FCC-ee physics overview

FCC week 2018
Amsterdam, 9th April 2017

David d'Enterria
(on behalf of the FCC-ee study group)

CERN
Standard Model of particles & interactions

- Renormalizable QFT of electroweak $SU(2)_L \times U(1)_Y$ & strong $SU(3)_c$ gauge interactions

$O(20)$ parameters: Couplings, H mass&vev, H-f Yukawa, CKM mix., CP phases.

Experimentally confirmed to great precision for over ~50(!) years:

**Renormalizable QFT of electroweak & strong interactions**

\[ \mathcal{L} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{8} \text{tr}(W_{\mu\nu} W^{\mu\nu}) - \frac{1}{2} \text{tr}(G_{\mu\nu} G^{\mu\nu}) \]

\[ + (\bar{v}_L, \bar{e}_L) D^{\mu} \left( \begin{array}{c} \nu_L \\ e_L \end{array} \right) + (\bar{e}_R, \bar{\nu}_R) D^{\mu} e_R + (\bar{\nu}_R, \bar{\nu}_R) i D^{\mu} \nu_R + (\text{h.c.}) \]

\[ - \frac{\sqrt{2}}{v} \left[ (\bar{v}_L, \bar{e}_L) \phi M^e e_R + \bar{e}_R M^e \phi \left( \begin{array}{c} \nu_L \\ e_L \end{array} \right) \right] - \frac{\sqrt{2}}{v} \left[ (\bar{e}_L, \bar{\nu}_L) \phi^* M^\nu \nu_R + \bar{\nu}_R (\nu_L, \nu_L) \left( \begin{array}{c} -\nu_L \\ -\nu_L \end{array} \right) \right] \]

\[ + (\bar{u}_L, \bar{d}_L) D^{\mu} \left( \begin{array}{c} u_L \\ d_L \end{array} \right) + (\bar{u}_R, \bar{d}_R) D^{\mu} u_R + (\bar{d}_R, \bar{d}_R) i D^{\mu} d_R + (\text{h.c.}) \]

\[ - \frac{\sqrt{2}}{v} \left[ (\bar{u}_L, \bar{d}_L) \phi M^d d_R + \bar{d}_R \phi M^d \phi \left( \begin{array}{c} u_L \\ d_L \end{array} \right) \right] - \frac{\sqrt{2}}{v} \left[ (\bar{d}_L, \bar{u}_L) \phi^* M^{u} u_R + \bar{u}_R (\nu_L, \nu_L) \left( \begin{array}{c} -u_L \\ -u_L \end{array} \right) \right] \]

\[ + (D^{\mu}\phi) D^{\mu} \phi - m_{\phi}^2 \left( \bar{\phi}\phi - v^2 / 2 \right)^2 / 2v^2 \].

**Flavour sector:**

**QCD sector:**
Standard Model of particles & interactions

- Renormalizable QFT of electroweak $SU(2)_L \times U(1)_Y$ & strong $SU(3)_c$ gauge interactions

O(20) parameters: Couplings, H mass&vev, H-f Yukawa, CKM mix., CP phases. Experimentally confirmed to great precision for over ~50(!) years:

EWK sector:

$\mathcal{L} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{8} tr(W_{\mu\nu} W^{\mu\nu}) - \frac{1}{2} tr(G_{\mu\nu} G^{\mu\nu})$

$+ (\bar{\nu}_L, \bar{e}_L) \bar{\psi}^\mu i D_\mu \left( \nu_L, e_L \right) + (\bar{\nu}_R, \bar{\nu}_R) \bar{\psi}^\mu i D_\mu \nu_R + (\bar{\nu}_R, \bar{\nu}_R) \bar{\psi}^\mu i D_\mu \nu_R + (h.c.)$

$- \frac{\sqrt{2}}{v} \left[ (\bar{\nu}_L, \bar{\nu}_L) \phi M^e e_R + \bar{e}_R M^e \phi \left( \nu_L, e_L \right) \right] - \frac{\sqrt{2}}{v} \left[ (\bar{\nu}_R, \bar{\nu}_L) \phi M^\nu \nu_R + \bar{\nu}_R M^\nu \phi \left( \nu_L, e_L \right) \right]$

$+ (\bar{u}_L, \bar{d}_L) \bar{\psi}^\mu i D_\mu \left( u_L, d_L \right) + \bar{d}_R \bar{\psi}^\mu i D_\mu d_R + \bar{u}_R \bar{\psi}^\mu i D_\mu u_R + (h.c.)$

$- \frac{\sqrt{2}}{v} \left[ (\bar{u}_L, \bar{d}_L) \phi M^d d_R + \bar{d}_R M^u \phi \left( u_L, d_L \right) \right] - \frac{\sqrt{2}}{v} \left[ (\bar{d}_L, \bar{u}_L) \phi M^u u_R + \bar{u}_R M^u \phi \left( u_L, d_L \right) \right]$

$+ (D_{\mu\nu} D^{\mu\nu} \phi - m_h^2 \phi^2 / 2 v^2)$

Higgs sector:
Open questions in the SM (1)

\[ \mathcal{L} = -\frac{1}{4} B_{\mu \nu} B^{\mu \nu} - \frac{1}{8} \text{tr}(W_{\mu \nu} W^{\mu \nu}) - \frac{1}{2} \text{tr}(G_{\mu \nu} G^{\mu \nu}) \]

\[ + (\bar{\nu}_L, \bar{e}_L) \sigma^\mu i D_\mu \left( \begin{array}{c} \nu_L \\ e_L \end{array} \right) + \bar{\nu}_R \sigma^\mu i D_\mu e_R + \bar{\nu}_R \sigma^\mu i D_\mu \nu_R + (\text{h.c.}) \]

[Lepton dynamics]

\[ - \frac{\sqrt{2}}{v} \left[ (\bar{\nu}_L, \bar{e}_L) \phi M^e e_R + \bar{\nu}_R \phi^* M^e \phi \left( \begin{array}{c} \nu_L \\ e_L \end{array} \right) \right] - \frac{\sqrt{2}}{v} \left[ (-\bar{\nu}_L, \bar{\nu}_L) \phi^* M^\nu \nu_R + \bar{\nu}_R \phi^* M^\nu \phi^T \left( \begin{array}{c} -e_L \\ \nu_L \end{array} \right) \right] \]

[Lepton masses]

\[ + (\bar{u}_L, \bar{d}_L) \sigma^\mu i D_\mu \left( \begin{array}{c} u_L \\ d_L \end{array} \right) + \bar{u}_R \sigma^\mu i D_\mu u_R + \bar{d}_R \sigma^\mu i D_\mu d_R + (\text{h.c.}) \]

[Quark dynamics]

\[ - \frac{\sqrt{2}}{v} \left[ (\bar{u}_L, \bar{d}_L) \phi M^d d_R + \bar{d}_R \phi^* M^d \phi \left( \begin{array}{c} u_L \\ d_L \end{array} \right) \right] - \frac{\sqrt{2}}{v} \left[ (-\bar{d}_L, \bar{u}_L) \phi^* M^u u_R + \bar{u}_R \phi^* M^u \phi^T \left( \begin{array}{c} -d_L \\ u_L \end{array} \right) \right] \]

[Quark masses]

\[ + (D_\mu \phi) D^{\mu} \phi - m_h^2 [\phi^2 - v^2/2] \sqrt{2} v^2. \]

[Higgs dynamics & mass]

\[ \boxed{\textbf{Light-masses generation: } 1^{\text{st}}\text{-gen. fermion (and all } \nu \text{'s) masses Yukawas?}} \]
Open questions in the SM (2)

$$\mathcal{L} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{8} \text{tr}(W_{\mu\nu} W^{\mu\nu}) - \frac{1}{2} \text{tr}(G_{\mu\nu} G^{\mu\nu})$$

[Gauge interactions: U(1)$_Y$, SU(2)$_L$, SU(3)$_c$]

$$+ (\bar{\nu}_L, \bar{e}_L) \sigma^\mu i D_\mu \left( \nu^L \atop e^L \right) + \bar{e}_R \sigma^\mu i D_\mu e_R + \bar{\nu}_R \sigma^\mu i D_\mu \nu_R + \text{(h.c.)}$$

[Lepton dynamics]

$$- \frac{\sqrt{2}}{v} \left[ (\bar{\nu}_L, \bar{e}_L) \phi M^e e_R + \bar{e}_R \tilde{M}^e \phi^* \left( \nu^L \atop e^L \right) \right] - \frac{\sqrt{2}}{v} \left[ (-\bar{\nu}_L, \bar{\nu}_L) \phi M^\nu \nu_R + \bar{\nu}_R \tilde{M}^\nu \phi^* \left( \nu^L \atop \nu^L \right) \right]$$

[Lepton masses]

$$+ (\bar{u}_L, \bar{d}_L) \sigma^\mu i D_\mu \left( \bar{u}^L \atop d^L \right) + \bar{u}_R \sigma^\mu i D_\mu u_R + \bar{d}_R \sigma^\mu i D_\mu d_R + \text{(h.c.)}$$

[Quark dynamics]

$$- \frac{\sqrt{2}}{v} \left[ (\bar{u}_L, \bar{d}_L) \phi M^d d_R + \bar{d}_R \tilde{M}^d \phi^* \left( u^L \atop d^L \right) \right] - \frac{\sqrt{2}}{v} \left[ (-\bar{d}_L, \bar{u}_L) \phi M^u u_R + \bar{u}_R \tilde{M}^u \phi^* \left( u^L \atop u^L \right) \right]$$

[Quark masses]

$$+ (D^\mu \phi) D^{\mu} \phi - m_h^2 [\phi \phi - v^2/2]^2/2v^2. \quad \text{[Higgs dyn. & mass]}$$

+ new particles/symmetries?

✘ **Light-masses generation**: $1^{\text{st}}$-gen. fermion (and all $\nu$'s) masses Yukawas?

✘ **Fine-tuning**: Higgs mass virtual corrections «untamed» up to Planck scale
Open questions in the SM (3)

\[ \mathcal{L} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{8} \text{tr}(W_{\mu\nu} W^{\mu\nu}) - \frac{1}{2} \text{tr}(G_{\mu\nu} G^{\mu\nu}) \]

\[ + (\bar{\nu}_L, \bar{e}_L) \sigma^\mu i D_\mu \left( \frac{\nu_L}{e_L} \right) + \bar{e}_R \sigma^\mu i D_\mu e_R + \bar{\nu}_R \sigma^\mu i D_\mu \nu_R + \text{(h.c.)} \]

\[ - \frac{\sqrt{2}}{v} \left[ (\bar{\nu}_L, \bar{e}_L) \phi M^e e_R + \bar{e}_R \bar{M}^e \phi \left( \frac{\nu_L}{e_L} \right) \right] \]

\[ + (\bar{u}_L, \bar{d}_L) \sigma^\mu i D_\mu \left( \frac{u_L}{d_L} \right) + \bar{u}_R \sigma^\mu i D_\mu u_R + \bar{d}_R \sigma^\mu i D_\mu d_R + \text{(h.c.)} \]

\[ - \frac{\sqrt{2}}{v} \left[ (\bar{u}_L, \bar{d}_L) \phi M^d d_R + \bar{d}_R \bar{M}^d \phi \left( \frac{u_L}{d_L} \right) \right] \]

\[ + (\bar{D}_\mu \phi) D_\mu \phi - m_h^2 (\bar{\phi} \phi - v^2/2)^2 / 2v^2. \]

[Gauge interactions: U(1)_Y, SU(2)_L, SU(3)_c]

[Lepton dynamics]

[Lepton masses]

[Quark dynamics]

[Quark masses]

[Higgs dynamics & mass]

**Light-masses generation**: 1\textsuperscript{st}-gen. fermion (and all v's) masses Yukawas?

**Fine-tuning**: Higgs mass virtual corrections «untamed» up to Planck scale

**Flavour**: SM cannot generate observed matter-antimatter imbalance
Open questions in the SM (4)

\[ \mathcal{L} = -\frac{1}{4} B_{\mu \nu} B^{\mu \nu} - \frac{1}{8} tr(W_{\mu \nu} W^{\mu \nu}) - \frac{1}{2} tr(G_{\mu \nu} G^{\mu \nu}) \]

[Gauge interactions: U(1), SU(2)_L, SU(3)_c]

\[+ (\bar{\nu}_L, \bar{e}_L) \bar{\sigma}^{\mu} i D_{\mu} \left( \begin{array}{c} \nu_L \\ e_L \end{array} \right) + \bar{\nu}_R \sigma^{\mu} i D_{\mu} e_R + \bar{\nu}_R \sigma^{\mu} i D_{\mu} \nu_R + (h.c.) \]  
[Lepton dynamics]

\[- \sqrt{2} \left[ (\bar{\nu}_L, \bar{e}_L) \tilde{\phi} M^e e_R + \tilde{\nu}_R \tilde{\phi}^T \left( \begin{array}{c} \nu_L \\ e_L \end{array} \right) \right] - \sqrt{2} \left[ (-\bar{e}_L, -\bar{\nu}_L) \phi^* M^e \nu_R + \tilde{\nu}_R \tilde{\phi}^T \left( \begin{array}{c} -e_L \\ \nu_L \end{array} \right) \right] \]  
[Lepton masses]

\[+ (\bar{u}_L, \bar{d}_L) \bar{\sigma}^{\mu} i D_{\mu} \left( \begin{array}{c} u_L \\ d_L \end{array} \right) + \bar{u}_R \sigma^{\mu} i D_{\mu} u_R + \bar{d}_R \sigma^{\mu} i D_{\mu} d_R + (h.c.) \]  
[Quark dynamics]

\[- \sqrt{2} \left[ (\bar{u}_L, \bar{d}_L) \tilde{\phi} M^d d_R + \tilde{u}_R \tilde{\phi}^T \left( \begin{array}{c} u_L \\ d_L \end{array} \right) \right] - \sqrt{2} \left[ (-\bar{d}_L, -\bar{u}_L) \phi^* M^d u_R + \tilde{u}_R \tilde{\phi}^T \left( \begin{array}{c} -d_L \\ u_L \end{array} \right) \right] \]  
[Quark masses]

\[+ (D_{\mu} \phi) D^\mu \phi - m_h^2 [\phi \phi - v^2/2]^2/2v^2. \]  
[Higgs dyn. & mass]  

+ new particles/symmetries?

- **Light-masses generation**: 1st-gen. fermion (and all ν's) masses Yukawas?
- **Fine-tuning**: Higgs mass virtual corrections «untamed» up to Planck scale
- **Flavour**: SM cannot generate observed matter-antimatter imbalance
- **Dark matter**: SM describes only 4% of Universe (visible fermions+bosons)
Open questions in the SM (5)

\[ \mathcal{L} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{8} tr(W_{\mu\nu} W^{\mu\nu}) - \frac{1}{2} tr(G_{\mu\nu} G^{\mu\nu}) \]

[Lepton dynamics]

- (\bar{\nu}_L, \bar{e}_L) \bar{\sigma}^\mu i D_\mu \left( \begin{array}{c} \nu_L \\ e_L \end{array} \right) + \bar{e}_R \sigma^{\mu\nu} D_\mu e_R + \bar{\nu}_R \sigma^{\mu\nu} i D_\mu \nu_R + (\text{h.c.})

[Lepton masses]

- \frac{\sqrt{2}}{v} \left[ (\bar{\nu}_L, \bar{e}_L) \phi^{\ast} M^\nu \nu_R + \bar{\nu}_R \phi^{\ast} M^\nu \nu_R + \nu_L \phi \left( \begin{array}{c} -e_L \\ \nu_L \end{array} \right) \right]

[Quark dynamics]

- (\bar{u}_L, \bar{d}_L) \bar{\sigma}^\mu i D_\mu \left( \begin{array}{c} u_L \\ d_L \end{array} \right) + \bar{u}_R \sigma^{\mu\nu} D_\mu u_R + \bar{d}_R \sigma^{\mu\nu} i D_\mu d_R + (\text{h.c.})

[Quark masses]

- \frac{\sqrt{2}}{v} \left[ (\bar{u}_L, \bar{d}_L) \phi^{\ast} M^d d_R + \bar{d}_R \phi \left( \begin{array}{c} u_L \\ d_L \end{array} \right) \right] - \frac{\sqrt{2}}{v} \left[ \phi^{\ast} M^u u_R + \bar{u}_R \phi \left( \begin{array}{c} d_L \\ u_L \end{array} \right) \right]

[Lepton masses]

- (D_\mu \phi) D^\mu \phi - m_h^2 [\phi \phi - v^2/2]^2/2v^2. [Higgs dyn. & mass]

+ new particles/symmetries?

✘ **Light-masses generation**: 1\textsuperscript{st}-gen. fermion (and all \nu's) masses Yukawas?

✘ **Fine-tuning**: Higgs mass virtual corrections «untamed» up to Planck scale

✘ **Flavour**: SM cannot generate observed matter-antimatter imbalance

✘ **Dark matter**: SM describes only 4% of Universe (visible fermions+bosons)

✘ **Others**: Strong CP, quantum gravity, cosmological const, dark energy, inflation,...

Some/Most(?) of these questions will not be fully answered at the LHC
BSM physics at $e^+e^-$ colliders

- New physics: Beyond present reach? Hiding well? At smaller couplings?
- BSM searches at electron-positron colliders:
  - Direct model-indep. discovery of new particles coupling to $Z^*/\gamma^*$ up to $m \sim \sqrt{s}/2$
  - Small & very-well understood backgrounds: Fill “blind spots” in p-p searches
  - Indirect via high-precision measurements sensitive to virtual corrections:

- New physics scale ($\Lambda$) limits from generic SM-EFT:
  - New scalar-coupled physics: $\Lambda \gtrsim (1 \text{ TeV})/\sqrt{(d_{g_{HXX}}/g_{HXX}^{SM})/5\%}$
    - HL-LHC: ~5% deviations of Higgs couplings wrt. SM: $\Lambda \gtrsim 1$ TeV
    - FCC($e^+e^-$): $10^6$ Higgs: ~0.1% Higgs couplings precision: $\Lambda \gtrsim 7$ TeV
  - New electroweak-coupled physics: $\Lambda \propto (1 \text{ TeV})/\sqrt{\delta X}$
    - NP excluded below $\Lambda \gtrsim 3$ TeV by current EWK precision fit.
    - FCC($e^+e^-$): $\times 5 \cdot 10^5$ more stats. ($10^8$ W's, $5 \cdot 10^{12}$ Z's)
      $\times 10^{2.5}$ precision w.r.t. LEP ($10^4$ W's, $10^7$ Z's)
      i.e. $\Lambda \gtrsim 45$ TeV
**FCC-ee: Z(\(\times 5 \cdot 10^5\) LEP), W(\(\times 10^4\) LEP), H, top factory**

- \(\sqrt{s}=91\) GeV, \(10^{12}\) Z's
- \(\sqrt{s}=161\) GeV, \(10^8\) W's
- \(\sqrt{s}=240\) GeV, \(10^6\) H's
- \(\sqrt{s}=350\) GeV, \(10^6\) t's

**FCC-ee core physics programme to be completed in ~13 years**
Detector requirements:

- **Track p resolution:** \( \sigma_{1/p} = 3 \cdot 10^{-5} \text{ GeV}^{-1} \) [comparable to \( e^+e^- \) beam energy spread at Z]
- **Jet E resolution:** \( \delta E/E = 30\% / \sqrt{E(\text{GeV})} \) [comparable to natural \( Z(qq) \) width]
- **Impact-param. resol:** \( \sigma_{d_0} = a + b / (p \cdot \sin^{3/2} \theta) \); \( a=5\mu m \), \( b = 15\mu m \) [\( b,c,\tau \) tagging]
- **PID:** \( \gamma/\pi^0 \), \( e/\mu/h \), \( \pi/k/\rho \) separation (high granularity)

IDEA detector concept based on current state-of-the-art technologies:

- **Beam pipe:** \( \sim 1.5 \text{ cm (0.5\% } X_0 \) )
- **Vertex detector:** MAPS (ALICE ITS)
  - 5 layers (3\% \( X_0 \)). Point resol.: 5\( \mu m \)
- **Ultralight Drift Chamber:** MEG2-type
  - \( \text{He-iC}_4\text{H}_{10} \) (90:10); 110 layers (1.5\% \( X_0 \))
  - Point resol.: \( \sim 100(\text{xy}), 700 (\text{z}) \mu m \)
  - PID: via cluster counting
- **Preshower counter:** \( 2X_0/\text{SiStrip}/1X_0/\text{SiStrip} \)
- **Dual readout Pb/fiber calorimeter** (\( d=1.6m \)):
  - \( \sim 6-8\lambda_{\text{int}}, \) Scintillation/Cherenkov signals.
- **B-field:** 2 T. Instrumented return yoke for \( \mu \)
- **Forward (<150 mrad):** MDI & LumiCal (1.2m)
FCC-ee detector concept (CLD)

- CLD (L=10.6 m) inspired in CLIC/ILC detectors & optimized for FCC-ee conditions:
  - Beam pipe: ~1.5 cm (0.5% $X_0$)
  - Vertex detector: Si pixels
    3x2 double-layers (1% $X_0$). Point resol.: 3µm
  - Tracker detector: Si pixels & microstrips
    6 layers (8% $X_0$). Point resol.: 7x90 µm
  - EM & HCAL Calorimeters:
    - Si-W sampling calo (22 $X_0$, 1$\lambda_{int}$)
    - Sci/Steel sampling calo (5.5 $\lambda_{int}$)
  - B-field: 2 T (superconducting coil)
  - Muon system: 6 RPCs
  - Forward region (<150 mrad): MDI & LumiCal

Proven concept,
Performances from full simulation
[See O.Viazlo, Tues. 10th]
Open issue in the SM (1): Hierarchy problem solved via BSM W,Z,t -coupled physics

- Many BSM realizations: SUSY, Z', composite top,...
- Parametrize (B)SM as an Effective Field Theory:
  \[ \mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots \]
  \[ \mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \quad \text{[}[\mathcal{O}_i] = d\text{]} \]
- Indirect (loop) constraints on new physics coupled to gauge bosons:
  \[ \Lambda \propto (1 \text{ TeV})/\sqrt{\delta X} \]
  ~0.1% precision of W,Z couplings ($10^{4,6}$ W,Z LEP): \( \Lambda \gtrsim 3 \text{ TeV} \)
  ~0.0005% W,Z couplings precision ($\sim 10^{8,12}$ W,Z): \( \Lambda \gtrsim 45 \text{ TeV} \)
FCC-ee physics: High-precision W, Z, top

- Z resonance: TeraZ
  - ALEPH
  - DELPHI
  - L3
  - OPAL
  - Average measurement, error bars increased by factor 10

- WW threshold scan: OkuW
  - LEP
  - Top threshold scan: MegaTops

- Lineshape
  - Exquisite $E_{\text{beam}}$ (unique!)
  - $m_Z, \Gamma_Z$ to 10 keV (stat.)
  - 100 keV (syst.)

- Asymmetries
  - $\sin^2\theta_W$ to $5\times10^{-6}$

- Branching ratios, $R_{ll}, R_b$
  - $\alpha_s(m_Z)$ to 0.0002

- Predict $m_{\text{top}}, m_W$ in SM

- Threshold scan
  - $m_W$ to 500 keV

- Threshold scan + 4D fit
  - $m_{\text{top}}$ to 10 MeV (stat.)
  - $\lambda_{\text{top}}$ to 13% (th.)
  - EWK couplings to 1–10%

- Radiative returns $e^+e^-\rightarrow\gamma Z$ ($Z\rightarrow\nu\nu, \mu^+\mu^-$)
  - $N_\nu$ to 0.001

- Mostly thanks to:
  - (i) huge statistics,
  - (ii) threshold scans with $\delta E_{\text{cm}} \sim 0.1, 0.3, 2., 4.$ MeV (Z, W, ZH, t)

[See A. Blondel, Tues. 10th]
# High-precision W, Z, top: FCC-ee uncertainties

- Exp. uncertainties (stat. uncert. ~negligible) improved wrt. LEP by factors $\times 20$:

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<thead>
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<tbody>
<tr>
<td>$m_z$ (MeV)</td>
<td>Lineshape</td>
<td>$91187.5 \pm 2.1$</td>
<td>0.005</td>
<td>&lt; 0.1</td>
<td>QED corr.</td>
</tr>
<tr>
<td>$\Gamma_z$ (MeV)</td>
<td>Lineshape</td>
<td>$2495.2 \pm 2.3$</td>
<td>0.008</td>
<td>&lt; 0.1</td>
<td>QED / EW</td>
</tr>
<tr>
<td>$R_t$</td>
<td>Peak</td>
<td>$20.767 \pm 0.025$</td>
<td>0.001</td>
<td>&lt; 0.001</td>
<td>Statistics</td>
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<tr>
<td>$R_b$</td>
<td>Peak</td>
<td>$0.21629 \pm 0.00066$</td>
<td>0.000003</td>
<td>&lt; 0.00006</td>
<td>$g \rightarrow b\bar{b}$</td>
</tr>
<tr>
<td>$N_v$</td>
<td>Peak</td>
<td>$2.984 \pm 0.008$</td>
<td>0.00004</td>
<td>&lt; 0.004</td>
<td>Lumin. meas.</td>
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<tr>
<td>$\sin^2\theta_W^{\text{eff}}$</td>
<td>$A_{FB}^{\mu\mu}$ (peak)</td>
<td>$0.23148 \pm 0.00016$</td>
<td>0.000003</td>
<td>&lt;0.000005*</td>
<td>Beam energy</td>
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<tr>
<td>$1/\alpha_{QED}(m_z)$</td>
<td>$A_{FB}^{\mu\mu}$ (off-peak)</td>
<td>$128.952 \pm 0.014$</td>
<td>0.004</td>
<td>&lt; 0.004</td>
<td>QED / EW</td>
</tr>
<tr>
<td>$\alpha_s(m_z)$</td>
<td>$R_t$</td>
<td>$0.1196 \pm 0.0030$</td>
<td>0.00001</td>
<td>&lt;0.0002</td>
<td>New Phys.</td>
</tr>
<tr>
<td>$m_w$ (MeV)</td>
<td>Threshold scan</td>
<td>$80385 \pm 15$</td>
<td>0.6</td>
<td>&lt; 0.6</td>
<td>EW Corr.</td>
</tr>
<tr>
<td>$\Gamma_w$ (MeV)</td>
<td>Threshold scan</td>
<td>$2085 \pm 42$</td>
<td>1.5</td>
<td>&lt;1.5</td>
<td>EW Corr.</td>
</tr>
<tr>
<td>$N_v$</td>
<td>$e^+e^- \rightarrow \gamma Z, Z \rightarrow vv$, II</td>
<td>$2.92 \pm 0.05$</td>
<td>0.001</td>
<td>&lt; 0.001</td>
<td>?</td>
</tr>
<tr>
<td>$\alpha_s(m_w)$</td>
<td>$B_{\text{had}} = (\Gamma_{\text{had}}/\Gamma_{\text{tot}})_W$</td>
<td>$67.41 \pm 0.27$</td>
<td>0.00018</td>
<td>&lt; 0.0001</td>
<td>CKM Matrix</td>
</tr>
<tr>
<td>$m_{\text{top}}$ (MeV)</td>
<td>Threshold scan</td>
<td>$173340 \pm 1760 \pm 500$</td>
<td>20</td>
<td>&lt;40</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>$\Gamma_{\text{top}}$ (MeV)</td>
<td>Threshold scan</td>
<td>?</td>
<td>40</td>
<td>&lt;40</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>$\lambda_{\text{top}}$</td>
<td>Threshold scan</td>
<td>$\mu = 1.2 \pm 0.3$</td>
<td>0.08</td>
<td>&lt; 0.05</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>ttZ couplings</td>
<td>$\sqrt{s} = 365 \text{ GeV}$</td>
<td>~30%</td>
<td>~2%</td>
<td>&lt;2%</td>
<td>QCD corr</td>
</tr>
</tbody>
</table>

- Theoretical developments needed to match expected experimental uncertainties

* work to do: check if we can't improve
High-precision W, Z, top: Theory uncertainties

- Current TH uncertainties to be improved by $\sim \times 5$ to match expected exp. ones:
  
  **Today**
  
  \[
  m_W = 80.3584 \pm 0.0055_{\text{m}_{\text{top}}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{\text{QED}}} \\
  \pm 0.0020_{\alpha_S} \pm 0.0010_{m_H} \pm 0.0040_{\text{theory}} \text{GeV}
  
  = 80.358 \pm 0.008_{\text{total}} \text{GeV},
  \]

  \[
  m_W^{\text{direct}} = 80.385 \pm 0.015 \text{GeV},
  \]

- With FCC-ee
  
  \[
  m_W = 80.3584 \pm 0.0002_{\text{m}_{\text{top}}} \pm 0.0001_{m_Z} \pm 0.0005_{\alpha_{\text{QED}}} \\
  \pm 0.0002_{\alpha_S} \pm 0.0000_{m_H} \pm 0.0040_{\text{theory}} \text{GeV}
  
  = 80.3584 \pm 0.0006_{\text{exp}} \pm 0.0040_{\text{theory}} \text{GeV},
  \]

  \[
  m_W^{\text{direct}} = 80.385 \pm 0.0006 \text{GeV}.
  \]

- Theory R&D

  "Precision EW Calculations Mini-Workshop" [Jan. 2018]: Required N$^3$LO SM corrections of EWPOs are theoretically doable in 5–10 years (with appropriate financial support and training programs)
High-precision Z pole measurements: $\alpha_{\text{QED}}$ coupling

- BSM searches require reduced SM parametric uncertainties ($\alpha, \alpha_s, m_W, m_t, \ldots$)
- $\mu\mu$ forward-backward asymmetry around Z pole: Unparalleled sensitivity to QED coupling & weak mixing angle:

$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu+} - N_B^{\mu+}}{N_F^{\mu+} + N_B^{\mu+}} \approx f(\sin^2 \theta_W^{\text{eff}}) + \alpha_{\text{QED}}(s) \frac{s - m_Z^2}{2s} g(\sin^2 \theta_W^{\text{eff}})$$

[See P. Janot, Tues. 10th]

- 6 months at $\sqrt{s} = 87.9, 94.3$ GeV reduces current e.m. coupling uncertainty by factor $\times 3$: $\delta\alpha/\alpha(m_Z) \sim 3 \cdot 10^{-5}$ (mostly statistical)
High-precision W,Z measurements: $\alpha_s$ coupling

- BSM searches require reduced SM parametric uncertainties ($\alpha, \alpha_s, m_W, m_t, \ldots$)

- Hadronic W width (BR) known at N$^3$LO (NNLO). Sensitivity to $\alpha_s$ (only beyond Born) requires exquisite experimental uncertainties:

$$\Gamma_{W, \text{had}} = \sqrt{2 \over 4\pi} G_F m_W^3 \sum_{\text{quarks } i,j} \left| V_{i,j} \right|^2 \left[ 1 + \sum_{k=1}^{4} \left( \frac{\alpha_s}{\pi} \right)^k + \delta_{\text{electroweak}}(\alpha) + \delta_{\text{mixed}}(\alpha \alpha_s) \right]$$

- Current $\Gamma_W$ measurement yields poor extraction: $\delta \alpha_s \sim 25\%$

- FCC-ee prospects: Huge $e^+e^-\rightarrow WW$ stats ($10^8$ $\times$ $10^8$ LEP): $\delta \alpha_s < 0.2\%$

[D.d'E, M.Srebre, PLB763(2016)465]

$\alpha_s(M_Z) = 0.117 \pm 0.030_{(\text{exp})} \pm 0.003_{(\text{th})} \pm 0.001_{(\text{par,CKM=1})}$

$\alpha_s(M_Z) = 0.1188 \pm 0.0002_{(\text{exp})}$

FCC-ee estimate

[R_W \equiv B_{\text{had}/lep} = B_{\text{had}/(1 - B_{\text{had}})} in three $e^+e^- \rightarrow W^+W^-$ final states ($\ell\nu, \ell\nu qq, qq qq$)]
High-precision $W$, top measurements: masses, widths

- Threshold scans for high-accuracy extraction of $W$, top masses & widths:

  ![Threshold scan graph]

  [See P. Azzurri, Tues. 10th]

- Combined $(m_{\text{top}}, m_W, m_H)$ electroweak fit:

  ![Combined fit graph]

  [See F. Simon, P. Azzi, Tues. 10th]
Higher-dimensional operators as relic of new physics

Generic BSM corrections to the SM Lagrangian at scale $\Lambda$:

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

$$\mathcal{O}_R^e = (i H^\dagger \bar{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$$

$$\mathcal{O}_{LL}^{(3)} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$$

$$\mathcal{O}_W = \frac{ig}{2} \left( H^\dagger \sigma^a \bar{D}_\mu H \right) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2} \left( H^\dagger \bar{D}_\mu H \right) \partial^\nu B_{\mu}$$

$$\mathcal{O}_T = \frac{1}{2} \left( H^\dagger \bar{D}_\mu H \right)^2$$

LEP constraints: $\Lambda_{\text{NP}} > 3-10$ TeV

After FCC-ee: $\Lambda_{\text{NP}} > 30-100$ TeV

Sensitivity to Weakly-coupled NP

[J. Ellis and T. You, arXiv:1510.04561]
Open issue in the SM (2): Hierarchy problem solved via BSM scalar-coupled physics

- Many BSM realizations: SUSY, little-H, 2HDM, composite H,...
- Parametrize (B)SM as an Effective Field Theory:
  \[
  \mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots
  \]
  \[
  \mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \quad \quad \quad \quad [\mathcal{O}_i] = d
  \]
- Indirect (loop) constraints on new physics coupled to Higgs:
  \[
  \Lambda \gtrsim (1 \text{ TeV})/\sqrt{(\delta g_{HXX}^g/g_{HXX}^{\text{SM}})/5\%}
  \]
  \[
  \sim 5\% \text{ deviations of Higgs couplings wrt. SM: } \Lambda \gtrsim 1 \text{ TeV}
  \]
  \[
  \sim 0.1\% \text{ Higgs couplings precision (}\sim 10^6\text{ Higgs): } \Lambda \gtrsim 7 \text{ TeV}
  \]
FCC-ee = Higgs boson factory

- Cross section: $\sigma(e^+e^-\rightarrow H+X) \approx 200 + 50 \text{ fb}$
- 1 million Higgs bosons produced with small & controlled backgrounds, plus no pileup:

<table>
<thead>
<tr>
<th>Total Integrated Luminosity (ab$^{-1}$)</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Higgs bosons from $e^+e^-\rightarrow HZ$</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Number of Higgs bosons from boson fusion</td>
<td>25,000</td>
</tr>
</tbody>
</table>

- Access to precision ($<<1\%$) Higgs couplings, and rare & BSM decays
Precision H couplings, width, mass at FCC-ee

- Recoil method in H-Z(\(ll\)) unique to lepton collider: reconstruct H 4-mom. independent of H decay mode.
- High-precision (0.4%) \(\sigma_{ZH}\) provides model-indep. \(g_Z\) coupling \(\sigma(ee \rightarrow ZH) \propto g_Z^2\), with ±0.2% uncert.

Total width \((\Gamma_H)\) with ~1% precision from combination of measurements \(\sigma(ee \rightarrow ZH), \sigma(ee \rightarrow ZH \rightarrow ZZ^*), \Gamma_{H \rightarrow ZZ}\): \[\sigma(e^+e^- \rightarrow HZ \rightarrow ZZ^*) = \sigma(e^+e^- \rightarrow HZ) \times \frac{\Gamma(H \rightarrow ZZ)}{\Gamma_H}\]

- Limits in invisible decay from missing mass: <0.5% (95% CL)
- Higgs mass \((m_H)\) from recoil mass in \(Z \rightarrow \mu\mu, ee\)
### Precision H couplings, width, mass at FCC-ee

- **e⁺e⁻ colliders** provide factor > 50 (10) improvement in precision w.r.t. model-dependent LHC (HL-LHC) expectations:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current*</th>
<th>HL-LHC*</th>
<th>FCC-ee</th>
<th>ILC</th>
<th>CEPC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ</td>
<td>7+8+13 TeV (70 fb⁻¹)</td>
<td>14 TeV (3 ab⁻¹)</td>
<td><strong>Baseline</strong> (10 yrs)</td>
<td>Lumi upgrade (20 yrs)</td>
<td>Baseline (10 yrs)</td>
<td>Baseline (15 yrs)</td>
</tr>
<tr>
<td>σ(HZ)</td>
<td>–</td>
<td>–</td>
<td>0.4%</td>
<td>0.7%</td>
<td>0.5%</td>
<td>1.6%</td>
</tr>
<tr>
<td>g_{zz}</td>
<td>10%</td>
<td>2–4%</td>
<td>0.15%</td>
<td>0.3%</td>
<td>0.25%</td>
<td>0.8%</td>
</tr>
<tr>
<td>g_{WW}</td>
<td>11%</td>
<td>2–5%</td>
<td>0.2%</td>
<td>0.4%</td>
<td>1.6%</td>
<td>0.9%</td>
</tr>
<tr>
<td>g_{bb}</td>
<td>24%</td>
<td>5–7%</td>
<td>0.4%</td>
<td>0.7%</td>
<td>0.6%</td>
<td>0.9%</td>
</tr>
<tr>
<td>g_{cc}</td>
<td>–</td>
<td>–</td>
<td>0.7%</td>
<td>1.2%</td>
<td>2.3%</td>
<td>1.9%</td>
</tr>
<tr>
<td>g_{ττ}</td>
<td>15%</td>
<td>5–8%</td>
<td>0.5%</td>
<td>0.9%</td>
<td>1.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>g_{ττ}</td>
<td>16%</td>
<td>6–9%</td>
<td>13%</td>
<td>6.3%</td>
<td>–</td>
<td>4.4%</td>
</tr>
<tr>
<td>g_{μμ}</td>
<td>–</td>
<td>8%</td>
<td>6.2%</td>
<td>9.2%</td>
<td>17%</td>
<td>7.8%</td>
</tr>
<tr>
<td>g_{e^+e^-}</td>
<td>–</td>
<td>–</td>
<td>&lt;100%</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>g_{ζζ}</td>
<td>–</td>
<td>3–5%</td>
<td>0.8%</td>
<td>1.0%</td>
<td>1.7%</td>
<td>1.4%</td>
</tr>
<tr>
<td>g_{γγ}</td>
<td>10%</td>
<td>2–5%</td>
<td>1.5%</td>
<td>3.4%</td>
<td>4.7%</td>
<td>3.2%</td>
</tr>
<tr>
<td>g_{Zγ}</td>
<td>–</td>
<td>10–12%</td>
<td>(to be determined)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Δm_h</td>
<td>200 MeV</td>
<td>50 MeV</td>
<td>11 MeV</td>
<td>15 MeV</td>
<td>5.9 MeV</td>
<td>32 MeV</td>
</tr>
<tr>
<td>Γ_Hi</td>
<td>&lt;26 MeV</td>
<td>5–8%</td>
<td>1.0%</td>
<td>1.8%</td>
<td>2.8%</td>
<td>3.6%</td>
</tr>
<tr>
<td>Γ_{inv}</td>
<td>&lt;24%</td>
<td>&lt;6–8%</td>
<td>&lt;0.45%</td>
<td>&lt;0.29%</td>
<td>&lt;0.28%</td>
<td>&lt;0.97%</td>
</tr>
</tbody>
</table>

Most precise $g_{zz} \sim 0.2\%$ coupling sets limit on new scalar-coupled physics at: $\Lambda \gtrsim (1 \text{ TeV})/\sqrt{\left(\frac{\delta g_{HXX}}{g_{HXX}^{\text{SM}}}\right)/5\%} \gtrsim 7 \text{ TeV}$
FCC-ee Higgs boson precision measurements improve greatly scalar-coupled BSM limits.

NP bounds: Higgs+EWPO combined: \( \Lambda \gtrsim 50 \text{ TeV} \)

Open SM issue (3): Generation of lightest fermion (u,d,s; e; \nu's) masses

- LHC can only access 3rd (plus few 2nd)-gen. Yukawas. What about the rest?
1\textsuperscript{st} - 2\textsuperscript{nd}-gen. quark Yukawa couplings at FCC-ee

- 1\textsuperscript{st} & 2\textsuperscript{nd} gen. quark Yukawa accessible via exclusive $H\rightarrow V\gamma$, $V=\rho,\omega,\phi$

![](image1)

- Bound vector meson

- $H\rightarrow \rho(\pi\pi)\gamma$ channel most promising: $N\sim40$ counts expected, low backgds

- Sensitivity to $u/d$ quark Yukawa couplings:

$$\frac{BR_{h\rightarrow \rho\gamma}}{BR_{h\rightarrow b\bar{b}}} = \frac{\kappa_{\gamma}[(1.9 \pm 0.15)\kappa_{\gamma} - 0.24\kappa_u - 0.12\kappa_d]}{0.57\kappa_b} \times 10^{-5}$$

  ($k_q = y_q/y_b$)

- All channels accessible with higher stats at FCC-pp.
  But much worse backgrounds (QCD and pileup).
**e± Yukawa via s-channel Higgs at \( \sqrt{s}=125 \) GeV**

- Resonant s-channel Higgs production at \( \sqrt{s} = 125 \) GeV has tiny x-sections:
  
  \[
  \sigma(e^+e^-\rightarrow H)_{\text{Breit-Wigner}} = 1.64 \text{ fb} \\
  \sigma(e^+e^-\rightarrow H)_{\text{visible}} = 290 \text{ ab} \\
  \]
  
  (incl. ISR + \( \sqrt{s}_{\text{spread}} = \Gamma_H = 4.2 \) MeV)

  Mono-chromatization required to achieve \( \sqrt{s}_{\text{spread}} \sim \Gamma_H \)

- Preliminary study for signal + backgrounds in 10 Higgs decay channels.

- Significance & limits on e-Yukawa coupling:

  Optimized monochromatization (10 MeV, 7 ab\(^{-1}\)): \( S=0.43\sigma, g_{eH} < 2.2\times g_{eH,SM} \) (95% CL)
Right-handed neutrinos from Z decays

Opportunities for direct searches for new physics through rare decays

- $10^{12}$ ($10^{13}$) Z, $10^{11}$ b, c or τ: A fantastic potential that remains to be explored.
- E.g., search for right-handed neutrino in Z decays

$$Z \rightarrow N \nu_i, \text{ with } N \rightarrow W^* l \text{ or } Z^* \nu_j$$

Number of events depend on mixing between N and $\nu_i$ and on $m_N$

FCC-ee sensitivity down to $|U|^2 \sim 10^{-12}$ for $m_N \sim 1$–100 GeV

[See E. Graverini, Tues. 10th]

[A. Blondel et al. arXiv:1411.5230]
Open issue in the SM (4):
CP violation, baryon asymmetry, flavour physics

- CP Violation beyond that in the SM is needed in order to explain the baryon asymmetry in universe.
- Pattern of fermion masses & flavour mixings unexplained.
- Indirect searches of new virtual particles contributing to higher-order (Penguin, box) loops in flavour-changing charged current processes.
- Unparallelled b-, c-quark, tau statistics available at FCC-ee:

<table>
<thead>
<tr>
<th>Particle production</th>
<th>$B^0 / \bar{B}^0$</th>
<th>$B^+ / B^-$</th>
<th>$B_s^0 / \bar{B}_s^0$</th>
<th>$\Lambda_b / \bar{\Lambda}_b$</th>
<th>$c\bar{c}$</th>
<th>$\tau^- / \tau^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle II</td>
<td>27.5</td>
<td>27.5</td>
<td>n/a</td>
<td>n/a</td>
<td>65</td>
<td>45</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>1000</td>
<td>1000</td>
<td>250</td>
<td>250</td>
<td>1000</td>
<td>500</td>
</tr>
</tbody>
</table>

Access to very rare B-meson: decays, branching fractions, decays asymmetries, oscillation frequencies, ...
Current tensions (several 2-3σ 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 $B \rightarrow K^{(*)} \tau^+\tau^-$
  - Extremely challenging in hadron colliders
  - With $10^{12} Z \rightarrow b\bar{b}$, FCC-ee is beyond any foreseeable competition
    - Decay can be fully reconstructed
    - Full angular analysis possible

Also sensitive to new physics: $B_s \rightarrow \mu^+\mu^-$

- None found yet at the LHC (∼50 events)
  - $BR(B^0_s \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ ~SM
  - Expect a few 1000’s by the end of LHC
  - $B_s \rightarrow \tau^+\tau^-$ is 250 times more abundant
    - But almost hopeless at the LHC
  - Again, FCC-ee is beyond any foreseeable competition
    - Several 100,000 events expected – reconstruction efficiency under study

[See S. Monteil, Tues. 10th ]
Open issue in the SM (5): Dark matter

For $M_{DM} < M_{H,Z}/2$:

- $(e^+) \bar{q}$
- $(e^-) q$
- $(e^+) \bar{q}$
- $(e^-) q$

[B(H→inv)>5% expected for HL-LHC]
Dark Matter via invisible $Z, H \rightarrow \chi \chi$ decays

- DM freeze-out fixes $\sigma \cdot v \approx 3 \times 10^{-26} \text{cm}^3/\text{s}$. If $m_{\text{DM}}$ is just below $m_{Z,H}/2$, then DM freeze-out dominated by resonant $Z,H$ exchange, fixing $\Gamma_{Z,H}$.

- $\sim 10^{-4}, \sim 5 \cdot 10^{-3}$ precision measurements of $Z$ & $H$ invisible widths are best collider option to test any $m_{\text{DM}} < m_{Z,H}/2$ coupling via SM mediators.

- Limits on $\sigma(\text{DM-nucleon})$ vs. $m_{\text{DM}}$ in Higgs-portal models competitive with future direct DM-searches experiments.

---

FCC Week, Amsterdam, April’18

David d'Enterria (CERN)
Summary

- FCC-ee provides unparalleled luminosities $O(1–50 \text{ ab}^{-1})$ at $\sqrt{s}=90–350$ GeV for high-precision ($\ll 0.1\%$ uncert.) W, Z, H, top studies, setting unique constraints on new physics up to $\Lambda \gtrapprox 6$ TeV (scalar-), 50 TeV (weak-coupled).

- Plus: 1st gen. Yukawas, right-handed $\nu$'s, flavour physics, dark matter, ...

---

FCC Week, Amsterdam, April’18

David d’Enterria (CERN)
Backup slides
New physics constraints: SUSY

- FCC-ee measurements significantly improve limits in benchmark SUSY models (CMSSM, NUHM1):

**Precision Electroweak**

**Precision Higgs**

Best Fit Predictions

[arXiv:1308.6176]
**New physics constraints: Other models**

- **Higgs-coupled new physics in SMEFT**
  - Probes dim 6 operators for $\Lambda/\sqrt{c}$ up to $5 - 30$ TeV

- **Specific models: pattern of deviations**
  - E.g., Composite Higgs Model to solve hierarchy problem
    - Deviations in Higgs couplings
    - Deviations in EW top couplings
    - Deviations in EW lepton couplings
  - Correlations between observations
    - Allow unique characterization of the model
  - For example, gauge sector parameters in benchmark A
    - $f = 1.6$ TeV, $g^* = 1.78$, $m_{Z'} \approx 3$ TeV, $\Gamma_{Z'} \approx 600$ GeV
    - With the FCC-ee precision
      - $Z'$ mass predicted with 2% precision
      - Scale $f$, coupling $g^*$ predicted with 8% precision
Higgs self-coupling through $\sigma(H+Z)$

- Higgs trilinear indirectly constrained through loop corrections to $\sigma(H+Z)$:

\[
\sigma_{ZH} = e^2 + 2 \text{Re} \left[ \frac{\sigma}{\sigma_H} \right] \cdot \left( Z^+ e^- h^+ + Z^- e^+ h^- \right)
\]

\[
\delta_{240} = 100(2\delta_Z + 0.014\delta_h) \%
\]

Self-coupling correction $\delta_h$: energy-dependent
$\delta_z$: energy-independent (distinguishable).

- Tiny effect, but visible thanks to extreme (0.4%) precision on $\sigma_{ZH}$ coupling reachable at FCC-ee.

- Indirect limits on trilinear $\lambda$ coupling at $\sim 30\%$ level combining HL-LHC+ FCC-ee at 240+350GeV

[M. McCullough, 2014]

[G. Durieux, Wed. session]
Higgs self-coupling through $\sigma(H+Z)$

- Addition of FCC-ee 240+350GeV Higgs cross section solves 2\textsuperscript{nd} minimum on $\lambda$ from HL-LHC data alone.

- Higgs self-coupling constrained to within $\sim$30%. Higher-energy $e^+e^-$ collisions required to reduce it to $\sim$20%.
Right-handed neutrinos decaying into Higgs

Consider (symmetry-protected) seesaw scenario with 2 sterile $\nu$ ($N_i$):
large neutrino Yukawa couplings & masses: $y_{\nu} \approx 10^{-3}$, $m_N \approx 10^2$ GeV

$N_i$ decay to Higgs+$\nu$. Signature: mono-Higgs(jj) plus missing energy

FCC-ee sensitivity down to $|y_{\nu e}| \sim 5 \times 10^{-3}$ for unexplored $m_N \sim 100–350$ GeV

[See E. Graverini, Tues. 10th]

[Antusch, Cazzato, Fischer, arXiv:1512.06035]
FCC-ee exploits recipes from past $e^+e^-$, pp colliders

- LEP: high energy SR effects
- B-factories: high beam currents top-up injection
- KEKB & PEP-II: crab waist
- Super B-factories: low $\beta_y^*$
- S-KEKB: $e^+$ source
- HERA, LEP, RHIC: spin gymnastics

Combining successful ingredients of recent colliders → extremely high luminosity at high energies
FCC-ee: $Z(x5\cdot10^5 \text{ LEP}), W(x10^4 \text{ LEP}), H, \text{top factory}$

- Unique exploration of the 10–100 TeV energy scale through high-precision studies of the 4 heaviest fundamental SM particles: $W, Z, H, \text{top}$
## FCC-ee beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>W</th>
<th>H (ZH)</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>175-182.5</td>
</tr>
<tr>
<td>Arc cell optics</td>
<td>60/60</td>
<td>60/60</td>
<td>90/90</td>
<td>90/90</td>
</tr>
<tr>
<td>Emittance hor/vert [nm]/[pm]</td>
<td>0.27/1.0</td>
<td>0.84/1.7</td>
<td>0.63/1.3</td>
<td>1.4/2.8</td>
</tr>
<tr>
<td>$\beta^*$ horiz/vertical [m]/[mm]</td>
<td>0.15/.8</td>
<td>0.2/1</td>
<td>0.3/1</td>
<td>1/1.6</td>
</tr>
<tr>
<td>SR energy loss / turn (GeV)</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>9.21</td>
</tr>
<tr>
<td>Total RF voltage [GV]</td>
<td>0.10</td>
<td>0.75</td>
<td>2.0</td>
<td>8.8-10.3</td>
</tr>
<tr>
<td>Energy acceptance [%]</td>
<td>±1.3</td>
<td>±1.3</td>
<td>±1.7</td>
<td>±2.4-2.8</td>
</tr>
<tr>
<td>Energy spread (SR / BS) [%]</td>
<td>0.038 / 0.132</td>
<td>0.066 / 0.165</td>
<td>0.099 / 0.165</td>
<td>0.15 / 0.20</td>
</tr>
<tr>
<td>Bunch length (SR / BS) [mm]</td>
<td>3.5 / 12.1</td>
<td>3.0 / 7.5</td>
<td>3.15 / 5.3</td>
<td>2.75 / 3.80</td>
</tr>
<tr>
<td>Bunch intensity [$10^{11}$]</td>
<td>1.7</td>
<td>2.3</td>
<td>1.8</td>
<td>3.2-3.35</td>
</tr>
<tr>
<td>No. of bunches / beam</td>
<td>16640</td>
<td>1300</td>
<td>328</td>
<td>40-33</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>6.4-5.4</td>
</tr>
<tr>
<td>SR total power [MW]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>230</td>
<td>34</td>
<td>8.5</td>
<td>1.9-1.7</td>
</tr>
<tr>
<td>Luminosity lifetime [min]</td>
<td>70</td>
<td>24</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>Allowable asymmetry [%]</td>
<td>±5</td>
<td>±3</td>
<td>±3</td>
<td>±3</td>
</tr>
</tbody>
</table>
FCC-ee: CERN study project

Physics Studies Coordination
A. Blondel, P. Janot (EXP), J. Ellis, C. Grojean (TH), M. McCullough

Synergy with FCC-hh physics, LC physics, LEP physics

EW Physics (Z pole)
R. Tenchini, F. Piccinini
S. Heynemeier, A. Freitas

Diboson Physics (MW)
R. Tenchini, F. Piccinini
S. Heynemeier, A. Freitas

Higgs Properties
M. Klute, K. Peters
S. Heynemeier, A. Freitas

Top Quark Physics
P. Azzi, F. Blekman
S. Heynemeier, A. Freitas

QCD and γγ Physics
D. D’Enterria
P. Skands

Flavor Physics
S. Monteil
J. Kamenik

New Physics
M. Pierini, C. Rogan
M. McCullough

Global Analysis, Combination, Complementarity
J. Ellis

Develop the necessary tools
Offline Software
C. Bernet, B. Hegner, C. Helsens

Synergy with FCC-hh, LC, LHC

Online & Trigger
C. Leonidopoulos, E. Perez

Understand experimental conditions

MDI
N. Bacchetta, M. Boscolo

Joined with FCCee-acc

Set constraints on possible detector designs to match statistical precision

Detector Design
A. Cattai, M. Dams, G. Rolandi

Synergy with Linear Colliders and others
Higgs physics at FCC-ee(125): H-e Yukawa

- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s} = 125$ GeV):
  \[
  \sigma(e^+e^-H)_{B-W} \sim 1.64 \text{ fb} \\
  \sigma(e^+e^-H)_{\text{visible}} \sim 280 \text{ ab} \ (\text{ISR } + \text{E}_{\text{beam-spread}} \sim \Gamma_H = 4.2 \text{ MeV})
  \]

- Signal + backgrounds study for 7 decay channels:
  - $WW^*(2j,lv)$ ($\sigma = 28$ ab), $WW^*(2l2\nu)$ ($\sigma = 6.7$ ab),
  - $WW^*(4j)$ ($\sigma = 29.5$ ab), $ZZ^*(2j2\nu)$ ($\sigma = 2.3$ ab), $ZZ^*(2l2j)$ ($\sigma = 1.14$ ab),
  - $bb$ ($2j$) ($\sigma = 156$ ab), $gg$ ($2j$) ($\sigma = 24$ ab)

- Preliminary analysis:
  \[ L_{\text{int}} = 10 \text{ ab}^{-1}, S=0.65: \text{BR(Hee)} < 4.63 \times \text{BR}_{\text{SM}} (3\sigma), g_{\text{hee}} < 2.15 \times g_{\text{Hee,SM}} (3\sigma) \]
  Evidence (observation?) will require further improvements in large-BR (huge background) jet channels: $H \rightarrow bb$, $H \rightarrow WW \rightarrow 4j$

- Challenging accelerator conditions: mono-chromatization, huge lumi

- Fundamental & unique physics accessible if measurement feasible:
  - Electron Yukawa coupling
  - Higgs width measurable (“natural” threshold scan)
Channels combination using Roostats-based tool for LHC Higgs analyses: Profile likelihood & hybrid significances all give ~identical results, which are also very close to naive S/\sqrt{B} expectation (no background uncertainty).

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance (1 ab⁻¹)</th>
<th>Significance (10 ab⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW → lν2j,2l2ν,4j</td>
<td>0.15±0.09±0.03</td>
<td>0.50±0.30±0.08</td>
</tr>
<tr>
<td>ZZ → 2j2ν,2l2j,2l2ν</td>
<td>0.07±0.05±0.01</td>
<td>0.21±0.16±0.03</td>
</tr>
<tr>
<td>bb</td>
<td>0.03</td>
<td>0.10</td>
</tr>
<tr>
<td>gg</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>ττ</td>
<td>–</td>
<td>0.02</td>
</tr>
<tr>
<td>γγ</td>
<td>–</td>
<td>0.01</td>
</tr>
<tr>
<td>Combined</td>
<td>0.2</td>
<td>0.7</td>
</tr>
</tbody>
</table>

For 10 ab⁻¹: Significance ≈ 0.7 (preliminary, optimizations under study)

Limit (95% CL) for branching ratio: BR(H→ ee) < 2.8×BR_{SM} (H→ ee)

Limit (95% CL) for SM Yukawa: g_{eH} < 1.7×g_{eH,SM}
\( \sigma(e^+e^-\rightarrow H) \) reduction: Beam energy spread + ISR

- Extra \(~40\%\) reduction also due to initial state radiation:

\[
\frac{\sigma_{\text{BW}}(e^+e^- \rightarrow H^0)}{\sigma_{\text{BW}}(e^+e^- \rightarrow H^0)}
\]

\( \sigma(e^+e^-H) = 290 \text{ ab} \)

\( \sqrt{s_{\text{spread}}} \sim \Gamma_H = 4.2 \text{ MeV} \)

Reduc. factor: \(~45\%\)
mono-chromatization at 2x63 GeV?

direct s channel Higgs production \( e^+e^- \rightarrow H \)

rms beam energy spread at 63 GeV \( \sim 30 \) MeV
total width of SM Higgs \( \Gamma \sim 4 \) MeV

effective collision energy spread is decreased by introducing opposite-sign IP dispersion

\[
\frac{\sigma_W}{W} = \sqrt{\frac{2 \varepsilon_x}{\left( \frac{D_x^*}{\beta_x^*} + \frac{\varepsilon_x}{\sigma_{\varepsilon}^2} \right)}}
\]

first proposed by A. Renieri (1975); historical studies for VEPP4, SPEAR, LEP, \( \tau \)-c factory; never tested experimentally

reducing cm energy spread \( \times 1/10 \) w/o loss of luminosity?! implementation for crab-waist scheme?
## e+e- colliders: FCC-ee vs. LEP, CEPC

### 2016 baseline parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-ee</th>
<th>CEPC</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy/beam [GeV]</td>
<td>45</td>
<td>120</td>
<td>175</td>
</tr>
<tr>
<td>bunches/beam</td>
<td>90000</td>
<td>770</td>
<td>78</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>1450</td>
<td>30</td>
<td>6.6</td>
</tr>
<tr>
<td>luminosity/IP x 10^{34} cm^{-2}s^{-1}</td>
<td>70</td>
<td>5</td>
<td>1.3</td>
</tr>
<tr>
<td>energy loss/turn [GeV]</td>
<td>0.03</td>
<td>1.67</td>
<td>7.55</td>
</tr>
<tr>
<td>synchrotron power [MW]</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF voltage [GV]</td>
<td>0.08</td>
<td>3.0</td>
<td>10</td>
</tr>
<tr>
<td>rms bunch length (SR,+BS) [mm]</td>
<td>1.6, 3.8</td>
<td>2.0, 2.4</td>
<td>2.1, 2.5</td>
</tr>
<tr>
<td>rms emittance $\varepsilon_{x,y}$ [nm, pm]</td>
<td>0.09, 1</td>
<td>0.61, 1</td>
<td>1.3, 2.5</td>
</tr>
<tr>
<td>longit. damping time [turns]</td>
<td>1320</td>
<td>72</td>
<td>23</td>
</tr>
<tr>
<td>crossing angle [mrad]</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>beam lifetime [min]</td>
<td>251</td>
<td>75</td>
<td>62</td>
</tr>
</tbody>
</table>

### FCC-ee: 2 separate rings

### CEPC: single beam pipe like LEP
FCC-ee characteristics

- $\sqrt{s}$ limited to $\sim 400$ GeV by SR$\sim E^4/R$: R$\sim 80$ km ($\times 3$ LEP radius)
- Large # of circulating bunches: $\times 10^4$ LEP bunches +crab-waist collisions
  - High Lumi (better at low $\sqrt{s}$): $\times 10^4$–10 more lumi than ILC for $\sqrt{s} = 90$–400 GeV
  - Top-up injection ring to compensate L burnoff
- Various Interaction Points possible: 2 baseline, 4 target
- Precise $E_{\text{beam}}$ from resonant depolarization: $\pm 0.1$ MeV (2 MeV at LEP)
Beam energy spread via resonant depolarization

Resonant depolarization
- use naturally occuring transverse beam polarization
- add fast oscillating horizontal B field to depolarize at Thomas precession frequency

Experience from LEP: Depolarization resonance very narrow: ~100 keV precision for each measurement
- However, final systematic uncertainty was 1.5 MeV due to transport from dedicated polarization runs
- At FCC-ee, continuous calibration with dedicated bunches: no transport uncertainty

Scaling from LEP experience:
- Polarization expected up to the WW threshold

< 100 keV beam energy calibration at Z peak and at WW threshold
Luminosity gain: FCC-ee vs. LEP

Employ B-factory design to gain factor $\sim 500$ w.r.t. LEP:
Low vertical emittance combined small value of $\beta^*_y$ (very strong focussing in vertical plane):
- Electrons and positrons have a much higher chance of interacting
  - Very short beam lifetimes (few minutes)
  - Top-up injection: feed beam continuously with an ancillary accelerator

![Diagram of accelerator and collider rings]

Two separate beam pipes for $e^+$ and $e^-$ to avoid collisions away from IPs

Hence, a total of three beam pipes
Example: $t_L t_L Z$ and $t_R t_R Z$ couplings, $g_L$ and $g_R$

- Couplings most sensitive to composite Higgs models

$$2e F^{z}_{1V} = g_R + g_L$$
$$2e F^{z}_{1A} = g_R - g_L$$

Adapted from S. de Curtis et al. 
arXiv:1504.05407