A Higgs-Factory $\mu^+\mu^-$ Collider

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ABSTRACT

In the future, the growing evidence for a Higgs scalar sector could require a factory for the copious production of Higgs particles. This could be even more important if the complex SUSY–Higgs scalars exist. It is also possible that the Higgs sector will be only partially resolved at the LHC. We show how a $\mu^+\mu^-$ collider could provide such a factory. Starting from the $\mu^\pm$ source, the collider will only be a fraction of the cost and can be custom designed for the energy range required. We also show that large $\mu^\pm$ polarization is essential for the collider.

I. INTRODUCTION

Recently there has been a great deal of activity concerning $\mu^+\mu^-$ colliders, starting with the Napa workshop in 1992 [1,2]. We have proposed that such a collider is very useful to study the scalar sector of the electroweak interaction [3]. In this brief report, we discuss the arguments for a Higgs factory (Table I).

The strongest argument for the low-energy 250 × 250-GeV collider comes from the growing evidence that the Higgs should exist in this low-mass range from:

1. The original works of Cabibbo and colleagues [4], which shows that, when $m_t > M_Z$ and assuming a grand unification theory (GUT), $M_H < 2\,M_Z$ [4];
2. Fits to LEP data imply that a low mass h^0 could be consistent with $m_t > 150$ GeV [5];
3. The extrapolation to the GUT scale that is consistent with SUSY also implies that one of the Higgs should have a low mass, perhaps below 130–150 GeV [5].

This evidence implies the exciting possibility that the Higgs mass is just beyond the reach of LEP II and in a range that is very difficult for the LHC to detect [6].

Table I: Arguments for a Higgs-factory $\mu^+\mu^-$ collider.

1. The $m_\mu \backslash m_e$ ratio gives coupling 40,000 times greater to the Higgs particle. In the SUSY model, one Higgs $m_h < 120$ GeV!!
2. The low radiation of the beams makes precision energy scans possible.
3. The cost of a "custom" collider ring is a small fraction of the $\mu^\pm$ source.
4. Feasibility report to Snowmass established that $\mathcal{L} \sim 10^{33}$ cm^{-2} s^{-1} is feasible.

We expect the supercollider LHC to extract the signal from background (*i.e.*, seeing either $h^0 \to \gamma\gamma$ or the very rare $h^0 \to \mu\mu\mu\mu$ in this mass range, since $h \to b\bar{b}$ is swamped by hadronic background). However, detectors for the LHC are designed to extract this signal. Figure 1 gives a picture of the various physics thresholds that may be of interest for a $\mu^+\mu^-$ collider. In this low mass region, the Higgs is also expected to be a fairly narrow resonance and, thus, the signal should stand out clearly from the background from

$$\mu^+\mu^- \to \gamma \to b\bar{b} \to Z_{\rm tail} \to b\bar{b} \quad . \tag{1}$$

For masses above 180 GeV, the dominant Higgs decay is

$$h^0 \to W^+W^- \quad \text{or} \quad Z^0Z^0 \quad , \tag{2}$$

and the LHC should easily detect this Higgs particle. Thus the $\mu\mu$ collider is better adapted for the low mass region. The report of Barger *et al.* is very illuminating regarding the physics potential of a $\mu\mu$ collider (see Table II) [5–7].

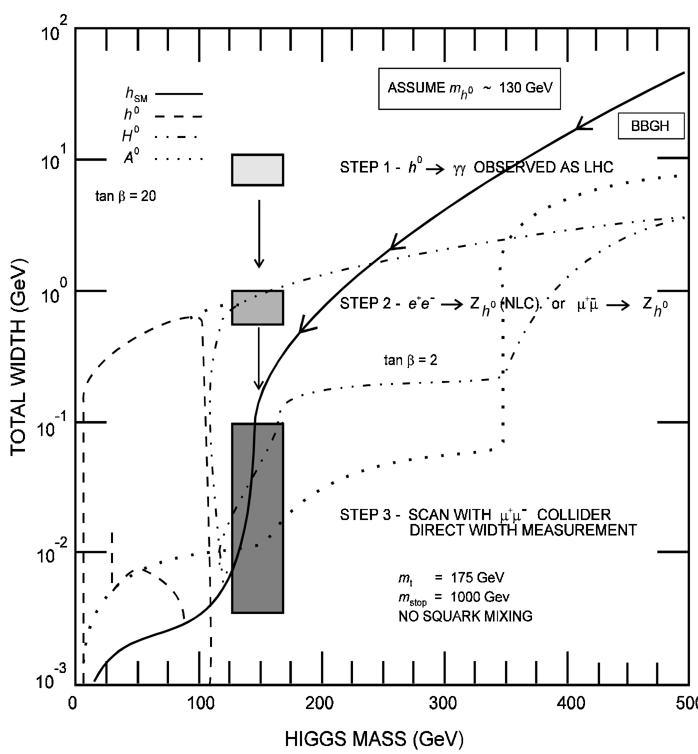

Figure 1: Higgs-factory $\mu^+\mu^-$ collider concept. The Higgs is discovered at the LHC (CMS) and the width further reduced at the NLS or at a $\mu^+\mu^-$ collider. The final stage is to scan for the Higgs at the $\mu^+\mu^-$ collider. Existing models can be distinguished by their widths. {Adapted from [5] (BBGH = Barger, Berger, Gunion, Han) and [8].}

Table II: The scalar sector.

With a high-mass t quark, precision LEP/SLD data and the theorists' dreams of a SUSY world, the scalar (pseudo-scalar sector) is possibly very complex and may require several types of colliders.[7] Consider:

- If the low mass Higgs has $m > 130$ GeV, MSSM is not allowed.
- If $m > 200$ GeV, there are constraints from the requirement that perturbation theory be useful up to very high energy and from the stability of the vacuum.
- If $m < 130$ GeV, MSSM is possibly ok, but we may expect other particles (H, A), and the width of the low mass Higgs may change.
- The scalar sector may be extremely complex, requiring pp (LHC) and $\mu^+\mu^-$ colliders (and possibly NLC and $\gamma\gamma$ colliders).
- In high energy collisions, vector states are allowed unless a special method is used. Consider $\mu^+\mu^-$ colliders with polarized $\mu^\pm$:

$\mu^+\mu^-$	(100–500) GeV – scalars (H, A, ...)	W^+W^-
	$\geq$ 2 + TeV	Z^0Z^0 production in scalars

This cannot be done for pp or e^+e^- colliders.

- A $\mu^+\mu^-$ collider is complimentary to the LHC/CMS detector.

II. SCAN FOR HIGGS MASS AND WIDTH: SUSY OR NOT

In this section, we assume for the sake of argument that the CMS detector at the LHC has barely detected signal at $m \sim 130$ GeV ($h^0 \to \gamma\gamma$) and at an experimental width of ~8 GeV (Step 1, illustrated in Fig. 1). The question will now be

1. Is this a Higgs boson or not?
2. Is it the standard model Higgs or a SUSY Higgs?

We envision the next step would be to construct the $\mu^+\mu^-$ collider operating between the energies of $E_{\mu^+\mu^-} \sim m_{h^0}$ (CMS) and $E_{\mu^+\mu^-} \sim m_z + m_{h^0}$ (CMS) or the use of the NLC to observe $e^+e^- \to Z^0h^0$ [9]. We build the $\mu^+\mu^-$ collider (after already having built a $\mu^\pm$ source), and for Step 2 operate near the $Z^0 + h^0$ (CMS) threshold to determine m_{h^0} and Γ_{h^0} to ~ 1 GeV. (See Fig. 2 for the cross sections). For Step 3, we envision an energy scan of the mass region by varying the $\mu^+\mu^-$ energy [6,8]. At some point, the mass and width are determined and then used to distinguish between the standard model Higgs and a SUSY Higgs (Fig. 3).

The final step is to measure the branching fractions for different decay modes [10]. Figure 4 shows the expectations for the standard model Higgs.

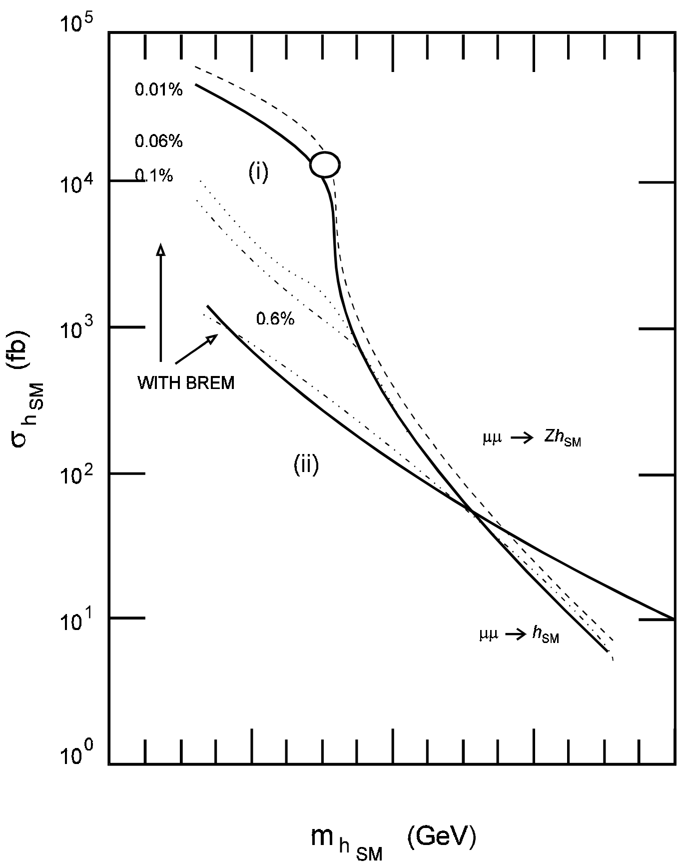

Figure 2. Cross sections versus $m_{h_{SM}}$ for inclusive standard-model Higgs production: (i) the s-channel $\bar{\sigma}_h$ for $\mu^+\mu^- \to h_{SM}$ with R = 0.01%, 0.06%, 0.1%, and 0.6%; and (ii) $\sigma(\mu^+\mu^- \to Zh_{SM})$ at $\sqrt{s} = m_Z + \sqrt{2}\, m_{h_{SM}}$. Also shown is the result for R = 0.01% if bremsstrahlung effects are not included. (Adapted from [5].)

III. POLARIZED COLLIDER

The most interesting question in particle physics now is associated with the origin of mass. It is generally assumed that the exchange of fundamental scalar particles, called the “scalar sector”' is somehow responsible for this. For super-symmetry modes, this scalar sector is even more complex and interesting (see Table II) [11,12].

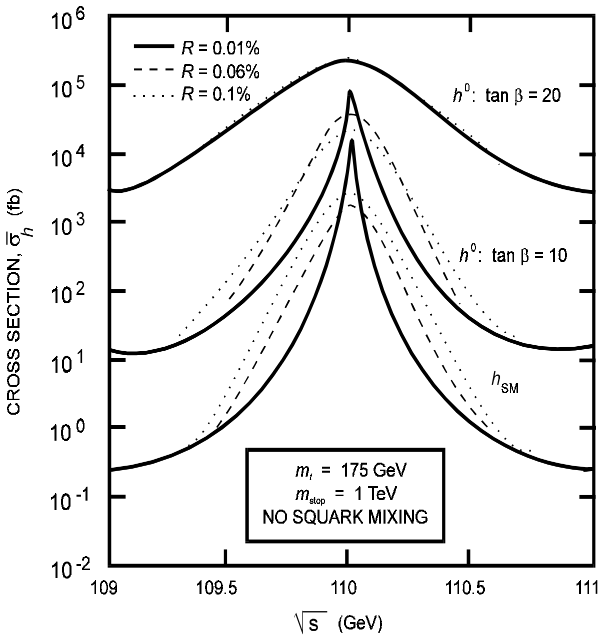

Figure 3. The effective cross section, $\bar{\sigma}_h$, obtained after convoluting σ_h with the Gaussian distributions for R = 0.01%, 0.06%, and 0.1%, is plotted as a function of $\sqrt{s}$ taking m_h = 110 GeV. Results are displayed in the cases h_{SM}, h^0 with tan β = 10 and = 20. In the MSSM h^0 cases, two-loop/RGE-improved radiative corrections have been included for Higgs masses, mixing angles, and self-couplings assuming $m_{\tilde{t}}$ = 1 TeV and neglecting squark mixing. The effects of bremsstrahlung are not included in this figure. (Adapted from [5].)

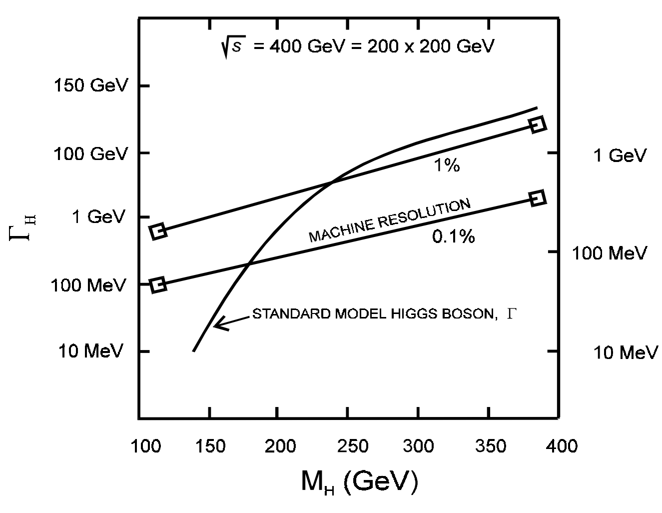

Figure 4. Machine requirements for Higgs scan [11].

In this section, we highlight one of the most interesting goals of a $\mu^+\mu^-$ collider: the discovery of a Higgs boson in the mass range beyond that to be covered by LEP I & II (~ 80–90 GeV) and the natural range of the supercolliders.

There are several ways to determine the approximate mass of the Higgs boson in the future [9]. Suppose it is expected to be at a mass of 135 ± 2 GeV, the energy spread of a $\mu^+\mu^-$ collider can be matched to the expected width (see Fig. 5). An energy scan could yield a strong signal to background especially with polarized $\mu^+\mu^-$ in the scalar configuration [11,12]. Once the Higgs is found, the following could be carried out:

1. Measurement of width, to separate standard model Higgs from SUSY or other Higgs models [4,5],
2. Measurement of the Branching fractions, the rare decay will involve loop effects that can sample very high energies.

Polarization will play an essential role for any $\mu^+\mu^-$ collider [12,13]!

Polarization is natural for $\mu^\pm$ since they are produced in weak decays and are initially fully polarized because of this $V-A$ interaction. There are three proposed methods for producing intense polarized $\mu^\pm$ beams:

- Accelerate polarization and cool the $\pi^\pm$ (A. Skrinsky *et al.*) [14],
- Use $K^\pm$ decays and "narrow-band neutrino-like beam,"
- Use pion decays and a short proton bunch [8].

Figure 5 shows the tradeoff between intensity and polarization in one of these schemes [8,12,14]. This is one of the major areas of research for $\mu^+\mu^-$ colliders.

IV. SOME EXAMPLES OF POSSIBLE $\mu^+\mu^-$ COLLIDERS FOR HIGGS FACTORIES

At this meeting, the U.S. $\mu^+\mu^-$ collider consortium presented a feasibility design of a $\mu^+\mu^-$ collider [8]. The important point is that $\mathcal{L} \sim 10^{33}$ cm^{-2} s^{-1} was shown to be possible for this collider. We consider this an existence of proof of sorts. This collider is complex, the simplest part being the actual storage ring for the $\mu^+\mu^-$ collisions. It is important to note that this collider ring is likely a minor part of the cost of the overall complex.

There are other possible $\mu^+\mu^-$ collider designs that may serve as a Higgs factory. These designs differ by either the assumptions about the $\mu^\pm$ cooling method or the type of overall collider. Figure 6 shows a schematic design for a $\mu^+\mu^-$ collider in Japan that uses the high-current 50-GeV accelerator now being designed for KEK [15]. The cooling method is by frictional cooling of low-energy $\mu^\pm$ beams.

Figure 7 shows a scheme worked out by the author and A. Bogacz, which uses crystal channeling for both the cooling and the collisions [16]. In the latter case, if the $\mu^\pm$ can be confined to a crystal channel (~ 10–30 Å) then high luminosity can be achieved using modest $\mu^\pm$ intensities, greatly reducing the background and possible cost of the Higgs factory.

A hypothetical schedule for a Higgs-factory $\mu^+\mu^-$ collider is given in Table III, which is of course entirely the author's own viewpoint.

I wish to thank members of the CMS collaboration, the U.S. $\mu^+\mu^-$ Consortium, and V. Barger, J. Gunion, and T. Han for helpful comments.

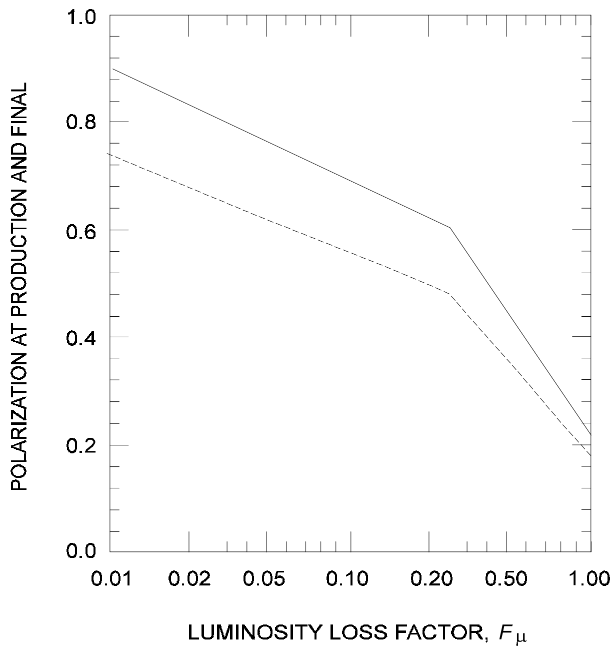

Figure 5: Polarization versus the fraction, F_μ, of muons accepted (solid line: polarization at source; dashed line: after cooling) [7].

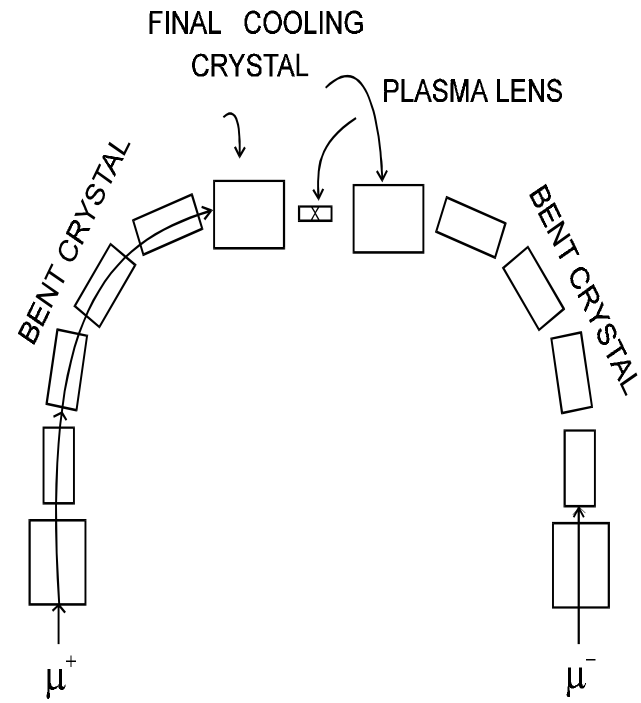

Figure 7: Crystal quantum collider concept [16].

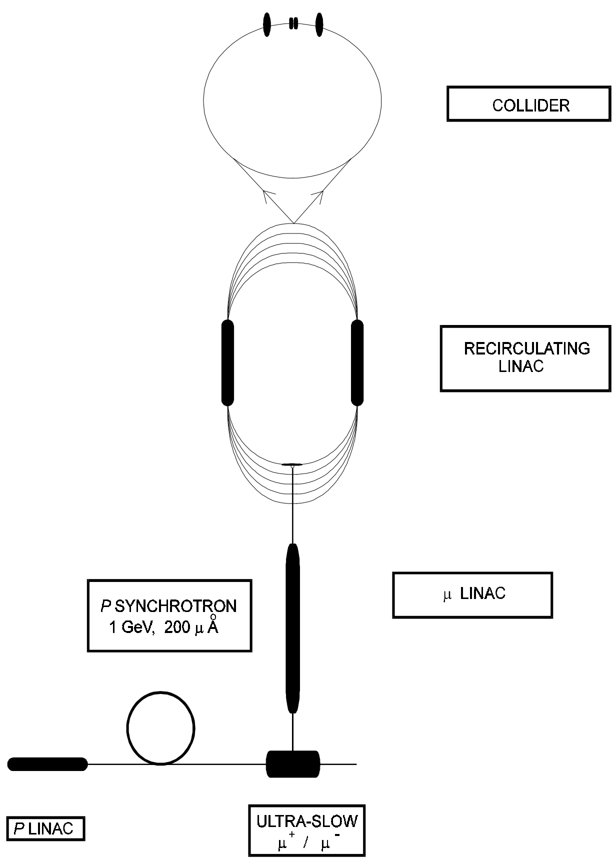

Figure 6: Japanese $\mu^+\mu^-$ collider concept [15].

Table III. Possible scheme for a Higgs-factory $\mu^+\mu^-$ collider.

~ 2003:	Start construction of $\mu^\pm$ source.
~ 2006:	First observation of h^0 in CMS (ATLAS).
~ 2007:	Design final collider; start construction.
~ 2009:	Higgs factory operates; scan for h^0.
~ 2010:	$\rightarrow 10^5\, h^0$ in direct channel.

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