GOALS of the Muon Collider Design Study

(https://indico.cern.ch/event/930508):

Study to develop a **baseline concept** for a muon collider at two centre-of-mass energy ranges:

- The first **around 3 TeV**, well above Higgs factory
- The second **at or above 10 TeV** extends the energy reach well beyond the capabilities of normal conducting linear colliders. This would likely require more advanced technologies that might not be ready within the next 10-20 years. Try to find the energy limit.

The potential to use the technology for other purposes such as a Higgs or neutrino factory will be explored, provided this is found synergetic with the high-energy collider study.

The collaboration will identify an **R&D path** toward a conceptual design

The collaboration will design a **demonstrator** ➔ *which possible physics?*

TOPICS:

Physics and Benchmarks

Target energies for the studies should be: 3, 10, (14), 30 TeV
While 30 TeV is currently not a target, it is useful to understand trends and limitations of the tools. Could be a target for Snowmass studies in the US, and matches the "Alegro" study group energy, making the independent publications partially "reusable" in that context.

We propose to set-up a dedicated task force to study the energies below 1 TeV.

Generator tools have to be developed and validated at all the energies of interest, for signal and physics background.
The goal is to produce sensitivity estimates assuming a target for final detector performances on high-level objects. This target should evolve while Detector/Beam-Induced-Background (BIB) studies proceed, with the design of the machine.

Physics
Based on previous meetings and on on-going activities, below a list of items to be studied in view of presenting the muon collider physics case. Ideally, we would like the muon collider to appear in all the relevant Physics Briefing Book [1910.11775] plots.
For Snowmass, as for FCC, and CLIC, the studies should produce independent publications to be eventually collected in input documents for the Snowmass process. The list below can be considered a sufficient and realistic target as a starting point and for Snowmass:

1. Direct reach on heavy particles. Stop, Top Partners, EW-inos.
   Suggestion: Open and compressed spectra [see "benchmarks"]".
   Many more particles could be considered, if there is manpower. E.g. Sleptons, Extra scalars not coupling to quarks, Heavy Neutrinos, Axions, ...

2. Higgs 3-linear and 4-linear with backgrounds, realistic cuts and some shape analysis.

3. Measurements of WW, ZH, ff (including tt) for Effective Field Theroy projections, with interpretations in Composite Higgs, Top Compositeness, Z' models.

4. Minimal WIMP DM. Indirect and Direct. One should look at mono-photon direct reach. Crucially relies on BIB estimate and detailed dedicated Detector studies.

5. Single-Higgs coupling measurements and EFT interpretation. In order to contribute to the ECFA effort on Higgs factories. The essential question is what do we lose by not having low-energy runs to measure HZ.

Additional studies can be added, as:

6. A global view on VBS scattering at TeV energies. Includes VBS>HH [https://arxiv.org/pdf/1002.1011.pdf], which is also good for Composite Higgs in point “3”.

7. VBF opportunities for BSM particle production. Detailed analyses including backgrounds and cuts already exist for the scalar singlet [https://arxiv.org/abs/1807.04743, https://arxiv.org/pdf/1910.04170.pdf] at muon colliders. The former is reported in the Physics Briefing Book. A complete calculation of VBF BSM production cross-sections is in https://arxiv.org/pdf/2005.10289.pdf.

8. Dark photons/Dark sectors. Exploiting large rate for Higgses. Exotic Higgs decays could be interesting in the same context.

Benchmarks

A subset of the items above should be studied with the full detector simulation.
The aim is to establish how far [or close] we are from the target performances on real physics sensitivity. And to outline concrete physically relevant use cases for the detector.

Some of the items below have been studied already and/or are already under investigation.

It would be ideal if the experimental groups active on each item were supported by and analysis “expert” [theorists or experimentalist] with direct experience on the specific item.

Physics Validation Studies

Create a list of physics benchmark processes to be studied following two different paths:

- Identify the physics process for which the full simulation is mandatory and study them including the BIB (example: dark matter, wimp,... to be detailed). Lower pT thresholds?
- Use efficiencies and resolutions à la Delphes, whenever it is possible but "cum grano salis" to make sure biases are not created.

An (evolving) Delphes card seems the most effective way to encapsulate the (evolving) target. It should be evaluated if a "v0" of this card, based on target performances similar to those of CLIC and/or FCC-hh could be produced as soon as possible and the level of reliability.

Detector Studies

- Tracking system where position, momentum and time resolution have to be pushed to the limit. What kind of technology is the most suited? What kind of shape and structure? Which R&D should we collaborate with? What should we use for the current simulation?
- Calorimetry exploiting time information at least in the inner part is necessary. What kind of technology? What kind of design? What should we use for the current simulation?
- Muon system: would it be possible to reconstruct and identify muons by using an integrated technique exploiting tracking + calorimeter and a "light" muon detector? What should we use for the current simulation?
- Design one detector or better, two with different specialization.

Nozzles design optimization define angular acceptance.

Some recommendations for final discussion:

Assuming 1 interaction point, but knowing that the optimal solution is 2 experiments

- Vary luminosity around (or widely below) the current target [1] and quantify impact in each analysis, in view of a global assessment of the required luminosity.
  - Consider discussing if and to what extent the absence of Beamstrahlung and the reduced ISR, compared with CLIC, helps the analysis [in e.g. mono-photon or mono-X, or in backgrounds due to the Beamstrahlung tail or by photon-photon]
- Discuss the impact of critical parameters (see below) related with the detector response.
- Study if relevant gain with beam polarizations [low priority].

Proposed physics benchmarks to be studied by dedicated subgroups:

1. SUSY production, from "open" to "compressed" spectra, using standard Simplified Models for LHC/Future Colliders. This could prove sensitivity to heavy particles in the easy open spectrum configuration and in the increasingly harder case where the mass-splitting decreases. The soft objects produced in the compressed decay could be hard to see because of BIB, allowing to quantify its impact. For example, 1308.1461 studies sleptons at ILC in the compressed region. Also, see 2002.01239v1. However choosing sleptons is because of the low mass-reach of ILC. One should do the same for particles like the Stop, which are more central in the SUSY paradigm. On the other hand, if the purpose is to quantify detector performances on low-pt objects, one can consider any SUSY compressed decay to muons, tau, bottom, ...

2. Long-lived Particles. Few examples of Future Collider studies that could be repeated using the same benchmark models.
   https://agenda.linearcollider.org/event/8217/contributions/44770/attachments/34895/54069/UlrikeSchnoor_chargedLLP_CLIC3TeV.pdf (charged long-lived)
   https://cds.cern.ch/record/2625054] Hidden pion (neutral long-lived)
   A standard long-lived particle benchmark is "X" produced from H -> XX

3. Measurement of the di-Higgs differential cross-section.
   The suggestion is to target a measurement of the doubly-different di-Higgs invariant-mass and c.o.m.-angle di-Higgs distribution.
   At low mass (and not too forward in angle), sensitive to the 3-linear [see CLIC studies].
   At high mass, this is sensitive to one important EFT operator [see previous bullet "6"] and also to the direct production of the scalar singlet [see bullet "7"].
   Such a measurement in the entire spectrum would thus cover Higgs physics, EFT, and BSM reach at once.

4. Measurements of Higgs cross-sections and BR in all final states.

[1] https://arxiv.org/pdf/1901.06150.pdf integrated over 5 years and 1 interaction point