Theory Summary and Prospects

JOHN ELLIS

Theoretical Particle Physics and Cosmology Group, Department of Physics,
King’s College London, Strand, London WC2R 2LS, U.K;
Theory Division, Physics Department, CERN, CH 1211 Geneva 23, Switzerland

ABSTRACT

This talk reviews some of the theoretical progress and outstanding issues in QCD, flavour physics, Higgs and electroweak physics and the search for physics beyond the Standard Model at the Tevatron and the LHC, and previews some physics possibilities for future runs of the LHC and proposed future hadron colliders.

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1 Introduction

The year 2014 is a year of anniversaries. In the world of physics, it was 150 years ago that Maxwell announced the unification of electricity and magnetism. On the other hand, World War 1 started 100 years ago, World War 2 started in Europe 75 years ago, and D-Day was 70 years ago. Back in the world of physics, Feynman diagrams were formulated 65 years ago, and $\pi^0 \rightarrow \gamma \gamma$ decay was calculated by Jack Steinberger. In 1954, 60 years ago, Peter Higgs obtained his PhD, CERN was founded, and Fermi extrapolated future accelerators to the circumference of the Earth. 50 years ago, 1964 was a bumper year: quarks were postulated, as were charm and colour; spontaneous symmetry breaking in gauge theories was discovered, Bell’s theorem was proved, the $\Omega^-$, CP violation and the cosmic microwave background were discovered. Meanwhile, in the larger world the civil rights legislation was passed in the US, and the Beatles invaded. Supersymmetric field theories in four dimensions were first proposed 40 years ago, and the year 1974 also witnessed the November revolution when the $J/\psi$ particle was discovered. In 1979, 35 years ago, the gluon was discovered. The first LHC workshop was held 30 years ago in 1984, and supersymmetry was not discovered for the first time at the CERN $p-p$ collider. 25 years ago, 1989 saw the invention of the World-Wide Web, as well as the downfall of (much of) communism. The approval of the LHC came 20 years ago, in 1994, and the first low-energy collisions took place 5 years ago, in 2009.

This conference has provided an opportunity to review the current landmarks in collider physics [1]. What should we remember from 2014? [2]

2 QCD

The foundation for all physics at the LHC is QCD [2, 3]: it is the dominant force in particle production, providing us with backgrounds and pile-up events [4] as well as tests of the Standard Model, and better understanding may enable us to dig out new possible signals, e.g., in boosted jets [5]. Here I will just discuss a few QCD topics: top physics, especially the top quark mass, the production of new particles, especially the Higgs boson, $W^+W^-$ production, and heavy-ion collisions.

The top quark mass $m_t$ is a basic parameter of the Standard Model, whose exact value is crucial for the stability of the electroweak vacuum [6]. Understanding QCD accurately is crucial for extracting from data a precise value of $m_t$ using some suitable theoretical definition related to the underlying Lagrangian. However, simulations for comparison with experiment are typically calculated in terms of a Monte Carlo mass whose relation to the pole or running mass is unclear.

An experimental world average value of $m_t$ was recently announced:

\[
\text{World} : \quad m_t = 173.34 \pm 0.36 \pm 0.67 = 173.34 \pm 0.76 \text{ GeV}. \quad (1)
\]

Additionally, two new measurements using lepton + jets final states were reported at this meeting:

\[
\begin{align*}
\text{CMS} [1] : \quad m_t &= 172.04 \pm 0.77 (0.19 \pm 0.75) \text{ GeV}, \\
\text{D0} [6] : \quad m_t &= 174.98 \pm 0.76 (0.58 \pm 0.49) \text{ GeV},
\end{align*}
\]

and CMS has subsequently reported a measurement $m_t = 172.08 \pm 0.90 (0.36 \pm 0.83) \text{ GeV}$ using all-jet final states [7]. It is essential that the theoretical QCD uncertainties in the Monte Carlo $\rightarrow$ running mass $\rightarrow$ pole mass corrections be reduced below the improving experimental precision. At present, it is estimated that these corrections are [8]

\[
\begin{align*}
\text{Monte Carlo $\rightarrow$ Running mass} &\pm 0.7 \text{ GeV}, \\
\text{Running mass $\rightarrow$ Pole mass} &\pm 0.5 \text{ GeV},
\end{align*}
\]

which are not negligible. The first of these sources of uncertainty will be removed if the measurement of the total $t\bar{t}$ production cross section can be used in the future [9], but this will require significant reductions in the theoretical and experimental uncertainties.

*The references are largely to plenary talks at the conference: I apologize to those I omit, to the uncited parallel session speakers, and to the authors of many uncited original papers.
Another instance where accurate higher-order QCD calculations are at a premium is in the dominant
quark-gluon fusion contribution to the Higgs production cross section [10]. Several different NNLO calculations
are available, and are included in various publicly-available tools. Unfortunately the agreement between them
is unsatisfactory. Fortunately, progress is being made on an NNNLO calculation. This will improve the
theoretical accuracy, but progress in convergence between the PDFs will also be needed in order to reduce
the theoretical uncertainties below the experimental measurement uncertainties [11].

Overall, perturbative QCD calculations are doing a fantastic job of predicting the production cross
sections of jets, massive vector bosons [12, 13] and the Higgs boson at the LHC, the most striking exception
being $W^+W^-$ production [14]:

\[
\text{CMS 8 TeV: } 69.9 \pm 2.8 \pm 5.6 \pm 3.1 \text{ pb } \text{ cf, Theory: } 57.3^{+2.3}_{-1.6} \text{ pb,}
\]
\[
\text{ATLAS 7 TeV: } 51.9 \pm 2.0 \pm 3.9 \pm 2.0 \text{ pb } \text{ cf, Theory: } 44.7^{+2.1}_{-1.9} \text{ pb}
\]

This discrepancy has triggered some enthusiastic ambulance-chasing with scenarios involving a light stop
squark, chargino and bino [15]. However, there is an ongoing debate whether the experimental discrepancy
with theory should yet be taken seriously: anomalous electroweak interactions seem unable to explain the
enhancements in the cross sections, but higher-order QCD corrections increase the $W^+W^-$ cross section by several % [16], and better understanding of jet resummation and the modelling of the experimental
jet vetos may also reduce the discrepancy [17].

A very different QCD arena is provided by heavy-ion collisions, which probe the nature of hot and dense
quark-gluon matter [18]. Lattice calculations provides quantitative understanding of the equation of state,
and attention now focuses on its dynamical properties. The transverse flow pattern in near-central collisions
‘remember’ the transverse shapes of the nuclei initiating each ‘Little Bang’, and experimental measurements
indicate [19] 20] that the quark-gluon medium behaves like a near-perfect fluid, as illustrated in Fig. 1. It
has a very low shear- viscosity-to-entropy ratio $\eta/s$ lying within a factor $\sim$ 2 of the lower bound $\eta/s = 1/4\pi$
that holds in a wide class of strongly-interacting field theories, as was first found using the AdS/CFT
correspondence [21] developed on the basis of holography as formulated in the context of string theory [1].
Jet quenching provides another probe of quark-gluon matter [24]: it seems that the ‘missing’ energy splashes
out at relatively large angles to the jet axis, though interpretations in terms of Mach cones or Čerenkov
radiations have not been confirmed. The production of quarkonia also probes the quark-gluon medium: $J/\psi$
production is strongly suppressed at lower energies, as is $\phi$ production at the LHC, presumably because of
Debye screening or dissociation in the medium. On the other hand, $J/\psi$ production recovers at LHC
energies, presumably because of $c\bar{c}$ regeneration in the medium [25].

Relativistic heavy-ion collisions at RHIC and the LHC have certainly produced a medium with interesting
collective properties: its characterization is still a work in progress.

3 Flavour Physics

The Cabibbo-Kobayashi-Maskawa (CKM) description of flavour mixing and CP violation in the quark sector
also works very well [20]. It has made many successful predictions, including many modes of CP violation in
the $K^0$, $B^0$, $B^\pm$, and $B_s$ systems [27]. A while back, there was an indication of CP violation in $D^0$ decays
at a level that would have been very difficult to explain within the CKM picture, but this indication has
not been confirmed by additional data [27]. Another success for the CKM model has been the prediction of
the branching ratio for the rare decay $B_s \rightarrow \mu^+\mu^-$, which is confirmed by experiment at the 30% level,
providing an interesting constraint on extensions of the Standard Model such as supersymmetry. A key
prediction of CKM and related minimal flavour violation (MFV) models that remains to be tested is the
ratio of $B_d \rightarrow \mu^+\mu^-/B_s \rightarrow \mu^+\mu^-$. 

Despite these successes, there is still considerable scope for new physics beyond the CKM paradigm.
For example, there could still be a substantial BSM contribution to the mixing amplitude for $B_s$ mesons:

\[\Delta\text{-shaped?} [23]\]

\[\text{Another instance where accurate higher-order QCD calculations are at a premium is in the dominant quark-gluon fusion contribution to the Higgs production cross section [10]. Several different NNLO calculations are available, and are included in various publicly-available tools. Unfortunately the agreement between them is unsatisfactory. Fortunately, progress is being made on an NNNLO calculation. This will improve the theoretical accuracy, but progress in convergence between the PDFs will also be needed in order to reduce the theoretical uncertainties below the experimental measurement uncertainties [11]. Overall, perturbative QCD calculations are doing a fantastic job of predicting the production cross sections of jets, massive vector bosons [12, 13] and the Higgs boson at the LHC, the most striking exception being $W^+W^-$ production [14]:}

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\[\text{This discrepancy has triggered some enthusiastic ambulance-chasing with scenarios involving a light stop squark, chargino and bino [15]. However, there is an ongoing debate whether the experimental discrepancy with theory should yet be taken seriously: anomalous electroweak interactions seem unable to explain the enhancements in the cross sections, but higher-order QCD corrections increase the } W^+W^- \text{ cross section by several % [16], and better understanding of jet resummation and the modelling of the experimental jet vetos may also reduce the discrepancy [17]. A very different QCD arena is provided by heavy-ion collisions, which probe the nature of hot and dense quark-gluon matter [18]. Lattice calculations provides quantitative understanding of the equation of state, and attention now focuses on its dynamical properties. The transverse flow pattern in near-central collisions \textit{remember} the transverse shapes of the nuclei initiating each \textit{Little Bang}, and experimental measurements indicate [19] 20] that the quark-gluon medium behaves like a near-perfect fluid, as illustrated in Fig. 1. It has a very low shear-viscosity-to-entropy ratio $\eta/s$ lying within a factor $\sim$ 2 of the lower bound $\eta/s = 1/4\pi$ that holds in a wide class of strongly-interacting field theories, as was first found using the AdS/CFT correspondence [21] developed on the basis of holography as formulated in the context of string theory [1]. Jet quenching provides another probe of quark-gluon matter [24]: it seems that the \textquoteleft missing\textquoteright{} energy splashes out at relatively large angles to the jet axis, though interpretations in terms of Mach cones or Čerenkov radiations have not been confirmed. The production of quarkonia also probes the quark-gluon medium: $J/\psi$ production is strongly suppressed at lower energies, as is $\phi$ production at the LHC, presumably because of Debye screening or dissociation in the medium. On the other hand, $J/\psi$ production recovers at LHC energies, presumably because of $c\bar{c}$ regeneration in the medium [25]. Relativistic heavy-ion collisions at RHIC and the LHC have certainly produced a medium with interesting collective properties: its characterization is still a work in progress.}

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Figure 1: Measurements of the transverse flow parameters $v_n$ in lead-lead collisions at the LHC are in good agreement with hydrodynamic simulations with a shear viscosity-to-entropy ratio $\eta/s \sim 0.2$ [19, 20].

$$A = A_{|SM} \times (1 + h_s e^{i\sigma})$$, as seen in Fig. 2 [28]. It is still an open question whether any new TeV-scale physics must necessarily copy CKM slavishly a la MFV. Indeed, there a few anomalies to whet the appetite. The CP asymmetries in $B^0 \to K^{\pm}\pi^\mp$ and $B^\pm \to K^{\pm}\pi^0$ are quite different, though this most likely due to poorly-understood strong-interaction effects. The branching ratio for $B^\pm \to \tau^{\pm}\nu$ differs from the Standard Model prediction by $\sim 2\sigma$, though this seems difficult to explain within 2-Higgs-doublet models or supersymmetry. There is an $\sim 3.7\sigma$ anomaly in the $P_5'$ angular distribution for $B^0 \to K^{*0}\mu^+\mu^-$ that could be explicable by the contribution of a $Z'$ boson (though its significance is reduced to $\sim 0.5\%$ when the look-elsewhere effect is taken into account). There are discrepancies in the determinations of the CKM matrix element $V_{ub}$ that might be a signature of a vector-like quark. There is a persistent anomaly in the diimuon asymmetry at the Tevatron [29]. On the other hand, measurements of the $t\bar{t}$ forward-backward asymmetry now agree quite well with higher-order QCD calculations [29], as does the corresponding $t\bar{t}$ rapidity asymmetry at the LHC.

Figure 2: Experimental constraint on a possible non-Standard Model contribution to $B_s$ mixing [28].

There are plenty of flavour issues to be addressed in future LHC runs, and at Super-KEKB.
4 Higgs Measurements

The mass of the Higgs boson is most accurately measured in the $\gamma\gamma$ and $ZZ^*$ final states [30, 31]. For some time, there has been tension between the masses measured in these channels by ATLAS. The new values reported at this conference are [32, 33, 34, 35, 36, 37]

\[
H \rightarrow \gamma\gamma : m_H = 125.98 \pm 0.42 \pm 0.28 \text{ GeV} = 125.98 \pm 0.50 \text{ GeV},
H \rightarrow ZZ^* : m_H = 125.51 \pm 0.52 \pm 0.04 \text{ GeV} = 125.51 \pm 0.52 \text{ GeV},
\]

ATLAS combined : $m_H = 125.36 \pm 0.37 \pm 0.18 \text{ GeV} = 125.36 \pm 0.41 \text{ GeV},$

with a mass difference:

\[
\Delta m_H = 1.47 \pm 0.67 \pm 0.18 \text{ GeV} = 1.47 \pm 0.72 \text{ GeV},
\]

that has $\sim 2$-$\sigma$ significance. At the conference, CMS reported a precise mass only in the $ZZ^*$ channel [33]:

\[
H \rightarrow ZZ^* : m_H = 125.6 \pm 0.4 \pm 0.2 \text{ GeV},
\]

but CMS has subsequently also reported a precise value in the $\gamma\gamma$ channel [34]:

\[
H \rightarrow \gamma\gamma : m_H = 124.70 \pm 0.31 \pm 0.15 \text{ GeV} = 124.70^{+0.35}_{-0.34} \text{ GeV}.
\]

Combining the two measurements [30, 31, 32, 33], one finds

\[
\text{CMS combined : } m_H = 125.03^{+0.26}_{-0.27}^{-0.33}_{+0.33} \text{ GeV} = 125.03 \pm 0.30 \text{ GeV}.
\]

Amusingly, there is also some tension between the two CMS measurements [30, 31, 32, 33]:

\[
\Delta m_H = -0.9 \pm 0.4 \pm 0.2^{+0.34}_{-0.35} \text{ GeV},
\]

but it has the opposite sign from the ATLAS mass difference [30]. Combining naively the ATLAS and CMS measurements yields

\[
m_H = 125.15 \pm 0.24 \text{ GeV}.
\]

The precise value of $m_h$ is also important for the stability of the electroweak vacuum in the Standard Model, as will be discussed later.

Before that, however, it is worth remembering that the fitted values of $m_h$ measured in $\gamma\gamma$ and $ZZ^*$ final states should differ as a result of interference in the $\gamma\gamma$ final state between $H$ production and QCD production of $\gamma$ pairs. This effect depends on the total width $\Gamma_H$ of the Higgs boson, but its magnitude is very small in the Standard Model: $\Delta m_H = -54 \text{ MeV}$ [30], which is far below the current precision and probably beyond the reach of the high-luminosity LHC.

The strongest bound on $\Gamma_H$ currently comes from constraints on the off-shell Higgs contribution to $ZZ$ production [35]. The pioneering measurement reported at this conference by CMS gave [36]

\[
\Gamma_H \leq 5.4 \times \Gamma_H|_{SM},
\]

as seen in Fig. 3, which is to be compared with the Standard Model prediction $\Gamma_H = 4.2 \text{ MeV}$. Subsequently ATLAS has also reported an upper limit [37]

\[
\Gamma_H < 10.7 \times \Gamma_H|_{SM},
\]

However, there is some model-dependence in the interpretation of these limits, since some extensions of the Standard Model could also affect the $ZZ$ production rate [38].

Combining their measurements of the coupling strengths of the Higgs boson to $\gamma\gamma$, $ZZ^*$, $WW^*$ [30, 31], $b\bar{b}$ and $\tau^+\tau^-$ [33, 34], ATLAS and CMS report the following mean signal strengths:

\[
\text{ATLAS : } \mu = 1.30 \pm 0.12 \pm 0.10 \pm 0.09,
\]

\[
\text{CMS : } \mu = 1.00 \pm 0.09^{+0.08}_{-0.07} \pm 0.07 = 1.00 \pm 0.13.
\]

Overall, the available measurements are quite compatible with the Standard Model, and there are no signs of any other Higgs bosons [39, 40]. Measurements at the Tevatron are also compatible with a Standard Model Higgs boson [41].
Figure 3: CMS constraint on $\Gamma_H$ from the off-shell Higgs contribution to $ZZ$ production [36].

5 Quo Vadis?

Run 1 of the LHC has sown a great amount of theoretical confusion, since many fashionable scenarios for physics beyond the Standard Model had predicted either that new particles or other phenomena would be observed, or that the Higgs boson would either be significantly different from that predicted in the Standard Model or that it would not exist at all. Instead, there is no evidence for extra dimensions opening up, no signs that the Higgs boson may be composite, and no indication of supersymmetry. There has been a mass extinction of theories, and the survivors have had to evolve. Many theorists are asking whether our ideas of naturalness should be modified or even abandoned. Does Nature care, or should we be happy if we can survive somewhere in the string landscape? In the case of supersymmetry, for example, theorists have been considering models with split or high-scale SUSY? My own point of view is that SUSY anywhere is better than nowhere. On the other hand, it is clear that SUSY could not explain by itself the hierarchy of mass scales in physics, and new ideas beyond SUSY are needed. To paraphrase that well-known contemporary philosopher Lionel Messi “In football as in watchmaking particle theory talent and elegance mean nothing without rigour and precision” [10].

Faced with the apparent completion of the Standard Model by the discovery of a (the?) Higgs boson, one might be tempted to think there is no physics beyond the Standard Model, but beware historical hubris! In 1894, Albert Michelson declared that “The more important fundamental laws and facts of physical science have all been discovered”, just three years before the discovery of the electron. Not to be outdone, in 1900 Lord Kelvin declared that “There is nothing new to be discovered in physics now, all that remains is more and more precise measurement”, just five years before Einstein postulated the photon as an explanation of the photoelectric effect, explained Brownian in terms of atoms and proposed special relativity. More recently, in 1981 Stephen Hawking asked “Is the end of theoretical physics in sight?”. To paraphrase James Bond, there are plenty of reasons to think that the Standard Model is not enough [14], but let me just mention 007 of them. 1) “Empty” space is probably unstable, if one takes at face value the measured values of $m_t$ and $m_H$ discussed above, and there is no additional physics. 2) The Standard Model does not have a candidate for the dark matter required by astrophysics and cosmology. 3) The Standard Model does not explain the origin of matter in the Universe. 4) The Standard Model does not explain the small neutrino masses. 5) The Standard Model does not explain why the weak interactions are so strong relative to gravity (the hierarchy problem). 6) The Standard Model is (probably) not capable of inflating the Universe [15], in particular because the effective Higgs potential is probably negative at high scales, as discussed in the next Section. 7) How does one make a consistent quantum theory of gravity?

In the following sections I discuss some of these.
6 The Instability of the Electroweak Vacuum

We think that the effective potential in the Standard Model resembles a Mexican hat, rotationally symmetric, unstable at the origin, with a circular valley where \( \langle H \rangle \equiv v = 246 \text{ GeV} \), and beyond it a rising brim. But with the measured values of \( m_t \) and \( m_H \), it seems that renormalization by the top quark turns the electroweak brim down at large field values, like an Australian bush-hat whose brim is weighed down by dangling corks. This means that the desired electroweak vacuum with \( v = 246 \text{ GeV} \) is unstable with respect to quantum tunnelling though the brim, into an anti-de-Sitter 'Big Crunch'.

Calculations in the Standard Model indicate that the brim turns down at a Higgs scale \( \Lambda \) given by \(^\text{(15)}\)

\[
\log_{10} \left( \frac{\Lambda}{\text{GeV}} \right) = 11.3 + 1.0 \left( \frac{m_H}{\text{GeV}} - 125.66 \right) - 1.2 \left( \frac{m_t}{\text{GeV}} - 173.10 \right) + 0.4 \left( \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right). \tag{15}
\]

Inserting the values \(^\text{(1)}\) and \(^\text{(11)}\), we find the estimate

\[ \Lambda = 10^{10.5 \pm 1.1} \text{ GeV} \tag{16} \]

(beware that the errors are not symmetric and Gaussian). This calculation is most sensitive to \( m_t \), as seen in Fig. 4. If we use the new D0 value of \(^\text{(2)}\) reported at this conference, we find that \( \log_{10}(\Lambda/\text{GeV}) \) decreases by 2.0, but if we use the new CMS value reported at this conference \(^\text{(2)}\) we find that \( \log_{10}(\Lambda/\text{GeV}) \) increases by 1.6. Hence we would welcome a more accurate value of \( m_t \).

Figure 4: The regions of vacuum stability, metastability and instability in the \((m_H, m_t)\) plane, from \(^\text{(46)}\).

One might have chosen to ignore this instability on the grounds that the lifetime of the vacuum would (probably) be much longer than the age of the Universe, but this is made more difficult by the suggestion from the cosmic microwave background that the Universe once had a much higher energy density during an inflationary epoch \(^\text{(45)}\). Fluctuations during this epoch could have enhanced the rate for transition out of the region of the local electroweak minimum and towards the anti-de-Sitter region \(^\text{(47)}\). The subsequent evolution would have been described by the Fokker-Planck equation, and one would expect the anti-de-Sitter region to dominate, though one could perhaps argue that we have been lucky enough to survive in a non-anti-de-Sitter pocket. This might not be so implausible if there was a non-minimal amount of inflation, and the problem could perhaps be avoided altogether with a judicious choice of higher-dimensional terms in the effective potential \(^\text{(48)}\). However, such cosmological arguments underline that electroweak vacuum instability is a potential problem (pun intended).
7 Elementary or Composite?

The discussion in the previous Section assumed implicitly that the H boson is (effectively) elementary up to a large energy scale. What evidence do we have that this might be the case? It used to be thought that a composite Higgs boson would normally have a mass comparable to the scale of compositeness, but this can be reduced if it is a pseudo-Nambu-Goldstone boson whose mass is protected by some symmetry. One way to probe such a possibility is to look for deviations from the Standard Model predictions for the H couplings. The left panel of Fig. 5 shows one particular example, in which one looks for possible rescalings of the H couplings to bosons by a factor a and to fermions by a factor c: clearly there is no sign of a significant deviation from the Standard Model case a = c = 1.

![Figure 5](image)

Another test, this time of the dependence of H couplings on particle masses, using a parameterization of the form

$$\lambda_f = \sqrt{2} \left( \frac{m_f}{M} \right), \quad g_V = 2 \left( \frac{m_V^{(1+\epsilon)}}{M^{1+2\epsilon}} \right)$$

for fermions and bosons, respectively. As seen in the right panel of Fig. 5, the data are quite consistent with the Standard Model prediction $\epsilon = 0, M = 246$ GeV: we find

$$\epsilon = -0.022^{+0.020}_{-0.043}, \quad M = 244^{+20}_{-10}$$.  

(18)

For this reason, we wrote in one of our papers that the H particle ‘walks and quacks like a Higgs boson’. As we heard at this meeting, there are excellent prospects for testing the mass dependence of H couplings, ranging from the muon to the top quark, with the energy and luminosity upgrades of the LHC and possible future colliders, though the trilinear H self-coupling may prove elusive.

A powerful and systematic way to probe for physics beyond the Standard Model is to explore the constraints various experiments place on higher-dimensional interactions that respect the Standard Model symmetries and might be generated in extensions of the Standard Model. For example, composite models might generate such interactions with coefficients depending inversely on the scale of compositeness. There are many such interactions already with dimension 6, and many sources of constraints including precision electroweak measurements as well as Higgs measurements. As an example, the latter can be used to

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† It was also assumed that the spin of the H boson is zero; by now simple alternatives are excluded with a very high degree of confidence.  

constrain the combination

\[
\Delta \mathcal{L} = \frac{c_T}{v^2} \mathcal{O}_T + \frac{c_V}{m_W^2} (\mathcal{O}_W + \mathcal{O}_B) + \frac{c_{(3)LL}^{(3)}}{v^2} \mathcal{O}_{(3)LL}^{(3)},
\]

(19)

where the operators \( \mathcal{O}_{T,W,B} \) and \( \mathcal{O}_{(3)LL}^{(3)} \) are defined in [52]. The left panel of Fig. 6 displays the current constraints on the coefficients \( c_{T,W,B} \) and \( c_{(3)LL}^{(3)} \) of these operators, and the right panel displays the prospective constraints that might be placed by measurements at a possible large future circular \( e^+e^- \) collider (FCC-ee [53]). (Note the large difference in the horizontal scale!)

Figure 6: Left panel: current experimental constraints on the coefficients of dimension-6 operators [52]. Right panel: possible future constraints from FCC-ee experiments [53]. The vertical ‘tram-lines’ have the same locations in the two plots.

8 What Else is There? Supersymmetry!

I consider supersymmetry to be the best-motivated possible accessible extension of the Standard Model [54]. In addition to all the familiar motivations for supersymmetry at the TeV scale, such as making the hierarchy of mass scales more natural, providing an origin for the dark matter, facilitating grand unification and playing an essential role in string theory, Run 1 of the LHC has provided three additional motivations for supersymmetry. 1) It can stabilize the electroweak vacuum. 2) It predicted the existence of a Higgs boson with a mass less than about 130 GeV, as measured. 3) It predicted that the \( H \) couplings would resemble those of the Standard Model Higgs boson, also as measured.

However, despite all these motivations, direct searches for supersymmetry at the LHC have so far revealed nothing [56, 57], as is also the case with searches for the scattering of dark matter particles, indirect searches in flavour physics, etc.. Combining all these constraints and requiring that the supersymmetric relic density lie within the range required by cosmology for cold dark matter imposes important bounds on the parameters of supersymmetric models, as seen in the left panel of Fig. 7 for the minimal supersymmetric extension of the Standard Model with the soft supersymmetry-breaking parameters \( (m_0, m_{1/2}) \) constrained to be universal at the input GUT scale (the CMSSM), and in variants with different soft supersymmetry-breaking contributions to the Higgs multiplet masses (NUHM1,2) [58]. The right-hand panel of Fig. 7 displays the one-dimensional likelihood functions for the right-handed squark mass in the CMSSM and NUHM1,2. The lower-mass regions allowed in these models could be explored by searches for squarks and gluinos at the LHC.

\[\text{§}^5\text{Most probably the LHC has discovered the lightest supersymmetric Higgs boson, but it is also possible that the LHC may have discovered the second one, and that there is a lighter supersymmetric Higgs boson still waiting to be discovered [55].}\]
9 If you knows of a Better ’Ole, go to it!

This was the caption of a famous cartoon from World War 1, and has some relevance to the situation in particle physics today. The LHC has presented us with a paradox: is there really nothing else in the electroweak sector besides a single light Higgs boson? On the one hand, if there is something else relatively light, why has it not shown up at the LHC, and why is there no indirect evidence for it? On the other hand, if there really is nothing else light, is a light Higgs boson unnatural?

Some people take the point of view that the hierarchy problem is a red herring: it is a mathematical artefact of one particular renormalization scheme that has no physical content. Others say that we just have to accept the fine-tuning of the electroweak/Planck mass hierarchy: maybe there is an anthropic explanation, possibly provided by the landscape of string theory. Others seek to solve, or at least rewrite the hierarchy problem by postulating extra dimensions that may be warped. Yet others postulate new physics at the TeV scale in the form of compositeness or supersymmetry [59].

Personally, I do not know of a better ’Ole than supersymmetry. In my view, the hierarchy problem is just as pressing than ever, and supersymmetry is increasingly the best solution we have. As discussed above, Run 1 of the LHC has certainly not provided any additional motivations for composite models or extra dimensions. However, as discussed in the previous section, LHC Run 1 has provided new motivations for supersymmetry, but Nature is not described by simple models unless the scale of supersymmetry breaking is a TeV or more. However, one should regard supersymmetry as a framework, and not get hung up on specific models, of which there are a large number, and many novel possibilities for supersymmetry remain. Maybe R-parity is violated [60]? Or maybe the spectrum is compressed? Or maybe it is hidden or stealthy in some other way? Or maybe it is (semi-)split [59]? Run 2 of the LHC and beyond will certainly tighten the screws on possible scenarios for physics beyond the Standard Model.

10 The Future of Hadron Colliders

Plans for future runs of the LHC include Run 2 with 30 to 100/fb at 13 or 14 TeV, followed by Run 3, which will aim at 300/fb at 14 TeV [61]. Plans for upgrades of the LHC experiments are well underway [62, 63, 64, 65]. Now included in CERN’s planning are preparations for a project to increase the LHC luminosity further (HL-LHC), which aims at 3000/fb at 14 TeV [61], which will offer plenty of prospects for studying the Higgs boson [66] and searching for new physics. Beyond this, one possibility is to put high-field magnets in the LHC tunnel (HE-LHC), which would aim at 3000/fb of collisions at 33 TeV in the centre of mass.
More ambitious proposals would involve digging new circular tunnels with circumferences between 50 and 70 km, as suggested in China [67], or between 80 and 100 km, as in the FCC-hh suggestion for CERN that would aim at 3000/fb of luminosity at 100 TeV [61, 68].

Detailed studies of such machines are starting now, and the physics agenda, which could include high-luminosity $e^+e^-$ collisions in the same tunnel [53], has yet to be developed. However, it is already clear that such a machine would offer unique prospects for Higgs physics, with over an order of magnitude more Higgs bosons than HL-LHC in many channels, almost two orders of magnitude more for $t\bar{t}H$ production. Such a collider would also extend greatly the physics reach for new particles, being able, e.g., to discover gluinos weighing over 10 TeV [69]. Would such a machine be guaranteed to find supersymmetry (if it exists), or to discover dark matter (if it was once in thermal equilibrium in the early Universe)?

In the CMSSM and related models with R-parity, the dark matter density constraint typically allows very heavy masses only along strips where the LSP is nearly degenerate with one or more other sparticles, such as the lighter stau slepton or stop squark. The LHC will be able to explore thoroughly the stau coannihilation strip in the CMSSM, but only part of the stop coannihilation strip, which may extend to an LSP mass $\sim 6500$ GeV [70]. Simple scaling arguments indicate that in some cases the stop coannihilation strip could be completely explored by the FCC-hh via standard searches jets and missing transverse energy, or monojets, but more work on this question is required.

11 Patience!

At the time of the Higgs discovery, The Economist, a well-known “dismal science” journal, published a graphic illustrating the time-lags between the theoretical proposal and experimental discovery of many Standard Model particles. In some cases, such as the muon, there was no time-lag, because theorists had not thought of the particle beforehand: as the famous Columbia University physicist I. I. Rabi famously remarked “Who ordered that?” The longest time-lag was that for the Higgs boson: 48 years between proposal and discovery. Lovers of supersymmetry should be patient: four-dimensional supersymmetric field theories were first published in 1974: only 40 years so far. If Run 2 of the LHC discovers supersymmetry, the time-lag will still have been less than for the Higgs boson!

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