Physics potential of high energy pp (ep) colliders

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Why hadron collider?

Highest energies achieved in the lab. Offers a first direct glance at shortest distances.
LHC and recent proposals

100 TeV, a “standard” benchmark. FCC-hh, SppC

27 (HE-LHC), 37 (LE-FCC)

LHC

Physics case for 27, 37, and 100 TeV have been studied.
Beyond the known options

higher?

<table>
<thead>
<tr>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
</tr>
</tbody>
</table>

A goal post beyond 100 TeV?

100 TeV, a “standard” benchmark. FCC-hh, SppC

27 (HE-LHC), 37 (LE-FCC) another benchmark?

LHC
My talk

- Go over the physics potential of high energy pp colliders.
  - A broad brushed picture of physics at > 100 TeV pp collider (based on simple extrapolations)

- My thoughts on the benchmarks.
Cross section at hadron collider, for producing heavy new physics with mass $M$.

\[
\sigma \sim L_p \cdot \hat{\sigma} \propto \frac{1}{M^{2a}} \hat{\sigma} \quad \hat{\sigma} \propto \frac{1}{M^2}
\]

Sharp falling Parton Luminosity $L_p \leftrightarrow a \gg 1$
Hadron collider reach

Cross section at hadron collider, for producing heavy new physics with mass $M$.

$$\sigma \sim L_p \cdot \hat{\sigma} \propto \frac{1}{M^{2a}} \hat{\sigma} \propto \frac{1}{M^2}$$

Sharp falling Parton Luminosity $L_p \rightarrow a \gg 1$

For two colliders with different energy and luminosity $E_1, \mathcal{L}_1$ and $E_2, \mathcal{L}_2$

Reach in new physics mass, $M_1$ and $M_2$ scales as

$$\frac{M_1}{M_2} = \left( \frac{E_1}{E_2} \right)^{\frac{a}{a+1}} \left( \frac{\mathcal{L}_1}{\mathcal{L}_2} \right)^{\frac{1}{2a+2}}$$

Reach scale with energy.
With a weaker dependence on luminosity
Physics program at hadron collider

Figure 7: Cross sections for the production of dijet pairs with invariant mass $M_{jj} > M_{\text{min}}$, at c.m. energies $p_s = 14$ and 100 TeV. The jets are subject to the $p_T$ and $\phi$ cuts shown in the legend.

Notice that the benefit of luminosity is more prominent at low mass than at high mass. We also notice that, considering the multi-year span of the programme, and assuming a progressive increase of the luminosity integrated in a year, an early start at low luminosity does not impact significantly the ultimate reach after a fixed number of years.

Figure 8: Evolution with time of the mass reach at $\sqrt{s} = 100$ TeV, relative to HL-LHC, under different luminosity scenarios (1 year = 6\times10^6 sec). The left (right) plot shows the mass increase for a $(q\bar{q})$ resonance with couplings enabling HL-LHC discovery at 6 TeV (1 TeV). These results are not an argument for modest luminosity as an ultimate goal, but a reminder of the advantages of high collider energy. Should specific very-high-mass targets arise, the overall optimization of energy and luminosity need not be restricted to a single parameter.

Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108
Physics program at hadron collider

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Rapid gain in mass reach

Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108
Physics program at hadron collider

$\sqrt{s} = 100$ TeV

Mass Reach compared to HL-LHC 3 $ab^{-1}$

- $1 \times 10^{32}$ cm$^2$s$^{-1}$
- $1 \times 10^{33}$ cm$^2$s$^{-1}$ (2 yrs) + $3 \times 10^{34}$ cm$^2$s$^{-1}$ (1 yrs)
- $3 \times 10^{34}$ cm$^2$s$^{-1}$
- $1 \times 10^{35}$ cm$^2$s$^{-1}$

Rapid gain in mass reach

Precision measurement becomes possible

Hinchliffe, Kotwal, Mangano, Quigg, LTW, 1504.06108
A big step on energy frontier

Cohen et al, 2013

Gori, Jung, LTW, Wells, 2014

Felix Yu, 2013

e.g. 100 TeV: x 5 (more) improvement, into (10) TeV regime
Precision measurements

- Maybe the new physics scale is above $10^2$ TeV.

- The NP effect can be parameterized by EFT operators

\[ \frac{1}{\Lambda^2} \mathcal{O}^{(6)}, \frac{1}{\Lambda^4} \mathcal{O}^{(8)}, \ldots \quad \Lambda \sim \text{scale of new physics} \]

- Can only probe through precision measurements.
Energy = precision

At FCC-ee/CEPC/ILC

\[(\delta \sigma / \sigma)_{ee} \sim \frac{m_W^2}{\Lambda^2} \sim (10^{-3})_{\text{exp}}\]

At hadron collider

\[(\delta \sigma / \sigma)_{\text{had}} \sim \frac{E^2}{\Lambda^2}\]

Effects larger at higher energies!

E = parton energy \(\approx 0.1 \ E_{\text{CM}}\)

Can probe: \(\Lambda \sim 0.1 \times E_{\text{CM}}(\delta \sigma / \sigma)^{-1/2}_{\text{exp.error}}\)

For example: \((\delta \sigma / \sigma)_{\text{exp.error}} \sim 10 \%\), \(\Lambda \sim 30 \text{ TeV}\) with \(E_{\text{CM}} = 100 \text{ TeV}\)
What are we looking for?
No lose theorem?

- Are we guaranteed to discover $X$ (e.g. $X=$SUSY)?
  
  › No.

- Standard Model can be consistent up to the Planck scale.

- At the same time, we do have questions to answer, models to test. We need to go forward.
Physics targets

- Origin of the Electroweak scale.
- Understanding the Higgs better.
- Dark Matter
- Flavor/CP
- Matter anti-matter asymmetry.
- ...
Physics targets

- Origin of the Electroweak scale.
- Understanding the Higgs better.
- Dark Matter
- Flavor/CP
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- ...
Origin of the weak scale

For a detailed discussion: See V. Cavaliere and M. Reece, Session 126

Electroweak scale, 100 GeV.

$m_h, m_W \ldots$

Weak scale not fundamental!
The energy scale of new physics responsible for the weak scale

Electroweak scale, 100 GeV.

$m_h, m_W$ ...
Origin of the weak scale

\[ M_{\text{Planck}} = 10^{19} \text{ GeV?} \]

If so, why is so different from 100 GeV? Hierarchy problem.

Electroweak scale, 100 GeV.

\[ m_h, m_W \ldots \]
Origin of the weak scale

\[ M_{\text{Planck}} = 10^{19} \text{ GeV?} \]

Natural theory (low E SUSY, etc.). However, strong constraints from the LHC < TeV

Electroweak scale, 100 GeV. \( m_h, m_W \ldots \)
Which direction to go?

- More stealthy.
- Simpler theories.

exp. limits

clever model building

higher $M_{NP}$, more tuning

Our models
Which direction to go?

- More stealthy.
- Higher energy, better sensitivity.
- Simpler theories.
- Only experiment can tell!

Clever model building

Exp. limits

Higher $M_{NP}$, more tuning

Our models
All Colliders: Top squark projections
(R-parity conserving SUSY, prompt searches)

<table>
<thead>
<tr>
<th>Model</th>
<th>$\int L dt (ab^{-1})$</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>Mass limit (95% CL exclusion)</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}^0_1$</td>
<td>3</td>
<td>14</td>
<td>1.7 TeV</td>
<td>$m(\tilde{t}^0_1)=0$</td>
</tr>
<tr>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}^0_1/3$ body</td>
<td>3</td>
<td>14</td>
<td>0.65 TeV</td>
<td>$</td>
</tr>
<tr>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}^0_1/4$ body</td>
<td>3</td>
<td>14</td>
<td>0.95 TeV</td>
<td>$</td>
</tr>
<tr>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow b^+b^-/3$ body, $\tilde{t}^0_1$</td>
<td>15</td>
<td>27</td>
<td>3.65 TeV</td>
<td>$m(\tilde{t}^0_1)=0$</td>
</tr>
<tr>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}^0_1/3$ body</td>
<td>15</td>
<td>27</td>
<td>1.8 TeV</td>
<td>$</td>
</tr>
<tr>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}^0_1/4$ body</td>
<td>15</td>
<td>27</td>
<td>2.0 TeV</td>
<td>$</td>
</tr>
<tr>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow t^+t^-/3$ body</td>
<td>15</td>
<td>37.5</td>
<td>4.6 TeV</td>
<td>$m(\tilde{t}^0_1)=0$ (**)</td>
</tr>
<tr>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow t^+t^-/3$ body</td>
<td>15</td>
<td>37.5</td>
<td>4.1 TeV</td>
<td>$m(\tilde{t}^0_1)$ up to 3.5 TeV (**)</td>
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<tr>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow t^+t^-/4$ body</td>
<td>15</td>
<td>37.5</td>
<td>2.2 TeV</td>
<td>$</td>
</tr>
<tr>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow b^+b^-/3$ body, $\tilde{t}^0_1$</td>
<td>30</td>
<td>100</td>
<td>10.8 TeV</td>
<td>$m(\tilde{t}^0_1)=0$</td>
</tr>
<tr>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow b^+b^-/3$ body</td>
<td>30</td>
<td>100</td>
<td>10.0 TeV</td>
<td>$m(\tilde{t}^0_1)$ up to 4 TeV</td>
</tr>
<tr>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow b^+b^-/4$ body</td>
<td>30</td>
<td>100</td>
<td>5.0 TeV</td>
<td>$</td>
</tr>
</tbody>
</table>

fine-tuning = \( \frac{1}{16\pi^2} \frac{m_T^2}{m_h^2} \) vs \( m_h^2 = (125 \text{ GeV})^2 \)
mental value only for stops in the multi-TeV range or larger. Indeed, in the minimal SUSY model, the prediction of the Higgs mass agrees with the experimental value of the Higgs mass can be used as an indicator of the scale of SUSY particle masses.

A five-fold increase in reach is expected for the HE-LHC [53]. SUPERSYMMETRY

The exclusion limits are summarised in Fig. 8.3.

All Colliders: Top squark projections (R-parity conserving SUSY, prompt searches)

<table>
<thead>
<tr>
<th>Model</th>
<th>$\langle L_{d} \rangle_{ab}^{-1}$ (1 fb$^{-1}$)</th>
<th>Mass limit (95% CL exclusion)</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \tilde{b}, \tilde{t}_{1} \rightarrow t\tilde{b}$</td>
<td>15</td>
<td>27</td>
<td>1.7 TeV</td>
</tr>
<tr>
<td>$t \tilde{b}, \tilde{t}_{1} \rightarrow t\tilde{b}$</td>
<td>15</td>
<td>27</td>
<td>0.85 TeV</td>
</tr>
<tr>
<td>$t \tilde{b}, \tilde{t}_{1} \rightarrow t\tilde{b}$</td>
<td>15</td>
<td>27</td>
<td>0.95 TeV</td>
</tr>
</tbody>
</table>

200 TeV pp

500 TeV pp

fine-tuning = $\frac{1}{16\pi^2} m_T^2$ vs $m_h^2 = (125 \text{ GeV})^2$
Clever model: Neutral naturalness

Still, S (must) couples to the Higgs.

- Signal: modifying Higgs coupling.
- Signal: $pp \rightarrow h \rightarrow SS$.
- Signal: $h$ decay into lighter states in the $S$-sector

$S$: States "protect" the weak scale
Standard Model singlet.
Part of a hidden sector.
Not easily produced at colliders.

$m_S \sim \sqrt{1/\epsilon} \cdot 500 \text{ GeV}

\epsilon \sim \text{level of tuning}

\text{No tuning} \rightarrow m_S \sim \text{TeV}
Probing neutral naturalness

100 TeV Testing tuning to 10%

200(500) push down to several%

Probing $m_S > \text{TeV}$

$h \rightarrow \text{dark sector }$

(LLP, ... )

100 TeV collider can improve at least a factor of 10 beyond the LHC.

$h \rightarrow \text{dark sector }$

(LLP, ... )

100 TeV collider can improve at least a factor of 10 beyond the LHC.
Understanding the Higgs better

What we know from LHC
LHC upgrades won’t go much further

Addition info on Higgs measurements at pp collider:
European strategy physics briefing book, 1910.11775
Understanding the Higgs better

What we know from LHC
LHC upgrades won’t go much further

“wiggles” in Higgs potential

Big difference in triple Higgs coupling

Addition info on Higgs measurements at pp collider: European strategy physics briefing book, 1910.11775
Larger statistics at higher energies

At 100 TeV, rate 40 times the LHC
Fig. 3.10: Sensitivity at 68% probability on the Higgs self-coupling parameter \( k_3 \) at the various future colliders. All the numbers reported correspond to a simplified combination of the considered collider with HL-LHC, which is approximated by a 50% constraint on \( k_3 \). For each future collider, the result from the single-\( H \) from a global fit, and double-\( H \) are shown separately. For FCC-ee and CEPC, double-\( H \) production is not available due to the too low \( p_s \) value. FCC-ee is also shown with 4 experiments (IPs) as discussed in Ref. [75] although this option is not part of the baseline proposal. LE-FCC corresponds to a pp collider at \( p_s = 3.5 \) TeV.

In order to achieve this sensitivity, we need to consider the development in the field of precision measurements over the last years. For both e+e- and pp colliders, we have already shown that the dominant uncertainties in most Higgs couplings at the HL-LHC are theoretical, even after assuming a factor of two improvement with respect to the current state of the art. Higgs couplings will be approaching the percent level at HL-LHC. At the e+e- Higgs factories, detailed measurements of the electroweak Higgs production cross sections and (independently) of the decay branching ratios will be performed. Higgs couplings will be probed at approaching the per mille level. At e+e- colliders, a campaign of electroweak measurements at the \( Z \)-pole and at the \( WW \) threshold is foreseen. The increase in the number of \( Z \) and \( WW \) events with respect to LEP/SLD, as shown in Fig. 3.5, indicates that statistical errors will decrease by as much as two orders of magnitude at the future machines. As a consequence of this increased statistical precision, the requirements on the theoretical errors for EWPO [78] are even more stringent than for precision Higgs physics.

To interpret these precise results, significant theoretical improvements in several directions are required. The first is the increase of the accuracy of fixed order computations of inclusive quantities, e.g. from next-to-leading-order (NLO) to next-to-next-to-leading order (NNLO) and beyond. This reduces the so-called intrinsic uncertainties, i.e. those corresponding to the left-over unknown higher order terms in the perturbative expansion. Another important element is the accuracy in the logarithmic resummations that are needed to account for effects of multiple gluon or photon radiation in a large class of observables. In this case, different techniques and results are available, some numerical and some analytic, of different accuracy (from next-to-leading log (NLL) to next-to-next-to-leading log (NNLL) and beyond). Extrapolating to higher energies more difficult. We should expect a factor of a few improvement.
Statement #1: Parameter space with first order electroweak phase transition has large deviation in \( h_{ZZ} \), which can be probed by CEPC. 

\[ \delta Z_h \]

\( h_{ZZ} \) coupling: \( \delta Z_h \)

\( h_{hh} \) coupling: \( \lambda_3/\lambda_{3,SM} \)

Orange = first order phase transition, \( \nu(T_c)/T_c > 0 \)
Blue = “strongly” first order phase transition, \( \nu(T_c)/T_c > 1.3 \)
Green = very strongly 1PT, could detect GWs at eLISA

FCC-hh/SppC
The simplest WIMP model: DM part of EW multiplet.
Interaction: Standard Model gauge interactions.
WIMP Dark matter

The simplest WIMP model: DM part of EW multiplet.
Interaction: Standard Model gauge interactions.

Very predictive. Thermal relic abundance → $m_{DM} > \text{TeV}$
Really need (very) high energy colliders!
100 TeV pp collider is needed to cover the EW doublet (Higgsino) and triplet (wino) DM.
EW Dark matter reach

Higher energy needed to cover higher dimensional multiplets.

Either discovery or exclusion, we can make a clear statement of this very compelling WIMP DM scenario.
ep collider

Strong in PDF and related measurements

Helpful in Higgs measurements

Sensitive to NP.

A good complement to a pp program.
Hadron vs lepton (intuition)

**pp collider**
- Higher energy.
- Messier, noisier.
- Probing more interactions, Stronger if NP has strong interaction.

**lepton collider**
- Lower energy.
- Cleaner environment, better sensitivity, precision.
- Stronger for electroweak states.
Hadron vs lepton (intuition)

pp collider

- Higher energy.
- Messier, noisier.
- Probing more interactions, Stronger if NP has strong interaction.

lepton collider

- Lower energy.
- Cleaner environment, better sensitivity, precision.
- Stronger for electroweak states.

However, this comparison really depends on what is achievable.
Hadron vs lepton

See P. Meade’s talk in this session.

We “know” how to make hadron colliders.

But, we also need it to be much (O(10)) bigger.

What is our best route to (super) high energies?
Thoughts on benchmarks

100 TeV, a "standard" benchmark. FCC-hh, SppC

27 (HE-LHC), 37 (LE-FCC)

LHC

A goal post beyond 100 TeV?

higher?

500

200

another benchmark?
Below 100.

- Physics at 27, 37, as well 100 has been studied.
- Physics potential in between bracketed.
- For example, 75 TeV would be also a good step above the LHC.
Above 100.

- Beyond 100, need to be as different as possible.
  - 150 won’t be too different than 100. Would be 50% better than 100.
  - 200?
  - 500???

- Important to understand where the upper limit is.
Conclusion: benchmark for physics studies

What is a reasonable upper limit?

- - - - - - - 500

To understand the physics potential, good to have a benchmark $> 100$ TeV.

- - - - 200

Ideally, $>> 100$ TeV.

__________ 100 TeV, a “standard” benchmark. FCC-hh, SppC

Good to have one at 75 TeV.

__________ LHC

What is a reasonable upper limit?
extras
Some Future Hadron collider proposals

<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-hh</th>
<th>FCC-hh-6T</th>
<th>HE-LHC</th>
<th>HL-LHC</th>
<th>LHC</th>
</tr>
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<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>100</td>
<td>37.5</td>
<td>27</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>16</td>
<td>6</td>
<td>16</td>
<td>8.33</td>
<td>8.33</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.5</td>
<td>0.6</td>
<td>1.1</td>
<td>1.1</td>
<td>0.58</td>
</tr>
<tr>
<td>synchr. rad. power/ring [kW]</td>
<td>2400</td>
<td>57</td>
<td>101</td>
<td>7.3</td>
<td>3.6</td>
</tr>
<tr>
<td>peak luminosity [10^{34} cm^{-2}s^{-1}]</td>
<td>5</td>
<td>30</td>
<td>10 (lev.)</td>
<td>16</td>
<td>5 (lev.)</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>1000</td>
<td>~300</td>
<td>460</td>
<td>132</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>3.75</td>
<td>1.4</td>
<td>0.7</td>
<td>0.36</td>
</tr>
</tbody>
</table>

• **NbTi technology from LHC, magnet with single-layer coil providing 6 T at 1.9 K:**
  - Corresponding beam energy 18.75 TeV or 37.5 TeV c.m.
  - Significant reduction of synchrotron radiation wrt FCC-hh (factor 50) and corresponding cryogenic system requirements.

• **Luminosity goal 10 ab^{-1} over 20 years or 0.5 ab^{-1} annual luminosity:**
  - Beam current 0.6 A or 20% higher than for FCC-hh, 1.2E11 ppb (FCC-hh: 1.0 ppb).
  - Stored beam energy 3.75 GJ vs 8.4 GJ for FCC-hh.

• **Analysis of physics potential, technology requirements and cost ongoing.**

M. Benedikt and F. Zimmermann, FCC week
### Future Hadron colliders

#### Hadron collider parameters $(pp)$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>HE-LHC</th>
<th>(HL) LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>100</td>
<td>27</td>
<td>14</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>16</td>
<td>16</td>
<td>8.3</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>100</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.5</td>
<td>1.12</td>
<td>(1.12) 0.58</td>
</tr>
<tr>
<td>bunch intensity $[10^{11}]$</td>
<td>1 (0.5)</td>
<td>2.2</td>
<td>(2.2) 1.15</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25 (12.5)</td>
<td>25 (12.5)</td>
<td>25</td>
</tr>
<tr>
<td>norm. emittance $\gamma\varepsilon_{x,y} [\mu m]$</td>
<td>2.2 (1.1)</td>
<td>2.5 (1.25)</td>
<td>(2.5) 3.75</td>
</tr>
<tr>
<td>IP $\beta_x$ [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.25</td>
</tr>
<tr>
<td>luminosity/IP $[10^{34} \text{ cm}^{-2}\text{s}^{-1}]$</td>
<td>5</td>
<td>30</td>
<td>28</td>
</tr>
<tr>
<td>peak #events / bunch Xing</td>
<td>170</td>
<td>1000 (500)</td>
<td>800 (400)</td>
</tr>
<tr>
<td>stored energy / beam [GJ]</td>
<td>8.4</td>
<td>1.4</td>
<td>(0.7) 0.36</td>
</tr>
<tr>
<td>SR power / beam [kW]</td>
<td>2400</td>
<td>100</td>
<td>(7.3) 3.6</td>
</tr>
<tr>
<td>transv. emit. damping time [h]</td>
<td>1.1</td>
<td>3.6</td>
<td>25.8</td>
</tr>
<tr>
<td>initial proton burn off time [h]</td>
<td>17.0</td>
<td>3.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Target luminosity HL-LHC: 3 ab$^{-1}$, HE-LHC and FCC-hh: 20-30 ab$^{-1}$
However, didn’t quite pan out

Supersymmetry

Composite Higgs

fine-tuning = comparison

current limit:

$$\frac{1}{16\pi^2} m_T^2 \text{ vs } m_h^2 = (125 \text{ GeV})^2$$

$$m_T \sim 1 \text{ TeV}$$
reached for which is not considered here (see discussion in Sect. FCC. At this precision, the uncertainty is potentially limited by the intrinsic theory uncertainties more modest. For the colliders is similar in their first stages. The improvements seen for HE-LHC and LHeC are parameters related to top, colliders improve most parameters by about factors of 5-10. The exceptions are the coupling of effective couplings, are shown. Again, it is seen that compared to the HL-LHC the to untagged decays are typically probed with a precision of sensitivity to branching ratios as small as 0 be improved by a factor 3 (CLIC) to 10 (FCC-ee, ILC) with respect to HL-LHC. For FCC-hh a of various other combination of aspects of the FCC programme is documented in Ref. \[ is based on the direct search for from very large event samples. The improvement in seen, particularly for couplings to top quark, muons, photons and couplings, please see Ref. \[ be reached, while the SM sensitivity would be reached in a five-year run. For the light quark reach of a dedicated run at \[ is about 4%.
Table 10.1: Summary of the future colliders considered in this report. The number of detectors given is the number of detectors running concurrently, and only counting those relevant to the entire Higgs physics programme. The instantaneous luminosity per detector and the integrated luminosity provided are those used in the individual reports. For $e^+e^-$ colliders the integrated luminosity corresponds to the sum of those recorded by all the detectors. For HL-LHC this is also the case, while for HE-LHC and FCC-hh it corresponds to 75% of that. The values for $p\bar{p}$ are approximate, e.g. when a scan is proposed as part of the programme this is included in the closest value (most relevant for the $Z$, $W$ and $t$ programme). For the polarisation, the values given correspond to the electron and positron beam, respectively. For HL-LHC, HE-LHC, FCC, CLIC and LHeC the instantaneous and integrated luminosity values are taken from Ref. [636]. For these colliders, the operation time per year, listed in the penultimate column, is assumed to be $1.22 \times 10^7$ s, based on CERN experience [636] (this is reduced by a margin of 10–18% in the projections presented for physics results from FCC-ee). CEPC (ILC) assumes $1.3 \times 10^7 (1.6 \times 10^7)$ s for the annual integrated luminosity calculation. When two values for the instantaneous luminosity are given these are before and after a luminosity upgrade planned.

<table>
<thead>
<tr>
<th>Collider</th>
<th>Type</th>
<th>$\sqrt{s}$</th>
<th>$\mathcal{P}$ [%]</th>
<th>$N_{\text{Det}}$</th>
<th>$\mathcal{L}_{\text{inst/Det.}}$ [10^{34} \text{cm}^{-2}\text{s}^{-1}]$</th>
<th>$\mathcal{L}$ [ab^{-1}]</th>
<th>Time [years]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL-LHC</td>
<td>$pp$</td>
<td>14 TeV</td>
<td>–</td>
<td>2</td>
<td>5</td>
<td>6.0</td>
<td>12</td>
<td>[23]</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>$pp$</td>
<td>27 TeV</td>
<td>–</td>
<td>2</td>
<td>16</td>
<td>15.0</td>
<td>20</td>
<td>[23]</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>$pp$</td>
<td>100 TeV</td>
<td>–</td>
<td>2</td>
<td>30</td>
<td>30.0</td>
<td>25</td>
<td>[637]</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>$ee$</td>
<td>$M_Z$</td>
<td>0/0</td>
<td>2</td>
<td>100/200</td>
<td>150</td>
<td>4</td>
<td>[637]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$2M_W$</td>
<td>0/0</td>
<td>2</td>
<td>25</td>
<td>10</td>
<td>1-2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>240 GeV</td>
<td>0/0</td>
<td>2</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$2m_{top}$</td>
<td>0/0</td>
<td>2</td>
<td>0.8/1.4</td>
<td>1.5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1y SD before $2m_{top}$ run)</td>
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<td></td>
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<tr>
<td>ILC</td>
<td>$ee$</td>
<td>250 GeV</td>
<td>$\pm 80/\pm 30$</td>
<td>1</td>
<td>1.35/2.7</td>
<td>2.0</td>
<td>11.5</td>
<td>[342]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>350 GeV</td>
<td>$\pm 80/\pm 30$</td>
<td>1</td>
<td>1.6</td>
<td>0.2</td>
<td>1</td>
<td>[346]</td>
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<tr>
<td></td>
<td></td>
<td>500 GeV</td>
<td>$\pm 80/\pm 30$</td>
<td>1</td>
<td>1.8/3.6</td>
<td>4.0</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1y SD after 250 GeV run)</td>
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<tr>
<td>CEPC</td>
<td>$ee$</td>
<td>$M_Z$</td>
<td>0/0</td>
<td>2</td>
<td>17/32</td>
<td>16</td>
<td>2</td>
<td>[509]</td>
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<td></td>
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<td>$2M_W$</td>
<td>0/0</td>
<td>2</td>
<td>10</td>
<td>2.6</td>
<td>1</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>240 GeV</td>
<td>0/0</td>
<td>2</td>
<td>3</td>
<td>5.6</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>CLIC</td>
<td>$ee$</td>
<td>380 GeV</td>
<td>$\pm 80/0$</td>
<td>1</td>
<td>1.5</td>
<td>1.0</td>
<td>8</td>
<td>[638]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5 TeV</td>
<td>$\pm 80/0$</td>
<td>1</td>
<td>3.7</td>
<td>2.5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0 TeV</td>
<td>$\pm 80/0$</td>
<td>1</td>
<td>6.0</td>
<td>5.0</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2y SDs between energy stages)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>LHeC</td>
<td>$ep$</td>
<td>1.3 TeV</td>
<td>–</td>
<td>1</td>
<td>0.8</td>
<td>1.0</td>
<td>15</td>
<td>[636]</td>
</tr>
<tr>
<td>HE-LHeC</td>
<td>$ep$</td>
<td>1.8 TeV</td>
<td>–</td>
<td>1</td>
<td>1.5</td>
<td>2.0</td>
<td>20</td>
<td>[637]</td>
</tr>
<tr>
<td>FCC-eh</td>
<td>$ep$</td>
<td>3.5 TeV</td>
<td>–</td>
<td>1</td>
<td>1.5</td>
<td>2.0</td>
<td>25</td>
<td>[637]</td>
</tr>
</tbody>
</table>

Abbreviations are used in this report for the various stages of the programmes, by adding the energy (in GeV) as a subscript, e.g. CLIC$^{380}$; when the entire programme is discussed, the highest energy value label is used, e.g. CLIC$^{3000}$; this is always inclusive, i.e. includes the results of the lower-energy versions of that collider. Also given are the shutdowns (SDs) needed between energy stages of the machine; SDs planned during a run at a given energy are included in the respective energy line.