 MV/m), 2 km-long, RF system
    - Loads of synchrotron radiation (100 MW) to deal with
    - A booster (for top up injection), and probably a double ring for $e^+$ and $e^-$
    - An optics with very low $\beta^*$, and large momentum acceptance
    - Transverse polarization for beam energy measurement
    - Up to four experiments to serve
    - ... and much more
  - It is supported by 50 years of experience and progress with $e^+e^-$ circular machines
    - Most of the above challenges will be addressed at SuperKEKB
      - FCC-ee will have to build on this experience
  - It is the first step towards a 100 TeV proton-proton collider
Linear or Circular ? (6)

- Performance target for $e^+e^-$ colliders

![Graph showing luminosity vs. $\sqrt{s}$]

- Complementarity
  - Ultimate precision measurements with circular colliders (FCC-ee)
  - Ultimate $e^+e^-$ energies with linear colliders (CLIC)

LEP@Z-pole:
$L = 0.01 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Linear or Circular? (7)

- Performance target for $e^+e^-$ colliders
  - Number of events per year for the FCC-ee

<table>
<thead>
<tr>
<th>Vs (GeV)</th>
<th>90 (Z)</th>
<th>160 (WW)</th>
<th>240 (HZ)</th>
<th>350 (tt)</th>
<th>350+ (WW$\rightarrow$H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi (ab$^{-1}$/yr)</td>
<td>30</td>
<td>4</td>
<td>1</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Events/year</td>
<td>$1.5\times10^{12}$</td>
<td>$1.5\times10^7$</td>
<td>$2.0\times10^5$</td>
<td>$2.0\times10^5$</td>
<td>$2.0\times10^4$</td>
</tr>
<tr>
<td># years</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Events@FCCee</td>
<td>$10^{13}$</td>
<td>$3\times10^7$</td>
<td>$10^6$</td>
<td>$10^6$</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>

- Total running time of $\sim 18$ years ($\sim 10$ years with recent more optimistic lumi numbers)

- Scenario for the ILC precision physics programme (first 10-15 years)
  - with $\pm 80\%$ / $\pm 30\%$ polarization for $e^-/e^+$ beams

| # years | 3 ? (*) | 3 ? (*) | 3 | 1 | 4 |
| Tot lumi (ab$^{-1}$) | 0.1 | 0.5 | 0.5 | 0.2 | 0.5 |
| Events@ILC | $3\times10^9$ (*) | $2\times10^6$ (*) | $1.4\times10^5$ | $10^5$ | $3.5\times10^4$ |

(*) No design available at the Z pole and the WW threshold: non-trivial to achieve with a linear collider
Precision Higgs physics at FCC-ee and ILC (1)

- Dominant production processes for $\sqrt{s} \leq 500$ GeV

1. Effect of beam polarization (exercise)
   - Higgs-strahlung cross section multiplied by $1 - P_- P_+ - A_e \times (P_ - P_+)$
   - Boson fusion cross section multiplied by $(1 - P_-) \times (1 + P_+)$
The plan is to run at $\sqrt{s} = 240-250$ GeV and 350-500 GeV in order to

- Determine all Higgs couplings in a model-independent way
- Infer the Higgs total decay width
- Evaluate (or set limits on) the Higgs invisible or exotic decays

Through the measurements of

$$\sigma(e^+e^- \rightarrow H + X) \times BR(H \rightarrow YY)$$

with $Y = b, c, g, W, Z, \gamma, \tau, \mu$, invisible

- $m_H = 125$ GeV is a very good place to be for precision measurements!
- All decay channels open and measurable – can test new physics from many angles
Physics backgrounds are “small”
- For example, at $\sqrt{s} = 240$ GeV
  - $e^+e^- \rightarrow q\bar{q}, l^+l^-$: 60 pb
  - $\gamma\gamma \rightarrow q\bar{q}, l^+l^-$: 30 pb
  - $e^+e^- \rightarrow W^+W^-$: 16 pb
  - $e^+e^- \rightarrow Z\gamma$: 3.8 pb
  - $e^+e^- \rightarrow Ze$: 1.4 pb
  - $e^+e^- \rightarrow ZZ$: 1.3 pb
  - $e^+e^- \rightarrow Z\nu\bar{\nu}$: 32 fb

- "Blue" cross sections decrease like $1/s$
- "Green" cross sections increase slowly with $s$

To be compared to
- Only one to two orders of magnitude smaller
  - vs. 11 orders of magnitude in pp collisions
    - Trigger is 100% efficient (no need for trigger with ILC – all crossings are recorded)
    - All Higgs events are useful and exploitable
    - Signal purity is large
Example of a Higgs boson event
- Tagged with a Z boson
- Very clean signature

$e^+e^- \rightarrow HZ$
Example: Model-independent measurement of $\sigma_{HZ}$ and $\kappa_z$

- The Higgs boson in $HZ$ events is tagged by the presence of the $Z \rightarrow e^+e^-, \mu^+\mu^-$
  
- Select events with a lepton pair $(e^+e^-, \mu^+\mu^-)$ with mass compatible with $m_Z$
  
- No requirement on the Higgs decays: measure $\sigma_{HZ} \times BR(Z \rightarrow e^+e^-, \mu^+\mu^-)$
  
- Apply total energy-momentum conservation to determine the “recoil mass”

\[ m^2_{H_{\text{rec}}} = s + m^2_Z - 2s (p_+ + p_-) \]

Exercise !

- Plot the recoil mass distribution – resolution proportional to momentum resolution

- Provides an absolute measurement of $\kappa_Z$ and set required detector performance
Repeat the search in all possible final states

- For all exclusive decays of the Higgs boson: measure \( \sigma_{HZ} \times BR(H \rightarrow YY) \)
  - Including invisible decays
    - event containing only the lepton pair with correct \( (m_{\text{miss}}, m_{\text{recoil}}) \), else empty
  - For all decays of the Z (hadrons, taus, neutrinos) to increase statistics
- For the WW fusion mode (\( H\nu\bar{\nu} \) final state): measure \( \sigma_{WW\rightarrow H} \times BR(H \rightarrow YY) \)

**ZH \rightarrow l^+l^- + nothing, 0.5 \text{ ab}^{-1}**

\[ BR(H \rightarrow \text{invis}) = 100\% \]

- CMS simulation

**ZH \rightarrow q\bar{q} b\bar{b}, 0.25 \text{ ab}^{-1}**

- ILC simulation

\( m_H = 125 \text{ GeV} \)
\( \sqrt{s} = 240 \text{ GeV} \)
Indirect determination of the total Higgs decay width

- From a counting of $HZ$ events with $H \rightarrow ZZ$ at $\sqrt{s} = 240$ GeV
  - Measure $\sigma_{HZ} \times BR(H \rightarrow ZZ)$

\[ \sigma_{HZ} \text{ is proportional to } k_Z^2 \]
\[ BR(H \rightarrow ZZ) = \Gamma(H \rightarrow ZZ) / \Gamma_H \text{ is proportional to } k_Z^2 / \Gamma_H \]
\[ \sigma_{HZ} \times BR(H \rightarrow ZZ) \text{ is proportional to } k_Z^4 / \Gamma_H \]

Infer the total width $\Gamma_H$
**Indirect determination of the total Higgs decay width (cont’d)**

- From a counting \( WW \rightarrow H \rightarrow b\bar{b} \) events at 350-500 GeV in the \( b\bar{v}v \bar{v} \) final state:

  - Measure \( \sigma(WW \rightarrow H \rightarrow bb) \)
  - Take the branching ratios into \( WW \) and \( bb \) from \( \sigma_{HZ} \) and \( \sigma_{HZ} \times \text{BR}(H \rightarrow WW, bb) \)
  - Infer the total width

\[
\Gamma_H \propto \sigma_{WW \rightarrow H} / \text{BR}(H \rightarrow WW) = \sigma_{WW \rightarrow H \rightarrow bb} / \text{BR}(H \rightarrow WW) \times \text{BR}(H \rightarrow bb)
\]
**Precision Higgs physics at FCC-ee and ILC (9)**

- **Comparison with LHC**

<table>
<thead>
<tr>
<th>Coupling</th>
<th>HL-LHC</th>
<th>ILC (+)</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_W$</td>
<td>2-5%</td>
<td>0.8%</td>
<td>0.19%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>2-4%</td>
<td>0.6%</td>
<td>0.15%</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>4-7%</td>
<td>1.5%</td>
<td>0.42%</td>
</tr>
<tr>
<td>$\kappa_c$</td>
<td>-</td>
<td>2.7%</td>
<td>0.71%</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>2-5%</td>
<td>1.9%</td>
<td>0.54%</td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>$\sim$10%</td>
<td>20%</td>
<td>6.2%</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>2-5%</td>
<td>7.8%</td>
<td>1.5%</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>3-5%</td>
<td>2.3%</td>
<td>0.8%</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>$\sim$12%</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>$\text{BR}_{\text{invis}}$</td>
<td>$\sim$10-15%?</td>
<td>&lt; 0.5%</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>$\sim$50%?</td>
<td>3.8%</td>
<td>0.9%</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>7-10%</td>
<td>18%</td>
<td>13% (*)</td>
</tr>
<tr>
<td>$\kappa_H$</td>
<td>30-50% ?</td>
<td>77%</td>
<td>80%(*)</td>
</tr>
</tbody>
</table>

**Model-independent results**

**Sensitive to new physics at tree level**

- Expected effects $< 5\% / \Lambda_{NP}^2$
- 1% precision needed for $\Lambda_{NP} \sim 1\text{TeV}$
- Sub-percent needed for $\Lambda_{NP} > 1\text{TeV}$

**Sensitive to new physics in loops**

**Sensitive to light dark matter particles ($\nu$, $\chi$, ...) and to other exotic decays**

**Need higher energy to improve on LHC**

(*) Factor 2 smaller errors if lumi upgrade and an additional 10-15 years of running
Higgs couplings are affected by new physics

- Example: Effect on $\kappa_Z$ and $\kappa_b$ for 4D-Higgs Composite Models

$\Delta g_{Hbb} / g_{Hbb}$

$\Delta g_{HZZ} / g_{HZZ}$

$4D$-CHM (*)

$f < 2$ TeV
Higgs couplings are affected by new physics

Example: Effect on $\kappa_Z$ and $\kappa_b$ for 4D-Higgs Composite Models

4D-CHM $f < 2 \text{ TeV}$
Precision electroweak physics at FCC-ee (1)

- Reminder: The FCC-ee goals in numbers (after commissioning)

<table>
<thead>
<tr>
<th>√s (GeV)</th>
<th>Running time</th>
<th>FCC-ee Statistics</th>
<th>ILC</th>
<th>LEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>91</td>
<td>5-6 years</td>
<td>$10^{12}$ ($10^{13}$) Z decays (Tera-Z)</td>
<td>$3 \times 10^9$ (*)</td>
<td>$2 \times 10^7$</td>
</tr>
<tr>
<td>161</td>
<td>2 years</td>
<td>$3 \times 10^7$ WW pairs (Oku-W)</td>
<td>$2 \times 10^6$ (*)</td>
<td>$4 \times 10^4$</td>
</tr>
<tr>
<td>350</td>
<td>5 years</td>
<td>$10^6$ top pairs (Mega-Top)</td>
<td>$10^5$</td>
<td>–</td>
</tr>
</tbody>
</table>

(*) Estimate: not in the core programme

- FCC-ee is the ultimate Z, W, Higgs and top factory
  - 10 to 3,000 times the ILC targeted statistics at the same energies
  - $10^5$ 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 difficult
  - Conservatively, use LEP experience for systematics. This is just the start

- 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?
Measurement of the beam energy at LEP

- Ultra-precise measurement unique to circular colliders (crucial for $m_Z$, $\Gamma_Z$)

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

\[ E \sim p = e B R = (e/2\pi) B L \]

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

\[ E = \frac{e}{2\pi} \oint_{\text{LEP}} B \, dl \]

To be measured

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

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

NB. Polarization can be kept in collision (was attempted only once at LEP).
**Precision electroweak physics at FCC-ee (3)**

- **Measurement of the beam energy at LEP (cont’d)**
  - The spin precesses around $B$ with a frequency proportional to $B$ (Larmor precession)
  - Hence, the number of revolutions $\nu_S$ for each LEP turn is proportional to $B_L$ (or $\int B dB$)

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

- Resonant depolarization:

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

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

**Z resonance: TeraZ**

![Graph showing Z resonance measurements](image)

**WW threshold scan: OkuW**

![Graph showing WW threshold scan](image)

**tt threshold scan: MegaTop**

![Graph showing tt threshold scan](image)

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

**Asymmetries**
- $\sin^2 2\theta_W$ 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 $R_{\ell}$, $R_b$**
- $\alpha_s(m_z)$ to 0.0002 (0.002)

**Threshold scan**
- $m_W$ to 0.5 MeV (15 MeV)
- Branching ratios $R_{\ell}$, $R_b$
- $\alpha_s(m_z)$ to 0.0002

**Radiative return $e^+e^- \rightarrow Z\gamma$**
- $N_{\gamma}$ to 0.0004 (0.008)

**Threshold scan**
- $m_{\text{top}}$ to 10 MeV (500 MeV)
- $\lambda_{\text{top}}$ to 10%
- EW couplings to 1%
Precision electroweak physics at FCC-ee (5)

- Measurements of $t_L t_L Z$ and $t_R t_R Z$ couplings, $g_L$ and $g_R$
  - Couplings most sensitive to, e.g., composite Higgs models

FCC-ee@370 GeV: Leptons and b-jets distributions
ILC@500 GeV: Total rate and $A_{FB}^{tt}$
Precision electroweak physics at FCC-ee (5)

- Measurements of $t_L t_L Z$ and $t_R t_R Z$ couplings, $g_L$ and $g_R$
  - Couplings most sensitive to composite Higgs models

4D-CHM

- 4D-CHM
- b-jets only
- Leptons only

FCC-ee@370 GeV: Leptons and b-jets distributions
ILC@500 GeV: Total rate and $A_{FB}^{tt}$

Other NP models (tested at the LHC)
Combination of all precision electroweak measurements

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

The Standard Model has nowhere to go

- Constraints on new physics?
Precision electroweak physics at FCC-ee (7)

- Higher-dimensional operators as a parametrization of new physics
  - Possible corrections to the Standard Model
  - Standard Model Effective Theories (SMEFT)

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

### Dimension six SMEFT (EWPD): Present vs. Future

- Limits on new physics scale, \( \Lambda \):
  - Today: \( \Lambda > 5\text{-}10 \text{ TeV} \)
  - After FCC-ee: \( \Lambda > 50\text{-}100 \text{ TeV} \)
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

\[
M_W = 80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta \alpha_{\text{had}}} \\
\pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{\text{theo}} \\
= 80.359 \pm 0.011_{\text{tot}}
\]

\[
\sin^2\theta_{\text{eff}} = 0.231496 \pm 0.000030_{m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta \alpha_{\text{had}}} \\
\pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm 0.000047_{\text{theo}} \\
= 0.23150 \pm 0.00010_{\text{tot}}
\]

- Parametric uncertainties and missing higher orders in theoretical calculations:
  - Are of the same order
  - Smaller than experimental uncertainties
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

\[
M_W = 80.3593 \pm 0.0005
\]

\[
\sin^2 \theta_{\text{eff}} = 0.231496 \pm 0.000006
\]

- 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
    - Lot of interesting work for future generations of theorists
Opportunities for discoveries at FCC-ee

- Searches for new physics through rare decays
  - $10^{13} Z$, $10^{12} b$, $c$ or $10^{11} \tau$: A fantastic potential that remains to be explored
  - E.g., search for right-handed neutrino in $Z$ decays

\[ Z \to N\nu_{i_f} \quad \text{with} \quad N \to W^* l \text{ or } Z^* \nu_j \]

- Number of events depend on mixing between $N$ and $\nu$, and on $m_N$

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For example, the diagram illustrates the search for right-handed neutrinos in $Z$ decays. The figure shows the region of parameter space where right-handed neutrinos can be searched for at FCC-ee, compared to previous searches. The SHiP experiment can improve the current limits on Heavy Neutral Leptons by several orders of magnitude, scanning a large part of the parameter space below the $B$ meson mass. Similarly, SHiP can greatly improve present constraints on dark photons. Right-handed neutrinos with larger mass can be searched for at a future $Z$ factory. The synergy between SHiP and a future $Z$ factory would allow the exploration of most of the $n$MSM parameter space for sterile neutrinos.

Acknowledgments

This work would not have been possible without the precious theory support by M. Shaposhnikov. We thank A. Blondel for useful discussions about the FCC-ee project. We are indebted to all our...
Precision with $e^+e^-$ colliders: Summary (1)

- The small mass of the Higgs boson allows two options to be contemplated
  - A 250 – 500 GeV linear collider: ILC (also CLIC at $\sqrt{s} = 380$ GeV)
  - A 88-370 GeV circular collider: FCC-ee (also CEPC at $\sqrt{s} = 240$ GeV)

- Precision measurements at the EW scale are sensitive to new physics
  - To potentially very high scales (up to ~100 TeV with FCC-ee)
    - Through a study of the $Z$, $W$, $H$, and top properties with unprecedented statistics
  - To potentially very small couplings (sterile neutrinos, dark matter, ...)

- Understanding this physics requires an $e^+e^-$ collider at the EW scale
  - In an ideal world, this understanding could even benefit from having two of them

- Significant synergies (detectors) and complementarities (physics)
  - Between circular (FCC-ee, CEPC) and linear collider projects (ILC, CLIC)
    - FCC-ee offers the highest luminosities and discovery potential ($Z$, $WW$, $ZH$)
      - These features will remain unchallenged if a linear collider is built
    - Linear colliders can reach energies beyond 500 GeV
      - This advantage will remain unique if the FC-ee is built
In practical terms

- If a linear collider is built, the FCC-ee need not run at the top energy
  - Thus saving some RF cavities and running time
    - While remaining a real discovery machine
- If FCC is built, a linear collider can concentrate on the highest energies
  - Where it is most effective and useful

In a real world: both are technologically/politically/financially challenging

- Both can potentially be ready for collisions in the 2030’s
  - Go through the slides again to form your personal opinion – at this level – of the scientific capabilities of each option

If a choice is to be made, high energy capabilities are essential to decide

- The likelihood of new physics below 1 TeV has reduced considerably with LHC Run1 (+ 2)
  - A new evaluation will have to be made after Run2 (soon!)
    - High-energy frontier capabilities discussed in 3rd lecture
Extra Slides
What if we are poor: LEP3

- If we do not have funding to construct a new tunnel, neither circular nor linear
  - After HL-LHC refurbish LEP/LHC tunnel with a state of the art modern e⁺e⁻ collider
    - Will be comfortably able to work as a Higgs factory (remember LEP was close)

- Will of course be able to cover Z and WW programmes
- However, will not be able to operate at t¯t threshold
  - Synchrotron energy loss of 35 GeV per turn, i.e. 20%
  - Missing out on top mass and couplings and some of the Higgs programme (g_{HHH}, g_{t})
- Fast estimate says that luminosity could be ⅛ of that of FCC-ee
  - However, we can operate with four detectors and regain a factor of ~2
- Cost effective way to carry through Z, WW, and Higgs parts of FCC-ee programme

Further studies needed