Muon Collider Physics Program

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October 18, 2001
Outline

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- Lower Energy Higgs Factory
• **Lower Energy Higgs Factory**

• **Higher Energy Higgs Factory**

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• Higher Energy Higgs Factory

• High Energy
In first two topics, I will focus on what is unique about a muon collider. One should keep in mind that $\mu^+\mu^-$ collision capabilities = $e^+e^-$ collision capabilities for same $L$, but that at the moment $L$ for a muon collider would be much less than $L$ for the LC.
MUC can measure rate for $\mu^+\mu^- \rightarrow h \rightarrow b\bar{b}$ for light ($m_h \sim 110 - 130$ GeV) SM-like Higgs very precisely. For a SM-like $h$, at $\sqrt{s} = m_h \approx 115$ GeV and for $R = 0.003\%$ beam energy resolution, the $b\bar{b}$ final state rates are

\begin{align}
\text{signal} & \approx 10^4 \text{ events} \times L(\text{fb}^{-1}) , \\
\text{background} & \approx 10^4 \text{ events} \times L(\text{fb}^{-1}) ,
\end{align}

Further, this measurement is very independent of uncertainties in $m_b$ because of cancellations between various effects (decreasing $m_b \Rightarrow$ decreasing rate at naive level, but narrower width $\Rightarrow$ increased rate, ...).

Expected error = 3.5\% (0.5\%) for $0.2\text{fb}^{-1}$ ($10\text{fb}^{-1}$ = ‘crazy’ CERN study number) $(0.2\text{fb}^{-1} = \text{two years of Snowmass/standard luminosity for } R = 0.003\% \text{ beam energy resolution}) \Rightarrow \text{competitive to (with possibly less sytematic error) LC ability to distinguish SM Higgs from } h^0 \text{ of MSSM.}$
• Measurement of $\Gamma_{\text{h}}^{\text{tot}}$ of $\pm 20\%$ at $m_h = 110$ GeV ($L = 0.2 \text{fb}^{-1}$) would be competitive with LC, but LC wins at higher $m_h$ (using $WW^*$ mode) unless MUC can get more $L$.

Of course, seeing the Higgs width by direct scan is much more physically appealing than the indirect LC methods required to extract the width.

• Nothing can beat the $1 - 3 \times 10^{-6}$ fractional error on $m_h$ that can be achieved at a MUC via scanning, but can theory ever reach this level of predictive power.

In SUSY context, for $m_{h^0} \sim 110$ GeV, theory must make prediction as a function of SUSY parameters to level of 0.3 MeV. Currently, theory error at 1+2 loops is $\pm 2$ GeV or so. Some theorists hope to push to 100 MeV, but this will be the limit in the next decade.

If SUSY loop calculations are ever pushed to the few MeV level, the MUC measurement of $m_h$ would become an incredibly powerful constraint on / check of the theory.

• The MUC will certainly have the best measurement of the $h \rightarrow \mu^+\mu^-$ coupling ($\pm 4\%$ for $L = 0.2 - 0.3 \text{fb}^{-1}$ at $R = 0.003\%$).
To achieve this in a model-independent way, some combination with LC (or ‘$e^+e^-$-mode’ MUC) data is required, but direct LC cannot compete even for $L = 1000 \text{fb}^{-1}$.

This level of error will (typical MSSM parameters) reveal deviations of $h^0$ relative to $h_{\text{SM}}$ for $m_{A^0} \lesssim 600 - 700 \text{ GeV}$, i.e. well into ‘decoupling’ regime of MSSM. ⇒ would know where to look for the nearly degenerate $H^0, A^0$ of the MSSM.

Even more importantly, it is fundamentally important to have this direct check on our understanding of the mechanism for fermion mass generation.

- The MUC would also be able to see a $s$-channel produced light SM-like Higgs in the $\tau^+\tau^-$ final state mode, thereby allowing a measurement of the $h \rightarrow \tau^+\tau^-$ coupling, an important complement to the $\mu^+\mu^-$ coupling measurement.

To really clarify this signal, one will wish to sum over both $\rho\nu_\tau$ and $\pi\nu_\tau$ channels for $\tau$ decay and have $R \leq 0.005\%$ and 25% beam polarization. Precision measurements will require 1 $\text{fb}^{-1}$ luminosity, for which the
expected errors are

\[
\sqrt{s} = m_h \ (\text{GeV}) \quad 100 \ 110 \ 120 \ 130 \\
\epsilon \ (\%) \quad 27 \ 21 \ 23 \ 32
\] (3)

The uncertainties on the cross section measurements determine the extent to which the \( h \rightarrow \tau^+\tau^- \) coupling can be measured.

• Suppose there is a light \( A^0 \) in a general 2HDM.

Such a light \( A^0 \) is one possible explanation for the deviation of \( a_\mu \) from the SM value (although current deviation is probably somewhat too large).

Detection of a light \( A^0 \) with \( m_{A^0} \lesssim 250 \) GeV will probably be possible at a high-\( L \) LC using \( e^+e^- \rightarrow \nu\bar{\nu}A^0A^0 \) and \( e^+e^- \rightarrow Z^* \rightarrow ZA^0A^0 \), but we will really want to know how it couples to \( \mu^+\mu^- \).

Detection of a light \( A^0 \) with tightly constrained mass (from LC detection) at the MUC would be easy.

Note: such a light \( A^0 \) is entirely consistent with precision electroweak constraints, and would be highly motivated (for maintaining consistency with precision electroweak data) if the LHC finds a heavy (\( \sim 1 \) TeV) SM-like scalar Higgs boson.
• Higgs triplets are called for in the left-right symmetric models that lead to see-saw mechanism generation of neutrino masses (via a lepton number violating Majorana coupling).

The presence of this coupling, plus L-R symmetry, implies a $\mu\mu \rightarrow \Delta_{L}$ coupling of magnitude such that a strong resonance signal for $\Delta_{L}$ production would be seen.

Generally speaking, a $\mu\mu$ collider is the best place to look for and directly measure/study such a coupling — the ultimate sensitivity to the coupling-squared is a factor of roughly $10^8 - 10^9$ better than current limits.

The LHC would see the $\Delta_{L}$ so that we would know its mass fairly precisely, but, except in very special cases, would not be able to determine the $\mu\mu \rightarrow \Delta_{L}$ coupling $\Rightarrow$ MUC = mandatory if $\Delta_{L}$ is seen at LHC.

• A MUC is the best machine for study/discovery of the pseudo-Nambu-Goldstone bosons of a technicolor theory. This is because the lightest of these PNGB’s, the $P^0$, has strong $\mu^+\mu^-$ and $b\bar{b}$ couplings, while its other couplings (e.g. to $WW, ZZ$) that are needed for LC/LHC production are ‘anomaly’ generated and therefore weak.

Hopefully, LHC could make an early weak detection of the lightest PNGB
and then the MUC would be mandatory for studying it.

- If there is leptonic R-parity violation in SUSY (an attractive means for generating neutrino masses), then there is very likely a non-zero $\mu^+ \mu^- \rightarrow \tilde{\nu}$ coupling.

In fact, a MUC can probe incredibly small values of this coupling, well below the range needed for $m_\nu$ generation.
Discovery of the $H^0, A^0$ of the MSSM is not guaranteed at Tevatron, LHC + LC.

There is a significant no-discovery wedge beginning at

$$m_{A^0} \gtrsim \max \left\{ \frac{\sqrt{s}}{2} \text{ (LC)}, 250 \text{ GeV (LHC)} \right\}$$

(4)

in the moderate $\tan \beta$ zone.

LHC wedge is set by capabilities of $gg \to b\bar{b}H^0, b\bar{b}A^0$ (dominant and highly visible at high $\tan \beta$) and $gg \to H^0, A^0$, followed by $H^0, A^0 \to \tau^+\tau^-$. Lower $m_{A^0}$ limit on LC wedge is set by fact that the only large production process at moderate $\tan \beta$ and significant $m_{A^0} \sim m_{H^0}$ is $e^+e^- \to H^0A^0$ pair production, requiring $\sqrt{s} > m_{A^0} + m_{H^0} \sim 2m_{A^0}$.

Upper limit in $\tan \beta$ on wedge at LC is set by visibility of $e^+e^- \to b\bar{b}A^0, b\bar{b}H^0, btH^\pm$. 

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$5\sigma$ discovery contours for MSSM Higgs boson detection in various channels are shown in the $[m_{A_0}, \tan \beta]$ parameter plane, assuming maximal mixing and an integrated luminosity of $L = 300\text{fb}^{-1}$ for the ATLAS detector. This figure is preliminary.
Strategies for wedge

- Raise $\sqrt{s}$! — more later.

- Use precision $h^0$ measurements to get first indication of presence of $A^0, H^0$ and rough determination of $m_{A^0} \sim m_{H^0}$.

Then scan narrow range of $m_{A^0}$ at MUC to look for $H^0, A^0$ (usually overlapping) combined signal over narrow interval.

$< 1$ year’s luminosity needed if you know $m_{A^0}$ within $\sim 50$ GeV.

- If $m_{A^0}$ is unconstrained by precision $h^0$ measurements and/or we distrust ‘standard scenario’ interpretations of these measurements, $\Rightarrow$ two options:
  - Bremsstrahlung tail:
    3 years of operation at maximum energy $\Rightarrow 4\sigma m_{b\bar{b}}$ bump for $m_{A^0} < 2m_t$ if $\tan\beta > 6 - 7$ and for all $\tan\beta$ if $m_{A^0} > 2m_t$

Mass resolution in $b\bar{b}$ and $t\bar{t}$ final states is critical: we have assumed a value consistent with current LC claims for above statement.

Study needed.
- Scanning:

Use strategy of adjusting $R$ as expected size of $\Gamma_{A^0}^{\text{tot}}, \Gamma_{H^0}^{\text{tot}}$ increases with mass, ⇒ $4\sigma$ signal after 3 years for $\tan \beta > 5$ if $m_{A^0} < 2m_t$) and for all $\tan \beta > 1$ if $m_{A^0} > 2m_t$.

Mass resolution in $b\bar{b}$, $t\bar{t}$ final states again important.

Once found, a fine scan can separate out even very degenerate $A^0$ and $H^0$.

Note: $m_{A^0} - m_{H^0}$ will provide a very important constraint on SUSY parameters.

- Turning to the case of general 2HDM where $A^0$ is the only ‘light’ Higgs, such an $A^0$ can be found at a muon collider for any $\tan \beta$ if $m_{A^0} \gtrsim 2m_t$, a region where it would not be seen at either the LHC or a LC.

As above for $A^0, H^0$ of MSSM, simplest technique is to look for resonance signal over background in $b\bar{b}$ (higher $\tan \beta$) or $t\bar{t}$ (low $\tan \beta$) final state mass spectrum coming from bremsstrahlung (radiative return) tail at low $E_{\mu^+\mu^-}$.

A carefully designed scan would also work nicely and be more reliable if $m_{A^0} < 500$ GeV.
Can the MUC reach higher energies than LC and CLIC, with decent luminosity? We don’t know for sure yet, but whichever of $e^+e^-$ or $\mu^+\mu^-$ collision machines can achieve $>1$ TeV energies should be built.

Such a machine would allow:

- Detection and, especially, precision study of heavy SUSY particles.

  Recall that FCNC and coupling unification (with $\alpha_s(m_Z) \leq 0.12$) both prefer heavy SUSY scale especially for squarks and sleptons.

- Detection and study of $H^0, A^0$ in pair production mode $\mu^+\mu^- \rightarrow H^0A^0$ when $m_{A^0}$ is large.

  In fact, precise probabilities for $H^0, A^0$ decays to different channels (including pairs of SUSY particles) ⇒ immensely powerful probe of soft SUSY breaking and, thence, GUT scenario.

  But, must separate different final state channels ([3\ell, 2b], [1\ell, 0b], . . . . — maybe 15 or 20 different channels) and know efficiencies for different channels with good precision.
• But, one channel that will be hard to see in pair production is $H^0, A^0 \rightarrow \mu^+\mu^-$. One will want $\mu^+\mu^- \rightarrow H^0, A^0$ s-channel production no matter how heavy these Higgs are, just to determine this very crucial coupling.

• If there is no Higgs sector, a LC or MUC with $\sqrt{s} \gtrsim 3$ TeV would be required to provide a full elucidation (in all isospin channels if both $\mu^-\mu^-$ and $\mu^+\mu^-$ collisions are available) of the strong $WW$ sector.

• In Technicolor, there are many heavy particles that would require high energy for production.

• There might be one or more new $Z'$s.

• Extra dimension signals really come into their own at very high energies.

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As a general remark applicable to all energies, the ability to have a very narrow beam energy spread can make MUC competitive for certain precision measurements with a much higher $L$ LC.

Some examples:

- $t\bar{t}$ and $WW$ threshold precision studies.
- $Zh$ threshold determination of $m_h$.
- SUSY particle pair thresholds for determining SUSY masses with good precision.
- ...
**CP DETERMINATIONS**

Vital for sorting out a complex Higgs sector. At a muon collider Higgs factory there is a particularly appealing approach. For resonance, $R$, production at a MUC with $\bar{\mu}(a + ib\gamma_5)\mu$ coupling to the muon,

$$\bar{\sigma}_S(\zeta) = \bar{\sigma}_S^0 \left( 1 + P_L^+ P_L^- + P_T^+ P_T^- \left[ \frac{a^2 - b^2}{a^2 + b^2} \cos \zeta - \frac{2ab}{a^2 + b^2} \sin \zeta \right] \right)$$

$$= \bar{\sigma}_S^0 \left[ 1 + P_L^+ P_L^- + P_T^+ P_T^- \cos(2\delta + \zeta) \right] \quad (5)$$

- $\delta \equiv \tan^{-1} \frac{b}{a}$,

- $P_T$ ($P_L$) is the degree of transverse (longitudinal) polarization: no $P_T \Rightarrow$ sensitivity to $\bar{\sigma}_S^0 \propto a^2 + b^2$ only.

- $\zeta = \text{angle of the } \mu^+ \text{ transverse polarization relative to that of the } \mu^- \text{ as measured using the the direction of the } \mu^- \text{'s momentum as the } \hat{z} \text{ axis.}$

- Only the $\sin \zeta$ term is truly CP-violating, but $\cos \zeta$ also $\Rightarrow$ significant sensitivity to $a/b$. 
Ideal = isolate $\frac{a^2-b^2}{a^2+b^2}$ and $\frac{-2ab}{a^2+b^2}$ via the asymmetries (take $P_T^+ = P_T^- \equiv P_T$ and $P_L^\pm = 0$)

$$\mathcal{A}_I \equiv \frac{\bar{\sigma}_S(\zeta = 0) - \bar{\sigma}_S(\zeta = \pi)}{\bar{\sigma}_S(\zeta = 0) + \bar{\sigma}_S(\zeta = \pi)} = P_T^2 \frac{a^2 - b^2}{a^2 + b^2} = P_T^2 \cos 2\delta,$$

$$\mathcal{A}_{II} \equiv \frac{\bar{\sigma}_S(\zeta = \pi/2) - \bar{\sigma}_S(\zeta = -\pi/2)}{\bar{\sigma}_S(\zeta = \pi/2) + \bar{\sigma}_S(\zeta = -\pi/2)} = -P_T^2 \frac{2ab}{a^2 + b^2} = -P_T^2 \sin 2\delta.$$

But, must account for polarization precession: $\Rightarrow$ can’t fix polarization directions. But, precession can be easily incorporated (JFG, Pliszka)

Excellent determination of $b$ and $a$ is possible if luminosity can be upgraded from current benchmarks dating back to SM96.
A MUC is a very attractive future machine

Aside from all the specifics mentioned above, a MUC would in general be required to determine at a precision level and at high energy the extent to which there is some fundamental physics that depends upon the lepton flavor, $e$ vs. $\mu$.

To really fulfill its potential the MUC should:

(a) get more R&D funding;

(b) design for higher luminosity for all $R$ values and for higher degrees of beam polarization.

A factor of 5 increase in the luminosities would:

- allow precision studies of SM-like Higgs that would exceed in many respects the LC sensitivity to higher scale phenomena.
- allow the best CP determination of both light/narrow and heavy/broader Higgs bosons using transverse polarization asymmetries.
• allow scan discovery of Higgs bosons with no $WW, ZZ$ coupling for all $\tan \beta \gtrsim 1$; followup measurements of properties including CP determination would also be possible with high precision.

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KEEP PUSHING FORWARD