Themes: *Beyond the Standard Model at colliders (present and future); Electroweak physics (physics of the W, Z, H bosons)*

# Further searches of the Higgs scalar sector

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***Abstract***

Recent decades have witnessed remarkable confirmations of the Standard Model (SM) describing the Electro-Weak and Strong Interactions. The experimental discovery of the Higgs boson $H^o$ at the CERN/LHC has crowned a success of the SM and calls for further studies on this newly observed sector. New and more precise activities are needed in order to extend more precisely this new discovery within Particle Physics. Like for the previous $Z^o$ studies, additional projects using leptons rather than hadrons should be investigated.

The presently described ($\mu^+ \mu^-$) initiated cross section is greatly enhanced with respect to the one with ($e^+ e^-$), since $H^o$ particle is a scalar and therefore the leptons pair coupling is proportional to the square of the lepton mass. The $\mu^+\mu^-$ Collider is preferable to the other proposed huge $e^+e^-$ future options because of its much smaller dimensions and cost and since it may easily fit within one of the already existing European sites. However it requires the success of a substantial R&D in order to convincingly produce the adequate accumulation and cooling in 6D phase space of the muon beams.

High intensity bunches from a negative $H^-$ source are converted into protons, producing secondary particles (mostly $\pi^\pm$). The π's decay to μ's and the μ's are captured, bunched, cooled and accelerated in a storage ring to produce an appropriate rate of high energy muon collisions.

The ($\mu^+\mu^-$) Collider is primarily concentrated on the optimal scenario offered by further developments of the *European Spallation Source (ESS)* already under construction in the Lund site as the most intense future source of spallation neutrons.

Two configurations are described: the Higgs mass s-channel resonance at $\sqrt{s}$ = 125.5 GeV to study with very small backgrounds the many $H^o$ decay modes with $L \approx 10^{32}$ cm$^{-2}$ s$^{-1}$ and the higher energy Collider with $L \approx 10^{34}$ cm$^{-2}$ s$^{-1}$at $\sqrt{s}$ = 500 GeV to study the other main $H^o$ related processes of the scalar sector.

As a preliminary part of the program, cooling should be experimentally studied in the $\mu^+\mu^-$ ring configuration with the much cheaper and simpler *Initial Cooling Experiment*. Several European laboratories, like for instance in the UK, Switzerland, France, CERN or Sweden (Lund) could be considered as possible locations of this initial program.

Provided muon cooling has been experimentally verified in its many aspects, the subsequent realization of the full scale $\mu^+\mu^-$ Collider program may be carried out for instance at the laboratory of the European Spallation Source (ESS) with the help of several conventional accelerator technologies of reasonable dimensions.

### *1.- Expectations and limits of the LHC.*

Five years ago, ATLAS and CMS have observed at the CERN-LHC a narrow line at a mass of about 125.5 GeV, compatible with the Higgs boson $H^o$. A major luminosity upgrade — the HL-LHC — has been recently approved. ATLAS and CMS detectors will be upgraded to handle an instantaneous luminosity of about $5 \times 10^{34}$ $cm^{-2}\,s^{-1}$ for operation at $\sqrt{s}$ = 14 TeV and the visible cross section $\sigma_{vis}$ = 85 mb. The proton energy stored in the HL-LHC beams will be about 1000 MJ. Targets for the HL-LHC are of 250 $fb^{--1}$/year and an integrated luminosity of 3000 fb$^{-}$1 that may be achieved by year 2037, *the presently planned termination of the HL-LHC data taking.*

The HL-LHC may be however capable to perform $H^o$ related measurements only with rather large uncertainties. For 3000 $fb^{-1}$ estimates are expected to improve only by a factor less than 2 (*Figure* 1). Rare channels such as Zγ, μμ and invisible decays may be measured, but also with an ultimate single standard deviation precision of order 10 %.

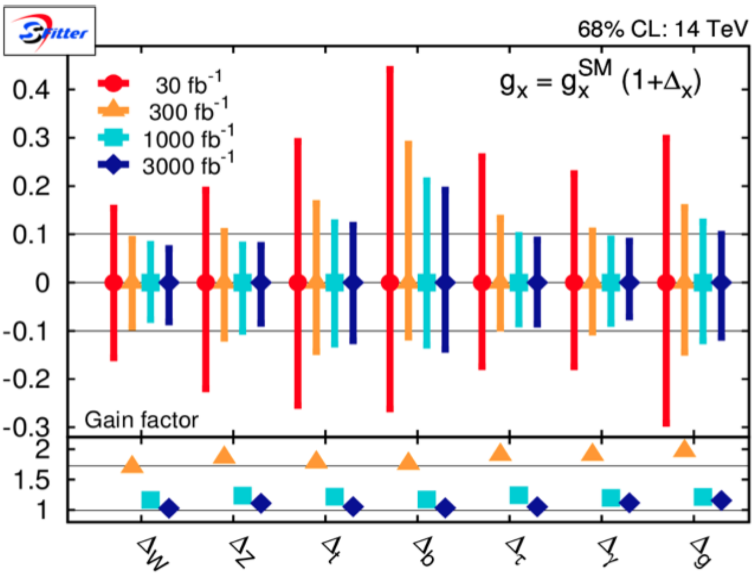


***Figure 1.-*** *Higgs estimates of the present and future LHC programs of the ATLAS and CMS collaborations, accumulating increasing amounts of data, however dominated by the systematic errors. These are 1 standard deviation values.*

The experimental determinations of the Higgs sector will extend the previously well-known observations of the $Z^o$ and the W's, in which the initial search and discovery with the P-Pbar hadron collider had been followed by the systematic studies with leptons at LEP. Also in the present case, additional and more precise determinations are needed in order to place this new scalar $H^o$ particle more precisely beyond the HL-LHC. Like in the previous $Z^o$ case, projects using new Colliders should be investigated with leptons (either $e^+e^-$ or, as described later on, with $\mu^+\mu^-$) rather than with hadrons.

### *2.- Main features of The Higgs sector.*

According to the Standard Model (SM), the width of $H^o$ is only ≈ 4.2 MeV to be compared for instance to the previous and much larger $Z^o$ width of 2.5 GeV. At $\sqrt{s}$ = 125.5 GeV the $H^o$ resonance has several substantive decay branching fractions): (bb), 60%; (WW), 20%; (gg), 9%; (ττ), 6%; (ZZ), 3%; (cc), 3%. The channel (γγ) with 0.2% is also substantive due to its high mass resolution and relatively low background.

The $H^o$, in contrast with the previous cases of $Z^o$ and W's, is a *scalar* (spin = 0) particle, characterized by a much stronger coupling when initiated from muons rather than from electrons colliding with opposite signs. The narrow $H^o$ width may be quantified convoluting the Breit–Wigner resonance with a gaussian beam energy spread (BES) and the Initial State Radiation (ISR) QED effects. Effective $\mu^+\mu^-$ cross sections at √s = 125.5 GeV are of 71 pb for resonance profile alone and of 10 pb and 22 pb with both BES and ISR effects included and for energy resolutions R = 0.01 % and R = 0.003 %. The corresponding and much smaller $e^+e^-$ cross sections are of 1.7 fb (1 fb is equal to $10^{-3}$ pb, i.e. $10^{-36}$ $cm^2$) for Breit–Wigner resonance profile alone and of 0.048 fb and 0.15 fb for both the BES and ISR effects included and with R = 0.04 % and R = 0.01 %.

However, extensive studies at √s = 125.5 GeV are not entirely sufficient to fully elucidate the physics of the $H^o$. Diagrams involving the production of single and double $H^o$ in higher energy collisions should be detailed up to energies of the order of several hundred GeV, well beyond the √s = 125.5 GeV mark. The main cross sections (Figure 2) are the so-called Higgs-strahlung diagram, the W-boson fusion process and the top-quark association. Double Higgs boson diagrams are generated mainly by the off-shell Higgs-strahlung and by the W-boson fusion processes. The study of all these diagrams requires new and substantial energies up to √s ≈ 0.5 to 1.0 TeV and a detailed search in much cleaner conditions of what already possible with hadrons from HL-LHC.

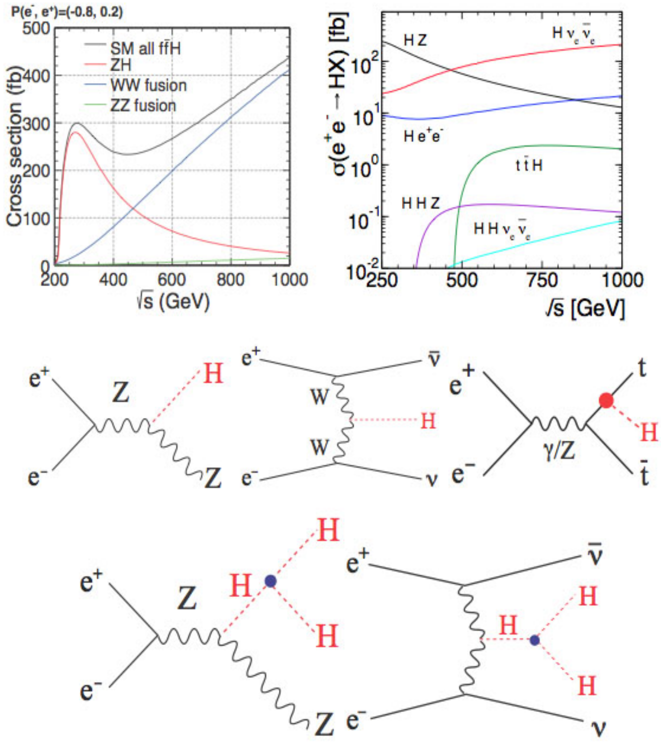


***Figure 2.*** *-Production cross sections $e^+$-$e^{--}$ → Higgs + X as a function of √s up to 1 GeV. On the top: The Higgs-strahlung diagram (Left), the W-boson fusion process (middle) and the top-quark association (right). On the bottom: double Higgs boson diagrams via off-shell Higgs-strahlung (left) and W-boson fusion (right).*

### *3.- Future $e^+$ $e^-$ colliders for Higgs searches*

At the end of the HL-LHC program — now foreseen for the year 2037 — a revisited CERN 27 km tunnel could study up to √s ≈ 240 GeV the reaction $e^+ + e^- \rightarrow H^o + Z$ (LEP3). Most of the already existing infrastructures could be reused, including the tunnel, cryogenics, injection and the two general-purpose LHC experiments ATLAS and CMS. A separate accelerator complex should inject periodically high-energy electrons and positrons to top up the beams. The LEP3 collider should have a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ (about 100 x LEP), an energy loss/turn of ≈ 7 GeV with a luminosity lifetime of a few minutes. According to the Standard Model (SM) with a cross section of 200 fb, of the order of 2 x $10^4$ $H^o$ events may be collected in each of two experiments with an effective $10^7$ s/year, offering very precise measurements of the $H^o$ mass, cross-section and decay modes, including invisible ones. The total wall plug power of the LEP3 complex would be between 200 and 300 MWatt.

Several similar $e^+e^-$ projects in huge new sites have been described. Both (a) a relatively conventional *Collider Ring* and (b) a *Linear Collider (ILC)* are possible.

As alternatives (a) we quote the FCC-ee from CERN with a circumference of 100 km (3.7 x LEP), and CEPC from China with a circumference of 54 km (twice LEP) or eventually of 70 km with an expectation of about $10^6$ Higgs in 10 years of operation, primarily from $e^+e^- \rightarrow H^o + Z$.


***Figure 3.-*** *The T-LEP collider in a new tunnel in the Geneva area. The study comprises a 90-400 GeV high luminosity $e^+e^-$ machine (FCC-ee) and a 100 TeV p-p collider* (FCC-hh). *The complex would allow the use of heavy ions and of e-p collisions*

Alternative (b) of a Linear Collider (ILC) is a major new technology being developed up to $\sqrt{s} \approx 1$ TeV and a a length of ≈ 50 km, Two bunches of 5 nm (0.005 $\mu$m!), each with 2 x $10^{10}$ particles are colliding 14'000 times per second.

Nearly 300 laboratories and universities around the world are presently involved in the ILC development program: more than 700 people are working on the accelerator design and another 900 people on detectors. Design is coordinated for the accelerator by the Global Design Effort and for physics and detector by the World Wide Study. According to early European accounting, the cost of the 500 GeV ILC option is ≈ 8 Billion $ (2012).

To develop such a technology, tATF2 (*Accelerator Test Facility*) has been constructed in Japan at KEK, including other participants like SLAC and LBNL in the US, PAL in Korea, IHEP in China, BINP in Protvino, Russia, DESY in Germany and CERN.

A relatively short-term approval, financing and actual construction of any of these gigantic new $e^+e^-$ options, ether (a) a Ring or (b) a Linear Collider may be rather unlikely.

### *4.- A muon Collider as a future $H^o$ Facility.*

The $\mu^+\mu^-$ Collider may be highly preferable to the previously described huge $e^+e^-$ options because of its much smaller dimensions and cost and since it may easily fit within one of the already existing European sites.

The muon does not have strong interactions. Its higher mass relative to the electron means that it can pass through matter without significant hadronic or electromagnetic showers. Thus, it is the perfect candidate for the presently described Ionization Cooling. Muons loose energy passing through a low-Z material and the longitudinal component is restored by RF cavities. This technique allows to reduce in a very short time the angular spread of a beam of muons to the limits determined by multiple scattering.

However, it requires the success of a substantial R&D in order to convincingly produce the adequate accumulation and compression space of the muon beams. As a preliminary and essential part of the $\mu^+\mu^-$ program, the *Initial Cooling Experiment* is also described in the present paper.

Two different configurations of the $\mu^+\mu^-$ Collider are described, namely the Higgs mass s-channel resonance at $\sqrt{s}$ = 125.5 GeV and L ≈ $10^{32}$ $cm^{-2}$ $s^{-1}$ to study the many $H^o$ decay modes and a higher energy configuration of up to $\sqrt{s}$ ≈ 0.5 TeV and L ≈ $10^{34}$ $cm^{-2}$ $s^{-1}$ to explore the main $H^o$ related processes of the scalar sector.

At the $\sqrt{s}$ = $H^o$ mass, the $\mu^+$ $\mu^-$ Collider ring will require *at* 7 Tesla the tiny ≈ *30 m* bending magnetic radius, extended for instance to ≈ *115 m* at $\sqrt{s}$ ≈ 500 GeV. A realistic Collider configuration with two beam crossing points at $\sqrt{s}$ = 125.5 GeV will have a circumference of less than 400 m, slightly above twice the previously $Z^o$ associated AA CERN Accumulator Ring of 188 m, only 0.4 km/27 km = 1.4% of the LEP3. For the higher energy option a stronger magnetic field of up to about 20 Tesla is possible, with corresponding reductions of the circumference of this ring.

An extension of the *European Spallation Source (ESS),* already under construction at the Lund site may be considered primarily, because of its very large beam power and fast repetition rate. The ESS may become the highlight project for the further studies of the Higgs sector in Europe, since in other existing locations, like for instance at CERN, the development of an adequately intense muon producing beam power is presently no longer under active consideration.

*M*uons may be produced either by $\mu^+\mu^-$ pair electro-production from a high energy (45 GeV) $e^+$ accelerator on $e^-$ at rest (however without cooling) or production of pions and kaons from protons, subsequently decaying into muons, as here proposed for the ESS.

As schematically shown in Figure 4, a pair of proton storage rings, the *"Accumulator"* to collect the LINAC pulse and the *"Compressor"* to steer the beam are followed by a secondary pion production target, a linear Front End where a strong correlation develops between time and energy and an extensive 6D muon cooling, followed by the acceleration at the appropriate energy and of the Collider ring with two narrow final muon bunches of opposite signs and two collision points.

The beam transfer from the LINAC to the Accumulator is performed by a multi-turn injection of $H^-$. Negative [p+2e-] ions — i.e. three simultaneous m.i.p.'s, two electrons and a proton — are accelerated by the LINAC, stripped of their two electrons at the entrance of the accumulator ring, either with a thin absorbing foil or of an appropriate LASER beam.

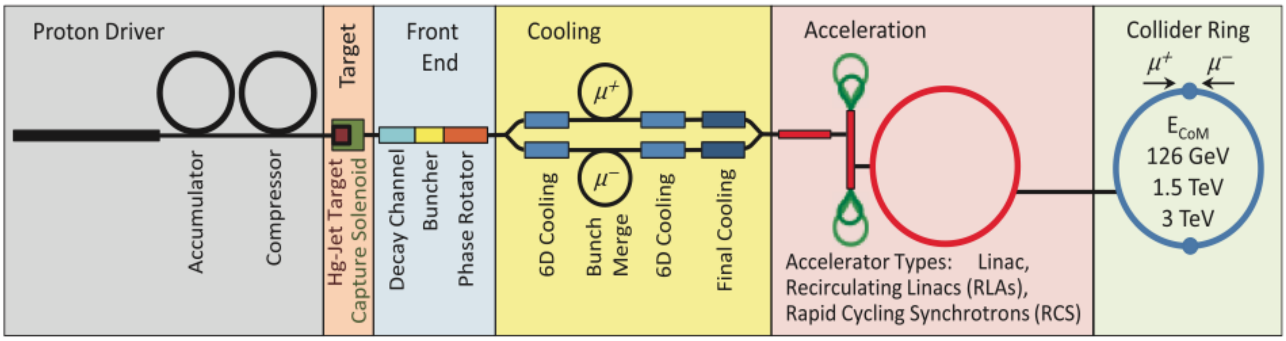


**Figure.4.-** *The ESS scenario. High intensity bunches from the negative H- source are converted into protons, producing secondary particles (mostly $\pi^{\pm}$). The $\pi$'s decay to $\mu$'s and $\mu$'s are then captured, bunched, cooled and accelerated in a storage ring to produce an appropriate rate of high energy $\mu^+\mu^-$ collisions.*

As a first option, the *stripping of carbon foils* — already chosen for instance for the SNS–US program — may be employed for a charge exchange injection. An adequate converter could be a ≈ 300 $\mu$g/cm$^2$ foil. In order to limit the particle density to ≈ 6.0 x $10^{13}$ particles/ mm$^2$/cycle and to keep the foil temperature well under 2,500 K margin with ≈ 500 K, the "painting" of a full LINAC pulse of $10^{15}$ protons requires about 20 mm$^2$. The first ESS protons must perform in the accumulator as many as 5958 traversals and the energy loss to be compensated will be of 4.67 MeV lower than the last arriving protons.

The second option is based on stripping with the help of *a LASER beam*. The $H^-$ has two electrons, one tightly bound (binding energy of 13.6 eV), another loosely bound (binding energy of 0.75 eV). The beam from the ESS may strip off the lower eV electron with the help of a high field dipole magnet through the process of Lorentz stripping ($H^-$ to $H^O$). The second inner electron is much too tightly bound to be easily stripped off. With a conventional magnet, a LASER is used to excite the electron to a higher quantum state ($H^O$ to $H^{O*}$) with a smaller binding energy. While in the excited state, the $H^{O*}$ is passed through a second dipole magnet of comparable strength to the first, which strips off the remaining electron to produce a proton ($H^{O*}$ to p).

LASER stripping was presented over three decades ago. Successful (> 90%) stripping of a 6 ns, 1 GeV H- beam using a 10 MWatt UV-LASER has been demonstrated. Unfortunately, a direct scaling of this experiment to the full ESS duty factors implies unrealistically larger LASER powers. To advance this concept one must find novel ways to reduce the LASER power requirement to a more achievable level.

To conclude, in view of its large power, both the foil stripping and the LASER methods *require future further developments and a more conclusive proof.*

The Proton *Accumulator ring* may have Q-values of 7.37 (H) and 5.77 (V), well above the actual energy. The ring period is 660 ns at $\beta_P$ = 0.9476 (radius = 30 m), and it can be filled by each dedicated pulse of the main ESS LINAC with four $H^-$ to p stripping pulses each 120 ns long, equally distributed with four ≈ 45 ns empty gaps for the preparation to the subsequent extractions to the Compressor. In order to fill t1.1 x $10^{15}$ protons from the LINAC to the Accumulator 5958 turns are required, reduced eventually to 3273 turns for a 3.5 GeV operation. Because of the additional empty gaps, the total duration of each related LINAC pulse will have to be extended from 2.86 ms to 3.93 ms. A overall stripping efficiency of ≈ 90% has been assumed.

The four 120 ns long batches – each with 2.5 x $10^{14}$ protons – are stored from the LINAC to the Accumulator and sequentially transferred to Compressor and where with the help of RF cavities a bunch rotation to a few ns width takes place.

At the end of the Compressor, the Laslett incoherent-space-charge transverse tune shift of the proton beam quantifies the severity of the effect. The so-called electromagnetic radius of the proton is $r_p = 1.535 \times 10^{-18}$ m, N = 2.5 x $10^{14}$, $\beta$ and $\gamma$ are the usual Lorentz kinematical factors at 2 GeV/c (i.e. $\beta\gamma^2 = 9.285$), b ≈ 2 ns / 120 ns = 1/60 is the bunching factor b of the initial 120 ns pulse rotated to 2 ns at the exit target point of the Compressor. A reasonable maximum value of the space-charge tune shift is $\Delta\nu_{sc} \approx 0.4$, determining the maximum acceptable transverse invariant emittances $\varepsilon_{V,H} = Nr_p / (2\beta\gamma^2 \Delta\nu_{SC} b)$ of the proton beam of the Compressor when ejected to the pion producing target. Notice that there is no dependence of the radius of the ring.

The resulting space charge l is $\varepsilon_{V,H}$ = 3.1 x $10^{-3}$ (π) m rad corresponding to a r.m.s. radius $\sigma = \mathrm{sqrt}(\varepsilon_{V,H}\beta^*/\gamma) = 0.0315 \times \mathrm{sqrt}(\beta^*)$ m. For $\beta^*$ = 0.3 m at the pion producing point, we find the large value $\sigma$ = 1.72 cm, not surprising in view of the relatively low proton energy and the large number of 2.5 x $10^{14}$ protons/bunch. Bringing the energy to 3.5 GeV will give $\varepsilon_{V,H}$ = 0.90 x $10^{-3}$ (π) m rad and $\sigma$ = 7.54 mm at $\beta^*$ = 0.3 m. Therefore, a higher proton energy could be beneficial for the realization of the appropriate target. Alternatively, maintaining the chosen value $\Delta\nu_{sc}$ = 0.4, the final compression by bunch rotation could be extended from ≈ 2 ns r.m.s. to a larger value of 6 ns with $\sigma$ = 5.7 mm at 2.0 GeV or $\sigma$ = 2.5 mm at 3.5 GeV.

The charged pion productions at the target have been estimated for a 30 cm long heavy Z (mercury) target at the 2.0 GeV proton kinetic energy. At the initial 20 Tesla field, the transverse momentum $p_T$ of pions produces a tight helix with a narrow magnetic radius $p_T$/60 in MeV/c and cm. The magnetic field is progressively reduced in a linear longitudinal structure to about 2.8 T, with secondary's in an axially symmetric solenoid field. Both polarities are focused and they will be sign separated only at a later stage. Some 30 m away, a 10 cm Beryllium absorber removes almost all remaining low energy protons and $e^+$ and $e^-$ electrons. Pions produced are quickly decaying into $\mu$'s with a lifetime ct = 7.8 m, Muons have ct = 659.1 m, i.e. 1.56 km decay at 250 MeV/c.

Muon bunches are followed by a drift space where a strong correlation develops between time and energy. In order to provide a nearly non-distorting phase rotation, either Induction Linacs or a chain of RF cavities with RF rotation can be used. The momenta of the faster muons are decreased and the slower muons increased.

A RF driven buncher consists of many frequencies between 200 and 300 Mhz and a length of some 30 m. The buncher is followed by a some 40 m long rotator embedded in 2.8 Tesla field, with many different frequencies and cavities, compressing muons to an average optimum cooling momentum of ≈ 250 MeV/c and a r.m.s. energy spread ≤ 10 %.

After some linear pre-cooling at the Front End, muons are sign separated. Differences between the helical and the circular geometries are negligible. The full process is shown in Figure 5. Several bunches of each sign can be cooled in a ring and later, after an intermediate stage, bunch rotated and accumulated to one bunch, which is extracted at the end of the cooling process. The circumference of each of the cooling rings should be of the order of 30 to 45 m. The final, normalized emittances after hydrogen cooling at equilibrium at 250 MeV/c are expected to be of $\varepsilon_\perp = 0.4(\pi) mm\, rad$ and $\varepsilon_L = 1.0(\pi)\ mm\ rad$

The normalized emittances at equilibrium with hydrogen cooling at the √s =125.5 GeV Higgs mass are appropriate to observe the many $H^0$ decay modes with the remarkable energy resolution R = 0.003 %. For the higher energies in the domain of 0.5 TeV In order to arrive to an acceptable event rate in excess of L > $10^{34}$ $cm^{-2}$ $s^{-1}$, the required transverse emittance must be further reduced, at the cost of a Louvillian increase of the longitudinal emittance. This can be obtained in liquid hydrogen with strong solenoids. The results of ICOOL simulation of cooling have been given with seven 50 T solenoids).

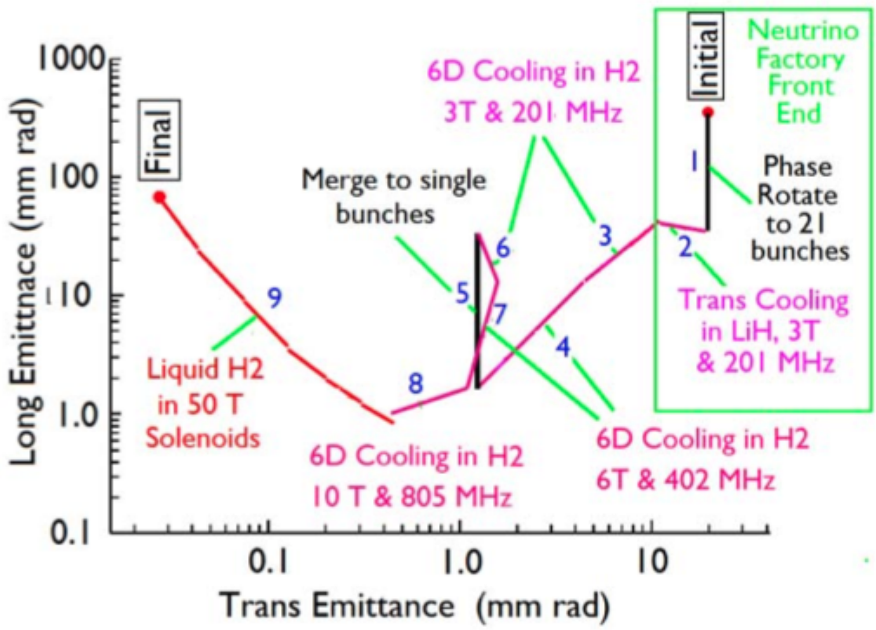


**Figure 5.-** *Complete scheme for a muon Collider at an average momentum of 250 MeV/c given in COOL 2007 [64], but adapted to the case of the ESS, numbered from, (#1) to (#9). The end of (#8) corresponds to .a configuration for √s = 125.5 GeV, R =0.04 % and a luminosity of $10^{32}$ $cm^{-2}$ $s^{-1}$. For the high energy option the luminosity is increased to $10^{34}$ $cm^{-2}$ $s^{-1}$ with the help of Liuvillian cooling (#9).*

The Liouvillian acceleration system increases progressively the energy of captured muons to $m_{Ho}/2$. After a pre-accelerator to an indicative energy of 2.5 GeV, the transport merges and accelerates $\mu^+$ and $\mu^-$. At the average acceleration of the order of 25 MVolt/m a total LINAC length of the order of 2.5 km is required, feeding both nearby kept $\mu^+$ and $\mu^-$ bunches in opposite directions with an common LINAC length of 1.25 km and small adjustments. A common bi-directional 360° FODO magnetic bending reverses the directions of the LINAC transport. The $\mu^+ + \mu^-$ decay losses of the acceleration process up to the Higgs mass are 10 %.

The higher energy option at √s = 0.5 TeV with the previous option will require a LINAC length of about 4 km, too large for the present ESS application. A possible option with N = 4 x 2 multiple passages would preserve the already chosen LINAC length of 1.25 km, requiring however a more complicated 360° FODO multiple magnetic bending with higher magnetic fields and/or larger radii on the left and right sides. A kicker synchronizes with a chain of short pulses of different values the separate FODO arcs to merge the beams to the common LINAC.

The final beam Collider at √s = 125.5 GeV is a relatively small SC ring at 62.5 GeV with a typical radius of ≈ 60 m and two low $\beta$ sections with a free length of about 10 m, where the two detectors are located.. Typical values could be $\beta_x = \beta_y = \beta^* = 5$ cm. For an additional dedicated ESS power of 5 MWatt (4% duty cycle) with a collision rate of 56 ev/s the number of $\mu$+ and $\mu$- accumulated at the Collider are respectively 2.9 x $10^{12}$ and 1.9 x $10^{12}$ $\mu$/bunch corresponding to a Higgs luminosity of 4.0 x $10^{\cancel{31}}$ $cm^{-2}$ $s^{-1}$ and 1.2 x $10^4$ events each crossing at $10^7$ sec/year. The more advanced alternative for √s = 0.5 TeV should require the luminosity of about 1.0 x $10^{34}$ $cm^{-2}$ $s^{-1}$.

### *5.- Advanced methods: Parametric-resonance Ionization Cooling (PIC)*

A linear magnetic transport channel has been designed where a half integer resonance is induced such that the normal elliptical motion of particles in x-x' phase space becomes hyperbolic (Figure 6). The half-integer parametric resonance introduces strong transverse focusing while ionization cooling limits the beam's angular spread with appropriately placed energy absorbers. PIC dynamics is expected to produce final transverse beam emittances that are smaller than the conventional ionization cooling and may offer the potentials either for a higher luminosity and/or a smaller number of muons.

Comparison of cooling factors (ratio of initial to final 6D emittance) with and without the PIC condition vs. number of cells indicates an ultimate gain of a more than 10 times of the final invariant emittances. However, provided the maximum value $\Delta\nu_{sc}$ = 0.4 is not exceeded at 250 MeV/c only the reduction of the dedicated number of muons is allowed. In order to increase the event rate, PIC cooling must the introduced after an additional acceleration of the muon momenta for instance to 2.0 GeV/c. .

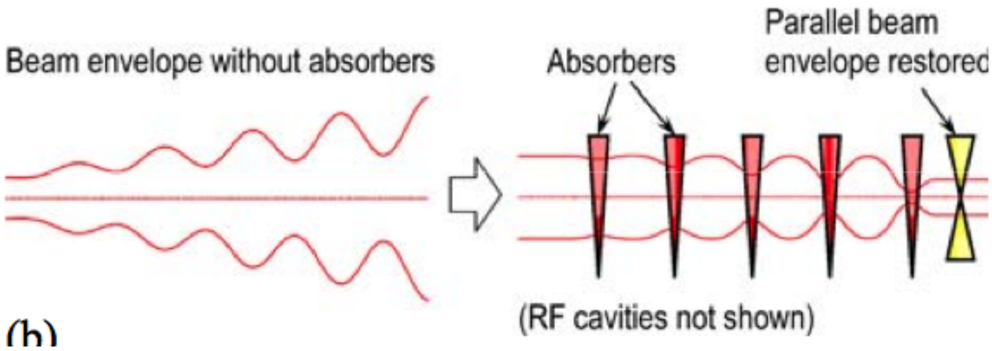


***Figure 6-.*** *Without damping, the PIC beam dynamics is not stable because the beam envelope grows with every period. Energy absorbers at the focal points stabilize the beam through the ionization cooling,*

### *6.- The Initial Cooling Experiment.*

With its remarkably small ring conference of about 45 meters, the Initial Cooling Experiment will require a much less intense muon beam and it can be realized at a far modest cost. The main goal of this experimental R&D program is to develop the muon Ionization Cooling hardware-wise to the point where a complete channel can be confidently designed. It may expand with a more elaborate setup the already approved MICE experiment under development at the Rutherford Appleton Laboratory, UK, a single lattice cell cooling by about 10% and expected to be operational by 2020, Several European laboratories, like for instance in the UK, Switzerland, France, CERN or Sweden (Lund) could be considered for a location of the Initial Cooling Experiment.

One may select a ≈ 100 ns long standard proton ESS LINAC pre-pulse of about 3 x $10^{11}$ protons at a repetition rate of a few seconds The proton target may be located very close to the cooling ring. Secondary particles of a nominal momentum of about 250 MeV/c are injected with a kicker magnet. The transition form pions to muons occurs almost entirely in less than one turn, accumulating forward muons of near momenta. The resulting accumulated $\mu^-$ rate at 250 MeV/c within ± 20 MeV/c window is estimated in about $10^{-4}$ the number of protons, corresponding to an initial population of 3 x $10^7$ $\mu^-$/pulse. The $\mu^+$/pulse rate is about twice this value. In its simplest configuration, cooling is realized with RF cavities at 20 MeV/m, occupying about 30 m corresponding to an acceleration of 600 MeV/turn.

A set of slightly bent solenoidal fields with alternate polarities, the so called "RFOFO" arrangement has been chosen. RF cavities may be either under vacuum or pressurized At 50 atm and 77 K, $H_2$ density is about 21.5% of L-$H_2$ and gradients of up to 330 MV/m. Individual bunches are phase rotated after initial cooling to lower their momentum spreads, followed by a 5 MHz RF to phase rotate the train into a single bunch that then can be re-captured using the high frequency RF.

After a specified number of turns, the muon beam will be extracted with the help of a second pulse of the kicker and momenta and directions will be fully analyzed in an elaborate external spectrometer channel.

## *7.- Concluding remarks.*

The experimental realization of the presently described $\mu^+\mu^-$ Ring Collider may represent the most attractive addition of the future programs on the Standard Model to further elucidate the physics of the $H^o$, requiring however a substantial amount of prior R&D developments, which must be experimentally confirmed by the help of the Initial Muon Cooling Experiment(al) program.

As a summary the full configuration of this project is briefly summarized. The ($\mu$+ $\mu$-) configuration should extend the proton beam at the ESS with additional 5 MWatt and a +4% duty cycle between 2.0 GeV and 3.5 GeV k.e. Two successive rings, the accumulator and the compressor, bring at 56 ev/s and $10^{15}$ p/p the resulting few ns wide proton bunches. Pions decay to muons after a heavy Z target with a longitudinal field of 20 Tesla progressively brought down to about 2 Tesla. A strong correlation generated between momentum and time, is used with the combined linear Front End with adequate RF to compress the muon beam momentum width to about 10%. A robust 6D Cooling with two "RFOFO" rings of opposite signs produces two short single muon bunches at 250 MeV/c. The muon bunches are finally accelerated either to $\sqrt{s}$ = 125.5 TeV or later at $\sqrt{s}$ = 0.5 TeV with multiple traversals in both directions in a single recirculating LINAC and produce an adequate Higgs related rate in the Muon Collider with a high magnetic field, small size and two collision points.

Compared to other alternatives, the advantages of such an appropriate $\mu^+\mu^-$ Ring Collider, even without PIC, are mainly the following:

- Larger cross section $\sigma$ ($\mu^+\mu^- \rightarrow H$) = 22 pb in s-channel $H^o$ resonance with both BES and ISR effects included and energy resolution R = 0.003 %.
- Small size footprint: it may fit in the ESS site
- Cost so far unknown but far smaller than for instance the ILC.
- No synchrotron radiation and beamstrahlung problems
- Precise measurements of line shape and decay width $\Gamma$
- Exquisite measurements of all channels and tests of SM up to 0.5 TeV
- A lower cost demonstration of Muon Cooling to be done first.

To conclude – in addition to the HL-LHC – the ESS may become the highlight project for the further studies of the Higgs sector in Europe.

## *8.- References.*

The comprehensive quotations of all numbered references are far too extensive to be included within the prescribed ten pages document. Complete list of the related subject are available in the enclosed Addendum.