The FCC-ee discovery potential

CDR submitted for publication
10-page documents submitted to ESPP
advertising the FCC integrated programme
The FCC integrated programme

- 27 km tunnel

- The next step: 100 km tunnel

- The FCC-ee can start seamlessly at the end of the HL-LHC
The FCC-ee offers the largest luminosities in the $88 \rightarrow 365$ GeV $\sqrt{s}$ range.

- **Ultimate precision:**
  - $100,000$ $Z$ / second (!)
    - $1$ $Z$ / second at LEP
  - $10,000$ $W$ / hour
    - $20,000$ $W$ at LEP
  - $1,500$ Higgs bosons / day
    - $10$ times ILC
  - $1,500$ top quarks / day
    - in each detector

...in a clean environment:
- No pileup
- Beam backgrounds under control
- $E_p$ constraints

**PRECISION and SENSITIVITY** to rare or elusive phenomena

- The FCC-ee discovery potential at the precision frontier is multiplied by the presence of the four heaviest SM particles ($Z$, $W$, $H$, and top) in its energy range.
## The FCC-ee operation model and statistics

- **185 physics days / year, 75% efficiency, 10% margin on luminosity**

<table>
<thead>
<tr>
<th>Working point</th>
<th>Z, years 1-2</th>
<th>Z, later</th>
<th>WW</th>
<th>HZ</th>
<th>tt 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>Run time (year)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

**Total : 15 years**

![Event statistics and $\sqrt{s}$ precision](image)

- **Event statistics**
  - $5 \times 10^{12}$ e$^+e^-$ → Z
  - $10^8$ e$^+e^-$ → W$^+W^-$
  - $10^6$ e$^+e^-$ → HZ
  - $10^6$ e$^+e^-$ → tt

- **$\sqrt{s}$ precision**
  - 100 keV
  - 300 keV
  - 1 MeV
  - 2 MeV

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FCC-ee workshop: Theory and Experiment  
CERN, 7-11 Jan 2019
The FCC-ee discovery potential (excerpt)

- EXPLORE the 10-100 TeV energy scale
  - With precision measurements of the properties of the Z, W, Higgs, and top particles
    - Up to 20-50-fold improved precision on ALL electroweak observables (EWPO)
      - $m_Z$, $m_W$, $m_{\text{top}}$, $\Gamma_Z$, $\sin^2 \theta_w^\text{eff}$, $R_b$, $\alpha_{\text{QED}}(m_Z)$, $\alpha_s(m_Z)$, $m_Z$, $m_W$, $m_t$, top EW couplings...
    - Up to 10-fold more precise and model-independent Higgs couplings measurements

- DISCOVER that the Standard Model does not fit
  - NEW PHYSICS! Pattern of deviations may point to the source.

- DISCOVER a violation of flavour conservation / universality
  - Examples: $Z \rightarrow \tau\mu$ in $5 \times 10^{12}$ Z decays; or $\tau \rightarrow \mu\nu / \tau \rightarrow e\nu$ in $2 \times 10^{11}$ $\tau$ decays; ...
  - Also $B^0 \rightarrow K^*0\tau^+\tau^-$ or $B_S \rightarrow \tau^+\tau^-$ in $1 \times 10^{12}$ bb events

- DISCOVER dark matter as invisible decays of Higgs or Z

- DIRECT DISCOVERY of very-weakly-coupled particles
  - in the 5-100 GeV mass range, such as right-handed neutrinos, dark photons, ALPs, ...
  - Motivated by all measurements / searches at colliders (SM and “nothing else”)

FCC-ee is not only a Higgs factory. Z, WW, and $\bar{t}t$ factories are important for discovery potential


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Important features for precision (examples)

- **Statistics**
  - Very high statistics at the Z pole (70 kHz of visible Z decays)
  - Beam-induced background are mild compared to linear colliders, but not negligible
    - Readout must be able to cope with both
    - CW running imposes constraints on detector cooling

- **Luminosity measurement**
  - Aim at 0.01% from small angle Bhabhas
    - Requires μm precision for LumiCal
    - Requires measurement of outgoing e⁺ deflection from the opposite bunch
  - Need to study e⁺e⁻ → γγ to possibly reach 0.001%

- **√s calibration and measurement of √s spread**
  - 50 keV “continuous” $E_{\text{BEAM}}$ measurement with resonant depolarization
  - Powerful cross checks from di-muon acollinearity and polarimeter/spectrometer
    - Requires muon angle measurement to better than 100 μrad

- **Flavour tagging**
  - Beam pipe radius (15 mm) smaller than at linear collider (vertex detector 1st layer)
    - New CEPC studies claim Purity × Efficiency ~ 97% for $H \rightarrow bb$. And at FCC-ee?
Interaction Region Layout (MDI)

- **Unique and flexible design at all energies**
  - $L^* = 2.2 \text{ m}$
    - Acceptance: 100 mrad
  - **Solenoid compensation scheme**
    - Reduce $\varepsilon_y$ blow-up $\Rightarrow B_{\text{Detector}} \leq 2T$
  - **Beam pipe**
    - Warm, liquid cooled (~SuperKEKB)
    - Be in central region, then Cu
    - $R = 15\text{mm}$ in central region
      - Vertex detector close to the IP
    - SR masks, W shielding
  - **Mechanical design and assembly concept**
    - Under engineering study

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FCC-ee detector design concepts

- Two designs studied so far
  - It was demonstrated that detectors satisfying the requirements are feasible
    - Physics performance, invasive MDI, beam backgrounds
  - More complete studies, with full simulation, needed
    - Towards at least four detector proposals to be made by ~2026
      - Light, granular, fast, b and c tagging, lepton ID and resolutions, hadron ID
      - Cost effective
      - Satisfy constraints from interaction region layout
Beam Polarization and Energy Calibration

- Simulation show transverse polarization at the Z and WW energies
  - Energy calibration by resonant depolarization every 10 mins on pilot bunches
    - UNIQUE TO CIRCULAR COLLIDERS

![Graph showing polarization and energy calibration](image)

- Total $\sqrt{s}$ uncertainty of 100 keV @ Z pole, and 300 keV at the WW threshold

- Energy spread (~100 MeV) will be measured
  - From $e^+e^- \rightarrow \mu^+\mu^-$ longitudinal boost
    - $10^6$ events every 4 mins @ Z pole
      - Continuous 35 keV precision on $\delta\sqrt{s}$
    - Also measures $\Delta E = E^+ - E^-$ to at both IPs

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<table>
<thead>
<tr>
<th>Observable</th>
<th>Measurement</th>
<th>Current precision</th>
<th>Fasc-ee stat.</th>
<th>Fasc-ee syst.</th>
<th>Dominant exp. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$ (keV)</td>
<td>Z Lineshape</td>
<td>91187500 ± 2100</td>
<td>5</td>
<td>&lt; 100</td>
<td>Beam energy</td>
</tr>
<tr>
<td>$\Gamma_Z$ (MeV)</td>
<td>Z Lineshape</td>
<td>2495200 ± 2300</td>
<td>8</td>
<td>&lt; 100</td>
<td>Beam energy</td>
</tr>
<tr>
<td>$R_i$ ($\times 10^3$)</td>
<td>Z Peak ($\Gamma_{\text{had}}/\Gamma_{\text{lep}}$)</td>
<td>20767 ± 25</td>
<td>0.06</td>
<td>0.2 – 1</td>
<td>Detector acceptance</td>
</tr>
<tr>
<td>$R_b$ ($\times 10^6$)</td>
<td>Z Peak ($\Gamma_{\text{bb}}/\Gamma_{\text{had}}$)</td>
<td>216290 ± 660</td>
<td>0.3</td>
<td>&lt; 60</td>
<td>$g \rightarrow \text{bb}$</td>
</tr>
<tr>
<td>$N_{\nu}$ ($\times 10^3$)</td>
<td>Z Peak ($\sigma_{\text{had}}$)</td>
<td>2984 ± 8</td>
<td>0.005</td>
<td>1</td>
<td>Lumi measurement</td>
</tr>
<tr>
<td>$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)</td>
<td>$A_{FB}^{\mu\mu}$ (peak)</td>
<td>231480 ± 160</td>
<td>3</td>
<td>2 – 5</td>
<td>Beam energy</td>
</tr>
<tr>
<td>$1/\alpha_{\text{QED}}(m_2)$ ($\times 10^3$)</td>
<td>$A_{FB}^{\mu\mu}$ (off-peak)</td>
<td>128952 ± 14</td>
<td>4</td>
<td>&lt; 1</td>
<td>Beam energy</td>
</tr>
<tr>
<td>$\alpha_s(m_Z)$ ($\times 10^4$)</td>
<td>$R_i$</td>
<td>1196 ± 30</td>
<td>0.1</td>
<td>0.4 – 1.6</td>
<td>Same as $R_i$</td>
</tr>
<tr>
<td>$m_w$ (MeV)</td>
<td>WW Threshold scan</td>
<td>80385 ± 15</td>
<td>0.6</td>
<td>0.3</td>
<td>Beam energy</td>
</tr>
<tr>
<td>$\Gamma_w$ (MeV)</td>
<td>WW Threshold scan</td>
<td>2085 ± 42</td>
<td>1.5</td>
<td>0.3</td>
<td>Beam energy</td>
</tr>
<tr>
<td>$N_{\nu}$ ($\times 10^3$)</td>
<td>$e^+e^-\rightarrow \gamma Z, Z\rightarrow \nu\nu$, ll</td>
<td>2920 ± 50</td>
<td>0.8</td>
<td>small</td>
<td>Beam energy</td>
</tr>
<tr>
<td>$\alpha_s(m_w)$ ($\times 10^4$)</td>
<td>$B_i = (\Gamma_{\text{had}}/\Gamma_{\text{lep}})_W$</td>
<td>1170 ± 420</td>
<td>2</td>
<td>small</td>
<td>CKM Matrix</td>
</tr>
<tr>
<td>$m_{\text{top}}$ (MeV)</td>
<td>Top Threshold scan</td>
<td>173340 ± 760 ± 500</td>
<td>17</td>
<td>&lt; 40</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>$\Gamma_{\text{top}}$ (MeV)</td>
<td>Top Threshold scan</td>
<td>?</td>
<td>45</td>
<td>&lt; 40</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>$\lambda_{\text{top}}$</td>
<td>Top Threshold scan</td>
<td>$\mu = 1.28 \pm 0.25$</td>
<td>0.10</td>
<td>&lt; 0.05</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>$ttZ$ couplings</td>
<td>$\sqrt{s} = 365$ GeV</td>
<td>± 30%</td>
<td>0.5 – 1.5%</td>
<td>&lt; 2%</td>
<td>QCD corr.</td>
</tr>
</tbody>
</table>
With $m_{\text{top}}$, $m_H$ and $m_W$ known, the standard model has nowhere to go

- Precision of theory predictions may also spoil sensitivity to new physics
- Theoretical calculations need to be brought to higher orders (more later)

Reduced theory uncertainties

Effect of BSM physics
- Modify EW observables through quantum effects (cf top & H @ LEP)
- Blue (direct) & red (Z pole) ellipses may not overlap
- Standard Model may not fit

Improvement from all fronts
- Missing ingredients would spoil sensitivity to BSM physics
e.g. $m_Z$, $\alpha_{\text{QED}}$, $m_{\text{top}}$, ...
- FCC-ee experimental programme well justified and unique
- From Z pole to top threshold with the highest luminosities
Higgs production at the ILC

At the ILC, the SM Higgs boson processes are small, as shown in Fig. 1.4 (Left). As the center-of-mass sections at the ILC are shown in Figs. 1.4 (Left) and (Right) as a function of the collision energy by logarithmically with the center-of-mass energy. The Higgs boson is also produced in association with the Higgsstrahlung process associated Higgs boson production and double Higgs boson production mechanisms. Each particle shown in Fig. 1.1 can be well tested by measuring these branching ratios as well as the a Higgs mass of 126 GeV, a large number of decay modes have similar sizes and are accessible to the Higgs boson mass production), where the Higgsstrahlung process is dominant and the contributions of the fusion process, whereas vector boson fusion is a

In Table 1.2, the predicted value of the total decay width of the Higgs boson is also listed for each value of the Higgs mass.

- 10^6 e^+e^- → ZH events with 5 ab^-1 – cross section predicted with great accuracy
  - Target: (few) per-mil precision, statistics-limited.
  - Complemented with 200k events at √s = 350 – 365 GeV
    - Of which 30% in the WW fusion channel (useful for the Γ_H precision)

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Higgs tagged by a Z, Higgs mass from Z recoil

\[ m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-) \]

- Total rate \( \propto g_{HZZ}^2 \) → measure \( g_{HZZ} \) to 0.2%
- \( ZH \to ZZZ \) final state \( \propto g_{HZZ}^4 / \Gamma_H \) → measure \( \Gamma_H \) to a couple %
- \( ZH \to ZXX \) final state \( \propto g_{HXX}^2 g_{HZZ}^2 / \Gamma_H \) → measure \( g_{HXX} \) to a few per-mil / per-cent
- Empty recoil = invisible Higgs width; Funny recoil = exotic Higgs decays

Note: The HL-LHC is a great Higgs factory (10^9 Higgs produced) but ...

- \( \sigma_{i\to f}^{(\text{observed})} \propto \sigma_{\text{prod}} (g_{Hi})^2 (g_{Hf})^2 / \Gamma_H \)
  - Difficult to extract the couplings: \( \sigma_{\text{prod}} \) is uncertain and \( \Gamma_H \) is largely unknown
    - Must do physics with ratios or with additional assumptions.
## Result of the “kappa” fit

### Relative precisions for HL-LHC and the FCC-ee

<table>
<thead>
<tr>
<th>Collider</th>
<th>HL-LHC</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity (ab⁻¹)</td>
<td>3</td>
<td>5 @ 240 GeV</td>
</tr>
<tr>
<td>Years</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>$\delta \Gamma_H / \Gamma_H$ (%)</td>
<td>SM</td>
<td>2.7</td>
</tr>
<tr>
<td>$\delta g_{HZZ} / g_{HZZ}$ (%)</td>
<td>1.3</td>
<td>0.2</td>
</tr>
<tr>
<td>$\delta g_{HWW} / g_{HWW}$ (%)</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>$\delta g_{HDD} / g_{HDD}$ (%)</td>
<td>2.9</td>
<td>1.3</td>
</tr>
<tr>
<td>$\delta g_{HZc} / g_{Hc}$ (%)</td>
<td>SM</td>
<td>1.7</td>
</tr>
<tr>
<td>$\delta g_{Hgg} / g_{Hgg}$ (%)</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>$\delta g_{ttH} / g_{H}$ (%)</td>
<td>4.4</td>
<td>10.1</td>
</tr>
<tr>
<td>$\delta g_{HHH} / g_{HH}$ (%)</td>
<td>1.6</td>
<td>4.8</td>
</tr>
<tr>
<td>$\delta g_{Htt} / g_{Htt}$ (%)</td>
<td>2.5</td>
<td>-</td>
</tr>
<tr>
<td>BR (90%)</td>
<td>SM (0.0)</td>
<td>&lt;1.2</td>
</tr>
</tbody>
</table>

- The FCC-ee precision better than HL-LHC by large factors (copious modes)
  - With no need for additional assumptions – best on the $e^+e^-$ collider market
- It is important to have two energy points (240 and 365 GeV), as at the FCC-ee
  - Combination better by a factor 2 (4) than 240 (365) GeV alone
- (HL-)LHC measures the $\sigma_{ttH}$, but requires assumptions for the $g_{Htt}$
  - Absolute $g_{Htt}$ measurement in a combination with the FCC-ee (precision: 2.4%)
Combining precision Higgs and EW measurements in SMEFT

- Higgs and EWPO measurements are well complementary ($b, c, \tau$ PO to be added)
- EWPO are more sensitive to heavy new physics (up to 50-70 TeV)
  - Sensitivity was at the level of up to ~5 TeV at LEP
- Larger statistics pays off for Higgs measurements (4 IPs ?)
- Further improvement in theory predictions pays off for EWPO measurements
Precision of theory predictions

- Improving the precision of EW and QCD calculations for the FCC
  - Is a great challenge (exponentially growing number of diagrams with # loops)
  - Has discovery potential (see previous slide)
  - Is therefore recognized as strategic
    - *Included in the FCC-ee CDR volume as a target for “Strategic R&D”*

- First workshop on “Methods and tools” in January 2018
  - 33 participants
  - Produced a 250+ pages proceedings!
  - Conclusion of the workshop
    - We cannot promise, but yes, we can do it!
    - Requires ~500 person-year (50 MCHF) over the next 20 years

- Workshop series is being continued
  - This workshop in January 2019: [https://indico.cern.ch/event/766859/](https://indico.cern.ch/event/766859/)
  - Topics cover the whole FCC-ee programme, 106 registered participants!
    - Z, W, Higgs, top, b, c, QED, Monte Carlo, software, and detector technologies

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FCC-ee workshop: Theory and Experiment

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Pattern of deviations

- May point to specific BSM physics
  - E.g., 4D Composite Higgs Model
    - Deviations in Higgs couplings
      \[ \sqrt{s} = 240, 350, 365 \text{ GeV} \]
    - Deviations in EW top couplings
      \[ \sqrt{s} = 365 \text{ GeV optimal} \]
    - No need for beam polarization
    - Deviations in EW lepton couplings
      - All energies
- Pattern of deviations may become significant
  - Correlations between observations
  - Allow first characterization of the model
  - For example, gauge sector parameters in benchmark A
    - \( f = 1.6 \text{ TeV}, g^* = 1.78, m_{Z'} \sim 3 \text{ TeV}, \Gamma_{Z'} \sim 600 \text{ GeV} \)
    - With the FCC-ee precision
      - \( Z' \) mass predicted with 2% precision
      - Scale \( f \), coupling \( g^* \) predicted with 8% precision

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Direct discoveries

- Discover right-handed neutrinos
  - vMSM: Complete particle spectrum with the missing three right-handed neutrinos
    - Could explain everything: Dark matter (N_2), Baryon asymmetry, Neutrino masses
    - Searched for in very rare Z → νN_{2,3} decays
      - Followed by N_{2,3} → W^+\ell or Zν

Very small νN mixing: long lifetime, detached vertex

A. Blondel et al. arXiv:1411.5230
Discover the dark sector

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

\[ \gamma + E_{\text{MISS}} \text{ for very light } a \]
\[ \gamma\gamma \text{ for light } a \]
\[ \gamma\gamma\gamma \text{ for heavier } a \]

Orders of magnitude of parameter space accessible at FCC-ee
Lepton flavour universality is challenged in $b \to s \ell^+\ell^-$ transitions @ LHCb

- This effect, if real, could be enhanced for $\ell = \tau$, in $B \to K^{(*)} \tau^+\tau^-$
  - Extremely challenging in hadron colliders
  - With $10^{12} Z \to bb$, FCC-ee is beyond any foreseeable competition
    - Decay can be fully reconstructed; full angular analysis possible

- Not mentioning lepton-flavour-violating decays
  - $\text{BR}(Z \to e\tau, \mu\tau)$ down to $10^{-9}$ (improved by $10^4$)
  - $\text{BR}(\tau \to \mu\gamma, \mu\mu\mu)$ down to a few $10^{-10}$
  - $\tau$ lifetime vs $\text{BR}(\tau \to e\nu_e\nu_\tau, \mu\nu_\mu\nu_\tau, \tau)$: lepton universality tests

Talk from A. Bondar

J.F. Kamenik et al.

arXiv:1705.11106

Also $100,000 B_S \to \tau^+\tau^- @ FCC-ee$

Reconstruction efficiency under study
And if there is time ...

- **Spend few years at \( \sqrt{s} = 125.09 \) GeV with high luminosity**
  - For s-channel production \( e^+e^- \rightarrow H \) (a la muon collider, with \( 10^4 \) higher lumi)

- **FCC-ee monochromatization setups**
  - Default: \( \delta \sqrt{s} = 100 \) MeV, \( 25 \) ab\(^{-1}\) / year
    - No visible resonance
  - Option 1: \( \delta \sqrt{s} = 10 \) MeV, \( 7 \) ab\(^{-1}\) / year
    - \( \sigma(e^+e^- \rightarrow H) \approx 100 \) ab
  - Option 2: \( \delta \sqrt{s} = 6 \) MeV, \( 2 \) ab\(^{-1}\) / year
    - \( \sigma(e^+e^- \rightarrow H) \approx 250 \) ab
  - Backgrounds much larger than signal
    - \( e^+e^- \rightarrow q\bar{q}, \tau\tau, WW^*, ZZ^*, \gamma\gamma, \ldots \)

- **Expected signal significance of \( \approx 0.4\sigma / \sqrt{\text{year}} \) in both option 1 and option 2**
  - Set a electron Yukawa coupling upper limit: \( \kappa_e < 2.5 \) @ 95% C.L.
  - Reaches SM sensitivity after five years (or 2.5 years with 4 IPs)

- **Unique opportunity to constrain first generation Yukawa’s**
Is a $\sqrt{s} = 500$ GeV upgrade required/useful?

- From European Strategy Update in 2013:

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.

ESPP Update 2013, CERN Council
Is a $\sqrt{s} = 500$ GeV upgrade required/useful?

- According to the white book of ESU 2013:
  
  At energies of 500 GeV or higher, such a machine could explore the Higgs properties further, for example the coupling to the top quark, the self-coupling, and the total width.
  
  - The same arguments are used by some documents submitted to ESU 2020!
  - So, should we foresee an upgrade of FCC-ee at $\sqrt{s} = 500$ GeV?
    - For the total width and the coupling to the top quark: the answer is NO (slide 14)
    - For the Higgs self-coupling ($\kappa_\lambda$):

At $\sqrt{s} = 500$ GeV

- Di-Higgs production

At FCC-ee

- $\sigma_{HZ}$

M. McCullough
arXiv:1312.3322
Higgs self-coupling at the FCC-ee

- Effect of Higgs self coupling ($\kappa_\lambda$) on $\sigma_{ZH}$ and $\sigma_{\nu H}$ depends on $\sqrt{s}$

- Two energy points lift off the degeneracy between $\delta\kappa_Z$ and $\delta\kappa_H$
  - Precision on $\kappa_\lambda$ with 2 IPs at the end of the FCC-ee (91+160+240+365 GeV)
    - Global EFT fit (model-independent) : $\pm 34\% (3\sigma)$ ; in the SM : $\pm 12\%$
  - Precision on $\kappa_\lambda$ with 4 IPs : $\pm 21\%$ (EFT fit) ($5\sigma$) ; $\pm 9\%$ (SM fit)
    - $5\sigma$ discovery with 4 IPs instead of 2 – much less costly than 500 GeV upgrade (in time and funds, in view of FCC-hh)

- And, most importantly
  - Only FCC-hh, in combination with FCC-ee, can measure $\kappa_{\text{top}}$ and $\kappa_\lambda$ to 1% and 5%, resp.
Synergies and complementarities with 100 TeV pp collider

- **Higgs physics**
  - ee breaks model dependence ($\Gamma_{Ht}$, $g_{HZZ}$) – and measures precisely top EW couplings
    - Turns $\sigma(ttH)$ measurement @ HL-LHC to an absolute $ttH$ coupling precision of 3%
    - First 3-4$\sigma$ observation or 5$\sigma$ discovery of the Higgs self coupling, without a 500 GeV upgrade
  - pp measures ratios-of-BR and gives huge statistics of $ttZ$, $ttH$, and HH events
    - Bring top Yukawa and Higgs self coupling precisions to the per-cent level, in particular

- **Search for heavy physics (with at least weak couplings)**
  - ee gives precision measurements sensitive to heavy physics up to 50 TeV and more
    - Patterns of deviations may points to specific BSM
  - pp gives access to direct observation at unprecedented masses and $p_T$’s
    - Also huge samples of Z, W, Higgs, top

- **Right-handed neutrinos (and all very weakly-coupled particles)**
  - ee: powerful and clean, but flavour blind: $Z \rightarrow \nu N$, all $\nu$ flavours together
  - hh: more difficult, but charge- and flavour-sensitive: $W \rightarrow l_1 (Q_1) N, N \rightarrow l_2 (Q_2) W^*$

- **Flavour “anomalies” (if they persist – rich flavour physics programme otherwise)**
  - ee beyond any foreseeable competition with in $B \rightarrow K^{(*)} \tau^+\tau^-$ and $B_s \rightarrow \tau^+\tau^-$
  - hh gives direct access to Z’ gauge bosons and leptoquarks

- **QCD**
  - ee gives $\alpha_s$ to ±0.0002 or better (Rf for Z and W), but also 100k $H \rightarrow gg$ (gluon fragmentation!)
  - Improves signal and background predictions for new physics discovery at pp
Conclusions

- The FCC design study is establishing the feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology
  - The FCC CDR is on the verge of being publicly released and published

- Both FCC-ee and FCC-hh have outstanding physics cases
  - Each in their own right (Electroweak Factory and Energy Frontier)
  - The sequential implementation: FCC-ee → FCC-hh maximises the physics reach
    - Taking full advantage of multiple synergies and complementarities
  - Can serve High-Energy Physics in a cost effective manner throughout the 21st century

- The FCC-ee design is now robust and mature
  **FCC-ee can start physics seamlessly at the end of HL-LHC**
  - We must get ready to move to the next step – *many routes are barely touched*
    - Prepare MDI mechanical infrastructure
    - Work on several (at least four) detector proposals
    - Requires full simulation / reconstruction within user-friendly FCC software
    - Bring theory precision on par with experimental sensitivity