Detecting Dipolar Dark Matter in Beam Dump Experiments

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September 9, 2015

Beam Dump Experiments

- Direct and indirect searches for Dark Matter(DM) have been analysed in various models of DM
- Complimenting these searches are the so called **beam dump experiments** or **fixed target experiments**
- Beam dump experiments involve high energy beam incident on fixed target
- DM particles are produced in the high energy collision, subsequently detected in suitable detector
- We focus here on **E613** experiment conducted at Fermilab originally to study prompt muon neutrino production
- Advantage of such experiment over direct detection is higher luminosity
- On the other hand only light DM masses can be probed (1-10 GeV)

Dipolar DM model

- Previously *Soper etal, Phys. Rev. D* **90**, *no. 11, 115005 (2014)*, discussed E613 constraints on DM in context of dark vector boson
- We follow the same approach to study constraints on "Dipolar DM" model
- Dipolar DM model assumes DM couples to photons via loops to give rise to electric and magnetic dipole moments
- The effective lagrangian for such interactions can be written as

$$\mathcal{L}_{ddm} = -\frac{i}{2}\bar{\chi}\sigma_{\mu\nu}(\mu + \gamma^5\mathcal{D})\mathcal{F}^{\mu\nu}$$

E613 Beam Dump Experiment

- E613 experiment comprises of a 400 GeV proton beam that strikes a Tungsten target producing a beam of DM particles which pass through appropriate shielding
- A lead detector placed after the shielding then detects these DM particles as they scatter off lead nuclei

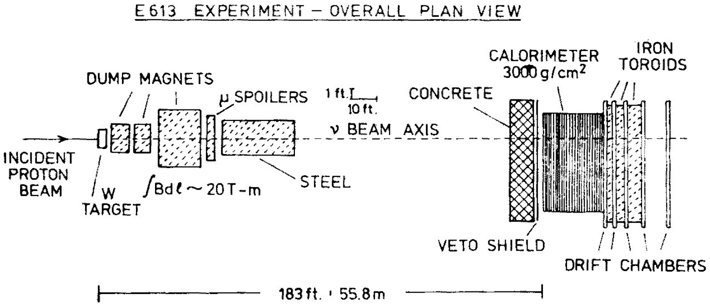
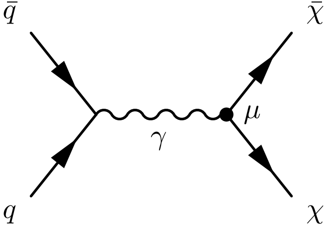


Fig. 2. E613 overall plan view

DM production from proton beam

- DM particles are produced when proton beam strikes the Tungsten target



- Calculate cross section for the process $p\,p \to \chi\chi$ (using MadGraph)
- Distribution of DM thus produced is

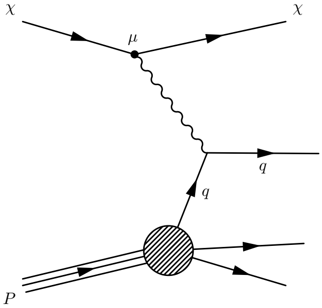
$$\frac{dN}{dEd\theta} = A\frac{d\sigma(pp \to \chi\chi)}{dEd\theta} L_T n_T n_p$$

- No. of DM particles produced is restricted by detector geometry,

$$\frac{dN}{dE} = \int_0^{\theta_{max}} d\theta \frac{dN}{dEd\theta}, \;\; \theta_{max} = 0.0134$$

DIS of DM

- Scattering of light DM particles produced from a 400 GeV proton beam can be treated as deep inelastic scattering (DIS)
- DIS of DM involves dipolar interaction DM with quarks via photon



DIS of DM

- Following DIS formalism we can write

$$\frac{d\sigma}{d\nu dQ^2} = \frac{e^2 g_{dipole}^2}{16\pi m_N(E_\chi^2 - m_\chi^2)} \frac{L^{\mu\nu} W_{\mu\nu}}{Q^4}$$

- We calculate the leptonic piece as
  μDM :

$$\begin{aligned} L^{\mu\nu} =& Q^2 \left[4p_\chi^\mu p_\chi^\nu - 2\left(k^\mu q^\nu + q^\mu k^\nu\right) + q^\mu q^\nu\right] \\ & - 4m_\chi^2 \left(Q^2 g^{\mu\nu} + q^\mu q^\nu\right) \end{aligned}$$

  EDM :

$$L^{\mu\nu} = Q^2 \left[4k^\mu k^\nu - 2\left(k^\mu q^\nu + q^\mu k^\nu\right) + q^\mu q^\nu\right]$$

DIS of DM

- Finally we end up with the differential scattering cross section μDM :

$$d\sigma = \frac{e^2\mu^2}{16\pi}\frac{d\nu dQ^2}{E^2 - m_\chi^2}\frac{\nu}{Q^4}\left[\frac{Q^2\left(2E-\nu\right)^2}{\nu^2+Q^2} - Q^2 + 4m_\chi^2\right] \sum_q x f_{q/A}(x, Q^2)$$

  EDM :

$$d\sigma = \frac{e^2\mathcal{D}^2}{16\pi}\frac{d\nu dQ^2}{E^2 - m_\chi^2}\frac{\nu}{Q^4}\left[\frac{Q^2\left(2E-\nu\right)^2}{\nu^2+Q^2} - Q^2 - 4m_\chi^2\right] \sum_q x f_{q/A}(x, Q^2)$$

- We use pdfs for lead nucleus provided at leading order by Hirai-Kumano-Nagai

E613 constraint

- The differential scattering cross section is then integrated over the following limits

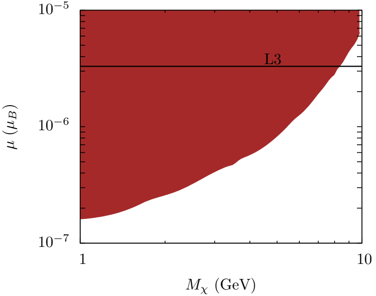
$$E_{\rm cut} < \nu < E - m_\chi \qquad (1)$$

$$Q_l^2 < Q^2 < 4(k^2 - E\nu) - Q_l^2 \qquad (2)$$

where $Q_l^2 = \dfrac{2m_\chi^2\nu^2}{k^2 - E\nu + \sqrt{(k^2 - E\nu)^2 - m_\chi^2\nu^2}}$ with $k^2 = E^2 - m_\chi^2$ and $E_{\rm cut} = 20$ GeV

- Cross section so obtained gives the MFP $\lambda = \rho\sigma$ and the probability of DM scattering inside detector, $P = 1 - e^{-L/\lambda}$
- Total no. of events : $N_{\rm ev} = \int dE \, [P_{\rm Pb}(1 - P_{\rm Fe})] \, \dfrac{dN}{dE}$
- Only those values of *mchi*, μ and $\mathcal{D}$ allowed for which no. of events less than 180

Results



- Bound on magnetic dipole moment of DM from helioseismological data is estimated to be 1.6×10^{-17} e-cm, for DM mass < 4.3 GeV (Lopes etal, Astrophys. J. Lett. **780**, L15 (2014))
- Momentum and/or velocity dependent scattering of DM find most favorable DM mass to be ~ 3 GeV (Vincent etal, JCAP **1508**, no. 08, 040 (2015))

Summary

- We study constraint from Beam Dump experiment E613 consisting of a 400 GeV proton beam striking Tungsten target in context of Dipolar DM model
- We see a low mass region (1-10 GeV) of DM which is strongly constrained by Beam Dump experiment
- Bounds from solar physics data are also broadly compatible with this mass range and dipole moment
- Dipolar DM model offers an alternative that is compatible with constraints from wide ranging experimental data from beam dump experiments to helioseismology
- Future experiments like the new fixed target facility proposed at the CERN SPS called SHiP (Search for Hidden Particles) can explore this possibility