LHC BSM physics opportunities and theoretical challenges

Tevong You
Outline

• Context

• BSM theory challenges

• BSM physics opportunities

• Beyond the LHC

• Conclusion
Outline

• Context
  • BSM theory challenges
  • BSM physics opportunities
  • Beyond the LHC

• Conclusion
Context

• 3 lessons from history
Context

• *1930s*: *everything* is made of **protons, neutrons, and electrons**

![Diagram of particles]

*Minimal, economical theory! However...*

• Held together by **electromagnetism** and the **strong force**
Context

- **1930s**: *everything* is made of **protons**, **neutrons**, and **electrons**

  "If we consider protons and neutrons as elementary particles, we would have three kinds of elementary particles [p,n,e].... This number may seem large but, from that point of view, two is already a large number."

  Paul Dirac 1933 Solvay Conference

  From D. Tong slide

- Held together by **electromagnetism** and the **strong force**

**Lesson 1: Beauty** in fundamental physics is not an economy of particle multiplicities, it’s an economy of theoretical principles
Context

- **Weak force** explains *radioactivity*

- **Neutron** can change into **proton**, emitting **electron**
Context

- **Weak force** explains *radioactivity*

![Diagram showing neutron decaying into proton, emitting electron.]

**Missing energy?** Pauli postulates “*a desperate remedy*”

(Bohr suggests fundamental violation of energy conservation principle)

- **Neutron** can change into **proton**, emitting **electron**
Context

- **Weak force** explains *radioactivity*

  Missing energy? Pauli postulates “a desperate remedy”

  (Bohr suggests fundamental violation of energy conservation principle)

- **Neutron** can change into **proton**, emitting **electron** and elusive **neutrino**
Context

- **Weak force** explains *radioactivity*

- **Neutron** can change into **proton**, emitting **electron** and elusive **neutrino**

**Missing energy?** Pauli postulates “*a desperate remedy*”

(Bohr suggests fundamental violation of energy conservation principle)

**Lesson 2: perceived prospects of experimental confirmation is not a useful scientific criteria for establishing what nature actually does**
• **Weak force** explains *radioactivity*

(Lesson 2.5: Sometimes nature chooses the *least radical option*)

- **Neutron** can change into **proton**, emitting **electron** and elusive **neutrino**

- **Missing energy?** Pauli postulates **“a desperate remedy”**
  - (Bohr suggests fundamental violation of energy conservation principle)

**Lesson 2:** *perceived* prospects of experimental confirmation is *not a useful scientific criteria* for establishing *what nature actually does*
• Dirac: Einstein’s *relativity + quantum mechanics = antiparticles*

• *Every particle has an oppositely charged antiparticle partner*
Context

• Dirac: Einstein’s **relativity** + **quantum mechanics** = **antiparticles**

  *c.f. Lesson 1*: antiparticles double the particle spectrum. Nevertheless, the theory is much tighter, less arbitrary, and more elegant

• **Every particle has an oppositely charged antiparticle partner**
Context

- *Higgs* (+Brout+Englert): **particle masses** require a new **scalar boson H**
Context

• Higgs(+Brout+Englert): particle masses require a new scalar boson $H$

Lesson 3: Ideas initially dismissed as unrealistic (e.g. non-abelian gauge theories and spontaneous symmetry breaking because they predicted unobserved massless gauge bosons and goldstones) can click together suddenly and make sense.
Context

- The Higgs boson discovery caps a remarkable century of particle physics

- What next?
Outline

• Context

• **BSM theory challenges**

• BSM physics opportunities

• Beyond the LHC

• Conclusion
BSM theory challenges

• Until now, there had been a **clear roadmap**
BSM theory challenges

• Until now, there had been a clear roadmap
BSM theory challenges

- Until now, there had been a clear roadmap

Conventional symmetry-based solutions have not shown up!
BSM theory challenges

• Until now, there had been a clear roadmap

Maybe just around the corner…
BSM theory challenges

• Until now, there had been a **clear roadmap**

...but the larger the separation of scales, the more **fine-tuned** the underlying theory is

The Higgs is **more mysterious** than ever!
BSM theory challenges

• Until now, there had been a **clear roadmap**

...but the larger the separation of scales, the more **fine-tuned** the underlying theory is

The Higgs is **more mysterious** than ever!

**Vacuum energy** is also **peculiarly tiny**
BSM theory challenges

• Why is fine-tuning such a big deal?
BSM theory challenges

• *Why is fine-tuning such a big deal?*
• Delicate **UV-IR cancellations** indicate *an unprecedented breakdown of the effective theory* organisational structure of nature

Effective theory at each scale is **predictive** as a **self-contained** theory at that scale

**Un-natural Higgs** means the next layer *is no longer predictive* without including contributions from much smaller scales
The Hierarchy Problem

- Hierarchy problem *is still a problem*: $(m_h)^2_{\text{tree}} + (m_h)^2_{\text{radiative}} = (m_h)^2_{\text{v}}$

\[
\delta m^2_\phi \propto m^2_{\text{heavy}}, \quad \delta m_{\psi} \propto m_{\psi} \log \left( \frac{m_{\text{heavy}}}{\mu} \right)
\]

Historical precedent

- Take aesthetic issues seriously
- Earliest example of an unnatural, **arbitrary** feature of a fundamental theory:
  \[ m_{\text{inertial}} = q_{\text{gravity}} \]

- Classical electromagnetism fine-tuning:
  \[
  (m_e c^2)_{\text{obs}} = (m_e c^2)_{\text{bare}} + \Delta E_{\text{coulomb}}, \quad \Delta E_{\text{coulomb}} = \frac{e^2}{4\pi\varepsilon_0 r_e}
  \]

- Pions, GIM mechanism, etc.

- Higgs? Expect new physics close to weak scale

[If Higgs mass is *calculable* in underlying UV theory]
Understanding the origin of EWSB

- The SM has many \textit{arbitrary} features put in by hand which hint at \textit{underlying structure}
  - \textit{Pattern of Yukawa couplings, CKM}
  - \textit{QCD Theta term}
  - \textit{Neutrino mass}
  - \textit{Higgs potential}
  - ...

- Maybe it just is what it is \(\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\)

- but we would like a \textbf{deeper understanding} i.e. an \textit{explanation} for why things are the way they are
  - \textit{e.g. PQ axion for Theta term, see-saw for neutrino mass, Froggat-Nielsen for Yukawas...}

- In SM, \textbf{no understanding} of Higgs sector: Higgs potential and couplings \textit{put in by hand and unexplained}

- We feel there must be some underlying system that \textbf{explains the origin of EWSB}

- In any such theory \textit{in which the Higgs potential is calculable}, there is a \textbf{UV sensitivity} to the Higgs mass (\textit{that is no longer a free parameter}) which requires fine-tuned cancellations

- Unlike solutions to other arbitrary features, this one points to \textbf{weak-scale new physics} or a \textbf{breakdown of EFT}
BSM theory challenges

• What is the origin of the Higgs?

• What is the origin of matter?

• What is the origin of flavour?

• What is the origin of dark matter and dark energy?

• What is the origin of neutrino mass?

• What is the origin of the Standard Model?
Outline

• Context

• BSM theory challenges

• BSM physics opportunities

• Beyond the LHC

• Conclusion
BSM physics opportunities

- **LHC Run 3**: *improved detector performance and double the data*

- Establish *Higgs coupling to second generation*

- **SND/FASERnu**: *Neutrinos from colliders* to be detected for the first time

- **Anomalies** and **excesses** will be *confirmed* or *refuted*

- New types of searches / **new types of theories**

- **SM EFT** analyses will further *probe indirectly* the scale of new physics
SM to SMEFT framework

- New physics appear to be decoupled at higher energies
- Given particle content, write down *all* terms allowed by symmetries...
- ...Including **higher-dimensional** operators!
- Generated by new physics at scale $\Lambda \gg v$
We’ve always been doing EFT (even before we knew about EFT)

- QED EFT = QED + Euler-Heisenberg + Fermi theory

\[ L_{\text{QED}}^{\text{EFT}} = \bar{\psi} i \gamma^\mu D_\mu \psi - m \bar{\psi} \psi - \frac{i}{4} F_{\mu \nu} F^{\mu \nu} \]

Fermi theory
(1933)

+ \sum \frac{c_i^{(1)}}{\Lambda^2} (\bar{\psi} \gamma^\mu \gamma^\nu \psi)(\bar{\psi} \gamma^\nu \gamma^\mu \psi)

\[ \Gamma = \{ 1, \gamma_5, \gamma_\mu, \gamma_\nu, \gamma_\mu \gamma_\nu, \gamma_{\mu \nu} \} \]

Euler-Heisenberg
(1936)

+ \frac{c_8^{(1)}}{\Lambda^4} (F_{\mu \nu} F^{\mu \nu})^2 + \frac{c_8^{(2)}}{\Lambda^4} F_{\mu \nu} F^{\nu \rho} F_{\rho \sigma} F^{\sigma \mu} + \ldots

- EFT fits to experimental data established V-A structure
SMEFT: phenomenology in the 21st century

- **Standard Model Effective Field Theory (SMEFT)** framework

\[ \mathcal{L}_{UV} = ? \]

\[ \mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \]

\[ \mathcal{L}_m = \bar{Q}_L i \gamma^\mu D^L_\mu Q_L + \bar{q}_R i \gamma^\mu D^R_\mu q_R + \bar{L}_L i \gamma^\mu D^L_\mu L_L + \bar{l}_R i \gamma^\mu D^R_\mu l_R \]

\[ \mathcal{L}_G = -\frac{1}{4} B_\mu B^\mu - \frac{1}{4} W^a_\mu W^a_\mu \]

\[ \mathcal{L}_H = (D^L_\mu \phi)^\dagger (D^{ \mu} \phi) - V(\phi) \]

\[ \mathcal{L}_Y = y_d \bar{Q}_L d_{L} + y_u \bar{Q}_L u_{R} + y_d \bar{L}_L \phi_{L} + y_L \bar{L}_L \phi_{R} + \text{h.c.} \]
SMEFT: phenomenology in the 21st century

- **Standard Model Effective Field Theory (SMEFT) framework**
  - Characterises *heavy* new ultra-violet (UV) physics
  - Parametrised by coefficients $c_i$ and heavy energy scale $\Lambda$

\[
\mathcal{L}^{\text{EFT}} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y + \frac{c_5}{\Lambda} \mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2} \mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3} \mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4} \mathcal{O}^{(8)} + \ldots
\]

\[
\mathcal{L}_m = \bar{Q}_L i \gamma^\mu D^\mu_Q L + \bar{q}_R i \gamma^\mu D^\mu_R q_R + \bar{L}_L i \gamma^\mu D^\mu_L L + \bar{\nu}_R i \gamma^\mu D^\mu_R \nu_R
\]

\[
\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu}
\]

\[
\mathcal{L}_H = (D^\mu_\mu \phi)^\dagger (D^\mu_\mu \phi) - V(\phi)
\]

\[
\mathcal{L}_Y = y_d \bar{Q}_L \psi_R d + y_u \bar{Q}_L \psi_R u + y_d \bar{L}_L \phi R + \text{h.c.}
\]
SMEFT: phenomenology in the 21\textsuperscript{st} century

\textbf{• Standard Model Effective Field Theory (SMEFT) framework}

- What are the experimental constraints on the \textbf{energy scale} of new physics, \( \Lambda \) ?

- What are the experimental constraints on their \textbf{interaction strengths}, \( c_i \) ?

\[ \mathcal{L}_{\text{UV}} = ? \]

\[ \mathcal{L}^{\text{EFT}}_{\text{SM}} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y + \frac{c_5}{\Lambda} \mathcal{O}^{(5)} + \frac{c_6}{\Lambda^2} \mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3} \mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4} \mathcal{O}^{(8)} + \ldots \]

\[ \mathcal{L}_m = \bar{Q}_L \gamma^\mu D^L_\mu Q_L + \bar{q}_R \gamma^\mu D^R_\mu q_R + \bar{L}_L i \gamma^\mu D^L_\mu L_L + \bar{l}_R i \gamma^\mu D^R_\mu l_R \]

\[ \mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} \]

\[ \mathcal{L}_H = (D^L_\mu \phi)^\dagger (D^L_\mu \phi) - V(\phi) \]

\[ \mathcal{L}_Y = y_d \bar{Q}_L \phi q_R^d + y_u \bar{Q}_L \phi^c q_R^c + y_L \bar{L}_L \phi l_R + \text{h.c.} \]
SMEFT: phenomenology in the 21st century

- What are the experimental constraints on the energy scale of new physics, $\Lambda$?

- What are the experimental constraints on their interaction strengths, $c_i$?

- *e.g.* Combined global fit to Top, Higgs, diboson, and electroweak experimental data

J. Ellis, Madigan, Mimasu, Sanz, TY [2012.02779]
SMEFT: phenomenology in the 21st century

- What are the experimental constraints on the energy scale of new physics, $\Lambda$?

- What are the experimental constraints on their interaction strengths, $c_i$?

- e.g. Combined global fit to Top, Higgs, diboson, and electroweak experimental data

J. Ellis, Madigan, Mimasu, Sanz, TY [2012.02779]
SMEFT: phenomenology in the 21st century

- Standard Model Effective Field Theory (SMEFT) framework

- What are the experimental constraints on the energy scale of new physics, $\Lambda$?

- What are the experimental constraints on their interaction strengths, $c_i$?

  J. Ellis, Madigan, Mimasu, Sanz, TY [2012.02779]

- *e.g.* Combined global fit to Top, Higgs, diboson, and electroweak experimental data


- Can now include also triboson
SMEFT Analysis of $m_W$

- **S+T fit excluding** $m_W$: *other data* compatible ($\sim 1.5\sigma$) with *measurements avg. including* CDF

- **True in SMEFT more generally?**

\[
\frac{v^2}{\Lambda^2} C_{HWB} = \frac{g_1 g_2}{16\pi} S, \quad \frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1 g_2}{2\pi(g_1^2 + g_2^2)} T
\]

Note: sign of shift
SMEFT Analysis of $m_W$

- S+T fit excluding $m_W$: other data compatible ($\sim 1.5\sigma$) with measurements avg. including CDF

Note: sign of shift
SMEFT Analysis of $m_W$

- S+T fit excluding $m_W$: other data compatible ($\sim 1.5\sigma$) with measurements avg. including CDF

- True in SMEFT more generally?

\[
\frac{v^2}{\Lambda^2}C_{HWB} = \frac{g_1 g_2}{16\pi} S, \quad \frac{v^2}{\Lambda^2}C_{HD} = -\frac{g_1 g_2}{2\pi(g_1^2 + g_2^2)} T
\]

Note: sign of shift
**SMEFT Analysis of $m_W$**

Bagnaschi, Ellis, Madigan, Mimasu, Sanz, and You [2204.05260]

- **S+T fit excluding $m_W$:** other data compatible ($\sim 1.5\sigma$) with **measurements avg. including CDF**

- **True in SMEFT more generally?**

\[
\frac{v^2}{\Lambda^2} C_{HWB} = \frac{g_1 g_2}{16\pi} S, \quad \frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1 g_2}{2\pi(g_1^2 + g_2^2)} T
\]

- Note: sign of shift
SMEFT Analysis of $m_W$

- **S+T fit excluding $m_W$:** other data compatible ($\sim 1.5\sigma$) with measurements avg. including CDF

- True in SMEFT more generally?

\[ \frac{v^2 \Delta\chi_{HWB}}{\Lambda^2} = g_1 g_2 \frac{S}{16\pi} , \quad \frac{v^2 \Delta\chi_{HD}}{\Lambda^2} = -\frac{g_1 g_2}{2\pi(g_1^2 + g_2^2)} T \]

Note: sign of shift
SMEFT Analysis of $m_W$

Bagnaschi, Ellis, Madigan, Mimasu, Sanz, and You [2204.05260]

- **S+T fit excluding $m_W$:** other data compatible ($\sim 1.5\sigma$) with measurements avg., including CDF

Note: sign of shift

$$\frac{v^2}{\Lambda^2} C_{HWB} = \frac{g_1 g_2}{16\pi} S, \quad \frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1 g_2}{2\pi(g_1^2 + g_2^2)} T$$

- True in SMEFT more generally?

$$\frac{\delta m_W^2}{m_W^2} = \frac{-\sin 2\theta_W}{\cos 2\theta_W} \frac{v^2}{4\Lambda^2} \left( \frac{\cos \theta_w}{\sin \theta_w} C_{HD} + \frac{\sin \theta_w}{\cos \theta_w} \left( 4C_{HI}^3 - 2C_{II} \right) + 4C_{HWB} \right)$$

Note: sign of shift
**SMEFT Analysis of** $m_W$

Bagnaschi, Ellis, Madigan, Mimasu, Sanz, and You [2204.05260]

- **S+T fit excluding $m_W$:** other data compatible ($\sim 1.5\sigma$) with measurements avg. including CDF

### Measurements of $m_W$

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP2</td>
<td>80376 ± 33</td>
</tr>
<tr>
<td>D0 II</td>
<td>80375 ± 23</td>
</tr>
<tr>
<td>ATLAS</td>
<td>80370 ± 19</td>
</tr>
<tr>
<td>LHCb</td>
<td>80354 ± 32</td>
</tr>
<tr>
<td>CDF II</td>
<td>80434 ± 9</td>
</tr>
<tr>
<td>World Avg. (w/o CDF)</td>
<td>80370 ± 12</td>
</tr>
<tr>
<td>World Avg. (w/ CDF)</td>
<td>80411 ± 8</td>
</tr>
</tbody>
</table>

- **SM**
- **SM electroweak fit**
- **SM + S,T fit**

### VW Width

$$\frac{v^2}{\Lambda^2} C_{HWB} = \frac{g_1 g_2}{16 \pi} S$$

$$\frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1 g_2}{2 \pi (g_1^2 + g_2^2)} T$$

- **True in SMEFT more generally?**

$$\frac{\delta m_W^2}{m_W^2} = \sin 2\theta_w \frac{v^2}{\cos 2\theta_w} \frac{\cos \theta_w}{\sin \theta_w} C_{HD} + \sin \theta_w \frac{\cos \theta_w}{\cos \theta_w} \left( 4C_{HI}^3 - 2C_{HI} \right) + 4C_{HWB}$$

### Diagram

- **Note:** sign of shift
SMEFT Analysis of $m_W$  

Bagnaschi, Ellis, Madigan, Mimasu, Sanz, and You [2204.05260]

- **SMEFT fit excluding $m_W$: other data** prefer dim-6 subsets that include **CHD** or **CHD+Cll**

| Subset                              | Value  
|-------------------------------------|--------
| $C_{HWB}$                          | 80385 ± 5  |
| $C_{HD}$                            | 80408 ± 7   |
| $C_{ll}^{(3)}$                      | 80386 ± 5   |
| $C_{Hl}^{(3)}$                      | 80390 ± 6   |
| $C_{HWB},C_{HD}$                    | 80409 ± 7   |
| $C_{HWB},C_{ll}^{(3)}$              | 80389 ± 6   |
| $C_{HWB},C_{Hl}^{(3)}$              | 80392 ± 6   |
| $C_{HD},C_{ll}^{(3)}$               | 80412 ± 8   |
| $C_{ll},C_{Hl}^{(3)}$               | 80410 ± 8   |
| $C_{HWB},C_{HD},C_{ll}^{(3)}$       | 80412 ± 8   |
| $C_{HWB},C_{HD},C_{Hl}^{(3)}$       | 80410 ± 8   |
| $C_{HWB},C_{ll},C_{Hl}^{(3)}$       | 80392 ± 6   |
| $C_{HD},C_{ll},C_{Hl}^{(3)}$        | 80412 ± 8   |
| $C_{HWB},C_{HD},C_{ll},C_{Hl}^{(3)}$| 80412 ± 8   |
| 20-parameter fit                    | 80412 ± 8   |

- **Flat direction** in **CHD+Cll**, lifted by $m_W$ measurement

(Also lifted by CKM unitarity measurements, see v2)
SMEFT Analysis of $m_W$

- **SMEFT fit excluding $m_W$:** other data prefer dim-6 subsets that include CHD or CHD+CII

- **Flat direction** in CHD+CII, lifted by $m_W$ measurement

(Also lifted by CKM unitarity measurements, see v2)
SMEFT Analysis of $m_W$

- SMEFT fit excluding $m_W$: *other data* prefer dim-6 subsets that include CHD or CHD+CII

- Flat direction in CHD+CII, lifted by $m_W$ measurement

(Also lifted by CKM unitarity measurements, see v2)
SMEFT Analysis of $m_W$

- **SMEFT fit excluding $m_W$:** other data prefer dim-6 subsets that include **CHD** or **CHD+CII**

- **Flat direction in CHD+CII**, lifted by $m_W$ measurement

(Also lifted by CKM unitarity measurements, see v2)
SMEFT Analysis of $m_W$

- **SMEFT fit excluding $m_W$:** other data prefer dim-6 subsets that include CHD or CHD+CII

- Flat direction in CHD+CII, lifted by $m_W$ measurement

(Also lifted by CKM unitarity measurements, see v2)
SMEFT Analysis of $m_W$

- **SMEFT fit excluding $m_W$:** other data prefer dim-6 subsets that include CHD or CHD+CII

$$
\begin{align*}
C_{HWW} & = 80385 \pm 5 \\
C_{HD} & = 80408 \pm 7 \\
C_{II} & = 80386 \pm 5 \\
C_{III} & = 80390 \pm 6 \\
C_{HWW,HD} & = 80409 \pm 7 \\
C_{HWW,II} & = 80389 \pm 6 \\
C_{HWW,III} & = 80392 \pm 6 \\
C_{HD,II} & = 80412 \pm 8 \\
C_{HD,III} & = 80410 \pm 8 \\
C_{II,III} & = 80390 \pm 6 \\
C_{HWW,HD,II} & = 80412 \pm 8 \\
C_{HWW,HD,III} & = 80410 \pm 8 \\
C_{HWW,II,III} & = 80392 \pm 6 \\
C_{HD,II,III} & = 80412 \pm 8 \\
C_{HWW,HD,II,III} & = 80412 \pm 8 \\
20-parameter fit & = 80412 \pm 8
\end{align*}
$$

- **Flat direction in CHD+CII, lifted by $m_W$ measurement**

(Also lifted by CKM unitarity measurements, see v2)
SMEFT Analysis of $m_W$

- **SMEFT fit excluding $m_W$:** Other data prefer dim-6 subsets that include CHD or CHD+Cll.

2022 update:

- No $m_W$
- 2 parameter fit
- 4 parameter fit
- SM

Flat direction in CHD+Cll, lifted by $m_W$ measurement.

(Also lifted by CKM unitarity measurements, see v2)
SMEFT Analysis of $m_W$

- SMEFT enables **more systematic** phenomenological survey of UV completions *and* their pulls
- e.g. Tree-level single-field extensions with simplified couplings assumption:

De Blas, Criado, Perez-Victoria, Santiago [1711.10391]

<table>
<thead>
<tr>
<th>Model</th>
<th>Pull</th>
<th>Best-fit mass (TeV)</th>
<th>1-σ mass range (TeV)</th>
<th>2-σ mass range (TeV)</th>
<th>1-σ coupling$^2$ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_1$</td>
<td>6.4</td>
<td>3.0</td>
<td>[2.8, 3.6]</td>
<td>[2.6, 3.8]</td>
<td>[0.09, 0.13]</td>
</tr>
<tr>
<td>$B$</td>
<td>6.4</td>
<td>8.6</td>
<td>[8.0, 9.4]</td>
<td>[7.4, 10.6]</td>
<td>[0.011, 0.016]</td>
</tr>
<tr>
<td>$\Xi$</td>
<td>6.4</td>
<td>2.9</td>
<td>[2.8, 3.1]</td>
<td>[2.7, 3.2]</td>
<td>[0.011, 0.016]</td>
</tr>
<tr>
<td>$N$</td>
<td>5.1</td>
<td>4.4</td>
<td>[4.1, 5.0]</td>
<td>[3.8, 5.8]</td>
<td>[0.040, 0.060]</td>
</tr>
<tr>
<td>$E$</td>
<td>3.5</td>
<td>5.8</td>
<td>[5.1, 6.8]</td>
<td>[4.6, 8.5]</td>
<td>[0.022, 0.039]</td>
</tr>
</tbody>
</table>
Flavour anomalies in B physics

• New physics **beyond the Standard Model** in processes involving $b \to s \mu^+\mu^-$ transitions?
Flavour anomalies in B physics

• New physics **beyond the Standard Model** in processes involving $b \to s \mu^+\mu^-$ transitions?

• LHCb **3.4 $\sigma$** in **P5’ angular distribution** of $B \to K^* \mu^+\mu^-$ (2 $\sigma$ for Belle)

• 3.2 $\sigma$ in $B_s \to \phi \mu^+\mu^-$

• $\Rightarrow \sim 4 \sigma$ non-zero Wilson coefficient in global fit to these "messy" observables

• 2.5 $\sigma$ in "clean" observable $R_K$

• $2.5 \sigma$ in "clean" observable $R_{K^*}$

• $\Rightarrow \sim 4 \sigma$ non-zero Wilson coefficient in combined fit to just these two clean observables

• Consistency of all these various anomalies is non-trivial
Flavour anomalies in B physics

• New physics **beyond the Standard Model** in processes involving $b \to s \mu^+\mu^-$ transitions?

• LHCb **3.4 $\sigma$** in P5' angular distribution of $B \to K^* \mu^+\mu^-$ (2 $\sigma$ for Belle)

• Various **other kinematic observables** in $b \to s \mu^+\mu^-$

• **3.2 $\sigma$** in $B_s \to \phi \mu^+\mu^-$
Flavour anomalies in B physics

• New physics **beyond the Standard Model** in processes involving $b \rightarrow s \mu^+ \mu^-$ transitions?

• LHCb **3.4 σ** in P5' angular distribution of $B \rightarrow K^* \mu^+ \mu^-$ (2 σ for Belle)

• Various **other kinematic observables** in $b \rightarrow s \mu^+ \mu^-

• **3.2 σ** in $B_s \rightarrow \phi \mu^+ \mu^-$

• $\Rightarrow \sim 4 \sigma$ non-zero Wilson coefficient in **global fit** to these "messy" observables
Flavour anomalies in B physics

• New physics **beyond the Standard Model** in processes involving $b \rightarrow s \mu^+\mu^-$ transitions?

• LHCb **3.4 $\sigma$** in P5’ angular distribution of $B \rightarrow K^*\mu^+\mu^-$ (2 $\sigma$ for Belle)

• Various **other kinematic observables** in $b \rightarrow s \mu^+\mu^-$

  • **3.2 $\sigma$** in $B_s \rightarrow \phi \mu^+\mu^-$
  
  • $\Rightarrow$**~4 $\sigma$** non-zero Wilson coefficient in **global fit** to these “messy” observables

• **2.5 $\sigma$** in “clean” observable $R_K$

• **2.5 $\sigma$** in “clean” observable $R_K^*$
Flavour anomalies in B physics

• New physics **beyond the Standard Model** in processes involving $b \to s \mu^+\mu^-$ transitions?

• LHCb **3.4 σ** in $P5'$ angular distribution of $B \to K^* \mu^+\mu^-$ (2 σ for Belle)

• Various **other kinematic observables** in $b \to s \mu^+\mu^-$

• **3.2 σ** in $B_s \to \phi \mu^+\mu^-$

• $\Rightarrow \sim 4 \sigma$ non-zero Wilson coefficient in **global fit** to these “messy” observables

• **2.5 σ** in “clean” observable $R_K$

• **2.5 σ** in “clean” observable $R_K^*$

• $\Rightarrow$ **independent** $\sim 4 \sigma$ non-zero Wilson coefficient in combined fit to just these two “clean” observables

• **Consistency** of all these various anomalies is **extremely non-trivial**
Flavour anomalies in B physics

- New physics **beyond the Standard Model** in processes involving $b \to s \mu^+\mu^-$ transitions?

- LHCb $3.4 \sigma$ in P5' angular distribution of $B \to K^* \mu^+\mu^-$ ($2 \sigma$ for Belle)
- Various other kinematic observables in $b \to s \mu^+\mu^-$
- $3.2 \sigma$ in $B_s \to \phi \mu^+\mu^-$
- $\Rightarrow \sim 4 \sigma$ non-zero Wilson coefficient in **global fit** to these “messy” observables

- $2.5 \sigma$ in “clean” observable $R_K$
- $2.5 \sigma$ in “clean” observable $R_K^*$
- $\Rightarrow$ *independent* $\sim 4 \sigma$ non-zero Wilson coefficient in combined fit to just these two “clean” observables

- *Consistency* of all these various anomalies is **extremely non-trivial**

(19/10/2021): $1.4 \sigma$ in $R_{K^0_S}$, $1.5 \sigma$ in $R_{K^{*+}}$
Flavour anomalies in B physics

- New physics **beyond the Standard Model** in processes involving $b \to s \mu^+\mu^-$ transitions?

- LHCb **3.4 \(\sigma\)** in P5' angular distribution of $B \to K^* \mu^+\mu^-$ (2 \(\sigma\) for Belle)

- Various other kinematic observables in $b \to s \mu^+\mu^-$

- **3.2 \(\sigma\)** in $B_s \to \phi \mu^+\mu^-$

- $\Rightarrow \sim 4 \sigma$ non-zero Wilson coefficient in **global fit** to these “messy” observables

- **2.5 \(\sigma\)** in “clean” observable $R_K$

- **2.5 \(\sigma\)** in “clean” observable $R_K^*$

- $\Rightarrow$ **independent** $\sim 4 \sigma$ non-zero Wilson coefficient in combined fit to just these two “clean” observables

- **Consistency** of all these various anomalies is extremely **non-trivial**

- Could be due to a new **fundamental particle** e.g. $Z'$

(19/10/2021): **1.4 \(\sigma\)** in $R_{K^0_S}$, **1.5 \(\sigma\)** in $R_{K^+}$
Flavour anomalies in B physics

- New physics **beyond the Standard Model** in processes involving $b \rightarrow s \mu^+\mu^-$ transitions?

- LHCb **3.4 σ** in P5' angular distribution of $B \rightarrow K^* \mu^+\mu^-$ (**2 σ** for Belle)
- Various other kinematic observables in $b \rightarrow s \mu^+\mu^-$
- **3.2 σ** in $B_s \rightarrow \phi \mu^+\mu^-$
- $\Rightarrow \sim 4 \sigma$ non-zero Wilson coefficient in **global fit** to these “messy” observables

- **2.5 σ** in “clean” observable $R_K$
- **2.5 σ** in “clean” observable $R_K^*$
- $\Rightarrow$ independent $\sim 4 \sigma$ non-zero Wilson coefficient in combined fit to just these two “clean” observables

(19/10/2021): **1.4 σ** in $R_{K^0_s}$, **1.5 σ** in $R_{K^{*+}}$

- **Consistency** of all these various anomalies is extremely non-trivial
- Could be due to a new **fundamental particle** e.g. $Z'$, leptoquark, ...
Flavour anomalies in B physics

• If confirmed, can we guarantee a discovery at FCC-hh?

  80 TeV unitarity limit = no general no-lose theorem at FCC-hh [Di Luzio, Nardecchia, 1706.01868]

• Project Z’ sensitivity in most pessimistic scenario assuming only couplings required for $b \rightarrow s \mu^+ \mu^-$

Allanach, Gripaios, TY [1710.06363]
TY [1805.04418]
Flavour anomalies in B physics

• If confirmed, *can we guarantee a discovery at FCC-hh?*

  80 TeV unitarity limit = **no general no-lose theorem** at FCC-hh [Di Luzio, Nardecchia, 1706.01868]

• Project $Z'$ sensitivity in **most pessimistic scenario** assuming only couplings required for $b \to s \mu^+\mu^-$

![FCC-hh sensitivity](image)

Allanach, Gripaios, TY [1710.06363]
TY [1805.04418]
Flavour anomalies in B physics

• If confirmed, can we guarantee a discovery at FCC-hh?

80 TeV unitarity limit = no general no-lose theorem at FCC-hh [Di Luzio, Nardecchia, 1706.01868]

• Project LQ sensitivity in most pessimistic scenario assuming only couplings required for $b \to s\mu^+\mu^-$

Max $M_{LQ} = 37, 41, 18$ TeV for $S_3, V_1, V_3$
Flavour anomalies in B physics

• If confirmed, can we guarantee a discovery at FCC-hh?

  80 TeV unitarity limit = no general no-lose theorem at FCC-hh [Di Luzio, Nardecchia, 1706.01868]

• Project LQ sensitivity in most pessimistic scenario assuming only couplings required for $b \rightarrow s\mu^+\mu^-$

Allanach, Corbett, Madigan [1911.04455]
Theory opportunities: missing a new principle?

- **Cosmological evolution** could play a role
Cosmological relaxation of the weak scale

- **Axions** could solve a variety of fundamental problems
- **Relaxion** *scanning the Higgs mass* in the early universe

A *dynamical* solution to the hierarchy problem

\[
\langle h \rangle = 0 \quad \langle h \rangle \neq 0
\]

Graham, Kaplan, Rajendran ‘15
Cosmological Self-Organised Criticality

- **Self-Organised Localisation (SOL)**
  - Can relate **Higgs mass** to vacuum instability scale *(requires e.g. VL fermions)*
  - Potential solution to the vacuum energy **Cosmological Constant (CC) problem**

![Graph showing phases h and v](image)

**Phase h**: *hidden* vacuum with **vanishing Cosmological Constant** by supersymmetry and R-symmetry

**Phase v**: *visible* vacuum with broken supersymmetry but SOL localises at critical point with **vanishing CC**
Cosmological Self-Organised Criticality

- **Self-Organised Localisation (SOL)**  
  Giudice, McCullough, TY (2105.08617)

- Can relate **Higgs mass** to vacuum instability scale *(requires e.g. VL fermions)*

- Potential solution to the vacuum energy **Cosmological Constant (CC) problem**

\[ V(\varphi) \]

**Phase h**: hidden vacuum with **vanishing Cosmological Constant** by supersymmetry and R-symmetry

**Phase v**: visible vacuum with broken supersymmetry but **SOL localises at critical point with vanishing CC**
Cosmological Self-Organised Criticality

• **Self-Organised Localisation** (SOL)  

  Giudice, McCullough, TY (2105.08617)

• Can relate **Higgs mass** to vacuum instability scale *(requires e.g. VL fermions)*

• Potential solution to the vacuum energy **Cosmological Constant (CC) problem**

**Phase h**: hidden vacuum with **vanishing Cosmological Constant** by supersymmetry and R-symmetry

**Phase v**: visible vacuum with broken supersymmetry but SOL localises at critical point with **vanishing CC**
Cosmological Self-Organised Criticality

- **Self-Organised Localisation (SOL)**
- Can relate **Higgs mass** to vacuum instability scale (*requires e.g. VL fermions*)
- Potential solution to the vacuum energy **Cosmological Constant (CC) problem**

**Phase h**: hidden vacuum with **vanishing Cosmological Constant** by supersymmetry and R-symmetry

**Phase v**: visible vacuum with broken supersymmetry but **SOL localises at critical point with vanishing CC**

(See also J. Khoury et al 1907.07693, 1912.06706, 2003.12594)
Cosmological Self-Organised Criticality

• **Self-Organised Localisation (SOL)**

• Can relate **Higgs mass** to vacuum instability scale *(requires e.g. VL fermions)*

• Potential solution to the vacuum energy **Cosmological Constant (CC) problem**

Phase **h**: *hidden* vacuum with **vanishing Cosmological Constant** by supersymmetry and R-symmetry

Phase **v**: *visible* vacuum with broken supersymmetry but SOL *localises at critical point with vanishing CC*
Cosmological Self-Organised Criticality

- **Self-Organised Localisation (SOL)**
- Can relate **Higgs mass** to vacuum instability scale *(requires e.g. VL fermions)*
- Potential solution to the vacuum energy **Cosmological Constant (CC) problem**

**Phase h**: hidden vacuum with **vanishing Cosmological Constant** by supersymmetry and R-symmetry

**Phase v**: visible vacuum with broken supersymmetry but **SOL localises at critical point with vanishing CC**

(See also J. Khoury et al 1907.07693, 1912.06706, 2003.12594)
# BSM physics opportunities

### ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma ) Jets</th>
<th>E_{T}^{miss}</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD Gou ( g/g )</td>
<td>0, e, \mu, \tau</td>
<td>1</td>
<td>4</td>
<td>Yes</td>
</tr>
<tr>
<td>ADD Gou non-resonant</td>
<td>2</td>
<td>γ</td>
<td>36</td>
<td>139</td>
</tr>
<tr>
<td>ADD direct</td>
<td>2</td>
<td>γ</td>
<td>36</td>
<td>139</td>
</tr>
<tr>
<td>ADD direct ( m_{\gamma} )</td>
<td>0, e, \mu, \tau</td>
<td>2</td>
<td>36</td>
<td>139</td>
</tr>
<tr>
<td>RS1 Gou ( t )</td>
<td>2</td>
<td>γ</td>
<td>36</td>
<td>139</td>
</tr>
<tr>
<td>BuR RS Gou ( t ) ( \to H W )</td>
<td>1, \nu, 2</td>
<td>0</td>
<td>1</td>
<td>36</td>
</tr>
<tr>
<td>BuR RS Gou ( t ) ( \to q ) ( q )</td>
<td>1, \nu, 2</td>
<td>0</td>
<td>1</td>
<td>36</td>
</tr>
<tr>
<td>ZUED / IRPP</td>
<td>1, \nu, 2</td>
<td>0</td>
<td>1</td>
<td>36</td>
</tr>
</tbody>
</table>

### Gauge bosons

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma ) Jets</th>
<th>E_{T}^{miss}</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMZ ( \to \gamma ) ( \gamma )</td>
<td>2</td>
<td>γ</td>
<td>36</td>
<td>139</td>
</tr>
<tr>
<td>Leptophonic ( Z \to ) ( \ell \ell )</td>
<td>0</td>
<td>e, μ, τ</td>
<td>4</td>
<td>139</td>
</tr>
<tr>
<td>SMW ( \to \gamma )</td>
<td>2</td>
<td>γ</td>
<td>36</td>
<td>139</td>
</tr>
<tr>
<td>SMW ( \to ) ( t )</td>
<td>1</td>
<td>γ</td>
<td>36</td>
<td>139</td>
</tr>
<tr>
<td>HVT W ( \to ) ( W ) ( \to ) ( \gamma ) mode B</td>
<td>1, e, \mu, \tau</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>HVT Z ( \to ) ( Z ) ( \to ) ( \gamma ) mode B</td>
<td>2</td>
<td>e, \mu, \tau</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

### Cl

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma ) Jets</th>
<th>E_{T}^{miss}</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ci ( \gamma \gamma )</td>
<td>2</td>
<td>γ</td>
<td>40</td>
<td>139</td>
</tr>
<tr>
<td>Ci ( \ell \ell )</td>
<td>2</td>
<td>γ</td>
<td>40</td>
<td>139</td>
</tr>
<tr>
<td>Ci ( \gamma \ell )</td>
<td>2</td>
<td>γ</td>
<td>40</td>
<td>139</td>
</tr>
<tr>
<td>Ci ( \gamma \gamma )</td>
<td>2</td>
<td>e, μ, τ</td>
<td>40</td>
<td>139</td>
</tr>
</tbody>
</table>

### DM

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma ) Jets</th>
<th>E_{T}^{miss}</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector mediated, ( \ell \to \gamma \gamma )</td>
<td>0</td>
<td>e, μ, τ</td>
<td>40</td>
<td>139</td>
</tr>
<tr>
<td>Vector mediated, ( \ell \to \gamma ) ( \gamma )</td>
<td>0</td>
<td>e, μ, τ</td>
<td>40</td>
<td>139</td>
</tr>
<tr>
<td>Pseudo-scalar mediated, ( \ell \to \gamma ) ( \gamma )</td>
<td>0</td>
<td>e, μ, τ</td>
<td>40</td>
<td>139</td>
</tr>
<tr>
<td>Pseudo-scalar mediated, ( \ell \to \gamma \gamma )</td>
<td>0</td>
<td>e, μ, τ</td>
<td>40</td>
<td>139</td>
</tr>
</tbody>
</table>

### LQ

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma ) Jets</th>
<th>E_{T}^{miss}</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LG ( \ell, \gamma ) ( \ell ) ( \gamma )</td>
<td>0</td>
<td>e, μ, τ</td>
<td>40</td>
<td>139</td>
</tr>
<tr>
<td>LG ( \ell, \gamma ) ( \ell ) ( \ell )</td>
<td>0</td>
<td>e, μ, τ</td>
<td>40</td>
<td>139</td>
</tr>
<tr>
<td>LG ( \ell, \gamma ) ( \ell ) ( \gamma )</td>
<td>0</td>
<td>e, μ, τ</td>
<td>40</td>
<td>139</td>
</tr>
<tr>
<td>LG ( \ell, \gamma ) ( \ell ) ( \ell )</td>
<td>0</td>
<td>e, μ, τ</td>
<td>40</td>
<td>139</td>
</tr>
</tbody>
</table>

### Other

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma ) Jets</th>
<th>E_{T}^{miss}</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{6} = 8 ) TeV</td>
<td>13</td>
<td>4</td>
<td>2023</td>
<td>2030</td>
</tr>
<tr>
<td>( V_{6} = 13 ) TeV</td>
<td>13</td>
<td>4</td>
<td>2023</td>
<td>2030</td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown.
1 Small-radius (large-radius) jets are denoted by the letter \( J \).
BSM physics opportunities

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: July 2022

\[ \mathcal{L} dt = (32.8 - 139) \text{ fb}^{-1} \]

\[ \sqrt{s} = 13 \text{ TeV} \]

Reference

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>90% CL Exclusion (m [TeV])</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV ( t \rightarrow q )</td>
<td>displaced chargino + mini</td>
<td>( 0.901 )</td>
</tr>
<tr>
<td>RPV ( \tilde{t} \rightarrow c \tilde{\nu} \tilde{\nu} ) (SUSY)</td>
<td>displaced lepton pair</td>
<td>( 32.8 )</td>
</tr>
<tr>
<td>GMSB ( \tilde{t} \rightarrow 2 \tilde{\nu} )</td>
<td>displaced dimuon</td>
<td>( 32.9 )</td>
</tr>
<tr>
<td>GMSB ( \tilde{t} \rightarrow 2 \tilde{\nu} ) (SUSY)</td>
<td>non-disappearing or delayed ( \tilde{\nu} )</td>
<td>( 129 )</td>
</tr>
<tr>
<td>GMSB ( \tilde{t} \rightarrow 2 \tilde{\nu} ) (SUSY)</td>
<td>collimated diell</td>
<td>( 139 )</td>
</tr>
<tr>
<td>GMSB ( \tilde{t} \rightarrow 2 \tilde{\nu} ) (SUSY)</td>
<td>collimated diell</td>
<td>( 139 )</td>
</tr>
<tr>
<td>SUSY</td>
<td>disappearing track</td>
<td>( 139 )</td>
</tr>
<tr>
<td>SUSY</td>
<td>displaced chargino + mini</td>
<td>( 32.8 )</td>
</tr>
<tr>
<td>SUSY</td>
<td>( \tilde{t} \rightarrow 2 \tilde{\nu} ) (SUSY)</td>
<td>( 36.1 )</td>
</tr>
<tr>
<td>SUSY</td>
<td>( \tilde{t} \rightarrow 2 \tilde{\nu} ) (SUSY)</td>
<td>( 36.1 )</td>
</tr>
</tbody>
</table>

**Note:** Only a selection of the available lifetime limits is shown.
Search for heavy, long-lived, charged particles with large ionisation energy loss in $p p$ collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment and the full Run 2 dataset

The ATLAS Collaboration (2205.06013)

Observed yields and distributions agree with the SM background expectations, with the exception of an accumulation of events in the high-\(dE/dx\) and high-mass range. The local (global) significance of this excess is 3.6\(\sigma\) (3.3\(\sigma\)) in a sub-range of the signal region optimised for a target mass hypothesis of 1.4 TeV.
BSM physics opportunities
Outline

• Context

• BSM theory challenges

• BSM physics opportunities

• **Beyond the LHC**

• Conclusion
No BSM or new discoveries at LEP

- 1980-1990s: LEP physics programme **a resounding success**
- Improved our fundamental picture of nature *by orders of magnitude*

*Indirect precision probe* of physics at **higher energies**
No guarantee of new discoveries at FCC

• Further **zooming in** on our fundamental picture of nature

• **Rich physics programme** covering Higgs, top, electroweak, multi-bosons, flavour, rare decays, neutrinos, QCD, heavy ions *and more.*
No guarantee of new discoveries at FCC

- **No guarantee of discovery** at Tevatron either. Hadron collisions thought by some to be too messy to do physics.

- **Value in pushing frontiers:** we learn something *regardless of outcome*

- **Definite questions** are answered, *even if in the negative*

- Science is about *continually refining existing knowledge* and exploring the *unknown*

- **A new generation** of data management, analysis techniques, improved measurements, theoretical calculational tools, hardware development, cutting-edge engineering, large international collaboration, popular culture inspiration, and spirit of fundamental exploration, **can only benefit humanity** regardless of our own short-sighted disappointment at lack of BSM. *Doing good science is its own reward.*
Potential BSM discoveries at FCC

- First order electroweak phase transition
- CP violation
- Dark matter
- Light dark sectors
- Axion-like particles
- Sterile neutrinos
- Higgs portal
- BSM Higgs couplings
- Additional Higgs doublets
- Supersymmetric partners
- Top partners
- Leptoquarks
- New forces
- ...
- Implications for naturalness?
Potential BSM discoveries at FCC

- First order electroweak phase transition
- CP violation
- Dark matter
- Light dark sectors
- Axion-like particles
- Sterile neutrinos
- Higgs portal
- BSM Higgs couplings
- Additional Higgs doublets
- Supersymmetric partners
- Top partners
- Leptoquarks
- New forces
- ...
- Implications for naturalness?

Bauer et al 1808.10323
Knapen, Thamm 2108.08949
Potential BSM discoveries at FCC

- First order electroweak phase transition
- CP violation
- Dark matter
- Light dark sectors
- **Axion-like particles**
- Sterile neutrinos
- Higgs portal
- BSM Higgs couplings
- Additional Higgs doublets
- Supersymmetric partners
- Top partners
- Leptoquarks
- New forces
- ...
- Implications for naturalness?

FCC CDR Vol. 1

FCC CDR Vol. 1

Bauer et al 1808.10323

Knapen, Thamm 2108.08949
Potential BSM discoveries at FCC

- First order electroweak phase transition
- CP violation
- Dark matter
- Light dark sectors
- Axion-like particles
- Sterile neutrinos
- Higgs portal
- BSM Higgs couplings
- Additional Higgs doublets
- Supersymmetric partners
- Top partners
- Leptoquarks
- New forces
- ... 
- Implications for naturalness?

Bauer et al. 1808.10323

Knapen, Thamm 2108.08949
Potential BSM discoveries at FCC

- First order electroweak phase transition
- CP violation
- Dark matter
- Light dark sectors
- Axion-like particles
- Sterile neutrinos
- Higgs portal
- BSM Higgs couplings
- Additional Higgs doublets
- Supersymmetric partners
- Top partners
- Leptoquarks
- New forces
- ...
- Implications for naturalness?

---

FCC CDR Vol. 1

Bauer et al 1808.10323

Knapen, Thamm 2108.08949
Potential BSM outcomes for naturalness

- **Radically conservative**: naturalness restored just around the corner
  - Natural supersymmetry
  - Composite Higgs/extra dimensions

- **Creatively conservative**
  - Twin Higgs
  - Stealth supersymmetry

- **Post-naturalness BSM**
  - Split supersymmetry
  - Vector-like fermions only
  - Lowered vacuum instability scale
  - Weak-scale new physics for cosmological dynamics

- **Radically new?**
  - Breakdown of QFT/EFT above the TeV scale a real possibility
  - Hard to imagine what form this might take, by definition
  - How might this show up?
Potential BSM outcomes for naturalness

• **Radically conservative**: naturalness restored just around the corner
  • Natural supersymmetry
  • Composite Higgs/extra dimensions

• **Creatively conservative**
  • Twin Higgs
  • Stealth supersymmetry

• **Post-naturalness BSM**
  • Split supersymmetry
  • Vector-like fermions only
  • Lowered vacuum instability scale
  • Weak-scale new physics for cosmological dynamics

• **Radically new?**
  • Breakdown of QFT/EFT above the TeV scale *a real possibility*
  • Hard to imagine what form this might take, by definition
  • How might this show up?
Radically new BSM?

\[ \mathcal{L}_{IR} = \Lambda^4 + \Lambda^2 \mathcal{O}^{(2)} + m \mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{c_5}{\Lambda} \mathcal{O}^{(6)} + \frac{c_6}{\Lambda^2} \mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3} \mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4} \mathcal{O}^{(8)} + \ldots \]
Radically new BSM?

\[ \mathcal{L}_{IR} = \Lambda^4 + \Lambda^2 \mathcal{O}^{(2)} + m \mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{c_5}{\Lambda} \mathcal{O}^{(6)} + \frac{c_6}{\Lambda^2} \mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3} \mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4} \mathcal{O}^{(8)} + \ldots \]

\[ \mathcal{L}_{UV} = ? \]

E < \Lambda

\[ \Lambda \]

e.g. Consider indirect sensitivity to UV theory
Radically new BSM?

\[ E < \Lambda \]

\[ \mathcal{L}_{UV} = ? \]

\[ \mathcal{L}_{IR} = \Lambda^4 + \Lambda^2 \mathcal{O}^{(2)} + m \mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{c_5}{\Lambda} \mathcal{O}^{(6)} + \frac{c_6}{\Lambda^2} \mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3} \mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4} \mathcal{O}^{(8)} + \ldots \]

Matching explicit UV models populates a subspace of SMEFT coefficient space.
Radically new BSM?

Energy

\[ \Lambda \]

\( \mathcal{L}_{UV} = ? \)

Unitarity  Locality  Causality  ...

\[ E < \Lambda \]

\[ \mathcal{L}_{IR} = \Lambda^4 + \Lambda^2 \mathcal{O}^{(2)} + m \mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{c_5}{\Lambda} \mathcal{O}^{(6)} + \frac{c_6}{\Lambda^2} \mathcal{O}^{(6)} + \frac{c_7}{\Lambda^3} \mathcal{O}^{(7)} + \frac{c_8}{\Lambda^4} \mathcal{O}^{(8)} + \ldots \]

Positivity bounds forbid negative signs of SMEFT coefficients assuming only general fundamental principles in the UV.

Measuring the “wrong” sign experimentally would have truly revolutionary consequences for the underlying theory!
Radically new BSM?

May not even have a Lagrangian description

Positivity bounds forbid negative signs of SMEFT coefficients assuming only general fundamental principles in the UV

Measuring the “wrong” sign experimentally would have truly revolutionary consequences for the underlying theory!
Radically new BSM?

• Sometimes an anomaly in **indirect precision** measurement = *something missing*

Anomaly in orbit of Uranus → Discovery of Neptune

• Sometimes its implications are *far more radical*

Anomaly in orbit of Mercury → Explained by General Relativity
Radically new BSM?

• Sometimes an anomaly in **indirect precision** measurement = *something missing*

• Sometimes its implications are *far more radical*

Anomaly in Flavour physics

Discovery of Z’?

Anomaly in positivity bounds?

$\mathcal{L}_{UV} = ?$ Explained by ???
Outline

• Context
• BSM theory challenges
• BSM physics opportunities
• Beyond the LHC

• Conclusion
Conclusion

• Lack of new physics accompanying the Higgs is a major theoretical challenge

• It is also an opportunity to rethink BSM possibilities with an open mind

• Exploiting the full potential of the LHC and fully exploring the multi-TeV scale at FCC is crucial
Conclusion

• 1900: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness*.

• 1920s: A combination of precision measurements (Mercury), aesthetic arguments (relativity) supported by null experimental results (Michelson-Morley), and theoretical inconsistencies (Rayleigh-Jeans UV catastrophe) lead to an overhaul of the fundamental picture at smaller scales and higher energies after *pushing the frontiers of technology and theory into new regimes*. 
Conclusion

• 2020: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness*.

• 2050s: A combination of **precision measurements** (B mesons, Hubble), **aesthetic arguments** (naturalness) supported by **null experimental results** (LHC), and **theoretical inconsistencies** (black hole information paradox) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after pushing the **frontiers of technology and theory into new regimes**.