A millimole of muons for a Higgs Factory?

Carlo Rubbia

GSSI, L’Aquila, Italy

Institute for Advanced Sustainability Studies
Potsdam, Germany
As well known, CMS and Atlas have observed a narrow line of high significance at about 125 GeV mass compatible with the Standard Model Higgs boson.

Results of both experiments also exclude other SM Higgs bosons from 127 up to approximately 600 GeV.

Observations have been performed in several decay modes, however always in the presence of very substantial backgrounds.

Experimental energy resolutions have been so far much wider of any conceivable intrinsic Higgs width.

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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”.

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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 $Z_0$, the determination of the $H_\circ$ width will be crucial in the determination of the nature of the particle and the underlying theory: the SM prediction is only $\approx 4$ 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 $\leq$ a few MeV.
Alternatives to the Standard Model?

- 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>R.S. Gupta et al.</th>
<th>( \Delta hVV )</th>
<th>( \Delta htt )</th>
<th>( \Delta hbb )</th>
</tr>
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<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%</td>
</tr>
<tr>
<td>LHC 14 TeV, 3 ab(^{-1})</td>
<td>8%</td>
<td>10%</td>
<td>15%</td>
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</table>

\[
\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \approx 1 + 1.7\% \left( \frac{1 \text{ TeV}}{m_A} \right)^2
\]

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

\[
g_{hgg} \quad \frac{g_{h_{SM}gg}}{g_{hgg}} \approx 1 + 2.9\% \left( \frac{1 \text{ TeV}}{m_T} \right)^2,
\]

\[
g_{h\gamma\gamma} \quad \frac{g_{h_{SM}\gamma\gamma}}{g_{h\gamma\gamma}} \approx 1 - 0.8\% \left( \frac{1 \text{ TeV}}{m_T} \right)^2
\]

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 scalar sector is definitely one of the keys to the future understanding of elementary particle physics.

Once the Higgs mass is known, the SM may be entirely defined with the exception of neutrino masses, nature & mixings.

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 phase may be also necessary for the $H_0$.

In the case of the $H_0$, it would be necessary to produce at least $10^4$ events/year in very clean experimental conditions. Two future alternatives are hereby compared:

- A $e^+e^-$ collider at $L > 10^{34}$ and a $Z+H_0$ signal of $\approx 200 \text{ fb}$. The circumference of a new, LEP-like ring is of about $\approx 80 \text{ km}$.

- A $\mu^+\mu^-$ collider at $L > 10^{32}$ and a $H_0$ signal of $\approx 20'000 \text{ fb}$ in the s-state. The collider is much smaller, only $R \approx 50 \text{ m}$, but an appropriate “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
The luminosity has to be 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 (few $\times 10^{34}$), costs and power consumption ($\approx 100$ MW) are comparable to those of the linear collider ILC.

In order to reach luminosity (factor $\approx 1000 \times$ LEP2) and power consumptions (factor $5 \times$ 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 circular ring ($E_{cm} \approx 250$ GeV) performance is at a feasibility borderline. However the $H_{0}$ width cannot be directly 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?

- In a $\mu^+\mu^-$ collider when compared to an $e^+e^-$ collider, the direct $H^0$ cross section is greatly enhanced since the s-channel coupling to a scalar is proportional to the lepton mass ($\sigma \approx m^2$).

- Like in the well known case of the $Z^0$ production, the $H^0$ scalar production in the s-state offers conditions of 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 $H^0$ of SUSY or of other than any other collider.
A $\mu^\pm$ collider with an adequate muon cooling and $L > 10^{32}$ cm$^{-2}$ 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 $E_{\text{ave}} \approx 20$ GeV.
- The resonant signal, if sharp enough (for the SM $4.5$ MeV, $\Gamma/M_H = 3.6 \times 10^{-5}$) 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 forces 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 derivable from an Hamiltonian. Many alternatives are possible:

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

With such methods and with accelerating cavities replacing the momentum, one can compress the phase-space volume.
From antiprotons to muons

- Cooling is of course essential whenever secondary particles are produced from initial collisions and later accelerated and accumulated for instance 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.

- At high energies, muons may be stable enough to offer a (1) reasonable number of $\mu^+ \mu^-$ collisions for the Higgs resonance in the s-state or (2) $\mu \rightarrow e\nu\nu$ decays for a very high intensity, long distance neutrino beam for instance to study CP violation.

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

- 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.
Ionization cooling of muons

- This method, called “dE/dx cooling" closely resembles to the damping 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/cm² thick. An accelerating cavity is continuously replacing the lost momentum.

- Unfortunately for muons with $\gamma < 4$ 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.
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.

During the late ninety, extensive studies have been performed in the US and in several other international workshops and experiments of the MICE collaboration in the UK.

Conclusions were that muon cooling was investigated for:

- A 3 TeV collider and $L = 7 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
- A 600 CeV collider and $L = 10^{33}$ cm$^{-2}$ s$^{-1}$
- A Higgs factory at 110 GeV and $2.2 \times 10^{31}$ cm$^{-2}$ 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

Comprehensive technical reports

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. Cooling rings have also been considered.
Physics requirements and the studies already undertaken with muon cooling suggest that the next step, prior to but adequate for a specific physics programme could be the practical realization of a full scale cooling demonstrator.

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 extracted from an existing accelerator at low intensity.

Initial considerations are going on at INFN/LNF and elsewhere.

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, only after the success of the initial cooling experiment has been confirmed.
The emittance $\varepsilon_N$ evolves whereby $dE/dx$ losses are balanced by multiple scattering (Neuffer and McDonald):

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

$\beta^* = \text{beta at cross}$

$m_\mu, \beta_\mu = \text{mu values}$

$dE/dz = \text{ioniz. Loss}$

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:

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

  - $dE/dz = f_A \frac{dE}{ds}$, 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 ($H_2$) is given by:

    $\frac{d(\Delta E)^2}{dz}_{\text{straggling}} = \frac{\pi (m_e c^2)^2 (\gamma^2 + 1)}{4 \ln(287) \alpha X_o}$
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 H$_2$ (McDonald):

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

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 of 200-300 MeV/c the final energy spread is too wide for the Ho width!
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 cooling is acceptable but longitudinal emittance is much too large.

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. A $\approx 5$ MWatt nominal power and 10-50 cycles/s appear appropriate. 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 ear "Liuvillian" compression can performed with the help of dEdx compensating wedge.

From wide $\Delta p$ and narrow $\varepsilon_o$ to narrow $\Delta p$ and wide $\varepsilon_o$
An adequate configuration is required for the experimentally observed Ho width:

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
- only a few turns are necessary, and only integer resonances should be considered as harmful
- As a first cooler, the ionization absorber does not have to be made with LH$_2$: other solid materials (LiH) may be used.
- If needed, a stack of several independent small rings may be simultaneously operated with different momentum slices and then later merged into a common line.
Comprehensive cooling for the Higgs Factory

- The resulting beam must then be extracted and its momentum substantially reduced to about 50-80 MeV/c.
- An intermediate LH$_2$ absorber $\approx$ 3 m long inside a low $\beta^*$ channel reduces the vector muon momenta by range.
- A second “deep freezer” cooling ring must ensure an adequate asymptotic beam straggling with $\Delta E_{\text{rms}} \leq 1$ MeV

Bunch length $L_b = \pm 0.4$ m,

$\Delta p = m_\mu \varepsilon^z / L_b \approx 1$ MeV/c
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](image)
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.
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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<td>5</td>
<td>MWatt</td>
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<td>15</td>
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<td>s⁻¹</td>
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<td>π⁺/p (50-800 MeV/c):</td>
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<td>μ⁻/y (150-300 MeV/c):</td>
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<td>3.05E+21</td>
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<td>2.84E+21</td>
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</tr>
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</table>
Pion production and decay to muons

- 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 an 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 \( p_\perp = p_\perp^0 \sqrt{B/B_0} \) and \( p_\perp \) is reduced correspondingly. Therefore \( \langle p_\perp \rangle \approx 150 \text{ MeV/5} \approx 30 \text{ MeV/c} \)

<table>
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<th>Nominal muon data</th>
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<tr>
<td>Momentum:</td>
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<td>Kinetic Energy:</td>
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<td>Beta:</td>
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<td>Gamma:</td>
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<td>Lifetime:</td>
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<td>Mu decay length:</td>
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<th>Transverse</th>
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<td>Length, at target:</td>
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<td>Emittance:</td>
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<td>Normalized transv. emitt.:</td>
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<th>Longitudinal</th>
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<td>Spread, ( \Delta p_\perp ):</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>
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 $0.6 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ is achieved with $6.1 \times 10^{12} \mu$/bunch.

- The SM Higgs rate is $\approx 4400$ ev/year in each detector.

<table>
<thead>
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<th>Value</th>
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<tr>
<td>Luminosity:</td>
<td>0.63E+32</td>
</tr>
<tr>
<td>$H_0$ cross section:</td>
<td>2.000E-35</td>
</tr>
<tr>
<td>$H_0$ events/yr ($10^7$ s)/ each cross:</td>
<td>12610 (*)</td>
</tr>
<tr>
<td>Tune shift:</td>
<td>0.0864</td>
</tr>
<tr>
<td>Final bunch half-length:</td>
<td>9.743</td>
</tr>
<tr>
<td>Final $\Delta p$ muon:</td>
<td>3.808</td>
</tr>
<tr>
<td>Final $\Delta p$/muon:</td>
<td>6.093E-03</td>
</tr>
<tr>
<td>$\Delta E/E$ of $H_0$ resonance:</td>
<td>8.616E-05</td>
</tr>
<tr>
<td>Beam-beam intrinsic rms width:</td>
<td>5.385</td>
</tr>
<tr>
<td>Rms beam-beam signal surviving</td>
<td>35.0</td>
</tr>
</tbody>
</table>

(*) at zero beam-beam rms width

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Conclusions

- The development of a new collider will be necessary in order to study LHC potential discoveries beyond the present SM.
- A high energy $\mu^+\mu^-$-collider is the only possible circular high energy lepton collider that can be situated within the CERN or FNAL sites.
- However it requires two major developments, namely
  - the production and collection of a millimole of muons and
  - its 6D phase compression to a specified amount $\epsilon_{6D} \approx 10^{-6}$
- Many (>5?) workshops and a dedicated Intern. Collaboration have been continuing during the last twenty years, with very substantial improvements of the achievable performances.
- These programmes were primarily concentrated on the transverse cooling required in order to achieve the final luminosity for a competitive multi-TeV lepton collider.
The recent discovery of the Higgs particle of 125 GeV at CERN has brought in also the additional requirement of a remarkably small longitudinal emittance.

The unique feature of the direct production of a $H^0$ scalar in the s-state is that the mass, total width and all partial widths of the $H^0$ can be directly measured with remarkable accuracy.

The main innovative component 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 additional but conventional facilities necessary to realize the facility with the appropriate luminosity should be constructed only after the success of this “initial cooling experiment” has been conclusively demonstrated.
Thank you!
New boson sparks call for 'Higgs factory'

Jul 5, 2012  15 comments

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.