New Particles and Interactions at High Energy Muon Colliders

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Abstract. I give an overview of the ability of a high energy $\mu^+\mu^-$ collider to discover new particles and interactions. I start with heavy fermions which will be the most straightforward to produce and observe. I then discuss single leptoquark production which is produced via the quark content of the photon and the discovery potential for extra gauge bosons which will manifest themselves via deviations of observables from their standard model values. Finally, contact interactions are studied as the generalization of looking for new interactions via deviations from the standard model.

INTRODUCTION

Although the Standard Model (SM) of particle physics is in complete agreement with present experimental data, it is believed to leave many questions unanswered. This belief has resulted in numerous models that approximate the SM at presently accessible energies but which have a much richer particle spectrum above 100 GeV. Some models extend the SM gauge group by either embedding the extra gauge groups in a Grand Unified Group (GUT) or not embedding them. GUT theories also come in supersymmetric varieties which leads to further phenomenological consequences, in particular all the supersymmetric partners of the “conventional” particles and gauge bosons [1]. Another broad class of models are the various composite models where the gauge bosons are composite, the fermions are composite, or the Goldstone bosons that become the longitudinal components of the massive gauge bosons are composite (e.g. technicolour models).

These models lead to many types of new particles such as; extra gauge bosons ($Z'$s and $W'$s); new fermions which come in many forms such as 4th generation fermions, mirror fermions, vector fermions, and singlets like massive neutrinos; leptoquarks, bileptons and diquarks; extended Higgs sector; excited fermions which would signify substructure; and other truly weird particles that we have yet to imagine.

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To reveal what lies beyond the SM we need to elucidate and complete the TeV particle spectrum. In the remainder of this contribution I will survey the capability of high energy $\mu^+\mu^-$ colliders to discover new particles and interactions. Because this is such a broad topic the survey is necessarily incomplete. A good source of recent results is the contributions of the New Phenomena working group at the 1996 Snowmass Study on High Energy Physics [2].

NEW FERMIONS

New fermions [3] are generally classified by the quantum numbers of their chiral components. Fourth generation fermions are massive duplicates of SM fermions. In contrast the left and right handed components of vector fermions are in $SU(2)_L$ and $SU(2)_R$ doublets respectively and mirror fermions have their left handed components in $SU(2)_L$ singlets and their right handed components in $SU(2)_R$ doublets. Except for singlet neutrinos new fermions couple to the photon and/or weak bosons with full strength allowing for pair production with unambiguous cross section. Fermion-antifermion pairs are produced via $\mu^+\mu^- \rightarrow \bar{F}F$ through s-channel $\gamma$ or $Z^0$ so the cross section goes approximately like the QED point cross section. Fermions can be pair produced in sufficient numbers for discovery up to close to the kinematic limit, $\sqrt{s}/2$.

New fermions with conventional quantum numbers can mix with their SM partners. The mixing is severely constrained by the non-observation of FCNC. Nevertheless if the mixing is not too small new fermions can be produced singly in association with their light partners. This results in a significantly higher search limit, almost $\sqrt{s}$ of the collider.

LEPTOQUARKS

Leptoquarks are colour triplets or anti-triplets carrying both baryon and lepton quantum numbers and can have spin 0 or spin 1. They appear in a wide variety of models such as GUT’s, technicolour, and composite models [4]. Leptoquarks reveal themselves with a dramatic signal of a high $p_T$ lepton balanced by a jet.

In addition to being pair produced like the fermions of the previous sections [4] leptoquarks can also be produced singly via the quark content of a Weiszacker-Williams photon radiated off an incoming muon [5]. The cross-section for the process is found by convoluting the quark distribution inside the photon with the $q + \mu \rightarrow LQ$ cross section:

$$\sigma(s) = \int f_q/\gamma(z, M_s^2)\hat{\sigma}(\hat{s})dz = f_q/\gamma(M_s^2/s, M_s^2/2\pi^2\kappa\alpha_{em}s)$$

where the leptoquark couplings are replaced by a generic Yukawa coupling $g$ which is scaled to electromagnetic strength $g^2/4\pi = \kappa\alpha_{em}$. The resulting cross-section is then convoluted with the photon distribution to obtain the total cross section:
FIGURE 1. Event rates for leptoquark production at high energy muon colliders. The results were obtained using the GRV distribution functions for the quark content of the photon [6].

\[
\sigma(\mu^+\mu^- \to XS) = \frac{2\pi^2a_{em}\kappa}{s} \int_{M_2^2/s}^{1} \frac{dx}{x} f_{/\mu}(x, \sqrt{s}/2)f_{/\gamma}(M_s^2/(xs), M_s^2)
\]

The number of expected events \((L \times \sigma)\) for various muon collider parameters are shown in Fig. 1 where we have taken \(\kappa = 1\). Because this is a muon collider we are considering 2nd generation LQ’s so that we use the \(s\) and \(c\)-quark content of the photon as appropriate. Basing discovery on the production of 100 LQ’s leads to the search limits quoted in Table I. The OPAL [7] and DELPHI [8] collaborations have used this process to obtain limits on LQ’s at LEP200.

TABLE 1. LQ discovery limits at \(\mu^+\mu^-\) colliders for the given \(\sqrt{s}\) and integrated luminosity. The Scalar and Vector refers to the LQ spin and the \(-1/3\ -5/3\ etc.\ refers to its charge.

| \(\sqrt{s}\) (TeV) | \(L\) fb\(^{-1}\) | Scalar | Vector |
|-----------------|-----------------|--------|--------|
| 0.5             | 7               | -1/3, -5/3 | -4/3, -2/3 | -1/3, -5/3 | -4/3, -2/3 |
| 0.5             | 50              | 250     | 170    | 310     | 220     |
| 4.0             | 1000            | 3600    | 3000   | 3700    | 3400    |

NEW GAUGE BOSONS

New gauge bosons are a generic prediction of models with extensions of the SM gauge group [9]. They contribute to \(\mu^+\mu^-\) cross-sections in the s-channel [10]. The cross-sections for various \(Z''\)'s are shown in Fig. 2. It is clear from this figure that if production of real \(Z''\)'s is kinematically accessible it will be produced in a sufficiently large quantity so that its properties can be investigated in detail. For the highest energy muon colliders being contemplated this translates into production
FIGURE 2. $\mu^+\mu^-$ cross-section as a function for $\sqrt{s}$ for the SM (solid), $Z_\chi$ (dashed), $Z_{LR}$ (dotted), $Z_{ALR}$ (dot-dashed), and $Z_{SSM}$ (dot-dot-dashed).

of $Z'$s of $M_{Z'} = 4$ TeV (or 5 TeV depending on the actual $\sqrt{s}$ of the machine). By comparison, the LHC can achieve a discovery reach of 4-5 TeV, depending on the specific $Z'$, based on roughly 10 dilepton pairs clustering at the same invariant mass. Thus, the main advantage of the muon collider is that it could produce enough $Z'$s to study them in detail.

Searches for $Z'$s can be extended to masses much higher than $\sqrt{s}$ by looking for deviations from SM observables. This is illustrated in the $\sigma(\mu^+\mu^- \rightarrow e^+e^-)$ plotted in Fig. 2 where significant deviations from the SM occur below the $Z'$ pole due to interference of the $Z'$ propagator with the $\gamma$ and $Z^0$ propagators.

To represent a meaningful signal of new physics, deviations should be observed in as many observables as possible. Observables are constructed from cross sections to specific final state fermions. A set of such observables are; $\sigma^f$, the cross sections, $A^f_{FB}$, the forward-backward asymmetries, and $A^f_{LR}$, the left-right polarization asymmetries, where $f = \mu, \tau, c, b$, and $had =$sum over hadrons. To obtain discovery limits for new physics we look for statistically significant deviations from standard model expectations. In Fig. 3 a number of observables are shown with their standard model values and for various $Z'$s as a function of the $Z'$ mass. The $1 - \sigma$ error bars shown are based on the statistics expected in the standard model. What is important to note is that the different observables have different sensitivities to different models. For example, of the models shown, $\sigma(\mu^+\mu^- \rightarrow e^+e^-)$ is most sensitive to $Z_{ALR}$ while $R^{had}$ is most sensitive to $Z_\chi$. Therefore to have the highest possible reach for the largest number of possible models it is important to include all possible observables. We quantify the sensitivity to an extra gauge boson by comparing the predictions for various observables assuming the presence of a $Z'$ to the predictions of the standard model and constructing the $\chi^2$ figure of merit. The “discovery” limits were obtained by including the ten observables: $\sigma^\mu, \sigma^\tau, \sigma^c, \sigma^b, R^{had}, A^\mu_{FB}, A^\tau_{FB}, A^c_{FB}, A^b_{FB}$, and $P_\tau$. In calculating the $\chi^2$ we assumed 35% $c$-tagging efficiency and 60% $b$-tagging efficiency. The 99% C.L. discovery limits are
shown in Fig. 4 [10]. Only statistical errors are considered in obtaining the limits shown. We did not consider observables involving polarization of the initial state leptons for the muon colliders (although they were included for the $e^+e^-$ collider results). A very exciting development discussed at this meeting was the possibility of very high muon polarization without too large a decrease in the luminosity. Polarization asymmetries are in many cases the most sensitive observables so that polarization is potentially very important for searches for $Z'$s.

CONTACT INTERACTIONS

In the previous section we described how the existence of $Z'$s might reveal themselves through deviations from the SM. For very massive $Z'$s the $Z'$ propagator can be described by a 4-Fermi interaction [11]:

$$\frac{g_{Z'}^2}{s - M_{Z'}^2} \rightarrow \frac{g_{Z'}^2}{M_{Z'}^2} \sqrt{s}.$$  

(3)

Likewise, leptoquark exchange in the t-channel in processes like $\mu^+\mu^- \rightarrow q\bar{q}$ can also be described this way

$$\frac{\kappa \alpha_{em}}{t + M_{LQ}^2} \rightarrow \sqrt{s} \frac{\kappa \alpha_{em}}{M_{LQ}^2}.$$  

(4)

Form factors or residual effective interactions associated with fermion substructure is also often parametrized by contact terms in the low-energy Lagrangian. Thus
four fermion contact interactions represents a useful parametrization of many types of new physics originating at a high energy scale.

These contact interactions are described by non-renormalizable operators in the effective low-energy lagrangian. The lowest order four-fermion contact terms are dimension-6 and hence have dimensionful coupling constants proportional to $g_{\text{eff}}^2/\Lambda^2$. They are often written in the form [11]:

$$
\mathcal{L} = \frac{4\pi}{2\Lambda^2} [\eta_{LL} (\bar{e}_L \gamma_{\mu} e_L) (\bar{f}_L \gamma^\mu f_L) + \eta_{LR} (\bar{e}_R \gamma_{\mu} e_L) (\bar{f}_R \gamma^\mu f_L) + \eta_{RL} (\bar{e}_R \gamma_{\mu} e_R) (\bar{f}_L \gamma^\mu f_L) + \eta_{RR} (\bar{e}_R \gamma_{\mu} e_R) (\bar{f}_R \gamma^\mu f_R)] .
$$

(5)

Interference between the contact terms and the usual gauge interactions can lead to observable deviations from SM predictions at energies lower than $\Lambda$. The effects of a contact interaction are illustrated in Fig. 5 where the differential cross-section for $\mu^+ \mu^- \rightarrow b \bar{b}$ is plotted for various values of $\Lambda$.

To gauge the sensitivity to the compositeness scale we assume that the SM is correct and perform a $\chi^2$ analysis of the $\cos \theta$ angular distribution. To perform this we choose the detector acceptance to be $|\cos \theta| < 0.94$ (corresponding to $\theta = 20^\circ$) [12]. We note that angular acceptance of a typical muon collider detector is expected to be reduced due to additional shielding required to minimize the radiation backgrounds from the muon beams. We assume canonical LEP values, $\epsilon_b = 25\%$, $\epsilon_c = 5\%$ but warn the reader that these numbers are quite arbitrary and
FIGURE 5. The $\cos\theta$ distribution for $\mu^+\mu^- \to bb$ at $E_{CM} = 0.5$ TeV with $\eta_{LL} = +1$ for the SM (solid), $\Lambda = 5$ TeV (dashed), $\Lambda = 10$ TeV (dotted), $\Lambda = 20$ TeV (dot-dashed), $\Lambda = 30$ TeV (dot-dot-dashed).

are only used for illustrative purposes. We divide the angular distribution into 10 equal bins. The $\chi^2$ distribution is evaluated by the usual expression.

The 95\% C.L. bounds on $\Lambda$ are shown graphically in Fig. 6. Quite generally, high luminosity $\mu^+\mu^-$ colliders are quite sensitive to contact interactions with discovery limits ranging from 5 to 50 times the center of mass energy. As in the discussion of $Z'$s, polarization will be important, especially in unravelling the chirality of deviations if they are observed.

FIGURE 6. Sensitivity to the new physics scale, $\Lambda$, at high energy muon colliders. The criteria for obtaining these limits are described in the text.

FINAL COMMENTS

The main attractions of a muon collider are its high energy reach in a relatively clean environment. For certain types of physics a high energy muon collider could play a unique role. For example, if the LHC discovered a $Z'$ with mass of 4 TeV a muon collider of sufficiently high energy would be able to do detailed studies
of its properties. Another example is the existence of heavy leptons. These are notoriously difficult and maybe impossible to discover at a hadron collider. Yet for a high energy muon collider this would be straightforward.

The workshop discussed the likelihood of producing highly polarized beams. These would play an important role in identifying the nature of a new particle or interaction, whether it be a leptoquark or $Z'$. Identification studies using polarization would be a useful exercise.

Finally, we should keep our minds open to the possibility of genuine surprises which we have not yet imagined.

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