Search for Excited and Exotic Muons at CDF

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Abstract. We present a search for the production of excited or exotic muons ($\mu^*$) via the reaction $\bar{p} + p \rightarrow \mu^* + \mu \rightarrow \mu \gamma + \mu$ using 371 pb$^{-1}$ of data collected with the Run II CDF detector. In this signature-based search, we look for a resonance in the $\mu \gamma$ mass spectrum. The data are compared to standard model and detector background expectations, and with predictions of excited muon production. We use these comparisons to set limits on the $\mu^*$ mass and compositeness scale $\Lambda$ in contact interaction and gauge-mediated models.

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INTRODUCTION

In the standard model (SM), quarks and leptons are considered fundamental particles. An indication that quarks and leptons are composite particles would be the observation of their excited states [1]. Additionally, when the standard model is embedded in larger symmetry groups, exotic fermions are predicted [2]. We search for singly produced excited and exotic muons where the $\mu^*$ decays in the $\mu \gamma$ channel, resulting in a $\mu \mu \gamma$ final state signature. The $\mu \mu \gamma$ signal is fully-reconstructible with low background expectation.

EXCITED AND EXOTIC MUON MODELS

We consider two models for excited and exotic muon production: a contact interaction (CI) model and a gauge mediated (GM) model. In the CI model, excited muon production is described by a four-fermion Lagrangian of quarks to excited and SM muons [1]. The CI cross sections depend on the $\mu^*$ mass $M_{\mu^*}$ and compositeness scale $\Lambda$. The CI process is modeled by PYTHIA [3]. The production of $\mu^*$ in the GM model is described by its coupling to gauge bosons [4]. The GM cross sections depend on $M_{\mu^*}$ and $f/\Lambda$, where $f$ is a phenomenological coupling constant. The programs LANHEP [5] and COMPHEP [6] are used to calculate leading order GM cross sections and generate GM events. For both models, the $\mu^*$ decays are prescribed by the GM Lagrangian [7].

DATASET AND SIGNAL SELECTION

We use 371 pb$^{-1}$ of data collected with the high $p_T$ muon trigger at CDF from February 2002 through September 2004. We search for events consisting of two muons and a photon. The isolated muons must have $p_T > 20$ GeV/c and be located in the central portion of the detector ($|\eta| < 1$), with at least one detected in the muon chamber. Muons are identified by their minimum-ionizing particle properties. The isolated photon must have $E_T > 25$ GeV, can be located in the central or forward region, and is identified by its electromagnetic shower properties. In addition, we veto events with $81 < M_{\mu\mu} < 101$ GeV/c$^2$, to remove events produced by initial-state radiation (ISR) $p + \bar{p} \rightarrow Z + \gamma$.

TOTAL SIGNAL ACCEPTANCE

The total signal acceptance is measured using the GEANT [8]-based CDF detector simulation. The CI total signal acceptance increases from 13% at $M_{\mu^*} = 100$ GeV/c$^2$ to an asymptotic value of 21% for $M_{\mu^*} > 400$ GeV/c$^2$. For the
The CI exclusion region in the $\mu\mu\gamma$ signature can be produced by several standard model and detector sources: (1) $Z/\gamma' (\to \mu\mu) + \gamma$; (2) $Z/\gamma' (\to \tau\tau) + \gamma$; (3) $Z(\to \mu\mu) + \text{jet}$, where a jet is misreconstructed as a photon; (4) $t\bar{t} \rightarrow \mu\nu\mu\nu vbb$, where a fermion radiates a high-$E_T$ photon; (5) $W(\rightarrow e\nu) + Z(\rightarrow \mu\mu)$ and $Z(\rightarrow ee) + Z(\rightarrow \mu\mu)$, where an electron is misidentified as a photon. The primary background $Z/\gamma' (\to \mu\mu) + \gamma$ is modeled using the ZGAMMA program [9]. The $Z(\to \mu\mu) + \text{jet}$ is estimated using data. The total background prediction is $8.3 \pm 0.9$ events (16.6 $\pm 1.8 \mu\gamma$ combinations). In our ISR $Z + \gamma$ control region, $81 < M_{\mu\mu} < 101 \text{ GeV}/c^2$ and $E_T^\gamma < 50 \text{ GeV}$, we predict $7.4^{+1.2}_{-1.3}$ and observe 5 events.

In the signal region, we observe 17 events with a background prediction of $8.3 \pm 0.9$ events. The background prediction and data are shown as a function of $M_{\mu\gamma}$ in Figure 1(a). Several studies were done to understand the observed excess. The $Z \rightarrow \mu\mu\gamma$ background, where the $\gamma$ is produced via final-state radiation (FSR), is defined by $81 < M_{\mu\mu\gamma} < 101 \text{ GeV}/c^2$. In this region, we observe 11 events with a prediction of $5.5 \pm 0.5$ events, as shown in Figure 1(b). As a check, we lower the $E_T$ cut to 15 GeV and observe 43 events, with a prediction of $38.5 \pm 4.0$ events, as shown in Figure 2. These studies indicate that the excess at low mass is consistent with an upward statistical fluctuation, primarily in $Z \rightarrow \mu\mu\gamma$ FSR. There is no excess at high mass to indicate new physical processes.

**BACKGROUND ESTIMATES AND DATA OBSERVATIONS**

**FIGURE 1.** Background predictions and data observations for $M_{\mu\gamma}$ (a) and $M_{\mu\mu\gamma}$ (b).

**FIGURE 2.** Background predictions and data observations for photon $E_T$. 

GM model, the total signal acceptance increases from 12% at $M_{\mu^*-} = 100 \text{ GeV}/c^2$ to 23% for $M_{\mu^*-} > 300 \text{ GeV}/c^2$.

**$M_{\mu^*}$ LIMITS AND EXCLUSION REGIONS**

A Bayesian approach is used to obtain the upper limits on the experimental cross section at the 95% confidence level (C.L.). For $M_{\mu^*} = \Lambda$ ($M_{\mu^*} = \Lambda/f$) in the CI (GM) model, masses below $853 \text{ GeV}/c^2$ ($221 \text{ GeV}/c^2$) are excluded, as shown in Figure 3. Because the GM exotic muon cross section depends on both $M_{\mu^*}$ and $f/\Lambda$, we plot the two-dimensional $f/\Lambda - M_{\mu^*}$ exclusion region in Figure 4(a). The excited muon CI model is valid for $M_{\mu^*}/\Lambda < 1$; we plot the CI exclusion region in the $M_{\mu^*}/\Lambda - M_{\mu^*}$ plane in (b).
CONCLUSION

We have presented a search for excited and exotic muons in the $\mu \gamma$ channel. No evidence of a $\mu^*$ signal is found. Limits on the excited muon mass are established based on a contact interaction and a gauge-mediated model, the latter of which are the first limits at a hadron collider.

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