Physics at

Matthew McCullough
Where are we now?

After decades of combined effort...

We now have the correct effective theory (symmetries and particles) to describe all of the known fundamental particles.

This is a remarkable scientific achievement!
Where are we now?

After decades of combined effort...

Experiment.

Accelerator.

Theory.

The Higgs was the keystone,

bringing us to a new era of fundamental physics.
Where are we now?

The Higgs is the end of the first chapter...

and the beginning of the next, but LHC cannot address new frontier of fundamental questions.
How can we get there?

How we answer the next fundamental questions will boil down to the uncertainty principle:

**Energy Frontier**

To probe nature at the smallest distance scales, we must push to the highest momentum scales:

\[
\Delta x \geq \frac{\hbar}{2\Delta p}
\]

If new particles exist with a tiny Compton wavelength, high energy is the only way to observe them directly.

**Intensity Frontier**

Alternatively, we may gain indirect access to physics at the highest energies with high precision measurements:

\[
\Delta E \geq \frac{\hbar}{2\Delta t}
\]

If new interactions exist, beyond the Standard Model, the first cracks could show up in high precision.

FCC-ee, he, ee, fit both categories.
Where do we need to go?

Higgs! Higgs! Higgs!

- The Higgs is completely unique. We must strive to understand every aspect of it.
The question defines the machine...

The physics of the Higgs boson dictates some very clear physics targets.

Every measurement of the Higgs boson probes new physics. What precision should we aim for?
The Higgs boson is uncharged and carries no spin, so can interact readily with unknown particles. Even if we cannot “see” new particles, they affect the Higgs quantum mechanically, and we can search for these effects.

We can peek through the Higgs portal, by peering into the Higgs boson itself.
An $e^+e^-$ collider is the surgeon’s scalpel of particle physics.

- Dominant Higgs production at lower energies is associated production:

  \[ e^+ e^- \rightarrow Z h \]

  Can measure $Z$-recoils alone

- Total cross section independent of Higgs decays, unique to $e^+e^-$! Clear determination of width!
The measurements...

- SM dictates we must exceed an accuracy of few % to truly measure the quantum mechanics of the Higgs boson.

- FCC-ee would delve deep into this regime, with a measurement of 0.4% accuracy!

SM 1-loop electroweak quantum corrections to cross section are a few %.
The size of the Higgs boson...

- Probing deep into the quantum nature (substructure) of the Higgs boson.

Talk by De Blas at FCC Physics Week.

Would know about Higgs sub-structure, down to scales two orders of magnitude below Higgs Compton wavelength!

$$\lambda_h \approx 10^{-17} \text{ m}$$

$$\lambda_{10 \text{ TeV}} \approx 10^{-19} \text{ m}$$
A Portal to Hidden Worlds...

Dark matter is uncharged, suggesting there are other hidden sectors beyond the Standard Model...

The Higgs boson is uncharged and carries no spin, so can interact readily with such hidden sectors.

Even if generated at high energies, interactions remain relevant. Hence the term “Higgs Portal”.

We don’t know what’s out there, but there is something, and the Higgs is a great place to look.
The laboratory search for dark matter will hit a difficult background, called the "neutrino floor". FCC-hh Missing Energy searches, for example for decays of the Higgs to dark sector states, will hit the permille branching ratio level!

May not be a good thermal DM candidate...
The Dynamics of EWSB

How did the electroweak phase transition occur in the primordial Universe?

Now...

\[ V(H) \]

\[ \frac{1}{2} m_h^2 h^2 + \frac{1}{6} \lambda h^3 + \ldots \]

Mass

Self Interaction

Then?

This answer has important consequences...
The Higgs Potential...

Measuring the Higgs self-coupling is the only way to measure the structure of the Higgs potential.

\[ V(H) = \frac{1}{2} m_h^2 h^2 + \frac{1}{6} \lambda h^3 + ... \]

Discovering the Higgs was difficult enough, now we want to know how it behaves in private...
At FCC-hh gain sensitivity to self-interactions by searching for pair production:

There are many decay channels to consider, however most promising is:

\[ hh \rightarrow b\bar{b}\gamma\gamma \]
Compared to the LHC, pair production cross section grows by a factor of 40. Note that this is a much greater increase than in CM energy...

Huge increase in event numbers translates directly to a precise measurement of the nature of the Higgs potential!

From FCC Report

<table>
<thead>
<tr>
<th>process</th>
<th>precision on $\sigma_{SM}$</th>
<th>68% CL interval on Higgs self-couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HH \rightarrow b\bar{b}g\gamma$</td>
<td>3%</td>
<td>$\lambda_3 \in [0.97, 1.03]$</td>
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<tr>
<td>$HH \rightarrow b\bar{b}b\bar{b}$</td>
<td>5%</td>
<td>$\lambda_3 \in [0.9, 1.5]$</td>
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<td>$HH \rightarrow b\bar{b}4\ell$</td>
<td>$O(25%)$</td>
<td>$\lambda_3 \in [0.6, 1.4]$</td>
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<tr>
<td>$HH \rightarrow b\bar{b}\ell^+\ell^-$</td>
<td>$O(15%)$</td>
<td>$\lambda_3 \in [0.8, 1.2]$</td>
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<tr>
<td>$HH \rightarrow b\bar{b}\ell^-\gamma$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$HHH \rightarrow b\bar{b}b\gamma\gamma$</td>
<td>$O(100%)$</td>
<td>$\lambda_4 \in [-4, +16]$</td>
</tr>
</tbody>
</table>
The origins of matter...

The matter-antimatter imbalance can be generated during the primordial electroweak phase-transition. This needs to be strongly first-order. SM does not work, however scenarios modifying the Higgs potential, through the influence of new particles, can.

The “Nightmare scenario”: A gauge singlet scalar, is the most difficult to discover.

This plot assumes 10% accuracy.
The fate of the Universe...

The Higgs potential has another minimum...

If any evidence emerges for modifications of Higgs sector, huge consequences for our future...
Comment...

We got the symmetries: LEP.

\[ \text{SU}(2)_L \times \text{U}(1)_Y \rightarrow \text{U}(1)_{\text{EM}} \]

Then we got the mechanism: LHC.

\[ \langle H \rangle = v + h \]

Now it’s time to get the dynamics: FCC.

\[ V(H) = \frac{1}{2}m_h^2 h^2 + \frac{1}{6}\lambda h^3 + \ldots \]

Mass \hspace{1cm} Self Interaction
FCC-hh at Higgs Intensity frontier.

At FCC-hh TEN BILLION Higgs bosons produced. Allowing to study extremely rare behaviour.

**Higgs Production**

Higgs+jet production

Would occur at Higgs $p_T$'s as large as 7 TeV!

This is 56 times the mass, in other words, speed of 0.9998c.

**Higgs Decays**

Higgs coupling to muons

Would be measured to 1%. The interaction strength to Higgs is

$$\lambda_{\mu} \approx 6 \times 10^{-4}$$
The Higgs is the only particle in the SM that interacts with itself. The search for it came to the fore is in revealing how the Higgs behaves in private. We will use them as reference inputs to precisely correlate the strength of the Higgs boson, allowing the top-Higgs interaction to be measured with a statistical precision at the 1% level – a factor 10 improvement over what is hoped for from the LHC. Similar precision can be reached for a statistical precision at the 1% level – a factor 10 improvement over that which is 10,000 times more than collected by the LHC so far and 100 times more than will be available by the end of LHC operations.

Note that y-axis is logarithmic!
To summarise the Higgs programme...

Precision Higgs Physics

Unfilled numbers are, in many cases, because the study has not been performed yet...

Note that y-axis is logarithmic!
Where do we need to go?

Higgs! Higgs! Higgs!
- The Higgs is completely unique. We must strive to understand every aspect of it.

Dark Matter!
- We have no idea what 80% of the matter in nature is. We have to change this.
Dark Matters

Evidence for dark matter is now overwhelming

- Rotation curves
- CMB
- Large scale structure
- Velocity dispersions
- Gravitational lensing (Bullet Cluster)
- ....

Yet we have no clue what it is at the particle level!
Dark Matters

But there are some ideas...

Stolen from slides of Tim Tait
Despite overwhelming evidence for its existence, the particle nature of dark matter is unknown.

Cosmology provides a strong motivation for direct and collider searches...
- Thermal freeze-out predicts observed abundance for:
  \[ M_{DM} \sim \mathcal{O}(\text{few GeV}) \rightarrow \mathcal{O}(10\text{'s TeV}) \]

Motivates dark matter searches in ballpark of 100 TeV collider independent of hierarchy problem.
Simplified Dark Matter Models

Write down simple scenarios to model production of dark matter at colliders:

\[
\mathcal{L}_S \supset - \sum_q c_S \lambda_{h,q} S \bar{q} q - \frac{1}{2} m_{\text{MED}}^2 S^2 + \mathcal{L}(S, \bar{\chi}, \chi),
\]

\[
\mathcal{L}_P \supset - \sum_q i c_P \lambda_{h,q} P \bar{q} \gamma^5 q - \frac{1}{2} m_{\text{MED}}^2 P^2 + \mathcal{L}(P, \bar{\chi}, \chi),
\]

\[
\mathcal{L}_V \supset - \sum_q c_V V_{\mu} \bar{q} \gamma^\mu q - \frac{1}{2} m_{\text{MED}}^2 V_{\mu} V^\mu + \mathcal{L}(V, \bar{\chi}, \chi),
\]

\[
\mathcal{L}_A \supset - \sum_q c_A A_{\mu} \bar{q} \gamma^\mu \gamma^5 q - \frac{1}{2} m_{\text{MED}}^2 A_{\mu} A^\mu + \mathcal{L}(A, \bar{\chi}, \chi),
\]

100 TeV Study: Harris, Khoze, Spannowsky, Williams, 2015.
Consider a scenario where dark matter interacts via a new Z’ boson:

Dijet Resonances

Missing Energy

Relic Density

FCC-hh: Resonances and Dark Matter

Look at the x-axes!!

1606.00947
Where do we need to go?

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Neutrino Masses!
• The renormalisable Standard Model cannot explain this, so what is their origin?
Neutrino Masses!

Someone didn’t show up to the party...

Neutrino masses might be Dirac, but then why such a small interaction with the Higgs? They are all below the eV range...

Or Majorana, but then where is the right-handed neutrino?

Shaposhnikov et al.
Neutrino masses: Long-standing puzzle in fundamental physics.

New heavy right-handed neutrinos can generate mass. Can be at collider energy scales.

FCC-eh can probe TeV frontier, FCC-ee weak-scale.
Neutrino Masses!

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Where do we need to go?

New Particles!

• There is strong motivation for the existence of new particles in the multi-TeV range.
It is a very good idea to consider luminosity ratio plots. They tell us about a vast physics program if e.g. a heavy resonance is discovered...

- High precision in dominant production modes.
- Differential distributions.
- Rare/associated production modes.
- Rare/exotic decays.
- For exotic signatures can take full advantage of cross section if background is small. E.g. displaced vertices.

Made with NNPDF 2.3 nnlo
We do not know what new physics lies above, but we have hints...

- Neutrino masses? \( M_N \gtrsim 10^{10} \text{ GeV} \)
- Strong CP? \( M_{\text{PQ}} \gtrsim 10^{10} \text{ GeV} \)
- Unification? \( M_{\text{GUT}} \sim 10^{15} \text{ GeV} \)
- Quantum gravity?

\[ M_P = 2 \times 10^{18} \text{ GeV} \]
- Hypercharge Landau pole?

\[ M_{\Lambda_Y} \gg M_P \]
This has implications at the weak scale...

\[ h \quad ? \quad h \]

At quantum level, new physics will correct Higgs mass, pulling it up to \( m_h \sim \Lambda \).

Should expect \( m_H \sim \Lambda \). But I just argued \( \Lambda \gg M_W \) so how can we reconcile with

\[ m_h = 125 \text{ GeV} \]
The Naturalness Paradox

Hierarchy problem solutions typically involve a “Top Partner”:

\[
\begin{align*}
    h & \quad \bar{t}t \quad h + h \quad TP \quad h \\
    \approx & \quad \frac{3}{8\pi^2} m_{TP}^2 \log \Lambda
\end{align*}
\]

If top partner is near the weak scale, Higgs mass corrections logarithmically sensitive to new physics scales, hence naturally light Higgs.

For naturalness expect \( m_{TP} \lesssim 400 \text{ GeV} \).
Supersymmetry

What is supersymmetry?

Entirely new spacetime symmetry!

Unifies fields into superfields, transforming into one another!

Also predicts... $	ilde{g}_s = 3/2$
Supersymmetry

The last time a spacetime symmetry was discovered...
Supersymmetry

In supersymmetry top partner is “stop squark”.

**FCC-ee**
Coloured and charged, stops modify Higgs couplings:

![Higgs couplings 2σ C.L.](image)

\[ \frac{x_1}{\sqrt{m_{t_1}^2 + m_{t_2}^2}} = 0 \]

Higgs couplings 2σ C.L.
- HL-LHC (dotted)
- ILC 500 (solid)
- ILC 1000 (dashed)
- CEPC (solid)
- FCC–ee (solid)

1412.3107

**FCC-hh**
And show up directly at hadron colliders:

![CLs Exclusion](image)

\[ \sqrt{s} = 100 \text{ TeV} \]
\[ \int Ldt = 3000 \text{ fb}^{-1} \]
\[ \epsilon_{\text{sys,bkg}} = 20\% \]
\[ \epsilon_{\text{sys,sig}} = 20\% \]

1311.6480

**FCC-ee**: Indirect, but more “spectrum independent”, for a model.

**FCC-hh**: Direct confirmation, but direct might be hidden.
The paradigm of low energy supersymmetry has dominated ideas in physics beyond the Standard Model for decades. FCC-hh would provide the final word, by pushing far beyond the naturalness paradigm.
If the Higgs is made up of constituents

\[
H = \begin{array}{c}
\overline{f} f
\end{array} \sim f
\]

Then no hierarchy problem, since no fundamental scalar!

These models can be thought of as realising the Higgs boson analogously to the pion in QCD.

\[
\rho = \begin{array}{c}
\overline{f} f
\end{array} \sim \Lambda
\]

Should also get other heavy resonances then!
These models can be thought of as realising the Higgs boson analogously to the pion in QCD.

\[ \rho = \bar{f} f \sim \Lambda \]

Should also get other heavy resonances then!
Combining precision measurements with high mass resonance searches, can fully answer the question of Higgs compositeness.

\[
\xi \sim \frac{v^2}{f^2}
\]

\[
\rho = \sqrt{f f}
\]
Could there be a hidden “Top Partner”? Much attention now to alternative ideas:

**Folded SUSY**
Theory where EW-charged uncoloured scalars are top partners

...but they must be charged under new hidden QCD’.

**Twin Higgs**
Theory where top partners are SM gauge neutral fermions

...but they must be charged under new hidden QCD’.
Neutral Naturalness

Naturalness not hidden, just look in new places...

New hidden sector introduces exotic Higgs decays:

FCC-hh can thoroughly probe larger Twin scales through displaced searches.

FCC-ee has access for light top partners, including for well-motivated low confinement scales.
Neutral Naturalness

- What if the top partners are completely neutral and inert?

Even in this nightmare scenario at FCC-ee can probe the existence of hidden new particles through miniscule quantum mechanical shifts in Higgs couplings.

Note that no one has yet constructed such a theory yet...
The Naturalness Paradox

FCC can comprehensively test even the most contorted theoretical constructions.

Effective Field Theory has been a successful guide for decades, in high energy physics and elsewhere.

It’s failure at the weak scale would point to entirely new principles of nature.
Where do we need to go?

New Particles!
- There is strong motivation for the existence of new particles in the multi-TeV range.

New Weak Forces!
- Sometimes we overlook the role of future high energy colliders as intensity frontier machines.
There are models in which there is no preferred mass scale for new particles.

An “Axion-like particle” (ALP) is a canonical example:

\[ a \]

ALPs emerge as pseudo-Goldstone bosons of spontaneously broken global symmetries.

Since the parameter that gives mass breaks a symmetry, it can be naturally small.
ALPs can also couple to photons, gluons etc,

\[ \mathcal{L} \supset \frac{a}{f} B^{\mu\nu} \tilde{B}_{\mu\nu} \]

This is why we consider ALPs searches over many orders of magnitude...

But why do so many plots end here?
LEP+LHC already proven effective

Together they fill the gap from beam dumps to weak scale, but not at “intensity frontier”-level cross sections...
The extra two orders of magnitude luminosity at FCC-ee would push this further, to “intensity frontier level”!

Where should FCC-hh go on this plot?

Due to:

a) CM energy
b) Huge PDFs
c) Large $L_{\text{int}}$

FCC-hh would perform as “intensity frontier”:
Lower couplings than LHC, and higher masses than FCC-ee.
Where do we need to go?

New Particles!
• There is strong motivation for the existence of new particles in the multi-TeV range.

New Weak Forces!
• Sometimes we overlook the role of future high energy colliders as intensity frontier machines.

The Unexpected!
• We might not always be looking in the right places.
The Unexpected

Maybe the Higgs has some totally unexpected, weird decays

\[ h \rightarrow ? \]

At FCC-ee, reach for exotic decays is remarkable!
The Unexpected

Long-lived particles come up in many models.

Many exciting and creative ideas on the theoretical front...

- Hidden Valleys
- Baryogenesis
- Neutrino Masses
- Mini-Split
- Neutral Naturalness
- RPV
- RHD Neutrinos

FCC?
Conclusions.

This talk had a lot of plots. Things are qualitatively changing, as we see the physics possibilities come into focus.

With FCC we can examine the dynamics of electroweak symmetry breaking, and test the fundamental principles that have guided progress for decades.
Backup Slides.
Combining gluino and squark limits onto one plane:

Reach in combination stronger than individual reach to due enhanced production rates with all states present.
Dark Matter: Neutralino is a compelling ingredient of the SUSY setup:

- **Bino**: gauge-singlet fermion
- **Wino**: pseudoreal representation of SU(2)\textsubscript{W}.
- **Higgsino**: Complex representation of SU(2)\textsubscript{W}, with inelastic dark matter candidates (depending on splitting of neutral components).

Relic density points towards no more than few TeV!
Relic Neutralino Surface

Collider signatures considered: MET + Jet and either soft dileptons or lepton+photon

100 TeV Study: Bramante, Desai, Fox, Martin, Ostdiek, Plehn. 2015.
Complementarity

There are important aspects in which colliders would be complementary. E.g.

PDFs precisely determined at FCC-eh

Improvement in low-x predictions for FCC-hh.
The Unexpected

Exotic Higgs decays provide a signature “standard candle”

\[ h \rightarrow \chi \rightarrow \chi \rightarrow \chi \]

\[ m_\chi = 10, 25, 40 \text{ GeV} \]

This is LHC, reach scaling well with luminosity!

FCC-hh? Two orders of magnitude more H’s!