# Tutorial 18: The future of the energy frontier

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In this tutorial, we take a brief look into some of the projects and developments that will define the high-energy frontier in the future. These large, complex projects take decades to develop and build, due in part to the technical difficulties, but also due to the cost, and the need for complex international negotiations to ensure the success of these projects. There is still some uncertainty over exactly which projects will ultimately be built, the final decisions of what to build depend in part on the LHC Higgs boson measurements and searches for BSM physics in the next few years. We will briefly discuss some of the more well-developed proposals in this tutorial.

## 1 The LHC upgrades

The full exploitation of the potential of the LHC is a central part of the current European strategy for particle physics. The first long shutdown has recently finished, with the primary objective of completing the installation of safety systems on the LHC magnets that now allow them to accelerate protons up to the design energy of 6.5–7 TeV, instead of 3.5–4 TeV as in Run 1. Over the next decade, a series of further upgrades are planned. The second long shutdown, expected to occur in 2018–19, will further upgrade the

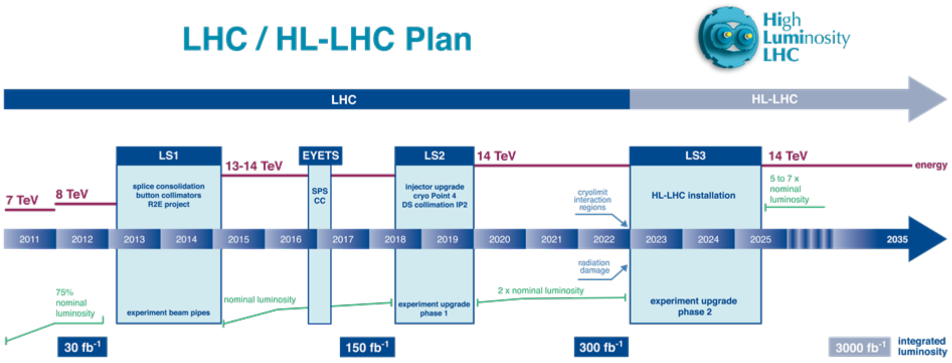

Figure 1: Planned timeline of the LHC and HL-LHC upgrades.

LHC magnet systems, to allow the instantaneous luminosity to be increased to double the nominal value of $10^{34}$ cm$^{-2}$s$^{-1}$. By the end of Run 3, as much as 300 fb$^{-1}$ of data may be collected, compared to 25 fb$^{-1}$ today.

Finally, in 2023–25, the so-called *HL-LHC*,[1] will be installed. The main purpose here is to increase the instantaneous luminosity as much as possible, potentially up to nearly 10 times the nominal value. This is needed because the statistical precision of LHC measurements (and searches) improve only as $1/\sqrt{L}$, if $L$ is the integrated luminosity. So, to halve the statistical uncertainty after Run 3 would require a four-fold increase in $L$, or an additional run time of nine years, as Run 3 is planned to be three years long. With the HL-LHC, this increase could be achieved in two and a half years. The ultimate target for the HL-LHC is to collect a few ab$^{-1}$ of data by the mid-2030s (1 ab$^{-1}$ = 1000 fb$^{-1}$). This large amount of data will allow the physics of the TeV regime to be fully explored by ATLAS and CMS.

During all of these shutdown periods, the LHC detectors are being repaired and upgraded, to cope with the increased hit rates and radiation damage of the upcoming run. The most extreme changes will occur for the HL-LHC, where, for example, ATLAS will need to install a completely new, all-silicon, inner detector.

Now, we will look at some parts of the physics case for these upgrades.

## 1.1 Prospects for LHC measurements and searches

The LHC upgrades are intended to provide a vast increase in the numbers of event candidates, with an important cost: *pile-up*. This refers to the number of $pp$ collisions that occur simultaneously in each bunch-crossing, which could reach about 140 for the HL-LHC, compared to an average of about 20 in 2012. This has a number of effects, such as making it more difficult to identify the primary vertex. Perhaps the most important effect is on the trigger rate, which will increase dramatically if nothing else is changed. It is possible to improve the algorithms used to select triggered events, and also to increase the output bandwidth, however it is certain that some trigger thresholds (usually in $p_{\mathrm{T}}$) will need to be raised in each new run. These factors mean that not all LHC measurements will be improved by the upgrade plans. In particular, many precision measurements of SM phenomena are already systematically limited, and will not benefit from the increased statistics. Examples include most measurements of the top quark, and $W$ and $Z$ bosons, such as the $W$ boson mass.[2] In addition, searches for new particles with low masses (e.g. $\lesssim 200 - 300$ GeV) will become increasingly difficult as the trigger thresholds increase.

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[1] High-luminosity LHC

[2] It is, however, always interesting to measure the production cross-section (and related quantities) of all of these particles at any new value of $\sqrt{s}$.

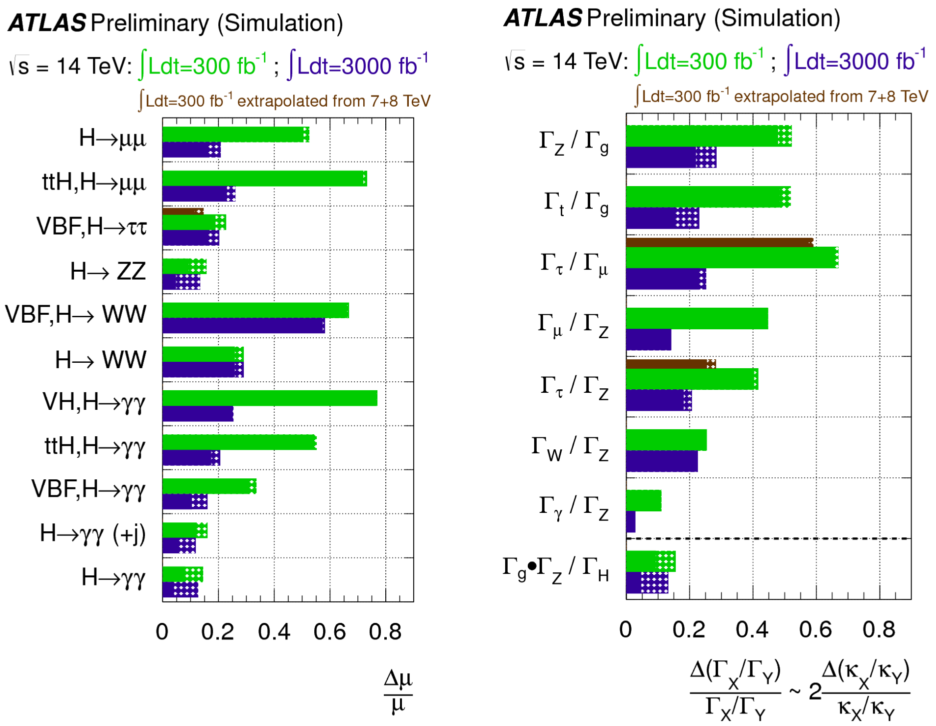

Figure 2: Expected uncertainties of Higgs boson measurements at the LHC and HL-LHC (300 fb$^{-1}$ and 3000 fb$^{-1}$, respectively). Left: signal strength $\mu$, right: various ratios of coupling constants. For comparison, some current uncertainties on $\mu$ with 20 fb$^{-1}$ are: $\sim$ 25% for $H \to \gamma\gamma$ and $H \to ZZ$, $\sim$ 20% for $H \to WW$ and $\sim$ 30% for $H \to \tau\tau$ (see tutorial 10).

The main beneficiaries of the luminosity upgrades are measurements and searches that are currently statistically limited. This includes nearly all studies of the Higgs boson. As made clear in tutorial 10, the decay modes of the Higgs boson that are easiest to detect tend to have small branching fractions, and therefore benefit greatly from more data. In addition, the increase in energy compared to Run 1 will increase the production cross-sections for associated modes ($VH$ and $t\bar{t}H$), where the associated object(s) can be used in the trigger, allowing more difficult decay modes such as $H \to b\bar{b}$ to be better explored.

Figure 2 shows the anticipated precision of Higgs boson measurements in about 2023 (300 fb$^{-1}$) and after the HL-LHC (3000 fb$^{-1}$). In addition to significant improvements in the precision of the discovery channels (see the figure caption), entirely new channels appear that have not been convincingly observed in current data. These include associated production with the decay $H \to \gamma\gamma$, and the anticipated observation of the decay $H \to \mu^+\mu^-$. In most cases, a precision of around 20% can ultimately be reached. These

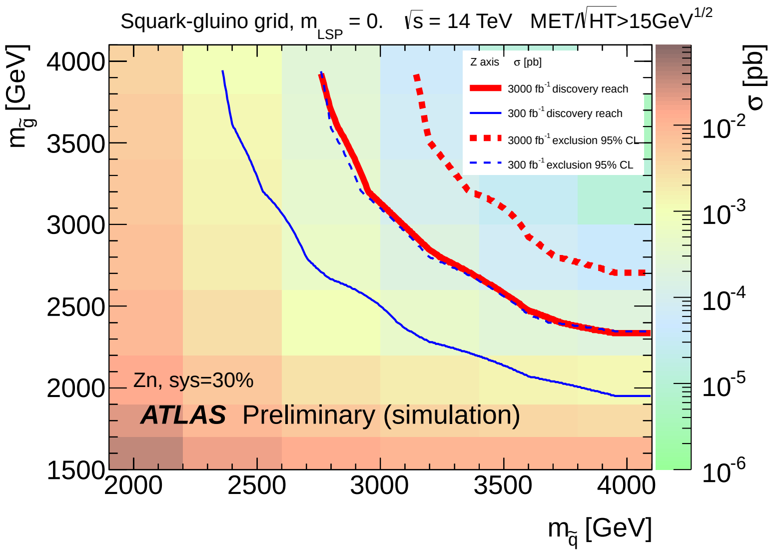

Figure 3: Expected mass reach in searches for squarks and gluinos at the LHC and HL-LHC (300 fb$^{-1}$ and 3000 fb$^{-1}$), assuming a massless neutralino LSP. The solid lines show the $5\sigma$ discovery range, while the dotted lines show the exclusion reach at 95% confidence level. The current limits with 20 fb$^{-1}$ are $m(\tilde{g}, \tilde{q}) \gtrsim 1500$ GeV (see tutorial 15).

channels will allow the SM Higgs couplings to be over-constrained, and ratios of couplings to be extracted, as shown in Figure 2 (right). However, the problems with extracting the absolute couplings discussed in tutorial 11 still apply.

Searches for high-mass particles will also benefit greatly from the LHC upgrades. Again, the increase in beam energy for Run 2 plays a major role too. To see why this is the case, recall from tutorial 5 that the average value of Björken $x$ required to produce a particle of mass $m$ with a beam energy of $E_b$ is approximately $m/(2E_b)$. The parton density functions fall rapidly at high values of $x$, and so an increase in $E_b$ can have a dramatic effect on the production cross-section of massive particles. For example, the production rate for gluino pairs with a mass of 2.5 TeV increases by a factor of more than 2500 when $\sqrt{s}$ increases from 8 TeV to 13 TeV. For the same reason, higher integrated luminosities allow for a greater reach in mass, even when $\sqrt{s}$ is fixed.

Using supersymmetry as an example, Figure 3 shows the projected sensitivity to squark and gluino production, where these particles decay into jets and a neutralino. The current result in this channel was seen in tutorial 15. With 300 fb$^{-1}$ of data, squarks and gluinos with masses of up to 2 TeV can potentially be discovered with $5\sigma$ significance, well beyond the current exclusion of $\sim$ 1400–1500 GeV. If nothing is observed, the HL-LHC

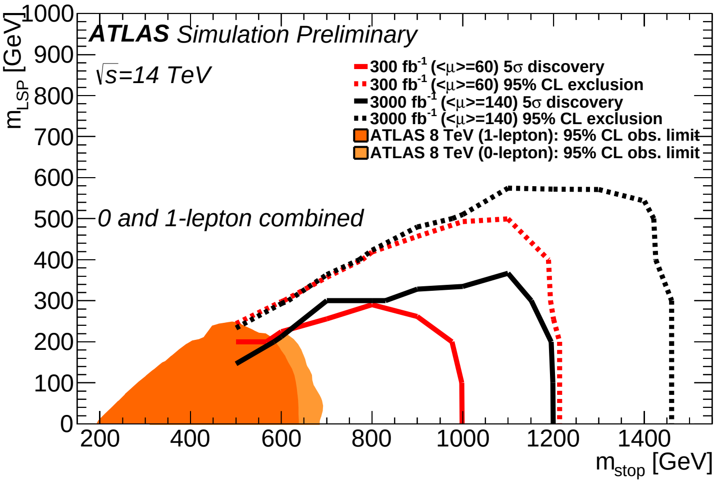

Figure 4: Similar to Figure 3, but for the top squark pair production, with $\tilde{t} \to t\tilde{\chi}_1^0$. The currently excluded region is shown in the lower left corner.

will have an exclusion reach of about 3 TeV. Even for top squark production alone, masses of up to 1.4 TeV could be excluded at 95% CL with the HL-LHC (Figure 4). Together, these results fully explore the mass range that is usually considered "natural" for a supersymmetric theory.

## 2 The ILC

To improve measurements of the Higgs boson beyond the precision shown in Figure 2, a different kind of collider is needed. The precision of any measurement made at a hadron collider is fundamentally limited due to the uncertainty of the initial state, the large background from QCD processes and pile-up. In addition, if any non-SM processes are discovered at the LHC, the same features mean that it will be difficult to fully understand their nature. Thus, there is a strong argument to produce a TeV-scale lepton collider, where the initial state is precisely known. The most well-developed concept for a lepton collider is the International Linear Collider, or ILC. However, most of what follows is relevant for any lepton collider, including the alternatives listed in Section 3.

The proposed layout of the ILC is shown in Figure 5. Electron bunches are produced using a GaAs photocathode, illuminated by a laser. The positrons are created from the interactions in a Ti-alloy of 10–30 MeV gamma rays, which in turn are created by passing the high-energy electron beam through a helical undulator. After the electron and positron beams are produced, they enter two damping rings, where they circulate with an energy of 5 GeV. The purpose of these is to reduce the emittance of the

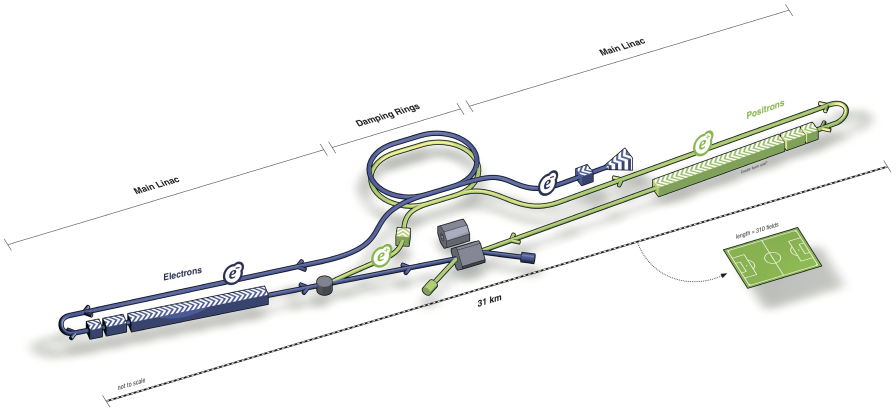

Figure 5: Proposed layout of the ILC, from their Technical Design Report.

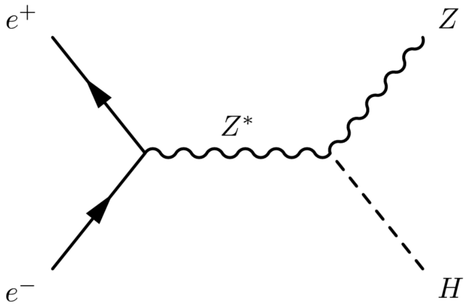

Figure 6: Diagram for $ZH$ production at the ILC.

beams, ready for use in the collider (see tutorial 7). Once prepared, the beams enter the main *linacs* (linear accelerators), which are each currently projected to be about 15 km long. On the return jouneys, the leptons are accelerated, ready for collision at the interaction point, after which they are dumped.

## 2.1 Physics at the ILC

Due to the small Yukawa coupling of electrons, direct $s$-channel Higgs production is not detectable at $e^+e^-$ colliders. Instead, for collision energies below $\sqrt{s} \sim 450$ GeV, the dominant Higgs production mode is associated production with a $Z$ boson, as shown in Figure 6, with a maximum cross-section of about 300 fb at $\sqrt{s} \approx 250$ GeV. Above 450 GeV, $e^+e^- \to \nu_e \bar{\nu}_e H$ dominates, mediated by $t$-channel $W$ boson exchange (or $WW$ fusion).

**Exercise:** Draw the leading order diagram for $WW$ fusion.

The $ZH$ production mechanism gives a unique handle on the Yukawa coupling of the $Z$ boson, irrespective of how the Higgs boson decays. Due to conservation of momentum, we can write

$$p_{e^+} + p_{e^-} = \begin{pmatrix} \sqrt{s} \\ 0 \\ 0 \\ 0 \end{pmatrix} = p_Z + p_H. \tag{1}$$

If the $Z$ boson decays leptonically, then $p_Z$ is known, allowing all four components of $p_H$ to be precisely determined. The peak in the invariant mass distribution $\sqrt{p_H^2}$ can be used to measure the $ZH$ production cross-section, which scales as $g_Z^2$ (using the notation from tutorial 11). In addition, number of detected $H \to ZZ^*$ decays, compared to the total $ZH$ cross-section, will allow the $ZZ$ branching fraction to be measured, which is proportional to $g_Z^2/\sum_i g_i^2$. Combining these two measurements allows the total Higgs decay width to be measured, as $\sigma(ZH)/\mathrm{BR}(H \to ZZ) \propto \sum_i g_i^2 \propto \Gamma_H$. With this information, it is possible to determine the absolute couplings involved in all Higgs boson decay modes, from the measurements of their rates (and also with LHC information on their ratios), in some cases to a precision of better than 1%. With beam energies of up to 500 GeV, it will even be possible to do this for the top quark, via the $t\bar{t}H$ production channel.

In addition, double-Higgs production will be accessible at the ILC. The cross-section is small, but unlike the LHC, it is possible to use the $b\bar{b}$ decay mode to aid detection. The Higgs bosons are again produced in association with $Z$ bosons, and using this channel it should be possible to extract the self-coupling of the Higgs boson with a precision of about 25%.

**Exercise:** Draw some diagrams of $e^+e^- \to ZHH$ to show how the Higgs self-coupling can be accessed using this channel.

The clean environment of a lepton collider also allows for precision measurements of the top quark, which has so far been produced only at hadron colliders. In particular, many ambiguities in top quark reconstruction (e.g. from pile-up jets) are absent, and this should allow the top quark mass to be measured with a precision of better than 100 MeV (compared to 760 MeV from the latest Tevatron+LHC combination).

Finally, the ILC (or another lepton collider) could have an important role to play in non-SM physics. If the LHC discovers non-SM particles, and they are within reach of the ILC, they can be characterised more precisely than before. Also, with precise tracking (helped by a lack of pile-up), particle lifetimes could be measured down to $10^{-5}$ ns. The ILC could also discover particles that were missed at the LHC, in certain scenarios. Taking supersymmetry as an example, charginos that are nearly degenerate with their associated neutralinos would produce only a very soft pion from the decay $\tilde{\chi}_1^\pm \to \pi^\pm \tilde{\chi}_1^0$ that could easily go unnoticed at the LHC. However, there would be potential to reconstruct this decay in a lepton collider.

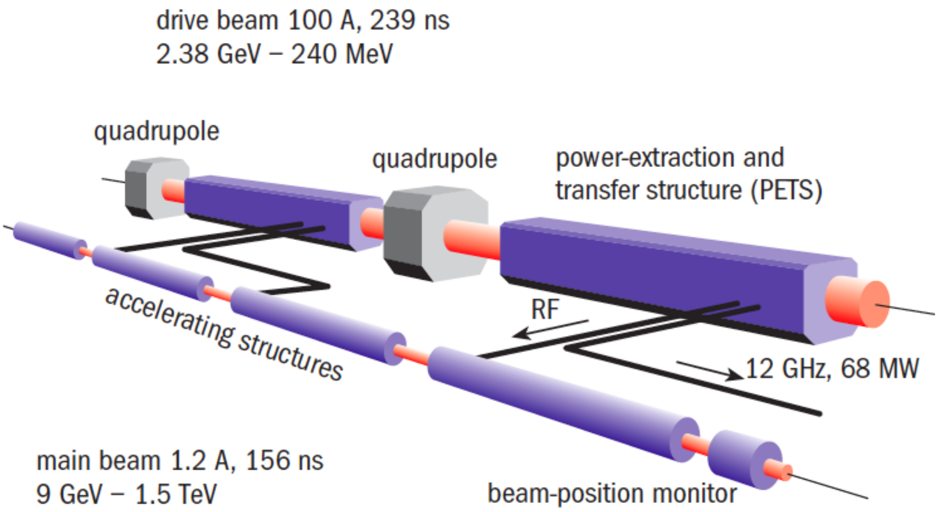

Figure 7: The two-beam acceleration scheme proposed by CLIC.

## 3 Alternatives to the ILC

If new particles discovered at the LHC have masses higher than about 500 GeV, then the ILC will not be able to produce them directly. In this case, another proposal, the Compact Linear Collider (CLIC), could be used to explore higher energies, potentially up to 3 TeV. This would be achieved by using a high intensity drive beam to provide the RF power to accelerate the main particle beam, essentially working as a transformer to transfer power from one beam to the other (see Figure 7). The field gradients produced in this way (for the main beam) would be much higher than in a conventional RF cavity ($\sim 100$ MV $\mathrm{m}^{-1}$), allowing higher beam energies to be produced. Ongoing work on using plasma wakefields to perform a similar function could ultimately produce accelerating fields of 50 GV $\mathrm{m}^{-1}$ or more, which could allow even higher energies to the explored.

Despite the apparent disadvantages, circular lepton colliders are also being discussed. With hindsight, we know now that LEP only narrowly missed out on seeing the Higgs boson (it had sensitivity up to 115 GeV). With a slightly increased beam energy of around 125 GeV, a circular $e^+e^-$ collider could, in principle, produce a large sample of Higgs bosons to study. The limiting factor is the synchrotron radiation emitted by the electrons and positrons as they circulate around the ring, which scales as $E^4$. At its highest beam energies, LEP consumed several MW of power, and while there is a proposal to re-use the LEP/LHC ring for an $e^+e^-$ collider (called LEP3), the synchrotron energy loss would severely limit the instantaneous luminosities that could be obtained.[3]

**Exercise:** Estimate roughly by how much would the energy consumed by LEP3 would be larger than that of LEP2 at its highest beam energy (104.5 GeV), assuming that the beam current is unchanged.

Synchrotron radiation in a circular $e^+e^-$ collider could of course be reduced by increasing the radius $r$ of the ring. CERN is currently investigating the feasibility of an 80–100 km circumference collider ring. Due to its size, this would encircle Geneva, passing right under Lac Léman. This tunnel, like the LEP/LHC tunnel, could initially hold an $e^+e^-$ collider, and then progress to hadron physics, colliding protons with energies of up to $\sqrt{s} \sim 80$–100 TeV.[4] The lepton collider option would be limited in its energy reach, up to about $\sqrt{s} \approx 400$ GeV, but the circular design would allow extremely large samples of Higgs bosons and top quarks to be collected.

One final possibility for a high-energy collider is one that uses muons instead of protons and electrons. While unstable, muons have a long enough lifetime that they can be accelerated to highly relativistic energies before they decay, in principle. All of the processes that can be explored with an $e^+e^-$ would also occur in $\mu^+\mu^-$ collisions, but in addition direct Higgs boson production via $\mu^+\mu^- \to H$ would be possible. Furthermore, many extensions to the SM predict couplings and/or masses that depend on the generation number, and so colliding muons could give unique opportunities to discover particles that are produced less often in collisions of first-generation particles. The main challenge here is one of beam cooling – all of the processes described in tutorial 7 take time, but a muon beam must be cooled within a fraction of a second. Research is ongoing into ways of how to do this. For example, ionisation cooling works on the same principle as a damping ring, except that the energy loss is achieved by passing the beam through a block of absorber material, rather than through synchrotron radiation, and can therefore be achieved over very short distances.

For various reasons, none of these potential collider ideas can be built in the very near future (say, the next decade). It's highly unlikely that *all* will be built, in all cases any final decisions will depend on the results of the LHC in the coming years.

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[3] In addition, it could not be built until the LHC ceases operations.

[4] There is also an *ep* proposal, like a higher energy version of the HERA collider.