At the heart of our visual identity is the Oxford logo. It should appear on everything we produce, from letterheads to leaflets and from online banners to bookmarks.

The primary quadrangle logo consists of an Oxford blue (Pantone 282) square with the words UNIVERSITY OF OXFORD at the foot and the belted crest in the top right-hand corner reversed out in white.

The word OXFORD is a specially drawn typeface while all other text elements use the typeface Foundry Sterling.

The secondary version of the Oxford logo, the horizontal rectangle logo, is only to be used where height (vertical space) is restricted.

These standard versions of the Oxford logo are intended for use on white or light-coloured backgrounds, including light uncomplicated photographic backgrounds.

Examples of how these logos should be used for various applications appear in the following pages.

NOTE

The minimum size for the quadrangle logo and the rectangle logo is 24mm wide. Smaller versions with bolder elements are available for use down to 15mm wide. See page 7.
A preamble

➤ this type of talk is often given by a theorist who builds models of new physics

➤ such a theorist can tell you with authority about the landscape of models that any given collider might probe
A preamble

➤ this type of talk is often given by a theorist who builds models of new physics

➤ such a theorist can tell you with authority about the landscape of models that any given collider might probe

➤ there are many kinds of theorist

➤ while I’m a theorist, I am not a BSM model-builder

➤ my “day job” is to calculate phenomena in QCD (jets, parton showers, etc.), in order to help augment colliders’ capabilities

➤ this talk will not involve specifics of models, but rather attempt to explore the case for new colliders more generically
desirable features of a worldwide HEP project?

an important target that is guaranteed to be reached
(no-lose theorem)

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (multiple experiments)

cost-effective construction & operation, low carbon footprint
top-down
figure out the best collider you can realistically build
establish what physics it will probe

bottom up
establish what you want to learn
figure out how to build a collider that will best achieve it
Dear Santa Claus,

We have been good these past decades. Please could you now bring us

- a dark matter candidate
- an explanation for the fermion masses
- an explanation of matter-antimatter asymmetry
- an axion, to solve the strong CP problem
- a solution to fine tuning the EW scale
- a solution to fine tuning the cosmological constant

Thank you, Particle Physicists

ps: please, no anthropics
4.3 The path toward DM discovery with direct detection

Many candidates in the "heavy" range will not be tested by the suite of current generation experiments that are under construction or operating. The next suite of experiments should have an order of magnitude larger exposure and be able to significantly enhance our capabilities to probe much of this high-priority parameter space. This future suite should probe models with spin-dependent interactions and others beyond the usual coherent DM-nucleus interactions. In addition, we cannot a

ord to eliminate support for successful DM search programs with unique sensitivity. Similarly, many candidates in the "light" range will not be tested with the current suite of "small scale projects". Continued investment to scale up in mass and/or reduce and understand low-energy backgrounds in programs to search for particle DM is thus crucial.

The benchmark for future generation experiments is to search for heavy DM candidates in the parameter space that reaches to the neutrino "fog", the expected background from the coherent elastic neutrino-nucleus scattering (CEνNS) of solar and atmospheric neutrinos, or that advances sensitivity by an order of magnitude beyond the reach of current generation experiments in spaces where the fog remains many orders of magnitude distant, such as spin-dependent interactions. For light mass DM candidates the goal over the next decade is to probe DM scattering down to 1 MeV and DM absorption down to 1 eV.

4.3.1 Enabling Discovery with Complementary Probes

The three categories of particle DM, as well as models within each category, give rise to distinct DM-SM interactions and experimental signatures in direct detection setups. Discovering particle DM requires a multi-faceted approach involving detectors that can measure different aspects of DM-SM interactions, as well as provide information about the DM distribution in our galactic halo.

Heavy DM candidates, such as WIMPs, are traditionally probed via their interactions with nucleons in the target material. Spin-independent interactions benefit from targets with high atomic mass due to the coherent $A^2$ enhancement of the scattering rate. On the other hand, spin-dependent interactions require
but we have been **lucky** in discovering a 125 GeV Higgs boson. It opens a door to the most mysterious part of the Standard Model.

https://www.symmetrymagazine.org/standard-model/
desirable features of a worldwide HEP project?

an important target that is guaranteed to be reached (no-lose theorem)

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (incl. multiple experiments)

cost-effective construction & operation, low carbon footprint
Higgs physics

Higgs is the last particle of the SM.
So the SM is complete, right?
The Lagrangian and Higgs interactions: two out of three qualitatively new!

\[ \mathcal{L}_{\text{SM}} = \cdots + |D_\mu \phi|^2 + \psi_i y_{ij} \psi_j \phi - V(\phi) \]

Gauge interactions, structurally like those in QED, QCD, EW, studied for many decades (but now with a scalar).

Yukawa interactions. Responsible for fermion masses, and induces "fifth force" between fermions. Direct study started only in 2018!

Higgs potential → self-interaction ("sixth?" force between scalars). Holds the SM together. Unobserved.
Almost every problem of the Standard Model originates from Higgs interactions

\[ \mathcal{L} = y H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0 \]

- flavour
- naturalness
- stability
- cosmological constant
Figure 5: Figure from Energy Frontier Higgs topical report illustrating the centrality of the Higgs and the connections to numerous fundamental questions.

To demonstrate the first point, we consider the precision on the Higgs couplings that can be achieved at muon colliders. Drawing on the Higgs exclusive channel inputs of Refs. 20, 22, we perform a global fit analysis. There are two main approaches that are followed for doing the global fits. The first is by assuming the same type of couplings as in the SM, but associating to each of them a rescaling factor $\kappa_i$. This approach has been dubbed "kappa framework" and enjoys the simplicity of a direct translation between different channels and the Higgs property precision. A second approach employs a full-fledged effective field theory, the SMEFT, which provides a consistent deformation of the SM which allows to perform accurate predictions and combine information across different scales and experiments as long as new physics exists only at a parameterically larger scale than probed. For consistency with the electroweak precision fit group at Snowmass, we use a modified SMEFT framework, where the Higgs width can be considered as an additional free parameter, yet not only Higgs measurements, but also electroweak precision observables and possibly other low-energy measurements are included to achieve a consistent projection of the overall precision.

We show the SMEFT projection results in Figure 6. Here we only report the Higgs couplings part in the Higgs basis, marginalizing on other parameters. The corresponding precision for the electroweak sector and trilinear gauge couplings can be found in the Snowmass report 26. In this plot, all muon collider projections are combined with the HL-LHC. The muon collider scenarios considered include a 3 TeV muon collider with 1 ab$^{-1}$ of luminosity, a 10 TeV muon collider with 10 ab$^{-1}$ and also its combination with a 125 GeV resonant muon collider Higgs factory with 0.02 ab$^{-1}$ integrated luminosity. The semi-opaque and opaque bars represent the results with and without the Higgs width $\Gamma_H$ left as a free parameter. As one can anticipate, considering $\Gamma_H$ as a calculable parameter in the SMEFT allows to attain a better precision. On the other hand, considering it a free parameter, introduces a "flat" direction in the fit, that needs very specific measurements (such as the direct $H$ measurement at the resonance peak $p_{s\mu} = m_H$ to be resolved). At high energies this can also be investigated by using indirect methods such as the "off shell" methods employed at LHC, and should have roughly the same precision as the direct lineshape measurement but with added theory assumptions. We would like to emphasize that these different frameworks and/or basis choices can be also associate to different UV hypotheses and are therefore useful also to develop an idea of different new physics effects. It is important to"
Yukawa interaction hypothesis

Yukawa couplings $\sim$ fermion mass

first fundamental interaction that we probe at the quantum level where interaction strength ($y_{ij}$) not quantised
(i.e. no underlying unit of conserved charge across particles)
Protons are lighter than neutrons→ protons are stable.
Giving us the hydrogen atom, & chemistry and biology as we know it
Protons are lighter than neutrons→ protons are stable. Giving us the hydrogen atom, & chemistry and biology as we know it

Supposedly because up quarks interact more weakly with the Higgs field than down quarks
The proton – neutron mass difference is depicted in the graph. The QED contribution is shown as a green bar at 1.5 MeV, while the total contribution is indicated by a blue bar at 0.75 MeV. The light blue area represents the uncertainty in the total contribution, the green area for QED, and the red area for the Yukawa interactions, which is the sum of up and down masses. The lattice calculation by the BMW collaboration gives values of 1306.2287 and 1406.4088 MeV.
Why do Yukawa couplings matter?

(2) Because, within SM conjecture, they’re what give masses to all leptons

\[ a_0 = \frac{4\pi\varepsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c \alpha} \propto \frac{1}{y_e} \]

Bohr radius

electron mass determines size of all atoms

it sets energy levels of all chemical reactions
currently we have no evidence that up and down quarks and electron get their masses from Yukawa interactions — it’s in textbooks, but is it nature?
Z-boson $\approx 91.2 \text{ MeV}/c^2$

W-boson $\approx 80.4 \text{ MeV}/c^2$

τ $\approx 1.78 \text{ GeV}/c^2$

top $\approx 173 \text{ GeV}/c^2$

b $\approx 4.18 \text{ GeV}/c^2$

μ $\approx 106 \text{ MeV}/c^2$

electron $\approx 0.511 \text{ MeV}/c^2$

down $\approx 4.7 \text{ MeV}/c^2$

First generation

Second generation

Third generation

H interactions
<table>
<thead>
<tr>
<th>First generation</th>
<th>Second generation</th>
<th>Third generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ (up)</td>
<td>$c$ (charm)</td>
<td>$t$ (top)</td>
</tr>
<tr>
<td>≈ 2.2 MeV/c²</td>
<td>≈ 1.27 GeV/c²</td>
<td>≈ 173 GeV/c²</td>
</tr>
<tr>
<td>$d$ (down)</td>
<td>$s$ (strange)</td>
<td>$b$ (bottom)</td>
</tr>
<tr>
<td>≈ 4.7 MeV/c²</td>
<td>≈ 93 MeV/c²</td>
<td>≈ 4.18 GeV/c²</td>
</tr>
<tr>
<td>$e$ (electron)</td>
<td>$μ$ (muon)</td>
<td>$τ$ (tau)</td>
</tr>
<tr>
<td>≈ 0.511 MeV/c²</td>
<td>≈ 106 MeV/c²</td>
<td>≈ 1.78 GeV/c²</td>
</tr>
</tbody>
</table>

established (5σ) at LHC by observation of direct interaction with H

- $W$ (W-boson) ≈ 80.4 MeV/c²
- $Z$ (Z-boson) ≈ 91.2 MeV/c²
Z-boson $\approx 91.2 \text{ MeV/c}^2$

W-boson $\approx 80.4 \text{ MeV/c}^2$

τ-lepton $\approx 1.78 \text{ GeV/c}^2$

\( t \)-quark $\approx 173 \text{ GeV/c}^2$

μ-lepton $\approx 106 \text{ MeV/c}^2$

First generation

- up quark $u \approx 2.2 \text{ MeV/c}^2$
- down quark $d \approx 4.7 \text{ MeV/c}^2$
- electron $e \approx 0.511 \text{ MeV/c}^2$

Second generation

- charm quark $c \approx 1.27 \text{ GeV/c}^2$
- strange quark $s \approx 93 \text{ MeV/c}^2$
- muon $\mu \approx 106 \text{ MeV/c}^2$

Third generation

- top quark $t \approx 173 \text{ GeV/c}^2$
- bottom quark $b \approx 4.18 \text{ GeV/c}^2$
- τ-lepton $\tau \approx 1.78 \text{ GeV/c}^2$

established (5σ) at LHC by observation of direct interaction with H

first evidence (3σ) to be conclusively established at the LHC within 3 – 10 years
<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (MeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z-boson</td>
<td>≈ 91.2</td>
</tr>
<tr>
<td>W-boson</td>
<td>≈ 80.4</td>
</tr>
<tr>
<td>tau</td>
<td>≈ 1.78</td>
</tr>
<tr>
<td>top</td>
<td>≈ 173</td>
</tr>
<tr>
<td>bottom</td>
<td>≈ 4.18</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
</tbody>
</table>

- **First generation**
  - up (u)
  - down (d)

- **Second generation**
  - charm (c)
  - strange (s)

- **Third generation**
  - top (t)
  - bottom (b)

**H interactions**

- First evidence (3σ) to be conclusively established at the LHC within 3 – 10 years
- Established (5σ) at LHC by observation of direct interaction with H

**no obvious path to SM-level measurement**

**bright ideas needed!**
Z-boson \approx 91.2 \text{ MeV/c}^2

W-boson \approx 80.4 \text{ MeV/c}^2

\tau \approx 1.78 \text{ GeV/c}^2

\mu \approx 106 \text{ MeV/c}^2

\tau \approx 1.78 \text{ GeV/c}^2

top \approx 173 \text{ GeV/c}^2

b \approx 4.18 \text{ GeV/c}^2

e \approx 0.511 \text{ MeV/c}^2

e \approx 0.511 \text{ MeV/c}^2

e \approx 0.511 \text{ MeV/c}^2

no evidence yet

guaranteed at FCC-ee

no obvious path to SM-level measurement

bright ideas needed!

H interactions

established (5\sigma) at LHC by observation of direct interaction with H

first evidence (3\sigma) to be conclusively established at the LHC within 3 – 10 years
Z-boson ≈ 91.2 MeV/c²

W-boson ≈ 80.4 MeV/c²

τ ≈ 1.78 GeV/c²

top ≈ 173 GeV/c²

tau ≈ 1.78 GeV/c²

electron ≈ 0.511 MeV/c²

First generation

Second generation

Third generation

e = electron

μ = muon

τ = tau

t = top

top ≈ 173 GeV/c²

c = charm

s = strange

b = bottom

b ≈ 4.18 GeV/c²

up ≈ 2.2 MeV/c²

down ≈ 4.7 MeV/c²

electron ≈ 0.511 MeV/c²

μ ≈ 106 MeV/c²

τ ≈ 1.78 GeV/c²

no evidence yet
guaranteed at FCC-ee

no obvious path to SM-level measurement

bright ideas needed!

no evidence yet
tantalisingly close to reach of FCC-ee

established (5σ) at LHC by observation of direct interaction with H

first evidence (3σ) to be conclusively established at the LHC within 3 – 10 years

W-boson

Z-boson

H interactions
Teaser from the analysis front [FCC-ee, H → hadrons]

- Tools fully incorporated in FCCSW [details]
  - Example: $Z(\rightarrow \nu\nu)H(\rightarrow quq)$

**Signal extraction: 2D fit**

**ParticleNet-ee**

Categorize events: $bb$, $cc$, $ss$, $gg$
Sub-categories with different S/B

**Results @ 5ab$^{-1}$**
(syst: 5% BKG, 0.1% SIG)

<table>
<thead>
<tr>
<th>$Z(\rightarrow \nu\nu)$</th>
<th>$H(\rightarrow quq)$</th>
<th>$bb$</th>
<th>$cc$</th>
<th>$ss$</th>
<th>$gg$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta \mu/\mu$ (%)</td>
<td>0.4</td>
<td>2.9</td>
<td>160</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

$|\kappa_S| < 1.9$

More on Friday:
G. Marchiori
## Results @ 5ab\(^{-1}\)
(syst: 5% BKG, 0.1% SIG)

<table>
<thead>
<tr>
<th>Event</th>
<th>bb</th>
<th>cc</th>
<th>ss</th>
<th>gg</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z(\rightarrow vv))</td>
<td>0.4</td>
<td>2.9</td>
<td>160</td>
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<td>0.4</td>
<td>2.9</td>
<td>160</td>
<td>1.2</td>
</tr>
</tbody>
</table>

\[ \delta \mu/\mu (\%) \]

* \(|\kappa_s| < 1.9\)

\[ Z(\rightarrow vv) \]

\[ H(\rightarrow qq) \]

Strange Yukawa tantalisingly close to being within reach would complete 2nd generation Yukawas
One of the toughest challenges, which requires in particular, at $\sqrt{s} = 125$ GeV
- Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at $\sqrt{s} = 240$ GeV
- Huge luminosity, achievable with with several years of running and possibly 4 IPs
- $\sqrt{s}$ monochromatisation: $\Gamma_H$ (4.2 MeV) $\ll$ natural beam energy spread ($\sim 100$ MeV)
Electron Yukawa coupling: Unique @ FCC-ee

- One of the toughest challenges, which requires in particular, at $\sqrt{s} = 125$ GeV
  - Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at $\sqrt{s} = 240$ GeV
  - Huge luminosity, achievable with with several years of running and possibly 4 IPs
  - $\sqrt{s}$ monochromatisation: $\Gamma_H (4.2 \text{ MeV}) \ll \text{natural beam energy spread} (-100 \text{ MeV})$

- First studies indicate a significance of 0.4$\sigma$ with one detector in one year
Electron Yukawa coupling: Unique @ FCC-ee

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  - Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at $\sqrt{s} = 240$ GeV
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- **First studies indicate a significance of $0.4\sigma$ with one detector in one year**

![Graph showing significance of $H$ production](image)

- With ISR
- $\delta\sqrt{s} = 6$ MeV
- $\delta\sqrt{s} = 10$ MeV

Still working on optimizing luminosity vs monochromatization

Original slide from Patrick Janot
Electron Yukawa coupling: Unique @ FCC-ee

- One of the toughest challenges, which requires in particular, at $\sqrt{s} = 125$ GeV
  - Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at $\sqrt{s} = 240$ GeV
  - Huge luminosity, achievable with several years of running and possibly 4 IPs
  - $\sqrt{s}$ monochromatization: $\Gamma_H (\approx 4.2$ MeV) $<<$ natural beam energy spread (~100 MeV)

- First studies indicate a significance of 0.4$\sigma$ with one detector in one year

---

![Graph showing significance of $e^+e^- \rightarrow H$](image)

- Born
- (1): with ISR
- (2): $\delta \sqrt{s} = 6$ MeV
- (3): $\delta \sqrt{s} = 10$ MeV

---

![Graph showing significance vs. luminosity](image)

- Significance $e^+e^- \rightarrow H$, $\sqrt{s}=125$ GeV
- $\delta \sqrt{s}$ spread (MeV)
- 4IPs: 1.7$\sigma$
- 2IPs: 1.3$\sigma$
- L/5: 0.6$\sigma$

- 5 yrs @ $\sqrt{s} = 125$ GeV

- Still working on optimizing luminosity vs monochromatization
electron Yukawa coupling: Unique @ FCC-ee

- One of the toughest challenges, which requires in particular, at $\sqrt{s} = 125$ GeV
  - Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at $\sqrt{s} = 240$ GeV
  - Huge luminosity, achievable with with several years of running and possibly 4 IPs
  - $\sqrt{s}$ monochromatisation: $\Gamma_H$ (4.2 MeV) $\ll$ natural beam energy spread (~100 MeV)

- First studies indicate a significance of 0.4$\sigma$ with one detector in one year

---

**Diagram:**

- Born amplitude vs. $\sqrt{s}$
  - (1): with ISR
  - (2): $\delta \sqrt{s} = 6$ MeV
  - (3): $\delta \sqrt{s} = 10$ MeV

- Significance $e^+e^- \rightarrow H$, $\sqrt{s}$=125GeV

- Luminosity vs. monochromatization settings per IP
  - 4IPs: 1.7$\sigma$
  - L$x$5: 3$\sigma$
  - 2IPs: 1.3$\sigma$

- Still working on optimizing luminosity vs monochromatization

---

*original slide from Patrick Janot*
One of the toughest challenges, which requires in particular, at \( \sqrt{s} = 125 \) GeV
- Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at \( \sqrt{s} = 240 \) GeV

Huge luminosity, achievable with several years of running and possibly 4 IPs

\( \delta \sqrt{s} \approx 4.2 \) MeV

\( \delta \sqrt{s} \ll \) natural beam energy spread (~100 MeV)

First studies indicate a significance of 0.4

\( e^-_e \rightarrow H \)

\( (1): \) with ISR
\( (2): \delta \sqrt{s} = 6 \) MeV
\( (3): \delta \sqrt{s} = 10 \) MeV

Still working on optimizing luminosity vs monochromatization

(Original slide from Patrick Janot)
Electron Yukawa coupling: Unique @ FCC-ee

One of the toughest challenges, which requires in particular, at $\sqrt{s} = 125$ GeV
- Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at $\sqrt{s} = 240$ GeV
- and possibly 4 IPs
- $\sqrt{s}$ at around 125 GeV
- with an achievable natural beam energy spread (~100 MeV)
- First studies indicate a significance of 0.4
- $e^+e^- \rightarrow H$, $\sqrt{s}=125$GeV
- Still working on optimizing luminosity vs monochromatization
- L/5 0.6 2IPs 1.3
- $4 \times 5$ 3\sigma
- $2 \times 5$ 1.7\sigma
- $L \times 5$ 3\sigma

some caution needed with the numbers (cf. Soyez @ 2022 FCC Physics Week on state-of-the art tagging of $H \rightarrow$gg)

still a couple of bright ideas away from concrete path to 5\sigma discovery of the origin of the electron mass; may simply not be feasible

— but would be a clear no-lose theorem for FCC-ee
A side comment on the near future at LHC

➤ particle physics normally deals with esoteric particles that have [almost] no relation with the world as we experience it

➤ LHC will reach 5σ sensitivity for $H \rightarrow \mu\mu$ in the coming years (if it is SM-like), offering first proof that particles other than 3rd generation also get their mass from Yukawa mechanism

➤ that will be a crucial step on the way from 3rd generation Yukawas to 1st

➤ it deserves a big event with the world’s press to announce it

➤ an opportunity to explain the quest for understanding the origin of the mass of the fundamental particles that **we are made of**
the Higgs potential
the Higgs mechanism gives mass to particles because the Higgs field $\phi$ is non-zero.

That happens because the minimum of the SM potential is at non-zero $\phi$.
Higgs potential

\[ V(\phi), \text{SM} \]

- Universe lives here
- Standard Model potential

Depth is

\[ \frac{m_H^2 v^2}{8} \quad (m_H \approx 125 \text{ GeV}, v \approx 246 \text{ GeV}) \]

A fairly innocuous sounding \( (104 \text{ GeV})^4 \)
Higgs potential – remember: it’s an energy density

\[ V(\phi), \text{ SM} \]

Corresponds to an energy density of
\[ 1.5 \times 10^{10} \text{ GeV/fm}^3 \]
i.e. 10 billion times nuclear density

Mass density of \( 2.6 \times 10^{28} \text{ kg/m}^3 \)
What does $2.6 \times 10^{28} \text{ kg/m}^3$ mean?
What does $2.6 \times 10^{28} \text{ kg/m}^3$ mean?
What does $2.6 \times 10^{28} \text{kg/m}^3$ mean?

fit the mass of the sun into a standard 40ft shipping container
cosmological constant & fine-tuning [classically]

\[ V_{\text{min}} = \left[ -\mu^2 |\phi|^2 + \lambda |\phi|^4 \right]_{\phi_0} + V_0 \]

\[ = -2.6 \times 10^{28} \text{ kg/m}^3 + V_0 = 5.96 \times 10^{-27} \text{ kg/m}^3 \]

- \( V_0 \) needs to be fine tuned for cosmological constant to have today’s size (also with respect to various sources of quantum correction)

- not the only fine-tuning problem in fundamental physics, — arguably special in that it appears already classically

- collider physics cannot tell us anything about \( V_0 \), — but it would seem negligent not to try and establish the rest of the potential
The potential expanded around the minimum

- take $h$ as the Higgs field excitation in units of the field at minimum

$$V = \frac{m_H^2 v^2}{8} \left( -1 + 4h^2 + 4h^3 + h^4 \right)$$

the Higgs boson mass term

prediction of the strength of HHH interaction

[modifier may be called $\kappa_4$ or $\kappa_3$]
Higgs self-coupling at FCC-ee

- **Statistics-limited sensitivity comes from** $\sigma_{ee \rightarrow ZH}$ **measurements at 240 and 365 GeV**
  - Thanks to the relative change with centre-of-mass energy

- **Estimate with present run plan and 2 IPs**: $\geq 2\sigma$ from $\kappa_\lambda = 0$
  - Analyses will improve, but no hope with 5 times less luminosity
    (Discovery)

- **With 4 IPs and optimization of run plan**: target $\geq 5\sigma$, $\delta \kappa_\lambda \sim 20\%$
  - Increase duration at 240 and 365 GeV (to 4 and 7 years)
    - Reduce $Z$ and $WW$ run duration @ constant statistics
  - Or better: increase specific luminosity and/or overall running time
    - If it is worth doing, it is worth doing well

**Figures**
- Diagrams showing Higgs self-coupling processes
- Graphs illustrating $\kappa_\lambda$ precision (global fit)

**Tables**
- List of values for total decay width of the Higgs boson
- Summary of Higgs production processes at the ILC

**Notes**
- The ILC operation will start with the first FCC week, London, June 2023
Testing SM $V(\phi)$ by measuring HH production at FCC: $\sim$3–5% accuracy

- kinematic shape of HH pair clearly distinguishes independent HH production from correlated HH
- FCC-hh $\rightarrow$ few % determination
  (needs accurate $t\bar{t}Z$ and Higgs couplings from FCC-ee)

### FCC-hh 68%cl precision (%) on double-Higgs production

- **$\delta_{\mu}$**
  - stat only: 2.2, 2.8, 3.7
  - stat + syst: 2.4, 3.5, 5.1
- **$\delta_{\kappa_\lambda}$**
  - stat only: 3.0, 4.1, 5.6
  - stat + syst: 3.4, 5.1, 7.8

(optimistic ~ LHC Run 2 perf) (30fb$^{-1}$ @ 100 TeV, Mangano, Ortona & Selvaggi, 2004.03505)

---

**FCC-hh Simulation**

- $g \, g \rightarrow H \, H$
- $\kappa_\lambda = 0$
- $\kappa_\lambda = 1$
- $\kappa_\lambda = 2$
- $\kappa_\lambda = 3$

**Powheg-V2 (NLO)**

$s=100$ TeV

---

Gavin Salam

FCC week, London, June 2023
when would we claim discovery? [5σ in each of two independent experiments is our gold standard]

➤ equivalent for an interaction is a bit ambiguous — but better than ±20% determination is probably a reasonable target

➤ for something of this importance, I am wary of relying on 20% only from a combination of N experiments — a result’s robustness comes from confirmation by independent experiments

➤ indirect v. direct:
  ➤ all measurements are indirect (we measure hadrons and leptons…)
  ➤ single H is good to have
  ➤ but HH & kinematic structure brings assurance that what we are seeing is indeed HHH coupling

➤ NB there exist different points of view on this
when would we claim discovery? [5σ in each of two independent experiments is our gold standard]

➤ equivalent for an interaction is a bit ambiguous — but better than ±20% determination is probably a reasonable target

➤ for something of this importance, I am of the view that a combined determination of parameter by independent experiments is probably necessary

➤ indirect vs. direct:

➤ all measurements are indirect (we measure hadrons and leptons…)

➤ single H is good to have

➤ but HH & kinematic structure brings assurance that what we are seeing is indeed HHH coupling

➤ NB there exist different points of view on this

my view: observation of HHH interaction is the "no-lose theorem" of combined FCC programme
Higgs potential – impact of measurements

this is a cartoon

caution needed: e.g. realistic BSM models do not just modify the potential, but may bring extra scalars (often modify other couplings, but not always, e.g. 2209.00666)

even if we take the picture seriously we may want to consider impact of limited constraints on $\lambda_4$ (how many coincidences are needed for a BSM model to leave $\lambda_3$ untouched while modifying $\lambda_4$?)
Higgs potential – impact of measurements

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➤ even if we take the picture seriously we may want to consider impact of limited constraints on $\lambda_4$
  (how many coincidences are needed for a BSM model to leave $\lambda_3$ untouched while modifying $\lambda_4$?)

$V(\phi)$, 2060 (FCC-ee, 4lP)

universe lives here

Standard Model potential

what we may know in 2060
$0.76 < \lambda_3/\text{SM} < 1.24$

$\lambda_4 = \text{SM}$

$\phi$

Gavin Salam

FCC week, London, June 2023
Higgs potential – impact of measurements

➤ this is a cartoon

➤ caution needed: e.g. realistic BSM models do not just modify the potential, but may bring extra scalars (often modify other couplings, but not always, e.g. 2209.00666)

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just modify the potential,
but may bring extra scalars
(often modify other couplings, but not
always, e.g. 2209.00666)

even if we take the picture
seriously we may want to
consider impact of limited
constraints on $\lambda_4$
(how many coincidences are needed for a
BSM model to leave $\lambda_3$ untouched while
modifying $\lambda_4$?)
A wildly speculative aside [science fiction!]

➤ common argument for fundamental research: it may pay off in terms of technological advances in a century or two

➤ in particle physics, it’s hard to conceive of a way in which this could be true

➤ **Attempt at counterexample:** if there were 2nd minimum in Higgs potential, could we create metastable bubbles of alternative vacuum? (cf. EW phase transition)

➤ likely very short lifetime, unless some kind of protection

➤ what might we do with it? E.g. very different nuclear physics, if light quarks get all mass from Yukawa interactions, long-range strong force (pion ~ massless), etc.

➤ this scenario is very far fetched: do not take it seriously! (But we can’t even tell how far fetched it is if we haven’t measured the potential)
desirable features of a worldwide HEP project?

- an important target that is guaranteed to be reached (no-lose theorem)
- exploration into the unknown by a significant factor in energy
- major progress on a broad array of particle physics topics
- likelihood of success, robustness (incl. multiple experiments)
- cost-effective construction & operation, low carbon footprint
various arguments favour a circular $e^+e^-$ collider [you all know them well]

➤ historical track record of delivering luminosity [LEP]
➤ unlike linear colliders, they naturally accommodate multiple experiments
➤ energy efficiency/unit luminosity from Z-pole to ZH
➤ electrons are a lot easier than muons

But some people ask if we need a lepton collider at all; should we not just go for the next hadron collider?

[practical arguments against: we don’t really know how to build the magnets for a 100 TeV collider; cost of 91km collider is high even with LHC-type magnets]
do you believe the measurement when it disagrees with your expectations?
we don’t know the precision limit of hadron colliders — but we may be close to reaching it

Parton Distribution Functions are one of several elements that may limit LHC/FCC-hh precision:
➤ essential for hadron-collider interpretation
➤ PDF fits are complex, e.g. involve (sometimes inconsistent) data, some of it close to non-perturbative scale
➤ only partial understanding of their limits

<table>
<thead>
<tr>
<th>Parton Distribution</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDF4LHC15</td>
<td>1.0000</td>
<td>± 0.0184</td>
</tr>
<tr>
<td>PDF4LHC21</td>
<td>0.9930</td>
<td>± 0.0155</td>
</tr>
<tr>
<td>CT18</td>
<td>0.9914</td>
<td>± 0.0180</td>
</tr>
<tr>
<td>MSHT20</td>
<td>0.9930</td>
<td>± 0.0108</td>
</tr>
<tr>
<td>NNPDF40</td>
<td>0.9986</td>
<td>± 0.0058</td>
</tr>
</tbody>
</table>

gg-lumi. ratio to PDF4LHC15 @ $m_H$

$\alpha_s(m_Z) = 0.118$

$gg$ partonic luminosity ($\sqrt{s} = 13$TeV)
**first approx N3LO PDFs**

Approximate N$^3$LO Parton Distribution Functions with Theoretical Uncertainties:

**MSHT20aN$^3$LO PDFs**

arXiv:2207.04739v1

J. McGowan$^a$, T. Cridge$^a$, L. A. Harland-Lang$^b$, and R.S. Thorne$^c$

- includes approximations & data-driven fits to parts of N3LO currently unknown
- **7.6% decrease in Higgs cross section** (w. N3LO $\sigma$)
- PDF part of uncertainty goes up by $\times2.5–3$
- fairly surprising; starting point for many future investigations

<table>
<thead>
<tr>
<th>$\sigma$ order</th>
<th>PDF order</th>
<th>$\sigma$ (pb) + $\Delta\sigma_+ - \Delta\sigma_-$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$^3$LO</td>
<td>aN$^3$LO (no theory unc.)</td>
<td>44.164 + 3.03% - 3.13%</td>
</tr>
<tr>
<td></td>
<td>aN$^3$LO ($H_{ij} + K_{ij}$)</td>
<td>44.164 + 3.34% - 3.15%</td>
</tr>
<tr>
<td></td>
<td>aN$^3$LO ($H_{ij}'$)</td>
<td>44.164 + 3.43% - 3.07%</td>
</tr>
<tr>
<td></td>
<td>NNLO</td>
<td>47.817 + 1.17% - 1.22%</td>
</tr>
</tbody>
</table>
a lepton collider as a next step ensures solid foundations for the field

e.g. measurement of $H \rightarrow gg$ at 1% at FCC-ee underpins precision of FCC-hh (and similarly ttZ coupling for ttH normalisation, etc.)

PDF part of uncertainty goes up by $\times 2.5$–3

fairly surprising; starting point for many future investigations
desirable features of a worldwide HEP project?

- an important target that is guaranteed to be reached (no-lose theorem)
- exploration into the unknown by a significant factor in energy
- major progress on a broad array of particle physics topics
- likelihood of success, robustness (incl. multiple experiments)
- cost-effective construction & operation, low carbon footprint
what should we expect as a step up in energy?

I like the $Z'_\text{SSM}$ as a simple measure of progress
(perhaps not very “exciting”, but simple and most experiments look for it)

<table>
<thead>
<tr>
<th>Tevatron</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\bar{p}$, 1.96 TeV, 10 fb$^{-1}$</td>
<td>$pp$, 13.6 TeV, 139 fb$^{-1}$</td>
</tr>
<tr>
<td>Exclusion limit $\sim$ 1.2 TeV</td>
<td>Exclusion limit $\sim$ 5.1 TeV</td>
</tr>
</tbody>
</table>

(if they had analysed all their data in electron and muon channels; actual CDF limit 1.071 TeV, 4.7 fb$^{-1}$, $\mu\mu$ only)
what should we expect as a step up in energy?

I like the $Z'_\text{SSM}$ as a simple measure of progress (perhaps not very “exciting”, but simple and most experiments look for it)

$LHC$

$\text{pp, 13 TeV, 139 fb}^{-1}$

Exclusion limit $\sim 5.1$ TeV

($\text{electron and muon channels, single experiment}$)

$\times 7.8$

$\text{FCC-hh}$

$\text{pp, 100 TeV, 20 ab}^{-1}$

Exclusion limit $\sim 41$ TeV

($\text{based on PDF luminosity scaling, assuming detectors can handle muons and electrons at these energies}$)
FCC-hh delivers the kind of step up in direct-search sensitivity ($\times 4 - 6$) that we would hope for.
It is important to take these conclusions somewhat impressionistically, as we have made a number of simplifying assumptions in order to paint the broad picture.
FCC-ee, e.g. axion and heavy-neutral lepton searches

benefits from huge Z-pole luminosity
(some models in these regions have potential to connect with dark matter, baryon asymmetry, neutrino masses, etc.)
Interpret higher precision as increase in indirect reach

![Graph showing sensitivity at 68% probability to deviations in the different effective Higgs couplings and aTGC from a global fit to the projections available at each future collider project. Results obtained within the SMEFT framework in the benchmark SMEFT ND. The HE-LHC results correspond to the $S_{02}$ assumptions for the theory systematic uncertainties in Higgs processes.]

### 3.4.2 Results for BSM-motivated effective Lagrangians

In this subsection, we adopt a more BSM-oriented perspective and present the global fit results in a way that can be easily matched to theory-motivated scenarios, such as composite Higgs models. For that purpose, we will restrict the results to the set of dimension-6 interactions in the effective Lagrangian in eq. (19) and adopt the usual presentation of results in terms of the bounds on the dimension-6 operator coefficients. We will also extend the global fits presented in previous sections, adding further studies available in the literature about high-energy probes of the EFT. These are designed to benefit from the growth with energy of the contributions of certain dimension-6 operators in physical processes, leading to competitive constraints on new physics, without necessarily relying on extreme experimental precision. In this regard, we note that these studies are usually not performed in a fully global way within the EFT framework, but rather focus on the most important effects at high energies. Therefore, the results when such processes dominate in the bounds on new physics should be considered with a certain amount of caution, although they should offer a reasonable approximation under the assumptions in (19) and (20).

In particular, we will add the following high-energy probes using di-boson and di-fermion processes:

- The constraints on the $W$ and $Y$ oblique parameters [48] (which can be mapped into $c_2^W$, $c_2^B$) from fermion pair production at the HL-LHC, HE-LHC [13], FCC-hh [49], ILC at 250, 500 and 1000 GeV [4], and CLIC [46].

It must be noted that, for the HE-LHC, only the sensitivity to $W$ and $Y$ from $pp \rightarrow \ell^+\ell^-$ is available in [13]. There is no sensitivity reported from charged-current process, which can constrain $W$ independently. No studies on the reach for the $W$ and $Y$ parameters were available for CEPC or the FCC-ee. For this section, for these two lepton colliders, it has been

The studies in [46] and [4] make use of significantly different assumptions for the systematic uncertainties and efficiencies for each $e^+e^-$ channel. The apparent small difference in terms of reach at the highest energy stages for CLIC/ILC is, however, due to the high luminosity assumed at ILC, as well as the use of positron polarization, which allow to partially compensate the lower energy achievable compared to CLIC.
Interpret higher precision as increase in indirect reach

Figure 3. Sensitivity at 68% probability to deviations in the different effective Higgs couplings and aTGC from a global fit to the projections available at each future collider project. Results obtained within the SMEFT framework in the benchmark SMEFT-ND. The HE-LHC results correspond to the assumptions for the theory systematic uncertainties in Higgs processes [13].

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Interpret higher precision as increase in indirect reach

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Interpret higher precision as increase in indirect reach

\[ \frac{\delta g}{g} [\%] \]

\[ g_{\text{eff}}^{\text{HZZ}} \]

Figure 3. Sensitivity at 68% probability to deviations in the different effective Higgs couplings and aTGC from a global fit to the projections available at each future collider project. Results obtained within the SMEFT framework in the benchmark SMEFT ND.

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increase in precision at FCC-ee is equivalent to $\times 4 - 5$ increase in energy reach
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Two messages

- with a rough estimate for systematics, FCC brings a big step forward (geom.avg. $= \times 18$, across $\geq 20$ observables)

- still huge scope for thinking about how to improve systematics (gain of up to further $\times 100$ in some cases)

This is the fun part for us as physicists! and will call for joint efforts by experiment/theory/accelerator physicists

---

*FCC-ee precision gain*
desirable features of a worldwide HEP project?

an important target that is guaranteed to be reached (no-lose theorem)

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (incl. multiple experiments)

cost-effective construction & operation, low carbon footprint
Rare/forbidden decays

"intensity frontier"

FCC-ee

Higgs

$m_{Higgs}, \Gamma_{Higgs}

Higgs couplings

self-coupling

Top

$m_{top}, \Gamma_{top}

EW top couplings

flavour factory

$(10^{12} bb/cc; 1.7\times10^{11} \tau\tau)$

tau physics

- $t$-based EWPOs
- lepton universality tests

B physics

- Flavour EWPOs ($R_B, A_{FB}^{b,c}$)
- CKM matrix
- CP violation in neutral B mesons
- Flavour anomalies, e.g., $b \rightarrow s\tau\tau$

vertexing, tagging

energy resolution

hadron identification

detector hermeticity

tracking, calorimetry

direct searches

of light new physics

- Axion-like particles, dark photons,
  Heavy Neutral Leptons
- long lifetimes - LLPs

EW & QCD

- $m_Z, \Gamma_Z, N_e$
- $R_t, A_{FB}$
- $m_W, \Gamma_W$
- $\alpha_S(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

Slide from C. Grojean @ FCC Week'22
threshold scan for top mass

limits on top FCNF

95%CL limits on top FCNF

SM

\[ \begin{align*}
\text{t} \rightarrow \text{Hc} & : 3 \times 10^{-14} \\
\text{t} \rightarrow \text{Hu} & : 2 \times 10^{-14} \\
\text{t} \rightarrow \text{yc} & : 5 \times 10^{-14} \\
\text{t} \rightarrow \text{yu} & : 4 \times 10^{-15} \\
\text{t} \rightarrow \text{gc} & : 5 \times 10^{-12} \\
\text{t} \rightarrow \text{gu} & : 4 \times 10^{-14} \\
\text{t} \rightarrow \text{Zc} & : 1 \times 10^{-14} \\
\text{t} \rightarrow \text{Zu} & : 7 \times 10^{-16}
\end{align*} \]
Flavour physics: 15× more b-pairs at FCC-ee than at Belle II

<table>
<thead>
<tr>
<th>Attribute</th>
<th>$\Upsilon(4S)$</th>
<th>$pp$</th>
<th>$Z^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All hadron species</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>High boost</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Enormous production cross-section</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Negligible trigger losses</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Low backgrounds</td>
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</tr>
<tr>
<td>Initial energy constraint</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 1: Advantageous attributes for flavour-physics studies at Belle II ($\Upsilon(4S)$), the LHC ($pp$) and FCC-ee ($Z^0$).

The one disadvantage that the $Z^0$ has in comparison with the LHC is the production cross section, but this is partially mitigated at FCC-ee by the enormous luminosity that is foreseen.

The number of $b\bar{b}$ pairs from which these yields arise is around fifteen times larger than that expected at Belle II.
FCC-ee & QCD: strong coupling, etc.

- strong coupling from EW precision to per-mil accuracy
- studies of colour reconnection in W-pair events
- jet rates, substructure, flavour, fragmentation
- etc.
PDFs from FCC-eh are potentially crucial for full exploitation of FCC-hh physics programme.

NB: potential worries about non-perturbative contributions in PDF fits to moderate-$Q^2$ DIS data & reliance on data from single experiment.
**FCC-hh PbPb collisions: top & W decays probe q/g-plasma across yoctosecond time-scales**

Fig. S.6 Left: total delay time for the QGP energy-loss parameter $\hat{q} = 4$ GeV$^2$/fm as a function of the top transverse momentum (black dots) and its standard deviation (error bars). The average contribution of each component is shown as a coloured stack band. The dashed line corresponds to a $\hat{q} = 1$ GeV$^2$/fm. Right: reconstructed W boson mass, as a function of the top $p_T$. The upper axis refers to the average total time delay of the corresponding top $p_T$ bin.

**Table S.4** Expected production yields for b-flavoured particles at FCC-ee at the Z run, and at Belle II (50 ab$^{-1}$) for comparison.

<table>
<thead>
<tr>
<th>Particle production</th>
<th>$B_0/\bar{B}_0$</th>
<th>$B_+ / B_-$</th>
<th>$\Lambda_1/\bar{\Lambda}_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC-ee</td>
<td>1000</td>
<td>250</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>250</td>
<td>170</td>
</tr>
<tr>
<td>Belle II</td>
<td>27.5</td>
<td>27.5</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>45</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>1000</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>1000</td>
<td>170</td>
</tr>
</tbody>
</table>

**Flavor physics**

The FCC flavour programme receives important contributions from all 3 machines, FCC-ee, hh, and eh. The Z run of the FCC-ee will fully record, with no trigger, $10^{12} Z \rightarrow b \bar{b}$ and $Z \rightarrow c \bar{c}$ events. This will give high statistics of all b- and c-flavoured hadrons, making FCC-ee the natural continuation of the B-factories. Of topical interest will be the study of possible lepton flavour and lepton number violation. FCC-ee, with detection efficiencies internally mapped with extreme precision, will offer 200,000 $B_0 \rightarrow K^* (892)^0 e^+ e^-$, 1,000 $K^* (892)^0 \tau^+\tau^-$ and 1000 ($100$) $B_s$ events, on order of magnitude more than the LHC upgrade. The determination of the CKM parameter will be correspondingly improved. First observation of CP violation in B mixing will be within reach; a global analysis of
desirable features of a worldwide HEP project?

an important target that is guaranteed to be reached (no-lose theorem)

exploration into the unknown by a significant factor in energy

major progress on a broad array of particle physics topics

likelihood of success, robustness (incl. multiple experiments)

cost-effective construction & operation, low carbon footprint
Our first responsibility (as particle physicists) is to do the maximum of science
- With the minimum energy consumption and the minimum environmental impact for our planet
  - Should become one of our top-level decision criteria for design, choice and optimization of a collider

All Higgs factories have a “similar” physics outcome (ESU’20 and Snowmass’21)
- Natural question: what is their energy consumption or carbon footprint for the same physics outcome?
  - Circular colliders have a much larger instantaneous luminosity and operate several detectors
  - FCC-ee is at CERN, where electricity is already almost carbon-free (and will be even more so in 2048)
conclusions
Conclusions

➤ There is a no-lose theorem: directly establishing Higgs self-interaction (it holds the SM together), which is made solid by precision of FCC-ee and direct measurement at FCC-hh

➤ is there a chance of a second no-lose theorem in establishing (or disproving) SM origin of electron mass?

➤ The step up in energy reach that we expect is $\sim \times 4 - 5$

➤ FCC-ee delivers that in “indirect” sensitivity, through precision increase $\sim \times 18$

➤ FCC-hh delivers that in direct search sensitivity

➤ The programme is diverse and robust

➤ One issue: timeline.

➤ Probably no realistic faster route to a new collider of any kind, but the field as a whole is at risk if we don’t soon consolidate the path to a new collider that starts in next c. 20 years.
PHYSICS WITH A MULTI-TeV HADRON COLLIDER

C.H. Llewellyn Smith,

Looking at the wide variety of alternatives which have been proposed, it might appear that theorists are in disarray but it seems to me that the present situation is an inevitable consequence of the successes of the 1970's. The problems of the 1960's - the nature of hadrons, the nature of the strong force, the nature of the weak force - have been solved. We now confront deeper problems - the origin of mass, the choice of fundamental building blocks (the problem of flavour), the question of further unification of forces including gravity, the origin of charge and of gauge symmetry. It is only to be expected that many of the first attempts to grapple with these problems will be misguided. As ever, we must reply on experiment to reveal the truth.
backup
Recalling the basic numbers
FCC-ee (numbers of events are for 2 detectors — baseline is now 4)

- ZH maximum: $\sqrt{s} \sim 240$ GeV, 3 years
- $t\bar{t}$ threshold: $\sqrt{s} \sim 350$ GeV, 5 years
- Z peak: $\sqrt{s} \sim 91$ GeV, 4 years
- WW threshold+: $\sqrt{s} \geq 161$ GeV, 2 years
- s-channel H: $\sqrt{s} = 125$ GeV, ?Years

- $10^6 e^+e^- \rightarrow ZH$
- $10^6 e^+e^- \rightarrow t\bar{t}$
- $5 \times 10^{12} e^+e^- \rightarrow Z$
- $>10^8 e^+e^- \rightarrow W^+W^-$
- $\sim 5000 e^+e^- \rightarrow H$

- Never done
- LEP x $10^5$
- LEP x $10^3$
- Never done

- $\sqrt{s}$ errors
  - 2 MeV
  - 5 MeV
  - <100 keV
  - <300 keV
  - <200 keV
Great energy range for SM heavy particles AND highest luminosities AND √s precision

Physics at FCC - ee - New opportunities for discovery

ZH maximum  \( \sqrt{s} \sim \) 240 GeV  3 years  \( 10^6 \) \( e^+ + e^- \xrightarrow{} Z H \)

tt threshold  \( \sqrt{s} \sim 350 \) GeV  5 years  \( 10^6 \) \( e^+ + e^- \xrightarrow{} t\bar{t} \)

Z \( \text{peak} \) \( \sqrt{s} \sim 91 \) GeV  4 years  \( 5 \times 10^{12} \) \( e^+ + e^- \xrightarrow{} Z \)

WW threshold + \( \sqrt{s} \sim 161 \) GeV  2 years > \( 10^8 \) \( e^+ + e^- \xrightarrow{} W^+ W^- \)...

FCC-ee (updated plot for 4 detectors)

- FCC-ee (2 IPs)
- FCC-ee (4 IPs)
- ILC (TDR, upgrades)
- CLIC (CDR, 2022)
FCC–hh: what do 20/30ab−1 @ 100 TeV buy you?

- ~ ×5 in mass reach of new-physics searches relative to HL-LHC (fairly independently of the new physics scenario)
- 100 → 500 × higher numbers of Higgs bosons, $t\bar{t}$ pairs, etc. than HL-LHC (much more at high-$p_T$ & for high-mass pairs)

### Table 1.1. Higgs production event rates for selected processes at 100 TeV ($N_{100}$) and statistical increase with respect to the statistics of the HL-LHC ($N_{100} = \sigma_{100 \text{ TeV}} \times 30 \text{ ab}^{-1}$, $N_{14} = \sigma_{14 \text{ TeV}} \times 3 \text{ ab}^{-1}$).

<table>
<thead>
<tr>
<th></th>
<th>gg → H</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>ttH</th>
<th>HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{100}$</td>
<td>$24 \times 10^9$</td>
<td>$2.1 \times 10^9$</td>
<td>$4.6 \times 10^8$</td>
<td>$3.3 \times 10^8$</td>
<td>$9.6 \times 10^8$</td>
<td>$3.6 \times 10^7$</td>
</tr>
<tr>
<td>$N_{100}/N_{14}$</td>
<td>180</td>
<td>170</td>
<td>100</td>
<td>110</td>
<td>530</td>
<td>390</td>
</tr>
</tbody>
</table>
together with PbPb [and maybe ep and ePb options]

<table>
<thead>
<tr>
<th></th>
<th>√s</th>
<th>L /IP (cm⁻² s⁻¹)</th>
<th>Int. L/IP(√s⁻¹)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>e⁺e⁻</strong></td>
<td>~90 GeV</td>
<td>230 x10³⁴</td>
<td>75</td>
<td>2-4 experiments</td>
</tr>
<tr>
<td><strong>FCC-ee</strong></td>
<td>160 GeV</td>
<td>28</td>
<td>5</td>
<td>Total ~ 15 years of operation</td>
</tr>
<tr>
<td></td>
<td>240 GeV</td>
<td>8.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>~365 GeV</td>
<td>1.5</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Z</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>WW</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>H</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>top</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>pp</strong></td>
<td>100 TeV</td>
<td>5 x 10³⁴</td>
<td>20-30</td>
<td>2+2 experiments</td>
</tr>
<tr>
<td><strong>FCC-hh</strong></td>
<td></td>
<td>30</td>
<td></td>
<td>Total ~ 25 years of operation</td>
</tr>
<tr>
<td><strong>PbPb</strong></td>
<td>√S_{NN} = 39 TeV</td>
<td>3 x 10²⁹</td>
<td>100 nb⁻¹/run</td>
<td>1 run = 1 month operation</td>
</tr>
<tr>
<td><strong>FCC-hh</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ep</strong></td>
<td>3.5 TeV</td>
<td>1.5 x 10³⁴</td>
<td>2 ab⁻¹</td>
<td>60 GeV e- from ERL Concurrent operation with pp for ~ 20 years</td>
</tr>
<tr>
<td><strong>Fcc-eh</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>e-Pb</strong></td>
<td>√S_{eN} = 2.2 TeV</td>
<td>0.5 x 10³⁴</td>
<td>1 fb⁻¹</td>
<td>60 GeV e- from ERL Concurrent operation with PbPb</td>
</tr>
<tr>
<td><strong>Fcc-eh</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NB ee numbers are outdated (2IP, should be 4)
FCC as a Higgs factory [NB numbers are for 2 IP — new baseline is 4 IP]

- Higgs provides a very good reason why we need both $e^+e^-$ AND pp colliders
  - FCC-e$e$ measures $g_{HZZ}$ to 0.2% (absolute, model-independent, standard candle) from $\sigma_{ZH}$
    - $\Gamma_H, g_{H_{bb}}, g_{H_{cc}}, g_{H_{tt}}, g_{H_{WW}}$ follow
    - Standard candle fixes all HL-LHC / FCC-hh couplings
  - FCC-hh produces over $10^{10}$ Higgs bosons
    - (1$^{st}$ standard candle $\rightarrow$) $g_{H_{\mu\mu}}, g_{H_{YY}}, g_{H_{ZZ}}, Br_{inv}$
    - Another standard candle
  - FCC-e$e$ measures top EW couplings ($e^+e^- \rightarrow t\bar{t}$)
    - $g_{H_{\mu\mu}}, g_{H_{YY}}, g_{H_{ZZ}}, Br_{inv}$
  - FCC-hh produces $10^8$ $t\bar{t}H$ and $2 \times 10^7$ HH pairs
    - (2$^{nd}$ standard candle $\rightarrow$) $g_{H_{tt}}$ and $g_{HHH}$

- FCC-e$e$ / FCC-hh complementarity is outstanding
  - Unreachable by high-energy lepton colliders

- FCC-e$e$ is also the most pragmatic, safest, and most effective way toward FCC-hh

Patrick Janot
Engagement meeting
26 Nov 2021

<table>
<thead>
<tr>
<th>Observable</th>
<th>( \sqrt{s} )</th>
<th>( m_Z )</th>
<th>( 2m_W )</th>
<th>( \text{HZ max.} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision EW (Z, W, top)</td>
<td>Transverse</td>
<td>( m_{\text{top}} )</td>
<td>( \text{Top} )</td>
<td></td>
</tr>
<tr>
<td>QCD (( \alpha_s )) QED (( \alpha_{\text{QED}} ))</td>
<td>( 5 \times 10^{12} ) Z</td>
<td>( 3 \times 10^8 ) W</td>
<td>( 10^9 ) H \rightarrow gg</td>
<td></td>
</tr>
<tr>
<td>Model-independent Higgs couplings</td>
<td>( ee \rightarrow H )</td>
<td>( \sqrt{s} = m_t )</td>
<td>( 1.2 \times 10^6 ) Z and ( 75 ) k WW \rightarrow H at two energies</td>
<td></td>
</tr>
<tr>
<td>Higgs invisible decays</td>
<td></td>
<td></td>
<td></td>
<td>&lt;1% precision (*)</td>
</tr>
<tr>
<td>Higgs self-coupling</td>
<td></td>
<td></td>
<td></td>
<td>&lt;1% precision (*)</td>
</tr>
<tr>
<td>Flavours (b, t)</td>
<td>( 5 \times 10^{12} ) Z</td>
<td></td>
<td></td>
<td>10 + BR sensitivity</td>
</tr>
<tr>
<td>RH ( \nu )'s, Feebly interacting particles</td>
<td>( 5 \times 10^{12} ) Z</td>
<td></td>
<td></td>
<td>Key to EWSB</td>
</tr>
<tr>
<td>Direct search at high scales</td>
<td></td>
<td>( M_H &lt; 230 \text{GeV} ) Small ( \Delta M )</td>
<td>( M_H &gt; 230 \text{GeV} ) Small ( \Delta M )</td>
<td>Direct NP discovery</td>
</tr>
<tr>
<td>Precision EW at high energy</td>
<td></td>
<td>( Y )</td>
<td>( W, Z )</td>
<td>Indirect Sensitivity to Nearby new physics</td>
</tr>
<tr>
<td>Quark-gluon plasma Physics w/ injectors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Leading Physics Questions**

- Existence of more SM-interacting particles
- Fundamental constants and tests of QED/QCD
- Test Higgs nature
- Portal to new physics
- Portal to dark matter
- Key to EWSB
- Direct NP discovery At low couplings
- Direct NP discovery At high mass
- Indirect Sensitivity to Nearby new physics
- OCD at origins

**Engagement meeting**

Green = Unique to FCC; Blue = Best with FCC; (*) = if FCC-\( \nu \)-hh is combined with FCC-ee; Pink = Best with other colliders
Table 3.3: Values for 1σ sensitivity on the $S$ and $T$ parameters. In all cases the value shown is after combination with HL-LHC. For ILC and CLIC the projections are shown with and without dedicated running at the $Z$-pole. All other oblique parameters are set to zero. The intrinsic theory uncertainty is also set to zero.

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>HL-LHC</th>
<th>ILC$<em>{250}$ &amp; ILC$</em>{91}$</th>
<th>CEPC</th>
<th>FCC-ee</th>
<th>CLIC$<em>{380}$ &amp; CLIC$</em>{91}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>0.13</td>
<td>0.053</td>
<td>0.012</td>
<td>0.009</td>
<td>0.0068</td>
<td>0.032</td>
</tr>
<tr>
<td>$T$</td>
<td>0.08</td>
<td>0.041</td>
<td>0.014</td>
<td>0.013</td>
<td>0.0072</td>
<td>0.023</td>
</tr>
</tbody>
</table>

FCC-ee brings $\times$ 14-18 increase in precision
It’s not inconceivable that the top mass could be sufficiently mis-measured at hadron colliders that the SM-universe is stable all the way to the Planck scale.

condition in terms of the pole top mass. We can express the stability condition of eq. (64) as

\[ M_t < (171.53 \pm 0.15 \pm 0.23\alpha_3 \pm 0.15M_h) \text{ GeV} = (171.53 \pm 0.42) \text{ GeV}. \]  

\textit{arXiv:1307.3536}
muon colliders
Higgs at muon collider

Table 6: 68% probability sensitivity to the Higgs couplings, assuming no BSM Higgs decay channels.

<table>
<thead>
<tr>
<th>Coupling</th>
<th>HL-LHC</th>
<th>HL-LHC + 125 GeV MuC</th>
<th>HL-LHC + 3 TeV MuC</th>
<th>HL-LHC + 10 TeV MuC</th>
<th>HL-LHC + 10 TeV MuC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5 / 20 fb⁻¹</td>
<td>1/2 ab⁻¹</td>
<td>10 ab⁻¹</td>
<td>10 ab⁻¹</td>
</tr>
<tr>
<td>$\kappa_W$ [%]</td>
<td>1.7</td>
<td>1.3 / 0.9</td>
<td>0.4 / 0.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$\kappa_Z$ [%]</td>
<td>1.5</td>
<td>1.3 / 1.0</td>
<td>0.9 / 0.7</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>$\kappa_\Phi$ [%]</td>
<td>2.3</td>
<td>1.7 / 1.4</td>
<td>1.2 / 1.0</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>$\kappa_\gamma$ [%]</td>
<td>1.9</td>
<td>1.6 / 1.5</td>
<td>1.3 / 1.2</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>$\kappa_{2\gamma}$ [%]</td>
<td>10</td>
<td>10 / 10</td>
<td>9.3 / 8.6</td>
<td>7.2</td>
<td>7.1</td>
</tr>
<tr>
<td>$\kappa_\mu$ [%]</td>
<td>-</td>
<td>12 / 5.9</td>
<td>6.2 / 4.4</td>
<td>2.3</td>
<td>1.1</td>
</tr>
<tr>
<td>$\kappa_b$ [%]</td>
<td>3.6</td>
<td>1.6 / 1.0</td>
<td>0.8 / 0.7</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>$\kappa_c$ [%]</td>
<td>4.6</td>
<td>0.6 / 0.3</td>
<td>4.2 / 4.0</td>
<td>3.4</td>
<td>3.2</td>
</tr>
<tr>
<td>$\kappa_\tau$ [%]</td>
<td>1.9</td>
<td>1.4 / 1.2</td>
<td>1.2 / 1.0</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>$\kappa_\mu^*$ [%]</td>
<td>3.3</td>
<td>3.2 / 3.1</td>
<td>3.1 / 3.1</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>$\Gamma_H^{1/2}$ [%]</td>
<td>5.3</td>
<td>2.7 / 1.7</td>
<td>1.3 / 1.0</td>
<td>0.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

† No input used for $\mu$ collider.
‡ Prediction assuming only SM Higgs decay channels. Not a free parameter in the fits.

Table 7: 68% probability intervals for the Higgs trilinear coupling.

<table>
<thead>
<tr>
<th>Coupling</th>
<th>3 TeV MuC</th>
<th>10 TeV MuC</th>
<th>14 TeV MuC</th>
<th>30 TeV MuC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L≈ 1 ab⁻¹ / 2 ab⁻¹</td>
<td>L= 10 ab⁻¹</td>
<td>L≈ 20 ab⁻¹</td>
<td>L= 90 ab⁻¹</td>
</tr>
<tr>
<td>$\delta K_\lambda$</td>
<td>[-0.5,0.5]</td>
<td>[-0.27,0.35] U [0.85,0.94] / [-0.15,0.16]</td>
<td>[-0.035, 0.037]</td>
<td>[-0.024, 0.025]</td>
</tr>
<tr>
<td>comb. w HL-LHC</td>
<td>-</td>
<td>[-0.2,0.22] / [-0.13,0.14]</td>
<td>[-0.035,0.036]</td>
<td>[-0.024,0.025]</td>
</tr>
</tbody>
</table>

Gavin Salam

FCC week, London, June 2023
triple Higgs at muon collider from 2003.13628

Figure 2: Expected cross sections (left) and signal event numbers for a reference integrated luminosity of 100 ab$^{-1}$ (right) for $\mu^+\mu^- \rightarrow HHH\nu\bar{\nu}$ versus the c.m. collision energy, for $M_{\nu\bar{\nu}} \gtrsim 150$ GeV. Cross sections for different assumptions of the trilinear and quartic couplings are presented, as well as for the SM case, obtained by WHIZARD (left-hand side) and MADGRAPH5_AMC@NLO (right-hand side). Details on the scenarios are given in the text.

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>Lumi (ab$^{-1}$)</th>
<th>Constraints on $\delta_4$ (with $\delta_3 = 0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>x-sec only 1 $\sigma$</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>$[-0.60, 0.75]$</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>$[-0.50, 0.55]$</td>
</tr>
<tr>
<td>14</td>
<td>33</td>
<td>$[-0.45, 0.50]$</td>
</tr>
<tr>
<td>30</td>
<td>100</td>
<td>$[-0.30, 0.35]$</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>$[-0.35, 0.60]$</td>
</tr>
</tbody>
</table>

Table 5: Summary of the constraints on the quartic deviations $\delta_4$, assuming $\delta_3 = 0$, for various muon collider energy/luminosity options, as obtained from the total expected cross sections (1 $\sigma$ and 2 $\sigma$ CL). The third column shows the bounds obtained from the combination of the constraints corresponding to the setups $M_{HHH} < 1$ TeV and $M_{HHH} > 1$ TeV.
Searches at muon collider

Plots being shown suggest:
4 TeV muon collider beats a 100 TeV pp collider in searches for new physics.

Useful to nuance the statement:

- 100 TeV pp, 20 ab\(^{-1}\) can discover \(Z'\) up to \(m_{Z'} \sim 38\) TeV
- For \(\mu\mu\) collider to discover \(Z'\) at \(m_{Z'} \sim 38\) TeV, it needs \(\sqrt{s} \sim 38\) TeV (with lower \(\sqrt{s}\) you would see deviation from SM, but not know what it is)
- However a 38 TeV muon collider would be much better at studying the \(Z'\) than the 100 TeV pp machine

https://arxiv.org/abs/2209.01318

fine-print: this is for 2\(\to\)2 processes
\( H \rightarrow gg \) at FCC-ee

\[ e^+ e^- \rightarrow Z \rightarrow q\bar{q} \text{ v. } e^+ e^- \rightarrow H \rightarrow gg \quad (\sqrt{s} = 125 \text{ GeV, no ISR}) \]

**Observed performance:**

- **per jet:** 6% quark mistag for 70% gluon efficiency
  
  Not quite the 1% quark mistag in 2107.02686

- **full event:** 0.8% quark mistag for 49% gluon efficiency
  
  full event worse than (jet)^2

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ROC curve: \( Z \rightarrow q\bar{q} \text{ v. } H \rightarrow gg \)

- **full event**
- **one hemisphere**
- **(one hemisphere)^2**

Lund-Net+ID

Pythia8.306, \( \sqrt{s} = 125 \text{ GeV} \)