Future Energy Frontier Collider Options for the United States

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The Snowmass community study gives us a great opportunity to take stock of the current status of our field, and envision how we extend that understanding in significant ways, what experimental facilities abroad do we partner with and what major facilities we host in the U.S. Since it takes many decades to plan, prepare and commission major global facilities, we need to initiate the required studies during this Snowmass. As the US community has participated in the planning process and strategy development abroad, this Snowmass is a great opportunity for the world HEP community to consider options for major complementary facilities that can be hosted in the United States.

The previous Snowmass process (2012-13) and the P5 recommendations (2014) have been widely praised for providing a strong program of *Building for discovery* in the US, in particular the flagship neutrino program of Long Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE), and a number of small and medium scale experiments in HEP and particle astrophysics. The US particle physics community united behind the P5 plan. Currently, the NOvA experiment, Short Baseline Neutrino (SBN) experiments and muon precision physics experiments are either underway or being prepared to come online shortly, at Fermilab. We are executing the plan for building the flagship neutrino program with international partners – LBNF/DUNE would be completed in the late 2020s. With PIP-II superconducting linac (also with strong international partners) being built in parallel will ensure that Fermilab will have the world's most powerful neutrino beam to send to the DUNE experiment to be installed at Sanford Lab in South Dakota, 1.6 km below surface.

Now is a great time to start long-range planning for future HEP facilities in the U.S., beyond LBNF/DUNE. The next round of Snowmass community study will most likely be at the end of the decade, and will be too late to start such an initiative. Given the history of high energy accelerators and colliders in the US [1], both lepton and hadron machines, and the pioneering of superconducting RF and high field magnet technologies in the U.S., it is fitting that we explore options for future collider(s) that could be hosted in the U.S., while also being partners in building global facilities abroad (such as the ILC in Japan and FCC at CERN).

We believe it is useful to explore options, old and new, with our updated knowledge in physics and technology and make informed evaluations, and consider interest and feasibility to host in the US. So we propose to review and address the following options.

Multi-TeV Muon Collider with nuSTORM and Higgs Factory as early phases:
There has been a resurgence of interest in the muon collider in the global particle physics community. An international collaboration is being formed in Europe and the US community could work within that collaboration to explore feasibility and opportunities. Several LOIs are being submitted on physics at the muon collider to this Snowmass. A 4 TeV muon collider would fit on Fermilab site, and initial phases of nuSTORM [2] would enrich the neutrino program at Fermilab; the muon collider could first operate as a Higgs factory and later upgraded to a multi-TeV collider. The initial phase would also provide excellent facility for muon cooling R&D needed to realize the collider stages.

Future proton-proton Colliders, from Compact to Very Large:
The European Strategy for Particle Physics (ESPP) [3] that was recently updated by the CERN Council calls for feasibility studies of Future Circular Colliders (FCC-ee/hh) in a 100 km ring to first host an e+e- collider (to study the electroweak sector – Z, W, Higgs and top) followed by the construction of a 100 TeV pp collider. In this case, the timescale for construction and operation of the pp collider will be in the 2050s and 2060s, respectively.

We propose to study an intermediate scale project [4] to be implemented on a timescale well before the 100 TeV collider. It is possible that short dipole magnets with field >20 T could be made by mid-2030s with LTS/HTS hybrid or HTS [5]. The R&D on iron-based superconductors [6], if aggressively pursued could provide cheaper and more robust high field magnets. It is conceivable that with novel cryomodule magnet assemblies [4] with short dipole magnets and integrated correctors rather than requiring traditional long accelerator magnets could cut a decade or more from the timeline for building a collider. In a 16 km ring, which fits on Fermilab site, with 20- 24 T magnets, a 24- 28 TeV pp collider would be possible. (A High-Energy LHC (HE-LHC) with 16 T magnets in the LHC tunnel that would provide pp collision energy of 27-28 TeV was considered in the ESPPU but was not recommended by the Strategy group.) The idea here is to build a collider with a smaller footprint but on a faster time-scale than currently envisioned for the 100 TeV collider. We plan to investigate innovative beam optics and lattice with proposed novel magnet designs, as well as injector options, beam lifetime and beam dynamics issues. This collider would enable a rich physics program and eventually help facilitate technology for higher energy hadron colliders, such as the FCC.

There have been extensive studies previously of Very Large Hadron Colliders of 230 km circumference [7] in the US, and more recently preliminary studies for pp (and e+e-) colliders in a 100 km ring [8]. These studies would be reviewed and reevaluated. The 230 km VLHC is attractive since the magnets for the first phase of a 40 TeV collider are 2T transmission line magnets, which have been demonstrated and can be readily manufactured. In the second phase, collision energy of 175 TeV with 9.8 T SC magnets, 200 TeV with 11.4 T magnets, are possible.

References:

1. P.C. Bhat and G.N. Taylor, "Particle Physics at Accelerators in the United States and Asia," *Nature Physics*, **16** (2020) 380-385.
2. D. Adey, R. Bayes, A. Bross, P. Snopok, "nuSTORM and a path to a Muon Collider," *Annu. Rev. Nucl. Part. Sci*. **65** (2015) 145-175.
3. https://europeanstrategy.cern/european-strategy-for-particle-physics
4. P.C. Bhat, Fermilab Annual Scientist Retreat, June 2019. (Unpublished)
5. See for e.g., X. Wang, S. A. Gourlay, S.O. Prestemon, "Dipole magnets above 20 Tesla: Research Needs for a path via High-temperature superconducting REBCO Conductors," *Instruments* **62** (2019) 3; G. Velev, A. Zlobin, private communication.
6. T. Spina, X. Xu, LOI submitted to Snowmass21_AF7_AF0
7. The VLHC Study Group, "Design Study for a Staged Very Large Hadron Collider," Fermilab-TM-2149 (2001)
8. C.M. Bhat et al., https://arxiv.org/abs/1306.2369