MEASURING THE RELATIVE CP-EVEN AND CP-ODD YUKAWA COUPLINGS OF A HIGGS BOSON AT A MUON-COLLIDER HIGGS FACTORY

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We study a possibility of a measurement of muon Yukawa couplings in s-channel Higgs boson production at a muon collider with transversely polarized beams. We investigate sensitivity to the relative size of the CP-odd and CP-even muon Yukawa couplings. Provided the event rate observed justify the operation of the \( \mu^+\mu^- \) Higgs boson factory, we have found that polarization degree 40% is sufficient to resolve the CP nature of a single resonance as well as disentangle it from two overlapping CP conserving resonances.

It is believed that the scalar sector is an inherent component of the theory of elementary interactions and, one or more physical Higgs, or Higgs-like bosons will, sooner or later, be discovered. Since the CP nature of Higgs bosons is a model dependent feature its determination would not only provide information concerning the mechanism of CP violation but would also restrict possible extensions of the Standard Model (SM) of electroweak interactions and therefore reveal the structure of fundamental interactions beyond the SM. A muon collider with transversely polarized beams is the only place where CP properties of a second generation fermion Yukawa coupling could be probed. This is the subject of our more complete analysis which is summarized in this talk. We follow the line of our previous works where we have tried to unveil the CP-nature of Higgs bosons in a model-independent way.

The attractive possibility of s-channel Higgs boson production at a muon collider has been discussed before together with the possibility of the measurement of CP violation in the muon Yukawa couplings. The latter is based on the fact that in any muon collider design there is a natural beam polarization on the order of 20% that allows for a rare possibility of direct...
Table 1. $1$ and $3\,\sigma$ exclusion limits on $\delta$ for $b\bar{b}$ final state for various luminosity and polarization configurations. Beam energy spread 0.003% and $b\bar{b}$ tagging efficiency 54% have been assumed.

| P[\%] | L[ pb^{-1}] | $m_R$=110 GeV | $m_R$=130 GeV |
|-------|-------------|---------------|---------------|
|       |             | $1\sigma$     | $3\sigma$     | $1\sigma$     | $3\sigma$     |
| 20    | 150         | 0.94          | -             | -             | -             |
| 39    | 75          | 0.30          | 1.14          | 0.41          | -             |
| 48    | 75          | 0.20          | 0.64          | 0.27          | 0.93          |
| 45    | 150         | 0.15          | 0.50          | 0.21          | 0.69          |

Higgs boson production with known polarization of initial state particles.

The cross section for the Higgs boson resonance production: $\mu^+\mu^- \rightarrow R$ depends on transverse $P_T^\pm$ and longitudinal $P_L^\pm$ beam polarizations and $\mu r \exp(i\delta\gamma_5)\mu$ muon Yukawa coupling in the following way:

$$\sigma_S(\zeta) = \sigma_0^S \left[ 1 + P_T^+ P_L^- + P_T^- P_L^+ \cos(2\delta + \zeta) \right]$$

(1)

where $\zeta$ is the angle in the transverse plane between beam polarizations and $\sigma_0^S$ is the unpolarized cross section. We stress that only the transverse polarization term is sensitive to $\delta$ of the muon Yukawa coupling. Since it is proportional to the product of the transverse polarizations, it is essential to have large $P_T^+$ and $P_T^-$, as obtained by applying stronger cuts while selecting muons from decaying pions (which, however, causes a reduction of luminosity). To compensate, more intensive proton source or ability to repack muon bunches will be needed. Another speculative option, would be high, up to 50%, polarization obtained by a phase-rotation technique which would lead to less luminosity reduction.

While varying $\zeta$ one can observe a maximum at $\zeta = -2\delta$ and a minimum at $\zeta = \pi - 2\delta$. Thus, studying $\zeta$ dependence is essential for resolving the $\delta$ value. A muon collider offers the unique possibility of a setup which in a natural way provides a scan over different $\zeta$ values. We will not discuss this option here. Our results will correspond to a configuration with four fixed $\zeta$ values: 0, 90, 180 and 270. Even though this cannot be accomplished experimentally, due to the spin precession in the accelerator ring, it can be well approximated by a simple but realistic setup that yields the same results as the fixed $\zeta$ analysis at the expense of 50% luminosity increase.

In order to illustrate the ability to reject different Higgs boson CP scenarios we can assume that the measured data is mimicked by the SM Higgs boson. For given luminosity $L$ and polarization $P$ we can place $1$ and $3\,\sigma$ limits on the $\delta$ value for the observed resonance, assuming the $\delta = 0$ SM is
Table 2. Event number pattern for different Higgs models as a function of \( \zeta \), assuming
\( P_L^\pm = 0 \) and \( P_T^\pm = P \); see Eq. (1).

| (\( \delta \)) | \( \zeta = 0 \) | \( \zeta = \pi/2 \) | \( \zeta = \pi \) | \( \zeta = 3\pi/2 \) |
|---------------|----------------|----------------|----------------|----------------|
| (0)           | \( 1 + P^2 \)  | \( 1 \)        | \( 1 - P^2 \)  | \( 1 \)        |
| (\( \pi/4 \)) | \( 1 \)        | \( 1 - P^2 \)  | \( 1 \)        | \( 1 + P^2 \)  |
| (\( \pi/2 \)) | \( 1 - P^2 \)  | \( 1 \)        | \( 1 + P^2 \)  | \( 1 \)        |
| (0) + (\( \pi/2 \)) | \( 1 \) | \( 1 \) | \( 1 \) | \( 1 \) |

The limits for Higgs boson masses of 110 and 130 GeV are presented in table 1. For the expected yearly luminosity of \( L = 100 \text{ pb}^{-1} \), even several years of running at the natural 20% polarization would be insufficient for useful limits. However, 1\( \sigma \) limits for the \( P = 39\% \) option (with reduced \( L \)) do give a rough indication of the CP nature of the resonance. 3\( \sigma \) limits in 110-130 GeV mass range require either > 40\% polarization or < 50\% luminosity loss. (The requirements are less stringent for a 110 GeV Higgs boson.) We stress that there is no other way the measurement of the muon Yukawa \( \delta \) can be done and that operation in the transverse polarization mode should not interfere with most of the other studies. For a heavier resonance, operation of a muon collider as an s-channel Higgs boson factory is justified only if the branching ratio \( BR(R \rightarrow \mu^+\mu^-) \) is enhanced. Then, the analysis sketched above applies as well. Such enhancement arises in the Minimal Supersymmetric Standard Model (MSSM) at large \( \tan \beta \). If the pseudoscalar mass is large (\( m_A > 300 \text{ GeV} \)), the \( H \) and \( A \) masses will be similar. For \( \tan \beta > 8 \) degeneracy may be such that we will not be able to see two separate peaks but only a single peak with both CP-even and CP-odd components. It would be crucial to distinguish such a case from a single CP-violating Higgs boson which may appear e.g. in MSSM. Table 2 illustrates the very distinct event number pattern as a function of \( \zeta \) that would yield the needed discrimination. The event rate for any single, CP conserving or CP violating Higgs boson, has a minimum and maximum as a function of \( \zeta \). In contrast, overlapping CP-even and CP-odd resonances result in a pattern independent of \( \zeta \). We have found that for simple MSSM test cases with \( m_A = 300 - 400 \text{ GeV} \) and \( \tan \beta > 8 \) (for which we cannot see separate resonance peaks) even natural 20\% polarization will allow us to distinguish two overlapping resonances from any single one at more than the 3\( \sigma \) level. Higher polarization will allow for a precise measurement of the relative contribution from the CP-even and the CP-odd component.
To summarize, we have presented results of a realistic study of measuring the CP properties of the muon Yukawa couplings in Higgs boson production at a muon collider with transversely polarized beams. We have found that transverse polarization is essential for determining the CP nature of the muon Yukawa couplings. In particular, a collider with $P \approx 40\%$ and at least $50\%$ of the original luminosity retained will ensure that the CP nature of the produced scalar resonance will be revealed.

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