Muon Collider Physics Program

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- **High Energy**

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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.

Lower Energy Higgs Factory

- MUC can measure rate for $\mu^+\mu^- \to h \to b\overline{b}$ for light ($m_h \sim 110-130~\mathrm{GeV}$) 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 $b\overline{b}$ final state rates are

$$\text{signal} \approx 10^4 \text{ events} \times \mathrm{L}(\mathrm{fb}^{-1}), \quad (1)$$

$$\text{background} \approx 10^4 \text{ events} \times \mathrm{L}(\mathrm{fb}^{-1}), \quad (2)$$

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, $\ldots$).

Expected error = 3.5% (0.5%) for $0.2\mathrm{fb}^{-1}$ ($10\mathrm{fb}^{-1}$ = 'crazy' CERN study number) ($0.2\mathrm{fb}^{-1}$ = two years of Snowmass/standard luminosity for $R=0.003\%$ beam energy resolution) $\Rightarrow$ competitive to (with possibly less sytematic error) LC ability to distinguish SM Higgs from h^0 of MSSM.

- **Measurement of $\Gamma_h^{\rm tot}$ of $\pm 20\%$ at $m_h = 110~{\rm GeV}$ ($L = 0.2 {\rm fb}^{-1}$) 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 $m_{h^0} \sim 110~{\rm GeV}$, theory must make prediction as a function of SUSY parameters to level of 0.3 MeV. Currently, theory error at 1+2 loops is $\pm 2~{\rm GeV}$ or so. Some theorists hope to push to $100~{\rm MeV}$, 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 $h \to \mu^+\mu^-$ coupling ($\pm 4\%$ for $L = 0.2 - 0.3 {\rm fb}^{-1}$ 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 $L = 1000\mathrm{fb}^{-1}$.

This level of error will (typical MSSM parameters) reveal deviations of h^0 relative to $h_{\rm SM}$ for $m_{A^0} \lesssim 600 - 700~\mathrm{GeV}$, i.e. well into 'decoupling' regime of MSSM. $\Rightarrow$ 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 $h \to \tau^+\tau^-$ 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 τ decay and have $R \leq 0.005\%$ and 25% beam polarization. Precision measurements will require $1~\mathrm{fb}^{-1}$ luminosity, for which the expected errors are

$$\begin{array}{lcccc} \sqrt{s} = m_h \ (\text{ GeV}) & \mathbf{100} & \mathbf{110} & \mathbf{120} & \mathbf{130} \\ \epsilon\ (\%) & \mathbf{27} & \mathbf{21} & \mathbf{23} & \mathbf{32} \end{array} \tag{3}$$

The uncertainties on the cross section measurements determine the extent to which the $h \to \tau^+\tau^-$ 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_μ from the SM value (although current deviation is probably somewhat too large).

  Detection of a light A^0 with $m_{A^0} \lesssim 250 \text{ GeV}$ will probably be possible at a high-L LC using $e^+e^- \to \nu\overline{\nu}A^0A^0$ and $e^+e^- \to Z^* \to ZA^0A^0$, 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 ($\sim 1 \text{ TeV}$) 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 $\mu^-\mu^- \to \Delta_L^{--}$ coupling of magnitude such that a strong resonance signal for Δ_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 Δ_L^{--} so that we would know its mass fairly precisely, but, except in very special cases, would not be able to determine the $\mu^-\mu^- \to \Delta_L^{--}$ coupling $\Rightarrow$ MUC = mandatory if Δ_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 $b\overline{b}$ 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 $\mu^+\mu^- \to \widetilde{\nu}$ coupling.**

  In fact, a MUC can probe incredibly small values of this coupling, well below the range needed for m_ν generation.

HIGHER ENERGY HIGGS FACTORY

- 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

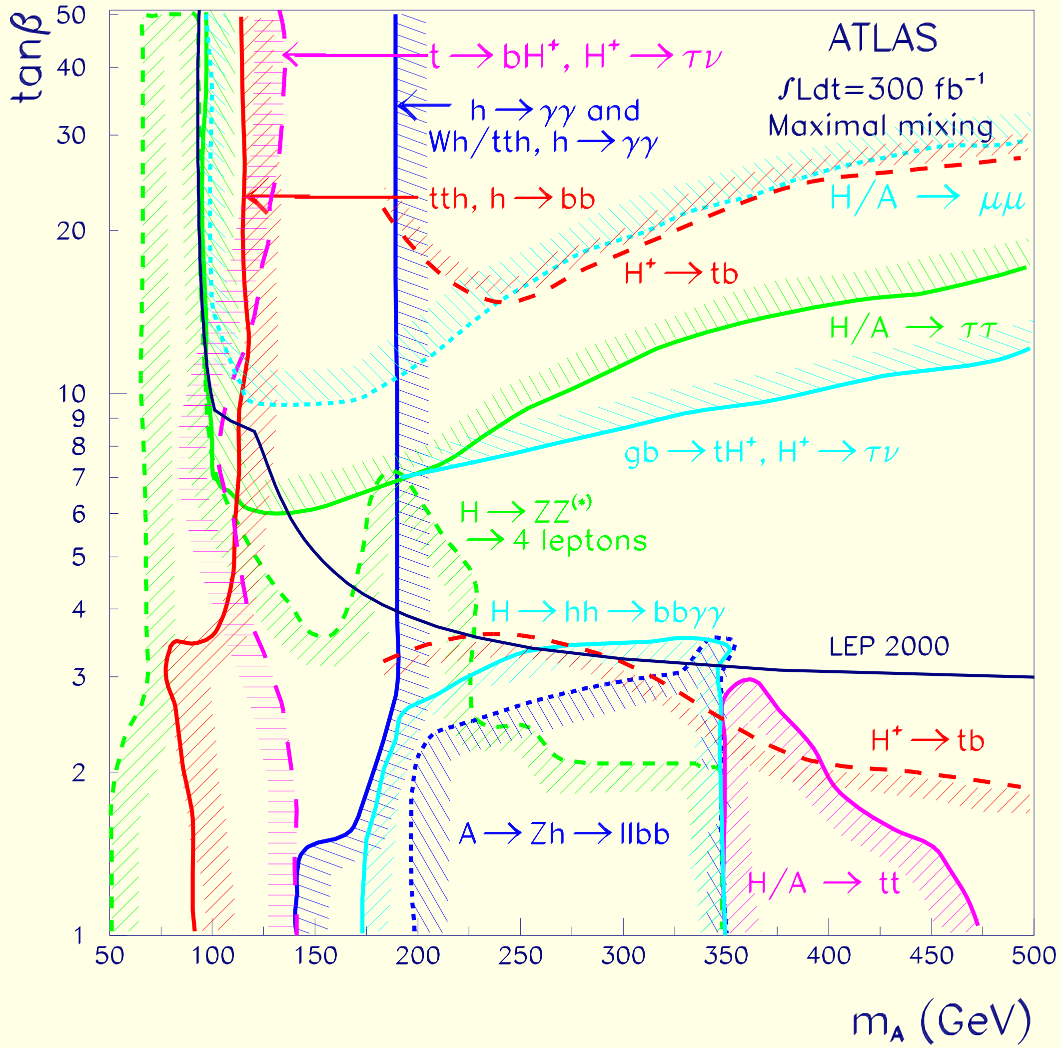
$$m_{A^0} \gtrsim max\left\{\frac{\sqrt{s}}{2}\ (\mathrm{LC}), 250\ \mathrm{GeV}\ (\mathrm{LHC})\right\} \quad (4)$$

  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 $e^+e^- \to b\bar{b}A^0, b\bar{b}H^0, btH^{\pm}$.



5σ 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 $L = 300\mathrm{fb}^{-1}$ 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 $\sim 50~\mathrm{GeV}$.

- **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 $\Gamma^{\rm tot}_{A^0}, \Gamma^{\rm tot}_{H^0}$ increases with mass, $\Rightarrow$ 4σ 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 $m_{A^0} < 500~{\rm GeV}$.

HIGH ENERGY

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 $\mu^+\mu^- \to H^0 A^0$ when m_{A^0} is large.**

  In fact, precise probabilities for H^0, A^0 decays to different channels (including pairs of SUSY particles) $\Rightarrow$ 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 $H^0, A^0 \to \mu^+\mu^-$.**

  One will want $\mu^+\mu^- \to H^0, A^0$ 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.**

- **. . .**

NARROW BEAM ENERGY SPREAD ADVANTAGES

- 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.
  - $\ldots$

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 $\overline{\mu}(a + ib\gamma_5)\mu$ coupling to the muon,**

$$\begin{aligned} \overline{\sigma}_S(\zeta) &= \overline{\sigma}_S^0 \left(1 + P_L^+ P_L^- + P_T^+ P_T^- \left[\frac{a^2 - b^2}{a^2 + b^2}\cos\zeta - \frac{2ab}{a^2 + b^2}\sin\zeta\right]\right) \\ &= \overline{\sigma}_S^0 \left[1 + P_L^+ P_L^- + P_T^+ P_T^- \cos(2\delta + \zeta)\right] , \end{aligned} \qquad (5)$$

- $\delta \equiv \tan^{-1}\frac{b}{a}$,
- P_T (P_L) is the degree of transverse (longitudinal) polarization: no $P_T \Rightarrow$ sensitivity to $\overline{\sigma}_S^0 \propto a^2 + b^2$ only.
- ζ = angle of the μ^+ transverse polarization relative to that of the μ^- as measured using the the direction of the μ^-'s momentum as the $\hat{z}$ 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 $P_L^\pm = 0$)

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

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

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.

CONCLUSIONS

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. μ.

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.**
- $\ldots$.

KEEP PUSHING FORWARD