Muon cooling
for the Higgs Factory?

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The myth of symmetry breaking at TeV scale

- It had been widely argued by very influential theorists that “new physics” must also necessarily appear at the TeV scale, one of the main reasons for arguing for the necessity of a nearby SUSY.
- This was based on the argument that the otherwise divergent self-interaction of the Higgs sector does require a cutoff at the TeV scale.
- However, this does not hold for the recently observed Higgs mass of 125 GeV, since now stability conditions may allow without novelties a legitimate cutoff up to the Planck Mass.
- Thus, there may be only one standard model (SM) Higgs to be confirmed experimentally and no need of the “no fail theorem”.

Frascati_December2014
The future of LHC/Higgs

- During the next twenty years (!) CERN plans to pursue the hadronic production of the Higgs related sector and of the possible existence of SUSY. The existence of additional Higgs particles is assumed as unlikely within the LHC energy range.

- Therefore studies will concentrate on the properties of the already discovered mass. The High Luminosity-LHC will already be a sort of “Higgs factory”, able to perform relatively accurate (typically ± 10%) measurements.

- There are plenty of opportunities to check the couplings since a 125 GeV SM Higgs boson has several substantive branching fractions: $B(\text{bb})$ 60%, $B(\text{WW})$ 20%, $B(\text{gg})$ 9%, $B(\text{tt})$ 6%, $B(\text{ZZ})$ 3%, $B(\text{cc})$ 3%, etc.

- $B(\gamma\gamma)$ with 0.2% is also substantive due to the high mass resolution and relatively low background.
In particular, like in the case of the Z₀, the determination of the H₀ width will be crucial in the determination of the nature of the particle and the underlying theory: the SM prediction is only ≈4 MeV, a formidable task!

Cross section is shown here, convoluted with a Gaussian beam distribution.

Signal is not affected only if the rms beam energy width is ≤ a few MeV.
Possible alternatives

- What precision is needed in order to search for possible additional deviations from the SM, under the assumption that there is no other additional “Higgs” state at the LHC?

- Predicted ultimate LHC accuracies for “exotic” alternatives

<table>
<thead>
<tr>
<th></th>
<th>$\Delta hVV$</th>
<th>$\Delta h\bar{t}t$</th>
<th>$\Delta hbb$</th>
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</thead>
<tbody>
<tr>
<td>Mixed-in Singlet</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Composite Higgs</td>
<td>8% tens of %</td>
<td>tens of %</td>
<td></td>
</tr>
<tr>
<td>Minimal Supersymmetry</td>
<td>&lt; 1%</td>
<td>3%</td>
<td>10%(^a)</td>
</tr>
<tr>
<td>LHC 14 TeV, 3 ab(^{-1})</td>
<td>8%</td>
<td>10%</td>
<td>15%</td>
</tr>
</tbody>
</table>

R.S. Gupta et al.

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{hTT}}{g_{h_{SM}TT}} \approx 1 + 1.7% \left( \frac{1 \text{ TeV}}{m_A} \right)^2$$

$$\frac{g_{hff}}{g_{h_{SM}ff}} \frac{g_{hVV}}{g_{h_{SM}VV}} \approx 1 - 3% \left( \frac{1 \text{ TeV}}{f} \right)^2$$

$$\frac{g_{hgg}}{g_{h_{SM}gg}} \approx 1 + 2.9% \left( \frac{1 \text{ TeV}}{m_T} \right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \approx 1 - 0.8% \left( \frac{1 \text{ TeV}}{m_T} \right)^2$$

Ultimate at LHC
$1 \text{ ab} = 10^{-42} \text{ cm}^2$

SUSY $\tan(\beta) > 5$

Composite Higgs

Top partners

- Sensitivity to “TeV” new physics for “5 sigma” discoveries may need per-cent to sub-per-cent accuracies on rates.
The Higgs particle after the CERN-LHC
The scalar sector is definitely one of the keys to the future understanding of elementary particle physics. After the p-pbar discovery of the $Z^0$, the detailed studies at LEP and SLAC in very clean conditions have been a necessary second phase.

A similar second phase may be also necessary for the $H_0$. In the case of the $H_0$, it would be necessary to produce a very large number of events/year in very clean experimental conditions. Two future alternatives are hereby compared:

- $e^+e^-$ collider at $L > 10^{34}$ and a $Z+H_0$ signal of $\approx 200$ fb. The circumference of a new, LEP-like ring is of about $\approx 80$ km.
- $\mu^+\mu^-$ collider at $L > 10^{32}$ and a $H_0$ signal of $\approx 20'000$ fb in the s-state. The collider radius is much smaller, only $\approx 50$ m, but the novel “muon cooling” is necessary.
The first option: a huge $e^+ e^-$ LEP like ring.

Options for circular $e^+ e^-$ Higgs factories are becoming popular around the world.

F. Zimmerman
Super Tristan

80 km ring in KEK area

12.7 km
TLEP tunnel in the Geneva area

«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG
Requirements for the Higgs with a $e^+e^-$ collider

- The luminosity is pushed to the beam-strahlung limit.
- Collisions are at an angle, but with fewer bunches than for a B-Factory: a nano-beam scheme
- Luminosity (several $\times 10^{34}$ cm$^{-2}$ s$^{-1}$), costs and power consumption ($\approx$100 MW) are comparable to those of a linear collider ILC.
- In order to reach luminosity (factor $\approx$ 1000 x LEP2) and power consumptions (factor 5 x LEP2) the main cures are
  - Huge ring (80 km for SuperTristan or for T-LEP)
  - Extremely small vertical emittance, with a beam crossing size the order of 0.01 $\mu$ (it has been 3 $\mu$ for LEP2)
- The performance is at the border of feasibility ($E_{cm} \approx$ 250 GeV).
- However the $H_0$ width of $\approx$4.0 MeV cannot be detected.
Linear collider and circular ring have comparable costs and power consumptions. The more conservative ring alternative is preferred.
The second option: a $\mu^+\mu^-$ collider?

- The direct $H^o$ cross section is greatly enhanced in a $\mu^+\mu^-$ collider when compared to an $e^+e^-$ collider, since the $s$-channel coupling to a scalar is proportional to the lepton mass.

- Like in the well known case of the $Z^0$ production, the $H^o$ scalar production in the $s$-state offers conditions of unique cleanliness.

- An unique feature of such process — if of an appropriate luminosity — is that its actual mass, its very narrow width and most decay channels may be directly measured with accuracy.

- Therefore the properties of the Higgs boson can be detailed over a larger fraction of model parameter space than at any other proposed accelerator method.

- A particularly important conclusion is that it will have greater potentials for distinguishing between a standard SM and the SM-like $H^o$ of SUSY or of other than any other collider.
A muon collider with adequate muon cooling and \( L > 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \).

- Decay electron backgrounds are important: \( 2 \times 10^{12} \mu^\pm \) decays produce \( 6.5 \times 10^6 \) collimated \( e^\pm \) decays/meter with \( E_{\text{ave}} \approx 20 \text{ GeV} \).

- The very narrow resonant signal (4.5 MeV, \( \Gamma/M_H = 3.6 \times 10^{-5} \) for the SM) will dominate over most non resonant backgrounds.
Already at MURA in the fifties it was realised that some beam phase-space compression may be often necessary from the source to the collision point (O'Neill, Piccioni, Symon).

**Liouville theorem:** whenever there is an Hamiltonian (i.e. for a force derivable from a potential) then the six dimensional phase space is preserved, namely, at best $\Delta V/dt = 0$.

Therefore we need some kind of *dissipative non-Liouvillian drag force* working against the particle speed and not derived from an Hamiltonian. Several alternatives are possible:

- **Synchrotron radiation**: but only for electrons and positrons;
- **Electron cooling**: an electron beam bath travelling with a speed equal to the one of the circulating beam (Budker);
- **Stochastic cooling**: statistical fluctuations (Van Der Meer);
- **Ionization cooling**: $dE/dx$ losses are added to the beam.

With any of such methods and with accelerating cavities replacing the losses, one can compress the phase-space volume.
Cooling is essential whenever secondary particles are produced from initial collisions and later accelerated for instance to be accumulated in a storage ring.

A well known case is the one of antiprotons, in which both stochastic and electron cooling have been vastly used. P-pbar colliders have permitted the discoveries of W/Z and the Top.

Ionization cooling is specific for muons, since they have only electromagnetic interactions with matter.

The muon lifetime may be long enough to offer with the help of cooling a reasonable number of $\mu^+\mu^-$ collisions with a collider at the Higgs resonance in the s-state and about 62.5 GeV/beam.

The idea has been discussed by Budker and Skrinsky in the seventies. A comprehensive analysis has been given f.i. by Neuffer in the early nineties.

T. Neuffer Particle Accelerators 1983 Vol. 14 pp. 75-90
This method, called “dE/dx cooling” closely resembles to the synchrotron compression of relativistic electrons — with the multiple energy losses in a thin, low Z absorber substituting the synchrotron radiated light.

The main feature of this method is that it produces an extremely fast cooling, compared to other traditional methods. This is a necessity for the muon case.

Transverse betatron oscillations are “cooled” by a target “foil” typically a fraction of g/cm$^2$ thick. An accelerating cavity is continuously replacing the lost momentum.

Unfortunately for slow muons the specific dE/dx loss is increasing with decreasing momentum. In order to “cool” also longitudinally, chromaticity has to be introduced with a wedge shaped “dE/dx foil”, in order to reverse (increase) the ionisation losses for faster particles.
Early cooling scenarios

Most scenarios during the late nineties were based on single-pass linear cooler, in which a large number of RF cavities restore the energy lost in the low Z absorbers (for instance LH2 or LiH) and in the ionization cooling. However, cooling rings have also been considered. MICE is an ongoing experiment.

MICE

Cooling rings (Balbekov, Palmer)

Guggenheim channel
Previous studies on muon cooling

- Over the past decade, there has been significant progress in developing the concepts and technologies needed to produce, capture, cool and accelerate $O(10^{21})$ muons per year.
- Extensive studies have been performed about 20 years ago in the US and elsewhere and widely discussed in several international workshops.
- Conclusions were that cooling was possible for instance with:
  - A 3 TeV collider and $L = 7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
  - A 600 GeV collider and $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
  - A Higgs factory at 110 GeV and $2.2 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
  - A neutrino factory (NF), where high-energy muons decay to produce an intense beam of neutrinos and antineutrinos
- The recent discoveries of the Higgs particle at 125 GeV and the observation of the $\sin(\theta_{13})$ neutrino oscillation mechanism have strongly revived also the interest for these studies.
A large amount of work already on Higgs factory physics

- D. B. Cline, "Physics potential of a few hundred GeV $\mu^+\mu^-$ collider," Nucl. Instrum. Meth. A350 (1994) 24,
Comprehensive technical reports


The experimental realization of an initial cooling experiment to ensure full 6D cooling of muons
Physics requirements and the studies already undertaken with muon cooling suggest that the next subsequent specific physics programme could be the practical realization of a full scale cooling demonstrator capable of the full cooling capability in three dimensions.

Indicatively this corresponds to the realization of a cascade of unconventional but very small rings of few meters radius, in order to achieve the theoretically expected longitudinal and transverse emittances with asymptotically cooled muons.

In order to demonstrate this “initial cooling experiment” muons may be produced by an existing accelerator at low intensity.

All other conventional facilities, namely (1) the high intensity proton accelerator, (2) the pion/muon production target, (3) the subsequent muon acceleration and (4) the accumulation in a storage ring may be constructed later and only after the success of the initial cooling experiment has been confirmed.
Muon cooling ring: transverse emittance

- The emittance $\varepsilon_N$ evolves whereby $dE/dx$ losses are balanced by multiple scattering (Neuffer and McDonald):

$$\frac{d\varepsilon}{dz} \approx \frac{\varepsilon dE}{\beta^2 E dz} + \frac{\beta^* (13.6)^2}{2\beta^3 E m_\mu X_o} \to 0$$

\[\beta^* = \text{beta at cross}\]
\[m_\mu \beta_\mu = \text{mu values}\]
\[X_o = \text{Rad. Length}\]
\[dE/dz = \text{ioniz. Loss}\]

- The cooling process will continue until an equilibrium transverse emittance has been reached:

$$\varepsilon_N \to \frac{\beta^* (13.6 \text{ MeV/c})^2}{2\beta_\mu m_\mu} \frac{1}{(X_o dE/dz)}$$

- The equilibrium emittance $\varepsilon_N$ and its invariant $\varepsilon_N/\beta_\gamma$ are shown as a function of the muon momentum.

- For $H_2$ and $\beta^* = 10 \text{ cm}$, $\varepsilon_N/\beta_\gamma \leq 700 \text{ mm mr}$ from 80 to 300 MeV/c

- For a 125 GeV collider and $\beta^* = 5 \text{ cm}$
  bunch equil. transverse size is $\approx 240 \mu$
Muon cooling ring: longitudinal emittance

- **Longitudinal** balance is due to heat producing straggling balancing $dE/dx$ cooling. A $dE/dx$ radial wedge is needed in order to exchange longitudinal and transverse phase-spaces.

- Balancing heating and cooling for a Gaussian distribution limit:

$$\frac{d(\Delta E)^2}{dz} = -2(\Delta E)^2 \left[ f_A \frac{d}{dE} \left( \frac{dE_o}{ds} \right) + f_A \frac{dE}{ds} \left( \frac{d\delta}{dx} \right) \frac{\eta}{E\delta} \right] + \frac{d(\Delta E)^2}{straggling dz}$$

  - $dE/dz = f_A dE/ds$, where $f_A$ is the fraction of the transport length occupied by the absorber, which has an energy absorption coefficient $dE/ds$
  
  - $\eta$ is the chromatic dispersion at the absorber and $\delta$ and $d\delta/dx$ are the thickness and radial tilt of the absorber

  - the straggling (H2) is given by

$$\frac{d(\Delta E)^2}{straggling dz} = \frac{\pi \left( m_ec^2 \right)^2 (\gamma^2 + 1)}{4\ln(287)\alpha X_o}$$
The thickness of the absorber must vary with the transverse position, producing the appropriate the energy dependence of energy loss, resulting in a decrease of the energy spread.

Energy cooling will also reduce somewhat the transverse cooling, according to the Robinson’s law on sum of damping decrements.

Energy equilibrium spread for liquid H₂ (McDonald):

\[
(\Delta E)^2 = \frac{1.1\text{MeV}^2\gamma^3\beta^4(\gamma^2 + 1)}{\left(1 - \frac{\gamma^2}{12}\right)}
\]

A fast dependence from \(p_\mu\):

- \(p_\mu \approx 220\text{ MeV/c}, \Delta E_{\text{rms}} \leq 10\text{ MeV}\)
- \(p_\mu \approx 85\text{ MeV/c}, \Delta E_{\text{rms}} \leq 1\text{ MeV}\)
- \(p_\mu \approx 50\text{ MeV/c}, \Delta E_{\text{rms}} \leq 0.35\text{ MeV}\)

At an optimal muon producing momentum the energy spread is too wide for the Ho width!
The initial cooling experiment

- A single sign muon cooling arrangement with two rings, either $\mu^+$ or $\mu^-$ is required and with few particles.
- A low intensity pion-$\rightarrow$ muon beam is produced from an appropriate accelerator in the form of a very short pulse.

Diagram:

- Cooling ring
  - $<p_\mu> \approx 250$ MeV/c
  - $<p_\mu> \approx 80$ MeV/c

- Decay channel
  - $\pi^+ \rightarrow \mu^+$

- Low $\beta$ channel
  - $250 \rightarrow 80$ MeV/c

- To 6D analysis of decay muons
The proposed initial cooling experiment

- A first “wide band” cooling ring must collect the widest muon spectrum peaked around 200 – 400 MeV/c and to introduce a first major reduction in the transverse and longitudinal emittances (but still with $\Delta E_{\text{rms}} > 10$ MeV), namely:
  
  - solenoids instead of quadrupoles have a wider acceptance
  - with a few turns, only integer resonances are harmful
  - As a first cooler, the ionization absorber does not have to be made with LH$_2$: other solid materials (LiH) may be used.

- An intermediate LH$_2$ absorber $\approx 3$ m long inside a low $\beta^*$ channel reduces the vector muon momenta by range.

- The resulting beam must then be extracted and its momentum substantially reduced to about 50-80 MeV/c.

- A second “deep freezer” cooling ring must ensure an adequate asymptotic beam straggling with $\Delta E_{\text{rms}} \leq 1$ MeV
Examples of wide angle cooling rings

- Some practical but still conceptual descriptions of RFOFO ring coolers by Balbekov and by Palmer
- The average muon momentum is 220 MeV/c and the approximate diameter $\approx 10$ m.
- Acceptance $\approx \pm 20\%$

![Diagram of RFOFO Ring Parameters]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>33 m</td>
</tr>
<tr>
<td>Cells</td>
<td>12</td>
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<tr>
<td>Max Bz</td>
<td>2.7 T</td>
</tr>
<tr>
<td>Coil Tilts</td>
<td>2.6 deg.</td>
</tr>
<tr>
<td>Ave Momentum</td>
<td>220 MeV/c</td>
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<tr>
<td>Min Trans. Beta</td>
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<tr>
<td>Dispersion</td>
<td>8 cm</td>
</tr>
<tr>
<td>Wedge Absorber Material</td>
<td>H$_2$</td>
</tr>
<tr>
<td>Central thickness</td>
<td>28.6 cm</td>
</tr>
<tr>
<td>Wedge angle</td>
<td>100 deg.</td>
</tr>
<tr>
<td>RF Cavities/cell</td>
<td>6</td>
</tr>
<tr>
<td>Frequency</td>
<td>201.25 MHz</td>
</tr>
<tr>
<td>Gradient</td>
<td>12 MV/m</td>
</tr>
</tbody>
</table>
A straightforward design for the achromatic cooling ring

- A realistic study is the one of Garren et al. (NIM, 2011).
- The four-sided ring has four 90° arcs with 8 dipoles separated by solenoids.
- Arcs are achromatic both horizontally and vertically. The dispersion is zero in the straight sections between the arcs.
- Injection/extraction kickers are used in a straight section; a superconducting flux pipe is used for the injected beam.
From the initial cooling experiment to a milli-mole of cooled muons
From the initial cooling experiment to the final setup.

\[ \Delta p = m \varepsilon_n / L_b \approx 1 \text{ MeV/c} \]

- The intensity may be further increased by constructing a stack of several superimposed PS-Booster like cooling rings.
- Separate momentum windows are matched to rings with \( \text{dE/dx} \).

Bunch length \( L_b = \pm 0.4 \text{ m} \).

\[ L \text{H}_2 \text{ absorber} \]

\[ \text{Cooling ring} \]

\[ <p_\mu > \approx 250 \text{ MeV/c} \]

\[ <p_\mu > \approx 80 \text{ MeV/c} \]

Separate momentum windows are matched to rings with \( \text{dE/dx} \).
Two main physics initiatives

- The achievable equilibrium emittances can be compared with the expectations of two main physics alternatives:
  - **(A) multi TeV muon collider** at \( L > 10^{34} \) and with large \( dp/p \approx 2 \% \). The equilibrium emittances are too large transversely and too small longitudinally. This can be compensated with a final cooling with 50 T solenoids.
  - **(B) 125 GeV Higgs factory**, with extremely small \( dp/p \approx 10^{-4} \% \). Transverse and longitudinal cooling are acceptable.

A high-intensity $H^-$ source to a $p$-compressor ring

- A tight $p$ bunch may be realized with the help of an accumulation storage ring, starting from the $H^-$ beam produced by a LINAC and stripped to $p$ in order to produce a number of short pulses finally condensed into a single short bunch.

### Linac beam data

<table>
<thead>
<tr>
<th>Proton Energy:</th>
<th>2</th>
<th>8</th>
<th>16</th>
<th>20</th>
<th>GeV</th>
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<tbody>
<tr>
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<td>5</td>
<td>5</td>
<td>5</td>
<td>MWatt</td>
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<tr>
<td>Protons/s:</td>
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<td>3.91E+15</td>
<td>1.95E+15</td>
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</tr>
<tr>
<td>Repetition rate:</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>s-l</td>
</tr>
<tr>
<td>Protons/pulse:</td>
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<td>1.30E+14</td>
<td>1.04E+14</td>
<td></td>
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<tr>
<td>pi+/p (50-800 MeV/c):</td>
<td>4.27E+13</td>
<td>1.04E+14</td>
<td>1.09E+14</td>
<td>1.01E+14</td>
<td></td>
</tr>
<tr>
<td>pi-/p (50-800 MeV/c):</td>
<td>2.19E+13</td>
<td>1.02E+14</td>
<td>9.64E+13</td>
<td>9.48E+13</td>
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<tr>
<td>mu+/p (150-300 MeV/c):</td>
<td>8.54E+12</td>
<td>2.08E+13</td>
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<td>2.02E+13</td>
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<tr>
<td>mu-/p (150-300 MeV/c):</td>
<td>4.38E+12</td>
<td>2.03E+13</td>
<td>1.93E+13</td>
<td>1.90E+13</td>
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<tr>
<td>Protons/y (1y=10^7 s):</td>
<td>1.56E+23</td>
<td>3.91E+22</td>
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<tr>
<td>mu+/y (150-300 MeV/c):</td>
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<td>3.13E+21</td>
<td>3.28E+21</td>
<td>3.03E+21</td>
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<tr>
<td>mu-/y (150-300 MeV/c):</td>
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<td>3.05E+21</td>
<td>2.89E+21</td>
<td>2.84E+21</td>
<td></td>
</tr>
</tbody>
</table>
A high field 20-T solenoid should collect secondary particles at about 100 mr off-axis angle to separate protons from pions. The MERIT/CERN experiment has successfully injected a Hg-jet into a 15-T solenoid.

The best focussing is realized with secondaries in a axially symmetric solenoidal field following the Bush theorem. Particles of both signs are focussed and they can then be later separated magnetically. By reducing the field the rotational motion is converted into the longitudinal one, according to $p_\perp = p_\perp^o \sqrt{B/B_o}$ and $p_\perp$ is reduced correspondingly. Therefore $<p_\perp> \approx 150 \text{ MeV}/5 \approx 30 \text{ MeV}/c$

<table>
<thead>
<tr>
<th>Nominal muon data</th>
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<tbody>
<tr>
<td>Momentum:</td>
</tr>
<tr>
<td>Kinetic Energy:</td>
</tr>
<tr>
<td>Beta:</td>
</tr>
<tr>
<td>Gamma:</td>
</tr>
<tr>
<td>Lifetime:</td>
</tr>
<tr>
<td>Mu decay length:</td>
</tr>
<tr>
<td>Tranverse</td>
</tr>
<tr>
<td>Average $p_t$, at target:</td>
</tr>
<tr>
<td>Rms angle:</td>
</tr>
<tr>
<td>Length, at target:</td>
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<td>Radius, at target:</td>
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<tr>
<td>Emittance:</td>
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<td>Normalized transv. emitt:</td>
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<td>Longitudinal</td>
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<td>Nominal $p$:</td>
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<tr>
<td>Spread, delta$p$:</td>
</tr>
<tr>
<td>Min. $p$:</td>
</tr>
<tr>
<td>Max. $p$:</td>
</tr>
<tr>
<td>Bunch, 1/2 length:</td>
</tr>
<tr>
<td>Normalized long. emitt:</td>
</tr>
</tbody>
</table>
Matching cooling rings to proton beam

- The muon spectrum for cooling must be optimized with the energy spectrum as produced by the high energy protons.
- Muons will be produced by an appropriate high power proton accelerator of a few GeV kinetic energy. The resulting optimum muon momentum is in the order of 200-500 MeV/c.
- For protons of above a few GeV, secondary spectra are roughly proportional to the actually produced beam power.
- In order to match the $p_\mu$ production to an acceptable smaller $\Delta p_\mu$ spread in the cooling ring, a first, an early "Liuvillian" compression can be performed with the help of a dEdx compensating wedge.

From wide $\Delta p$ and narrow $\varepsilon_0$ to narrow $\Delta p$ and wide $\varepsilon_0$
From the fully cooled muons to the final storage ring
In order to realize a Higgs Factory at the known energy of 125 GeV, an acceleration system is progressively rising the energy of captured muons to $m_{H_0}/2$, with the help of a series of several recirculating RLAs.

Adiabatic longitudinal Liouvillian damping from $p_i = 0.22$ GeV/c to $p_f = 62.5$ GeV/c (a factor $(p_f/p_i)^{1/4} = 4.92$), is increasing the final momentum spread $\Delta p_f$ to $0.927 \times 4.92 = 4.56$ MeV/c and reducing the bunch length $L_{b,f} = \pm 0.4/4.92 = \pm 0.081$ m.

Recirculating energy gain/pass = $62.5/8 = 7.75$ GeV
Collider low beta structure

- Lattice structure at the crossing point, including local chromaticity corrections with $\beta_x = \beta_y = \beta^* = 5$ cm.

Ankenbrandt et al. (1999)
Estimated performance of the $H^0$-factory ($r \approx 50$ m)

- Two asymptotically cooled $\mu$ bunches of opposite signs collide in two low-beta interaction points with $\beta^* = 5$ cm and a free length of about 10 m, where the two detectors are located.

- The bunch transverse rms size is 0.2 mm and the $\mu-\mu$ tune shift is 0.086.

- A luminosity of $0.6 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ is achieved with $6.1 \times 10^{12} \mu/\text{bunch}$.

- The SM Higgs rate is $\approx 4400$ ev/year in each detector. Higher rates ($\times 4$) are possible stacking two superposed cooling rings.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton accelerator rate:</td>
<td>15.00 s⁻¹</td>
</tr>
<tr>
<td>Proton beam power</td>
<td>5.0 MWatt</td>
</tr>
<tr>
<td>Higgs mass</td>
<td>125 GeV/c2</td>
</tr>
<tr>
<td>Final momentum</td>
<td>62.50</td>
</tr>
<tr>
<td>Final gamma</td>
<td>589.6</td>
</tr>
<tr>
<td>Final lifetime</td>
<td>1.295 ms</td>
</tr>
<tr>
<td>Mu decay length</td>
<td>388.6 km</td>
</tr>
<tr>
<td>Average number of turns</td>
<td>1110.</td>
</tr>
<tr>
<td>Collider circumference:</td>
<td>350.0 m</td>
</tr>
<tr>
<td>Input muon momentum</td>
<td>220 MeV/c</td>
</tr>
<tr>
<td>Input momentum spread</td>
<td>± 20 %</td>
</tr>
<tr>
<td>Cooled momentum</td>
<td>80 MeV/c</td>
</tr>
<tr>
<td>Transverse inv. emittance cooled</td>
<td>0.4600 $\pi \text{ mmrad}$</td>
</tr>
<tr>
<td>Longitudinal inv. emittance cooled</td>
<td>3.500 $\pi \text{ mm rad}$</td>
</tr>
<tr>
<td>Initially produced muons/bunch</td>
<td>2.032 E+13 %</td>
</tr>
<tr>
<td>Cooled surviving fraction</td>
<td>30.0 %</td>
</tr>
<tr>
<td>Colliding muons/bunch</td>
<td>6.09 E+12</td>
</tr>
<tr>
<td>Bunch trans. rms size</td>
<td>197.5 microns</td>
</tr>
<tr>
<td>No effective luminosity turns</td>
<td>555.2</td>
</tr>
<tr>
<td>Crossings/sec: (at 15 Hz)</td>
<td>8328.</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.63 E+32 cm⁻² s⁻¹</td>
</tr>
<tr>
<td>$H_\phi$ cross section</td>
<td>2.000E-35 cm²</td>
</tr>
<tr>
<td>$H_\phi$ events/y (10^7 s)/ each cross</td>
<td>12610 (*)</td>
</tr>
<tr>
<td>Tune shift</td>
<td>0.0864 cm</td>
</tr>
<tr>
<td>Final bunch half-length</td>
<td>9.743 cm</td>
</tr>
<tr>
<td>Final $\Delta p$ muon</td>
<td>3.808 MeV</td>
</tr>
<tr>
<td>Final $\Delta p$ muon</td>
<td>6.093E-03 %</td>
</tr>
<tr>
<td>rms $\Delta E$ of $H_\phi$ resonance</td>
<td>8.616E-05 MeV</td>
</tr>
<tr>
<td>Beam-beam intrinsic rms width</td>
<td>5.385 MeV</td>
</tr>
<tr>
<td>Rms beam-beam signal surviving</td>
<td>35.0 %</td>
</tr>
</tbody>
</table>

(*) at zero beam-beam rms width
Conclusions

- The recent discovery of the Higgs particle of 125 GeV at CERN has highlighted the unique features of the direct production of a H$^0$ scalar in the s-state, in analogy with the two steps of the Z with the PbarP and LEP programmes and where the mass, total and partial widths of the H$^0$ can be directly measured with a remarkable accuracy and a very large number of events.

- **A high energy $\mu^+\mu^-$-collider is the only possible circular high energy lepton Higgs collider that can be easily situated within the existing CERN (or FNAL) sites.**

- **A first step to could be the practical and experimental realization of a full scale cooling demonstrator**, a relatively modest and low cost system but capable to conclusively demonstrate “ionization cooling” at the level required for a Higgs factory and eventually as premise for a subsequent multi-TeV collider and/or a long distance $\nu$ factory.
The full realization of this Muon Factory requires two major and subsequent steps, namely

- its 6D phase compression to a specified amount $\varepsilon_{6D} \approx 10^{-6}$ based on the demonstration of the initial cooling experiment with a chain of very tiny “warm” rings, followed by
- the production and collection of a millimole of muons from an appropriate high intensity proton accelerator and
- its acceleration and accumulation in an appropriate cooling ring at 62.6 GeV.

The luminosity may be further increased by constructing a stack of several superimposed PS-Booster like cooling rings and different pion momentum windows (Luminosity $\ll N^2$).

The conventional facilities to realize the full facility should be constructed only after this “initial cooling experiment” has been conclusively demonstrated, eventually at a different location.
Thank you!
The First Muon Collider (?)
125.5 GeV Higgs

David Neuffer

July 2012
New boson sparks call for 'Higgs factory'

CERN's discovery of a new fundamental particle – most likely a Higgs boson – was barely hours old when physicists speaking at this year’s Lindau Nobel Laureate Meeting in Germany argued the case for a new facility to measure its properties in detail. Speaking out in favour of a new machine was former CERN boss Carlo Rubbia, who shared the 1984 Nobel Prize for Physics for the discovery of the W and Z bosons. "The technology is there to construct a Higgs factory," he claimed. "You don't need €10bn; it could be done relatively cheaply."

"With a Higgs of 125 GeV we need only a modest machine, perhaps not a large linear collider." Rubbia points out that muons colliding at a combined energy of roughly 125 GeV would suffice – just over half the energy of LEP and requiring a machine with a much smaller radius.