Bias alert

- I am the US representative to the FCC “Physics, Detectors, Experiments” executive committee.
- I am a member of the US DOE/NSF Higgs factory steering committee (4 members)
- I am very excited about the physics of future electron-positron colliders.

About me:
- B.A. Gettysburg college 1984
- PhD U. Rochester AMY experiment at KEK in Japan
- Postdoc U. Chicago CDF experiment at Tevatron
- Faculty at Maryland since 1993 working on the DØ experiment at the Tevatron, the CMS experiment at the LHC, and FCC.

Known for my work in
- Studies of QCD using W and Z bosons
- W mass, W width
- New particle searches (4th generation quarks, leptoquarks, dark matter with a QCD-like dark sector)
- Radiation damage in plastic scintillators
- Calorimetry (especially dual-readout crystal calorimetry)

I love both ATLAS and ILC but will often forget to show them my love. I have only two slides on CEPC, although I think it is also great.

Also I’m vice chair of the DPF division of APS so please join now so we can have our fair number of fellows.

8/6/2024
S. Eno, SLAC summer school, 2024
e^+e^- colliders have long been a leading source of our knowledge of the Higgs boson

The previous denizen of the LHC tunnel told us exactly where to look. LEP 1989 – 2000.
And since its discovery at LHC, we have learned a lot more

Higgs cross section at 14 TeV is ~60 pb (arXiv:2209.07510). 300 fb$^{-1}$ yields about $2 \times 10^7$ Higgs.
A historical aside...

The history of our field would have been very different if LEP 2 had been able to go just a little higher.
Higgs

So far, it may be that the EWK symmetry is broken via the textbook version of the Higgs mechanism. But we do not know:

- if Higgs gives mass to first and second generation quarks.
- what sets its Yukawa couplings.
- what gives neutrinos their mass?
- if dark matter is indeed a massive particle, what gives it its mass?
- Since the Higgs determines the CKM matrix, it is the source of SM CP violation in the quark sector. Is there more to this interesting fact?
- Are there any new particles that affect its couplings to the known particles via loop corrections? (or even at tree level through mixing)

We are here

300 fb⁻¹

2024-2025
LHC Run 3

2026-2028
LS3

2029-2041
HL-LHC

3000 fb⁻¹

We will get increased precision, maybe extending to new areas such as coupling to charm quarks and the Higgs triple coupling, during the HL-LHC running. What will remain to learn at a new e⁺e⁻ machine? What are some challenges with what we will be learning at HL-LHC.
Higgs nomenclature

Sometimes κ
sometimes µ

At the LHC, each measurable is a product of terms related to production and to decay. Some of these contain more than one κ. We’ll discuss e⁺e⁻ later.
In Scenario 1, all systematic uncertainties are left unchanged. In Scenario 2, the theoretical uncertainties are scaled by a factor of 1/2, while other systematic uncertainties are scaled by the square root of the integrated luminosity.

<table>
<thead>
<tr>
<th>L (fb(^{-1}))</th>
<th>(\gamma\gamma)</th>
<th>WW</th>
<th>ZZ</th>
<th>bb</th>
<th>(\tau\tau)</th>
<th>Z(\gamma)</th>
<th>(\mu\mu)</th>
<th>inv.</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>[6, 12]</td>
<td>[6, 11]</td>
<td>[7, 11]</td>
<td>[11, 14]</td>
<td>[8, 14]</td>
<td>[62, 62]</td>
<td>[40, 42]</td>
<td>[17, 28]</td>
</tr>
<tr>
<td>3000</td>
<td>[4, 8]</td>
<td>[4, 7]</td>
<td>[4, 7]</td>
<td>[5, 7]</td>
<td>[5, 8]</td>
<td>[20, 24]</td>
<td>[20, 24]</td>
<td>[6, 17]</td>
</tr>
</tbody>
</table>

\[
\sqrt{10} \sim 3.2 \quad [1.5, 1.5] \quad [1.5, 1.6] \quad [1.7, 1.6] \quad [2.2, 2] \quad [1.6, 1.7] \quad [3.1, 2.6] \quad [2.1, 7] \quad [2.8, 1.6]
\]

Surely will gain a factor of 1.5 to 2. May gain more (hard to know) Maybe at 2-10%?
What these precisions mean...

Some models do exceed these reaches for a given precision. HL-LHC puts us at 2-10%
Maybe enough. Or...

Report of the Topical Group on Higgs Physics for Snowmass 2021:
The Case for Precision Higgs Physics
https://arxiv.org/abs/2209.07510

Table 3: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(\delta WW)$ and $g(\delta ZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\delta t\bar{t}$</th>
<th>$c\bar{c}$</th>
<th>$gg$</th>
<th>$WW$</th>
<th>$\tau\tau$</th>
<th>$ZZ$</th>
<th>$\gamma\gamma$</th>
<th>$\rho\rho$</th>
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</thead>
<tbody>
<tr>
<td>MSSM [49]</td>
<td>+4.8</td>
<td>-0.8</td>
<td>-0.8</td>
<td>-0.2</td>
<td>+0.4</td>
<td>-0.5</td>
<td>+0.1</td>
<td>+0.3</td>
</tr>
<tr>
<td>Type II 2HD [42]</td>
<td>+10.1</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0.0</td>
<td>+9.8</td>
<td>0.0</td>
<td>+0.1</td>
<td>+9.8</td>
</tr>
<tr>
<td>Type X 2HD [42]</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0.0</td>
<td>+7.8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>+7.8</td>
</tr>
<tr>
<td>Type Y 2HD [42]</td>
<td>+10.1</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0.0</td>
<td>-0.2</td>
<td>0.0</td>
<td>0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>Composite Higgs [44]</td>
<td>-6.4</td>
<td>-6.4</td>
<td>-6.4</td>
<td>-2.1</td>
<td>-2.1</td>
<td>-2.1</td>
<td>-6.4</td>
<td>-6.4</td>
</tr>
<tr>
<td>Little Higgs w. T-parity [45]</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-6.1</td>
<td>-2.5</td>
<td>0.0</td>
<td>-2.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Little Higgs w. T-parity [46]</td>
<td>-7.8</td>
<td>-4.6</td>
<td>-3.5</td>
<td>-1.5</td>
<td>-7.8</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-7.8</td>
</tr>
<tr>
<td>Higgs-Strangeness [47]</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>Higgs Singlet [48]</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
</tr>
</tbody>
</table>

Often, the reach goes as $\sqrt{p}$
Factor 10 is factor of 3
Or we may end up here.

Pushing down systematic uncertainties can be done, but it requires cross checks. Some systematics can be reduced more reliably than others.

CDF: $80433 \pm 9$ MeV (0.01% measurement)
Measurements of the Higgs boson production cross section and couplings in the WW boson pair decay channel in proton-proton collisions at √s=13 TeV:


Chart shows clearly the need for the emphasis of this school. This will also apply to FCCee.

Getting the experimental uncertainties down in a high pileup environment will give experimentalists lots of fun. Not a trivial challenge.
A new hope

We are here

Given our other scientific commitments, an “affordable” path to make sure there is no gap in having a running high energy collider.

Recommendation 2

a. **CMB-S4**, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals (section 4.2).

b. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

c. **An off-shore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 8), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics (section 3.2).

d. **An ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4.1).

e. **IceCube-Gen2** for study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter covering higher mass ranges using neutrinos as a tool (section 4.1).

All good things must end. 2041 is only 17 years from now.
ILC and FCC-ee

Seventeen years is a short time. Luckily we have two options that we have a high confidence can be made to work on this time scale that can produce large, clean Higgs samples.

Shiltsev, DPF-Pheno 2024
Any new machine is hard

Nakayama, London

All accelerator physics is hard, even “relatively straightforward” plans. This can happen at any option.
seventeen years is a short time
accelerator physics is a very challenging highly technical area

Vladimir Shiltsev: DPF/Pheno 2024 in Pittsburg

Hard “Simple” Question

- Why does it (“your accelerator R&D”) take so long?
  - 1990’s: SLAC linac had 17 MV/m → Now: XFEL has ~25 MV/m (ILC 31.5 MV/m)
  - Muon collider R&D since 1990s → Now: still no CDR
  - 2000s: LHC 8 T NbTi SC magnets → Now: still no 16 T magnets
  - 2006: 1 GeV plasma acceleration stage → Now: still no demo of multistage

- No “simple” answer … combination of:
  - Our modern-day technologies are too far from industrial applications
  - Chasing “pCM dreams”: 100 GeV → 1 TeV → 10 TeV → 100 TeV → PeV ??
    - Higher energy, higher luminosity, larger [size, cost, power, complexity] → more [$$, people, time] for R&D
  - Always – limited budget… more and more often - inadequate expertise:
    - bigger scale + “brain drain” to other fields + beam physics abandoned at Universities (in the US)
Higgs and so much more

FCC-ee nominal strawman run plan

<table>
<thead>
<tr>
<th>Working point</th>
<th>Z, years 1-2</th>
<th>Z, later</th>
<th>WW, years 1-2</th>
<th>WW, later</th>
<th>ZH</th>
<th>t tt</th>
</tr>
</thead>
<tbody>
<tr>
<td>√s (GeV)</td>
<td>88, 91, 94</td>
<td>157, 163</td>
<td>240</td>
<td>340-550</td>
<td>305</td>
<td></td>
</tr>
<tr>
<td>Lumi/IP (10^{34} cm^{-2} s^{-1})</td>
<td>70</td>
<td>140</td>
<td>10</td>
<td>29</td>
<td>5.0</td>
<td>0.75</td>
</tr>
<tr>
<td>Lumi/year (ab^{-1})</td>
<td>34</td>
<td>68</td>
<td>4.8</td>
<td>9.6</td>
<td>2.4</td>
<td>0.36</td>
</tr>
<tr>
<td>Run time (year)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Number of events: $6 \times 10^{32} Z \times 2.4 \times 10^8 WW \times 1.9 \times 10^{4} ZH + 1.9 \times 10^{6} ZH$

ILC nominal strawman run plan

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>91 GeV</th>
<th>250 GeV</th>
<th>350 GeV</th>
<th>500 GeV</th>
<th>1000 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>f Z (ab^{-1})</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>duration (yr)</td>
<td>1.5</td>
<td>11</td>
<td>0.75</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>beam polarization (e^-/e^+; %)</td>
<td>80/30</td>
<td>80/30</td>
<td>80/30</td>
<td>80/30</td>
<td>80/20</td>
</tr>
<tr>
<td>$\gamma$ (6, ++, +, +) (%)</td>
<td>(10, 40, 40, 10)</td>
<td>(10, 40, 40, 10)</td>
<td>(5, 45, 45, 5)</td>
<td>(5, 45, 45, 5)</td>
<td>(10, 40, 40, 10)</td>
</tr>
<tr>
<td>$\delta_{BR}$ (%)</td>
<td>10.8</td>
<td>11.7</td>
<td>12.0</td>
<td>12.4</td>
<td>13.0</td>
</tr>
<tr>
<td>$\delta_{BS}$ (%)</td>
<td>0.16</td>
<td>2.6</td>
<td>1.9</td>
<td>4.5</td>
<td>10.5</td>
</tr>
</tbody>
</table>

For more on these machines, see https://arxiv.org/abs/2209.14136

- It is interesting to note that HL-LHC gives about 2E8 Higgs while FCCee will give about 1E6 Higgs
- Linear colliders allow polarization, which is a great asset for exploring EWK physics due to its V-A structure
Higgs at $e^+e^-$

- Model independent coupling measurements
- Measurement of loop corrections to the Higgs couplings
- “Closure” tests of the standard model
- Decay channels too difficult to handle in hadron collider environment

I’ve always been a fan of closure tests. But of course observing Higgs to dark matter would also be super cool.
One of the strengths of the LHC program is the access to so many Higgs production diagrams. This benefit can also be accessed at FCCee.

Run plan for optimal Higgs studies involves two energies, 240 and 365 to pick up the two main diagrams (365 also gives us the $\tt$ sample).

We can also see there are *in principle* non-trivial backgrounds (it is a log plot).
Higgs mass

At the LHC, the Higgs mass is measured in ZZ to 4 leptons and $\gamma\gamma$ final states. Current measurement (pdg) is $125.20 \pm 0.11$ GeV using 25 $fb^{-1}$ of data. Projected HL-LHC should roughly scale as $1/\sqrt{2500/25}=1/10$ (about 0.01 GeV).

https://new-cds.cern.ch/doi/10.17181/jfb44-sod81

To see the new physics beyond the Higgs loop, need mass to about 10 MeV or better.

$$\sin^2 \theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1 - \Delta r}$$

$$\Delta r \sim \ln(m_h)$$

If we want to measure the Higgs coupling to electrons, need to know this number to about 4 MeV.

Might guess you would measure it in $e^+e^-$ collisions in a similar way.
Higgs can be identified independent of decay mode using the “missing mass” or “boson recoil mass” method. If an event has an identified Z boson, use its 3-momentum as the 3-momentum of the recoil particle and the center-of-mass collision energy to calculate the mass of whatever is recoiling against the Z.

The ZZ background is not negligible, so works best if you can use a Z decay with excellent resolution, generally Z to muons (with a really great tracker).
Missing mass

Muons!

Although the jet channel is certainly usable
Note that for FCCee Z pole running, the magnetic field is limited to 2T to achieve luminosity goals. Not a requirement at ZH, although designing magnets and detectors to work well at different fields can be challenging.
Missing mass and H mass

- Invariant mass of the di-lepton pair: $86 \text{ GeV} < m_{ee} < 96 \text{ GeV}$ (Fig. A1);
- Di-lepton momentum: $20 \text{ GeV} < p_{ee} < 70 \text{ GeV}$ (Fig. A2);
- Recoil mass: $120 \text{ GeV} < m_{\text{recoil}} < 140 \text{ GeV}$ (Fig. A3);
- Cosine of missing momentum: $|\cos(\theta_{\text{miss}})| < 0.98$ (Fig. A4).

For Higgs, this last cut has a decay-mode dependency (but is very good at getting rid of the Z (not ZZ) background)

Expected uncertainty combining all channels and energies around $0.0038 \text{ GeV}$
Work needed on resolution measurements, beam energy spread
Cross sections

At a future Higgs factor, cross section measurements are the key. These are the measurements that give us the access to the partial widths (and thus the loops).

These need to be measured as precisely as possible
• A precision measurement of the total Higgs cross section in a model-independent way using the missing mass.
• Excellent control over luminosity calculation
• Excellent control acceptance/efficiency
• Compare to a highly precise theory calculation

Results often reported using the kappa framework (there are variations regarding how possible non-SM decays are included).

\[
\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\text{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\text{SM}}}
\]

(sometimes \( \mu \) is used instead of \( \kappa \))

High precision on the calculated SM value in the denominator is required.
What we measure is a cross section for a production mode and a decay. And not really even that, since each set of selection criteria is only enriched in a single production+decay diagram. For this analysis, at least the VH seems clean.

Expected signal composition in each STXS bin. Generator-level bins are reported in the horizontal axis, and the corresponding analysis categories on the vertical axis.

arXiv:2206.09466
Giant fit

Input analyses

- Single H: all the main production channels and decay modes
- HH: GGF, VBF and VHH modes
- An extremely large statistical combination
- Guess how many parameters are used?

6500 parameters

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Int. luminosity (fb⁻¹)</th>
<th>Max. granularity</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>138</td>
<td>STXS 1.2</td>
<td>Eur. Phys. J. C 81 (2021) 488</td>
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<tr>
<td>$ggH (bb)$</td>
<td>138</td>
<td>Inclusive</td>
<td>JHEP 12 (2020) 085</td>
</tr>
<tr>
<td>$VH \rightarrow bb$</td>
<td>77</td>
<td>Inclusive</td>
<td>Phys. Rev. Lett. 121 121801</td>
</tr>
<tr>
<td>$t\bar{t}H (bb)$</td>
<td>36</td>
<td>Inclusive</td>
<td>JHEP 03 (2019) 026</td>
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<tr>
<td>$t\bar{t}H$ multilepton</td>
<td>138</td>
<td>Inclusive</td>
<td>Eur. Phys. J. C 81 (2021) 378</td>
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<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>138</td>
<td>Inclusive</td>
<td>JHEP 01 (2021) 148</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>138</td>
<td>STXS 1.2</td>
<td>JHEP 07 (2021) 027</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>138</td>
<td>STXS 1.2</td>
<td>JHEP 03 (2021) 257</td>
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<tr>
<td>$H \rightarrow WW$</td>
<td>138</td>
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<td>Eur. Phys. J. C 83 (2023) 562</td>
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HH searches

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Int. luminosity (fb⁻¹)</th>
<th>Targeted production modes</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HH \rightarrow b\bar{b}\gamma$</td>
<td>138</td>
<td>$ggHH$ and $qqHH$</td>
<td>JHEP 03 (2021) 257</td>
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<td>$HH \rightarrow b\bar{b}\gamma$</td>
<td>138</td>
<td>$ggHH$ and $qqHH$</td>
<td>Phys. Lett. B 812 (2023) 137531</td>
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<tr>
<td>$HH \rightarrow b\bar{b}b\bar{b}$ (resolved)</td>
<td>138</td>
<td>$ggHH$ and $qqHH$</td>
<td>Phys. Rev. Lett. 129 041802</td>
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<tr>
<td>$HH \rightarrow b\bar{b}b\bar{b}$ (boosted)</td>
<td>138</td>
<td>$ggHH$ and $qqHH$</td>
<td>Phys. Rev. Lett. 131 041803</td>
</tr>
<tr>
<td>$HH$ (leptons)</td>
<td>138</td>
<td>$ggHH$</td>
<td>JHEP 2307 (2023) 005</td>
</tr>
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<td>$HH \rightarrow b\bar{b}WW$</td>
<td>138</td>
<td>$ggHH$ and $qqHH$</td>
<td>CMS-PAS-HIG-21-005</td>
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<td>$VHH \rightarrow b\bar{b}$</td>
<td>138</td>
<td>VHH</td>
<td>CMS-PAS-HIG-22-006</td>
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<table>
<thead>
<tr>
<th>Runtime</th>
<th>Memory usage (GB)</th>
</tr>
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<tbody>
<tr>
<td>Workspace creation</td>
<td>2-3 days</td>
</tr>
<tr>
<td>Fit Asimov dataset</td>
<td>12-24 hours</td>
</tr>
<tr>
<td>Impacts of systematic uncertainties</td>
<td>7-8 days</td>
</tr>
</tbody>
</table>
At the LHC, each measurable involves at least two couplings (production and decay). By measuring several processes, the individual couplings can be disentangled, but with substantial correlations.

And anybody who has ever done this kind of fit will surely agree with the quoted text from the paper.
Right now, uncertainties on cross sections at hadron colliders can be substantial.

Uncertainties on branching fractions tend to be around 2%.
At $e^+e^-$, again use the missing mass magic

e$^+e^-$ collisions allows a very pure extraction of the ZH cross section.

Removing the Z suppression cut to remove virtually all dependence on Higgs decay mode at the cost of additional backgrounds.

https://new-cds.cern.ch/records/a68b8-3mt57
But we still need to compare to the predicted values. And the theory calculations require input of measured SM parameters.
To understand Higgs, need to understand the Z

This plot shows the ratio of the uncertainty in a scenario to that if all EWK parameters were known to infinite precision. As you can see, reducing the uncertainties on fundamental EWK parameters at the Z running has a strong impact on error bars on all measurements. (take say the turquoise $\delta g_H^{ZZ}$. . . . with Z running the uncertainty is just over than 1. without it is almost 2.

No orange line connects the Higgs to the EWK, illustrating broken correlation
## Orders of magnitude

<table>
<thead>
<tr>
<th>Observable</th>
<th>present value (GeV)</th>
<th>error</th>
<th>present value (GeV)</th>
<th>error</th>
<th>Comment and loading error</th>
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</thead>
<tbody>
<tr>
<td>$m_Z$</td>
<td>91187000</td>
<td>± 2000</td>
<td>4</td>
<td>100</td>
<td>From Z line shape scan, Beam energy calibration</td>
</tr>
<tr>
<td>$\Gamma_Z$</td>
<td>2490200</td>
<td>± 2000</td>
<td>4</td>
<td>25</td>
<td>From Z line shape scan, Beam energy calibration</td>
</tr>
<tr>
<td>$\sin^2\theta_W$</td>
<td>231480</td>
<td>± 160</td>
<td>2</td>
<td>2.4</td>
<td>From $\Delta m^2_{31}$ at Z peak, Beam energy calibration</td>
</tr>
<tr>
<td>$\sin^2\theta_{QED}$</td>
<td>128952</td>
<td>± 14</td>
<td>3</td>
<td>small</td>
<td>From $\Delta m^2_{31}$ off peak, QED/LEW errors dominate</td>
</tr>
<tr>
<td>$B_f^2$</td>
<td>20767</td>
<td>± 25</td>
<td>0.06</td>
<td>0.2-1</td>
<td>Ratio of hadrons to leptons, Acceptance for leptons</td>
</tr>
<tr>
<td>$\alpha_{em}(m_Z^2)$</td>
<td>1196</td>
<td>± 30</td>
<td>0.1</td>
<td>0.4-1.6</td>
<td>From $B_f^2$</td>
</tr>
<tr>
<td>$\alpha_{em}^2$</td>
<td>41541</td>
<td>± 37</td>
<td>0.1</td>
<td>4</td>
<td>Peak hadronic cross-section, Luminosity measurement</td>
</tr>
<tr>
<td>$N_e(x^0)$</td>
<td>2006</td>
<td>± 7</td>
<td>0.005</td>
<td>1</td>
<td>Z peak cross-section, Luminosity measurement</td>
</tr>
<tr>
<td>$R_b$</td>
<td>212900</td>
<td>± 660</td>
<td>0.3</td>
<td>&lt; 60</td>
<td>Ratio of $b\to s$ to hadrons, Stat. extrapol. from SLD</td>
</tr>
<tr>
<td>$\Delta m^2_{31}$</td>
<td>992</td>
<td>± 16</td>
<td>0.02</td>
<td>1.3</td>
<td>b-quark asymmetry at Z pole, From jet charge</td>
</tr>
<tr>
<td>$A_{FB}^{\tau}$</td>
<td>1488</td>
<td>± 49</td>
<td>0.15</td>
<td>&lt; 2</td>
<td>$\tau$ polarization asymmetry, $\tau$ decay physics</td>
</tr>
<tr>
<td>$\tau$ lifetime (fs)</td>
<td>2903</td>
<td>± 0.5</td>
<td>0.001</td>
<td>0.04</td>
<td>Radial alignment</td>
</tr>
<tr>
<td>$\tau$ mass (MeV)</td>
<td>1776.86</td>
<td>± 0.12</td>
<td>0.004</td>
<td>0.04</td>
<td>Momentum scale</td>
</tr>
<tr>
<td>$\tau$ leptonic ($\mu^0_p\nu\tau$) B.R. (%)</td>
<td>17.38</td>
<td>± 0.04</td>
<td>0.0001</td>
<td>0.003</td>
<td>$\mu^0_p$/hadron separation</td>
</tr>
<tr>
<td>$m_W$ (MeV)</td>
<td>80350</td>
<td>± 15</td>
<td>0.25</td>
<td>0.3</td>
<td>From WW threshold scan, Beam energy calibration</td>
</tr>
<tr>
<td>$\Gamma_W$ (MeV)</td>
<td>2085</td>
<td>± 42</td>
<td>1.2</td>
<td>0.3</td>
<td>From WW threshold scan, Beam energy calibration</td>
</tr>
<tr>
<td>$\alpha_{em}(m_Z^2)$</td>
<td>1010</td>
<td>± 270</td>
<td>3</td>
<td>small</td>
<td>From $B_f^2$</td>
</tr>
<tr>
<td>$N_e(x^0)$</td>
<td>2020</td>
<td>± 50</td>
<td>0.8</td>
<td>small</td>
<td>Ratio of invic. to leptonic, in radiative Z returns</td>
</tr>
<tr>
<td>$m_{top}$ (MeV)</td>
<td>172740</td>
<td>± 500</td>
<td>17</td>
<td>small</td>
<td>From $t\bar{t}$ threshold scan, QCD errors dominate</td>
</tr>
<tr>
<td>$\Gamma_{top}$ (MeV)</td>
<td>1419</td>
<td>± 190</td>
<td>45</td>
<td>small</td>
<td>From $t\bar{t}$ threshold scan, QCD errors dominate</td>
</tr>
<tr>
<td>$\lambda_{top}/\Lambda_{QCD}^{SM}$</td>
<td>1.2</td>
<td>± 0.3</td>
<td>0.10</td>
<td>small</td>
<td>From $t\bar{t}$ threshold scan, QCD errors dominate</td>
</tr>
<tr>
<td>t+jZ couplings</td>
<td>± 30%</td>
<td>0.5 - 1.5 %</td>
<td>small</td>
<td>From $\sqrt{s} = 65$ GeV run</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>total FCC</th>
<th>error/past</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>90</td>
<td>6</td>
</tr>
<tr>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>17</td>
</tr>
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<td>20</td>
<td>16</td>
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<tr>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>200</td>
</tr>
<tr>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
</tr>
<tr>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>1.2</td>
</tr>
<tr>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
Once we have the ZH cross section regardless of branching ratio, each decay mode directly measures only one coupling.

Not a surprise that we improve most regarding the coupling to the Z at what is essentially a Z factory.

https://new-cds.cern.ch/records/511pr-rd590

<table>
<thead>
<tr>
<th>Coupling</th>
<th>HL-LHC (%)</th>
<th>FCC-ee 4 IPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_W$ [%]</td>
<td>1.5*</td>
<td>0.33</td>
</tr>
<tr>
<td>$\kappa_Z$ [%]</td>
<td>1.3*</td>
<td>0.14</td>
</tr>
<tr>
<td>$\kappa_t$ [%]</td>
<td>2*</td>
<td>0.77</td>
</tr>
<tr>
<td>$\kappa_{\gamma}$ [%]</td>
<td>1.6*</td>
<td>1.2</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$ [%]</td>
<td>10*</td>
<td>10</td>
</tr>
<tr>
<td>$\kappa_c$ [%]</td>
<td>-</td>
<td>1.1</td>
</tr>
<tr>
<td>$\kappa_b$ [%]</td>
<td>3.2*</td>
<td>3.1</td>
</tr>
<tr>
<td>$\kappa_\mu$ [%]</td>
<td>2.5*</td>
<td>0.56</td>
</tr>
<tr>
<td>$\kappa_\tau$ [%]</td>
<td>1.6*</td>
<td>0.55</td>
</tr>
<tr>
<td>BR$_{inv}$ (&lt;%, 95% CL)</td>
<td>1.9*</td>
<td>0.15</td>
</tr>
<tr>
<td>BR$_{unt}$ (&lt;%, 95% CL)</td>
<td>4*</td>
<td>0.88</td>
</tr>
</tbody>
</table>
Higgs width

Non standard modeling decay modes of the Higgs give an increased width.

Could the Higgs provide dark matter mass? a portal to a dark sector? or to other light or long-lived particles? Or to particles whose backgrounds are too large to allow detection?

Standard model prediction for the Higgs width is 4.07 MeV $\pm 4\%$ (pdg)
Standard model prediction for BR to invisible is the negligible contribution from ZZ to four neutrinos ($10^{-3}$).

SUSY-based “glueballs” model as function of top partner mass.

https://link.springer.com/article/10.1140/epjc/s10052-019-6904-3
At LHC

Current measurement at LHC is $3.7^{+1.9}_{-1.4}$ Mev (pdg) (50% measurement)
After HL-LHC, maybe 14% measurement? (including invisible decays in the model-dependent fit to all cross sections gives 6-17% uncertainty)

Measurement also done in $l\bar{v}v$ channel

Note the interference term between continuum and signal is destructive.
Higgs width at $e^+e^-$

Much easier, much less model dependent at a Higgs factory

Two ways:
- Both start with $ZH$ cross section at 240 GeV
  - First uses $ZH \rightarrow ZZ^{*}$ at 240 GeV (about a 4.6% measurement)
  - Second uses $\nu\nu H \rightarrow bb$ at 370 GeV (about a 3.2% measurement)
- These two plus other channels for the second method could lead to about 1% measurement

Although combining many few percent measurements to get a 1% measurement is never a trivial thing to do
Well, maybe these things are harder than I’m implying.

Many of the decay modes we want to measure are hadronic.

And surely we’ll want to look for flavor violating decays as well.
These are interesting. Consider Higgs to gluon

**Higgs → gg decay and BSM**

- **H → gg partial width** known today theoretically at N^{4LO} (approx) accuracy

![Diagram showing Higgs decay to gluons]

- **Percent deviations on Higgs-gluon coupling in BSM models:**

<table>
<thead>
<tr>
<th>Model</th>
<th>bb</th>
<th>αχ</th>
<th>gg</th>
<th>WW</th>
<th>ττ</th>
<th>ZZ</th>
<th>γγ</th>
<th>μμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MSSM [40]</td>
<td>+4.8</td>
<td>-0.8</td>
<td>-0.8</td>
<td>-0.2</td>
<td>+0.4</td>
<td>-0.5</td>
<td>+0.1</td>
<td>+0.3</td>
</tr>
<tr>
<td>2 Type II 2HD [42]</td>
<td>+10.1</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0.0</td>
<td>+9.8</td>
<td>0.0</td>
<td>+0.1</td>
<td>+9.8</td>
</tr>
<tr>
<td>3 Type X 2HD [42]</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0.0</td>
<td>-7.8</td>
<td>0.0</td>
<td>0.0</td>
<td>+7.8</td>
</tr>
<tr>
<td>4 Type Y 2HD [42]</td>
<td>+10.1</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0.0</td>
<td>-0.2</td>
<td>0.0</td>
<td>0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>5 Composite Higgs [44]</td>
<td>-6.4</td>
<td>-6.4</td>
<td>-6.4</td>
<td>-2.1</td>
<td>-6.4</td>
<td>-2.1</td>
<td>-2.1</td>
<td>-6.4</td>
</tr>
<tr>
<td>6 Little Higgs w. T-parity [45]</td>
<td>0.0</td>
<td>0.0</td>
<td>-6.1</td>
<td>-2.5</td>
<td>0.0</td>
<td>-2.5</td>
<td>-1.5</td>
<td>0.0</td>
</tr>
<tr>
<td>7 Little Higgs w. T-parity [46]</td>
<td>-7.8</td>
<td>-4.6</td>
<td>-3.5</td>
<td>-1.5</td>
<td>-7.8</td>
<td>-1.5</td>
<td>-1.0</td>
<td>-7.8</td>
</tr>
<tr>
<td>8 Higgs-Radion [47]</td>
<td>-1.5</td>
<td>-1.5</td>
<td>+1.0</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.0</td>
<td>-1.5</td>
</tr>
<tr>
<td>9 Higgs Singlet [48]</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
</tr>
</tbody>
</table>


Biggest change for some model.

Also pattern can help distinguish between different models.
So need to ID jet flavor

Kaon (strange) tagging could be key to this program

Although note that this is not easy. The differences in the kaon content are not large, and training on MC could lead to biases due to uncertainties in fragmentation.

arXiv:2310.03440
Charm fragmentation

https://arxiv.org/abs/2105.06335

Some disagreement between LEP and b factories. Considerable disagreement between these and pp.

Charm-quark fragmentation fractions into charm hadrons measured in pp collisions at $\sqrt{s} = 5.02$ TeV in comparison with experimental measurements performed in $e^+e^-$ collisions at LEP and at B factories, and in ep collisions at HERA.
Unlike at ATLAS/CMS, kaon ID will be available

**Diagram:**

- Time of flight 30 ps dN/dx via “cluster counting”

**Text:**

It has been realized previously that cluster counting might greatly improve the particle identification. It is believed that most of the relativistic rise of energy loss is due to the increase of the number of primary collisions. The energy content of the cluster is almost independent of particle velocity, and its fluctuations are responsible for the large fluctuations in conventional total charge measurement.


**Points:**

- He based gas mixtures \( \rightarrow \) signals from ionization acts are spread in time to few ns
- Fast read-out electronics (GHz sampling) \( \rightarrow \) efficiently identify them
- Counting dN/dx (# of ionization acts per unit length) \( \rightarrow \) make possible to identify particles (P.I.D.) with a better resolution than dE/dx
- Collect signal and identify peaks
- record the arrival time of the clusters generated in every ionisation act (+12cm⁻¹)
- reconstruct the trajectory at the most likely position

**Equations:**

\[
\frac{\sigma_{\text{d}E/\text{d}x}}{\text{dE/dx}} = 0.41 \cdot N^{-0.44} \cdot L_{\text{ion}} \cdot m \cdot P_{\text{atm}} \text{ (empirical parameterization)}
\]

\[
\frac{\sigma_{\text{d}N/\text{d}x}}{\text{dN/dx}} - \langle \delta_n, L_{\text{ion}} \rangle^{-0.2} \cdot N^{-0.4} \text{ (Poisson)}
\]
Two taggers

Jet Flavour Tagging for Future Colliders with Fast Simulation

Franco Bedeschi\textsuperscript{a}, Loukas Gouskos\textsuperscript{b} and Michele Selvaggi\textsuperscript{c}

\textsuperscript{a}INFN Sezione di Pisa, Italy
\textsuperscript{b}CERN, CH-1211 Geneva 23, Switzerland

E-mail: bed@fnal.gov, loukas.gouskos@cern.ch, michele.selvaggi@cern.ch

Both use graph neural nets.
Liang et al

Non-trivial correlations

For strange, non-trivial charge mis-id. Lots of mis-id to u, d, g (30%)

Even b’s only correctly id’d 90% of the time (ignoring charge misid)
Can see we really do not get a measurement of the strange coupling yet. More work and clever ideas needed!

Also the measurement of the charm coupling relies strongly on the Z to invisible, but...

### Details

- **Signal & most BKGs:** free floating parameters [correlated across categories]
- **Systematics:** Signal 0.1%, BKG 5% [constrained to <1%]
SIG-vs-BKG discrimination

- Different SIG and BKGs shapes in $m_{\text{rec}}$ & $m_{jj}$
- Bump hunt in 2D
  - simultaneous fit in all categories
Detector implications (beyond kaon tagging)

HCAL and jets -- Higgs hadronic final states

Largest gain from JER expected for S/B << 1:

If relative improvement $\alpha$, expect $\sqrt{\alpha}$ increase in precision

Observe less degradation than expected, studies will have to be repeated with full simulation
Higgs top coupling

Really cannot be done at FCCee. 3% measurement at ILC/CLIC/C3. Also hl-lhc expects 3% measurement

arXiv:2209.07510
Beyond the kappa framework

The Higgs coupling measurements have been widely studied in the corresponding design studies through global fits in the so-called κ framework. While very helpful in illustrating the precision reach of Higgs measurements, this κ framework can miss interactions of Lorentz structure different from that of the SM. This method is a more realistic way of including potential effects of new physics.

These can include the relations between the longitudinal components of the WZ to higgs couplings.

https://arxiv.org/abs/2206.08326

As done in [8,9], some of the results will be presented, not in terms of the Wilson coefficients of the manifestly gauge-invariant operators, but in terms of pseudo-observable quantities, referred to as *effective Higgs and electroweak couplings*, computed from physical observables and thus independent of the basis one could have chosen for the dimension-6 Lagrangian. This is done by performing the fit *internally* in terms of the Wilson coefficients and then, from the posterior of the fit, compute the posterior prediction for the quantities

\[
g_{\mu \lambda} \equiv \frac{\Gamma_{H \to X}^{\mu \lambda}}{\Gamma_{H \to X}^{\text{SM}}}. \quad (15)
\]
Kappa framework work

Higgs coupling sensitivity

<table>
<thead>
<tr>
<th>Coupling</th>
<th>HL-LHC</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_W$ [%]</td>
<td>1.5*</td>
<td>0.33</td>
</tr>
<tr>
<td>$\kappa_Z$ [%]</td>
<td>1.3*</td>
<td>0.14</td>
</tr>
<tr>
<td>$\kappa_t$ [%]</td>
<td>2*</td>
<td>0.77</td>
</tr>
<tr>
<td>$\kappa_\gamma$ [%]</td>
<td>1.6*</td>
<td>1.2</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$ [%]</td>
<td>10*</td>
<td>10</td>
</tr>
<tr>
<td>$\kappa_G$ [%]</td>
<td>–</td>
<td>1.1</td>
</tr>
<tr>
<td>$\kappa_t$ [%]</td>
<td>3.2*</td>
<td>3.1</td>
</tr>
<tr>
<td>$\kappa_b$ [%]</td>
<td>2.5*</td>
<td>0.56</td>
</tr>
<tr>
<td>$\kappa_\mu$ [%]</td>
<td>4.4*</td>
<td>3.7</td>
</tr>
<tr>
<td>$\kappa_\tau$ [%]</td>
<td>1.6*</td>
<td>0.55</td>
</tr>
</tbody>
</table>

$\text{BR}_{\text{inv}}$ (<%, 95% CL) | 1.9* | 0.15 |

$\text{BR}_{\text{unt}}$ (<%, 95% CL) | 4* | 0.88 |
EFT framework

HL-LHC $\kappa_W$ precision goes from 1.5 to 2%

Note that, especially for the couplings to electroweak vector bosons, the results of the $\kappa$ fit are not directly comparable to those of the SMEFT fit. In particular, the latter incorporates all the correlations associated with gauge invariance or custodial symmetry, which are absent in the general form of the $\kappa$ framework. On the other hand, because of the absence of such correlations, the $\kappa$-fit result could also give, within its limitations, information that goes beyond some of the assumptions implicit in the SMEFT results presented above.
Higgs coupling to electron

Would take a couple of years, so not clear this would ever happen, but a fun idea. LEP did run at this energy, but not enough int lum to make an event.
CP violation

\[ A_{CP} = \frac{\sigma(\cos \theta < 0) - \sigma(\cos \theta > 0)}{\sigma_{SM,NLO}} \]

\( \Theta \) is the angle between the incoming electron and the outgoing Higgs

- Four CP violating operators

\[ O_{W'} = \epsilon_{abc} \tilde{W}_{\mu}^{a \nu} W_{\nu}^{b \rho} W_{\rho}^{c, \mu} \]

\[ O_{\phi W} = \tilde{W}_{\mu}^{a} W_{\mu}^{a \nu b} (\phi \phi) \]

\[ O_{\phi B} = \tilde{B}_{\mu}^{a \nu} B_{\nu}^{a \mu} (\phi \phi) \]

\[ O_{\phi W B} = \tilde{W}_{\mu}^{a} B_{\mu}^{a \nu} (\phi \phi) \]

- Assuming \( \Lambda = 1 \text{ TeV}, C_i = 1 \) and \( \sqrt{s} = 240 \text{ GeV} \) (FCC-ee)

\[ \frac{\sigma_{NLO}}{\sigma_{SM,NLO}} = 1 + \sum_i C_i(\mu) \frac{\Delta_i + \Delta_i \log \frac{\mu}{s}}{\Lambda^2} \]

arXiv:2406.03557
JHEP 03, 050 (2016)
Konstantin Asteriadis et al
Higgs self coupling

One of the main drivers of the length of the HL-LHC run

$$V(H) = \mu^2 \left( H^\dagger H \right) + \lambda \left( H^\dagger H \right)^2$$

$$m_H = \lambda v \ M_W = \frac{e v}{2 \sin^2 \theta_W}$$

Requires a center-of-mass energy of 500 GeV, which FCC-ee can’t really do, although linear colliders could with enough money. FCChh could also access these energies once magnets are developed (and money found)

https://cds.cern.ch/record/2805993?ln=en


Predicted in the SM
Higgs self coupling

Can be measured indirectly at FCC-ee to about 30%

\[
\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{3!} \delta_h A_{h, SM} h^3
\]

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

\[
\delta_{240}^{240, 350, 500} = 1.4, 0.3, -0.2 \times \delta_h \%
\]

How to distinguish modifications to hZZ and hhh

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.90.015001
Extended higgs-like sectors

Through their effects on the couplings

arXiv:1910.11775

FIG. 34: This figure is from [88] Figure 8.11, where the LHS shows the direct and indirect sensitivity to a singlet which mixes with the SM Higgs, while the RHS shows the limit of no-mixing, but overlaid with regions of parameter space where a strong first-order phase transition is allowed.
Extended higgs-like sectors

doublet

FIG. 40: Higgs portal model with $h \rightarrow SS$. The shaded region allows for an electroweak phase transition. From Ref [93]. See also [128].
Can I avoid thinking about this?
summary

• A Higgs factory will give us precision information about what is both the oddest part, and the part that sets most of the physics, of the standard model
• The required work is challenging and fun
• However, none of the three possibilities will happen if the world particle physics community doesn’t push.
<table>
<thead>
<tr>
<th>Model</th>
<th>$\bar{b}b$</th>
<th>$c\bar{c}$</th>
<th>$gg$</th>
<th>$WW$</th>
<th>$\tau\tau$</th>
<th>$ZZ$</th>
<th>$\gamma\gamma$</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MSSM [40]</td>
<td>+4.8</td>
<td>-0.8</td>
<td>-0.8</td>
<td>-0.2</td>
<td>+0.4</td>
<td>-0.5</td>
<td>+0.1</td>
<td>+0.3</td>
</tr>
<tr>
<td>2 Type II 2HD [42]</td>
<td>+10.1</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0.0</td>
<td>+9.8</td>
<td>0.0</td>
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<tr>
<td>3 Type X 2HD [42]</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0.0</td>
<td>+7.8</td>
<td>0.0</td>
<td>0.0</td>
<td>+7.8</td>
</tr>
<tr>
<td>4 Type Y 2HD [42]</td>
<td>+10.1</td>
<td>-0.2</td>
<td>-0.2</td>
<td>0.0</td>
<td>-0.2</td>
<td>0.0</td>
<td>0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>5 Composite Higgs [44]</td>
<td>-6.4</td>
<td>-6.4</td>
<td>-6.4</td>
<td>-2.1</td>
<td>-6.4</td>
<td>-2.1</td>
<td>-2.1</td>
<td>-6.4</td>
</tr>
<tr>
<td>6 Little Higgs w. T-parity [45]</td>
<td>0.0</td>
<td>0.0</td>
<td>-6.1</td>
<td>-2.5</td>
<td>0.0</td>
<td>-2.5</td>
<td>-1.5</td>
<td>0.0</td>
</tr>
<tr>
<td>7 Little Higgs w. T-parity [46]</td>
<td>-7.8</td>
<td>-4.6</td>
<td>-3.5</td>
<td>-1.5</td>
<td>-7.8</td>
<td>-1.5</td>
<td>-1.0</td>
<td>-7.8</td>
</tr>
<tr>
<td>8 Higgs-Radion [47]</td>
<td>-1.5</td>
<td>1.5</td>
<td>+10.0</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.0</td>
<td>-1.5</td>
</tr>
<tr>
<td>9 Higgs Singlet [48]</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
<td>-3.5</td>
</tr>
</tbody>
</table>

Table 5: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.
backup
Timely progress on understanding the tunnel

- Site investigations in areas with uncertain geological conditions:
  - Optimisation of localisation of drilling locations ongoing with site visits since end 2022
  - Alignment with FR and CH on the process for obtaining authorisation procedures. Planned start of drillings in Q2/2024

- Contract Status:
  - Engineering service contracts since July 2022
  - Site investigation tendering ongoing
  - Contract placement approved by Council in December 2023 and mobilization after contracts are signed
Areas with highest geological uncertainty

- Jura
  - Limestone/molasse interface uncertain.
  - Risk of karts and high water pressures.

- Le Rhône
  - Moraine/molasse interface uncertain.
  - Proximity to protected area.

- Vuache
  - Limestone/molasse interface uncertain.
  - Risk of karts and high water pressures.
  - Proximity to main active fault.

- Les Usses
  - Moraine/molasse interface uncertain.
  - Low tunnel rock cover.

- Lac Leém
  - Moraine/molasse interface uncertain.
  - Soils and rock properties uncertain.
  - High uncertainty in the hydrogeological conditions and water pressure.

- Vallée de l’Arve
  - Moraine/molasse interface uncertain.
  - Lack of reliable boreholes.

- Bornes
  - Insufficient deep boreholes information.
  - Complex faulted region, thrust zone.
  - Quality of molasse is uncertain. High overburden. Large span experimental caverns should be constructed in good molasse.

- Mandallaz
  - Fractured limestone formations, characteristics and locations of karts unknown.
  - High water pressures.

On-site investigation works 2024-25
All details being scrutinized

- **Road accesses** identified and documented for all 8 surface sites
- **Four possible highway connections** defined (material transport)
- **Total amount of new roads required** < 4 km (at departmental road level)

**Detailed road access scenarios & highway access creation study carried out by Cerema**, including regulatory requirements in France.

**Updated FCC-ee energy consumption**

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>W</th>
<th>H</th>
<th>TT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (GeV)</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>Max. Power during beam operation (MW)</td>
<td>222</td>
<td>247</td>
<td>273</td>
<td>357</td>
</tr>
<tr>
<td>Average power / year (MW)</td>
<td>322</td>
<td>138</td>
<td>152</td>
<td>202</td>
</tr>
<tr>
<td>Total FCC-ee yearly consumption (TWh)</td>
<td>1.07</td>
<td>1.2</td>
<td>1.33</td>
<td>1.77</td>
</tr>
<tr>
<td>Yearly consumption CERN &amp; SPS (TWh)</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td>Total yearly consumpt. CERN &amp; SPS &amp; FCC-ee (TWh)</td>
<td>1.77</td>
<td>1.90</td>
<td>2.03</td>
<td>2.47</td>
</tr>
</tbody>
</table>

The loads could be distributed on three main sub-stations (optimally connected to existing regional HV grid):

- Point D with a new sub-station covering PB – PD – PP – PG
- Point H with a new dedicated sub-station for collider RF
- Point A with existing CERN station covering PB – PL – PU

- **Connection concept was studied and confirmed by RTE (French electrical grid operator)** requested loads have no significant impact on grid
- **Powering concept and power rating of the three sub-stations compatible with FCC-eh**
- **R&D efforts aiming at further reduction of the energy consumption of FCC-ee and FCC-eh**

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8/6/2024

S. Eno, SLAC summer school, 2024
Cool things about the machine
One of the things I find most fascinating about this machine is the possibility to do an extremely precise energy calibration via "resonant depolarization", used to measure the spin precession frequency, which is related to the beam energy via:

\[ \Omega = \frac{g_e - \frac{2}{\gamma} E}{2 m_e} \]

where the cyclotron frequency is:

\[ \Omega_c = \frac{e B}{2 m_e} \]

So the "spin tune" or number of spin progressions in one turn, the part beyond 1:

\[ \nu = \frac{g_e - \frac{2}{\gamma} E}{2} \]

440.6486

If the beam is excited by a magnetic field perpendicular to the beam axis, it rotates the spin around the radial direction. If this kick is in phase with the spin progression, you can push the spin into the horizontal plane and then flip it.

Each time moves a bit farther away

https://inspirehep.net/literature/1650329
https://cds.cern.ch/record/267514/
Resonant depolarization

Polarimeter studies

Compton polarimeter a vital tool in beam-energy calibration with multiple tasks:
- Measure transverse polarization level for RDP measurement;
- Measure precession of longitudinal polarization in FSP measurement;
- Measure residual longitudinal (and transverse) polarization in physics bunches;
- Transverse and longitudinal measurements requires detection of both scattered $\gamma$ and $e$.
- Provide real-time energy measurement of $E_b$ through scattered electron distribution.

Excellent initial conceptual work of N. Muchnoi and A. Martens now being augmented with more refined studies and considerations of practical implementation and tolerances.

Some mechanisms of $E_b$ variation

Short- (tide) and long- (fake) terming distortions. NB at FCC-ee effects will be $\sim$10x larger due to smaller momentum-compaction factor.

Rise of dipole fields due to stimulation from returning current from TGV.

A strategy to suppress systematics due to $E_b$ variation with time

RDP (or FSP) measures mean $E_b$ at a particular moment. It is well known from LEP experience that $E_b$ varies with time and evolves between measurements.

Indeed, modelling these effects, and the representativeness of the RDP sampling, was dominant source of the $\sim$2 MeV systematic uncertainties on $m_b$ & $F_b$ at LEP.

The problem was that RDP measurements took hours, and were incompatible with physics operation. Therefore they were made at start of end of selected fills.

Proposed strategy at FCC-ee:
- (near) continual measurement of $e^+$ and $e^-$ measurements on pilot bunches, order of ~5 measurement every hour;
- Continual adjustment of RF frequency to keep beams centred in quadrupoles, therefore suppressing any tidal effects.

In addition: insist on exhaustive logging of all relevant machine parameters, and allocated adequate Machine Development time to study residual effects.

Goal is 4 keV. LEP measurement was 1.2-1.7 MeV

This process requires strong collaboration between accelerator and machine physicists
Interesting news from CEPC on longitudinal polarization
Zhe Duan’s talk

**Motivation of CEPC polarized beam program**

- **Vertical polarization for resonant depolarization**
  - Essential for precision measurements of $Z$ and $W$ properties
  - $> 5\% - 10\%$ polarization, for both $e^+ / e^-$ beams

- **Longitudinal polarization for colliding beams**
  - Figure of merit: Luminosity $\propto (P_{e^+} P_{e^-})$
  - $50\%$ or more polarization is desired, for at least one beam; polarizing both beams is beneficial

- **Propects of Z-pole polarization for CEPC**
  - Injecting polarized beam(s) to the Collider
  - $50\%-70\%$ longitudinal polarization for $e^-$ versus unpolarized $e^+$
    - Polarized $e^+$ source requires technology innovations; self-polarization at a low energy ring is possible, a tradeoff between the challenges & costs of the ring versus reduction injection rate & luminosity (need more study);
  - E- spin helicity flexibly adjusted by changing laser helicity at polarized e- source
  - RD measurements w/ a few pilot non-colliding bunches, no physics deadtime
  - Accurate 3D polarimetry is needed
    - Inside the IR -> deduce longitudinal polarization @ IP
    - Outside the IR -> RD measurements

- Supported by National Key R&D Program 2018-2023 to design longitudinally polarized colliding beams at Z-pole
- Summarized as a chapter in the Appendix of CEPC TDR.
The additional funding being sought pushes the cost of the project to about $4 billion. Including financing over the 36-year life of the project, the cost is $10 billion.
Change in an observable with an single external higgs line with change in hhh delta kappa lambda