1 Introduction to Higgs Factories

Why is it we live in a large-scale universe? By all rights, the Higgs mechanism should have made elementary particles extremely heavy and in doing so should have made gravity and the electroweak interactions of comparable scale and in doing do should have created a universe the size of a small dot. The discovery of the Higgs boson shows that we understand Nature's tools at a purely mechanical level, but we can't figure out how these tools ended up making the universe that we live in.

The Higgs boson discovery presents us for the first time with a layer of elementary structure that is different from all others uncovered by short-distance particle interactions – a fundamental scalar field. What opportunities does this discovery open up for reaching a deeper level of understanding of the laws of physics?

We have found one and only one boson at this time. Are there really no other degrees of freedom in the Higgs sector? That is question #1 - answer by exploration - we know that if an extended Higgs sector is found that there is likely to be additional symmetries and potentially even evidence for physics at the grand unification scale and beyond. We know that additional scalars could appear in decays of the found boson or have mixed states with shared final states at higher mass.

Question #2 - is there something awry with the boson that has been found? Here we turn to the approach commonly known as a Higgs factory. A dedicated environment that provides direct, high precision measurements of the Higgs boson couplings and properties so that by overconstraining the measurements we see deviations at the QFT level. The most obvious discrepancy would be in the partial widths of the Higgs boson to particular final states or on the expected total width of the resonance, indicating something new. But unexpected behavior could appear in other aspects of the Higgs boson in the form of CP violation or anomalous Higgs self-couplings.

The 14 TeV LHC program will achieve the highest rate of Standard Model Higgs boson production in the foreseeable future, and from that standpoint is a Higgs factory with 10^7 to 10^8 Higgs bosons produced in a hadron collider environment. It is also a broadband discovery environment to answer question #1.

Some numbers: The production cross sections at the LHC are approximately 50pb for gluon-gluon fusion (ggF), 4.2pb for VBF, 1.5pb(0.9pb) for HW(HZ), and 0.6pb for ttH. At 33 TeV the cross sections increase to 178pb(ggF), 15pb VBF, 4.3pb(2.7pb) for HW(HZ), and 4.4pb for ttH. The triple Higgs production in ggF(VBF) increases from 34fb(1.8fb) at 14 TeV to 207fb(11fb) at 33 TeV.

What can we measure well at the LHC? From the table of SM branching fractions, Table 1, start from the bottom. The highest measurement precision will be on measuring ZZ, WW, and gamma-gamma decays. Those are important modes. Custodial symmetry will be the law of the land, and the two richest loop diagrams, the top quark loop for production and the loops that couple to gamma-gamma for decay (and some precision on the loop-induced Z-gamma decay) will be known with good accuracy. Arguably, the loop content contributing to the gamma-gamma final state is the most important place to look for indirect evidence for new physics. Only an s-channel gamma-gamma collider has the potential to supersede the LHC measurement precision. This makes the argument that the LHC should push for extraordinary precision for measuring the gamma-gamma partial width in high luminosity operation - however, the current detector phase2 development appears to be aiming at constant performance of even downscaling on gamma-gamma. There are a broad range of production modes at the LHC (ggF with top loop, VBF, HW, HZ, ttH), some with unique properties to reduce measurement systematics - such as the tag and probe topologies. There may be new production modes (such as from cascade decays) - so verifying the production sources is also a way to search for H+X in new physics. A wide range of decays (include the $b\bar{b}$, $\tau^+\tau^-$, and $\mu^+\mu^-$ fermion pair decays and the Z-gamma loop-mediated decay) can be observed and established at better than 3 standard deviations. With such a large statistics of Higgs boson, new unexpected decays at 10^3–10^6 branching fraction levels could potentially be detected.

The most important property of the SM Higgs is the self-coupling that establishes the present-day physical vacuum and which extrapolates to a metastable minimum at small length scales. This observation of the Higgs tri-linear coupling requires upgrades to the existing LHC program. The higher the LHC beam energy, the more sensitivity there will be to the self-coupling - this sensitivity should be compared with 3 TeV lepton colliders where a precision of 20% is estimated. The Higgs sector itself is largely undefined, and may contain a host of new scalar fields, including a two-doublet sector as required by supersymmetry. The broadband search capabilities of the LHC in this regard is largest motivation to increase the luminosity and energy. The burden on providing a strong program high luminosity 14 TeV LHC (beyond 300 fb^{-1}) is on innovative and exceptional improvements in the detector technologies to allow interesting events to be separated from background. Higher energy operation will provide higher production cross sections (nearly an order of magnitude for HHH self-couplings) and is effectively a cleaner environment in comparison to lower energy, higher luminosity operation.

Process	Branching fraction	Relative uncertainty
$H \to b\bar{b}$	57.7%	$(+3.2 - 3.3)\%$
$H \to \tau^+\tau^-$	6.32%	$(+5.7 - 5.7)\%$
$H \to \mu^+\mu^-$	0.022%	$(+6.0 - 5.9)\%$
$H \to c\bar{c}$	2.91%	$(+12.2 - 12.2)\%$
$H \to gg$	8.57%	$(+10.2 - 10.0)\%$
$H \to \gamma\gamma$	0.228%	$(+5.0 - 4.9)\%$
$H \to Z\gamma$	0.154%	$(+9.0 - 8.8)\%$
$H \to W^+W^-$	21.5%	$(+4.3 - 4.2)\%$
$H \to ZZ$	2.64%	$(+4.3 - 4.2)\%$

Table 1: SM Higgs decay branching fractions (M_H=125 GeV) [LHC Higgs Cross Section Group]. The relative uncertainties on the branching fractions are several % or more. This comes from the uncertainty on the total width which is turn is limited by $H \to b\bar{b}$.

Looking at Table 1, one could ask, "Where are the high precision predictions against which experimental measurements can be compared?" The answer is that the branching fraction uncertainties are limited by the lack of direct measurements on the total width of the Higgs boson and therefore from the most uncertain prediction of the known visible decays – the $H \to b\bar{b}$ branching fraction. There is a plan to potentially improve the $H \to b\bar{b}$ theory error down to 1% if α_s can also be improved. As we will see for Higgs factories, the direct measurement of $H \to b\bar{b}$ will eventually supersede theory, and it is likely that this measurement will be used to reduce the total width uncertainty contribution to other branching fractions. For a precision Higgs program, in the absence of improvements on $H \to b\bar{b}$ and the total width, ratios of branching fractions need to be constructed to isolate the highest precision predictions that can be made from theory, or theory extrapolations of other, independent, high precision measurements. The natural width of the SM Higgs boson at $m_H = 125$ GeV, $\Gamma_H \approx 4.07$ MeV $(+4.0 - 3.9)\%$, is two orders of magnitude smaller than direct measurement resolutions at the LHC. The only constraints that can be applied are based on assumptions of cross-section times branching fraction measurements and are, in general, limited to the 10-20% level.

Returning to Question #2. The issue with question 2 is that if we are going search for deviations that point to physics beyond the sensitivity that can achieved with existing precision measurements, the additional precision in the Higgs sector has to be matched with order of magnitude improvements in the electroweak sector and in the W boson and top quark mass measurements. In the event of new discoveries at the LHC, the higher precision on gauge couplings will more precisely fit for the existence of a grand unification point in the presence of high mass thresholds from new physics - the most far-reaching indication for a common origin of the present day interactions.

Resonant (s-channel) Higgs Factories - there are two possible approaches, $\mu^+\mu^-$ and $\gamma\gamma$.

What is interesting about a mu collider - other than the spectacular technology needed to produce, accelerate, and collide muons within their short, time-dilated lifetime?

By far the most amazing capability of the mu collider is its unique capabilities to scan the natural line shape of the Higgs boson. The energy spread of a muon beam can be reduced to 0.2 MeV with a knowledge of the beam energy of 10 keV using g-2 precession methods. The line shape scan unambiguously measures the total width of the Higgs boson to a precision of 0.4 MeV. The Higgs boson production rate with two experiments on the ring is 80000/year. The most precise (sub-percent) and unique measurement will be of the Higgs-muon coupling, where the muon mass is the best known of all heavy fermion masses (better than a part per million). The precision on the range of potential branching fraction measurements are set mainly by the Higgs boson production statistics - which will be compared against other potential dedicated machines - circular machines generally produce more integrated luminosity. There are longitudinal beam polarization capabilities for tests of CP violation, but generally circular colliders do not achieve large longitudinal beam polarizations.

The mu collider has many interesting aspects that support several areas of particle physics beyond the Higgs. The high luminosity capability at the Z peak and at energies of 1, 3, and 6 TeV make it the highest energy reach, highest luminosity lepton collider. It is also the most compact, and fits within the Fermilab site. The ultra-low beam energy spread and beam energy calibration capabilities may provide the highest precision top mass measurement. The luminosity measurement with tracking as opposed to calorimetry and reduced effects from radiative corrections may make for a high precision luminosity determination, but this level of study has not been done. The mu collider environment has a substantial source of background from the constant dumping of off-momentum electrons from muon decay - backgrounds are generated in the beam dumps and stream out in all directions. The detector backgrounds have been found to be minimal with the bulk of the particles being MeV-scale electrons and out-of-time tracks are removed with high precision timing methods. The mu collider has a complete physics program of GigaZ, HZ and VBF, precision W boson and top quark mass threshold scan, ttH coupling measurement, triple-H self-coupling, and 3 TeV or higher lepton collider new physics capabilities - so what is the sticking point? The mu collider design has several non-trivial hurdles to overcome in the accelerator and detectors. The outlook for the muon collider is a 20 year time scale with several intermediate stages of muon accelerator development, some of which support high intensity neutrino physics programs.

The gamma-gamma s-channel collider is an interesting approach. The gamma-gamma collisions can be realized with an extremely compact electron-electron machine with inverse Compton scattered photons from a powerful pulsed laser incident on the electron beams. The energy resolution of the gamma-gamma collider is wider than the s-channel resonance, so there is no capability for a line shape scan. There is a large capability for polarized photons. The strongest area one can explore are in tests of CP violation with polarized initial-states and the measurement precision on the gamma-gamma loop-induced production vertex. There are expected to be substantial backgrounds from charged-fermion final-states, but most of these backgrounds can be removed with kinematical cuts. The development of the laser technology is common with developments in inertial confinement fusion (LIFE) and also free electron lasers (FEL) and energy recovery linacs. The gamma-gamma option could be also added to a linear e^+e^- collider rather than running as a dedicated electron-electron machine.

The story of the maximum energy for an e^+e^- collider started with a paper by Burt Richter. In his paper he drew a line (reasonably defined at the time) in beam energy where e^+e^- circular colliders would end (based on synchrotron energy loss) and where linear colliders could continue. Total power consumption is the main limitation of a linear collider, where one stops at the scale of GigaWatts. In the meanwhile, the KEK-B factory developed a dual-ring technology for topping up beam current at full energy. Not surprisingly this technique nearly doubles the maximum energy of a circular e^+e^- collider and makes it practical to achieve a 350 GeV e^+e^- collider in a 80-100km ring. Typically, one gets one to two orders of magnitude in inst. luminosity with a circular collider.

The ILC was designed to go 1 TeV. This range covered the possible range of Higgs boson masses and in many regards provided a completely parallel route to the Higgs boson discovery we have today. The cleaner environment of e^+e^- collisions offsets to a large extent the lower rate of Higgs boson production, approximately 10,000 per year in the ZH channel at the peak cross section, to upwards of 40,000 per year at 1 TeV in VBF. The ZH data provide an important alternative technique to measure the total width - through the recoil mass. The bulk of the precision on couplings is achieved from the statistics at 1 TeV and this is also where precision on the ttH coupling is maximal with a 4% precision that can be reached. CLIC is an alternative e^+e^- linear collider technology that can be pushed up to 3 TeV using a pair of collinear beams - one used for generating an acceleration gradient. The incremental gain of the 3 TeV operation is most relevant for the HHH self-coupling measurement where better than 20% can be achieved. TLEP is the proposal to install an additional ring of 80-100km to extend the existing LHC accelerator complex. This proposal would achieve the highest rate of Higgs boson production for an e^+e^- collider, exceeding 400,000 Higgs bosons per year. TLEP would provide higher luminosity for all precision measurements including the top quark mass. The missing elements of this program are the ttH and HHH self-coupling measurements which require higher center-of-mass energies. A new 80-100km tunnel would leave open the future possibility of a 100 TeV proton-proton machine, where yet a whole new domain of exploration would be possible.

What are the major issues for Higgs factories? First of all, there cannot be a high precision search for new physics from branching fraction deviations in the Higgs sector unless the uncertainty stemming mainly from $H \rightarrow b\bar{b}$ and in general, the measurement of the total width of the Higgs boson is known to better than 1%. Improvements from theory require a high precision program that improves all electroweak measurements, α_s, and the W boson and top quark mass measurements. Alternatively, a high precision direct measurement of $H \rightarrow b\bar{b}$ will allow measurement to supersede the theory uncertainties so that precision comparisons can be made for the remaining branching fractions, which are few in number for factories that produce a limited number of Higgs bosons. Precision theory predictions for ratios of branching fractions and experimental programs to measure the total width to better than 1% need to be investigated, such as from very high statistics on the recoil mass method and potentially supplemented with direct line shape scans when possible.

The only two resonance production methods for the Higgs boson ($\mu^+\mu^-$ and $\gamma\gamma$) involve technologies that we have not developed yet - but we do believe they will be developed eventually. The other directions for high precision Higgs studies involve accelerators that are themselves new energy frontier machines or in some way are designed to expand into new energy frontier machines. Since these machines use non-resonant processes, the Higgs boson measurements get most of their precision from their highest energy operation. Low energy operation is for specific measurements, such as the recoil mass technique to measure the total width. By choosing these machine technologies we are effectively choosing the future direction of the energy frontier before having decisive constraints to guide us. That might be the only answer, but it would choose between:

- linear e^+e^- up to 1 TeV or 3 TeV – here there are two accelerator technologies
- circular e^+e^- up to 240 GeV (350 GeV) followed by pp at 33 TeV (100 TeV) where the 33 TeV program is HE-LHC in the existing LEP tunnel
- And it should be noted that $\mu^+\mu^-$ could be extended up to at least 3 TeV
- And that $\gamma\gamma$ could be included in a linear e^+e^- energy frontier machine

There are different time-scales for different approaches, and some are more challenging than others. In terms of keeping an edge on new physics, the LHC will keep the community actively engaged for at least the next 10 years making this a unique time to plan with an open view on the most compelling physics case for a new collider.

Summary. There are impressive new capabilities in accelerator and detector technologies that will shape the future of Higgs physics. The list of alternatives is understood, all of which are driven and inspired by the continued pursuit of physics at the smallest length scales. There may be a case to move forward on a new machine at this time, but it is clear that the enabling technologies of the accelerators and detectors should continue to be pursued and that in the immediate future the 14 TeV data from the LHC is still the most direct way to new discoveries.