Searching for Light Dark Matter with the SLAC Millicharge Experiment

M. Diamond[1,*] and P. Schuster[2,†]

[1]Physics Department, University of Toronto, Toronto, Ontario M5S 1A7, Canada
[2]Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada
(Received 21 August 2013; published 27 November 2013)

New sub-GeV gauge forces ("dark photons") that kinetically mix with the photon provide a promising scenario for MeV–GeV dark matter and are the subject of a program of searches at fixed-target and collider facilities around the world. In such models, dark photons produced in collisions may decay invisibly into dark-matter states, thereby evading current searches. We reexamine results of the SLAC mQ electron beam dump experiment designed to search for millicharged particles and find that it was strongly sensitive to any secondary beam of dark matter produced by electron-nucleus collisions in the target. The constraints are competitive for dark photon masses in the $\sim$1–30 MeV range, covering part of the parameter space that can reconcile the apparent $(g-2)_\mu$ anomaly. Simple adjustments to the original SLAC search for millicharges may extend sensitivity to cover a sizable portion of the remaining $(g-2)_\mu$ anomaly-motivated region. The mQ sensitivity is therefore complementary to ongoing searches for visible decays of dark photons. Compared to existing direct-detection searches, mQ sensitivity to electron-dark-matter scattering cross sections is more than an order of magnitude better for a significant range of masses and couplings in simple models.

DOI: 10.1103/PhysRevLett.111.221803 PACS numbers: 95.35.+d, 12.60.−i, 14.80.−j, 41.75.Ht

Identifying dark matter is one of the most pressing open problems in fundamental physics. Although a rich experimental program continues to probe dark-matter (DM) interactions for masses in the 10 GeV–TeV range, sensitivity to DM at lower masses remains remarkably poor. There are well-motivated scenarios of sub-GeV DM [1], especially those that include new gauge forces ("dark forces") that kinetically mix with the photon [2,3]—these models can account for the observed relic density consistently with all available data and have been the focus of intense discussion in the literature.

In this Letter, we show that the electron beam dump millicharge search at SLAC (mQ) was sensitive to sub-GeV DM interacting through dark photons. In a simple model, we compute the total detection yield for MeV-scale DM components that would have been produced in the mQ target. We use these yields and the original mQ analysis to establish constraints on such DM. The new constraints cover part of the parameter space that can reconcile the apparent $(g-2)_\mu$ anomaly, and future adjustments to the original analysis may significantly extend sensitivity. We also provide estimates for the level of sensitivity that might be attained with a redesigned version of this experiment at modern high-intensity electron beam facilities. These results highlight the potential for using electron beam dump experiments to powerfully probe *any* DM components (or other long-lived particles) that couple to leptons and quarks (see Ref. [4]), and they complement the ongoing effort to search for dark matter using proton beams [5–7] and dark photons in visible decay channels [8].

As a simple example, we consider a benchmark model consisting of a long-lived fermion χ coupled to a dark sector $U(1)_D$ gauge boson that kinetically mixes with the photon. The Lagrangian is

$$\mathcal{L} \supset \frac{\epsilon_Y}{2} F^{Y,\mu\nu} F_{D,\mu\nu} - \frac{1}{4} F_D^{\mu\nu} F_{D,\mu\nu} + \frac{m_{A'}^2}{2} A'^{\mu} A'_{\mu} + g_D J^{\mu}_{A'} A'_{\mu},$$

where $F_{Y,\mu\nu} = \partial_{[\mu} B_{\nu]}$ is the field strength tensor for standard model (SM) hypercharge $U(1)_Y$, $F_{D,\mu\nu} = \partial_{[\mu} A'_{\nu]}$ for the new $U(1)_D$, and $J^{\mu}_{A'}$ is the interaction current of the A' with any dark-sector fields, in this case, a fermion χ. We define $\epsilon \equiv \epsilon_Y \cos\theta_W$, where θ_W is the SM weak mixing angle, and $\alpha_D \equiv (g_D^2/4\pi)$. A field redefinition removes the kinetic mixing term and generates a coupling $\epsilon e A'_\mu J^\mu_{\rm EM}$ between the A' and SM electrically charged particles. This effectively gives charged particles a small dark force charge, without giving dark-sector particles electric charge. Kinetic mixing with $\epsilon \sim 10^{-3}$–10^{-2} can be generated by loops of heavy fields charged under both $U(1)_D$ and $U(1)_Y$ and is a natural range to consider [9].

Previous literature has considered numerous constraints on sub-GeV DM derived from the cosmic microwave background, supernovae, B-factory searches, rare Kaon decay measurements, and precision $(g-2)_\mu$ and $(g-2)_e$ measurements [10]. For comparison to the mQ sensitivity, we include the constraints relevant for the low $m_{A'}$ range. A companion paper [4] discusses the viability of using the simple benchmark Lagrangian above to model fixed-target physics, where χ can be all of or a subdominant part of the DM consistent with all available data.

In the mQ experiment, 1.35 Coulombs ($8.4 \times 10^{18} e^-$) of 29.5 GeV electrons were deposited on a tungsten production target. Approximately 90 m of sandstone separated the target from the detector (Bicron-408 plastic scintillator), which was sensitive to signals as small as a single scintillation photon and subtended a solid angle of 2×2 mrad^2. SM particles essentially ranged out in the sandstone, while any penetrating particles like mQs were able to reach the detector and trigger a small scintillation signal [11]. Collected data consisted entirely of the timing and height of photomultiplier tube (PMT) pulses. No significant signal was found over a rather large ($\sim$ 146 K) but well-measured instrumental background [12].

As illustrated in Fig. 1, this setup would have produced significant numbers of A''s in the target via a bremsstrahlunglike process. We examine the case of prompt invisible decay $A' \to \chi\bar{\chi}$; the χ's would have traversed the sandstone given their large mean free path. The secondary beam of χ's could have deposited energy in the mQ detector via Z^2-enhanced elastic scattering off carbon nuclei (and subdominantly though quasielastic χ-nucleon scattering, which we neglect).

Our analysis assumes $2m_\chi < m_{A'}$ (on-shell A'), but we expect this approach to have sensitivity even for $2m_\chi > m_{A'}$, where χ's are produced via an *off-shell* A' (see Ref. [9]). We used the procedure in Ref. [9], based on a variation on the Weizsacker-Williams method, for computing A' production. We also simulated all reactions using MADGRAPH and MADEVENT 4 [13].

The typical emission angle for the A' relative to the beam is parametrically smaller than the opening angle of A' decay products and is collinear to a good approximation. Neglecting m_e, $(d\sigma_{A'\mathrm{prod}}/dx) \approx (8Z^2\alpha^3\epsilon^2 x \times Log/3m_{A'}^2)(3+(x^2/1-x))$, where Z is the atomic number of the target nucleus, $x \equiv E_{A'}/E_0$ with E_0 the lab-frame energy of the beam electron, and Log is an $O(10)$ factor dependent upon kinematics, atomic screening, and nuclear size effects [9].

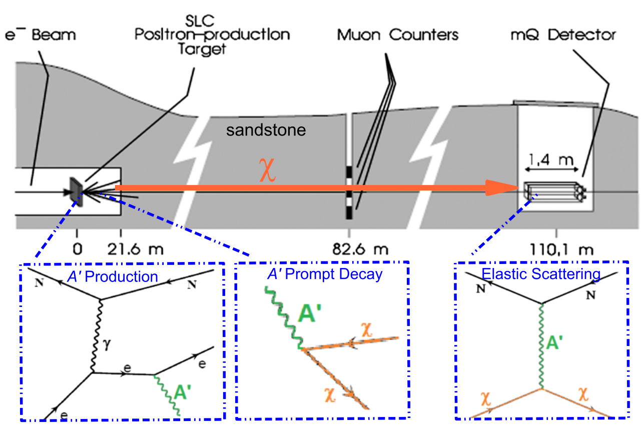

FIG. 1 (color online). Layout of the SLAC mQ experiment [11]. We investigate the possibility of A' production in the target, followed by prompt decay to long-lived dark-sector particles χ, which could traverse the sandstone and undergo elastic scattering off carbon nuclei in the detector.

Since the angular size of the mQ detector was $\theta_d \approx 2$ mrad, angular acceptance limits overall sensitivity. Produced A''s typically carry most of the beam energy, with $x_{\mathrm{median}} \sim 1 - \min((m_e/m_{A'}), (m_{A'}/E_0))$ [9]. In the $A' \to \chi\chi$ decay, the angle θ_χ of the χ's relative to the beam line scales as $m_{A'}/E_0$. The angular distribution of χ is shown in Fig. 2 for reference.

Following the procedure in Ref. [9], we computed the coherent scattering illustrated in Fig. 1. With T the lab-frame kinetic energy of the recoiling nucleus of mass $M \gg T$, the coherent scattering cross section is approximately

$$\frac{d\sigma_{\chi N\mathrm{scatt}}}{dT} \approx \frac{-8\pi\alpha\alpha_D\epsilon^2 Z^2 M}{(m_{A'}^2 + 2MT)^2}. \tag{1}$$

The recoil distributions in full simulation for representative $m_{A'}$ are shown in Fig. 3. The nuclear recoil energy is typically $O(0.025\text{–}1.0)$ MeV. Based on neutron scattering experiments with a plastic scintillator, a proton recoiling with kinetic energy 1 MeV should produce $\sim$770–1530 scintillation photons, and 0.1 MeV $\sim$50–65 γ's [14,15]. (There is some variation between experiments, and nonlinearity in γ's vs proton energy.) The quenching factor for a C nucleus exceeds that for a proton; an energy-dependent ratio can be obtained from the semiempirical fits in Ref. [15], yielding $\sim$330–655 γ's for a 1 MeV recoiling C and $\sim$40–50 γ's for 0.1 MeV. To convert scintillation yield to photoelectrons in mQ, Ref. [12] gives PMT quantum efficiency 20%, geometric acceptance 20%, and a calibration factor $\frac{17.4}{22}$. Therefore, a 1 MeV recoiling C would yield $\sim$10.5–20.7 PEs, and 0.1 MeV $\sim$1.3–1.6 PEs. Figure 3 shows that with a $\sim$0.1 MeV threshold for producing a photoelectron (PE), about 20% of the χ-C events would produce at least a single PE at $m_{A'} = 0.03$ GeV and 90% at $m_{A'} = 0.25$ GeV.

In finding the total number of χ produced in the target, we can neglect χ production in lower energy showers

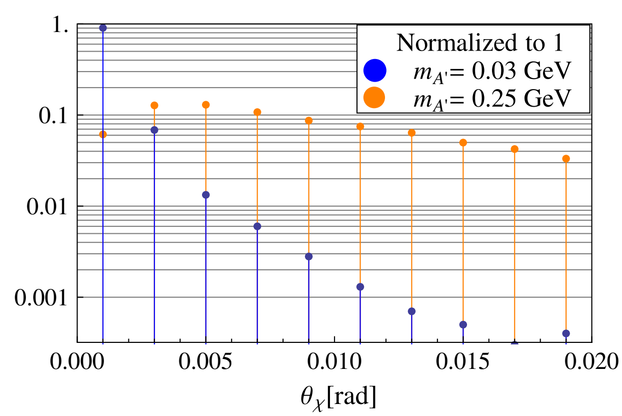

FIG. 2 (color online). Sample MG/ME χ angular distributions ($m_\chi = 10$ MeV). mQ angular acceptance is 0.002 rad. $m_{A'} = 0.03$ GeV (steep curve) is 90% accepted. $m_{A'} = 0.25$ GeV (shallow) is 6% accepted.

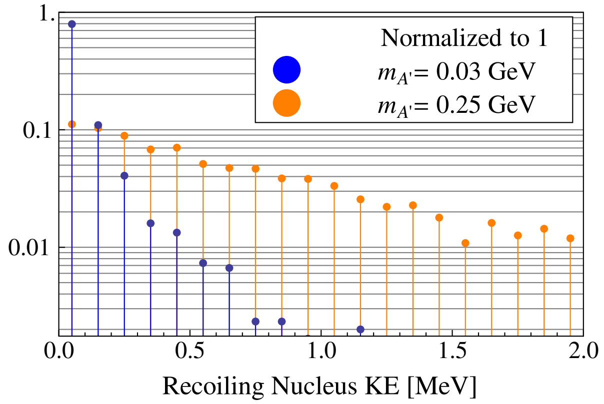

FIG. 3 (color online). Sample nuclear recoil distributions, generated using MG/ME ($m_\chi = 10$ MeV), at the approximate median χ lab-frame energy (12 GeV for $m_{A'} = 0.03$ GeV, 27 GeV for $m_{A'} = 0.25$ GeV).

initiated by the beam electron because the angular acceptance of mQ is small. To account for the more important effect of the energy loss of the beam e^- as it traverses the target, we use an "effective" radiation length of $T_{\rm eff} = 1$. This can be justified as follows. For the small angular size of mQ, the angular acceptance scales as E^2 (for low A' masses), where E is the beam electron energy. Thus, the E^2-weighted average of the beam energy distribution integrated over the thickness of the target (6 radiation lengths) and energy yields an effective thickness (in units of radiation length). Using the beam energy distribution $I(E, E_0)$ in Ref. [9], we obtain $T_{\rm eff} = \int ds \int dE (E/E_0)^2 I(E, E_0, s) = \frac{3}{2}\ln 2 \approx 1$. To a good approximation, the differential production yield for fixed χ energy E_χ is $(dN_\chi/dE_\chi) \approx 2T_{\rm eff}(N_e N_0 X_0/A)(d\sigma_{\chi{\rm prod}}/dE_\chi)$, where N_e is the total number of beams e^- incident on target, N_0 is Avogadro's number, X_0 is the unit radiation length of target material, and A is the target atomic mass. The differential production cross section at fixed χ energy $(d\sigma_{\chi{\rm prod}}/dE_\chi)$ was computed with full simulation. To find the number of expected $\chi - N_d$ scattering events in the mQ detector $N_{\rm evts}$, we include angular acceptance cuts with full simulation, which reduces N_χ to $N_{\chi{\rm acc}}$. The final yield is then

$$N_{\rm evts} = \int dE_\chi \frac{dN_{\chi{\rm acc}}}{dE_\chi} \sigma_{\chi N{\rm scatt}}(E_\chi) t_{\rm det} \rho_{\rm det}, \qquad (2)$$

where $t_{\rm det}$ is the detector thickness and $\rho_{\rm det}$ is the number density of C nuclei in the detector.

An order-of-magnitude estimate can be obtained by $N_{\chi{\rm acc}} \approx 2N_e P_{\rm prod} P_{\rm scatt} F$, where the probability per beam e^- to produce a χ pair is

$$P_{\rm prod} \approx 1.2 \times 10^{-11}\left(\frac{\epsilon^2}{10^{-6}}\right)\left(\frac{0.05\ {\rm GeV}}{m_{A'}}\right)^2,$$

the probability of χ-C coherent nuclear scattering is

$$P_{\rm scatt} \approx 2.5 \times 10^{-8}\left(\frac{\epsilon^2}{10^{-6}}\right)\left(\frac{0.05\ {\rm GeV}}{m_{A'}}\right)\frac{\alpha_D}{\alpha_{\rm EM}},$$

and $F \sim (\theta_d E_0/m_{A'})^2$ is the fraction of χ's that pass angular acceptance cuts. The agreement between this estimate and the full simulation is quite good.

Using five "benchmark" points with $m_\chi = 0.01$ GeV, in the $m_{A'} = 0.03$–0.25 GeV range, we evaluated the limits in the $(m_{A'}, \epsilon)$ parameter space by comparing total yields to single PE mQ background measurements. Figure 4 shows the 2σ constraints that would be obtained for $m_\chi = 10$ MeV with no background reduction and with $100\times$ reduction in background. We assume every scattering event in the detector produces at least one photoelectron and is observed. Losses from failure to produce any PEs could reduce sensitivity by a factor of ~ 2 in the lowest (~ 30 MeV) part of the $m_{A'}$ range—a dedicated study by mQ would be required to remove this uncertainty. Beyond this effect, the limits are conservative in that we have neglected secondary showering in the target that could increase χ production, although we expect this effect to be negligible given the small acceptance of mQ. Additional simulation uncertainties on our results are at the $\sim 10\%$ level.

The mQ data analysis estimated $\sim 94\%$ of the 146 061 background events involved only a single PE [12]. For $m_{A'} > 100$ MeV, scattering events should produce much more than one PE, so it should be possible to use a PMT pulse-height cut to help separate χ signal from background. It is reasonable to expect such a cut to improve S/B by at least an order of magnitude in the higher $m_{A'}$

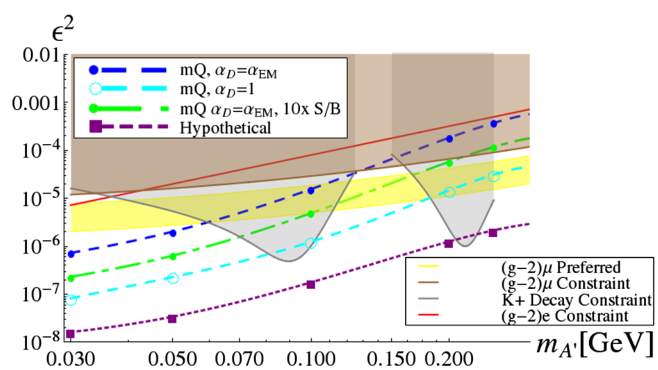

FIG. 4 (color online). For each benchmark $m_{A'}$ with $m_\chi = 0.010$ GeV, the ϵ that would correspond to a 2σ result in SLAC mQ (see the text for comments about known uncertainties in these results). Note the dependence on α_D and the improvement that would come from achieving $10\times$ the reported mQ S/B. These results change fairly little with m_χ. Overlaid on existing $A' \to$ inv constraints, $(g-2)_e$ is a 2σ power constrained limit [17] (see Ref. [4] for discussion). The yellow band represents the region favoured by the $(g-2)_\mu$ anomaly [3]. The gray band represents constraints from $K^+ \to \pi^+$inv decays [3,18]. Note that LSND would be expected to provide additional constraints, at the level of $\epsilon^2 \sim 10^{-6}$–10^{-8} for $m_{A'} \le 0.05$ GeV.

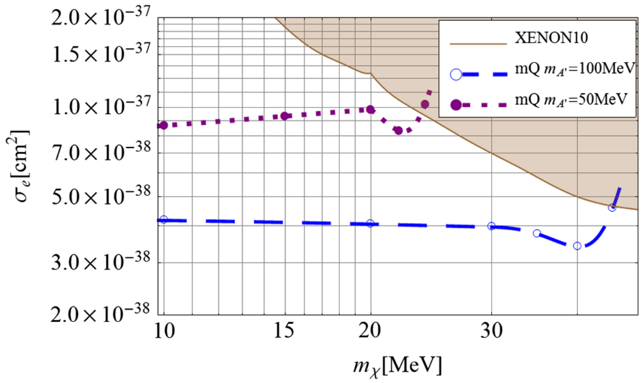

FIG. 5 (color online). For benchmark m_χ with $m_{A'} = 0.10$ GeV and $m_{A'} = 0.05$ GeV ($\alpha_D = \alpha_{\rm EM}$), the constraints on the scattering cross section of DM off e^- corresponding to a 2σ result in mQ, assuming the reported mQ signal to background. Overlaid on the XENON10 direct-detection results [16]; direct comparison is valid only assuming χ accounts for all the DM in the Universe.

range because the vast majority of the background is single PE noise. Given significant background reduction, mQ would be able to cover a sizable swath of unexplored parameter space, including part of the $(g-2)_\mu$ anomaly-motivated region for $m_{A'} \sim 0.03$–0.160 GeV. It should be noted that there is currently a MiniBooNE proposal for further running specifically to cover this range [7]. Likewise, LSND could likely impose constraints at the level of $\epsilon \sim 10^{-4}$–10^{-3} for $m_{A'} < O(100\text{ MeV})$, $m_\chi \ll (m_{A'}/2)$ [6].

Our analysis results can be interpreted as constraints on $e^- - \chi$ scattering cross sections σ_e, which can also be probed by direct detection. Recent results from XENON10 established limits on σ_e as a function of DM mass in the 1–1000 MeV range [16]. Using benchmark points shown in Fig. 5, we employed mQ constraints on $(m_{A'}, \epsilon)$ to establish constraints on σ_e via $\sigma_e = (16\pi\alpha_{\rm EM}\alpha_D\epsilon^2 m_e^2/m_{A'}^4)$. If χ accounts for *all* the DM, mQ sets limits more stringent than XENON10 for $m_\chi < 20$ MeV. χ could instead be a subdominant DM component, in which case XENON10 constraints are weakened.

It is convenient to consider mQ because the data already exist—but this experiment was not optimized for light DM searches. Characteristics that would make future e^- beam dumps even more effective for this purpose include optimal sensitivity to quasielastic χ-nucleon processes, broader angular acceptance, greater luminosity, and an effective background-rejection scheme [4]. The main backgrounds are typically intrinsic detector noise, cosmic rays, γ's from ambient radioactivity, and fast neutrons (produced from the target). Neutral-current ν interactions are negligible [12]. As an exercise, each benchmark point in Fig. 4 was recalculated for a luminosity of 10^{22} electrons, with no angular acceptance cuts. This luminosity could be reasonably achieved at a facility such as Jefferson Laboratory or a future linear collider. Sensitivity to 500 signal events, for example (realistic for $\gg 1$ PE yield signals), would cover an impressive swath of parameter space (dotted line in Fig. 4).

In conclusion, we find that the SLAC mQ search is indeed relevant for exploring the parameter of models where a dark photon of mass ∼30–300 MeV decays to lighter, long-lived χ's. This includes a parameter region in which dark photon models can alleviate the current $(g-2)_\mu$ discrepancy, and adjustments to the original SLAC analysis are expected to strengthen the constraints—or make a discovery—in this region. In a broader context, our analysis provides a proof of concept for the use of e^- beam dumps to search for DM particles with masses of tens to hundreds of MeV, a regime that poses great difficulty for direct detection and collider experiments. In simple models, we find that mQ constrains the DM-electron scattering cross section $\sigma_e \lesssim 10^{-38}$–$10^{-37}$ cm^2 for $m_\chi \sim 10$–40 MeV—up to an order of magnitude stronger than the leading direct-detection limits where applicable.

We thank Natalia Toro, Gordan Krnjaic, and Eder Izaguirre for helpful feedback and discussion. This research was supported in part by the Perimeter Institute for Theoretical Physics. Research at the Perimeter Institute is supported by the Government of Canada through Industry Canada and by the Province of Ontario through the Ministry of Research and Innovation.

*m.diamond@mail.utoronto.ca
†pschuster@perimeterinstitute.ca

[1] C. Boehm, T. Ensslin, and J. Silk, J. Phys. G **30**, 279 (2004); P. Fayet, Phys. Rev. D **70**, 023514 (2004); P. Fayet, Phys. Rev. D **75**, 115017 (2007).
[2] B. Holdom, Phys. Lett. **166B**, 196 (1986); M. Pospelov, A. Ritz, and M. B. Voloshin, Phys. Lett. B **662**, 53 (2008); N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, and N. Weiner, Phys. Rev. D **79**, 015014 (2009).
[3] M. Pospelov, Phys. Rev. D **80**, 095002 (2009).
[4] E. Izaguirre, G. Krnjaic, P. Schuster, and N. Toro (unpublished).
[5] P. de Niverville, M. Pospelov, and A. Ritz, Phys. Rev. D **84**, 075020 (2011); P. de Niverville, D. McKeen, and A. Ritz, Phys. Rev. D **86**, 035022 (2012).
[6] B. Batell, M. Pospelov, and A. Ritz, Phys. Rev. D **80**, 095024 (2009).
[7] R. Dharmapalan *et al.* (MiniBooNE Collaboration), arXiv:1211.2258.
[8] S. Abrahamyan *et al.* (APEX Collaboration), Phys. Rev. Lett. **107**, 191804 (2011); H. Merkel *et al.* (A1 Collaboration), Phys. Rev. Lett. **106**, 251802 (2011); R. Essig, P. Schuster, N. Toro, and B. Wojtsekhowski, J. High Energy Phys. 02 (2011) 009; B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **103**, 081803 (2009); B. Echenard, Adv. High Energy Phys. **2012**, 514014 (2012); D. Babusci *et al.* (KLOE-2 Collaboration), Phys. Lett. B

720, 111 (2013); P. Adlarson *et al.* (WASA-at-COSY Collaboration), Phys. Lett. B **726**, 187 (2013).

[9] J. D. Bjorken, R. Essig, P. Schuster, and N. Toro, Phys. Rev. D **80**, 075018 (2009); R. Essig, P. Schuster, and N. Toro, Phys. Rev. D **80**, 015003 (2009).

[10] J. Hewett, H. Weerts, R. Brock, J. Butler, B. Casey *et al.*, arXiv:1205.2671.

[11] A. Prinz, R. Baggs, J. Ballam, S. Ecklund, C. Fertig *et al.*, Phys. Rev. Lett. **81**, 1175 (1998).

[12] A. Prinz, Ph.D. thesis, Stanford University, 2001.

[13] J. Alwall, P. Demin, S. de Visscher, R. Frederix, M. Herquet, F. Maltoni, T. Plehn, D. L. Rainwater, and T. Stelzer, J. High Energy Phys. 09 (2007) 028.

[14] S. P. Ahlen, T. M. Liss, C. Lane, and G. Liu, Phys. Rev. Lett. **55**, 181 (1985).

[15] L. Reichhart, D. Y. Akimov, H. Araujo, E. Barnes, V. Belov *et al.*, Phys. Rev. C **85**, 065801 (2012).

[16] R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, and T. Volansky, Phys. Rev. Lett. **109**, 021301 (2012).

[17] G. Giudice, P. Paradisi, and M. Passera, J. High Energy Phys. 11 (2012) 113; H. Davoudiasl, H.-S. Lee, and W. J. Marciano, Phys. Rev. D **86**, 095009 (2012); M. Endo, K. Hamaguchi, and G. Mishima, Phys. Rev. D **86**, 095029 (2012).

[18] A. Artamonov *et al.* (E949 Collaboration), Phys. Rev. Lett. **101**, 191802 (2008).